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European Strategy for Particle Physics Accelerator R&D Roadmap

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European Strategy for Particle Physics - Accelerator R&D Roadmap
Final Report

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Abstract
The 2020 update of the European Strategy for Particle Physics emphasised the importance of an intensified and better-coordinated programme of accelerator R&D, supporting the design and delivery of future particle colliders in a timely, affordable and sustainable way. The European Laboratory Directors Group was mandated to lead the process of producing such a roadmap by the end of 2021. This Interim Report summarises the findings to date of the five expert panels set up to deliver the roadmap. It is intended to give an indication of the scope and nature of the final roadmap, and to generate further feedback and input from stakeholders.

Keywords
Particle Physics; European Strategy; Accelerator; R&D; Roadmap.

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Contents

1 Introduction

1.1 Background

The 2020 update of the European Strategy for Particle Physics[1] (ESPPU) outlined the current status and prospects in the field, and delineated priorities for future particle physics collider facilities. In time order, these are: completion and commissioning of the CERN High Luminosity LHC (HL-LHC); a future electron-positron Higgs factory; and a future energy-frontier collider at the highest achievable energy.

It is recognised in the community, and was acknowledged in the ESPPU, that construction of the next generations of colliders will be extremely challenging. There are major technical difficulties in meeting the exceptional performance requirements of the new machines, which cannot be built using technologies available today. As documented throughout this report, achieving our scientific goals will require the exploration and maturation of new technologies, materials and techniques well beyond the current state of the art. Since many of these technologies are unique to particle physics in their (current) application, then this can only result from a new and extended phase of R&D, organised within our own institutes and in conjunction with industry and related scientific fields. This is similar to the precursor R&D that culminated in the successful delivery of previous generations of machines, but is likely to be significantly longer in duration, and more costly in both absolute terms and as a fraction of the total budget for international particle physics.

In addition to technical challenges, it is clear that there are practical issues in delivering the future machines. There will always be limits to the level of worldwide investment available to our field to support both the construction and operation of new facilities. It is also clear that optimal scientific progress depends on the timely and regular availability of new data from previously unexplored regimes, as well as on continuous opportunities to attract and train future generations of scientists, engineers and technicians. Therefore, the accelerator R&D programme must focus not only on improving machine performance, but also on making the new machines available at affordable cost, on useful timescales, and with appropriate consideration for sustainability. These requirements may require changes in the way we approach both R&D and decision-making around new facilities, and in the way we organise cooperative developments.

The ESPPU commented that:

> *The particle physics community should ramp up its R&D effort focused on advanced accelerator technologies.*

and that

> *The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.*

The European Laboratory Directors Group (LDG) was mandated by CERN Council in 2021 to oversee the process of developing an Accelerator R&D Roadmap, in parallel with the Detectors R&D Roadmap developed under the guidance of ECFA. Although LDG members represent the majority of large laboratories and national structures through which the majority of accelerator R&D investment is made, it is clear that the first step any such process should be the gathering of inputs and evidence from the widest possible set of stakeholders in the European and International fields. To this end, a set of expert panels has been set up, and this report summarises their initial findings. A second, final, report containing recommendations and delivery plans (i.e. the roadmap itself) will be presented to CERN Council in December 2021, and subsequently published.

[1] https://europeanstrategy.cern/home

1.2 Goals and content of the Roadmap

The European Strategy for Particle Physics represents the consensus view of the European field on the priorities for current and future work. Although it is not prescriptive on actions or investments to be undertaken by countries, laboratories, or institutes, it forms a structure around which local decisions and plans can be made with confidence and certainty. In a field where practically every new development requires extended cooperation between many partners, and investment over and extended period, this is an essential element in ensuring coherence. As an extension and specialisation of the Strategy, the Roadmap should play a similar role. It should express the consensus view of stakeholders on the pathway to delivering the necessary future facilities for particle physics, and likewise form an established basis for national and local planning.

The Roadmap is required to:

– provide an agreed structure for a coordinated and intensified programme of particle accelerator R&D, including into new technologies, across national laboratories and CERN,
– be compatible and commensurate with corresponding roadmaps in detectors, computing and other developments, with a compatible timeline and deliverables,
– Be based on the goals of the European Strategy for Particle Physics, with its implementation defined through consultation with the community and, where appropriate, through the work of expert panels
– Take into account, and coordinate with, international activities and work being carried out in other related scientific fields, including the development of new large-scale facilities
– Specify a series of concrete deliverables, including demonstrators, over the next decade
– Be designed to inform, through its outcomes, subsequent updates of the European Strategy for Particle Physics.

The lattermost point is crucial. The next updates to the Strategy are likely to express significant decisions on the future direction of collider physics. These decisions can only be made if full and robust information on the feasibility of each possible future option is available. The Roadmap must explicitly set down the steps to be taken over the next decade so that a full picture on the benefits, challenges, feasibility, risk and costs of each new development is in place.

The ESPPU explicitly identified a number of key areas where an intensification of R&D is required to meet scientific goals, which have been mapped onto five Roadmap study areas:

1. Further development of high-field superconducting magnet technology
2. Advanced technologies for superconducting and normally conducting RF structures
3. Development and exploitation of laser / plasma acceleration techniques
4. Studies towards future bright muon beams and muon colliders
5. Advancement and exploitation of energy-recovery linear accelerator technology

Expert panels have been set up to examine each of these areas, with membership drawn primarily from European accelerator institutes, but with international representation. The overall structure set up to deliver the roadmap is shown in Fig. 1.1. Another key aspect to future work in accelerator physics is the attraction, training and career management of researchers. However, the issues in this area are very close to those for detector-focussed particle physicists, and so both have been considered in common by Task Force 9 of the ECFA Detector R&D Roadmap, and the findings will be documented there.

The study areas are of course not entirely independent, with technological cross-links between the 'fundamental' areas of acceleration and magnets, and the more 'applied' areas of muon beams and ERLs. Neither are all the areas at equal stages of maturity. In the magnets and RF areas, the Roadmap constitutes the next phase of planning in an existing and mature R&D programme; for laser / plasma and ERL, it represents an attempt to capture the specific particle physics requirements and plans within ongoing R&D programmes of much wider applicability; for muons, it will be the first phase of a new development in the European field. It is clearly recognised that these topics form only a subset of the necessary R&D to deliver the necessary new technologies for future facilities. Moreover, any investment into new R&D will necessarily compete with the need to complete existing projects and to conduct studies and detailed planning for nearer-term new machines. The balance must be carefully struck, taking into account both the short- and long-term future of the field.

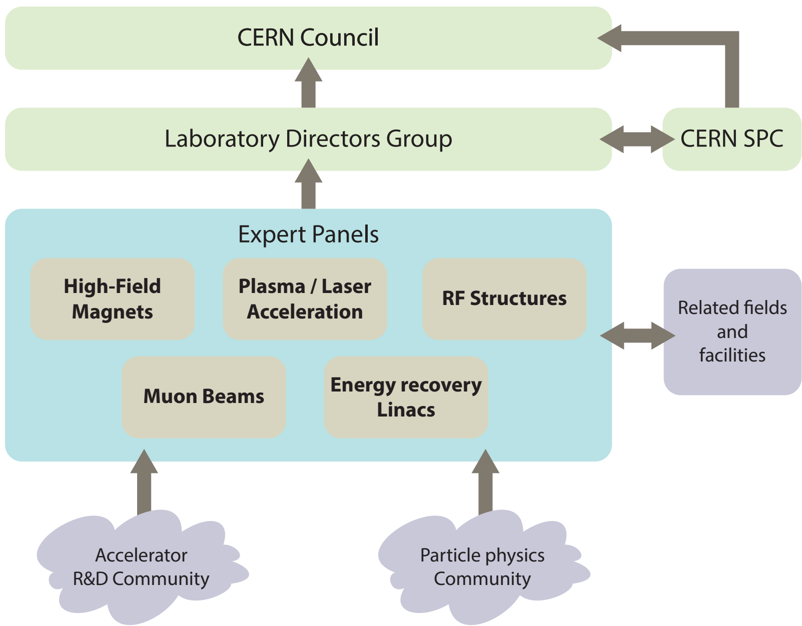

Fig. 1.1: Roadmap panel structure.

1.3 Assumptions concerning future facilities

Although the ESPPU highlighted a number of future facilities, it did not provide a plan or make assumptions on when they might be delivered. Indeed, the information required to make such a plan is intended to be an output of the R&D phase. On the other hand, without some common initial assumptions on the target dates and parameters of future machines, it is not possible to motivate, construct and balance an R&D strategy for either accelerators or detectors.

To this end, Fig. 1.2 illustrates an indicative future timeline for future collider and larger accelerator facilities. The projects shown in the diagrams are at differing stages of definition, approval and technical maturity. The dates shown in the diagram therefore have low precision, and are intended to represent the earliest 'feasible start date' (where a schedule is not already defined), taking into account the necessary steps of approval, development and construction for machine and civil engineering. They do not constitute any form of plan or recommendation, and indeed several options presented are mutually exclusive. Furthermore, the projects mentioned here are limited to those mentioned in the ESPPU. For other proposed projects (e.g. the proposed CEPC in China) there are large overlaps and synergies, and the specific needs of these projects have been considered by the expert panels where relevant.

The timelines—and potentially the scope—of the projects will naturally change depending on both future strategic decisions and the outcomes of R&D developments. The objective of both the accelerator and detectors roadmaps is to ensure that: (a) the basic R&D phase is not the limiting step, i.e. that

R&D is started sufficiently early and prioritised correctly to meet the needs of the long-term European particle physics programme in its global context; and (b) that the outcomes of the R&D programme are able to provide the necessary information on the feasibility and cost of future deliverables to allow such decisions to be made.

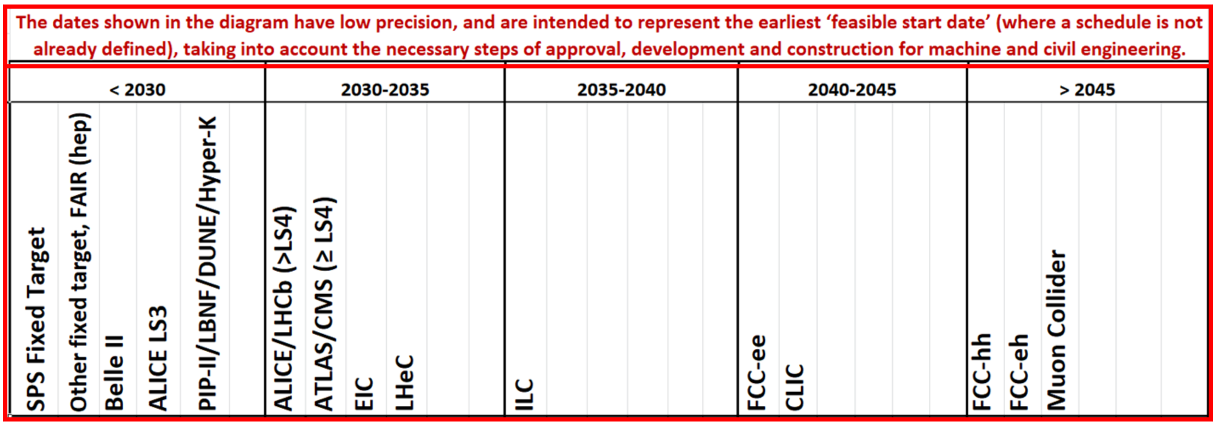

Fig. 1.2: Future accelerator facilities timeline.

1.4 Status and organisation of the field

Accelerator physics is a large, complex, multi-disciplinary field that is of relevance beyond the needs of collider-based particle physics. The field is fully international, and to some extent a 'European Roadmap' can only represent a portion of what must remain a fully-integrated worldwide programme. To the extent that the field necessarily centres around large infrastructures, much of the work is focussed on facilities at national or regional laboratories. However, it is also clear that key developments (including those with the potential to radically affect our assumptions and future plans) are taking place at institutes and universities. The majority of accelerators built are for industrial, medical or other scientific purposes. Some of these applications could also benefit directly from parts of the proposed new R&D. To that extent, accelerators physics is therefore not just a key element in enabling new scientific discoveries, but also a primary route for economic and societal impact from particle physics.

The field is well-organised, with a plurality of existing structures, steering bodies, cooperative programmes and communications channels. The field has benefited in the past from investment by supra-national agencies (e.g. via the European Commission) in recognition of its key supporting role across disciplines and industries. The Roadmap must take into account the pre-existing structures and commitments, and build upon them coherently. Although the execution of the Roadmap will require sufficient oversight to make sure the goals are being met, to ensure that the results and conclusions of the overall R&D programme are readily available to stakeholders, and to ensure consistency with corresponding work taking place in detectors, it is likely that in some cases this will be a thin layer of formal structure above projects coordinated on a multi-lateral basis by laboratories and institutes. In other cases, for instance where new topics are being given priority, it may be necessary to convene new groupings and formal collaborations with the overall R&D governance structure, or to merge or re-optimise existing programmes for greater efficiency. These aspects have been the topic of consultation with the community, and will form part of the final Roadmap recommendations.

1.5 Process

The overall timeline for the Roadmap process is shown in Fig. 1.3. As for the ESPPU, it consists essentially of two phases: the public consultation process, and documentation of R&D priorities; and the definition of the Roadmap which must be delivered to them. This Report marks the end of the first phase.

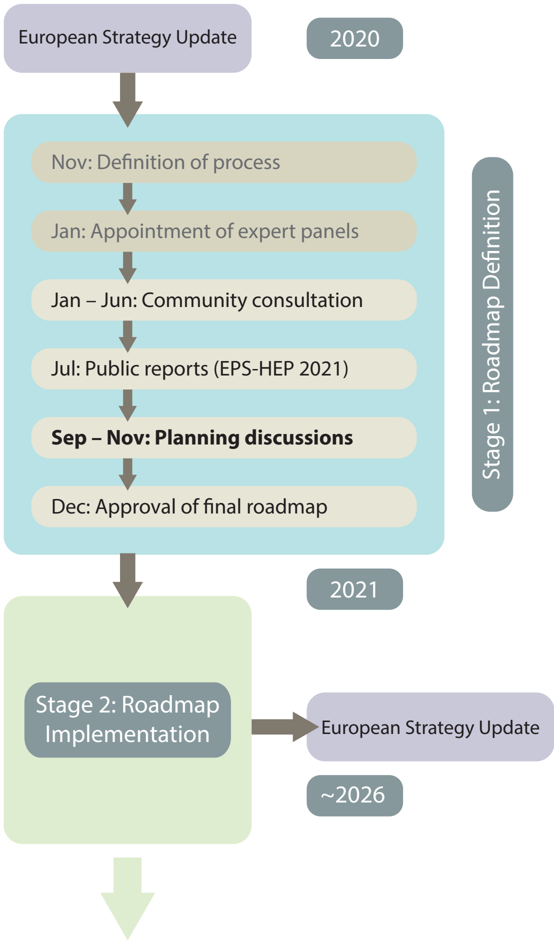

Fig. 1.3: Accelerator R&D Roadmap timeline.

The charge to each of the expert panels was to:

- establish the key R&D needs in each area, as dictated by the scientific priorities,
- consult widely with the European and international communities, taking into account the capabilities and interests of stakeholders,
- take explicitly into account the plans and needs in related scientific fields,
- propose ambitious but realistic objectives, work plans, and deliverables,
- give options and scenarios for European investment and activity level.

Conversely, in order to avoid confusion between the proposal of the Roadmap and the beginning of its execution, and to avoid overlap with other activities happening in parallel within laboratories, the following topics were deemed explicitly not in scope:

- detailed planning for specific future facilities,
- planning of funding routes, beyond the overall cost of the proposed R&D programme,
- statements of institutional or national commitment.

From January to July 2021, each of the expert panels held regular working meetings to define the scope and boundaries of their area, and to set up a process of community consultation. This typically took the form of a number of workshops combining invited talks with an open call for contributions. In other cases, the panels were able to draw upon the documented work of pre-existing consortia or collaborations. Some panels launched a formal written consultation with their community. These initiatives attracted the participation of a wide and representative subset of the international accelerator physics community, along with many stakeholders from particle physics. Overall, several hundred researchers have been actively involved in the process, with concrete contributions to this report from dozens of them. In some cases, it has been necessary to set up sub-panels with co-opted membership from the particle physics community, to consider specific aspects or applications of future technologies.

In early July, an open symposium was held specifically for the particle physics user community, in order to ensure that the field was kept well informed of progress. This was attended by around 150 people, and resulted in valuable feedback on priorities and cross-cutting aspects of the R&D programme (for instance, the inclusion of sustainability as an overriding issue). In addition, the particle physics community was challenged to provide input on potential direct scientific uses of intermediate-scale demonstrators and facilities. At the EPS-HEP conference in late July, both ECFA and LDG reported on the progress towards the Roadmaps, and the panels presented their findings.

This report contains summary findings from each of the panels, distilling the large volume of inputs received over several months, and expressing their initial judgement on the priority areas for R&D over the next five to ten years. The purpose of this report is to give a clear impression of the scope, breadth and direction of travel of the process now under way to formulate the Roadmap itself.

2 High-field Magnets

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2.1 Executive Summary of findings to date

Blablabla with reference example [1, 2].

2.2 Introduction to High-Field Accelerator Magnets

2.2.0.1 Historical perspective

High Field Magnets (HFM) are among the key technologies that will enable the search for new physics at the energy frontier. Starting from the Tevatron in 1983 [1], through HERA in 1991 [2], RHIC in 2000 [3] and finally the LHC in 2008 [4], all frontier hadron colliders were built using superconducting (SC) magnets. All colliders listed above made use of the highly optimized superconducting alloy of Niobium and Titanium [5], and it is a well-accepted fact that the LHC dipoles, with a nominal operating field of 8.33 T when cooled by superfluid helium at 1.9 K, represent the end-of-the-line in terms of performance of accelerator magnets based on this material[1] [6]. At the same time, approved projects and studies for future circular machines call for the development of superconducting magnets that produce fields beyond those attained in the LHC [7]. This is the case of the High-Luminosity LHC upgrade (HL-LHC) [8], which is currently under construction at CERN and collaborating laboratories, and the Future Circular Collider design study (FCC) [9], structured as a worldwide collaboration coordinated by CERN. Similar studies and programs are on-going outside Europe, such as the Super proton-proton Collider of China's

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CERN Yellow Reports: Monographs, CERN-2021-XXX, DOI: 10.23731/CYRM-2021-XXX, p. 7.

[1]Nb-Ti can produce field well in excess of the LHC nominal field of 8.33 T, as recently demonstrated by the spectacular achievement of ISEULT, a record full-body MRI solenoid operating at 11.7 T (see https://www.cea.fr/english/Pages/News/Iseult-MRI-Magnet-Record.aspx). This is done however at winding current densities that are typically one order of magnitude smaller than what is needed to build the compact windings of an accelerator magnet, and in a solenoid configuration which is magnetically twice as effective when compared to a dipole

(SppC) [10]. Significant advances in SC accelerator magnets were driven by past studies such as the Very Large Hadron Collider at Fermilab [11] and the US-DOE Muon Accelerator Program [12]. Similarly, first considerations on ultra-high-field (20 T) HTS dipoles were fostered by the High-Energy Large Hadron Collider study at CERN [13]. Finally, new accelerator concepts such as muon colliders presently considered at CERN and collaborators [14] will pose significant challenges on their magnetic systems. These High Energy Physics (HEP) initiatives provide a strong and sustained pull to the development of SC accelerator magnet technology beyond the LHC benchmark towards higher fields. Having reached the upper limit of Nb-Ti performance, all above projects and studies are turning towards other superconducting materials and novel magnet technology. On-going activities encompass both Low-Temperature and High-Temperature Superconductors (LTS and HTS, respectively). Besides the R&D driven directly by the projects and studies listed above, it is important to recall the coordinated efforts that have led to the present state-of-the-art in HFM for accelerators. The largest effort over the past 30 years was dedicated to the development of Nb_3Sn [15] conductor and the related magnet technology. A strong focus was given in the end of the 1990's by the US-DOE programs devoted to Nb_3Sn conductor and magnet development [16] [17] [18]. These programs enfolded as a collaboration among the US-DOE accelerator laboratories and associated institutions, and are now continuing in consolidated form under the US Magnet Development Program, with the added goal of developing HTS materials and magnets [19]. On the EU side the first targeted EU-wide activities were initiated under the EU-FP6 CARE (Coordinated Accelerator Research in Europe) [20] initiative, and in particular in the Next European Dipole Joint Research Activity (NED-JRA) [21]. NED-JRA ran from 2004 to 2009 and was followed by the EU-FP7 EuCARD [22]. The main fruit of these collaborations is FRESCA2, the dipole magnet that still detains with 14.6 T the highest field ever produced in a clear bore of significant aperture. We remind that FRESCA2 is a test facility magnet, designed with large operating margin, and not including some of the crucial features of an accelerator dipole. HL-LHC is presently the forefront of accelerator magnet technology and construction at the highest field ever attained in a magnet in an operating collider. The results achieved with the nominal performance of the 11T dipoles [23] and QXF quadrupoles [24] demonstrate that Nb_3Sn has the ability to surpass the state-of-the-art of Nb-Ti mentioned earlier. At the same time, it is clear that the solutions successfully implemented for the design and manufacturing of the HL-LHC Nb_3Sn magnets will need to evolve to improve robustness, industrial yield, and cost while the potential of the material enfolds completely. Finally, the interest in the exceptional high-field potential of High-Temperature Superconductors (HTS) for many domains of applied superconductivity has also reached accelerator magnets. Cuprates containing either rare-earths (REBCO [25]) or bismuth (BSCCO [26]) are in a stage of early technical maturity, and their application to the generation of ultra-high magnetic fields was recently proven. Laboratories and industry have shown that HTS are capable to produce fields in the range from 28 T in commercial NMR solenoids [27] to 45.5 T in small experimental solenoids in background field [28]. As discussed later in more detail, HTS technology for accelerator magnets is only at its promising beginning [29]. This is an area where we expect to see fast progress, along the path initiated in various laboratories, and fostered in Europe by the EuCARD [22], EuCARD2 [30], ARIES [31] and the on-going I-FAST [32] EU projects.

2.2.0.2 Highest Fields attained

The result of the efforts briefly outlined above can be appreciated graphically in Fig. 2.1, reporting the steady increase of field produced by dipole magnets built with LTS Nb_3Sn over the past forty years. The data is a loose collection of results obtained with short demonstrator magnets (i.e. simple configurations that lack an aperture for the beam and are not built with other constraints such as field quality), short model magnets (i.e. short version of magnets that are representative of the full-size accelerator magnets), and full-size accelerator magnets. We can trace first significant attempts back to the 1980's, at BNL [33] and LBNL [34]. This work eventually led to the achievement of D20 [35] in the 1990's, a dipole model with 50 mm bore. The path continued in the 2000's with the HD program at LBNL, reaching a field of

16 T in the simpler racetrack configuration. Field in the 16 T range was obtained at CERN [37] in 2015 and exceeded in 2020 [38] also in a racetrack configuration, as a result of the push provided by FCC-hh. The work in the 1990's and 2000's described above [39] has laid the foundations for the construction of the HL-LHC Nb_3Sn magnets. We also see in Fig. 2.1 that the timeline for progress in Nb_3Sn magnet technology is relatively slow. It took about ten years for CERN and associated laboratories [20, 21, 22], to reproduce the results obtained in the US. The conductor R&D initiated in 2004 led to significantly improved PIT conductor [40], with high-field performance comparable to RRP, though more sensitive to mechanical loading and lesser industrial maturity. PIT was used in RMC03, achieving a field of 16.2 T in 2015 [37] and bringing the EU efforts to a comparable level of maturity as in the US. This gives a good benchmark for the time scale necessary to enter this field of technology, including the procurement of the required infrastructure (e.g., heat treatment furnaces, impregnation tanks) and the development of the necessary skills. The result of this work is the record magnet FRESCA2, built in collaboration between CERN and CEA, and generating a field of 14.6 T in an aperture of 100 mm diameter [41]. As we indicated earlier, FRESCA2 is a test facility magnet, built with large operating margin and low engineering current density. This field level has been reproduced recently by the high-field model dipole MDPCT1 built within the scope of the US-MDP program [42] as a step towards the highest field that can be attained with a cos-theta coil configuration (4 layers), and features relevant to an accelerator magnet, including high operating engineering current density. Finally, the plot shows the remarkable achievement in the development of Nb_3Sn accelerator magnets, and in particular the MBH 11T dipole for HL-LHC built at CERN in collaboration with industry (GE-Alstom) [23]. Initiated in 2010, and profiting from the previous developments outlined above, it took a decade to produce the first magnet unit that met all stringent requirements for accelerator operation. The first such magnet, MBHB002, was tested in July 2019 and detains the record for his class [43]. Though successful in achieving the specified performance, the 11T program has also pointed out that there are still questions to be resolved on the long-term reliability of the specific design as well as the robustness of the manufacturing solutions, which will need to be addressed and resolved before this class of magnets can be used in an operating accelerator.

While Nb_3Sn is baseline for the high field magnets of HL-LHC, as well as the next step in SC accelerator magnet technology, great interest and significant progress was achieved recently in HTS accelerator magnet technology, reported graphically in Fig. 2.2. The general interest in the potential of this class of material with spectacular performance coagulated at about the same time in the EU and US, i.e., in the middle of the 2000's. On the US side, efforts were coordinated by the US-DOE sponsored Very High Field Superconducting Magnet Collaboration [44], which targeted Bi-2212 as HTS high-field conductor. This activity has now flown into the scope of US-MDP [19] which addresses both BSCCO-2212 and REBCO in various cables (Rutherford and CORC) and magnet (racetracks and canted cos-theta) configurations [45, 46, 47]. As mentioned above, in the EU, the first seeds were initiated with the EU-FP7 EuCARD collaboration [22], and were pursued intensely with the follow-up EU-FP7 EuCARD2 [30] and EU-H2020 ARIES [31] programs. Much of the conductor effort in Europe was directed to REBCO, with a conscious choice mainly driven by the perceived potential and presumably simpler magnet technology [29]. The result of these activities are small demonstrator magnets that have reached bore fields in the range of 3 to 5 T in stand-alone mode. Figure 2.2 shows clearly that this is the beginning of the path that will hopefully lead to results comparable to and exceeding Nb_3Sn. The next step, complementary to the further development of the technology, is to use these small-size demonstrators as inserts in large bore, LTS background magnets to boost the central field and quantify the ability to exceed LTS magnet performance, while at the same time exploring this new range of fields and related forces.

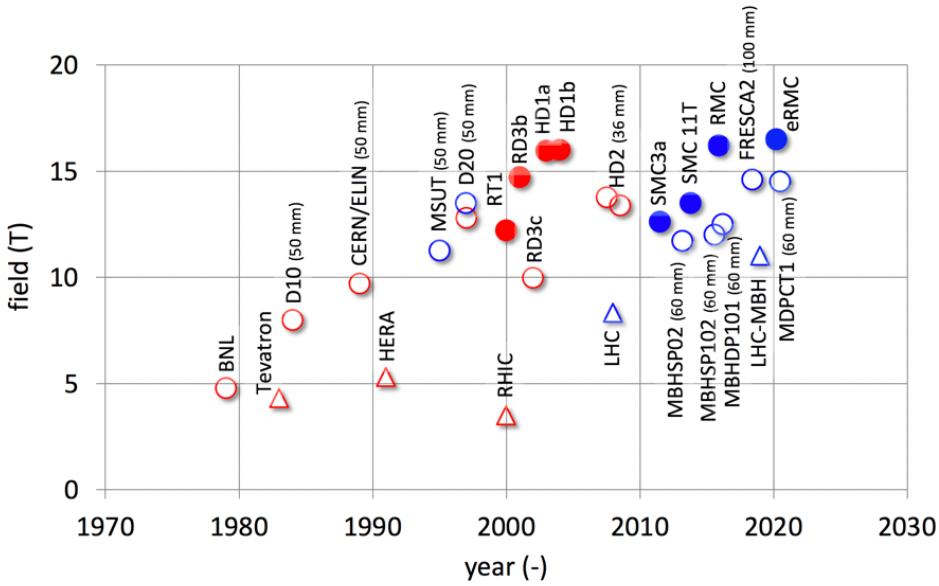

Fig. 2.1: Fields attained with Nb_3Sn dipole magnets of various configurations and dimensions, and either at liquid (4.2 K, red) or superfluid (1.9 K, blue) helium temperature. Solid symbols are short demonstrator, i.e. "racetracks" with no bore, while open symbols are short models and long magnets with bore. For comparison, superconducting collider dipole magnets past and present are shown as triangles.

2.3 Motivation and Nature of a High-Field Accelerator Magnets R&D

We can draw several conclusions from the rather simplified review of achievements outlined in the previous section:

- Lead times for the development of high-field magnets are long, the cycle to master new technology and bring novel ideas into application has a typical duration in excess of a decade. It is hence important to pursue R&D in parallel with scoping studies of new accelerators, to anticipate demands and guarantee that specific technology is available for a new HEP realization at the moment when the decision of construction is taken;
- The development of novel SC magnet technology at the high field frontier requires specific infrastructure, often of large size. The necessary investment is considerable. Continuity is hence important in a program that requires such infrastructure and the associated investment;
- The development of high field magnets naturally spans over many fields of science and requires a broad mix of competencies, implying a research team assembled as a collaboration ranging from academia to industry. As for the infrastructure, any such research team needs considerable investment for its constitution and operates most effectively with continuity.

These considerations point to the need of a sustained and inclusive R&D program for high-field superconducting accelerator magnets as a crucial element for the future of HEP, as underlined by the strong recommendation emitted by the European Strategy Group 2020 [48]. Not only should such a program respond to the demands driven by specific projects and studies, it should also unfold as a continuous line of structured R&D, ready to respond to future HEP requests, and capable of feeding HEP with opportunities. The program should include both, LTS and HTS materials in a synergetic manner and encompass the whole spectrum from conductor to accelerator magnets, including the key technologies

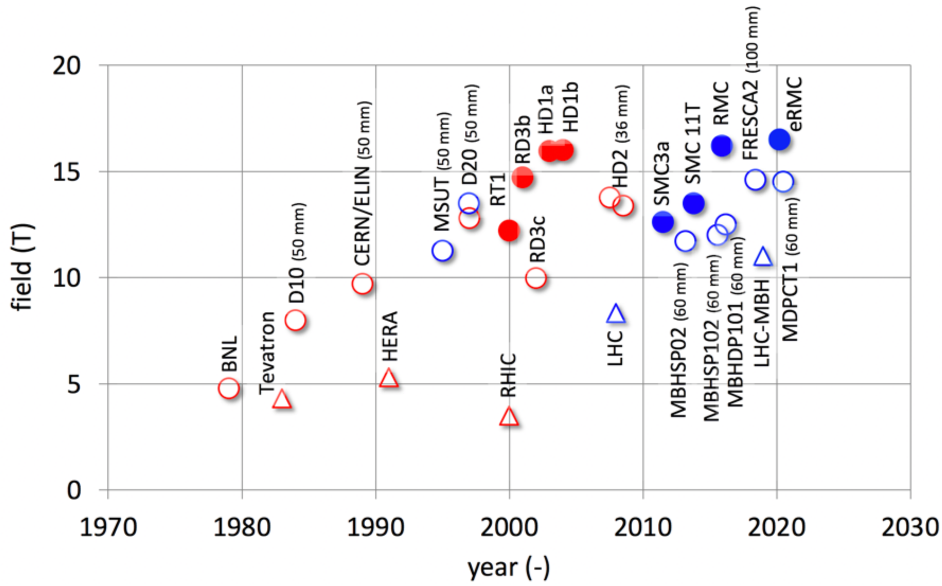

Fig. 2.2: Fields attained with HTS short demonstrator magnets of various configuration, producing a dipole field. All tests performed in liquid helium (4.2 K). Solid symbols are "racetracks" magnets with no bore, while open symbols are magnets with bore. Round symbols are magnets built with REBCO, square symbols with BSCCO-2212.

that are necessary for the realization of its goals. As mentioned earlier, such an R&D has a long lead time, with cycles of the order of ten years. Having dedicated teams will benefit focus and results, and may be necessary to match the timeline of the next European Strategy process, in about five to seven years. An important matter underlying the above considerations is that of cost. In this respect we have to consider not only the construction cost of magnets, which, as mentioned explicitly later, is a very significant challenge for future accelerators, but also the cost of the R&D itself, which may limit the scope and stretch the timeline, against the wish for a fast turn-around. This is especially true for HTS materials, which explains why the scale of the demonstrators described earlier, as well as that of future ones, is kept intentionally small. An effective R&D program will hence include practical considerations of cost. Given the ambitious scope, the long-term engagement, and the cost, such a program will have to be of collaborative nature, with strong partnership among national laboratories, universities, and industry. The R&D program should capitalize on the state-of-the-art and achievements obtained so far, continuing the work outline presented earlier, which is largely still on-going. Indeed, an R&D program with the characteristics outlined is consistent with the plans of other organizations in HEP already mentioned earlier [19, 49], as well as other research fields relevant to our discussion [50, 51, 52, 53]. Last but not least, it will be important to measure the impact of the R&D program against its relevance and impact towards other applications in science and society.

2.4 LDG HFM Panel Activities

Balblabla...

2.5 State-of-the-Art and Challenges

2.5.1 Superconductor

The prime challenge to achieve high magnetic fields of interest to HEP is to have a conductor with sufficiently high engineering current density, JE with good mechanical properties. Based on experience from superconducting accelerator built to-date, a target target of JE $\approx$ 600 A/mm2 at the operating field and temperature is appropriate to yield a compact and efficient coil design for an affordable magnet [magnet design]. The JE target should be reached with no degradation and limited training, and making use of the highest possible fraction of the current carrying capacity of the specific superconductor. All known high field superconductors (Nb_3Sn and HTS) are brittle, and it is of paramount importance that the state of stress and strain be mastered and controlled throughout all magnet fabrication and operation conditions.

An overview of the state-of-the-art JE for LTS and HTS technical superconductors is reported in Fig. 2.3. The performances reported there refer to the best industrial products, not necessarily produced in large scale. The LTS materials of interest are Nb-Ti, an industrial commodity, and Nb_3Sn, whose production is restricted to a single established manufacturer for the high-performance wires required by HEP. On the side of HTS, two high-field superconductors are currently available on the market, BSSCO, also produced at a single location worldwide, and REBCO, with several established producers in Europe and worldwide.

In the case of Nb_3Sn the target of JE can be translated in a minimum critical current density in the superconductor, JC, of the order of 1500 A/mm2 at 16 T and 4.2 K [ASC-2014]. This target is at the upper boundary of the state-of-the-art best wire performance (see Fig. 2.3) and exceeds by about 50% the performance specified for the industrial production of HL-LHC Nb_3Sn. This implies pursuing and industrializing the R&D work launched in the framework of the FCC CERN Conductor Development Program and undertaken in the last five years by the superconductors' community on basic material and wire fabrication [FCC CDP overview]. Results are encouraging and open the route for novel Nb_3Sn with high in-field electrical performance. In particular, the internal oxidation route has proven in two laboratories feasibility of exceeding the FCC target in multi-filamentary wires [Ref].

For HTS, the target JE is actually common practice for the present production industrial standards of REBCO and BSCCO materials (see again Fig. 2.3), so we do not envision a focused effort in the direction of increasing JC. However, other aspects of the conductor require tailored developments. It is interesting to note that recent developments have demonstrated that the target JE can be achieved by REBCO also at temperatures of 10 to 20 K.

Besides JE, and in common to both LTS and HTS, other performance parameters need to be met. In particular, mechanical strength and tolerance of wires, tapes and cables to stress and strain are of key importance. Field quality aspects, and in particular equivalent filament size, for Nb_3Sn, and impact of the large width of the tapes, for HTS, shall be studied. The latter is of key importance for confirming suitability of HTS tape for use in accelerator quality magnets. Finally, quench protection aspects need to be addressed starting already at the level of conductor, i.e. from wires and tapes, to cables, and eventually at the magnet level.

While Rutherford cables are the choice for LTS accelerator magnets, high current HTS cables suitable for use in accelerator magnets need to be developed and qualified.

Industrialization of high-quality conductor for large scale application and its cost are challenges to be addressed for both Nb_3Sn and HTS. Large scale production of conductor would help in the optimization of the manufacturing processes and therefore reduction of cost. In the development phase, selection of processes and technology has to be done taking into account the future need of industrialization. At the time of writing, several manufacturers of HTS tape exist worldwide – Europe, USA, Korea, Russia and China. However, only one manufacturer to date can produce long lengths of state-of-the-art HL-LHC

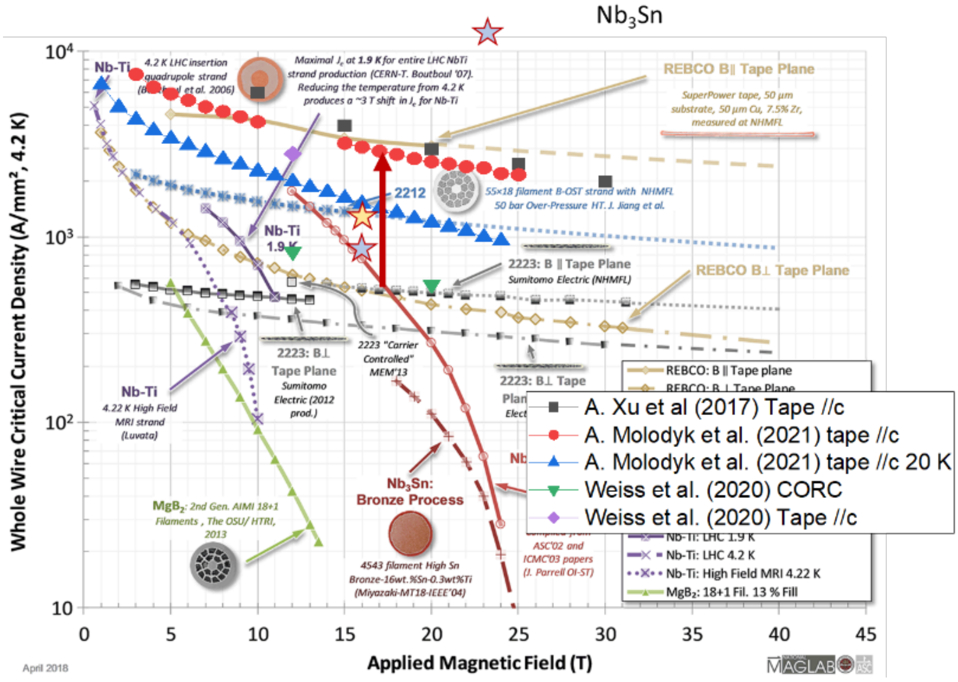

Fig. 2.3: Engineering current density JE vs. magnetic field for several LTS and HTS conductors at 4.2 K. The last results for REBCO tapes at 4.2 K are shown in the red dot line. The blue triangle line shows the same tape at 20 K.

Nb_3Sn wire. Effort still has to be made to guarantee availability of high-performance Nb_3Sn wire and build-up credibility for a potential future large scale production.

2.5.2 Mechanics

2.5.2.1 Stress and Strain in the Coil Composite

All high-field superconductors are strain and stress sensitive, and, as anticipated above, they are brittle. Besides the known reversible critical current dependency on applied strain, the main concern is that applied stress or strain exceeding allowable limits for any of the constituent of wire and tape generally leads to a reduction of critical current, eventually damage and permanent degradation. Examples of degradation mechanisms are plastic deformation of the Cu matrix of Nb_3Sn, taking place already at moderate stress, which can freeze a strain state and lead to irreversible JC reduction. At higher applied longitudinal and transverse stress, the brittle Nb_3Sn can fracture, which reduces the cross section available to current transport and the wire critical current. Degradation mechanisms for multi-filamentary BSCCO are broadly similar, whereby the Ag resistive matrix has even lower yield strength than the Cu matrix customarily used for Nb_3Sn. On layered REBCO tapes, in-plane shear or peeling forces can lead to de-lamination. For these reasons, the dominant engineering effort in state-of-the-art high-field superconducting magnets is the management of stress and strain.

The first measure in this direction is avoiding stress concentration. This is why the coils wound from brittle conductor or cable are cast in a polymer such as epoxy resin. The polymer is reinforced by fiber, customarily wrapped around the conductor and placed around the coil, necessary to increase strength and prevent cracking at cryogenic temperature. The coil is hence a composite material, whose main function is to provide local support to the conductor and alleviate the effect of local stress-concentration points.

We divide sources of stress and strain in the coil composite into sources of either external or internal origin.

Under external sources we classify the electro-magnetic (Lorentz) forces, forces or displacements transmitted at the coil-structure interface, and forces originating from the sudden conversion of electromagnetic energy into internal thermal loads associated with a quench in the coil. Lorentz forces scale with the magnetic field in the center of the aperture and the Ampere-turns, i.e., in first approximation quadratically with the field in the aperture, as shown in Fig. 2.4. In some quench scenarios, such as quench protection transients with fast current pulses driven by the Coupling Loss Induced Quench (CLIQ) system, or in non-insulated or partially insulated coils, Lorentz force patterns may vary significantly from the nominal configuration. Stress and strain transmission at the coil-structure interface is discussed in more detail below in the context of pre-load.

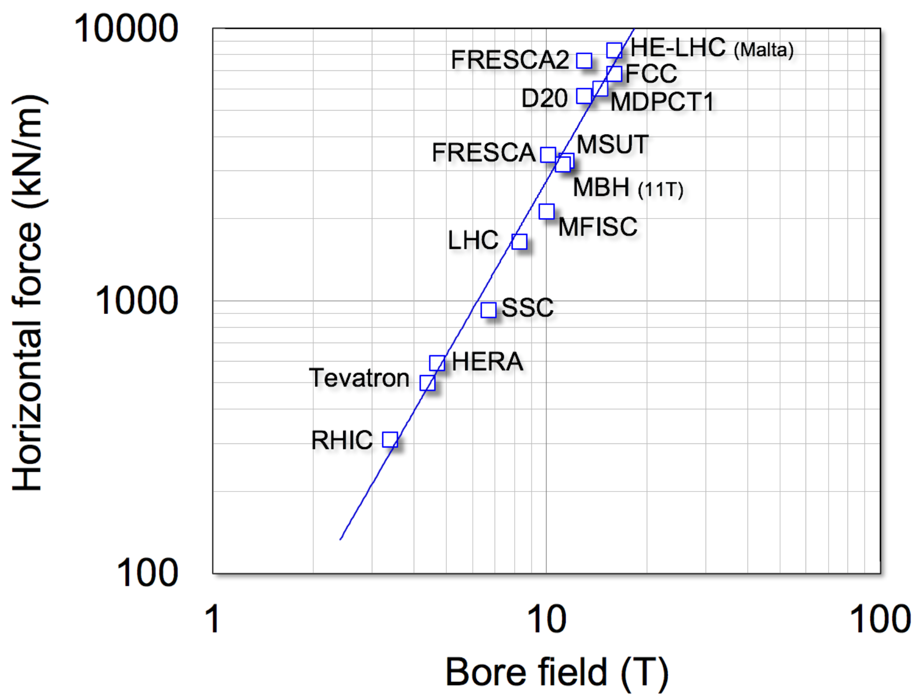

Fig. 2.4: Horizontal forces per quadrant in dipole accelerator magnets (built and tested or design studies).

Among the internal sources we list the residual stress state in the conductor induced by the difference of Coefficient of Thermal Expansion (CTE) among the constituents of the coil composite (e.g. conductor, glass fiber and epoxy resin). The differential stress is present after the heat treatment of Nb_3Sn, accumulated from the resin-curing temperature down to cryogenic conditions. Similarly, a magnet quench results in a localized swelling of the coil at the hot spot, as well as associated thermal stress.

The local stress and strain in the coil composite are the sum of all internal and external contributions. Good engineering requires the knowledge of critical values of stress and strain in the composite to produce a design that implements appropriate safety margins within realistic tolerances. We note that critical values may vary widely between conductor types and material compositions. Experimental studies and multi-scale modeling are required to establish reliable input into the design workflow. Moreover, we note that for a given central field, the level and orientation of stress and strain in the coil composite varies widely among different coil types, coil sizes, materials, mechanical concepts, etc.

2.5.2.2 *Structures, Pre-load and Stress Management*

The transverse and axial forces resulting from the loads identified above need to be reacted on a stiff internal or external structure, whose aim is to control and minimize the deformation of the coil under Lorentz forces. In fact, it is customary to design the mechanical structure so that it applies a coil compression (or pre-load) at cryogenic temperature. This pre-load is introduced to reduce the amount of relative movement between the coil and the structure under Lorentz forces. A commonly used design stratagem is so-called "full pre-load", which consists in providing enough pre-load at cryogenic conditions that all interfaces remain in compression up to the ultimate design current. While the full pre-load stratagem is frequently observed in the design phase, it is rarely rigorously applied in R&D practice, especially during the initial magnet assembly and powering. Indeed, the extent of required pre-load at cryogenic temperature is a matter of debate.

To meet the desired support goal, an external structure must have a CTE identical to the coil composite (to match dimensional change) or higher (to introduce additional load at cool-down). In the case of an external structures made from material with lower CTE compared to the coil, as is the case of several high-strength alloys, the structure can be tensioned, and coil pre-compressed at room temperature, so that the structure remains in contact with the coil throughout the cool-down. This has the disadvantage that the coil experiences a higher degree of pre-load at room temperature than at operating conditions, where it would be necessary.

An internal structure may be used to increase the coil's stiffness and to transmit the external structure's stiffness into the inner windings of the coil. An internal structure (often called stress management) may be a path towards reduced or no pre-load and overall lower coil stresses. It comes at the price of diluted engineering current density and wide-spread internal coil-structure interfaces that may be subject to electrical or mechanical failure.

2.5.2.3 *Mechanical Engineering Challenges in LTS, HTS, and Hybrid Magnets*

Nb_3Sn Magnets

Performance of Nb_3Sn magnets is intimately connected to mastering the magnet mechanics. This can be quantified by looking at the extent of magnet training (i.e. the number of training quenches required to reach the desired operating current) and the performance retention (e.g. re-training after thermal cycle, and avoiding degradation).

Magnet training is usually assumed to be linked to one or several of the following mechanical phenomena: (1) cracks in the glass-epoxy insulation, (2) resin-metal debonding, and (3) stick-slip movement between the coil and the structure. A performance limitation of mechanical origin, i.e., a failure to reach the design current, may be due to (1) conductor mechanical instability, (2) repetitive stick-slip movement, or (3) a reduced conductor performance/degradation due to excessive stress or strain.

As to the last point, studies on Nb_3Sn under stress and strain demonstrate relatively low tolerance to mechanical loads. Depending on the specific wire architecture and properties, permanent current reduction due to plastic deformation of the annealed-copper stabilizer starts at around 150 MPa transverse pressure, if applied homogeneously in cryogenic conditions. Filament fracture in these conditions may occur beyond 200 MPa. At room temperature, filament breakage may happen already at 150 MPa. This range of stress is typical of the average pre-load required by high-field Nb_3Sn magnets. It should be underlined that components and assembly tolerances affect the local stress and strain state, resulting in a spread which should be taken into account in the design and manufacturing.

Cyclic loads, be it powering cycles or cool-down-powering-warm-up cycles (CD-PO-WU), can lead to a degradation when a combination of relative movement (due to Lorentz forces and/or CTE mismatch) and friction leave the coil-structure interface in a different state than the original one. Repeated CD-PO-WU cycles may lead to detrimental ratcheting. Repeated quenching and high-peak-temperature quenches may lead to fatigue degradation of the insulation system, and softening if the local temperature approaches the glass temperature of the polymer.

HTS Magnets

HTS coils at low temperature have enthalpy margins up to 100 times larger than those observed in LTS coils. Consequently, energy-release and associated training due to cracking, debonding, or stick-slip motion are much less of a concern than in LTS coils. Still, the increased field reach of HTS magnets with respect to LTS ones results in a significant increase of Lorentz force, and poses an acute challenge to the composite coil and structural design.

High-strength materials are required to react forces within a relatively compact footprint of an accelerator tunnel. As for the coil composite, any stress concentrations on the HTS wire or tape must be avoided, either by design or via a supporting filler material. In the absence of stress concentrations, ReBCO tape will typically withstand very high transverse stress of up to 400 MPa. Much lower values are observed if the stress is localized. At the same time, it has been observed that a CTE mismatch with a filler like epoxy resin, can lead to tape delamination and result in severe degradation.

Screening currents in ReBCO tapes, i.e., non-zero dipolar induced current configurations, can reach high amplitudes in the low-field regions of a coil. Lorentz forces acting on screening currents produce shear and peeling forces, they have been linked to tape deformations and crack propagation in solenoid magnets, and need to be considered in the magnet design.

Lastly, coil-wide current-sharing mechanisms of no-insulation, partial-insulation, and other advanced-insulation schemes, inherently lead to hard-to-predict current and force patterns in the event of a quench. Such configurations may be exceedingly stable in almost all situations, but see their mechanical integrity compromised if a quench takes place.

Hybrid Magnets

Hybrid LTS+HTS magnets are considered mainly for cost reasons. In this case, the mechanical interface between the HTS high-field insert and the LTS lower-field outsert must protect the LTS conductor from excessive stress. A potentially risky mechanical scenario arises if a quench in one part of the coil is allowed to induce a rise in current in the other part.

2.5.3 Stored energy and magnet protection

In Fig. 2.5), we have collected the values of the stored energy per unit length (measured or computed) for a set of existing and conceptual magnet dipoles. The energy stored increased with the magnetic field to the power 2.5. This is consistent with the dependence of energy and field for ideal dipoles. Consequently, aiming at the range of 16 to 20 T, the increase in stored energy with respect to the LHC will be a factor of 4 to 10, ranging from 1 to 3 MJ/m per aperture. This has implications on magnet design and technology, stemming from considerations of powering (inductance and voltage required to ramp the string of dipoles), as well as magnet protection (energy density and dump time).

A second element of interest is the energy per unit volume, one of the key ingredients to the maximum temperature reached during a quench. As we see in Fig. 2.6, the energy density also increases. The LHC dipole magnets have a stored energy density of 50 MJ/m3. This increases up to 80 to 100 MJ/m3 for the HL-LHC Nb_3Sn magnets. The value reaches 200 MJ/m3 for the most compact 16 T FCC designs, i.e. a factor 4 larger than the LHC magnets.

Considerations of magnet ramping would favour large voltage or current, or a combination of both, to power the magnets of large stored energy. Increasing either terminal voltage or cable current is however not a trivial matter, and powering considerations need to be included from the start in the magnet

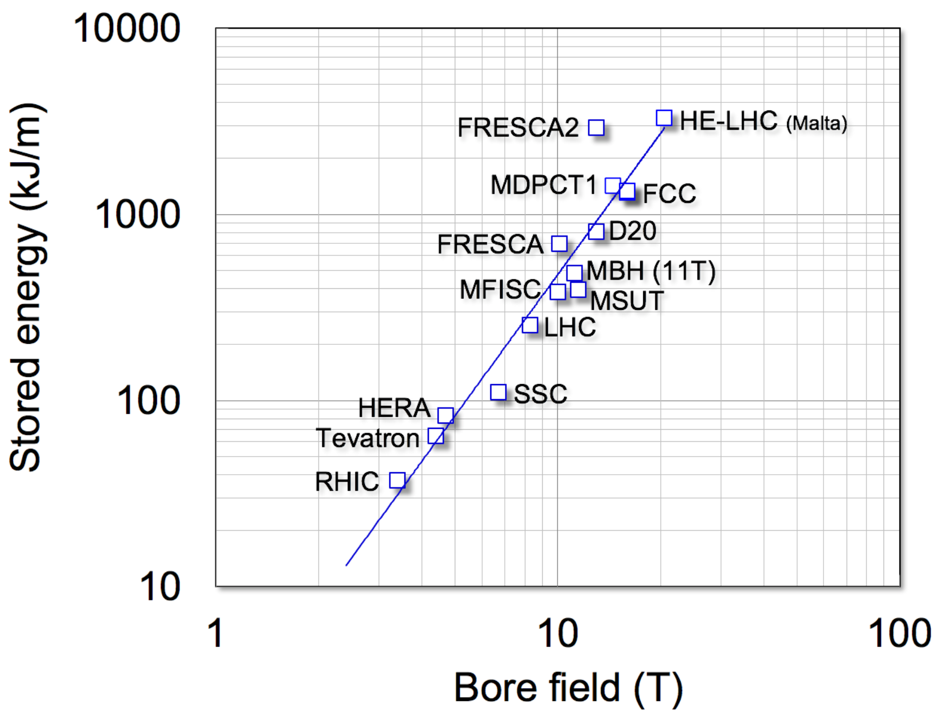

Fig. 2.5: Scaling of stored energy per unit length for dipole magnets built or designed (values refer to one aperture in case of the LHC, 11T, FCC and HE-LHC). The line represents the dependence of the energy with the magnetic field to the 2.5

design. Furthermore, in order to keep the hot-spot temperature in the coil after a quench below acceptable values (around 300 K to 400 K, but actual damage limits are not well assessed), the quench detection and active dump need to act at least three to five times faster than in the LHC. This is already challenging for Nb_3Sn, but may be perceived as a tantalizing task for HTS, whose quench propagation speed is an order of magnitude slower than in LTS, and quench detection based on established instrumentation would thus take an order of magnitude longer. In reality, quench initiation and evolution in the case of HTS is a much different process than the well-characterized behaviour of LTS. Though relatively unexplored, the large difference in quench initiation and propagation in HTS vs. LTS may actually be an opportunity to develop alternative schemes, e.g. profiting from the early low voltage quench precursors arising during the current sharing process to anticipate the evolution, or the relatively long time scales of voltage development to improve measurement sensitivity.

The challenges posed by magnet powering and protection have multiple facets, and they will need to be addressed in an integrated manner. There is a remarkable parallel between the challenges of magnet protection and mechanical design. Firstly, detection and protection in the regime of stored energy and energy density described above will require new concepts, especially for HTS (e.g. non-insulated or 'controlled-insulation' windings). Secondly, measurement and characterization of the thermo-mechanical and dielectric properties and limits of coils and structures will be a mandatory step to ensure that the design are safely within engineering limits.

2.5.4 Cost

Cost is the final grand challenge of high field magnets for accelerators. We have identified the following cost drivers and opportunities:

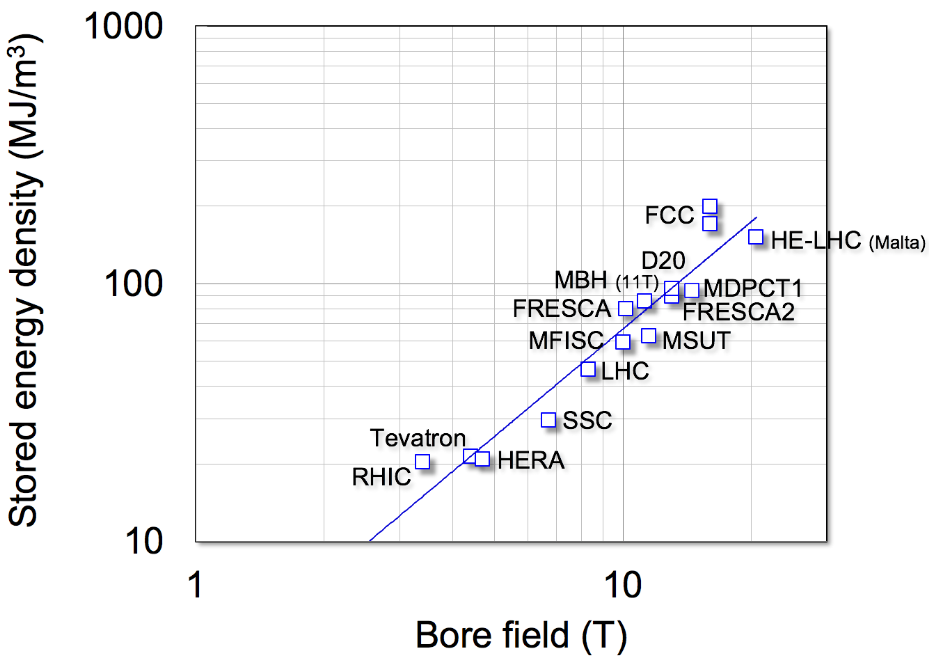

Fig. 2.6: Scaling of stored energy density for the dipole magnets considered in Fig. 2.5

– The conductor, which is the primary cost driver of high field magnets. This was the case already in the Nb-Ti based LHC, where the superconductor cost was about 25% of the total cost of the magnet (excluding the external services like power supply and other ancillaries). The cost of Nb_3Sn for an FCC-hh is projected to be half of the cost of the magnet system. Conductor R&D should prime solutions such as scalable architectures, or designs that are more tolerant of raw material properties as means to reducing the cost of the superconductor. Similarly, magnet designs should strive to make the most efficient use of the superconductor cross section, encouraging engineering solutions that go in this direction;
– The second largest cost is associated with the construction of the coil. Winding is the dominant part, but coil manipulation from winding to coil assembly should not be neglected, especially for Nb_3Sn. More in general, magnet design should aim at reducing construction complexity. Coil winding is at present an essentially manually driven operation, assisted by some level of automatization [2]. Given the experience gained on coil winding in recent projects (e.g. ITER and JT-60SA), and given the number of coils to be wound for a future accelerator (e.g. 20,000 identical coils for the FCC-hh dipoles) advanced robotics seems a crucial topic of R&D to reduce winding cost. The analysis of benefits of automation and robotics should also span beyond coil winding, i.e. coil handling through operations like insertion in the heat treatment oven, splicing, impregnation, metrology, etc. Note that this work can be staged, e.g. to take place in a second phase of R&D or in the pre-industrialization phase;
– The third cost driver is the magnet mechanical structure. The choice among available options (e.g. collars, bladders and keys, yoke-as-restrain, and other) shall be based not only on field reach, but

[2] Given the rapid evolution of the field is not advisable at this stage heavily investing in robotized tooling. The idea is rather to carry out a study of what are the areas of the whole magnet construction that would benefit from robotization. We also underline that robotization can be beneficial not only for reducing construction cost, but also for increasing construction quality and enhancing the homogeneity of the production, which, in last analysis, reflects also in cost (improved yield). The proposed study should also consider the time by which introducing robotization would be useful (neither too early, nor too late).

also on cost consideration of tooling and operation. Indeed, some structures seem more suitable to automatization and robotization (e.g. collar assembly), while other may rely on simpler tooling (e.g. bladders and keys). The above considerations should be injected early in the magnet R&D study, and may be a good investment to guide the best structure selection decision when the time will come..

The main challenge can be summarised in finding the true optimum between magnet performance and cost. To be noted that we should consider total cost, i.e. not only the initial investment but also cost of operation. This tends to favour operation at higher temperatures (e.g. 4.2K for Nb_3Sn and 20 K for HTS) where, besides the improved cryogenic efficiency, the enthalpy margin is higher and the burden of training is reduced, thus improving availability and reducing operation cost. Similarly, a robust magnet design, with large operating margin, is a way to avoid rejection and increase yield during production, thus reducing capital cost, as well as increasing availability, thus reducing operation cost. In general, simpler designs should be favoured, with repeated operations that might be more suitable to automatization as described earlier, even if slightly less performant. In order to forecast costs correctly, industry should be involved as soon as possible in an efficient manner[3]. The industry involvement will complement laboratory efforts made using existing large facilities. Lacking an engagement of industry, it is important that work in laboratories, and especially on long magnets, is followed up using a detailed budget accounting system that could be used as basis to devise industrial production cost.

Finally, HTS deserves a special mention, since their optimization is quite different from Nb_3Sn. Present HTS conductor cost is much higher than Nb_3Sn. However, differently from Nb_3Sn, it is decreasing, driven by demand and steady funding from fusion research (in particular two privately funded initiatives in EU and US) and the energy sector. Appreciable material quantities, much above HEP needs, are on order to satisfy the needs from these initiatives. In this respect, HEP should rather focus on cable and magnet engineering, leaving the cost of superconductor aside, at least in this phase.

As to the magnet construction and operation, depending on the HTS material (REBCO) there is no need of heat treatment, mechanical properties are better and stability much higher than LTS. Considering this, HTS magnet technology could be significantly less expensive than Nb_3Sn. This needs to be verified since it could lead to a change in paradigm for a FCC-hh or a muon collider, should the cost of HTS conductor attain the same level as Nb_3Sn. The above considerations can be included in the R&D program, where besides the technology development towards the step-by-step validation of the technology, it is important to include a near-full size HTS dipole (1 m long) to be manufactured and tested. This will allow gauging the true cost of an HTS accelerator magnet by tracking material and personnel investment throughout the entire construction process. A suitable target for one such magnet could be a typical HL-LHC model magnet size and field (e.g. 50…60 mm aperture, field in the 11…12 T range) for which cost is well established.

2.6 Objectives and Drivers of a High Field Magnets R&D Program

Based on the state-of-the-art and challenges described above, and the strong statements encouraging high-profile R&D activities on high field accelerator magnets contained in the ESPPU, we can formulate the following provisional long-term technical goals of the HFM R&D:

1. Demonstrate Nb_3Sn magnet technology for large scale deployment, pushing it to its practical limits, both in terms of maximum field as well as production scale. The drivers of this first objective

[3] As a side remark, we believe that industry will consider an involvement seriously only if:

- There is continuity of work and funding. Industry needs to make plans with at least five years horizon to be effective;
- The issue of IP is clarified. It is unlikely that industrial IP will be unveiled, and provide most qualified resources, if the IP protection and sharing is not fairly seteld from the start.

are to exploit Nb_3Sn to its full potential, which we think is not yet unfolded, developing design, material and industrial process solutions that are required for the construction of a new accelerator. We separate the search for maximum field from the development of accelerator-magnet technology by defining the following two dependent and linked sub-goals:

(a) Quantify and demonstrate Nb_3Sn ultimate field. This effort consists in the development of conductor and magnet technology towards the ultimate Nb_3Sn performance. The projected upper field limit for a dipole is presently 16 T (the reference for FCC-hh). This field should be intended as a target against which the performance of a series of short demonstration and model magnets shall be measured.

(b) Develop Nb_3Sn magnet technology for collider-scale production, through robust design, industrial manufacturing processes and cost reduction. The present benchmark for Nb_3Sn accelerator magnets is HL-LHC, with an ultimate field in the range of 12 T, and a production of the order of a few tens of magnets. Nb_3Sn magnets of this class should be made more robust, considering the full spectrum of electro-thermo-mechanical effects, and the processes adapted to an industrial production on the scale of thousand magnets. The success of this development should be measured against the construction and performance of long demonstrator and prototype magnets, initially targeting the 12 T range.

2. Demonstrate suitability of HTS for accelerator magnet applicationsproviding a proof-of-principle of HTS magnet technology beyond the reach of Nb_3Sn. The *Leitmotiv* of this program is to break the evolutionary changes of LTS magnet technology, from Nb-Ti to Nb_3Sn, by initiating a revolution that will require a number of significant innovations in material science and engineering. A suitable target dipole field for this development is set for 20 T, significantly above the projected reach of Nb_3Sn (see above). Besides answering the basic question on field reach and suitability for accelerator applications, HTS should be considered for specific applications where not only high field and field gradient are sought, but also higher operating temperature, large operating margin and radiation tolerance are premium.

In addition, it is also important to underline that the HFM R&D program is intended as a focused, innovative, mission-style R&D in a collaborative and global effort, intending that the R&D is expected to produce specific results relevant to future accelerators (focused), with well-defined timeline, deliverables and milestones (mission-style), and paying special attention to novel engineering solutions (innovative).

The above objectives can be traced to the requests originated from the European Strategy for Particle Physics (ESPP) process, and documented precisely in the ESPP update endorsed by the CERN Council, in June 2020 [48, 54][4].

[4]It is important to trace the origin of the objectives to the ESPP. The ESPP consultation and synthesis process started with the Open Symposium of Granada, in May 2019 [Granada], and was completed with the endorsement of the ESPP update by the CERN Council, in June 2020 [48, 54]. The references quoted contain strong and precise statements relevant to R&D activities on high field accelerator magnets, namely:

"[...] the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;" [48]

"The accelerator community, led in Europe by CERN with partners in the United States and Japan, is investing efforts in the design of high-field magnets based on Nb_3Sn superconductor. [...] A focused, mission-style approach should be launched for R&D on high-field magnets (16 T and beyond); this is essential for a future hadron collider, to maximise the energy and to minimise the development time and cost. Development and industrialisation of such magnets based on Nb_3Sn technology, together with the high-temperature superconductor (HTS) option to reach 20 T, are expected to take around 20 years and will require an intense global effort." [54]

The R&D mentioned above needs to respond to the request that:

"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage." [48].

It is possible to represent graphically the main objectives in the form reported in Fig. 2.7, where we plot a length of dipole magnets produced (i.e., magnet length times the number of magnets) vs. the bore field. The blue line gives an idea of the state-of-the-art, bounded on one side by the nearly 20 km of Nb-Ti LHC double-aperture magnets in the range of 9 T ultimate field, and at the high-field end by single model magnets with approximately 1 m length and in the range of 14.5 T maximum field. The HL-LHC point marks the production of 6 dipoles of 5.5 m length with 12 T ultimate field. The objectives listed above can be represented in this plot as an extension of the field reach by moving along the horizontal axis (magnetic field) thanks to advances in Nb_3Sn and HTS magnet technology, as well as an extension of the production capability by moving along the vertical axis (magnet length) thanks to the development of robust and efficient design and manufacturing processes. Note for clarity that the symbols at higher field (Nb_3Sn at 16 T, HTS at 20 T) and longer magnet length (5 km) represent targets, providing the desired R&D direction, and they should not be read as specified performance.

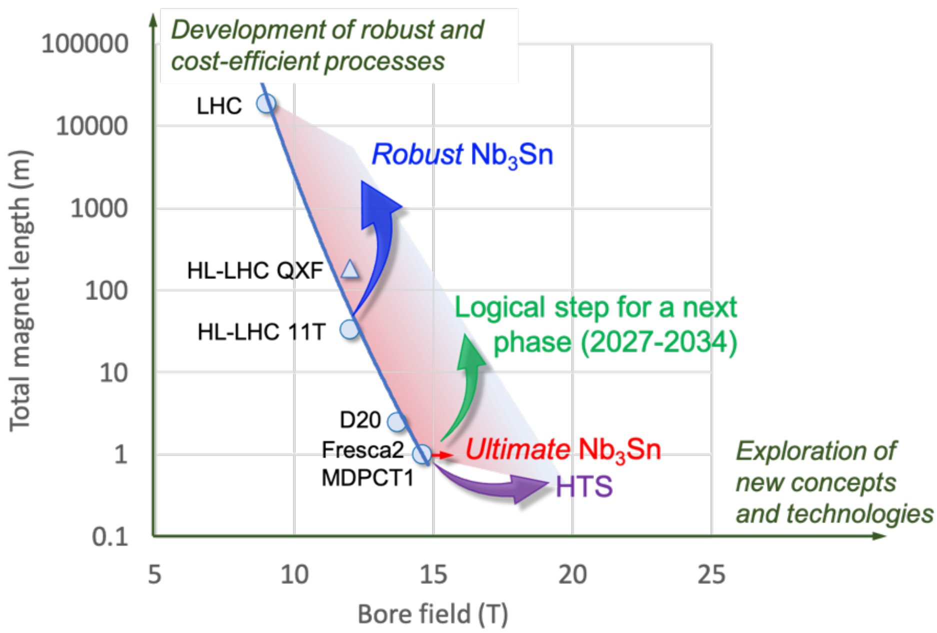

Fig. 2.7: Graphical representation of the objective of the HFM R&D program in this phase, 2021–2027. Both fronts of maximum field (red for Nb_3Sn, purple for HTS) and large-scale production (blue) are intended to be advanced at the same time. Also represented, in green, is a possible evolution for the longer term, 2027–2034.

The parallelism in the development is an important element of the program. We believe this is necessary to provide the requested significant advances within approximately five to seven year time frame, i.e., responding to the notion of a mission-style R&D that needs to feed the discussion for the next

As to the scope of the program:

"Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders [...] The technologies under consideration include high-field magnets, high-temperature superconductors [...]" [48]

"The particle physics community must further strengthen the unique ecosystem of research centres in Europe. In particular, cooperative programmes between CERN and these research centres should be expanded and sustained with adequate resources in order to address the objectives set out in the Strategy update." [48]

"Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes." [48]

"The implementation of the Strategy should proceed in strong collaboration with global partners and neighbouring fields." [48]

iteration of the European Strategy for Particle Physics with crucial deliverables.

The graphical representation of Fig. 2.7 discussed above only defines the first step in the R&D, which should enfold in the 2021-2027 period. Naturally, once it is proven that the field reach can be extended, and the actual level is demonstrated, we can foresee the need of a follow-up phase. This should enfold in the period 2027-2034, being dedicated to proving the new generation of high field magnets on a scale of accelerator-magnet prototype, i.e., several meters of cumulated magnet length. This is represented by the green arrow in Fig. 2.7, whereby the choice of the field level, and the actual magnet length to be realized are again only indicative, and will depend on the results of the next years of R&D.

A further element in support to the R&D targets formulated above is that they respond directly to the demands coming from principal stakeholders. As evident from the quotations of the reference ESPP documents, the HFM R&D targets formulated for Nb_3Sn magnets are stemming directly from the demands of an FCC-hh [9]. In the staged approach described here, they are also compatible with the allotted development time of the integrated FCC program [55]. Indeed, the parallelism proposed has the advantage that it will provide early elements for a decision on magnet technology towards the construction of the next hadron collider.

At the same time, while we recognize that the development of capture, cooling, acceleration and collider magnets for a muon collider [14] remains a formidable task, to be addressed by dedicated and targeted studies, an R&D on high-field Nb_3Sn and HTS magnets along the lines outlined above will be highly relevant to develop suitable design and technology solutions. Examples that will become clearer in the following discussion are (i) HTS conductor and coil winding technology towards the 20 T target, including partial- and no-insulation windings, whose results could be applied to the ultra-high field solenoids of the capture and cooling section, or to the high-field collider magnets; (ii) the study of stress management in Nb_3Sn magnets towards their ultimate performance, directly applicable to large aperture dipoles and quadrupoles for the high-energy collider main ring and IR magnets; or (iii) considering HTS magnet operation at temperature above that of liquid helium, not mentioned explicitly above but relevant to understanding operating margin in the high heat load and radiation environment of the high-energy collider ring.

2.6.1 Program Drivers

To define the work necessary to meet the objectives above, we can formulate practical questions that should be addressed in priority by a High Field Magnet R&D Program. These questions are the R&D program drivers, and they can be broadly divided into questions of relevance for Nb_3Sn, HTS, and common to both lines of development.

For Nb_3Sn high-field accelerator magnets the following leading questions can be drawn from the earlier discussion, and will need to be addressed being aware of the pioneering Nb_3Sn development that has led to the milestone HL-LHC magnets, the present reference technology:

- Q1: What is the practical magnetic field reach of Nb_3Sn accelerator magnets, driven by conductor performance, but bounded by mechanical and protection limits, and in particular is the target of 16 T for the ultimate performance of an affordable Nb_3Sn accelerator magnets realistic?
- Q2: Can we improve robustness of Nb_3Sn magnets, reduce training, guarantee performance retention, and prevent degradation, considering the complete life cycle of the magnet, from manufacturing to operation?
- Q3: Which mechanical designs and manufacturing solutions, from basic materials, composites, structures and interfaces need to be put in place to manage forces and stresses in a high-field Nb_3Sn accelerator magnet?
- Q4: What are the design and material limits of a quenching high-field Nb_3Sn magnet, and which detection and protection methods need to be put in place to remain within these limits?

– Q5: How can we improve design and manufacturing processes of a high-field Nb_3Sn accelerator magnet to reduce risk, increase efficiency and decrease cost as required by an industrial production on large scale?

For HTS high-field accelerator magnets, the leading questions are more essential to the potential and suitability for accelerators, with the awareness that the body of work in progress is not yet at the point where a reference technology can be defined:

– Q6: What is the potential of HTS materials to equal and surpass the magnetic field reach of high-field accelerator magnets beyond the present and projected limits of Nb_3Sn, and in particular is the target of 20 T for HTS accelerator magnets realistic?
– Q7: Besides magnetic field reach, is HTS a suitable conductor for accelerator magnets, considering all aspects from conductor to magnet and from design to operation?
– Q8:What engineering solutions, existing or to be developed and demonstrated, will be required to build and operate such magnets, also taking into account material availability and manufacturing cos ?

Finally, common to Nb_3Sn and HTS:

– Q9: What infrastructure and instrumentation are required for a successful HFM R&D, taking into account aspects ranging from applied material science to production and test of superconductors, cables, models and prototype magnets?
– Q10: What is the quantified potential of the materials and technologies that will be developed within the scope of the HFM R&D program towards other applications to science and society (medical, energy, high magnetic field science), and by which means could this potential be exploited at best ?

2.7 Proposed Program Structure and Deliverables

2.7.1 Conductor development

The main points of the Nb_3Sn R&D line are threefold: (i) to advance the performance of Nb_3Sn wires beyond present state-of-the-art, (ii) to make the performance of present and future Nb_3Sn conductors more robust, (iii) to increase the number of qualified manufacturers of HEP-class Nb_3Sn conductors and make the material less expensive in view of a demonstration of production scale-up. Here we intend with performance the full set of requirements, including manufacturing, mechanical and magnetic properties as specified for the FCC Conductor Development Program. Development is still needed to achieve those targets.

For HTS, activities in Europe are focusing on REBCO tapes. The emphasis will be on achieving controlled, homogeneous and reproducible geometrical and electro-mechanical properties along the full length, e.g. internal resistance in between layers, copper stabilizer electrical resistivity, the effect of the dog-bone shape of the copper stabilizer. Feedback shall be given by the community to tape manufacturers to make them aware of the needs and identified problems. Some innovative and more fundamental rethinking will be required, that may bring advantages in magnet design, e.g. material engineering to mitigate the anisotropy of REBCO. Industrialization should be addressed to assure the feasibility of long (1 km target) unit lengths as required for magnet manufacture. It is important to resolve the question of cables, through development, qualification, and identification of cable configurations suitable for accelerator quality magnets (stack, CORC, Roebel, novel concepts), addressing among other concerns the need for transposition.

A decision on practical conductor specifications (Nb_3Sn and HTS), with a cost-effective production perspective, will be one of the main outcomes of the development work planned in the coming years.

2.7.2 Nb_3Sn magnet development

There is intimate synergy between the development of ultimate-field and robust magnets. The development at this stage intends to master building blocks that may or may not be relevant for the eventual ultimate-field design (e.g. comparing different needs for high/low pre-stress compact coils, SM coils). The Timing of technology R&D vs. demonstrators is challenging. The need for technology R&D and innovation must be balanced with the need for demonstrator magnets tested by the next ESPP update. In the end, all developments must constitute stepping stones towards robust ultimate-field magnets. Specifically, developments that are applicable only in the 12 T (present HL-LHC) range shall not be in the scope of this roadmap. The R&D shall strive for fast-turnaround step-by-step validation, using agile design that incorporates insights from previous steps: from material samples to coil-composite samples and powered-cable samples, to subscale coils (e.g. SMC) or directly to 12 T range mirrors and magnets, and on to 14, 15, or 16 T magnets (depending on available conductor, robustness and maturity of technology). It is important to plan length scale-up from earliest design stages, and to promote automation and innovations leading to simplified processes, even if these do not yet get implemented in the first coils.

A decision on a feasible, cost-effective, and practical operating field for Nb_3Sn magnets will be one of the main outcomes of the development work planned in the coming years.

2.7.3 HTS magnet development

Given the cost of HTS the natural solution is a hybrid solution where LTS are used in the lower magnetic field area (below say 15 T), and HTS are used above. Such a configuration requires the use of liquid helium as coolant (though there are some concerns about using He-II with HTS). However, there is a great opportunity to work at 20 K with J_E well in excess of the 500-800 A/mm² that is usually required. We hence need to explore the possibility of intermediate temperature range (10-20 K) and dry magnet (conduction cooled). This may have deep implications for the overall thermal, mechanical and magnetic design.

The R&D on HTS magnets will likely focus on manufacturing and testing sub-scale and insert coils as a ‘R&D vehicle’ and demonstration of operation beyond the reach of Nb_3Sn. The controlled-insulation scheme for HTS coil will be explored by testing coils with reasonable current and with requirements for accelerators (e.g. ramp rate of 20 T in 1000 s in LHC, 20 mT/s). This question is very important since it can change dramatically the design principle not only of the magnet but also of the conductor. The coil shape design will be optimized to reduce wrong field components. The end design (cloverleaf, CCT, etc.) is a crucial issue that needs to be addressed to mitigate the complexity of tape ratio aspect and hard way bending. Finally, screening current effects (magnetization and time stability) need to be understood in detail, with ways to decrease/remove these effects (overshoot/vortex shaking/temperature increase).

2.7.4 Cross-cutting technologies

Advances will be required in these topics that are common to both Nb_3Sn and HTS magnets:

R&D programs on material development and characterization are already in place in Europe and the USA and must be reinforced. The global strategy is to:

- develop and characterize materials and composites relevant to HFM applications (including detailed material studies, advanced imaging and analytical techniques, material measurements and descriptions),
- develop new engineering solutions for thermal management of high field magnets (both internal, heat transfer to coolant, and external, heat transfer to cryoplant) to be integrated from the start,
- consolidate the modelling tools to complement short-model magnets (constitutive equations and models adapted to the whole spectrum of electro-thermo-mechanical, cryogenics and thermo-

physical properties relevant to HFM R&D).

The challenges posed by magnet powering and protection have multiple facets, and they will need to be addressed in an integrated manner. There is a parallel between the magnet protection and magnet mechanics challenges. Firstly, detection and protection in the regime of stored energy and energy density described above will require new concepts, especially for HTS (e.g. non-insulated or controlled-insulation windings). Secondly, measurement and characterization of the thermo-mechanical and dielectric properties and limits of coils and structures will be a mandatory step to ensure that the design is safely within allowable limits. Finally, comprehensive multi-physics models with augmented accuracy will be the main tool guiding design and analysis in the extended regime of field, stored energy, temperature and voltages. Also of high importance, and related to materials characterization, is the determination of degradation limits of Nb_3Sn and HTS magnets.

2.8 Facilities and infrastructure

The development of high field magnets requires, at the partners' laboratories, dedicated infrastructure suitable for R&D, from the start. Construction of full-scale prototypes, also engaging industry, is needed in a more advanced phase of the activity.

Among the dedicated infrastructure required for manufacturing both superconductors and magnets activities, we see a critical need for: Rutherford cabling machines for producing Nb_3Sn cables with large in-field current capability and a large number of strands (40 to 60); cabling machines for HTS cables; and automated winding machines for the production of LTS and HTS coils. The goal is to acquire such infrastructure by the end of this phase of the R&D, to be cooperatively shared among all collaborators.

For test and measurement of magnets, we need: test stations for the electro-mechanical qualification of conductors, at 1.9 K and 4.5 K, in external magnetic fields of up to 20 T and possibly beyond; test stations with high-field magnets having large bore aperture and enabling the measurement of HTS coils in a background magnetic field (a specific requirement for the qualification of HTS coils); and multi-purpose vertical or horizontal test stations for long coils and magnets.

A basic step at the beginning of this R&D is to review the existing diagnostic, instrumentation and test infrastructure as required by HFM R&D, and establish future needs. We will then need to coordinate instrumentation and test infrastructure development and upgrades and facilitate sharing of test resources within the scope of the HFM R&D.

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3 High-gradient RF Structures and Systems

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3.1 Motivation

All present particle accelerators used for High Energy Physics (HEP) are based on RF technology to produce the high accelerating gradients required to achieve intense high energy particle beams. Thanks to continuous R&D activities conducted worldwide, tremendous progress has been made in this area over the last 30 years, evidenced by the successful construction, commissioning and operation of several large scale facilities. However, the requirements of future facilities now being considered for HEP impose significant new challenges and the need to push forward RF acceleration technology.

As a primary objective, increasing the accelerating gradient is an absolute necessity to constrain the facility to a reasonable size while aiming at higher and higher particle energies. Then, economics always being a limiting factor, making progress towards more affordable RF systems at an industrial scale is also mandatory. Engineering programs aiming at optimizing the fabrication cost of systems will gain in importance in the coming years.

Other factors are now also growing in importance due to their scaling with the size of the facilities, and the required beam parameters become more and more difficult to achieve. Energy efficiency is a key parameter for any future HEP facility. Efforts should be made on all systems and sub-systems, from the RF source to the RF structure, to optimize and limit energy consumption. Another parameter of growing importance is the accelerator reliability. Even though particle physics experiments are based on data accumulation over long period, and can cope with short machine downtime, the overall effort to build

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and operate an entire facility requires highly reliable components, and this may lead to technological choices driven not only by pure acceleration performance.

Even though novel acceleration concepts such as laser-plasma acceleration are promising for the long term future, the actual or short-term potential for increased performance of RF acceleration is huge and can be exploited providing that R&D programs are well defined, and properly coordinated among the different stakeholders. This constitutes the main motivation to define and later on to implement an R&D roadmap for high-performance RF structures and systems.

3.2 Panel activities

High gradient RF Structures and Systems is one of the five key areas identified by the European Strategy for future HEP facilities where progress in R&D is needed. The scope of the panel covers normally conducting (NC) and superconducting (S) RF structures and related systems (power couplers, frequency tuners, high order mode couplers and dampers), high power RF sources and low level RF systems (LLRF). The main charge to the panel is to develop an R&D roadmap for the next ten years for this technology, taking into account the capabilities of the community.

The expert panel was fully constituted in April 2021 and held its first meeting on the 6th May. The panel held several meetings afterwards, every two weeks on average. The first task was to precisely determine the technological domain covered by the panel and then to define the state of the art. Both superconducting RF and normal conducting RF international scientific communities regularly exchange information on their progress through the Tesla Technology Collaboration (TTC) workshops the recurrent High Gradient Technology Workshops, respectively. Via these two consorita, information on the state of art is readily accessible.

The panel organized a dedicated workshop (held virtually) on the 7th and 8th July 2021[5] with the twofold objective of understanding the requirements and challenges of future HEP facilities regarding RF acceleration and defining key technologies and developments that are essential on the way towards the construction of future accelerators for high energy physics. Presentations and discussions during this workshop have been the primary material used to produce this report.

Links and coherence with the US Snowmass process, and in particular with the topical group of the Accelerator Frontier AF7 (Accelerator Technology R&D) has been ensured thanks to the participation of some members of our LDG expert panel in the AF7 group.

3.3 SRF challenges and R&D objectives

3.3.1 Bulk Niobium and the path towards high quality factors at high gradients

Bulk niobium technology for SRF cavities has been under constant optimization over 50 years and today is still the main operational technology for the construction of SRF accelerators.

The definition of material standards, standard recipes for surface preparation, and precise procedures for surface cleaning has set a very robust baseline allowing the construction of large scale SRF accelerators (examples include the European XFEL, LCLS-II at SLAC, and SHINE in Shanghai).

Even though the hard fundamental limit of niobium has been close to being reached for over a decade, surface and heat treatments have been investigated to tune the cavity performance to the very stringent specifications required by new projects and thus improve specifically the key parameters (Q_0, E_{max}, fabrication cost, reliability, among others). Niobium technology will remain competitive for years to come, compared to the new alternative thin film superconductors currently under investigation; many technical and technological challenges have to be overcome to allow their industrialization.

The various new treatments under investigation and optimization can be divided into three main areas:

[5] https://indico.cern.ch/event/1052657/

- **Material structure**: the fine grain structure (FG) obtained from laminated ingot, originally the only solution commercially available, has been surpassed in term of physical properties and cost by large grain structures (LG) obtained from sliced ingots. However, the latter suffer from technical limitations due to anisotropic mechanical properties. Challenges with respect to pressure vessel regulations are under discussion. Medium grain structures (MG) are under investigation and development as these could offer the same physical properties (superconducting, thermal) as LG with improved mechanical properties, compulsory for reliable cavity fabrication.
- **Heat treatments**: baseline heat treatments consist of a first 800°C hydrogen degassing/recrystallisation treatment and the so-called low temperature baking at 120°C over 48 hours. These baseline treatments, when associated with advanced surface treatment (final electro polishing below 15°C), demagnetization procedures and cooling procedures (high temperature gradients to promote magnetic flux expulsion) and magnetic hygiene revealed the efficiency and improvements offered by specific heat treatments such as nitrogen doping, nitrogen infusion and 2-step baking. Nitrogen doping allowed unprecedented Q_0 to be reached, at the expense of the maximum achievable accelerating gradient. On the contrary, nitrogen infusion and 2-step baking exhibit an only slight improvement of Q_0 but very high fields can be reached at low RF losses ($Q_0 > 10^{10}$ above 40 MV/m). Heat treatments at intermediate temperature (between 200°C and 600°C) have been recently investigated and revealed doping-like behavior (Q_0 rise versus accelerating gradient) but with a much simpler process.
- **Surface polishing**: for several years, the efforts made to reduce the temperature of electropolishing (EP) treatment below 15°C have led to unprecedented cavity performance. Low temperature during chemical treatment is the key to promote optimum performance after specific heat treatments as described earlier. Alternative polishing techniques as metallographic polishing (MP) and more recently electrolytic plasma polishing (EPP) are under investigation. The ambition is to reduce the cost and eventually the ecological footprint of the standard chemical processes. No real improvement of cavity is foreseen as roughness better than that achieved by EP does not seem to be a key parameter, unless for future deposition of thin films.

3.3.2 Field emission reduction

Field emission is one of the main reasons for the degradation of superconducting cavity quality factor. Its presence can limit the ultimate performance of SRF cavities and hence the cryomodule in which they are assembled. In general, the field emitted current tends to become more severe during beam operation; hence, it can affect the entire accelerator's final performance. Dust particles on the cavity surface are the most common sources of contamination leading to field emission during cavity operation.

For these reasons, it is essential to fully understand how this phenomenon is generated, and how it evolves from the SRF cavity preparation in the clean room, through the cavity assembly in the cryomodule, until the final accelerator module test and during machine operation.

The field emission issue can be addressed at three different levels:

- **Clean room preparation**: a clean environment is mandatory to preserve the cavity package's high performance. Improvement in manipulation, pumping/venting procedures and automation can be valuable assets for high performance and mass production. The introduction of robots in the assembly line can relieve operators from tedious, time consuming and heavy work while ensuring robustness and reproducibility. It can have a beneficial impact on the costs of mass production.
- **Diagnostics**: analyzing X- and γ-ray patterns emerging from the cryomodule is a valuable method to diagnose field emission. With a proper detector system it is possible to evaluate recovery or mitigation methods. Specific diagnostic tools need to be developed for cryomodule testing and operation.

– **Mitigation and recovery**: there are ongoing efforts to develop treatments capable of cavity performance recovery or to mitigate detrimental effects due to field emission in a cost-effective way. Plasma cleaning and dry-ice rinsing are very promising and need further development.

Field emission is a long-standing issue in the SRF field and will become even more relevant for future high-gradient and high-performance superconducting cavities, and therefore for future HEP facilities' operation.

3.3.3 Thin superconducting films for SRF cavities

There are major strategic European research initiatives on thin superconducting films for superconducting radio frequency cavities. Based on a survey of R&D work done throughout the world, four main research thrusts can be identified:

– **Niobium films on Cu cavities**: fabrication cost reduction for cavities with frequencies < 700 MHz. The goal is to reach RF performance (Q and E_{max}) similar to bulk niobium. As a standard for the ongoing R&D efforts, 1.3 GHz cavities will be used with performance targets of Q = 10^{10} at 20 MV/m, followed by Q = 10^{10} at 30 MV/m. As a second step, high performance will be established with lower frequency cavities (400 MHz and 600 MHz).
– **New superconductors on Cu cavities**: operation cost reduction (higher operation temperature > 4.2 K). Such superconductors are selected among A15 compounds (Nb_3Sn, Nb_3Al, V_3Si) or MgB_2. Proof of principle has been achieved with Nb_3Sn on niobium cavities. The goal is now to achieve the same performance on Cu cavities at 1.3 GHz: Q = 10^{10} at 15–18 MV/m and 4.2 K. Scaling to lower frequencies (600 MHz) cavities can then be attempted.
– **Multilayers**: operation and construction cost reduction by increasing the maximum accelerating gradient and the quality factor. The goal is to demonstrate improved performance on a 1.3 GHz superconducting RF cavity, i.e. 30–50% increase in the maximum accelerating field and a factor of two in Q_0.
– **Innovative cooling techniques**: operation cost reduction by optimizing cooling efficiency of SRF cavities and reduction of the dependence on helium. Higher operation temperature ($\geq$ 4.2 K) will open the way for cryocooled accelerating structures with optimized thermal links and structures made by additive manufacturing. The goal is to demonstrate the feasibility, i.e. conduct RF tests on a 3D printed cavity cooled with a cryocooler at 4.2 K.

The proposed R&D program relies on several key factors common to the four mentioned research thrusts:

– **Deposition techniques**: a large number of deposition techniques exists, and priority should be given to the ones that can be scaled up to complex geometric shapes such as SRF cavities. Optimised structural, chemical and electrical properties obtained on flat coupons have to be homogeneous and reproducible on a 1.3 GHz cavity shape. Vapour phase (CVD, ALD, PVD), plasma-assisted deposition (HIPIMS, custom DC/AC sputtering) and electrodeposition are promising methods that meet the complex geometric requirements.
– **Substrate preparation**: the structural and chemical properties of the substrate are a crucial aspect of thin film deposition with bulk-like superconducting properties. In particular, substrate roughness needs to be reduced well below the film thickness (1–5 microns), and the role of surface chemical properties (oxides, impurities) needs to be better controlled and understood. Chemical surface treatments such as electropolishing, buffered chemical polishing and passivation layer deposition are methods of choice that could be studied.
– **Characterisation techniques and RF tests**: high-throughput characterisation methods for samples with demonstrated predictive capability for overall cavity RF performances are an absolute

necessity for a successful R&D program prior to cavity scale-up. Besides all the usual structural (diffraction, MEB, TEM, etc.), chemical (spectroscopy, SIMS, etc.) and electronic (transport) characterization techniques applied to samples, efforts should be reinforced towards the development of tunneling spectroscopy, magnetometry and RF tests on samples with quarter wave resonators (QWR). To that end, the SRF community research program needs: i) a large number of RF cavities (mono-cell and multi-cell for relevant project frequencies) with various frequencies (400 MHz, 600 MHz, 700 MHz, 1.3 GHz), and ii) RF testing capability at cryogenic temperature (down to 1.8 K), that can handle a large spread of frequencies (400 MHz to 6 GHz), and which can be dedicated to R&D. This capability should handle 2–3 tests per week with in-situ metrology (magnetic field and temperature mapping, X-ray detectors, etc.).

– **Collaborations and task force**: A reinforced international collaboration framework (collaborative agreements) and international student program should be implemented to provide the necessary task force for a competitive and accelerated R&D throughput.

3.3.4 Challenges regarding the construction of SRF Couplers

Superconducting cavities cannot be operated without fundamental power couplers (FPC) and high order mode (HOM) couplers. Both types of RF couplers play a fundamental role with respect to R&D objectives for future HEP facilities. Whenever the community invests in better SRF cavities, driven by new challenging beam parameters, the FPCs and HOMCs will also require efforts. For a long time, the worldwide expert community has addressed design and technology issues: RF & multipacting simulations, the maximum RF power, the number of couplers per cavity, the choice of ceramic, its surface preparation (e.g. TiOx or TiN layers), possible discoloration, the copper coating of stainless-steel parts (bellows are critical), diagnostics, and last but not least, coupler conditioning and testing in dedicated infrastructures. All major laboratories and projects (including non-HEP large-scale facilities) have their own FPC and HOMC history, but many problems were and are shared. Key items like the ceramics for the windows (be it disk, cylindrical or coaxial) are of utmost importance, and heat transfer, the suppression of multipacting by coating or DC-voltage polarisation is to be studied. Qualification for clean room handling and cryostat integration are mandatory. Finally, mass production for large scale facilities requires highly qualified vendors who typically have the challenge that almost each project triggers a fabrication re-start after a long break between projects.

The charge of the RF power coupler community, with respect to future large scale HEP projects (and others, e.g. FEL and ERL) is to have sufficiently strong R&D activities and to address technology improvement but also sustainable production. Expertise in the laboratories can be preserved by addressing the identified main issues of performance improvement, reliability, cost-effectiveness and energy efficiency. Young researchers need to be trained in existing and new technical infrastructures. Expertise, knowledge and also infrastructure can be shared for many large-scale projects, the latter of course to be evaluated on a case-by-case basis.

3.4 NC RF challenges and R&D objectives

High-gradient acceleration through high-frequency NC structures (S, C, X bands) provides at present the highest accelerating fields on a scale suitable for a high energy physics facility like an e^+/e^- linear collider. In this respect, this is the best option as far as the facility size is of primary concern. The main challenges for building a HEP facility based on this technology include: improving the operational gradients, simplifying the construction process of all components, reducing the conditioning time, reducing the cost and delivery time of the RF power sources (klystrons), and transferring expertise to industry to allow production of all components over an orders-of-magnitude larger scale.

Gradients at or in excess of 100 MV/m have been demonstrated in many CLIC-type X-band accelerating sections, even those incorporating HOM dampers. Larger gradients have been demonstrated in tests of prototypes made in hard copper or copper alloys. However, reaching the highest gradients at an acceptable breakdown rate requires a long-lasting conditioning process, with a typical duration of months. Also, the peak RF power required to reach the highest gradients is substantial, and impractical for a facility where all sections are driven close to their physical limits by external RF power plants. In fact, the gradient baseline of all projects based on X-band klystron driving accelerating modules is in the 60–80 MV/m range, well below the demonstrated physical limits, that can mostly be exploited only in the two-beam configuration. To operate sections closer to the present and (hopefully improved) future breakdown limit it will be necessary to increase either the available RF peak power in the tubes or the intrinsic efficiency of the sections themselves. Obviously, the second would be preferable for cost and sustainability considerations. Clever design such as distributed input coupling, or suitable technologies such as the use of cryogenic copper, dielectrics and maybe even HTS superconductors, are promising roads to be explored in this respect, and may be relevant in bringing the efficiency of S-band and C-band technologies to a competitive level.

At present, high-gradient experimental R&D is carried out in a limited number of test facilities around the world, testing a few tens of structures per year. The number of the klystrons installed in the test facilities is also limited. Since a HEP infrastructure based on this technology would require of the order of 1000 RF modules, it is clear the scalability towards mass production and industry involvement are crucial issues to be addressed.

3.4.1 NC RF manufacturing technology

Accelerating structures are made with ultra-precision diamond machining involving tolerances in the μm range and surface roughness in the range of 0.1 to 0.1 μm. Subsequent bonding and brazing operations need to be carried out in inert atmosphere to avoid surface pollution. Several months of conditioning is needed per structure to reduce the breakdown limits. For large facilities like CLIC, the production cycle needs to be simplified and the reliability of the assembly of full modules with damping, absorbers and wakefield monitors needs to be improved, while the quality of the assembled structures needs to be maintained or even improved. At present, structures are measured and tuned by hand, which is a time-consuming process not applicable to large-scale fabrication. State-of-the-art gradients of 100-–120 MV/m have been achieved in modules, but this often requires repeated mechanical corrections to pass qualification.

3.4.1.1 Performance improvement

For industrialisation, vacuum brazing has already been applied at some labs and needs to be studied further. The production of two halves with subsequent electron-beam welding has been tested once and promises to reduce the production and conditioning time. The use of hard copper and of rectangular integrated discs deserves further R&D.

3.4.1.2 Technical infrastructure

High-precision milling, vacuum brazing, and ultra-precision metrology are available via various suppliers but the knowledge of using this infrastructure efficiently often hinges on a few technical experts, who quickly disperse in case of long production breaks. It is important to keep this expertise in at least a few laboratories. Structure assembly and handling may profit from procedures and clean-room environments as used for SRF cavities.

3.4.2 NC high-gradient RF in strong magnetic fields

To date, a muon collider is the only viable solution for a lepton collider with center-of-mass collision energy at the scale of 10 TeV. The Muon Accelerator Program (MAP) developed a concept where a short, high-intensity proton bunch hits a target and produces pions. The decay channel guides the pions and collects the muons produced in their decay into a beam. To provide the required luminosity several cooling stages then reduce the longitudinal and transverse emittance of the muon beam using a sequence of absorbers and RF cavities in a high magnetic field. The accelerating cavities are the key to cooling efficiently with limited loss of muons. They need to operate at frequency range of 300 to 700 MHz and provide a high gradient in a strong magnetic field, up to 30 MV/m in 13 T. It has been shown experimentally at Fermilab's MuCool Test Area that the achievable accelerating gradient in RF cavities based on conventional copper technology is significantly reduced in a strong magnetic field, which limits the use of cavities to low gradient and dramatically reduces the efficiency and increases the size of the muon cooling complex.

Two approaches have been considered in MAP high-pressure hydrogen-filled cavities and beryllium-wall cavities. Although the dedicated test program has demonstrated that both approaches result in cavities operating up to 50 MV/m in 3 T, this remains an unconventional technology with potential risks and hazards. It is necessary to experimentally develop it further before applying it to a muon cooling test facility and ultimately to the muon collider.

This R&D program includes:

– consolidation of achieved results (50 MV/m) and pushing to stronger magnetic fields of up to 13 T,
– investigation of other materials (Al, AlBe, CuBe, and other alloys) which may show similar or better performance and are better suited for RF cavity fabrication,
– investigation of operation parameters including lower (down to cryogenic) temperatures and shorter RF pulse lengths.

To perform this program, a dedicated RF test stand is mandatory. In addition to a MW-level peak RF power source, it must have high field ($\sim$10 T) solenoid. Now that the MAP program has stopped and MuCool Test Area been decommissioned no such test stand is available anywhere in the world. In addition, synergy with other ongoing high-gradient R&D programs should be exploited, including for example the CLIC study and CERN L4-RFQ spare project where in addition to RF test stands a high-voltage DC test setup has become an integral part of the R&D program. This offers a fast and cost-effective way to investigate the high-gradient properties of many different materials in a large parameter space including operating at cryogenic temperatures.

3.5 High RF power and LLRF: challenges and R&D objectives

3.5.1 High-efficiency klystrons & solid-state amplifiers

3.5.1.1 Main challenges

High-gradients NC structures can reduce the footprint of an accelerator, but they pose a challenge to the RF power sources. As the RF power requirements increase quadratically with the accelerating gradient, klystrons with up to 50 MW peak power are already being employed. CLIC uses the two beam scheme, which reduces the peak power requirements but needs essentially two accelerators for one physics beam. Even if larger gradients become possible in the future, they may not be usable because the RF sources become prohibitively expensive. Higher-efficiency tubes can reduce the voltage of the modulators, reduce the size of the RF stations, and provide higher output power. For continuous-wave (CW) or long-pulse acceleration, superconducting cavities are mostly used with gradients up to around 30 MV/m already in operation. Here it is not so much the peak power but the average power that determines the cost and size of RF power sources. Solid-state technology has gained ground in recent years but the volume, overall efficiency, power combination techniques and reliability can pose a challenge.

3.5.1.2 Main requirements for HEP facilities

Efficient high peak RF power in the X-band range is needed for NC accelerators, while efficient high-average-power devices up to $\sim$2 GHz are typically needed for SC accelerators. The first requirement is almost unique to HEP facilities with some possible applications for medical machines, light sources, or screening technologies, which means that the market is small. With the broadcasting industry moving to lower power devices in the GHz range, the market for high average power devices is also declining.

3.5.1.3 State of the art and performance requirements

High efficiency klystrons have made important progress in the last five years and successful prototypes have shown that the technology works with a frequency coverage from a few hundred MHz to tens of GHz. Solid-state technology has made the step into the MW range with the installation and operation of the CERN SPS solid-state plant at 200 MHz, a frequency so far not covered by klystrons. R&D on high-efficiency klystrons needs to be continued and several suppliers have shown interest and are ready to collaborate with laboratories in the production of prototypes and pre-production devices. While solid state is set to take over the market from tetrodes for lower frequency, high-power RF amplifiers, the technology needs to improve in efficiency. The combining networks are also of crucial importance as they will define the fault tolerance and maintainability. Improved efficiency at the transistor or amplifier module level is expected to be driven by industry. Combining networks or combining cavities, reliable operation, packing factor and overall efficiency are areas, where laboratories can contribute R&D.

3.5.1.4 Technical infrastructures

Testing RF power stations with peak power in the range of several tens of MW, as well as CW power stations in the MW range, needs significant infrastructure, which is often not available at the manufacturer. Larger industrial production will likely need lab-based test stations in order to keep down the cost. Prototyping of solid-state combining technologies and the development of high-efficiency klystrons in the labs are vital to i) enable industrial production, and ii) moderate the cost of the production of high-power RF systems in industry.

3.5.1.5 Technologies to reduce RF power needs for acceleration

The frequency control of high-Q superconducting cavities is an area for power savings that has further potential. Two areas are of particular interest: a) very low beam loading, and b) operation with rapidly changing beam currents.

Low-beam-loading cavities have a very small intrinsic bandwidth, down to a few Hz or tens of Hz. Keeping the frequency of the cavities controlled to such a level is often impossible due to small vibrations, coming from cryogenics, the vacuum system or other external sources. For this reason the fundamental power coupler (FPC) is usually over-coupled, resulting in a larger bandwidth of the cavity–coupler system. However, this means that the power needs are often increased tenfold with respect to the power needed for acceleration and the surface losses of the cavities. Correcting the cavity frequency fast enough to compensate microphonics can reduce the power needs for low-beam loading machines by up to a factor ten (e.g. LHeC, PERLE, HIE-ISOLDE, etc.).

For high-beam-loading cavities with rapidly changing currents such as the LHC cavities (e.g. at injection) the cavity frequency is usually adjusted to be optimum for either the full beam current or 50% of the beam current (half-detuning scheme) in order to optimize peak power needed from the RF system. The fixed detuning means that additional RF power is needed as soon as one departs the beam current that corresponds to the adjusted frequency detuning. The ability to change the cavity tune during the transients (no beam to full beam) could significantly reduce the peak power needs. In the case of HL-LHC the peak power needs during injection could be reduced by 50% or more.

3.5.1.6 Technology for rapid cavity tuning

With the rise of purpose-designed low-loss ceramics it has become possible to design tuning devices for SC cavities that do not rely on mechanical deformation. Instead a fraction of the stored RF power is coupled out, and sent through a Ferro Electric Fast Reactive Tuner (FE-FRT) which basically shifts the phase as a function of an externally applied voltage. The electromagnetic wave is then reflected back into the cavity, thereby changing the cavity frequency. The proof-of-principle has been demonstrated and R&D for a full-scale tuning device applicable to the LHC has started. Further work for ERLs and future circular colliders should follow.

3.5.2 MM-wave & Gyro-devices

MM-wave and THz acceleration is a growing area of research worldwide, including non-linear laser-based, electron-beam-based, and dielectric wakefield acceleration. As part of the compact light programme, Lancaster, CERN, INFN and Strathclyde have developed a novel Ka-band (36 GHz) RF system including the development of Ka-band RF sources, and travelling wave structures. While initially aimed at an intermediate gradient lineariser system, there is scope for such technology to operate at higher gradients than X-band technology. A key issue is the shortage of high-power RF sources, and klystron and gyro-klystron devices are being developed.

3.5.2.1 Main challenges and requirements for HEP facilities

The main challenges are the development of high-power, high-efficiency short-pulse mm-wave sources, and the beam dynamics (both transverse and longitudinal). Currently the power available in short pulses is tens of kW, while MW are required for HEP applications. MW level sources do exist but tend to be long pulse. Both laser-laser and electron-beam sources are under development with two 3 MW 36 GHz sources designed already. Laser sources can deliver GV/m fields in free space with instantaneous powers of up to 30 MW but in very short picosecond pulses that are difficult to synchronise; they have had little development so far. With higher frequencies come smaller apertures making transverse dynamics and short-range wakefield much more challenging. To be useful for HEP we must be able to transport higher charges with less drift space taken up by focusing systems. As the wavelength is smaller it takes electrons several tens of mm-wave periods to become relativistic, making longitudinal dynamics more complex, similar to proton linacs. In the long term, mass production of high frequency structures needs to be developed to minimise the cost.

Millimetre-wave accelerators are useful as short bunch injectors, where the small period allows tight bunching, as linearisers as part of a bunch compressor, for short pulse diagnostics or as main accelerators. For a main accelerator the advantage is the higher gradients (200 MV/m or more) possible due to the operation at higher frequencies, and shorter filling times, allowing shorter accelerators. However, the beam dynamics issues would have to be overcome to allow either higher bunch charges ($\sim$nC) or higher repetition rates (10 kHz or more).

3.5.2.2 State of the art and performance improvement

At Ka-band, a design was developed for Compactlight that used a 3 MW RF source to drive a 30 cm travelling wave structure at 38 MV/m, while previous studies at CERN used a two-beam accelerator to demonstrate gradients of 152 MV/m for an 8 ns pulse. At 100–300 GHz, high gradients have been demonstrated with wakefield driven structures. A maximum gradient of 400 MV/m has been demonstrated and electrons accelerated by up to 200 keV while Gyrotron driven structures have achieved 150 MV/m, although 3 MW laser-based sources are now available allowing gradients in excess of this. The bunch charges are typically tens of pC.

At Ka-band, the 3 MW sources should be built and proven to work. Coaxial gyro-klystrons offer the potential of 10 MW sources in the future. At 100–300 GHz the first challenge is to demonstrate >100 MV/m gradients and acceleration to 1 MeV; this should be accessible with current technology. Further development of mm-wave sources, either laser or electron-beam-based approaches, should allow substantially higher gradients. Little research has been done on beam transport between accelerating stages, and longitudinal dynamics in the injection stage, which would allow the development of full linacs. The shorter filling times could offer improved energy efficiency of future accelerators as less energy is wasted filling the structure, however this would need the development of more efficient mm-wave sources.

3.5.2.3 Technical infrastructures

MM-wave accelerators can currently be tested at the CLARA accelerator for fully relativistic beams but beam time is currently limited. At lower energy 100 keV-level DC guns and THz-driven guns exist in DESY, and Cockcroft.

3.5.3 Artificial Intelligence and machine learning

Machine learning is being developed in several labs for use in RF conditioning and operation of accelerators. This involves a computer algorithm being trained to identify the difference between a good RF pulse, a bad RF pulse and anomalies. The algorithm then constantly analyses RF traces and characterises them. This can be used to identify advance triggers, warnings of failures or real-time detection in order to take corrective actions. This is a new field but expertise exists in many labs including CERN, STFC and JLab.

Initial studies suggest it is possible to predict and avoid RF faults, but the field is new. The typical expected gain would be in minimisation of field emission, arcs and trips of RF systems. In some cases, the time window between fault prediction and the fault may be short, so we need consideration of what mitigations are possible (such as turning cavity voltages down temporarily).

To make progress in this field, there is a need to access to large volumes of the right data recorded at the right time to train the algorithm. This requires a fundamental change in how accelerators take data and make them available for machine learning.

3.6 Facilities and infrastructures

As already mentioned in several previous chapters, technical infrastructures are of primary importance in order to have all the means to conduct R&D programs on RF acceleration: clean rooms, furnaces, surface-preparation labs, material-deposition equipment, cryogenic infrastructure and test stands, high-power RF stations, material surface-characterisation devices, to name only a few. All of them are intensively used to fulfill R&D programs but also for accelerator construction, as only some of them are typically available in industry.

It is obviously not possible to duplicate all this costly and space-consuming technological infrastructure in every laboratory committed to the RF acceleration R&D programs, and so the community has to ensure that all these equipment are i) available in a sufficient number to fulfill the overall needs, and ii) accessible to external teams, i.e. organised and integrated in a network to allow an easy access.

Sustainability of these infrastructures, some of which might have high operational and maintenance costs, has also been a matter of concern for some years, especially during period when they are not used and so not financially supported by construction projects.

4 High-gradient Plasma and Laser Accelerators

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4.1 Executive Summary of Findings to Date

The field of plasma and laser accelerators has reached the stage of setting up the first user facilities in the European research landscape. The many national and regional activities will continue until the end of the 2020s with a strong R&D and construction program, aiming at lower energy research infrastructures (for example, a GeV-scale free-electron laser facility, high-resolution medical imaging). Various important milestones have been achieved or will be achieved over the next years at those ongoing programs, including strong programs at CERN, INFN, DESY, RAL, Helmholtz, CNRS, STFC, ELI, EuPRAXIA, SLAC, LBNL, Tsinghua University, Shanghai XFEL and others. This should be complemented by early HEP-targeted tests and R&D activities. Given that funding for ongoing activities is mostly from non-HEP sources, several HEP-related aspects are currently neglected, for example: staging to high energy; efficiency; positrons; and polarisation.

The panel proposes an R&D roadmap for particle physics that is based on three pillars (see section

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4.7.1). The plan includes the first international feasibility and pre-CDR study for high gradient plasma and laser accelerators and their particle physics reach. This paper study will lead to a comparative report on various options, a feasibility assessment, performance estimates, physics cases and a cost-size-benefit analysis for high energy (see section 4.7.2). A second pillar will demonstrate a number of technical feasibility issues of importance for particle physics experiments through a prioritised list of technical R&D topics. A full list of three technical R&D areas and sixteen topics has been established and analyzed for state of the art and R&D objectives (see sections 4.4, 4.5 and 4.7.3). A third pillar on integration and outreach in our proposed roadmap aims at capitalizing on the high potential for synergy with other fields and large projects like EuPRAXIA. This pillar also discusses access to distributed R&D facilities under clear rules and supports innovation with closely connected industry.

After successful demonstration of various milestones and successful completion of ongoing major programs (AWAKE, EuPRAXIA, national programs), a dedicated HEP test facility will likely become necessary and should be operational in the mid 2030's. At this time the effort could evolve to develop a plasma and laser accelerator test facility at CERN or another suitable location.

4.2 Motivation

Progress in accelerator-based high energy physics is affected by practical limitations of size and cost associated with the RF accelerator technology used so far. Novel accelerator technologies overcome limitations in accelerating gradients by relying on plasma or dielectric structures, driven by high-power lasers or particle beams. Accelerating fields can be increased from today's values (below 0.1 GV/m) to values above 1 GV/m, perhaps even to the 10-100 GV/m regime. A new generation of highly compact and more cost-effective accelerators can be envisaged, promising new scientific reach with particle accelerators.

The potential of high gradient plasma and laser accelerators is illustrated by recent advances, including up to 42 GeV energy gain in electron-driven [1], 8 GeV in laser-driven [2] and 2 GeV in proton-driven [3] plasmas. This is complemented by progress in beam quality (low energy spread, small emittance, etc.) and stability in different facilities or experiments, and by the first demonstrations of lasing with a beam from a laser-driven plasma accelerator at SIOM [4] and from a beam-driven plasma accelerator at LNF/INFN [5]. The community has grown together in the EU-funded EuroNNAc network [6], in the ALEGRO activity [7], the AWAKE collaboration [8], and in the EuPRAXIA conceptual design study [9]. Parallel progress has been achieved for dielectric accelerators (ACHIP [10], as well as individual efforts on dielectric laser and terahertz acceleration) with the potential of very high repetition rate (MHz) and mass production (accelerator on a chip).

The field is driven by a rapidly growing, diverse and young community with strong links to universities, research centers and industry. There are growing links to users in the fields of Free Electron Lasers (FEL) and health. It is important to grow links to the users in High Energy Physics (HEP) in parallel. Only with support from HEP can the promise of a highly compact and more cost-effective collider be realized on the 30-year time scale, opening timely new energy-frontier reach for particle physics. We note that plasma and laser accelerator technologies can support intermediate steps at lower energy, enabling HEP experiments in dark matter searchs and studies of highly non-linear QED. It can also be used to boost energy in appropriately designed RF collider designs or to replace large-scale beam injectors.

4.3 Panel Activities

4.3.1 Mandate and scope

The expert panel "High Gradient Acceleration – Plasma, Laser" is charged with defining the roadmap in the area of plasma wakefield and dielectric acceleration. This includes as particular tasks: (1) Develop a long-term roadmap for the next 30 years towards a HEP collider or other HEP applications. (2) Develop milestones for the next 10 years taking explicitly into account the plans and needs in related scientific fields, as well as the capabilities and interests of the stakeholders. (3) Establish key R&D needs matched to the existing and planned R&D facilities. (4) Give options and scenarios for European activity level and investment. (5) Define deliverables and required resources for achieving these goals until the next European strategy process in 2026, in order to enable as best as possible critical decisions for R&D lines for HEP.

4.3.2 Activity

The expert panel was formed during February 2021 and had its kick-off meeting on March 2, 2021. Since then, an extended process of consultation with the advanced accelerator community has been put in place. The process has been steered through sixteen meetings of the expert panel. The activity was announced world-wide, and experts were invited to subscribe to an email list. At the end of May, 231 experts in total have registered to this list and are participating in the roadmap process. A first town hall meeting was held on March 30 and set the scene for advanced accelerators for HEP. The meeting included talks on high-energy physics facilities or experiments at the energy frontier (linear collider) and at lower energies (dark matter search, highly non-linear QED, low energy gamma-gamma). HEP-relevant parameter examples and two possible case studies were assembled and distributed. Also, a number of questions were formulated by the panel and sent to the community, asking for input. A second and a third town hall meeting were held on May 21 and 31, where in total 48 speakers presented their input to the roadmap process. The meetings were attended by up to 135 participants at a given time. A fourth town hall meeting will take place later, where the roadmap will be reviewed.

4.3.3 International Activities and Integration

Particle physics is an international endeavor, and we recognize that a coordinated strategy will be the most successful. In parallel to the activities of this expert panel, there are ongoing international activities in the United States and Asia. Together, these international processes will define the most important questions for the field of particle physics and identify promising opportunities to address them. In the US, the Particle Physics Community Planning Exercise (a.k.a. 'Snowmass') is organized by the Division of Particles and Fields (DPF) of the American Physical Society. It provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the US and its international partners.

Input to Snowmass is organized through ten different frontiers including the Accelerator Frontier. The Accelerator Frontier has several topical groups including AF-6 'Advanced Accelerator Concepts'. Advanced Accelerator programs are developing new concepts for particle accelerators, generation, and focusing that could revolutionize the cost paradigm for future accelerators. To ensure the required international coordination and to arrive at a globally coherent roadmap for novel accelerators, the AF-6 convenors include membership from the Expert Panel and vice versa.

4.4 State of the Art

4.4.1 Sources of Electrons, Positrons, Plasmas and High Power Laser Pulses

High-quality LWFA injector: Many laser-wakefield acceleration (LWFA) experiments employing low-repetition-rate lasers (typically $f_{\rm rep} = 1$ Hz) have demonstrated the generation of electron bunches with energies of order 1 GeV [11], a bunch charge of tens of pC [12], and a divergence of 0.1 - 1 mrad [13]. We observed in recent years a transition from demonstration and physics studies experiments to accelerator research and development. Maier et al. have reported [14] continuous operation for 24 hours of a LWFA at a pulse repetition rate of 1 Hz.[6] This experimental arrangement designed as an accelerator allows the

[6]as example: Maier et al. have reported [14] $E = 368\,\mathrm{MeV} \pm 2.5\%$; $Q = 25\,\mathrm{pC} \pm 11\%$; $\Delta E/E = 15\%$; $\Delta\theta = 1.8\,\mathrm{mrad}$.

first advanced studies leading to strong improvement of the beam quality [15]. We note that kHz laser drivers have been used to demonstrate LWFA with beam energy up to 15 MeV [16, 17].[7]

High average power, high efficiency laser drivers and schemes: Currently Ti:sapphire lasers, pumped with frequency-doubled diode lasers or flash-lamp-pumped Nd:YAG, are the drivers of choice for LWFA. Commercial systems operate at high peak power (10 PW at ELI-NP) and useful repetition rates (1 PW @ 1 Hz, BELLA). However, laser drivers for LWFA-based colliders require much higher average power. Options for achieving this performance come under two main headings: improving Ti:sapphire lasers, including more efficient cooling of the laser for higher repetition rate; and better pump lasers (higher energy, repetition rate and efficiency) i.e. frequency doubled diodes or Yb-doped fibre lasers. The EuPRAXIA project, together with European laser industry (Amplitude and Thales), is aiming at the 20-100 Hz regime [9] and there are concepts for up to kHz rates. Beyond this, new lasers and technologies are needed to overcome the intrinsic limitations of Ti:sapphire lasers and to reach the tens of kHz required for an HEP-relevant collider. Options under development include: the combination of multiple low energy, high repetition rate Yb-doped fibre lasers, recently demonstrating pulses of 10s mJ, 100 fs, 10s kHz [18–21]; thin disk Yb-doped lasers generating joule-level pulses at kHz repetition rates so far at longer durations [22, 23]; Thulium doped lasers operating at 2 μm having produced GW, < 50 fs pulses [24]; and the Big Aperture Thulium (BAT) project developing Th:YLF lasers. Each of these technologies is being developed towards the capability to produce 30 J-class pulses at 10s of kHz and at pulse durations at or below the 100 fs level, providing multiple options to enable efficient plasma accelerators.

Positron technical demonstrations: Results on the acceleration of injected positrons in a beam-driven plasma accelerator have been achieved at FACET. An overview and outlook for efficiency and beam quality has been reported [25]. Concepts for positron generation at the GeV level have been developed at the Queens University Belfast and others. Publications include the conceptual design of a positron source and line for the EuPRAXIA facility [9].

Advanced plasma photoguns with ultra-low emittance: Plasma photocathodes promise production of electron beams with ultra-low normalized emittance in both planes. Such beams may obviate the need for damping rings for potential future HEP injectors and would be compatible with plasma-based collider schemes, and could in the short term be used as test beams. The first plasma photogun was realized in proof-of-concept experiments at SLAC FACET [26], and next experiments, e.g. at SLAC FACET-II aim to demonstrate the potential of the scheme towards normalized emittances of the order of 10 nmrad.

Hybrid laser-beam driver schemes: demonstration, stability, efficiency: LWFA-driven PWFAs utilise high peak-current (>6 kA) electron beams from compact laser-driven wakefield accelerators to subsequently drive a phase-constant PWFA stage. A European 'Hybrid' collaboration has been formed and has achieved major conceptual and experimental milestones in quick succession [27–31]. The hybrid concept aims at demonstrating an overall highly compact platform that combines the LWFA and PWFA schemes and delivers at the same time high quality electron beams.

Development of plasma sources for high-repetition rate, multi-GeV stages: Operation of plasma accelerators at high repetition rates of O(10 kHz) and high average powers of O (100 kW) driver per stage will be crucial to realize high-energy-physics experiments. Modern plasma sources are based on various technologies, e.g. capillary discharges, gas jets, plasma cells, and laser-shaped channels. These sources have been robustly characterised and used in low-repetition-rate (Hz to kHz-level) plasma-wakefield experimentation [32, 33]. Different source concepts are needed for laser or beam drivers and electron or positron acceleration to fulfil the specific requirements for high-quality and efficient plasma accelerator modules, all of which must become compatible with the required high rates and powers.

[7] as example: Salehi et al. have generated [17] $E = 15\,\text{MeV}$, $Q = 2.5\,\text{pC}$, $\Delta\theta = 7\,\text{mrad}$ bunches at $f_{\text{rep}} = 1\,\text{kHz}$.

4.4.2 System Tests: High Quality Electrons

Dielectric accelerator module with high quality beam for first applications: Significant progress has been made on dielectric laser accelerators (DLA) in recent years [10, 34]. The stated goal of the Accelerator-on-a-Chip International Program (ACHIP) is to demonstrate an energy gain of 1 MeV in a dielectric laser accelerator. The collaboration is confident that they will reach this by 2022. Simulations of the focusing effects of suitably designed structures have been verified by experiments.

High quality beams: electron-driven plasma accelerator-based FEL in saturation: Two test facilities in Europe, FLASHForward [35] at DESY and SPARC_LAB [36] at INFN-LNF, and a group at the Strathclyde University [37] (in collaboration with ASTeC, UCLA and SLAC), are conducting experiments with beam-driven plasma accelerators in order to produce high quality beam parameters and enable the possibility to observe FEL gain. Great progress has been made in recent years in demonstrator experiments for the preservation of beam quality in terms of energy spread and emittance [33, 38–41], and the first experimental evidence of the feasibility of a plasma photocathode has been shown. Very recently the first demonstration of exponential gain in a SASE FEL at 830 nm driven by a plasma accelerated beam has been also reported [5].

High quality beams: laser-driven plasma accelerator-based soft-x-ray FEL in saturation: Several proof-of-principle experiments for a laser-driven free-electron laser are being pursued in Europe, for example COXINEL at LOA/Soleil and LUX at DESY. In addition, experiments in Shanghai, China, and LBNL, United States, are making important progress. Beam quality is advanced, first lasing of a laser-plasma based free-electron laser has been reported [4] and a new high quality plasma acceleration scheme has been proposed within the EuPRAXIA project [42].

Proton-driven plasma wakefield acceleration: Proton drivers available today carry a large amount of energy of typically 10s to 100s of kJ (compared to less than 100 J with laser and electron drivers) and can therefore, in principle, accelerate electrons to TeV energies in a single plasma. The AWAKE Collaboration, a world-wide collaboration of 23 institutes working at CERN, has demonstrated for the first time that a long proton bunch, too long to drive large amplitude wakefields, self-modulates in a high-density plasma in a phase controlled way due to seeding, and then drives large amplitude fields [43, 44]. In addition the acceleration of externally injected electrons to multi-GeV energy levels in the proton driven plasma wakefields was demonstrated [3].

4.4.3 Collider Components

Staging of electron plasma accelerators including in- and out-coupling: Staging of plasma accelerators is essential to reach high energies together with high efficiency and high repetition rate. Major challenges arise from strong focusing in plasma and therefore highly diverging beams outside the plasma, as well as the need to in- and out-couple the driver without disrupting the accelerating beam. Advanced beam optics including plasma lenses [45] and plasma ramps will therefore be key to staging, as well as managing sub-fs synchronization and sub-μm misalignment tolerances [46], for example by deploying novel self-stabilization concepts [33]. Experiments at LBNL have demonstrated first acceleration in two independent laser-driven stages.

Polarised electrons: Laser-driven generation of polarised electron beams in combination with the development of advanced target technologies is being pursued in the framework of the ATHENA consortium and EuPRAXIA [9]. Novel target technologies will be tested at different laser facilities, e.g. at DESY in the near future. The goal is to demonstrate the capability of plasma wakefields to preserve beam polarisation during the acceleration process.

Plasma lens R&D: Radially symmetric focusing with a magnetic gradient of the order of kT/m has been demonstrated for electron beams by means of plasma-based lenses. Several results have been obtained with active plasma lenses (APLs), showing the focusing of relativistic electron beams both from laser-plasma and RF accelerators [45, 47–49]. Experimental measurements demonstrating that the beam emittance can be preserved (and lensing effect improved) by enhancing the linearity of the focusing field have been reported [50].

High transformer ratio in PWFA for high efficiency and low energy spread: Shaping the current profile of the drive bunch (DB) and witness bunch (WB) can control the excitation of wakefields and maximize the energy transfer efficiency from the DB to the WB [51]. A DB longer than the plasma period and with a triangular current profile, or a train of bunches with increasing charge can drive wakefields with accelerating fields much larger than decelerating fields. The ratio of these fields, the transformer ratio, as high as $\sim$8 has been demonstrated experimentally [52]. Shaping of the WB further allows for minimization of the final energy spread through precise flattening of the wakefields, i.e. beam loading. This field flattening has been controlled to the percent level in experiment [53]. Conservation of the transverse normalised emittance requires precise matching of the WB to the focusing force of the plasma column.

4.4.4 Conceptual Pre-Design Advanced Linear Collider at Energy Frontier

There exist a number of rough parameter sketches and ideas for an e^+e^- or $\gamma\gamma$ collider based on plasma or dielectric technology. In strong contrast to other novel concepts (for example the muon collider) there has never been a coordinated, pre-conceptual design study for such a collider worldwide. Such a coordinated study is missing to address feasibility, perform supporting simulations and to estimate rough size and costs.

4.4.5 Numerical and Theoretical Tools

Computer simulations and theory have been providing critical support to the development of plasma-based accelerators for decades. In order to enable successful progresstowards HEP-relevant developments, it is now of the highest importance to prepare an open-science model capable of taking full advantage of pre-exascale and exascale systems [54,55]. Global and sustained effort will be needed over the next decades in theory/numerical R&D activities, leading to accurate collider-relevant predictions.

4.5 R&D Objectives

4.5.1 Sources of Electrons, Positrons, Plasmas and High Power Laser Pulses

High-quality LWFA injector: Reaching injector charge and emittance at or exceeding the levels required for a collider requires an increase in the mean current of four orders of magnitude, and a decrease in the normalized emittance by about one order of magnitude compared to present values. We therefore identify three priorities: 1) Increasing the bunch charge of high-repetition-rate LWFAs by one or two orders of magnitude to the 0.1 - 1 nC range; 2) Developing laser drivers capable of $f_{\mathrm{rep}} > 10\,\mathrm{kHz}$; 3) Decreasing the bunch emittance for high-repetition-rate LWFAs by one or two orders of magnitude.

Dedicated accelerator test beamlines for all aspects of laser-driven accelerators are urgently required. These could be hosted in existing facilities, or one or more new facilities could be considered. Proposed milestones are:

2024: Models for nC-level, low-emittance LWFA injector proposed and validated by simulations.
2025: Experiments, optimization studies, possibly at lower charge and repetition rate at existing facilities.
2027: Experimental demonstration of $Q > 100$ pC, $\epsilon_n < 1\ \mu$m, $10 \leq f_{rep} \leq 100$ Hz.
2032: Experimental demonstration of $Q > 500$ pC, $\epsilon_n < 100$ nm, $f_{rep} > 1$ kHz.
2037: Experimental demonstration of $Q > 500$ pC, $\epsilon_n < 10$ nm, $f_{rep} > 10$ kHz.

High-average-power, high-efficiency laser drivers and schemes: For HEP applications, the goal is to produce a laser with an average power output of > 300 kW, a wall plug efficiency $> 15\%$, and < 100 fs pulse duration. For the power consumption to drive a 1 TeV beam at 15 μC/s (15 MW beam power) to be less than 200 MW, the wall plug to beam efficiency needs to be $> 7.5\%$. In addition, such a TeV accelerator with 100 stages requires the beam to gain 150 kW per stage; for a laser-to-beam efficiency of less than 50% this requires the average output power of the drive laser for each stage to exceed 300 kW and have an efficiency $> 15\%$. In order to eventually deliver 1, 10 and 300 kW lasers we identify three milestones:

2026: 1 kW: 10 J, 100 Hz, $<$ 100 fs laser for driving a high repetition rate test beamline facility.
2030: EuPRAXIA laser at 800 nm wavelength (few kW) [9]: pulse energy 50-100 J, repetition rate 20-100 Hz, pulse duration 50-60 fs, energy stability (RMS) 0.6–1%, pointing stability (RMS) 0.1 μrad.
2032: 10 kW: 10 J, 1 kHz laser producing multi-GeV beam energies at kHz rates.
2035: 300 kW: 30 J, 10 kHz $> 15\%$ efficient laser for HEP collider stages.

Positron technical demonstrations: R&D on generation and handling of high energy positrons is emerging with limited but rapidly evolving efforts. The key R&D objectives for positrons include:

2023: Demonstration of high-quality (pC, μm normalized emittance, 2% energy spread) positron beam from a plasma wake-field accelerator at the few hundred MeV level.
2026: Demonstration of high-quality positron beam from a plasma wake-field at the 1 GeV level.

Advanced plasma photoguns with ultra-low emittance: The key R&D objectives of advanced plasma photoguns concerning HEP activities for the next years include:

2024: Demonstration of few O(10 nmrad) normalized emittance.
2026: Demonstration of ultra-low normalized emittance beams with collider-level energy spread and energy stability.
2027: Development and demonstration of high-charge (100s of pC to nC, moderate to extreme currents), plasma photoguns with ultra-low normalized emittance.
2028: Demonstration of spin-polarized ultra-low emittance electron beams from plasma photocathodes.

Hybrid laser-beam driver schemes: demonstration, stability, efficiency: The compact LWFA$\rightarrow$PWFA platform can be implemented at numerous LWFA facilities worldwide for rapid development and testing of HEP-relevant building blocks, such as plasma energy boosters, components for inter-stage beam transport and beam extraction, and ultra-high brightness injectors based on selective ionisation injection in the PWFA stage [56–58]. Hybrid plasma wakefield accelerators can thus address a wide range of HEP-relevant R&D objectives:

- Fundamental PWFA research, including energy transfer efficiency, driver depletion and emittance preservation (ongoing).
- Demonstration of physics-concept-based stability enhancement from hybrid plasma wakefield accelerators (ongoing).

2023: Realization of tuneable PWFA internal injection schemes, including miniaturized plasma photoguns.
2024: Demonstration of emittance and brightness enhancement by a factor of 10 to 10000 compared to the initial LWFA output.
2027: Demonstration of advanced sources such as X-FEL.

Development of plasma sources for high-repetition rate, multi-GeV stages: A number of objectives will need to be reached in order to meet the R&D goal of plasma sources for collider-relevant repetition rates and average powers. This includes plasma containment and generation to maintain beam quality and high-rate operation, durability, energy transfer during plasma acceleration, plasma vessel cooling, and more. The route towards a demonstrator high-repetition-rate and high-average-power plasma accelerator may be broken down into three key parts:

2026: Study essential physics questions, e.g. wakefield process efficiency and repeatability.

2035: Push plasma source technology as close as possible towards that working point. To achieve this, a dedicated testbed for iterative plasma-source development will be required as part of a new test beamline for high-repetition-rate plasma accelerator research. Each iteration of the technology must then be tested with sustained operation at a repetition rate conducive with those of plasma-based-collider designs e.g. 10 kHz.

2035: The average powers per stage are pushed into the relevant multi−10 to 100 kW regime at a dedicated new facility consistent with the outcome of the proposed conceptual design report.

For the case of laser-driven acceleration, this strategy needs to be closely synchronized with the development of high-repetition-rate, high-average-power, and efficient drive laser technology.

4.5.2 System Tests: High Quality Electrons

Dielectric accelerator module with high quality beam for first applications: The ongoing and proposed work is demonstrating many of the elementary components of dielectric laser accelerators. At the same time, key aspects of relevance for high energy physics accelerators should be investigated. These include further improvements on beam focusing and containment, energy efficiency, as well as beam control, instrumentation and feedbacks. The proposed milestones are:

2023: Generation of a 5 MeV beam.

2024: Develop a simulation code capable of simulating a billion accelerating cells.

2025: Apply DLA beams for applications outside HEP and design and simulate a source of GeV beams.

2026: Design and simulate a linear collider at the energy frontier.

2028: Instrumentation and feedbacks for DLA: measurement of orbit and profile.

2030: Synchronization of laser sources, alignment of structures and develop a concept for power recirculation.

High quality beams: electron-driven plasma accelerator-based FEL in saturation: The main goal of FLASHForward is to demonstrate high-fidelity acceleration of electron bunches in GV/m-gradient wakes with final beam quality sufficient to produce gain in an FEL. The UK collaboration is aiming to drive an FEL with new beam injection schemes in plasma. On a longer time scale the European project EuPRAXIA [9] aims at the construction of a user facility driven by a plasma wakefield module. Expected to be operational by the end of 2029, EuPRAXIA envisions producing 10^{12} photons/pulse at 4 nm, in the so called "water window" spectral region, by using a 30 pC electron bunch with 3 kA peak current, normalized rms emittance $<1\ \mu$m and rms energy spread of 0.1%. The proposed milestones and the final deliverable are:

2021: Demonstration of FEL-SASE and seeded exponential growth at 830 nm.

2024: Demonstration of FEL saturation at short wavelength (< 830 nm).

2025: EuPRAXIA Technical Design Report ready.

2029: EuPRAXIA facility in operation with users.

High-quality beams: laser-driven plasma accelerator-based soft-x-ray FEL in saturation: A laser-plasma based FEL in full saturation is expected to be achieved at the DESY LUX experiment by 2030 at latest, proving sub-percent energy spread, kA peak current, and 24/7 operation at low repetition rate (up to 5 Hz). The EuPRAXIA project has produced a conceptual design of a 5 GeV plasma-based FEL facility including all required infrastructure. The proposed milestones and the final deliverable are:

2021: Demonstration of FEL-SASE [4].
2023: Decision laser-driven plasma FEL site EuPRAXIA.
2026: EuPRAXIA Technical Design Report ready.
2030: Demonstration fully saturated FEL at LUX. EuPRAXIA laser-driven facility operates with users.

Proton-driven plasma wakefield acceleration: demonstration of high energy gain, emittance control, scalability: AWAKE has a clear roadmap towards early applications for HEP. AWAKE Run 2 starts in 2021 [59] and aims to bring the technology to a point where particle physics applications can be proposed and realized.

2026: Until 2026 AWAKE plans to demonstrate the seeding of the self-modulation process with an electron bunch and optimize the process of generation of wakefields using a plasma density step to accelerate electrons to multi-GeV energies.
2030: Over the next ten years AWAKE aims to demonstrate the acceleration of an electron witness bunch to 10 GeV in 10 m with control of the incoming normalized emittance at the 10 mm-mrad level and percent energy spread, to develop scalable plasma sources 50–100 m long, and to demonstrate acceleration in a scalable plasma source (helicon or discharge) to 50 to 100 GeV energies.
>'30: Starting in 2030, by the successful end of Run 2, the AWAKE scheme will be ready for first high-energy physics applications [60–62]. Proton-driven plasma wakefield acceleration technology could be used in fixed target experiments for dark photon searches, and also for future electron-proton or electron-ion colliders at very high energies, where lower luminosity is acceptable.

4.5.3 Collider Components

Staging of electron plasma accelerators including in- and out-coupling: The challenges are described in 4.4.3 and include also developing and demonstrating the staging optics in a proof-of-principle experiment, understanding the full 6D dynamics across numerous stages in the presence of such optics, and determining whether any further self-correction mechanisms can be exploited, especially in the transverse phase space (e.g. betatron radiation damping at high energies). The required steps are:

2027: Experimental test of staging at 5 GeV. Extend the design to its use at 50 GeV and 180 GeV, for quadrupoles and for plasma lenses.
2027: Design and build plasma lenses for the high energy beams of 50 GeV and 180 GeV.
2034: Design, implement, and test complete transfer lines at 50 GeV and 180 GeV.

Polarised electrons: The generation of few 100 MeV polarised electron beams from plasma with high polarisation fraction for injection into conventional accelerators, and storage rings is an important next step. To reach this goal, hardware development and spin tracking simulations to provide polarised sources and polarisation conservation in plasma are carried out. In parallel, R&D work for polarised targets and polarimetry is being conducted. All developments will be supported by proof-of-principle experiments with polarised beams, e.g. at ARCturus and EuPRAXIA. Milestones are:

2024: Demonstration of polarised electron beams from plasma with 20% polarisation fraction.
2031: Increase of the polarisation fraction to $> 85\%$.

Plasma lens R&D: The demonstration of focusing effectiveness at high energy with round and flat beams, while preserving the quality of both electron and positron beams, is a fundamental achievement that could be integrated in a dedicated linear collider plasma module test facility. The proposed milestones are:

2024: Demonstration of focusing effect of high quality electron beams at multi-GeV energy range.

2025: Development and demonstration of collider concept for positron focusing with plasma lenses.

2026: Integration of plasma lenses in the HEP test facility CDR.

2030: Demonstration of a transversely tapered design for local chromaticity correction.

High transformer ratio PWFA for high efficiency and low energy spread: While plasma-based accelerators driven by particle bunches or laser pulses can operate with usual Gaussian-shaped beams or pulses, shaping of the driver and/or of the witness bunch will considerably improve the accelerator parameters in terms of beam quality and energy transfer efficiency. Milestones are:

2026: Emittance preservation over many betatron periods in a plasma module with simultaneous large energy gain (of order drive energy), high total efficiency (30% driver to witness), normalized emittance conservation (at the 1 μm level), and narrow energy spread (0.1%).

2030: Optimization of the transformer ratio while mitigating beam-plasma instabilities, such as beam hosing [63].

4.5.4 Numerical and Theoretical Tools

The priorities identified for the numerical and theoretical tools are (i) include missing physics (quantum mechanics [64, 65] and hydrodynamics), (ii) account for relevant radiation emission processes [66–68], (iii) develop user-friendly, numerically stable and accurate full and reduced computational models [69, 70], combined with AI/ML (iv) model driver/witness beams with arbitrary space-time and phase-space structures [71–74], (v) ensure stable acceleration [75] and mitigate unwanted instabilities [70,76–79], (vi) increase efficiency and quality of positron acceleration in plasma towards collider and HEP applications, (vii) determine repetition rate limits based on the long-term plasma dynamics. The required milestones are:

2022: Setup of simulation tools for electron case studies ($\geq$ 2 stages) with certain approximations.

2023: Repeat for positron case study.

2026: Study of spin preservation and beam-disruption mitigation strategies for a plasma-based collider.

2028: Demonstration of highly accurate (3D PIC, flat beams), stable and efficient numerical models.

2030: Start-to-end simulations of many plasma acceleration stages.

4.6 Facilities and Infrastructures

Here we summarise ideas and concepts for first particle physics experiments and facilities at intermediate (lower) beam energies. The advanced, compact particle physics collider is discussed in the following section, as a key element of our roadmap. In addition, we summarize required accelerator R&D facilities.

4.6.1 First Particle Physics Experiments and Facilities

As an intermediate step towards a linear collider at the energy frontier, we consider an accelerator capable of generating electrons with an energy of 15 to 20 GeV. One class of experiments that would profit from such an accelerator are fixed-target experiments aimed at the discovery of new weakly interacting particles. A design for such a low energy HEP application facility involving plasma and dielectric accelerators does not exist beyond the idea stage.

4.6.1.1 Single electron tagging experiments

High-quality electron beams in the energy range 15–20 GeV are scarce, but have potential application in HEP. A case for an experiment to search for dark photons has been made based on electrons in the SPS. In order to tag each incoming electron, single electrons enter the experiment. Such a scheme allows for the full reconstruction of the event and hence the possible decay of dark photons to 'invisible' dark matter candidates as well as e.g. e^+e^- pairs. For a possible list of parameters, see also Table 4.1.

A dielectric laser accelerator could be capable of generating such beams, possibly with a higher efficiency than conventional sources. However, the proposed particle energy is several orders of magnitude beyond present capabilities of dielectric laser accelerators.

4.6.1.2 Electron bunch experiments

In a bunched scheme, the individual incoming electrons cannot be tagged and signatures like the decay of dark photons to e^+e^- pairs in beam-dump mode are searched for. The AWAKE experiment has done a study of using such bunched electrons with energies of 50 GeV and above [60–62]. At the lower energy of about 20 GeV, the sensitivity at higher masses of the dark photon will be reduced, but the possibility to investigate an as yet unexplored region remains. Other novel accelerator technologies should also study the possibility of providing such high energy bunched electron beams.

Table 4.1: Specification for an electron beam for fixed-target (FT) experiments, generated by a dielectric laser accelerator (inspired by the eSPS specifications [80]) as well as for electron bunches for PEPIC [60–62], a low-luminosity LHeC-like collider [81], and for the LUXE experiment [82]. Such bunches (for PEPIC and LUXE) can also be used for a beam-dump experiment to search for dark photons. Note that the number of bunches per train in the European XFEL is 2700, but for LUXE only one is used.

Parameter	**Unit**	**single e FT**	**PEPIC**	**LUXE**
Bunch charge	pC	few e	800	250
Final energy	GeV	20	70	16.5
Relative energy spread	%	<1	$2-3$	0.1
Bunch length	μm	-	30	$30-50$
Normalized emittance	μm	100	10	1.4
Number of bunches per train	-	1	320	1
Repetition rate	-	1 GHz	0.025 Hz	10 Hz
Luminosity	$10^{27}\,\mathrm{cm^{-2}\,s^{-1}}$	-	1.5	-

The use of bunched electrons in the 15 to 20 GeV range is also proposed by the LUXE experiment using the European XFEL electrons [82]. This experiment will investigate non-linear QED by colliding the electron bunches with a high-power laser. This is then a natural application for plasma wakefield acceleration and dielectric laser accelerators which could achieve similar parameters.

The AWAKE study [60–62] also considered an electron–proton collider based on bunches of electrons at $\sim$50 GeV (PEPIC) or 3 TeV (VHEeP [83]). Using $\sim$50 GeV electrons is akin to the proposed LHeC project. Typical parameters are shown in Table 4.1 Although a significantly shorter electron accelerator is expected, much lower luminosity is also expected in the AWAKE scheme. Aspects that should be further considered are:

- Further study and optimisation of the AWAKE scheme, in particular to increase the luminosity.
- Other novel accelerator schemes should consider application to the LHeC.
- Other electron beam energies could be considered and discussed with HEP as to their interest.

Another compelling application yet to be considered by any novel accelerator scheme is a $\gamma\gamma$ collider, with a centre-of-mass energy of 12 GeV [84]. The current design is based on the use of the European XFEL electron beam but would require modifications/additions to the complex to run a collider.

4.6.2 Current Accelerator R&D Test Facilities

The ongoing R&D for advanced, high-gradient accelerators is being performed at accelerator or laser facilities that are located at research centers and universities. Access possibilities range from limited access, through collaboration-based access models to user facility operation with excellence-based access after committee review. We provide a preliminary working list of such facilities:

- **Facilities at CERN:** AWAKE experiment at the SPS (collaboration-based access), CLEAR (user-facility access).
- **Major national facilities in CERN member states** (facility defined access rules): **Laser facilities** (laser beam delivered to users): EPAC, CLF, APOLLON, PALLAS, DESY (LUX, *KALDERA*), Lund Laser Center, HZDR, LOA, Strathclyde, CALA, JuSPARC. **Accelerator facilities** (particle beam delivered to users): SPARC_LAB, DESY (FLASHForward, SINBAD/ARES), CLARA, SwissFEL.
- **European Research Infrastructures:** ELI-Beamlines (user-facility access), EuPRAXIA (user-facility access, placed on 2021 ESFRI roadmap update).
- **Large non-European facilities:** BELLA (collaboration-based access), FACET-II (user-facility access), facilities in China at Beijing and Shanghai (collaboration-based access), ImPACT program in Japan (collaboration-based access), Argonne Wakefield Accelerator (user-facility access) and Brookhaven's Accelerator Test Facility (user-facility access).

4.6.3 Possible Advanced Accelerator Test Facility for HEP Specific Aspects

A dedicated test facility for HEP-specific aspects of advanced acceleration concepts would greatly advance research in this area, as specific aspects of HEP relevant particle beams might not be fully addressed with existing facilities. These aspects include the generation and acceleration of positron beams, the generation and diagnostics of polarized beams, and detailed studies on energy efficiency. In addition, the scalability of the design, additional stages and accelerator lines should be studied, implemented and tested. The need and required technology for such a facility will be evaluated in the pre-CDR report in 2026. A dedicated test facility should include at least two accelerator lines, each one having two or three acceleration stages. Such a test facility will address issues and the R&D lines defined at the decision point after the pre-CDR. The facility might require lasers with a high repetition rate and sub-femtosecond synchronization for staged structures. Instrumentation for laser and particle beams and a fast feedback system would enable studies of the stability of the accelerator. Optionally, a connection to a conventional storage ring could be used to damp positron beams and re-inject them into the plasma.

The HEP collider solution requires a number of R&D developments to tackle different physical and technical challenges, which might require the use of an intermediate test facility targeting 15-20 GeV energy and a 100-200 pC charge in several stages. The following milestones could be envisaged for an intermediate facility:

2026: Pre-CDR as part of the overall pre-CDR report.
2030: TDR.
2033: Completion of construction. Start of commissioning.
2035: Operation.

4.7 Key Points of the Roadmap

The key points of the roadmap are summarized and described in this section. It is noted that novel accelerators are a relatively young and diverse field and we present only an interim snapshot. Extensive consultations, discussions and iterations are ongoing and the presented roadmap components will be updated accordingly.

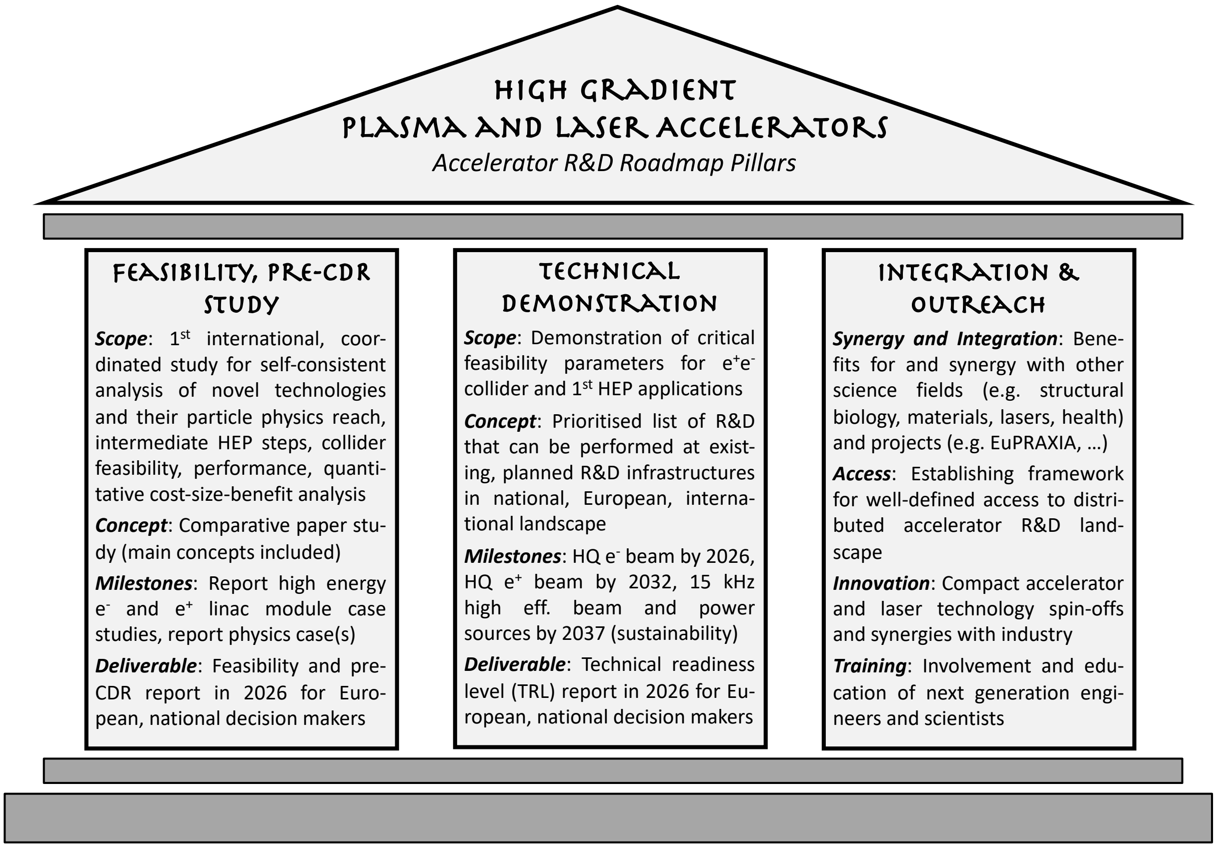

Fig. 4.1: Visualization of the three pillars that are proposed to form the accelerator R&D roadmap for plasma and laser accelerators.

4.7.1 Three Pillars of Advanced Accelerator R&D Roadmap for Particle Physics

The panel has discussed and agreed on a roadmap that is based on three pillars that should be pursued in parallel (see Fig. 4.1). The three pillars of our roadmap are:

1. The first international feasibility and pre-CDR study for high gradient plasma and laser accelerators and their particle physics reach. This paper study will lead to a comparative report on various options, a feasibility assessment, performance estimates, physics cases, intermediate HEP applications and a cost-size-benefit analysis for high energy.
2. A prioritised list of technical R&D topics that will demonstrate a number of technical feasibility issues of importance for particle physics experiments.
3. Integration and outreach measures. This exploits and ensures the very high synergistic potential with other fields and large projects, like EuPRAXIA. It enables access to distributed R&D facilities under clear rules and supports innovation with closely connected industry. Finally, it connects to the next generation of scientists in close collaboration with other activities in IFAST and the European Network for Novel Accelerators (EuroNNAc).

4.7.2 Proposed components of feasibility and pre-CDR study (findings)

The proposed components of the feasibility and pre-CDR study are shown in Fig. 4.2. They are commented on in the following.

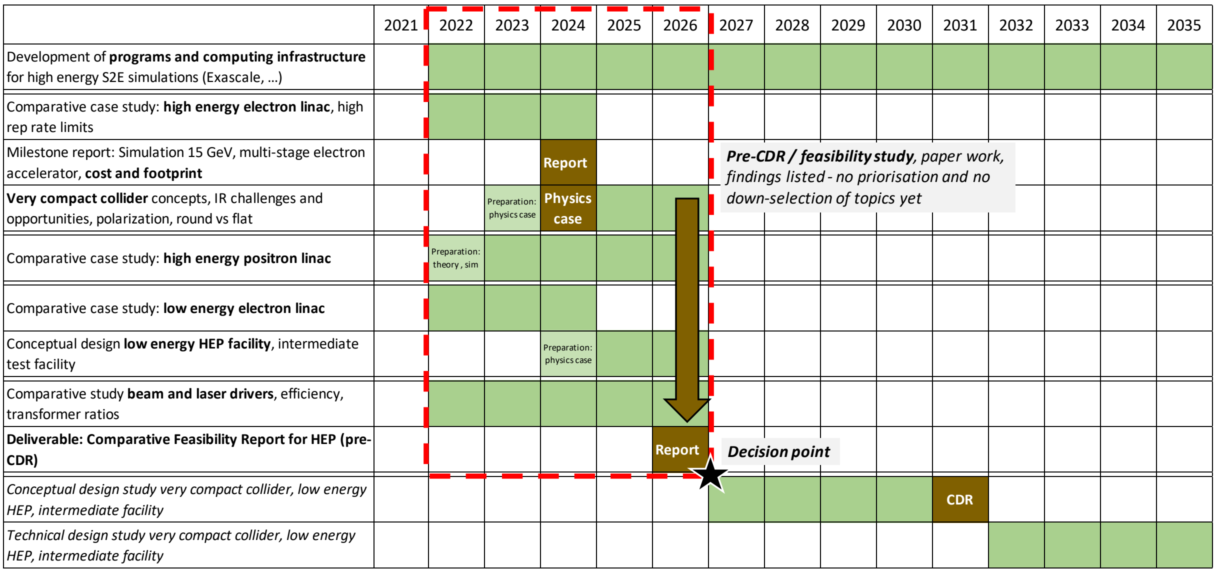

Fig. 4.2: Components and possible time line for the proposed common feasibility and pre-CDR study. This would be the first ever such study in the international context. No prioritisation or down-selection of the proposed components has been done yet.

4.7.2.1 Theory and simulation

The proposed design study will include a strong effort on theory and simulation. A beam physics and simulation framework will be set up that addresses all system aspects of a high energy physics machine. The work will include the preparation of numerical and simulation tools, as required for simulating multi-stage setups at high and low energy for the various options, both for electrons and positrons.

4.7.2.2 High-energy common study case

A high-energy study case assesses the feasibility in the high-energy collider regime, for which CLIC has already established an optimized set of parameters. We use here the CLIC parameters of the final 15 GeV of the CLIC 380 GeV main linacs [85]. The relevant study case is the design of an advanced accelerator module (two or more acceleration stages) accelerating electron or positron beams from 175 GeV (incoming) to 190 GeV (after acceleration in the advanced accelerator module). All required components for in- and out-coupling of the power drivers (e.g. laser, electron or proton pulses that drive the accelerating fields) should be included, see Table 4.2. A collider based on plasma or dielectric accelerator technology is not expected to reproduce exactly the same parameters, but this can serve as the basis for a comparative study as proposed in this report. The parameters will be adapted and modified to take into account the constraints and opportunities presented by plasma and laser technology.

4.7.2.3 Low-energy common study case

The potential for lower-energy particle physics applications is assessed by considering a parameter regime for fixed-target experiments, which could be realised in the nearer future with more relaxed beam parameters compared to colliders. We use beam parameters for an electron beam as shown in Table 4.1, generated by a dielectric laser accelerator (inspired by the eSPS specifications [80]) and for electron bunches for an LHeC-like collider [81] and for the LUXE experiment [82].

The relevant study cases are the design of an advanced accelerator (that can include the injector) to accelerate electrons to a final beam energy in the regime of 15 GeV to 50 GeV to be used for first HEP experiments as described in 4.6.1.

4.7.2.4 *Collider pre-conceptual design and feasibility report in 2026*

The relevant physics cases and collider concepts and solutions will be designed and simulated in detail once the case studies have established feasible accelerator modules for electrons and positrons. It is noted that there have already been various sketches of possible colliders relying on plasma or dielectric technology. Those studies are valuable starting points for further design work but do not include realistic designs of the accelerator layout (including in- and out-coupling of power drivers) nor solutions for multi-stage positron acceleration nor performance assessments with realistic simulations. The various published sketches provide an understanding of the required parameters for constructing linear collider at the energy frontier, see Table 4.3. The proposed design work will include the first ever cost-size-benefit analysis for such an advanced collider that is based on simulation-based design work. A report in 2026 will provide decision makers with the results needed to decide on future directions and priorities.

4.7.3 *Proposed technical demonstrations - areas and topics (findings)*

The proposed feasibility and pre-CDR study must be complemented by technical demonstrations that establish the experimental state of the art and can be used to assess technical readiness levels (TRL). The present state of the art and the required work on various technical R&D issues have been listed and summarized in the previous sections. In Fig. 4.3 we provide an overview of the proposed technical demonstration areas and topics. Figure 4.3 includes a first preliminary matching with facilities where this work could or will be done (no down-selection). There is a consensus in our expert panel and through our consultation process that this is a fairly complete list of challenges and work to be done. Prioritisation, scheduling and matching to facilities/resources will be done as the next step of the roadmap process.

R&D Area	*R&D Topic (in random order)*	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Sources of electrons, positrons, plasmas, and high power laser pulses *Address particle physics' unique requirements: 15kHz repetition rate, nanometer emittance, many MJ stored energy, component efficiency at 30-50% level, high rigidity of main beam, need for compact solutions*	High-quality electron beams from a LWFA injector		*PALLAS, ELI, DESY, EuPRAXIA, Tsinghua, CLF/RAL/EPAC, ...*										
	Advanced plasma photoguns with ultra-low emittance electron beams		*Strathclyde, FACET-2, ...*										
	Compact generation of positron beams up to GeV		*Queens University Belfast, EuPRAXIA, ...*										
	High average power, high effciency laser drivers and schemes		*CNR, DESY, STFC, CLF, Oxford, CNRS, EuPRAXIA, industry, Liverpool, LLNL, LBNL, ...*										
	Hybrid laser-beam driver schemes: demonstration, stability, efficiency		*HZDR, LMU University, Strathclyde, CNRS, CLARA/FEBE, CLF/RAL/EPAC, ...*										
	Development of plasma sources for high-repetition rate, multi-GeV stages		*Oxford, DESY, LNF/INFN, AWAKE, ...*										
System tests: high quality electrons *R&D often driven by other science fields that will benefit from first, lower energy applications. Results will of prove collider single bunch quality*	Dielectric accelerator module with high quality beam for first applications		*Erlangen, STFC, PSI, DESY,*			5 MeV, 1 pC	*CLARA, ...*						
	Electron-driven plasma accelerator-based Free-Electron Laser in saturation	First lasing LNF	*LNF/INFN, DESY, PWFA-FEL*			TDR EuPRAXIA	*/CLARA, EuPRAXIA, ...*			User OP EuPRAXIA			
	Laser-driven plasma accelerator-based soft-Xray Free-Electron Laser in saturation	First lasing SIOM	*SOLEIL/CNRS, DESY, ELI, BELLA,*				TDR EuPRAXIA	*EuPRAXIA,...*		User OP EuPRAXIA	Saturation		
	Electron beam with fixed target beam quality from p-PWFA		*AWAKE*								AWAKE Scalability	*--> Ready for Fixed Target Experiments*	
Collider components *Demonstrate various collider components or aspects that are of critical importance for particle physics applications*	Staging of electron plasma accelerators including in- and outcoupling		*BELLA, DESY, EuPRAXIA, CLARA/FEBE, CLF/RAL/EPAC, AWAKE, ...*										
	Polarized electrons: targetry, polarimetry, polarization conservation		*FZJ, DESY, ...*			Input to concepts							
	Plasma lens R&D, towards transversely tapered designs		*DESY, FACET-2, BELLA, Oslo University, CLARA/FEBE, Liverpool, CLEAR, ...*										
	Stable high transformer ratio PWFA with high eff. and low energy spread		*FACET-2, LNF/INFN, DESY, ...*										
	Positron high energy plasma acceleration module		*FACET-2, ...*										
	Proton-driven kJ electron acceleration module		*AWAKE*		e-seeding, high grad.				10GeV in 10m, low emit.				
Possible HEP test facility	Possible construction HEP test facility advanced accelerators (start OP in 2035), if in pre-CDR 2026												

Fig. 4.3: List of technical demonstration topics that have been proposed as part of the roadmap. No scheduling, prioritisation or down-selection of the proposed components has been done yet. Milestones or deliverables are indicated by brown boxes.

Table 4.2: Specification for an advanced high energy accelerator module, compatible with CLIC [85]. Additional CLIC design values are listed for reference in the second part of the table.

Parameter	**Unit**	**Specification**
Beam energy (entry into module)	GeV	**175**
Beam energy (exit from module)	GeV	**190**
Number of accelerating structures in module	-	$\geq$2
Efficiency wall-plug to beam (includes drivers)	%	$\geq$10
Bunch charge	pC	833
Relative energy spread (entry/exit)	%	$\leq$0.35
Bunch length (entry/exit)	μm	$\leq$70
Convoluted normalized emittance ($\gamma\sqrt{\epsilon_h\epsilon_v}$)	nm-rad	$\leq$135
Emittance growth budget	nm-rad	$\leq$**3.5**
Polarization	%	80 (for e^-)
Normalized emittance h/v (exit)	nm-rad	900/20
Bunch separation	ns	0.5
Number of bunches per train	-	352
Repetition rate of train	Hz	50
Beamline length (175 to 190 GeV)	m	**250**
Efficiency: wall-plug to drive beam	%	58
Efficiency: drive beam to main beam	%	22
Luminosity	10^{34}cm^{-2}s^{-1}	1.5

Table 4.3: Required parameters for a linear collider with advanced high gradient acceleration. Three published parameter cases are listed. Case 1 (PWFA) is a plasma-based scheme based on SRF electron beam drivers [86]. Case 2 (LWFA) is a plasma-based scheme based on laser drivers [87]. Case 3 (DLA) is a dielectric-based scheme [34].

Parameter	**Unit**	**PWFA**	**LWFA**	**DLA**
Bunch charge	nC	1.6	0.64	4.8×10^{-6}
Number of bunches per train	-	1	1	159
Repetition rate of train	kHz	15	15	20,000
Convoluted normalized emittance ($\gamma\sqrt{\epsilon_h\epsilon_v}$)	nm-rad	592	100	0.1
Beam power at 5 GeV	kW	120	48	76
Beam power at 190 GeV	kW	4,560	1,824	2,900
Beam power at 1 TeV	kW	24,000	9,600	15,264
Relative energy spread	%		$\leq$0.35	
Polarization	%		80 (for e^-)	
Efficiency wall-plug to beam (includes drivers)	%		$\geq$10	
Luminosity regime (simple scaled calculation)	10^{34}cm^{-2}s^{-1}	1.1	1.0	1.9

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5 Bright Muon Beams and Muon Colliders

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5.1 Executive Summary

Muon colliders have been identified as being uniquely well-suited to deliver high energy collisions with overwhelming potential in discovery searches and precision measurements to study fundamental physics. The muon collider has the potential to deliver physics reach at the highest energies on a cost, power consumption and time scale that may improve significantly on other proposed facilities. To understand the research required to deliver a muon collider, the Laboratory Directors' Group (LDG) initiated a muon collider collaboration and formed a panel to determine the required R&D programme to deliver a muon collider [1–3].

The Muon Beam Panel has confirmed that the muon collider is a promising path to highest energy lepton collisions and has identified the study of colliders having a centre-of-mass energy of 3 TeV and around 10 TeV as being of particular importance. A 10–14 TeV muon collider, accumulating 10–20 ab^{-1} respectively, has a physics reach comparable to a 100 TeV hadron collider with a footprint comparable to the LHC. A 3 TeV collider accumulating 1 ab^{-1} could be constructed by 2045 as an initial stage, given sufficient resources; this makes it suitable to follow on from the end of the HL-LHC if so required. The footprint would be considerably smaller than the LHC. Studies for staging between these facilities seem promising and very likely only the 4.5 km-long collider ring could not be reused for the full energy stage.

The initial goal is to establish, within the next five years, whether the investment into a full programme is scientifically justified. To this end the collaboration plans to provide a sufficiently detailed

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design of the key systems of the complex to demonstrate that the beam parameters required for luminosity can be achieved and that the cost and power consumption scales are sustainable. In parallel it will develop an R&D programme that will demonstrate the functional specifications where they are beyond the state of the art. In particular, a Demonstrator test stand will be developed to establish the muon cooling system, eventually including beam tests. A limited experimental programme to address technologies that are unique to the muon collider, such as fast-ramping magnets and the muon cooling RF, will help to support the assessment of performance predictions. This will allow the next ESPPU to make fully informed decisions and support similar strategy processes in other regions. Based on these decisions a significant ramp-up of resources could be made to accomplish construction of the collider by 2045.

Potential synergies between the collider complex in general and the demonstrator in particular with other projects will be explored and additional collaborative connections will be formed where they are beneficial to the study.

A number of key challenges have been overcome by previous R&D efforts. The panel has identified several remaining R&D challenges that need to be addressed in the next five years in order to enable subsequent prototyping. All of the challenges have viable solutions. The study of these challenges will enable timely development of the muon collider.

5.2 Motivation

Muon colliders offer enormous potential for exploration at the particle physics frontier. Muons, like electrons, are fundamental particles, so the full energy of the particle is available when they collide, whereas protons are composites of quarks and gluons so only a fraction of the energy is available. Unlike electrons, the high mass of the muon tends to suppress synchrotron radiation so that muons can be accelerated to high energy in rings. This results in a facility footprint that can be rather small compared to other proposed future facilities while yielding comparable results.

5.2.1 Physics Potential of the Muon Collider

A muon collider with 3 TeV center-of-mass energy would be likely to have similar or greater physics potential compared to an electron-positron collider such as CLIC, the physics reach of which is well established and documented [4]. A muon collider with a centre-of-mass energy of 10 TeV or more would open radically new opportunities for the exploration of fundamental physics. On the one hand, it would feature a mass-reach for the direct discovery of new particles that vastly surpasses the HL-LHC exclusion potential and that, in certain cases, is superior to future hadron collider projects. On the other hand, it would enable precision measurements through which new physics could be discovered indirectly, or the validity of the SM confirmed at a currently unexplored scale of energy. Detector studies indicate that the potential of the muon collider can be exploited with the present state-of-the-art technologies at 3 TeV and further R&D for a 10 TeV facility, as discusssed in the Detector R&D Roadmap.

5.2.2 Sustainability

As compared to other frontier particle accelerators and colliders under consideration, the Muon Collider shows particular advantages in terms of sustainability: a compact footprint, efficient electrical power consumption even at high collision energy and potential for phased construction with physics at each stage.

The accelerator complex is compact because a more modest energy is required for physics reach comparable to a proton collider and linacs are not required. For a collision energy per elementary constituent around 10 TeV, the footprint of the Muon Collider does not exceed linear dimensions of order 10 km, well below those of electron and hadron colliders of comparable physics reach.

The muon collider has a relatively small electrical power consumption per unit of luminosity. The luminosity that can be achieved per unit of beam power is shown in Fig. 5.1. For energies at or below

1 TeV, the power requirements of the muon production and cooling tend to dominate resulting in a less efficient facility. At energies above 1 TeV, the muon collider is expected to consume far less power for a given luminosity than equivalent electron or proton machines. For e^+e^- colliders Beamstrahlung dominates the uncertainty of collision energy but for muon colliders the limitation is given by the intrinsic energy spread of the beam. With increasing energy and under the condition of keeping the relative energy spread unchanged, the muon beam bunches can be reduced in length. Shorter bunches can be focused more strongly at the interaction point which leads to a gain of luminosity per grid power in proportion to the kinetic energy. Furthermore, the collision rate in the collider ring increases through the circulation frequency with stronger bending field B. The main parameters affecting the luminosity are summarised in the following scaling formula:

$$L \propto \gamma B P_{\text{beam}} \frac{N \sigma_\delta}{\varepsilon_n \varepsilon_l}. \tag{5.1}$$

P_{beam} denotes the beam power, N the particles per bunch, σ_δ the relative energy spread, ε_n the normalised transverse beam emittance and ε_l the normalised longitudinal beam emittance.

From this relation the advantageous scaling of luminosity with energy is evident. However, the absolute value of the power consumption for a certain center of mass energy has not been studied or optimised in detail. In particular the energy efficient design of rapid cycling synchrotrons with recovery of the magnetic field energy from cycle to cycle, and the reduction of large unrecoverable losses from eddy currents, are important topics for optimization. Other aspects include minimizing beam induced heat load at cryogenic temperatures and efficient RF acceleration systems.

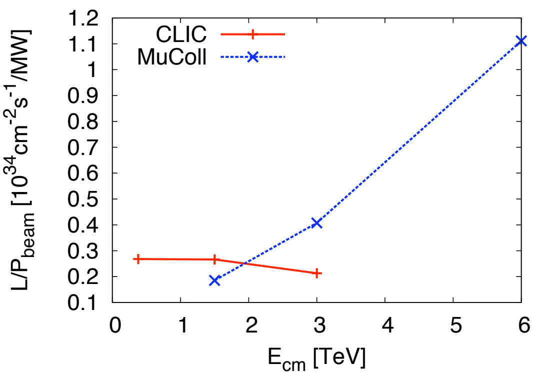

Fig. 5.1: Estimated luminosity of the muon collider and CLIC per MW of beam power, compared with the centre of mass energy at the collision point.

A staged scenario can be developed by constructing additional acceleration stages that would accelerate the beam to higher energies after the initial facility is constructed. An initial facility could have 1.5 TeV beam energy with 3 TeV centre-of-mass energy. Further acceleration to 5 TeV or more beam energy could then be constructed to reach 10 TeV centre-of-mass energy. This scheme allows first physics to be reached earlier and with less investment. The overall risk would be more evenly spread across the project as the requirements for the collider ring technology are less demanding at lower energy. Acceleration is achieved in a different ring to collisions, so the integrated cost would only increase by the cost of the 3 TeV collider ring, which initial studies indicate could have a circumference of 4.5 km.

Finally, the modularity of the Muon Collider complex will allow synergy with other accelerator projects through reuse of subsystems, e.g. the high-intensity proton driver which could also serve a neutrino factory.

5.3 Muon Beam Panel Activities

The muon beam panel is employing closed, fortnightly meetings of the panel, meetings of the broader muon collider collaboration and dedicated community meetings and workshops that draw on the worldwide expertise to develop the input for the roadmap. Three open community meetings have been held in 2021 with strong attendance from the international community and at least one more is planned.

This approach combines the expertise of the panel members, the participants in the new collaboration, as well as the participants in the earlier efforts. Contributions from the US community are necessarily limited pending the outcome of the ongoing US strategy process.

5.4 Muon Collider State of the Art

The Muon Accelerator Programme collaboration (MAP) developed the concept shown in Fig. 5.2. The proton complex produces a short, high-intensity proton pulse that hits the target and produces pions. The decay channel guides the pions and collects the muons produced in their decay into a buncher and phase rotator system to form a muon beam. Several cooling stages then reduce the longitudinal and transverse emittance of the beam using a sequence of absorbers and RF cavities in a high magnetic field. A linac and two recirculating linacs accelerate the beams to 60 GeV. One or more rings accelerate the beams to the final energy. These rings can be either fast-pulsed synchrotrons or fixed-field alternating-gradient accelerators (FFAs). Finally the two single-bunch beams are injected at full energy into the collider ring to produce collisions.

LEMMA is an alternative scheme to produce a muon beam with a very small emittance. Novel ideas are required to overcome limitations in muon beam current and luminosity so LEMMA is not considered as a baseline in this report.

5.4.1 Status of the Concept

MAP focused on demonstrating the feasibility of the key sub-systems required to deliver an energy frontier collider [5]. The test program at Fermilab's MuCool Test Area demonstrated operation of gas-filled and vacuum pillbox cavities with up to 50 MV/m accelerating gradients in strong magnetic fields [6, 7]; a 6D cooling lattice was designed that incorporated reasonable physical assumptions to meet the 6D cooling targets [8]; a Final Cooling Channel design, which implemented the constraint of a 30 T maximum solenoid field, came within a factor of ∼2 of meeting the transverse emittance goal for a high energy collider [9] and current development efforts appear poised to deliver another factor of ∼1.5 improvement; while further R&D is required, fast-ramping magnet concepts [10] exist that could deliver muon beams to the Terascale. Following the end of MAP, acceleration in a recirculating linear accelerator with FFA arcs was demonstrated by CBETA [11].

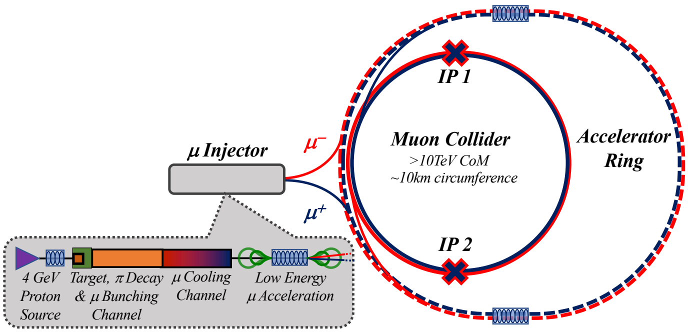

Fig. 5.2: A conceptual scheme of the muon collider.

In Europe, significant investment into muon accelerator R&D was made in neutrino factory design through the EuroNu and neutrino factory International Design Study [12]. The International Muon Ionization Cooling Experiment (MICE) completed a detailed measurement of the ionization cooling process for lithium hydride and liquid hydrogen absorbers and a number of different beam conditions [13]. Rapid acceleration in a fixed field accelerator was demonstrated by EMMA [14]. Schemes for high power targetry using liquid metal [15] and fluidised powder jets [16] were demonstrated, indicating potential for managing proton beam powers even beyond those required for the muon collider.

The MAP and European studies made sufficient progress to demonstrate a viable path forward to realisation of a muon collider.

5.5 R&D Objectives and Challenges

The International Muon Collider (IMC) Collaboration aims to deliver a start-to-end concept for the muon collider and to evaluate the cost and performance of the facility. This effort will include development of the detector concepts and an evaluation of the physics potential.

Table 5.1: Tentative target parameters for a muon collider at different energies based on the MAP design with modifications. These values are only to give a first, rough indication. The study will develop coherent parameter sets of its own.

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	$10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	N	10^{12}	2.2	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ϵ_{L}	MeV m	7.5	7.5	7.5
Transverse emittance	ϵ	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP beta-function	β	mm	5	1.5	1.07
IP beam size	σ	µm	3	0.9	0.63

In particular, the study will focus on the design of a machine with centre-of-mass energy of initially 3 TeV followed by a machine of at least 10 TeV. Potential synergies between the collider complex and other projects will be explored and additional collaborative connections will be formed where they are beneficial to the study. Currently, parameter sets based on scaling from MAP are investigated as starting points for 3, 10 and 14 TeV with the goal to reach luminosities, integrated over 5 to 10 years, of 1, 10 and 20 ab^{-1} respectively. This increase in luminosity compensates the decrease of the s-channel cross sections.

To achieve the maturity that allows commitment to the construction of a collider an R&D programme is required that includes the development of key collider technologies as well as the construction and operation of a demonstrator.

The initial goal of the collaboration is to establish, within the next five years, whether the investment into this R&D programme is scientifically justified. It will provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power-consumption drivers. It will also identify the R&D path to develop a full conceptual design for the collider and its experiments. This will allow fully informed decisions to be made at the next ESPPU and support similar strategy processes in other regions.

Given appropriate resources, the design can be optimised in the next stage and a demonstration programme can be implemented. The latter contains one or more test facilities as well as the development and testing of individual components and potentially dedicated beam tests. The resulting conceptual design will demonstrate the performance, cost and power consumption of the collider facility, making it possible to technically commit to the collider. In this case a technical design phase will follow to prepare for the approval and ultimate implementation of the collider.

The Panel endorses the goals of the collaboration. The focus on high energy develops the unique capability of the muon collider and avoids diluting efforts on energy ranges that are accessible with more mature technologies. The Panel also agrees that the muon collider concept should be further developed, including a start-to-end simulation, to assess whether it is a credible option for the future of particle physics. The proposed R&D programme mitigates the risk that the next ESPPU is not in a position to include the muon collider in its considerations and to make fully informed choices.

5.5.1 Key Challenges

Based on the MAP design, target parameter sets have been defined for the collider as a starting point, shown in Table 5.1. If all design goals are met, these parameters would deliver the desired integrated luminosities within five years from the end of commissioning. These design goals serve to clarify the critical design issues and, once detailed studies are available, operational budgets that account for sources of beam quality degradation will be added.

The parameter sets have a luminosity to beam-power ratio that increases with energy. They are based on using the same muon source for all energies and a limited degradation of transverse and longitudinal emittance with energy. This allows the bunch in the collider to be shorter at higher collision energy and the use of smaller beta-functions. The design of the technical components, such as the final focus quadrupoles, to achieve this goal are a key element of the muon collider study.

A 3 TeV muon collider would be highly novel while a 10 TeV lepton collider is uncharted territory and poses a number of key challenges, described below.

5.5.2 Neutrino Radiation

Muon decay produces a large flux of high-energy neutrinos in a very forward direction. In particular in the plane of the collider ring this can lead to a high local flux of neutrinos, which have a small likelihood of producing showers when exiting the ground at a distance from the facility. The insertions produce a very localised flux in a limited area; the arcs in contrast produce a ring of flux around the collider.

Minimising the flux in public areas is a prime goal of the study; this implies staying well below the legal limit for off-site radiation, for example at a level consistent with LHC operation. Estimates [17] indicate that a 10 TeV collider in a 200 m deep tunnel approaches the legal limit for the neutrino flux.

The proposed solution is a system of movers to deform the beamline periodically in the vertical plane so that narrow flux cones are avoided. Flux from insertions can be further minimised by acquiring the concerned land and by using a large divergence in the focusing triplets. This solution improves on a previous, less performant, proposal to move the beam within the magnet apertures [18]. The system could achieve radiation levels similar to the LHC. The development of a robust system is the key to siting the collider in a populated area. Impact on the ring performance must be minimised. Proper consideration for vacuum connections and cryogenics systems must be made. Management of the neutrino flux is a critical issue for the muon collider. The panel endorses the proposed strategy to reduce flux to levels consistent with LHC operation.

5.5.3 Machine Detector Interface (MDI)

Detector design at a muon collider has to be performed together with the machine-detector interface due to the presence of the huge flux of secondary and tertiary particles coming from the muon beam decay. Integrated studies of the detector and the collider are needed to ensure a properly optimised performance. Beam-induced-background, arising both from muon decays and incoherent e^+e^- pair production, is a serious concern for the detector performance. The current solution to mitigate the background arriving at the detector consists of two tungsten cone-shaped shields (nozzles) in proximity to the interaction point, accurately designed and optimized for each specific beam energy. A framework based on FLUKA has been developed to optimise the design at different energies [19]. Studies performed so far demonstrate that, given reasonable assumptions of detector performance, it will be possible to perform the most challenging physics measurements [20]. Optimisations, for example using improved pixel timing on the tracker detector and novel trigger algorithms, are in progress and may yield improved performance. This requires further studies at higher energies. Combined interaction region, detector shielding and detector design should be performed to confirm physics performance at 3 TeV and 10 TeV.

5.5.4 High-energy complex

Cooled muons are accelerated through a sequence of accelerators. MAP envisioned initial LINACs and recirculating LINACs (RLA) to reach energies below 100 GeV followed by a series of Rapid Cycling Synchrotrons to reach energies of 100s to 1000s of GeV.

Collider designs were developed for an s-channel Higgs Factory, as well as 1.5, 3.0 and 6.0 TeV centre-of-mass energies [21]. There are several notable features associated with the design of a muon collider ring. First, the luminosity performance of a muon collider is proportional to the dipole field that is used in the ring. Next, muon decays within the collider ring require large aperture superconducting magnets with shielding around the beam-pipe to prevent excessive radiation load on the magnets themselves. Finally, the use of straight sections in the ring must be minimized to prevent tightly focused beams of neutrinos from creating off-site radiation issues.

In the collider and accelerator rings of the high energy complex both muon beams will pass through the same magnet apertures moving in opposite directions; single aperture magnets are sufficient.

Longitudinal beam dynamics is the key to high luminosity. Each muon beam consists of one high-charge bunch and the accelerating cavities must be designed to have an acceptable single-bunch beam loading. This is more demanding at high energies where shorter bunches are required to boost the luminosity. A global lattice design for the high energy complex should be developed, including start-to-end simulations of key systems, taking into account the need to move the magnets in order to mitigate neutrino radiation. Particular attention should be paid to longitudinal collective effects such as beam loading. Consideration should be made of RF cavity design and effective beam loading compensation schemes.

In the baseline scheme, acceleration to 10 TeV centre-of-mass energies requires $\sim$30 km of 2 T fast-ramping normal-conducting magnets, which are interleaved with fixed-field superconducting magnets. The magnets for acceleration to 3 and 10 TeV are a large-scale system that can have significant impact on the cost and power consumption of the facility. Design and prototyping should be performed for these magnets. Alternative options based on high-temperature superconductors (HTS) should be explored.

The collider ring arc magnets have to combine high dipole field, to maximise the collision rate, and large aperture, to allow shielding in the magnet bore to protect the cold mass from the 500 W/m of high energy electrons and positrons produced by the muon beam decay around the ring. Combined function magnets are essential to minimise the neutrino flux and the field-free gap between magnets must be minimised for the same reason. Shielding of the collider ring magnets from muon decay products drives the aperture and consequently the maximum field that can be achieved. Particular attention needs to be given to optimise the aperture in order to yield the best performance.

The quadrupoles of the 3 TeV final focus pose similar challenges to the ones of High-Luminosity LHC (HL-LHC) or the hadron collider of the Future Circular Collider (FCC-hh). At 10 TeV larger aperture and higher magnetic field in the aperture are required and call for HTS. The design of the correction system to achieve the required bandwidth for the final focus system is a key challenge to ensure that the luminosity per beam power can increase with energy. The final focus magnets should be developed, paying attention to the needs of the detector and any beam-induced-background.

5.5.5 Muon Production and Cooling

Muons are produced via tertiary production ($p \to \pi \to \mu$) by delivering a multi-MW proton beam onto a target. Proton energy in the 5–15 GeV range yields a production rate proportional to beam power [22]. The proton beam strikes a target enclosed in a high-field, large-bore solenoid magnet to enable simultaneous capture of both positive and negative species [23]. RF cavities capture the muons into a bunch train. An Initial Cooling channel [24], capable of cooling both species of muons simultaneously, reduces the 6D phase space of the beam by a factor of 50. The two muon species are subsequently separated [25] into parallel 6D cooling channels to continue reducing the beam emittance to the levels required for luminosity production in a collider. The intermediate sections of cooling require high-gradient RF cavities operating in strong solenoid fringe fields. The final sections require state-of-the-art high field solenoids to reach the lowest emittances, and hence highest luminosity.

The system of solenoids around the target requires 15–20 T fields and large bores to accommodate shielding material. The short proton bunch length and 5 Hz operation result in a large instantaneous power which may cause significant damage to a solid target. A liquid metal [26] or a fluidised tungsten target [16] are alternative solutions. A preliminary engineering study of the target magnet should be performed, including consideration of radiation arising from beam interaction with the target. Studies of stress and heat load on the target should be performed and appropriate alternative solutions may be studied.

The overall design has to be optimised; further improvements would facilitate the machine design in the high energy complex. Alternative options have been proposed and need to be evaluated. In addition, the collective effects and beam-matter interactions should be explored further to validate the overall emittance performance. Integration of the muon production subsystem designs should be performed. Optimisation should be performed, paying particular attention to those areas that can significantly improve facility performance and current and expected future availability of high-gradient RF and high-field solenoids.

5.5.6 Proton Complex

Based on MAP calculations, the average proton beam power required in the target is in the range of 2 MW, but this needs to be fully validated by an end-to-end design of the facility. The proton beam energy should be in the range of 5–15 GeV. The power appears very feasible; spallation neutron sources like SNS and J-PARC already operate in the MW regime and others like ESS and PIP-II are in construction. The Superconducting Proton Linac (SPL), an alternative injector complex considered for the LHC, would have provided 4 MW of 5 GeV protons. The collector and compressor system merges the beam into 2 ns long pulses with a repetition rate of 5 Hz. Alternatively the use of an FFA or pulsed synchrotron could be considered, profiting from synergies with the next generation of spallation neutron sources in the UK. In this case the magnet design and collective effects needs studies and R&D. Scaling from existing and planned facilities is expected to give a good indication of required parameters. Eventually development of an accumulator and compressor system will be necessary, taking into account existing H^- ion sources and capability of H^- stripping systems for injection into the ring.

5.5.7 Physics and Technology Synergies

The ambitious programme of R&D necessary to deliver the muon collider has the potential to enhance the science that can be done at other muon-beam facilities.

nuSTORM and ENUBET offer world-leading precision in the measurement of neutrino cross sections and exquisite sensitivity to sterile neutrinos and physics beyond the Standard Model. nuSTORM in particular will require capture and storage of a high-power pion and muon beam and management of the resultant radiation near to superconducting magnets. The target and capture system for nuSTORM and ENUBET may also provide a testing ground for the technologies required at the muon collider and as a possible source of beams for the essential 6D cooling-demonstration experiment.

The next generation searches for charged lepton flavour violation exploit high-power proton beams impinging on a solid target placed within a high-field solenoid. The technological issues of target and muon capture for these experiments are similar to those present in the muon collider design.

The potential to deliver high quality muon beams could enhance the capabilities of muon sources such as those at PSI and ISIS. The use of frictional cooling to deliver ultra-cold positive and negative muon beams is under study at PSI and may be applicable to the muon collider.

FFAs have been proposed as a route to high proton beam power for secondary particle sources such as neutron spallation sources, owing to the potential for high repetition rate and lower wall plug power compared to other facilities. An FFA is under study as a possible means to upgrade the ISIS neutron and muon source.

High-power short-pulse proton drivers are in use throughout the world, for example at SNS and JPARC. In Europe ESS and ISIS are both studying options for upgrades to MW-class short-pulse proton production. Opportunities to learn from these facilities may be exploited.

The underlying technologies required for the muon collider are also of interest in many scientific fields. The delivery of high field solenoid magnets is of great interest to fields as wide ranging as particle physics, accelerator science and imaging technology. Operation of RF cavities with high gradient is of interest to the accelerator community.

5.6 Facilities and Infrastructure

A test stand is required to demonstrate the ability of the muon collider to deliver the requisite luminosity, initially to demonstrate engineering integration of RF, magnets and absorbers, and eventually incorporating beam tests. Achieving high luminosity rests on the solution of two critical issues; the ability to create a high-flux muon beam from pions created at the target, and the ability to efficiently cool the beam in all six phase-space dimensions. This technology represents the single most novel system of the muon collider and requires unique customization of key accelerator technologies. A demonstrator may be able to contribute to a cutting-edge physics programme and this possibility should be exploited.

The construction and operation of the demonstrator that can explore the full bandwidth of relevant accelerator technologies will be required. The test facility could be placed at any laboratory that can provide a proton beam having a sufficiently high instantaneous beam power or can afford to construct a new proton complex. Initial explorations are ongoing at CERN to identify a site with access to appropriate beam. Preliminary studies indicate that construction of a junction cavern may be required in the next long shutdown in order to meet the timeline of a muon collider by 2045. A design for the demonstrator should be developed. Detailed study of required preparatory activities should be performed and approval sought in order that, should the demonstrator be deemed necessary by the particle physics community, the programme is not delayed.

In addition, a dedicated programme of key component development will have to be executed. The cooling systems require normal conducting RF cavities that can operate with high gradient in strong magnetic fields, which can cause conventional cavities to break down. Test cavities have been developed that can exceed the required performance. The existing R&D should be exploited to develop and test production cavities for the cooling systems that can operate in the desired range. Such development will require an RF test stand with significant available RF power in an appropriate frequency range and a suitable high field, large aperture magnet.

High-field superconducting solenoids and accelerator magnets are key to the muon collider performance. This includes the target solenoid, cooling solenoids, collider ring magnets, the fast ramping magnet and powering system. Specific challenges arise from the combination of high field and large aperture that lead to stress in the magnets. Design studies of key magnets are required to translate the magnet technology progress into estimates of performance of magnets appropriate to the muon collider.

Development of efficient superconducting RF with large accelerating gradient is essential for the high energy complex. Existing RF infrastructure should be sought in order to perform tests of superconducting RF cavities.

The proposed power density in the target and surrounding magnet is significant. Damage to both the target itself and also the superconducting wires is a possibility. Tests of components in a high radiation environment should be carried out using existing facilities such as HiRadMat to establish the sustainability of the required power density.

5.7 Key Points of the Roadmap

The muon collider R&D programme will consist of the initial phase followed by the conceptual and the technical design phases. The initial phase will establish the potential of the muon collider and the required R&D programme for the subsequent phases. A technically limited timeline for the initial phase would need five years and is outlined in Fig. 5.3. Two sub-phases phases have been identified: the Exploratory Phase and the Definition Phase.

In the Exploratory Phase existing studies will be identified and early stage design work will be performed leading to a tentative parameter set. Design choices will be made and critical issues will be identified so that tasks can be prioritised. Additionally resources will be sought to perform more involved studies. The exploratory phase is ongoing and will continue until the end of 2022.

In the Definition Phase more involved design work will be performed. A complete baseline will be established including start-to-end simulation. Concepts for managing key technical issues and technologies which can drive the performance of the facility will be studied, where necessary including prototyping of the underlying equipment. In particular, a design of a facility to demonstrate an engineered muon ionisation cooling channel will be prepared. A more detailed parameter set will be established enabling an estimate for the performance, cost and power consumption to be performed. The R&D programme required to deliver a conceptual design report will be established. The Definition Phase will be completed by the end of 2025 so that a fully informed decision may be made during the next European strategy update.

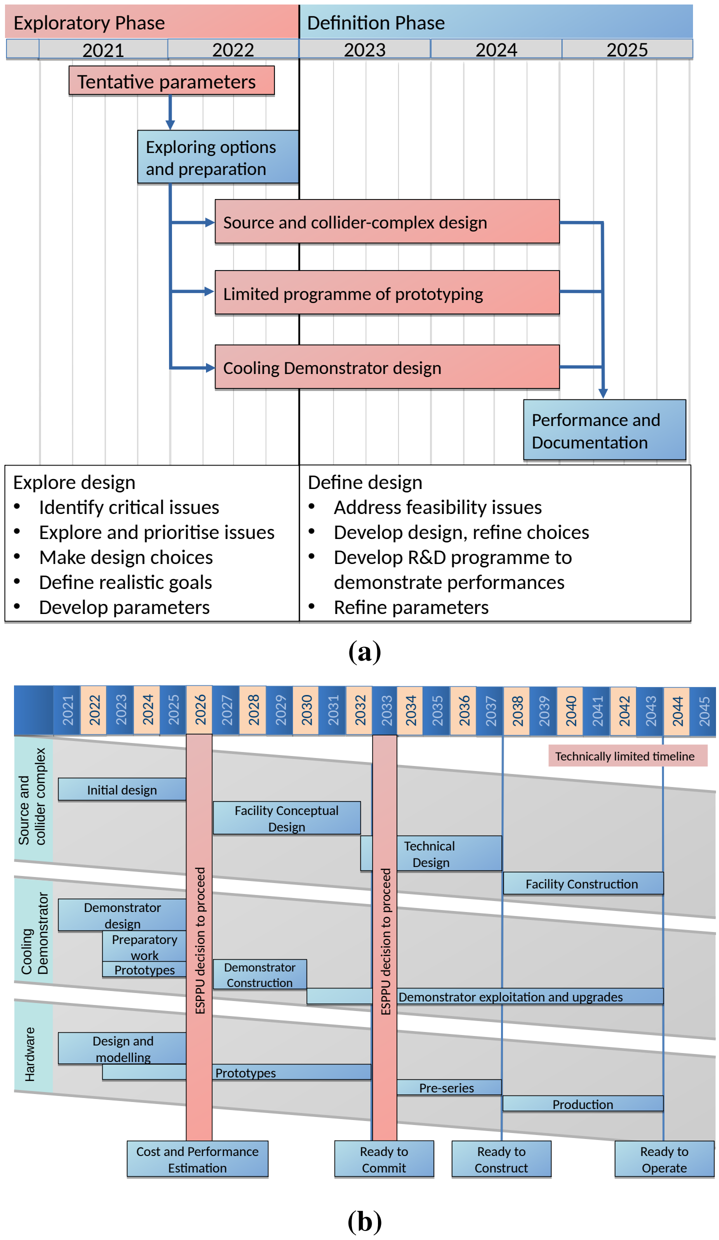

Fig. 5.3: Muon collider R&D roadmap (a) leading to the next ESPPU and (b) for the muon collider programme, assuming full resourcing.

The consecutive R&D programme will depend on the Strategy Decision. The most ambitious programme timeline leading to construction of a 3 TeV muon collider by 2045 is outlined in Fig. 5.3. Subject to the prioritisation made by the next European Strategy, the project could enter a conceptual design phase. The performance and cost of the facility would be established in detail. A programme of test stands and prototyping of equipment would be performed over a five-year period, including a cooling cell prototype and the possibility of beam tests in a cooling demonstrator. This programme is expected to be consistent with the development of high field solenoid and dipole magnets that could be exploited for both the final stages of cooling and the collider ring development. A technical design phase would follow in the early 2030s with a continuing programme focusing on prototyping and preseries development before production for construction begins in the mid-2030s, to enable delivery of a 3 TeV collider by 2045. The programme is flexible, in order to match the prioritisation and timescales defined by the next ESPPU.

5.8 Conclusion

The muon collider presents enormous potential for fundamental physics research at the energy frontier. Previous studies, in particular the MAP study, have demonstrated feasibility of the facility across the parameter range required. A number of proof-of-principle experiments and component tests, such as MICE, EMMA and the MuCool RF programme, have been carried out to practically demonstrate the underlying technologies.

The muon collider is based on novel concepts and is not as mature as some other lepton collider options such as ILC and CLIC. However, it promises a unique opportunity to deliver physics reach at the highest energies on a cost, power consumption and time scale that may improve significantly on other proposed colliders on a footprint that is consistent with the LHC. It is the only practical technique to deliver lepton collisions at energies beyond 3 TeV. At this stage the panel did not identify any showstopper in the concept.

The panel has identified a viable baseline parameter set and a development path that can address the major challenges and deliver a 3 TeV muon collider by 2045. The panel will propose the R&D effort that it considers essential to address these challenges during the next five years to a level that allows estimation of the performance and cost with greater certainty. Execution of this R&D is required in order to maintain the timescale described in this document. Ongoing developments in underlying technologies will be exploited as they arise in order to ensure the best possible performance. This R&D effort will inform the decision-making process at the next ESPPU. Based on these decisions a significant ramp-up of resources could be made to accomplish construction by 2045, or a continued base level of investment could enable development on a longer time scale. This would enable Europe to exploit the enormous potential of the muon collider.

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6 Energy-Recovery Linacs

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6.1 Executive summary of findings to date

Energy Recovery is at the threshold to become a major means for the advancement of accelerators. Recycling the kinetic energy of a used beam for accelerating a newly injected beam, i.e., reducing the power consumption, utilising the high injector brightness and dumping at injection energy: these are the key elements of a novel accelerator concept, invented half a century ago [1]. The potential of this technique may indeed be compared with the finest innovations of accelerator technology such as by Wideroe, Lawrence, Veksler, Kerst, van der Meer and others during the past century. Innovations of such depth are rare and their impact is only approximately predictable.

The fundamental principles of energy recovery linacs (ERLs) have now been successfully demonstrated across the globe. There can no longer be any doubt that an ERL can be built and achieve its goals. The history, present and future directions of the development of ERLs, for particle, nuclear and applied physics, are summarised in a long write-up on “The Development of Energy Recovery Linacs” [2] which accompanies the appearance of this roadmap. An important milestone of its preparation was an ERL Symposium [3] in June 2021 which in consultation with the particle and accelerator physics communities discussed the basis, status, impact, technology and prospects of the field of ERLs. The technique of energy recovery in superconducting linac cavities promises a luminosity increase for physics applications by orders of magnitude at a power consumption comparable to classic, lower luminosity solutions, which is a necessary step towards the sustainability of high-energy physics, as interaction cross sections fall with rising energy. Orders of magnitude higher luminosities are similarly crucial for opening new areas of low energy physics such as nuclear photonics or the spectroscopy of exotic nuclei. ERLs are

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also near utilisation in several industrial and other applications such as photo-lithography, free electron lasers, inverse photon scattering and others.

The novel high-energy ERL concepts targeted at energy-frontier electron-hadron, electron-positron and electron-photon colliders, as well as further physics and other applications, require the development of high-brightness electron guns and dedicated SRF technology as prime R&D objectives. Moreover, “it needs a facility comprising all essential features simultaneously: high current, multi-pass, optimised cavities and cryomodules and a physics-quality beam eventually for experiments" (Bob Rimmer in [3]).

The ERL roadmap presented here rests upon three major, interrelated elements:

A) Facilities in progress, including crucial technology developments and operation experience. These comprise sDALINAC (Darmstadt, Germany), MESA (Mainz, Germany) + cBETA (Cornell, US), cERL (KEK, Japan) and the normal conducting lower frequency Recuperator facility (Novosibirsk, Russia);

B) A key technology R&D program focused on high current electron sources and high power SRF technology and operation in the years ahead. Next generation ERLs lead to the major goal to be able to operate at 4.4 K cryogenics temperature [8] with high Q_0, and also including higher-order mode damping at large temperature, dual axis cavity developments and novel means for high current ERL diagnostics and beam instrumentation to deal with effects such a beam break-up or RF transients;

C) New ERL facilities in preparation for reaching higher currents and electron beam energies at minimum power consumption. These are, in Europe, bERLinPRO (Berlin, Germany) with the goal to operate a 100 mA, 1.3 GHz facility, and PERLE (hosted by IJCLab Orsay, France), as the the first multi-turn, high power, 802 MHz facility with novel physics appilcations. In the coming years the US will explore the near 10 GeV ERL operation with CEBAF5 (Jefferson Laboratory, Newport News) and develop the challenging 100 mA electron cooling of hadron beams at the EIC (BNL, Brookhaven).

ERLs are seen as the base of next generation electron-hadron colliders at high (LHeC and FCC-eh [4, 5]) and medium (EIC [6]) energies. An ERL based proposal has been published [7] for the generation of picometer class emittance muon beams by electron-photon collisions. Two concepts have been published and explored as part of this roadmap process for reaching higher luminosity at high energies - for the FCC-ee, termed CERC [8], and for the ILC, termed ERLC [9]. A particularly interesting prospect is to design and possibly build an energy efficient, ultra-high luminosity ERL-based electron-positron collider at 500 GeV, which would enable the exploration of the Higgs vacuum potential with a measurement of the tri-linear Higgs coupling in e^+e^-.

In summary, the panel notes with much interest that the ERL technology is close to its high-current and high-energy application, requiring dedicated and coordinated R&D efforts, with the stunning potential to revolutionise particle, nuclear and applied physics as well as key industry areas, at a time where caring for energy resources is an overarching necessity for this planet, not least big science. ERLs are therefore primed for inclusion among the grand visions our field has been generating, and for dedication of adequate support to it, in Europe as well as globally, for this unique potential to bear fruit.

6.2 Introduction

6.2.1 History

The idea of an energy-recovery linac traces back to Maury Tigner [10] in 1965. He was looking at ways to enhance the current in a collider for high-energy physics. Accelerating two beams, colliding them, and then dumping them is extremely inefficient. If one could recover the energy of the beams in the same cavities in which they were accelerated, then the efficiency of the machine could be greatly increased.

[8] The 4.4 K R&D program, hosted by the SRF panel, would also allow universities to adopt small superconducting accelerators for inverse Compton back-scattering, FELs, isotope production, etc. Apart from the societal aspect, this would provide a steady product line for SRF cavity and cryomodule production by industry, which would in turn benefit future HEP colliders.

The design of the final dump also becomes much simpler. Though the idea was sound, the implementation of an efficient solution relied on the development of reliable superconducting radiofrequency (SRF) accelerating cavities. These were developed over the next decade. The first large use of SRF cavities was at the High Energy Physics Lab (HEPL) at Stanford University. Researchers there installed a recirculation loop with the capability of varying the path length so that the electrons in a second pass through the accelerating cavities could be either accelerated or decelerated. Both options were demonstrated. This was the first ERL with SRF cavities [11]. This type of ERL is called same-cell energy recovery. The beam was not used for anything, and the current was pulsed, but evidence for energy recovery was clearly seen in the RF power requirements during the beam pulse.

Other demonstrations of energy recovery with room-temperature cavities were carried out at Chalk River [12] and Los Alamos National Lab [13]. The Los Alamos demonstration used coupled accelerating and decelerating cavities, and it had an FEL in the beamline so the overall FEL efficiency could, in principle, be increased, but the cavity losses and the RF transport losses led to an overall increase in the RF power required, showing the advantage of using nearly lossless SRF cavities in the same-cell energy recovery mode.

During the early development of CEBAF at what is now Jefferson Lab, the ability to recirculate beam in the newly-developed SRF cavities was tested in the Front End Test (FET) [14], where the beam was recirculated in a fashion similar to the HEPL experiment. The current in this case, however, could be run continuously, and both recirculation (two accelerating passes) and an energy-recovery configuration were demonstrated.

While all of this technology development work was taking place, several authors noted that the ERL was a natural way to increase the overall efficiency of a Free-Electron Laser (FEL) since the FEL usually only takes about 1 % of the energy of the electron beam out as laser radiation and then dumps the rest. If one could recover most of the power from beam at the exit of the FEL, one could greatly enhance the overall efficiency of the laser. The Los Alamos experiment demonstrated some of the concepts of an ERL-based FEL but was a low-average-power, pulsed device.

This led to the development of an IR Demo project at Jefferson Lab [15], based on the same cryomodules that had been developed for CEBAF. This was a resounding success, exceeding all of the ambitious goals that had been established with a 35 MeV to 48 MeV, 5 mA electron beam producing 2.1 kW of IR outcoupled to users. This enabled the development of an even more ambitious goal: to increase the power levels by a factor of ten. This was achieved by a rebuild of the recirculation arcs and an increase of the electron energy. This facility circulated 9 mA at up to 150 MeV, still the highest current that has been recirculated in an SRF ERL [16]. There was a considerable amount of beam optics studies which laid the foundation for the design of later ERL facilities.

The ERLs at Jefferson Lab were important demonstrations that one can produce high beam power without a large installed RF power source. The IR Upgrade ERL operated with over 1.1 MW of beam power with only about 300 kW of installed RF, thus demonstrating the most basic reason for building an ERL. Other devices were also built, however, which pushed other frontiers. Novosibirsk has built two ERLs using room-temperature cavities [17]. With the copper losses of the cavities, the efficiency is not high, but they were able to recirculate up to 30 mA of average current, still the record for recirculated current. The two ERLs are used for far-infrared FELs in a very active user program.

A group at JAERI built an ERL that used novel cryogenic cooling at long wavelengths to produce a very efficient ERL. They also pushed the efficiency of the FEL to record levels for an ERL [18]. The group at KEK commissioned a high-current ERL test machine that is designed for currents up to 100 mA and demonstrated 1 mA of beam recirculation before losing funding. The photocathode gun operates at 500 kV, the highest of any photocathode gun [19].

An ERL similar in design to the Jefferson Lab ERL, ALICE, was built at the Daresbury Lab. It operated pulsed due to radiation and refrigeration concerns but demonstrated both THz production and

IR FEL operation [20]. ALICE was shut down after ten years of successful operation, having achieved its objectives. As part of an ERL program for a light source, Cornell commissioned an injector with the highest average current demonstrated from a photocathode injector [21]. Following this, they reused the gun, booster and a single cryomodule as the basis for CBETA. The arcs that return the beam to the cryomodule used a novel technique, Fixed-Field Alternating-Gradient (FFAG) transport, to demonstrate the first multi-pass energy recovery in an SRF-based ERL [22].

6.2.2 Technology

Energy-Recovery Linacs are an extremely efficient technique for accelerating high-average-current electron beams. In an ERL, a high-average-current electron beam is accelerated to relativistic energies in (typically) a superconducting RF CW linear accelerator. The beam is then used for its intended purpose, i.e., providing a gain medium for a free-electron laser, synchrotron light production, a cooling source for ion beams, or a beam for colliding against ions. The application usually creates a large increase in the energy spread or emittance of the electron beam, but the majority of the beam power remains. To recover this power, the beam is then sent back through the accelerator again, only this time roughly 180° off the accelerating RF phase. The beam is therefore decelerated as it goes through the linac, putting its power back into the RF fields. Eventually, the beam energy becomes so low that transport of the beam becomes awkward, so the beam is dumped with some (small) residual energy.

Three major system benefits accrue from this manipulation: the required RF power (and its capital cost and required electricity) is significantly reduced, the beam power that must be dissipated in the dump is reduced by a large factor, and often the electron beam dump energy can be reduced below the photo-neutron threshold, minimizing the activation of the dump region, so the required shielding of the facility can be reduced. The cost savings associated with incorporation of energy recovery must be balanced against the need to provide a beam transport system to re-inject the beam to the linac for recovery. If significant growth in the energy spread or emittance of the electron beam has occurred in the process of utilizing the beam, then this transport system can necessitate significant manipulation of the beam phase space. These techniques are well understood by now, but a new machine requires considerable care in the design phase to minimize operational problems.

There are additional benefits that accrue from the geometry and physics of such a machine. An ERL has the ability to supply extremely low emittances (of approximately equal value in both planes) for the production of synchrotron light with high peak and average brightness, or for electron beam cooling. Additionally, the ERL has the advantage of being able to optimize beta functions independently without exceeding the dynamic aperture limitations that rings present.

Finally, the ability of the ERL to operate at low charges with small longitudinal emittances enables the production of very short electron pulses at extremely high repetition rates. To achieve these benefits requires careful design, including answering a number of physics issues.

There are several hardware aspects that have been improved to enable the potential of ERLs, notably SRF cavity design to allow high currents, including damping of unwanted Higher Order Modes (HOMs) to avoid beam break-up issues. However, the continual improvement in ERL capability is still pushing the technology limits in several areas, including SRF. Another active research area is the development of a high-current, ultra-high-brightness, CW electron source. Extensive development efforts for CW sources have been undertaken at many laboratories, and substantial efforts are also required for appropriate diagnostics.

All of the subjects, here mentioned and others related, have now been addressed at some level, but not always simultaneously. It is generally believed (and history bears this out) that progress in accelerator performance usually requires steps of about a factor of ten. This roadmap is established to show how the next 5-10 years may be used for ERLs to advance, as a base for electron-hadron and electron-positron colliders, as a hub for high intensity particle and nuclear physics at low energies and with an impact on industry and other science areas. It will become clear and to be exploited that ERLs are to a large extent a global, pioneering project. Europe will develop into a leading role with its existing and new facilities as well as with fundamental technology projects. A vision for ERLs, as will be outlined, is the development of the 4.4K technology, to reduce the power consumption of tens of km long linacs and to also revive SRF technology by making it accessible to smaller labs and Universities which do not have 2K Helium cryogenics available. Following a remarkable history, a next step of ERL development is near which will give entry of ERLs to energy frontier particle physics.

6.3 Motivation

6.3.1 Energy frontier particle physics and the economy of power

More than five decades of particle physics passed and we established the Standard Model (SM), a unified electroweak interaction with QCD attached to it. And yet, we are in a similar situation as before the discovery of quarks: theory provides questions, but no firm answers. The SM has known, fundamental deficiencies: a proliferation of too many parameters, a missing explanation of the repetitive quark and lepton family pattern, an unresolved left-right asymmetry in the neutrino sector related to lepton-flavour non-conservation, an unexplained flavour hierarchy, the intriguing question of parton confinement and others. The Standard Model carries the boson-fermion asymmetry, it mixes the three interactions but has no grand unification, the proton is stable, it needs experiment to determine the parton dynamics inside the proton, it has no prediction for the existence of a yet lower layer of substructure, and it does not explain the difference between leptons and quarks. Moreover, the SM has missing links to Dark Matter, possibly through Axions, and Quantum Gravity, while string theory still resides apart. The Standard Model is a phenomenologically successful theory, fine tuned to describe a possibly metastable universe [23].

Principally new theories, however, would be required to “turn the SM on its head" while, as Steven Weinberg also stated not long ago: “There isn’t a clear idea to break into the future beyond the Standard Model" [24], it remains the conviction, as Gian Giudice described it in his eloquent “imaginary conversation" with the late Guido Altarelli, that “A new paradigm change seems to be necessary" [25] in the “Dawn of the post naturalness era".

Apparently, particle physics is as interesting, challenging and far reaching as it ever was in recent history. It yet needs revolutionary advances in insight, observation and technologies, not least for its accelerator base. It demands that new generation hadron-hadron, electron-hadron and pure lepton colliders shall be developed and realised. Hardly a new paradigm can be established with just one type of collider in the future. The field needs global cooperation, trust and complementarity of its techniques, a lesson learned from the exploration of the Fermi scale with the Tevatron, HERA and LEP/SLC.

As interaction cross sections decrease with rising energy, and new phenomena may be expected to be rare, new colliders have to reach integrated luminosities increased by orders of magnitude as compared to the colliders of the recent past. With increasing energy and luminosity wall plug power demands rise to values which even when they still could be realised are essentially unacceptable in a world which fights for its sustainability and energy balance. To quote Frederick Bordry [26]: “There will be no future large-scale science project without an energy management component, an incentive for energy efficiency and energy recovery among the major objectives.” It is a built-in feature of energy recovery linacs that the power required for operation is an order of magnitude or more below the beam power. A prime motivation for the ERL panel had been to evaluate this feature and its underlying technology demands as a crucial part of the ERL strategy for the coming and future years ahead. This leads to emphasis on 4.4 K technology, fast reactive tuners (FRT) and other key elements of the ERL roadmap here described. ERLs, for electron-hadron and electron-positron colliders, are a route "royal" to high energy, high luminosity and limited power consumption, not easy but now possible to follow, owing to half a century of often generic ERL and SRF R&D efforts.

6.3.2 Accelerator developments

Energy-Recovery Linacs are an extremely efficient technique for accelerating high-average-current electron beams. In an ERL, an intense electron beam is accelerated to relativistic energies in (typically) a superconducting RF linear accelerator operating in continuous-wave (CW) mode. The beam is then used for its intended purpose, i.e., providing a gain medium for a free-electron laser, synchrotron light production, or a cooling source for ion beams. In high-energy physics, the interest is on an intense, low-emittance e^- beam for colliding against hadrons (eh), positrons (e^+e^-) or photons (eγ). They all rely on the provision of high electron currents (of I_e up to ~ 100 mA) and high-quality cavities ($Q_0 > 10^{10}$). As part of this roadmap, novel techniques are to be worked out and applied for monitoring beams of such high power, as is explained subsequently.

Energy Recovery is at the threshold to become a major means for the advancement of accelerators. Recycling the kinetic energy of a used beam for accelerating a newly injected beam, i.e., reducing the power consumption, utilising the high injector brightness and dumping at injection energy: these are the key elements of a novel accelerator concept, invented half a century ago [1]. The potential of this technique may indeed be compared with the finest innovations of accelerator technology such as by Wideroe, Lawrence, Veksler, Kerst, van der Meer and others during the past century. Innovations of such depth are rare and their impact only approximately predictable.

ERLs provide maximum luminosity through a high brightness source, high energy through possible multi-turn recirculation, and high power, which is recovered in the deceleration of a used beam. It is remarkable that following the LHeC design from 2012 [27] (updated in 2020 [4]), all these avenues have been pursued: for $\gamma\gamma$ collisions [28] using the LHeC racetrack, further for eh with the FCC-eh in 2018 [5], for e^+e^- in 2019 with an ERL concept for FCC-ee, termed CERC [8]), and in 2021 with an ERL version of the ILC termed ERLC [9]) and very recently also a concept for the generation of pico-emittance muon pairs through high-energy, high-current eγ collisions [7].

A common task for these colliders is precision SM Higgs boson measurements dealing with a small cross section (of 0.2/1 pb in charged current ep interactions at LHeC/FCC-eh and similarly of 0.3 pb in Z-Higgsstrahlung at e^+e^-). This makes maximising the luminosity a necessity to profit from the clean experimental conditions and to access rare decay channels while limiting power. High luminosity and energy are expected to lead beyond the Standard Model and are essential for precision measurements at the corners of phase space.

A particularly interesting prospect is to design and possibly build an energy efficient, ultra-high luminosity ERL-based electron-positron collider at 500 GeV, which would enable the exploration of the Higgs vacuum potential with a measurement of the tri-linear Higgs coupling in e^+e^-. In order for this to happen as a linear collider, it shall be based on novel cavity technology that exploits 4.4 K cryogenics for which pure Niobium is not suited as its Q_0 drops to 10^8. This sets a long term goal of a combination of high gradient, ≥ 20 MV/m, high Q_0, $\geq 3\,10^{10}$, achieved also with dual axis cavities, 4.4 K technology and room-temperature HOM damping to limit cost and power [9]. This goal has been translated to a long term, high-quality ERL R&D program, with quite a strong link to the SRF panel roadmap as is subsequently described.

While these requirements, as often in history, arise with particle physics, they are in line with and beneficial for general technical developments and applications. The 4.4 K technology is suited to reduce cryoplant cost and heat load for HOM extraction. This makes SCRF more cost effective both in capital and operating cost. Example industrial interest includes semiconductor lithography and gamma sources for nuclear industry. During previous studies of such applications with comparable scale, the capital cost of cryogenics comprised order 25% of full facility cost. Operational cost comprising electricity and maintenance again typically comprises 25% of full operating cost. Reducing these therefore has signifi-

[9]Emphasis on the 4.4 K program and the recognition of the e^+e^- ERL collider potential was strongly supported by the evaluation of two recent ingenuitive concepts, connected to FCC-ee and ILC, by the intense analysis of a sup-panel, the results are described as part of the subsequent panel activity Section 6.4.

cant impact on economics of deployment commercially. Finally and not least, at 4.4 K SRF technology becomes accessible to smaller research labs or universities avoiding the very special and expensive requirements posed by superfluid technology. This is expected to feed back to SRF industry on which particle physics depends to a considerable extent.

6.3.3 Physics opportunities with sub-GeV beams

The unique beam properties of ERLs, high intensity and small emittance, enable substantial experimental advances for a variety of physics goals at lower energies. This is described in detail in [2].

Form factors of nucleons and nuclei are classically accessed via elastic electron scattering. Recently, the low-Q^2 form factors of the proton was in the focus of increased scrutiny because of the proton charge radius puzzle (for a recent overview, see [**?**]), a more than 5 sigma difference in the charge radius extracted from muonic spectroscopy and all other determination methods. The determination of the proton form factors is limited by experimental systematics stemming from target-related background. The high beam current available at ERLs allow us to employ comparatively thin targets, for example cluster jets [29], which minimise this background, paving the way for a new generation of experiments. In a similar vein, the relatively high luminosity and typically small energies at places like MESA, allow us to measure the magnetic form factor, only accessible at backward angles at low-Q^2, with substantially increased precision – in a Q^2 range highly relevant for the magnetic and Zeman radii and where the current data situation is especially dire. Further electron scattering experiments include dark sector searches like DarkLight@ARIEL, aiming at masses of a couple of (tens of) MeV.

In backscattered photon scattering, the luminosity available exceeds that of ELI by a few orders of magnitude, paving the way to nuclear photonics, an area possibly comparable with the appearance of lasers in the sixties. For example, the intensities achievable at an ERL allow nuclear parity mixing to be accessed. Photonuclear reactions test the theory for nuclear matrix elements relevant for the neutrino mass determination from neutrino-less double beta decay. They can be used to study key reactions for stellar evolution. Ab initio calculations of light nuclei (e.g. [**?**]) are very advanced and need to be tested with precision measurements.

A further fundamental interest regards the exploration of unstable nuclear matter with intense electron beams of O(500) MeV energy as is characteristic for PERLE and envisaged for GANIL in France. This follows the recognition of the field by NuPECC in their strategic plan in 2017: "Ion-electron colliders represent a crucial innovative perspective in nuclear physics to be pushed forward in the coming decade. They would require the development of intense electron machines to be installed at facilities where a large variety of radioactive ions can be produced".

6.3.4 Industrial and other applications

The range of further applications, beyond particle and nuclear physics, is very remarkable. Examples include high-power lasers, photolithography, and the use of inverse Compton scattering (ICS) [2]. An ERL-FEL based on a 40 GeV LHeC electron beam would generate a record laser with a peak brilliance similar to the European XFEL but an average brilliance which is four orders of magnitude higher than that of the XFEL [30].

The industrial process of producing semiconductor chips comprises the placing of electronic components of nanometre scale onto a substrate or wafer via photolithography. For advancing this technology to nm dimensions, the FEL must be driven by a superconducting ERL. An ERL with electron beam energy of about 1 GeV would enable multi-kW production of extreme-ultraviolet (EUV) light. This would benefit the global semiconductor industry by allowing study of FEL capabilities at an industrial output level. Initial surveys and design studies were undertaken by industry some years ago. If the economic viability may be underpinned by large scale high reliability, ERLs might well reach into the market, which in 2020 was 400 B Euro.

A third example, interesting due to its applications for nuclear physics but also exotic medical isotope generation and transmutation, is the process of very intense inverse Compton scattering. An about 1 GeV energy superconducting ERL operating at high average electron current in the 10 to 100 mA range would enable a high-flux, narrowband gamma source based on ICS of the electron beam with an external laser within a high-finesse recirculating laser cavity. The production of 10 to 100 MeV gammas via ICS results in properties of the gamma beam fundamentally improved with respect to standard bremsstrahlung generation. This ICS process would be a step change in the production of high-flux, narrowband, energy-tunable, artificial gamma-ray beams. They will enable quantum-state selective excitation of atomic nuclei along with a yet-unexploited field of corresponding applications.

The panel highlighted a further example of ERL impact: Using high (15 T) field bending magnets at O(1) GeV energy range ERL, one can build a unique user facility with sub-picosecond X-ray pulses. Those cannot be achieved in contemporary sources, see [2], which have to use femto-slicing techniques [31] with very low photon flux instead. The JLab UV Demo FEL demonstrated less than 0.2 ps r.m.s. bunch duration (at an electron energy of 135 MeV and a longitudinal emittance of 50 keV·ps) [32]. Therefore, at higher energies it is possible to obtain 0.1 ps and less. For example, installation of 15 T bending magnets to the last orbit of PERLE at 500 MeV provides synchrotron radiation with a critical energy of 2.5 keV (leading to 7 keV energy photon), enough for most of the experiments that use femto-slicing now. For lower-energy ERLs, such as bERLinPro, there is a similar option with bremsstrahlung on a few-micron Carbon foil. The advantage of Carbon is a high fail temperature and, therefore, good radiation cooling of the foil, which allow high electron current density (small spot size) at the foil. The tests of such a scheme have been started with the Novosibirsk ERL (Recuperator) at 40 MeV. ERLs have a potential to radically advance our knowledge, science and industry as these few examples illustrate.

6.4 Panel activities

6.4.1 Summary

The ERL Roadmap Panel was recruited and its membership endorsed by the LDG in early 2021. It has 18 members from three continents, representing leading institutions and major ERL facilities (past, ongoing or in progress), and assembles key expertise such as on injectors, superconducting RF, operation and management. Supported by the LDG, the panel decided early on to write a baseline paper on ERLs for publication [2] for accompanying the appearance of this roadmap. That paper, written by about 50 co-authors, is about the history, present, challenges, prospects, physics and applications of ERL technology and thought to be an up-to-date, comprehensive reference paper, which neither the short interim report, delivered in July 21, nor this roadmap could represent.

On Friday 4$^{\text{th}}$ of June 21, an extended Symposium on the Development of Energy Recovery Linacs was held [3], introduced by Dave Newbold for the LDG. With a 100 participants, and including an hour-long discussion, this was an important consultation with a community of interested accelerator, particle and nuclear physicists. For a quick introduction the talks presented there - on ERL facilities (Andrew Hutton), high current electron sources (Boris Militsyn), SRF developments for ERLs (Bob Rimmer), ERL prospects for high-energy colliders (Oliver Brüning, Low energy physics with ERLs (Jan Bernauer), Industrial applications (Peter Williams) and Sustainability (Erk Jensen), chaired by Bettina Kuske and Olga Tanaka - are a suitable and interesting material one may still want to consult. Max Klein was invited to present intermediate summary reports to a TIARA meeting in June and to the EPS Conference at DESY (virtually) in July 21 [33].

Over summer, members of the panel and further colleagues, in a sub-panel, were involved in an evaluation of future e^+e^- ERL collider concepts and their implications for this roadmap. A summary of the findings of this sub-panel is given in the next section.

In the final phase of its activities, the panel's emphasis focused on the development of the genuine roadmap and this report. This was made possible through much work of the facility representatives, including ERL panel members, and further contributions and consultations with a number of colleagues world wide for which we are extremely grateful, leading beyond the list of authors of this report. What had begun as an attractive, interesting task developed to an intense process which hopefully will bear fruit. It had been motivated by the conviction to work on one of the most fascinating and forward pointing new accelerator concepts of which energy frontier particle physics has not so many.

6.4.2 Analysis of Future e^+e^- ERL collider prospects and their R&D

While our panel started to work, the ERLC concept was put forward [34] to possibly build the ILC as an energy-recovery twin collider, with the prospect of a major increase of the e^+e^- luminosity as compared to the ILC default. Similarly, the CERC concept had been published [35] to configure the FCC-ee as a circular energy-recovery collider, with very high luminosity extending to large cms energy O(500) GeV. This caused the formation, in agreement with the LDG, of a sub-panel[10] to evaluate the luminosity prospects, the involved R&D, schedule and cost consequences for both ERL-based e^+e^- collider options. This group met frequently over summer and had to also deal with changes of the parameters of CERC and ERLC which partially arose in a friendly dialogue with the authors of these concepts. A brief summary of this evaluation, of a topic in progress, is presented here, while a more detailed report will be available with the ERL baseline paper accompanying this roadmap report.

CERC

The Circular Energy Recovery Collider is proposed as an alternative approach for a high-energy high-luminosity electron-positron collider based on two storage rings with 100 km circumference and a maximum CM energy of 365 GeV. The main shortcoming of a collider based on storage rings is the high electric power consumption required to compensate the 100 MW of synchrotron radiation power. This concept aims to drastically reduce the electrical power for the RF. The sub-Panel task was to evaluate whether the total power would also be reduced compared to the FCC-ee.

According to the proponents, an Energy Recovery Linac (ERL) located in the same-size 100 km tunnel would allow a large reduction of the beam energy losses while providing a higher luminosity and extending the CM energy to 500 GeV, enabling double-Higgs production, and even to 600 GeV for ttH production and measurements of the top Yukawa coupling. This concept also proposes to recycle the particles as well as the energy to enable collisions of fully polarized electron and positron beams.

A sketch in Ref. [35] of a possible layout of the CERC with linacs separated by 1/6th of the 100 km circumference shows the evolution of the beam energy for electrons and positrons in a 4-pass ERL equipped with two 33.7 GeV superconducting (SRF) linacs. The number of interaction points and corresponding detectors is determined by the physics program. In this scheme the luminosity can be shared between detectors: e.g., by timing, the beam bunches collide in only one of the detectors, avoiding collisions in the others. Using this scheme, the luminosity is divided between detectors in any desirable ratio, compared to the FCC-ee where the total luminosity is the sum of the luminosity in each detector. Only beams at the top energy pass through detectors, while the other beam lines by-pass the IRs area. The energy loss caused by synchrotron radiation is significant at these high energies. It makes the process of the beam acceleration and deceleration asymmetric, and both the electron and the positron beams require separate beamlines for each of the accelerating and decelerating passes, meaning that the 4-pass ERL would require 16 individual transport lines around the tunnel. While adding complexity in the geometry of the accelerator, the authors propose to use small gap (~ 1 cm) combined-function magnets and a common vacuum manifold.

The authors estimated the maximum luminosity to be in excess of 10^{36} cm^{-2}s-1, which excited

[10] **Sub-Panel on e^+e^- ERLs**: Chris Adolphsen (SLAC), Reinhard Brinkmann (DESY), Oliver Brüning (CERN), Andrew Hutton (JLab, Chair), Sergei Nagaitsev (Fermilab), Max Klein (U Liverpool), Peter Williams (STFC Daresbury), Kaoru Yokoya (KEK), Akira Yamamoto (KEK), Frank Zimmermann (CERN).

a lot of interest among the future user community. This was achieved by using extremely flat beams for reduced beamstrahlung energy loss (a horizontal to vertical ratio of 500), which the authors stated would still avoid beam loss due to high vertical disruption. A fundamental difficulty with this concept is the choice of the bunch length; too short and beamstrahlung at the Interaction Point makes it impossible to recuperate the beams for deceleration; too long and the curvature of the RF increases the energy spread of the bunches so that they do not fit in the energy band-width of the final focus system. Neither of the two alternative bunch lengths suggested by the authors (2 mm and 5 cm) are viable, but an intermediate value might be acceptable. Clearly, this is a topic that needs careful simulation to move forward. Since neither parameter set was fully self-consistent, the sub-Panel was unable to validate the luminosity estimate. However, the sub-Panel identified several beam dynamics issues that should be studied to enable a more accurate simulation of the luminosity once a self-consistent parameter set has been developed. However, it is clear that the luminosity falls rapidly with increasing energy. The most important issue in the arcs is the preservation of the small vertical emittance of 8 nm over the 400 km orbit in the presence of strong focusing magnets. Emittance growth comes both from the misalignment of the combined-function magnets and the ground motion, and tolerances are normally tighter for stronger focusing. Alignment of the 16 small magnets would be a challenge, given the difficulty of access and the tight tolerances that must be achieved. The orbit correction algorithm must also be studied (the dispersion free method, in which the beam energy is changed, cannot be used). It also became clear early on in the evaluation that 2 GeV was too low an energy for the damping rings, and a later modification from the authors used 8 GeV.

The proposal was aimed at reducing the power needed for the accelerator, and the sub-Panel spent a lot of effort to evaluate this claim. The sub-Panel was able to confirm the reduction on synchrotron radiation and the consequent reduction in RF power required. However, there were two other effects that negated this advantage. First, the cryogenic power required to maintain the cryomodules at 2K for the t-tbar case was 153 MW assuming state-of-the-art SRF technology. In addition, the synchrotron radiation in the 2 GeV damping ring is not negligible and would exceed the synchrotron radiation in the 100 km arcs for the case of the 8 GeV damping rings. Overall, the power consumption was estimated to be 316 MW, similar to the FCC-ee. The cost of the proposal was also estimated by the sub-Panel, based on the cost of the arc magnets from the e-RHIC study and estimates from the FCC-ee for the rest. The total cost was estimated to be 138% of the FCC-ee for the same configuration.

The sub-Panel looked at the possibility of building the FCC-ee first, and upgrading to the CERC as a later upgrade. The CERC layout is required to minimize the synchrotron radiation losses in the arcs. The FCC-ee layout, on the other hand, foresees two to four interaction points and features several 2.1–2.8 km long SRF sections distributed around the ring. Implementing the CERC configuration inside the FCC-ee tunnel would require a redesign of the FCC tunnel layout with sufficient space for the CERC linacs next to the central interaction point. In addition, the required caverns for the detector placement are not compatible with the experimental caverns foreseen in the FCC-ee layout. The extent to which such a design iteration affects the FCC-ee performance reach and cost would need to be assessed.

Updated Parameters: As this report was being finalized, the authors proposed an updated set of operating parameters and gave specific choices for the linac cavity design, voltage gain and quality factor, which were not provided in the initial proposal. We had assumed a Q_0 of 3 10^{10}, the present state of the art. The authors assumed that the Q_0 would be 10^{11}, as a result of future R&D. They also reduced the gradient by a factor of 2. Taken together, these values would significantly lower the machine electrical power requirements from our assessment in the ttbar case, but would roughly double the number of linac cavities. Our simple cost model is not adequate to accurately assess these changes although an overall decrease in the cost is likely. However, the new parameters reduce the luminosity by a factor of three and do not change the large, beamstrahlung-induced bunch energy spread that brings into question the viability of this approach. With the new parameters, the CERC would still be significantly more expensive than the FCC-ee.

CERC Recommendations: The sub-Panel supports the idea of designing a collider based on an ERL to reduce the energy footprint of the facility, and the CERC is an excellent first attempt. While the present proposal has several flaws due to the limited effort that the authors were able to devote to the design, the sub-Panel chose to look for ways that the design could be improved rather than focus on the problem areas.
1) We strongly recommend the development of a self-consistent set of parameters with associated preliminary simulations to fully demonstrate that the idea is viable.
2) The bunch length is a critical parameter – too short and the beamsstrahlung becomes excessive; too long and the energy spread from the RF curvature becomes excessive. It will be necessary to carefully optimize the choice.
3) The energy requirements of the damping rings must be integrated in the design.
4) We recommend R&D on high Q0 cavities operating at 4.5K, which would reduce both the cost and the power consumption.

ERLC

The Energy Recovery Linear Collider was proposed by the author [34] as a high-luminosity alternative for the ILC. It is based on twin-axis superconducting cavities, with the bunches being decelerated after collision to recuperate the energy (see Figure 2 for the schematic layout). This would also permit the re-use of the bunches themselves so that the injectors only have to replace lost particles rather than the whole bunch charge. In the concept, the linacs operate with a 1/3 duty cycle, with two seconds on, four seconds off to reduce the cryogenic power needed to maintain the cryomodules at 2K. The luminosity is estimated by the author to be 5 $10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, a significant increase over the ILC. The sub-Panel carried out an evaluation of the luminosity as well as the cost and power consumption. In addition, there were several new beam-dynamics effects which arose in the course of the study. The idea of using a 1/3 duty cycle was not endorsed by the sub-Panel given the sensitivity of 2 K cryogenic plants to pressure variations. An additional problem with the pulsed RF is the time it takes for the RF to stabilize before the beams can be injected, and additionally, the beams have to be ramped slowly to limit the RF power required (because of the length of the linacs, it takes time for the energy to be restored in the outermost cavities). We therefore also looked at a version with full CW operation, with a reduced current.

The entire machine is a storage (damping) ring with an unusual insertion from the bunch compressor to the decompressor consisting of the acceleration linac, Final Focus system (FFS), Interaction point (IP), FFS, and the deceleration linac. The longitudinal dynamics can therefore be somewhat different from a normal storage ring due to this long insertion (the transverse may also be affected). The energy loss due to HOMs in the acceleration and deceleration linacs is also a large perturbation of the longitudinal dynamics. This new configuration needs careful study as it is likely to be a configuration used in other, future ERL concepts.

The vertical emittance is the same as in the ILC. However, since the proposed transverse damping time corresponds to $\sim$400 turns, some types of the emittance increase are accumulated for $\sim$ 400 turns to reach equilibrium in contrast to the case of single-pass colliders such as the ILC. Various stochastic effects belong in this category, and these need to be carefully evaluated. More complex is the emittance increase in the main linac (and FFS) due to misalignment and the wake field. The ILC expects 10 nm increase in the vertical normalized emittance in a single-pass. Obviously, the major components of this emittance increase are coherent turn-by-turn, but they do not accumulate over multiple turns, but some of them may be cumulative. Even 0.1 nm out of 10 nm single-pass effect can exceed the design emittance if multiplied by 400. The possible source of the cumulative components may be a combination of the above effects (misalignment and wake field) with the chromaticity, which cannot be compensated in the linacs, unlike in ring colliders.

The linac design was not specified in the proposal so assumptions were made about the CW SRF cavities that would be used. A CBETA-like cryomodule (CM) design was chosen, but with dual cavities, that is, side-by-side, 7-cell, 1.3 GHz cavities with Niobium cross connections so power can flow from one 7-cell cavity to its neighbor as required for energy recovery. The huge steady-state loading (1.6 GV/m) from each of the 53 mA beams makes the cavity fields very sensitive to imperfect loading cancellation (i.e., partial energy recovery). In particular, the relative timing of the e^- and e^+ bunches at the cavities may vary due to slow tunnel temperature changes that move the CMs longitudinally.

The cost of the ERLC is obviously more than the ILC as the average gradient is lower (longer tunnel) and the cavities are roughly twice as expensive. We estimated the total cost of the ERLC to be 224% of the ILC. The power requirements are harder to estimate as there are several different options. A major uncertainty is the fraction of the HOM power that is dissipated at 2K. In the ILC, this is 7%, which would be excessive for the high currents in the ERLC. We therefore assume that sufficient R&D has been carried out to enable 100% of the HOM load to be dissipated at room temperature. With this assumption, the power was estimated by the sub-Panel to be 427 MW instead of the 130 MW estimated by the author for a luminosity of $4.8\ 10^{35}\,\mathrm{cm^{-2}s^{-1}}$. An alternative was examined, with a duty cycle of 1/16 (and assuming that pulsing the cryogenic load is possible), the power consumption would be 104 MW for a luminosity of $9\ 10^{34}\,\mathrm{cm^{-2}s^{-1}}$. Note that recently, an optimization of the ILC parameters resulted in a luminosity of $1.35\ 10^{34}\,\mathrm{cm^{-2}s^{-1}}$. The ERLC concept has the potential to exceed the performance projections of the ILC by over an order of magnitude, but still requires vetting of the beam dynamics to affirm emittance preservation is possible in a recirculating linear collider with beam damping at low energy. If shown viable, the ERLC approach might be considered as future upgrade option for ILC although it would require a major reconfiguration of the accelerators and cooling systems. One appealing scenario could therefore be, to start the physics program with the baseline ILC configuration and to look at the ERLC as a future upgrade option of the collider. Noting that the Main Linac and SRF system amount to approximately 45% of the total ILC budget one can conclude further that such an upgrade of the ILC implies an additional investment of about half of the total ILC budget. While this clearly represents a significant cost item, it might still be an interesting option for the long-term exploitation of the ILC if one considers the potential increase of the collider performance by over one order of magnitude and the extension of the ILC exploitation period by perhaps another decade. This approach assumes that the ERLC cryostats are compatible with the main tunnel dimensions and that the Interaction Region design of the ERLC is designed to be compatible with the ILC Interaction Region.

Updated Parameters: The author developed an update to the published parameters with a reduced distance between bunches (23 cm instead of 1.5 m) with an equivalent reduction in the number of particles per bunch (https://arxiv.org/abs/2105.11015v3), which reduces the HOMs by the same factor. The luminosity is kept the same by adopting a smaller horizontal beam size at the IP (keeping the same vertical beam-beam tune shift). The new parameter set considers full CW operation, and the author estimates that the electrical power for the beams is 250 MW. This assumes that the cryogenic efficiency is equal to the Carnot efficiency (1/550). We estimate this efficiency to be 1/900 (the value obtained at LCLS II) to which 25% should be added to which 25% should be added to dissipate the cryoplant heat loads in cooling towers. Adding the site power requirements gives a total of over 600 MW, which the sub-Panel considers unacceptable. We also believe that the closer bunch spacing in the ERLC would require a crossing angle at the interaction region, with the added complexity of including a bend that returns the bunches to the decelerating linac after collision.

ERLC Recommendations: The sub-Panel supports the idea of designing a linear collider based on an ERL to reduce the energy footprint of the facility, and the ERLC is an excellent first attempt. The present proposal was developed by a single author and is therefore incomplete in many details. Therefore, the sub-Panel chose to look for ways that the design could be improved as part of a more detailed study:
1) We recommend a study of the new beam dynamics problems inherent in the integration of a linac and a damping ring.
2) We recommend R&D on high Q0 cavities operating at 4.5K, which would reduce both the cost and the power consumption.

3) We recommend the development of twin aperture SRF cavities in a common cryomodule.

Overall conclusions

The sub-Panel was presented with two, extremely interesting ideas to evaluate. While neither is ready to be adopted now, they point to the future in different ways. The CERC aims for multiple passes in a tunnel with an extremely large bending radius to minimize the synchrotron radiation loss. The ERLC proposes a single acceleration and deceleration, separating the two beams by using twin-axis cavities. Both of these ideas provide an indication of the variety of different ERL layouts that might be developed in the future. A particularly interesting prospect is to design an energy efficient, ultra-high luminosity ERL-based electron-positron collider at 500 GeV, which would enable the exploration of the Higgs vacuum potential with a measurement of the tri-linear Higgs coupling in e^+e^-. The most important R&D activity that would make this kind of development viable at a luminosity approaching $10^{36}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is to operate at 4.4K with high Q_0. We strongly recommend R&D on this topic also, since it would allow universities to adopt small superconducting accelerators for inverse Compton back-scattering, FELs, isotope production, etc. Apart from the societal aspect, this would provide a steady product line for SRF cavity and cryomodule production by industry, which would in turn benefit future HEP colliders.

6.5 State of the art and Facility plans - Roadmap Part A

6.5.1 Overview on facilities and requirements

A long way has been paved since the first SRF ERL [36] at Stanford. Key parameters of an ERL are the electron beam current I_e ($\propto$ luminosity) and energy E_e. The beam power is simply $P = I_\mathrm{e}E_\mathrm{e}$. Through recovery of the energy, it is related to the required externally supplied power P_0, which then gets augmented by a factor $1/(1-\eta)$ where η is the efficiency of energy recovery. This way, for example, the LHeC can be designed to reach a luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, for which a GW of beam power would be required without energy recovery. The current state of the art may thus be characterised by a facility overview, presented in Fig. 6.1, as an E_e vs I_e diagram with constant beam power values P drawn as diagonal lines. The plot includes three completed ERL facilities, the first European ERL facility ALICE at Daresbury, CEBAF (1-pass), which, with 1 GeV, reached the highest energy so far, and the JLab FEL, which reached the highest current, of 10 mA. Larger currents have been achieved in the normal-conducting, lower-frequency ERL facility at BINP (the Recuperator).

There are three currently operational superconducting ERL facilities (marked as 'ongoing' in dark green), S-DALINAC at Darmstadt, CBETA at Cornell and the compact ERL at KEK in Japan, to which we add as the fourth MESA at Mainz as this is not requiring additional resources from the roadmap process and expects to have beam in the not far future. These facilities, including that at Novosibirsk, all have important development plans as presented subsequently. There is no financial request to the roadmap here outlined, and yet, the development of the field of ERLs is based to a considerable extent on their progress, for which they have been introduced as part **A** of the ERL roadmap, see Sect. 6.1.

Four facilities in progress, two of which are in Europe, marked in dark blue on in Fig. 6.1, have complementary goals intending to reach higher energy in five turns (CEBAF 5-pass) or high current (bERLinPRO and the coherent electron cooler, CeC at the EIC), in a single pass. PERLE is designed for medium current (20 mA), 3-turn operation leading to 500 MeV beam energy. These new facilities are described in Sect. **??**. The two European projects, bERLinPRO at 100 mA and PERLE, constitute the core part **B** of the ERL roadmap subsequently presented.

Figure 6.1 also displays the parameters of the by now five design concepts for ERL applications at the energy frontier with electron beam energies between 50 GeV (LHeC) and 200 GeV (EXMP). CERC has a low current but a rather large number of beam lines. LHeC and FCC-eh are 3-turn linacs with about 20 mA current delivered by the gun but 120 mA load to their cavities. ERLC and EXMP are single pass linacs, with possibly twin-axis cavities. There follows a common demand on SC cavities to tolerate about 100 mA current load, which is the goal of PERLE (in three turns) and, in a single pass, of an upgraded bERLinPRO and the CeC at BNL in its most challenging configuration.

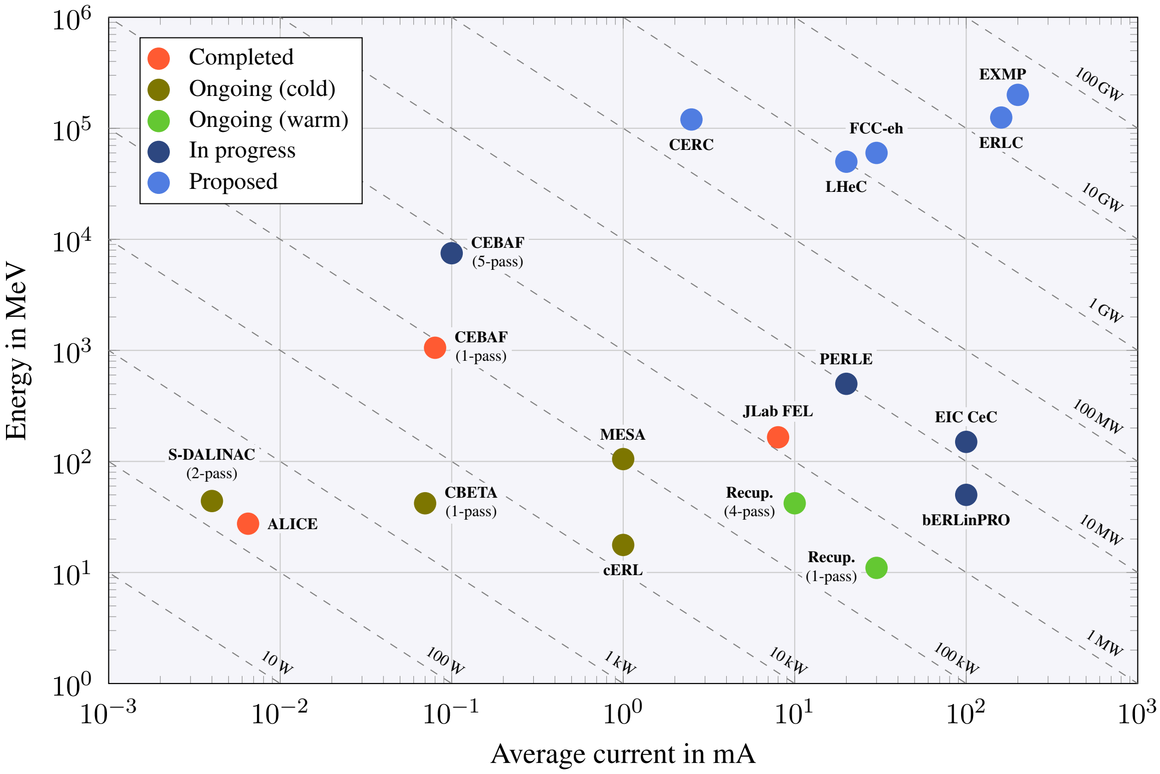

Fig. 6.1: Electron energy E vs. electron source current I for classes of past, present and possible future ERL facilities as are introduced in the text. Dashed diagonal lines are equi-power lines, $P = E \cdot I$. A brief account of the ERL history is presented in Sect. 6.2.1.

The $E - I$ graph provides an understanding of basic ERL facility characteristics. However, it does not display the collider luminosities or cryogenics power demands. From these, as is explained later in this summary, a vision arises of a 500 GeV cms energy electron-positron collider with the potential to reach 10^{36} cm^{-2} s^{-1}. Such a prospective version of ERLC, when based on warm (4.5 K) technology, would be power affordable and allow for a few % accurate test of the Higgs boson self-coupling in e^+e^-.

6.5.2 Recuperator BINP Novosibirsk

The Novosibirsk free electron laser (FEL) facility [37] includes three FELs [38] operating in the terahertz, far-, and mid- infrared spectral ranges. The first FEL of this facility has been operating for users of terahertz radiation since 2004. It remains the world's most powerful sources of coherent narrow-band radiation in its wavelength range (90 – 340 μm). The second FEL was commissioned in 2009. Now it operates in the range of 35 – 80 μm, but we plan to replace its undulator soon with a new variable-period one [39], and its short wavelength boundary will be shifted down to 15 μm. The average radiation power of the first and the second FELs is up to 0.5 kW and the peak power is about 1MW. The third FEL was commissioned in 2015 to cover the wavelength range of 5 – 20 μm, and provides average power about 100 W.

The Novosibirsk facility is the first multi-turn ERL in the world. Its peculiar features include the normal-conductive 180 MHz accelerating system, the electrostatic electron gun with the gridded thermionic cathode, three operation modes of the magnetic system, and a rather compact (6×40 m^2)

design.

The accelerator of Novosibirsk FEL has a rather complex design. One can consider it as three different ERLs that use the same injector and the same linac. The first ERL of the facility has only one orbit, the second and the third ones are two- and four-turn ERLs, respectively. The low RF frequency allows operation with long bunches and high currents.

The current of the Novosibirsk ERL is now limited by the electron gun. A new RF gun was built and tested recently [40]. It operates at a frequency of 90 MHz. An average beam current of more than 100 mA was achieved. In brief, the following work is planned for next years.

– Installation of the RF gun in the injector, while the existing electrostatic gun will be kept there. The RF gun beamline has already been manufactured and assembled on the test setup. It includes the RF chopper for the electrostatic gun beam.
– Continuation of routine operation with three FELs for users of the “Novosibirsk FEL" user facility.
– Optimisation of the optics for further reduction of beam loss at large energy spread induced by FEL operation.
– Optimisation of the optics for the reduction of beam loss at large emittance induced by the foil target for the bremsstrahlung radiation source. These experiments are aimed to create hard X-ray source with a few picosecond pulse duration and a few MHz repetition rate for users.
– Demonstration of the so-called electron outcoupling technique for the FEL oscillator at the third FEL [41].

6.5.3 S-DALINAC TU Darmstadt

The S-DALINAC is a superconducting multi-turn recirculating linear accelerator for electrons at TU Darmstadt [42]. It is used for scientific research and academic training in the fields of accelerator science, nuclear physics, nuclear astrophysics, and radiation science. The S-DALINAC employs eleven multi-cell niobium cavities for superconducting-radiofrequency (SRF) acceleration and operates at a frequency of 2.998 GHz. The SRF cavities have quality factors in excess of 10^9 at the operational temperature of 2 K and sustain field gradients of $4\breve{~}6$ MV/m. The S-DALINAC delivers a continuous-wave (CW) beam with electron bunches every 333 ps and a bunch length of about 1 ps.

The S-DALINAC has been put into operation in 1991. At the time, it consisted of a thermionic electron gun, a super-conducting injector linac, a main linac with two recirculations, and a suite of experimental beam lines. In 2015/16, the accelerator lattice has been extended by an additional recirculation beam line capable of operation in energy-recovery mode. The maximum beam energy after four passes of the electron beam through the main linac is 130 MeV. At this energy, the maximum beam current is technically and legally limited to 20 μA. The emittance of the electron beam amounts to < 1 mm mrad. The main accelerator consists of four cryomodules, each housing two 20-cell Niobium cavities. Any desired electron beam energy up to 130 MeV can be provided and delivered to the experimental hall by recirculating the beam up to three times through the main linac.

The ERL operation mode of the S-DALINAC has first been demonstrated in 2017 [43]. An energy-recovery effect of $90.1 \pm 0.3\%$ has been measured. It corresponds to the decrease of RF-power consumption due to beam loading of one of the main linac's RF cavities when the recirculated beam is decelerated in the cavity. This made S-DALINAC the first ERL operating in Germany.

In August 2021, S-DALINAC has been successfully operated in a twice-recirculating ERL mode. Full energy-recovery effects of up to 81.8 % had been measured for beam currents of up to 8 μA at a beam energy of 41 MeV. The beam load of the SRF cavities in the two situations - with either the beam accelerated only once or with the beam accelerated twice and decelerated once - resulted in the same beam-load within measurement uncertainties. The measurements, thus, indicate a complete energy-recovery in the first deceleration passage through the main linac with an efficiency of 100% within uncertainties.

Since the injection energy cannot be recovered in an ERL, and since a decrease of the injection energy by every single MeV reduces the power consumption of a 200 mA ERL with 5,000 hours of operation per year by 1 MkWh per year, each, it is worthwhile to improve the technology for low-energy injection ERLs for which relativistic phase slippage is largest. Main research topics at the currently address, therefore, the quantification of the phase-slippage effect in extended multi-cell SRF cavities and countermeasures for its mitigation including individual off-crest working points for various SRF cavities and individual phase advance to be made possible by multi-turn SRF ERLs with individual recirculation beam lines.

6.5.4 MESA Mainz

MESA is not only an accelerator project but will also become a facility for high intensity electron scattering experiments in the 100 MeV energy region [29, 44, 45]. It will represent a sustained infrastructure for such experiments but also be available for further research on ERLs for a long time to come. The civil construction for the new machine will be finalised in 2022. Following the installation and commissioning of the machine, first ERL tests are expected in 2025. External beam experiments are expected to start somewhat earlier. The ERL beam will be directed towards the so-called MAGIX experiment using a windowless gas target.

Radiation protection considerations call for a system of halo spoilers and collimators behind the MAGIX target. The unavoidable losses due to Coulomb scattering - the so called TArget Induced haLo, or TAIL for short - can therefore be mostly confined to a heavily shielded area which does not contain any sensitive components. The relative power losses in the ERL beam line are predicted to be below 10^{-5} of the beam power at the target when using the MAGIX hydrogen target with the nominal areal density. Therefore, a limit to the luminosity at 105 MeV under reasonable assumptions for radiation protection issues may be set to about $5 \times 10^{35}\,\mathrm{cm^{-2}s^{-1}}Z^{-2}$ with Z the nuclear charge of the target. This seems sufficient for the experiments that are presently discussed.

During the next years the project team will focus on the installation and commissioning of MESA. On the other hand, it will pursue accelerator research goals, specifically aiming at the following topics:

- **Improving electron beam polarimetry** in order to support the precision measurements of electroweak observables at MESA. This will include a chain of three polarimeters [**?**] which each will reach an accuracy well below $\Delta P/P < 1\%$, in some cases even below 0.5%. The chain will consist of two Mott polarimeters - both operating in the region of the source and the injector, respectively and the so-called Hydro-Möller polarimeter [**?**]. The latter will operate online and is based on a completely polarised electron target formed by trapped hydrogen atoms. With a target density of $\approx 3 \times 10^{16}\,\mathrm{cm^{-2}}$ it is suited for online operation but will also yield high statistical efficiency which will allow eliminating the slow drift of the polarisation of a few percent per week. More details can be found in [46]. The target will be incorporated in the external beam line leading to the electroweak P2-experiment. In the long run this beam line may be extended as a third recirculation in ERL mode.
- **Installing a second photo − source** at the MESA injector with the potential to provide bunch charges > 10 pC with good beam quality. The present source energy is operated at relatively low voltage because reliable operation parameters for the NEA-photocathodes are of utmost importance. The NEA-cathodes are mandatory for production of spin-polarised beam but do not tolerate field emission which is frequently associated with high voltages. Moreover, the spin-manipulation systems elongate the transfer beam line to the injector and create more complicated optics which is also detrimental for high bunch charges. However, according to simulations and experiments, an average current of 1 mA of MESA stage-1 can be produced with normalised emittance below $1\,\mu$ m which is sufficient for all presently planned experiments while limiting the available MESA

beam power in ERL mode to 100 kW. To enter the Megawatt regime, a second source will be installed which is dedicated for experiments not requiring spin-polarised beam. Due to the normal conducting injector system of MESA, the input energy can be changed with moderate effort. Simulations indicate that increasing the source energy to 200 keV will allow to have good beam quality with bunch charges exceeding 10 pC creating a nice test bed for experiments, e.g. dedicated to compensation studies of transient beam loading, ion trapping, Compton backscattering and others.

- **Improving the cavity higher − order mode damping** capabilities. At high average currents, HOM heating of the damping antennas will lead to superconductivity breakdown in the antenna and hence inhibit operation. This can be improved by coating the HOM antennas by layers of material with a high critical temperature, e.g. Nb_3Sn. The MESA research group has recently received funding to start corresponding investigations within a larger joint effort of German universities.

6.5.5 cERL KEK Tokyo

This is the essence (20.10.)- being updated

The compact ERL is a facility at KEK. Its future plans can be summarised as follows:

- R&Ds of 10kW class powerful ERL-based EUV-FEL are focused in realizing a high-intensity EUV light source for EUV lithography for semiconductor microfabrication. We are challenging a 10kW class EUV light source that surpasses the existing LPP (up to 250 W) by more than 40 times. Core accelerator technology development includes: high-efficiency superconducting cavity accelerator, and energy recovery type linac (ERL).
- Realization of a 100% energy recovery operation with the beam current of 10mA at cERL and FEL light production experiment.
- Development of the irradiation line for industrial application (CNF, polymers and asphalt production) based on the CW cERL operation.
- Realization of a high efficiency high gradient Nb3Sn acceleration cavity to produce a superconducting cryomodule based on the compact freezer. We are targeting a general-purpose compact superconducting accelerator system that that can be operated at universities, companies, hospitals, etc.

6.5.6 CBETA Cornell

Georg: to extend

- Improve transmission, which includes investigating better optics solutions;
- Developing improved diagnostics for the decelerating passes;
- Reducing halo by using a low-halo cathode, possibly in conjunction with beam collimation.

6.6 R&D objectives - Key technologies - ERL Roadmap Part B

ERL technology has much developed over the past decades. For reaching a new level of high electron currents and energy in calm, efficient well monitored ERL beam operation, for reducing the cost and cryogenics load and thus the power consumption, especially at big machines such as the ERLC, a number of key technologies have been identified which are introduced below. More information is given in the accompanying ERL overview paper [2]. Most of the topics described here lead to requirements on funding and effort which are summarised in the subsequent section 6.8, often appearing as part of new facility charts. This concerns, for example, the source developments, as upgrades of existing SRF and DC photocathode sources in Berlin and Orsay, respectively, or the establishment of the goal to develop a 4.4 K 802 MHz cavity-cryomodule for beam test with PERLE in about a decade hence.

6.6.1 High Current Electron Sources

Injectors for high-energy physics ERLs, which require high average current in combination with complicated temporal beam structure, are typically based on photocathode guns. These guns rely on photocathodes, e.g., semiconductor materials, which for high average current are based on (multi)alkali antimonides, or GaAs-based systems for polarised beams, in combination with a photocathode drive laser and extremely-high-vacuum accelerating structure.

The quality of the photocathode is relevant for the performance of the photoinjector in terms of emittance and current, and a long photocathode lifetime is essential for photo-injector operation. Reproducible growth procedures have been developed and months-long lifetimes under operational conditions have been achieved. For high-current operation, photocathodes with high quantum efficiency are necessary and are usually developed in-house. Quantum efficiencies above 10 % at the desired laser wavelength have been achieved in the laboratory.

One critical aspect is to preserve demanding vacuum conditions ($< 10^{-10}$ mbar) on the whole way from the preparation system, via the complete transfer line to the photo-injector and the photocathode gun itself. The photocathode substrates (usually made from molybdenum) are optimised regarding their cleanliness and surface finish (< 10 nm rms surface roughness) to achieve low emittance and to avoid field emission.

Especially in SRF photoinjectors, the superconducting cavity is extremely sensitive to any kind of contamination; therefore, the photocathode exchange process is very critical.

For weak interaction physics experiments, polarised electron beams are needed. These can be based on GaAs photocathodes, but their lifetime has still to be improved, e.g., by using newly developed activation processes.

Ongoing research topics in the field of photocathodes are the understanding of the photocathode materials (e.g., electronic properties), the photoemission process, and their intrinsic emittance. New growth procedures of high quantum efficiency, smooth, mono-crystalline photocathodes or multi-layer systems, and the screening of new photocathode materials are crucial for future electron accelerators.

A main research topic in the field of gun development relies on design of accelerator structure, which can provide a high cathode field in combination with extra-high vacuum conditions. Major efforts are concentrated on development of DC guns (Cornell University), VHF NCRF (LBNL), and lower- (BNL) and high-frequency SRF guns (bERLinPRO). Important insight can be gained from operating smaller facilities with high-current thermionic guns (BINP).

In brief, the field of laser systems for electron injectors, the technology of lasers with sufficient power to operate with antimonide-based photocathodes has been rather well developed. Major efforts are concentrated on the generation of laser pulses with elliptical temporal profile, which are necessary to deliver high charge bunches with ultra-low emittance.

6.6.2 SRF Technology and the 4.4 K Perspective

Near Term 2 K Developments

Superconducting RF is the key technology for energy-efficient ERLs. A vibrant global R&D program has aptly demonstrated the routine operation of SRF systems in many large-scale accelerators. This is described in much detail in the accompanying ERL overview paper [**?**]. Future developments must now push the technology to meet the stringent demands of next-generation ERLs while making strides in improving further the energy sustainability of the systems.

The focus for the linear e^+e^- collider has been the high accelerating gradient, achievable in pulsed operation. CW ERLs, however, must handle very high beam currents. Simultaneously, they must balance the requirement for high cryogenic efficiency and beam availability, with the need for a reasonably compact and cost-efficient design. This leads to a different optimisation, frequency lower than 1 GHZ and lower gradients. Presently, operation at moderate gradients (below or near to 20 MV/m) provides the best compromise between these competing requirements.

Critical ERL SRF system developments must now focus on

- system designs compatible with high beam currents and the associated HOM excitation,
- handling of transients and microphonic detuning that otherwise require a large RF overhead to maintain RF stability,
- enhanced cryogenic efficiency of SRF modules.

To ensure beam stability in future ERLs operating with currents of $\mathcal{O}(100\,\text{mA})$, requires cavity designs and systems that minimise both the excitation and trapping of higher-order modes, facilitate HOM extraction and enables their efficient damping outside of the helium bath. Low-frequency cavities (<1 GHz) are typically favoured, having fewer cells to provide the same voltage and larger apertures. HOM damper solutions include space-efficient waveguide-coupled absorbers with high power capability or more readily implemented beam line absorbers between cavities. The ultimate efficacy of solutions must be put to the test in beam test facilities.

Towards 4.4 K

A significant power consumption of ERLs is related to the dynamic cavity load in CW operation which can be estimated by

$$P = \frac{V_{acc}^2}{(R/Q) \cdot Q_0} \cdot N_{cav} \cdot \eta_T \tag{6.1}$$

where V_{acc} is the acceleration of a cavity, R/Q the shunt impedance, Q_0 the cavity quality factor, N_{cav} the number of cavities and η_T the heat transfer (Carnot) efficiency which is proportional to the ratio of the cryo temperature, T, and its difference to room temperature, $300 - T$. This power has to be provided externally. For the LHeC it is about 15 MW for T=1.8 K. A 500 GeV e^+e^- collider, however, with 10-20 times more cavities ($N_{cav} = O(10^4)$) than at LHeC, requires a few hundred MW power. This can be significantly reduced by a factor of about three with 4.4 K technology, for similar V_{acc} and Q_0 characteristics. The overriding request to limit HEP power consumption by building sustainable high energy accelerators in the future motivates a strong interest in 4.4 K developments. These have the additional important benefit of bringing SRF technology developments into University and smaller laboratory environments with a beneficial impact on their industrialisation for next generation colliders as has been emphasised in the e^+e^- sub-Panel report, see Sect. 6.3.

State-of-the-art Niobium has the highest critical temperature of all elements (9.2 K). For a reasonable BCS resistance in the 1 GHz frequency range, it must be cooled to 2 K to attain quality factors of order $Q_0 = 3 \cdot 10^{10}$. However, given Carnot and technical efficiencies of less than 0.7% and 20%, respectively, the overall efficiency of the cryoplant is only around 0.13%. Furthermore, complex cold compressors must be employed for sub-atmospheric liquid Helium operation. Operation at 4.4 K or above is mandatory to limit the required power with an increase of the Carnot efficiency. This operating mode also reduces the complexity of the cryoplant design. For low-energy accelerator applications such as industrial and medical systems, 4.4 K operation even carries the potential of eliminating the cryoplant altogether in favour of cryo-coolers, thereby removing a large financial and technical hurdle for the implementation of such systems.

For Niobium at ~ 1 GHz, operation at 4.4 K is no option because the efficiency gains are completely negated by an intolerable increase in BCS resistance, with Q_0 values of about 10^8, see Eq. 6.1). One therefore must revert to compound materials that, due to their physical properties, need to be coated on a substrate, options including Nb_3Sn, NbN, NbTiN, V_3Si, Mo_3Re and MgB_2. So far, only the first three have been explored reasonably extensively. While Q_0 values $\geq 10^{10}$ at 4.4 K are predicted, imperfect films suffer heavily from early flux penetration which currently limits the accelerating field values to values considerably below 20 MV/m. An approach to safeguard against this is to implement a multilayer S'-I-S structure consisting of a sub-micron thick high-temperature superconductor (S') on a nm-thick insulator (I) on a thick Nb substrate (S), as proposed by Alexander Gurevich.

There are two major technologies under development, a vapour infusion technique, mainly in the US [47] and ramping up in Japan, and sputtering with advances in Europe. A third one is atomic layer deposition with possibly good prospects towards 4.4 K based cavity systems. These basic technologies are followed in this roadmap by the SRF panel and may only briefly characterised below. A goal for future ERL applications, a decade hence, is the development of a complete cavity cryo-module and its test in a beam for which PERLE at 802 MHz is considered a suitable long-term option or possibly bERLinPRO depending on the frequency choice and how this field develops altogether.

** The following three technology paragraphs may finally move to the SRF roadmap
Nb_3Sn by Vapour Infusion So far, only Nb_3Sn by high-temperature Sn vapour infusion of a Niobium substrate has been successfully applied to cavities. This method has achieved Q_0 values above 10^{10} at 20 MV/m and frequencies above 650 MHz [Posen Paper] for single-cell cavities. For 9-cell, 1.3 GHz cavities, maximum fields of order 15 MV/m have been achieved. First attempts to produce structures for cryomodules have been limited to a few MV/m, but the effort so far has been very limited. The main challenges are (a) to develop infusion recipes that consistently deliver the correct Nb_3Sn stoichiometry for high-field operation, (b) extend these recipes to large, complex multicell structures and (c) subsequently design cryomodules that are able maintain the performance, despite the fact that Nb_3Sn systems are very sensitive to trapped flux, thermo-current generation during cooldown and cracked due to Nb_3Sn's extreme brittleness. In parallel, an active microphonics compensation system must be included to handle the larger pressure fluctuations at 1 bar, 4.4 K operation. Nb_3Sn vapour infusion activities are ongoing in the USA and ramping up in Japan. At present, only this technique appears in line with the desirable realisation of a 4.4 K accelerating module in the next decade. Yet, vapour infusion is not compatible with other substrates, in particular Copper, and it may not be adapted to other superconductors or used in multilayer systems.

Sputtering Techniques To address the limitations of vapour infusion, sputtering techniques, such as HiPIMS are being investigated. At the forefront are CERN and the European IFAST collaboration. Samples have achieved encouraging results, but first single cell (1.3 GHz) cavities are not expected before in a few years. Sputtering enables more precise control of material stoichiometry and it is able to synthesize a wide variety of superconductors on various substrates (including Copper). Being a "line-of-sight" method, its difficulty lies in coating complex 3D structures whose orientation to the cathode vary along the structure. Film quality and thickness both are thus geometry dependent. This may indeed complicate the production of cavities with multilayer structures.

Atomic Layer Deposition Atomic Layer Deposition (ALD) is a third technique that is very promising, but it currently is further behind than sputtering. The main research activities are ongoing in France. Inherently, the deposition is a self-limiting process with thickness control at the atomic level. Coating does not require line-of-sight to the substrate and thus in principle complex structures can be coated without the difficulties encountered with sputtering. However, coating rates are very low, of order 1 nm per minute (confirm numbers!). Unfortunately, ALD is not compatible with state-of-the-art Nb_3Sn. However, it can be used to coat materials such as NbN, NbTiN and MgB_2. Given its near perfect thickness control, it is well suited for the implementation of multilayer structures. Thus, its long-term potential for high-performance 4.4 K (and above) systems is likely to be greater than that of both the vapour infusion and sputtering techniques.

6.6.3 Fast Reactive Tuners

Since the accelerated and the decelerated beam are of equal size but in opposite phase of the operating RF, the total beam loading current in an ERL is nominally zero. For this reason, the RF power fed into the cavity in steady state can ideally be very small. However, to cope with beam transients and microphonics, strong overcoupling is called for. This overcoupling leads to a lowered external Q and thus significantly higher power requirements. Most of the power is reflected and dumped. A side effect is that the RF stability and hence beam stability also suffers.

A very fast tuner, fast enough to cope with microphonics and beam current transients, would allow operation with larger external Q and thus much reduced RF power. Recent developments and tests with so-called "Fast Reactive Tuners" show very promising results. They use piezo-electric material referred to as BST ($BaTiO_3$-$SrTiO_3$), the ε of which can be modified with a bias voltage. The suitability and longevity of these novel FRTs with full SRF systems without and with beam must be demonstrated to capitalize on their enormous potential. It is planned to validate the approach to use FRTs to compensate for transients and microphonics installing suitable prototypes, in collaboration with CERN, on cavities for BERLinPro (1.3 GHz, single turn) and for PERLE (802 MHz, three turns) to thoroughly investigate the use of this technology in ERL beams.

6.6.4 Monitoring and Beam Instrumentation

Motivation

Electron beam diagnostics and metrology systems at ERLs have unique tasks and challenges. First of all, these arise from ERLs combination of the very high average beam power (similar to synchrotrons) and the non-equilibrium (non-Gaussian) nature of linac's beams with small transverse and longitudinal emittances (similar to the high brightness linacs). Second, ERLs must operate with multiple beams of different beam energies transported in a beam-line. The experience of successfully operational ERLs shows that different, well-thought-through beam modes are indispensable. These serve for the machine setup, average current (power) ramp-up, and high power operation. The difference in the average beam current between the tune-up mode and the high-power more is typically 4 to 5 orders of magnitude. It will be even more significant for higher average beam power ERL systems. One more lesson of present and previously operational ERLs, and recirculating linacs is that local beam losses with an average power of about 1 W are an issue that cannot be ignored. Comparing this beam loss power level with the average beam power of 1 to 10 MW and the difference in the average beam current of the tune-up and high power modes shows the necessity of high-dynamics range beam measurements.

Critical open issues

Operational experience of the ERLs, which ran with the highest average beam power so far (1.2 MW at IR-Upgrade, at Jefferson Lab), showed that beam halo, which is a fraction of the phase-space distribution with large amplitude and small intensity, was one of the critical operational issues. The dynamic range of transverse beam profile measurements that are standard now and were used at IR-Upgrade are about 1e+3. Such measurements are made with the tune-up beam mode with the very low average beam current. Then some small intensity - large-amplitude parts of the beam, were essentially invisible for the measurements. However, in the high current mode would contribute to limits of the facility in terms of practically possible average current. If this remains unchanged, the average beam current and power at the next generation of ERLs, which should operate with 10 MW beam power, might become limited well below the design value. Moreover, the transverse beam optics setup at PERLE with six arcs, 5 of which will need to operate with two beams simultaneously, and with 3-pass acceleration and 3-pass deceleration could prove to be far more complex than this of IR-Upgrade. Thus, transverse beam profile measurements with a dynamic range far beyond 1e+3 appear to be mandatory for the next generation of ERLs.

Having two beams in one beam-line not only complicates the beam optics setup but also presents the beam diagnostics with an additional problem. When standard, invasive (intercepting) beam profile measurements are used, the beam is intercepted on the first pass. A beam viewer, which is as thin as practically possible, does not stop the beam but does cause enough multiple Coulomb scattering, such that when the beam arrives at the same location on the second, decelerating pass, its phase-space and the transverse profile are increased far beyond its original sizes. Although beam viewers allow preferred 2D beam profile measurements, they present a very serious problem for the second pass beam profile measurements. Thus either completely non-invasive or much less invasive methods must be considered.

To preserve the small transverse emittance, precise measurements and setup of the lattice functions will be needed. The well-established approach to such measurements is the differential orbit measurement made with the help of a beam position monitor (BPM) system. Here having multiple beams in a beam-line presents another challenge - implementing a BPM system, which could measure the position of multiple beams independently. Moreover, the BPM system will need to be used in the tune-up mode and the high current mode with CW beam so that the beam orbit and lattice functions stability can be ensured. The following strategy for beam diagnostics at ERLs has proven to be necessary and very productive. First, there needs to be a set of beam diagnostics, which allows detailed measurements of all physics relevant beam parameters when operating in the tune-up mode. Then there also must be a set of non-invasive measurements systems, which would allow monitoring for changes of beam parameters beyond the tune-up mode, i.e., during the current ramp-up and high power operation. The second set of monitors is not required to provide absolute measurements, as the first set of diagnostics used in the tune-up mode, but is required to work essentially in all beam modes, thus making a bridge between the tune-up and high current modes. From this strategy perspective, some of the necessary transverse beam profile monitors are missing. These are relevant to the transverse match and emittance preservation. Practically, only synchrotron radiation (SR) monitors are available for transverse beam size monitoring with high beam currents. The beam size monitoring in the ERL injector, where initial beam quality (emittance) is defined, is not possible.

For the efficient energy recovering and maintenance of stable beam energy and energy spread, beam arrival to an ERL's linacs must be set up and monitored precisely. At PERLE, with six beams simultaneously in each linac at a very high repetition rate, this presents another challenge. The beam arrival measurements system would need to work in all beam modes and have the resolution at least ps or better. Beam arrival measurements with such characteristics were not demonstrated so far and needed to be developed and implemented.

Necessary Developments

Based on the above description of the critical open issues. We propose that the following advanced beam diagnostic systems must be developed for the next generation of ERLs.

1. An advanced wire-scanner system needs to be developed, tested, and then implemented at PERLE for routine transverse beam profile measurements with the dynamic range of 1e+6. Most of the wire scanners implemented so far provide 2 or 3 projections of the transverse beam distribution. Often, when measuring non-equilibrial linac beams, the wire scanner measurements are inferior to beam viewer images. However, wire-scanner measurements provide much easier access to the LDR data. The number of measured projections could be relatively easily increased with different mechanical implementation. Recent developments in the tomographic reconstruction techniques show that a 2D distribution can be reconstructed well based on about 9 - 10 projections. The proposed advanced wire-scanner system is envisioned to take advantage of this recent development and provide topographically reconstructed 2D beam distributions. Moreover, wire-scanner measurements can be made with the help of detectors with a bandwidth much larger than the beam repetition rate. This makes it possible to set up the system to

measure beam profiles of multiple passes simultaneously. This will also be helped by the fact that the wire-scanner intercepts only a small fraction of the beam at any given time. Last but not least, if the wire moving speed can be made fast enough and the beam size is not extremely small, there is the potential that the wire-scanners will be able to operate with a high current CW beam.

2. Taking into account that beam imaging with the help of beam viewers or with SR frequently provides data superior to wire-scanners, we suggest that an optical system that mitigates diffraction effects to allow imaging with the dynamic range of 1e+6 needs to be investigated and tested in a laboratory. Then if successful, it should be tested with a beam.

3. BPM system capable of measurements with multiple beams needs to be prepared. Here one prototype unit needs to be developed and built first. Then it is suggested that it can be tested with a beam at one of the existing synchrotrons operating with the repetition rate of a few 100 MHz, thus simulating conditions very similar to the next generation of ERLs.

4. It appears that a 6-pass beam arrival monitor system will be indispensable for the operation of PERLE-like facilities. We suggest that such a system needs to be designed, prototyped, and tested in preparation for PERLE operation. The best candidate technology for such a system, at this point, appears to be a system based on very high bandwidth non-resonant pickups, an electro-optical modulator, and an ultrafast laser system with a sufficiently high repetition rate.

5. Dependent on available resources and human resources, it would be prudent to start work on a non-invasive beam size monitor for beams at low (injector-like) 5 to 10 MeV energies, where SR cannot be used. Here a physics design would be a good next step. A technique that could allow such measurements can use very low energy (50-100 keV), very low charge, short pulse probe electron beam. Similar probe-beam-based systems were implemented and tested previously. However, they operated either not with short pulses or were based on very sensitive photo-cathodes, which might not be very practical for a routinely operational diagnostic system. Here additional efforts are needed to simplify such systems to make them practical.

6.6.5 Simulation and Education

The design, construction and operation of ERL facilities have to be accompanied and prepared by reliable and detailed simulations. These require much experience and insight in the ERL beam physics and technology, from optimising guns through the injector, main loop onto the beam dump. Increasing beam brightness and energy requirements have to be met with advancements of simulation techniques using considerable CPU power. One can list a few specific beam dynamics studies related to ERLs:

- Study of CSR leading to microbunching and ultimately to beam quality degradation and emittance dilution. Simulations are instrumental in developing mitigation measures to suppress microbunching through appropriate lattice design. They are especially critical during the deceleration process, where the energy spread increases rapidly as the energy drops.
- Studies of wake fields and beam breakup (BBU) instability for multi-turn ERLs operating in CW mode, also addressing a long-standing question of BBU threshold scaling with the number of passes.
- Study of the longitudinal match to compress and decompress the electron bunch in order to optimise beam transport in energy-recovery mode. Implementation of second-order corrections to eliminate the curvature from the compressed bunch to further improve the longitudinal match without compromising the ability to transport the bunch in the decelerating passes.
- Collaborative efforts with BERLinPro on using OPAL package as a universal tool for simulating ERL beam-lines; starting from the cathode, through space-charge dominated regions of initial acceleration and beyond into high energy sections. Having one single tracking tool (vs. many) eliminates uncertainty of seamless transition at code junctions.

The above selection of beam dynamics studies illustrates that the ERL accelerator technology represents a challenging training ground for a next generation of accelerator scientists. Many of these topics are dealt with in PhD theses, and all of the facility centres (and beyond) are engaged in forming and educating accelerator talents. The tasks to be solved are far from conventional, and the rather short time scales for building smaller facilities a plus in the attraction of young physicists.

6.6.6 Higher Order Mode damping at high Temperature

ERLs operate at high current and hence the HOM power produced can be very high. Depositing the heat load in the cold mass would generate too much heat and hence the power must be extracted and deposited at room temperature loads. HOM couplers come in two main types, coaxial and waveguide. Coaxial are normally associated with low powers however the HOM couplers for the HL-LHC crabs were designed to handle up to 1 kW per coupler. Coaxial couplers are small and hence have a lower static heat load. Waveguide couplers are typically used for high powers but have a larger static heat load as it's a large metal link from room temperature to the cavity.

The design of HOM couplers must be multidisciplinary balancing both RF and mechanical (thermal) requirements, as well as balancing dynamic and static heat loads. The HOM powers and thermal budgets for the cryomodule must first be understood, as well as the impedance specification that must be reached. The lower the impedance specification the more heating on the coupler interface.

Fundamental power couplers can handle much higher powers than HOM couplers hence the HOM couplers may need to be designed using similar methodology. Conditioning HOM couplers to operate at high power is also an area where research is required.

It may be necessary to mount the HOM couplers directly on to the RF cell, so called on-cell couplers. Such concepts are common in low-beta and crab cavities but there are only a few examples for elliptical cells. One option could be the split SWELL cavities proposed for FCC where the cavity is made in 4 quarters with waveguides between each quarter.

In addition its critical that the frequencies above the beampipe cut-off are attenuated at warm and not inside the cryogenic environment. Losses in superconducting materials increase with frequency squared hence the attenuation at high frequencies can be very high. Beamline absorbers at no less than 50 K are required to efficiently remove the radiation without helium boil off.

Main Challenges are: High power operation of HOM couplers with acceptable static loss; Multipactor absorbing RF power; Coupling with strong coupling; High power windows; Conditioning of HOM couplers; Development of on-cell coupling for elliptical cavities; Modelling of high frequency wakefield. Effort and timeline are provided in Sect. 6.8.

6.6.7 SC Twin Cavities and Cryomodules

Twin axis cavities are required when the accelerating and decelerating beams are traveling in opposite directions through long linacs. There is one example of a single axis cavity being used for beams in opposite directions [Ref 8.2.4.1], but this is accelerating the beam in both directions to attain higher beam power, rather than recovering the energy. There are four examples of twin axis cavities that have been considered. The first design [1] was a purely theoretical calculation as part of a proposal to build a dual axis energy recovery linac. The second [2] was also a purely theoretical design involving two Tesla-style 9-cell cavities that were partially superposed to create a twin axis cavity. While this concept was interesting, construction of such a cavity would appear to be difficult, if not impossible. The third design [3] consisted of two three-cell cavities joined by a bridge at the power coupler end. A prototype carved out of a solid block of aluminium was built and the expected performance was demonstrated (Figure 1). The advantage of this design is that the accelerating and decelerating cavities do not have to be identical so that the cavities can be designed so that the higher order modes do not overlap. This extends the threshold for transverse beam break-up by a factor two (which is not negligeable in the context of high current beams). The fourth design [4] was a single cavity with two beam tubes for the accelerating and decelerating beams. The advantages of this design are that the largest overall transverse dimension is lower than the second design and the power is recovered in each cell, rather than being summed over all the cells and transferred via a bridge. A single cell prototype was built in niobium (Figure 2) and tested at cryogenic temperatures with excellent results. However, this was a single cell without the necessary power and HOM couplers, etc. In the last two designs, the placement of the power and HOM couplers was calculated, but not prototyped. In addition, the tuning mechanism would need to be developed for both designs. Given the advantages of this design in various accelerator projects, the two designs should be carried forward until it is possible to make an evaluation of the relative performance of full-scale prototypes, so that a selection can be made. An important part of the selection process would be the integration into a cryostat. Both designs are wider than single axis cavities, so packaging in a cryostat means starting from scratch. The HOM damping is important, with the power brought out to room temperature. This requires space in the cryomodule and must be integrated into the cryostat design from the beginning. Another integration detail is how adjacent cryomodules are connected as there are two independent beampipes that must be connected, and given the close spacing of the two beampipes (required to minimize the cryostat dimensions) the flange connections will require particular attention.

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6.7 New facilities - Roadmap Part C

The panel is convinced that ERLs represent a unique, high-luminosity, green accelerator concept: for energy-frontier HEP colliders, for major developments in lower-energy particle and nuclear physics and industrial applications, altogether an innovative area with far-reaching impacts on science and society. With strongly enhanced performance, achieved with power economy and beam dumps at injection energy, ERLs are a most remarkable, vital contribution to the development of a sustainable science.

A peculiarity of the ERL roadmap and development is that it needs operational facilities with complementary parameters and tasks to be successful. The global landscape of ongoing ERL facilities, including SDALINAC and soon MESA in Europe, which are under further development, is rich, as has been outlined in Sect. 6.5.

A crucial next step towards the application of ERLs in high energy physics and elsewhere is to conquer the O(10) MW power regime with higher energy or/and high currents. This step requires to solve key technology challenges, described in section **??**, in particular for bright electron sources, dedicated ERL cavity and cryomodule technology ($Q_0 > 10^{10}$) as well as associated techniques. These technologies are partially available and under development for timely application and test in the existing and a forthcoming generation of ERL facilities.

The regime of high currents, in the range of 100 mA load to SC cavities, will be developed at BNL (EIC cooler CeC), KEK (cERL) and possibly HZB Berlin (bERLinPRO), and BINP Novosibirsk with normal-conducting, low-frequency RF. An order of magnitude increase in beam energy, to 10 GeV, is the goal of a new experiment at CEBAF. PERLE is the only facility designed to operate at 10 MW in a multi-turn configuration and the only one proceeding in a large international collaboration.

6.7.1 New facilities in the US

High energy with CEBAF 5-pass at Thomas Jefferson Laboratory

Based on the large experience at Jefferson Lab, a novel project has been approved, which has the target to study an ERL at highest energy, chosen to be about 7.5 GeV, where the effects of synchrotron radiation on beam dynamics will notably occur. The limiting factor for ER@CEBAF with 5 passes is the arc momentum acceptance, which places a bound on the maximum energy gain one can support in the linacs. Above that energy gain, the synchrotron radiation energy losses are sufficiently large that the energy separation between accelerated and decelerated beams exceeds momentum acceptance of the arcs. Energy recovery would be made feasible in CEBAF by the addition of two modest hardware sections: a path-length delay chicane insertion at the start of the highest energy arc, and a low-power dump line at the end of the South Linac, before the first West spreader dipole magnet. These alterations are designed to remain in place permanently, and do not interfere with any capability of routine CEBAF 12 GeV operations. For the coming years, the project has the following plans, also in collaboration with STFC Daresbury, University of Lancaster and University of Brussels:

1. Engineering design for a half-lambda delay chicane;
2. Installation of dipoles for the delay chicane and the extraction dump;
3. Continue ongoing beam dynamics studies, including:
- Increasing momentum acceptance through adequate choice of RF phase and arc path length;
- Optimisation of the second-order momentum compaction in recirculating arcs to eliminate curvature from the compressed bunches without compromising beam transport for the decelerating passes;
4. Finalise the optics design, including sextupoles.

CEBAF5 is expected to begin beam operation in 2024. For the roadmap this experiment is of special relevance as it will reach high enough energies for the beam based study of significant effects of coherent synchrotron radiation in an ERL.

Electron Cooler at Brookhaven Nation Lab

The Electron-Ion Collider (EIC) is layed out as a ring-ring electron-hadron collider. Its luminosity, in order to reach O(10^{34}) cm^{-2}s^{-1} at its optimum energy of about 100 GeV in the cms, requires that the phase space of the RHIC hadron beam is reduced for which the technique of Coherent Electron Cooling (CeC), proposed a decade ago [48], has been chosen. Coherent Electron Cooling is a novel but untested technique which uses an electron beam to perform all functions of a stochastic cooler: the pick-up, the amplifier, and the kicker. Electron cooling of hadron beams at the EIC top energy requires a 150 MeV electron beam with about 100 mA electron current, i.e. an average power of 15 MW or even higher. This task is a natural fit for an ERL driver, while being out of reach for DC accelerators. Currently, BNL is developing two CeC designs. The first one is based on a conventional multi-chicane microbunching amplifier which requires a modification of the RHIC accelerator to separate the electron and hadron beams. It uses a 0.4 MeV DC gun and a single pass ERL. Alternatively, the second CeC design is based on a plasma-cascade microbunching amplifier, which uses a 1.5 MeV DC gun and a 3-pass ERL. Both CeC designs therefore require an ERL operating with parameters beyond the state of the art. This development, albeit involving more challenges than those posed by the ERLs, is of complementary value for other ERL developments for the chosen parameter range such as the 100 mA current. A decision on the CeC development is foreseen as part of the CD2 project phase.

6.7.2 bERLinPRO

Within the scope of the Berlin Energy Recovery Linac Project, a 50MeV ERL facility has been set up at the Helmholtz-Zentrum Berlin. The beam transport system and all necessary technical infrastructure for 100 mA operation are complete, the single-turn racetrack is closed and under ultra-high vacuum. In straight continuation of the gun, the ‘diagnostics line’ offers equipment for extensive gun characterisation. The machine is built in an underground bunker, able to handle up to 30 kW continuous beam loss at 50 MeV. An overview on bERLinPRO can be see in Fig. 6.2

Fig. 6.2: Left: Structure of bERLinPRO, which is essentially complete apart from the 1.3 GHz linac module and the (upgraded) gun, the main hardware elements of the roadmap for bERLinPRO; Right: View from the dump position on the injector (at the back) and first racetrack part (June 2021).

In 2022, the injection line will be supplemented with the initial high-current SRF gun, delivering up to 10 mA with an emittance better than 1 mm mrad. The in-house cathode development successfully produces CsK_2Sb-cathodes with quantum efficiencies QE >1 %, necessary to extract 77 pC bunch charge. Three pairs of newly developed high-power couplers were successfully tested and reached record values of 60 kW CW (administrative limit), sufficient to accelerate up to 50 mA in the booster. The assembly of the existing booster parts will take place in 2022 and commissioning of the booster is planned for 2023.

Table 6.1 specifies the existing hardware and the goal parameters of bERLinPro and compares them to the PERLE project. The table reveals, that bERLinPro is eminently suited to help take the necessary next steps towards the technological developments enabling future ERLs for HEP. As bERLinPro is expected to be ready for use in late 2022 it could conduct preparatory experiments supporting the PERLE development too. Both facilities test current loads of order 100 mA to the cavities which in the case of PERLE result from three-pass operation. In its final phase, PERLE will operate at ten times the energy, 500 MeV, compared to the bERLinPRO facility.

It is quite useful for future applications and this roadmap that the two facilities chose different gun technologies, SRF and DC photocathodes. There is no further emphasis put on bright gun developments in this European Roadmap because this is quite an active field worldwide, which the plans of MESA (Mainz) the Recuperator (Novosibirsk), the CeC (BNL) and cERL (KEK) underline. The challenges posed by high current sources and associated lasers have been sketched above (cf Sect. 6.6).

bERLinPro takes up the cause of developing the first high current SRF gun while PERLE is about to re-install the ALICE DC gun with optimised cathode shape. The SRF gun technology holds the promise of high cathode fields and CW operation, overcoming space charge and heat load problems. Although the RF frequencies are different in the two projects, the 50 MHz laser available at bERLinPro could provide a bunch spacing of 20 ns which is close to the 25 ns value chosen for PERLE owing to the LHC operation frequency.

The achievable bunch charge in bERLinPro strongly depends on the QE of the photocathode. The available laser power is chosen such, that 1 % QE would still be sufficient to achieve close to 100 mA at 77 pC. Successful photocathodes reach QE of 10 % and above. More research is needed to learn how to reliably preserve these high values from the production over the transport and during operation. Furthermore, Na-based photocathodes, that are less sensitive to vacuum conditions, are a promising new

parameters	bERLinPro	PERLE
gun related		
gun type	SRF photocathode	DC photocathode
cathode material	CsK_2Sb	
bunch charge [pC]	77	500
norm. emittance [mm mrad]	<1	6
gun exit energy [MeV]	2.4	0.
laser frequency [MHz]	50/1300	40
injector related		
injection energy [MeV]	7	7
merger	dogleg	dogleg
RF related		
RF frequency [MHz]	1300	801.58
bunch spacing [ns]	20/0.77	25
bunch spacing [MHz]	50/1300	40
average current [mA]	4/100	20
linac related		
modules	1 x SRF	2 x SRF
duty factor	CW	CW
energy gain/linac [MeV]	43	82
no. cavity	3	4
no. cells / cavity	7	5
av. accelerating field [MeV]	18	20
HOM absorber	wave guide/ beam tube	
tuner	mechanical/FRT	
no. of turns	1	3
final beam		
electron beam energy [MeV]	50	500
bunch length [mm]	0.6	3
norm. emittance at IP [mm mrad]		

Table 6.1: Comparison of facility characteristics for bERLinPro and PERLE. High current operation, tested at both facilities in complementary configurations, is essential for application of the ERL technique to future energy frontier colliders.

area of research, that could well be carried out by the HZB cathode development group. Enhanced cathode research could boost the bunch charge of the bERLinPro SRF gun towards a few hundred pC. The current gun set up allows maximum currents of 10 mA, the diagnostic line beam dump up to 30 kW. Depending on the laser repetition rate and the cathode QE, different bunch scenarios can be tested. The current limit of 10 mA is set by the fundamental power coupler.

A 1.3 GHz linac module with three 7-cell cavities is foreseen to accelerate the bunches to 50 MeV in bERLinPro. A new design for a linac with wave-guide HOM absorbers and mechanical tuners is ready for construction. However, one may consider adapting a proven, lower-risk design (such as the Cornell LINAC module), incorporating beam tube absorbers to integrate fast reactive tuners. Thus one could rapidly gain experience with this evolving technology for a sustainable solution. Once a linac is installed, all aspects of recirculation, such as phase matching or timing and beam stability issues, essential for energy efficiency, can be studied with the 10 mA beam and different bunch charges.

In order to increase the CW current above 10 mA and up to the maximal 100 mA compatible

Topic/Goal	Action required	Minimum Effort	Optimum Effort
Gun			
2022: commissioning of the SRF gun and the diagnostic line with 10 mA and an emittance <1 mm mrad.			1 postdoc position for commissioning
cathode research: QE preserving transport optimization			
cathode research: development of Na-based cathodes for reduced vacuum sensitivity			
bunch charge: test of high bunch charges with a current limit of ∼3.85 mA , depending on cathode QE		Dispenser material for additional cathodes beyond bERLinPro program	
2023: commissioning of the booster and beam transport through injector and low energy path, no linac			
high current: the current limit is set by the high power coupler. With an adapted cavity, the gun module could produce 100mA of current	construct and build the cavity, change coupler setting in booster for high current (dismantling of booster module)	cavity body, 2 additional Canon-Toshiba coupler	second module for high current, enabling operation and module preparation in parallel, (cold string exists), 1 gun cavity + 1-2 backup cavities, solenoid, 4 additional Canon-Toshiba coupler, 1 construction engineer
Linac			
linac with FRT (to dump): adapt linac design to FRT	construct, order, assembly and commissioning	complete linac module	linac and operational costs + spare cavities + one SRF engineer
50 MeV ERL operation: beyond-basic diagnostic in recirculator	order, assembly and commissioning of diagnostics	Additional electronics for diagnostics systems	
theoretical studies			
ERL operation with HEP parameters	study optimal beam transport for higher charges		

Table 6.2: Goals achievable at bERLinPro with respect to technology developments indispensable for HEP ERLs (left column). Next steps to be taken appear in column 2. Column 3 and 4 sketch the minimal effort and what would provide most efficient conditions, resp. Empty boxes indicate that topics will be worked on at HZB without requiring external funding.

with the 600 kW beam dump, the gun module needs to be re-equipped with a new cavity body that incorporates power-coupler ports able to accommodate the recently validated high-power coupler. Since the gun system is very complex, it is currently preferred to assemble an independent second module with an existing cold string which will mitigate risk and enable maximal progress through this parallel development. At present, the booster couplers are suited to minimize the reflected power at about 10 mA. To operate the booster at 100 mA, the booster module would require a reassembly without coupler spacers to increase the coupling.

Table 6.2 summarizes the necessary topics and goals where bERLinPro could efficiently contribute directly to the tasks at hand for HEP-ERL development. The total effort is estimated to require about 7.5 MCHF, and 33 FTEs for the period of 2022 to 2025 and possibly beyond. A graphic breakdown of the effort and investment over time is provided below in Sect. 6.8.

6.7.3 *PERLE*

Introduction

PERLE, a Powerful Energy Recovery Linac for Experiments, as detailed in [2], emerged from the design of the Large Hadron Electron Collider as a 3-turn racetrack configuration with a linac in each straight. With its 3 turns, 20 mA current leading to 120 mA cavity load, 802 MHz frequency and 500 MeV energy, PERLE is the ideal next generation ERL facility with which a new generation of HEP colliders can be prepared, the 10 MW power regime be studied and novel low energy experiments at high intensity be pursued. Its principles were published first at the IPAC conference 2014 [49]. Its CDR appeared in 2017 [50]. Following several years of organisation, development and review, a default footprint of the facility has been chosen, see Fig. 6.3, which fits into a large, free experimental hall at IJCLab Orsay. PERLE has now been established as a Collaboration of Institutes with mostly long experience on

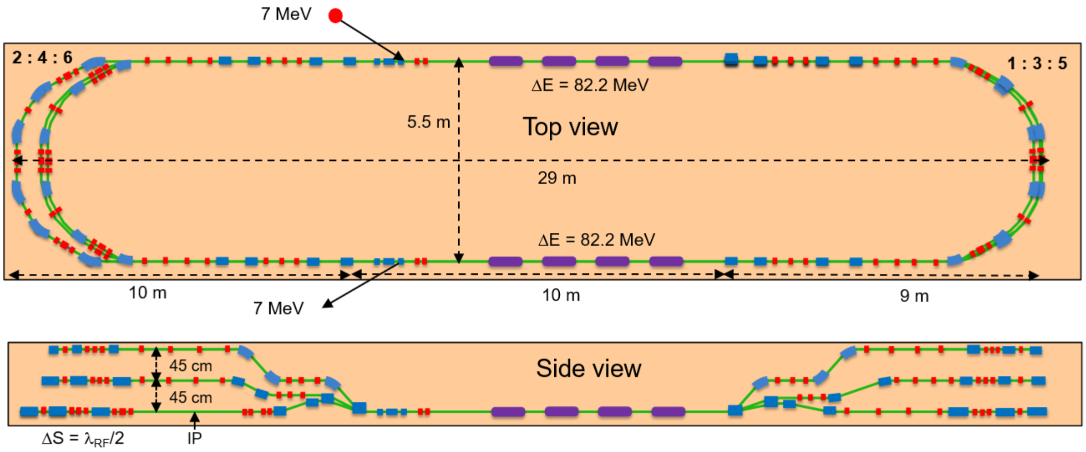

Fig. 6.3: Top and side views of the PERLE facility at IJCLab Orsay. An electron energy of 500 MeV is achieved in three turns passing through two cryomodules, each housing four 5-cell cavities of 802 MHz frequency. PERLE will be built in two stages, first with one linac cryomodule, adapted from the SPL module, and then completed with a newly designed one. The total number of magnets, including arcs, switchyards, merger and experiments is 84 dipoles, 33 or 66 cm long, of typically 0.5-1 T bend and 118 quadrupoles, 10 to 15 cm long, with fields between 0.4 and 5.5 kG/cm. Optics and further features of this configuration are briefly discussed below.

ERL, SRF and magnet technology as well as operation. The facility will be hosted by Irène Joliot Curie Laboratory at Orsay, and be built by a collaboration of BINP Novosibirsk, CERN, University of Cornell, IJClab Orsay, Jefferson Laboratory Newport News, University of Liverpool and STFC Daresbury including the Cockcroft Institute, with others expressing interest. Recently, an ambitious plan was endorsed aiming for first PERLE beam operation, with initially one linac, in the mid twenties, see below. This is not impossible as the Collaboration intends to use the ALICE gun, the JLab/AES booster and the SPL [51] cryomodules as available key components for an early start, while the bulk funding is yet to be realised.

Description

Following detailed simulations over three years and an international review end of 2020, the PERLE injector has been tentatively designed. The final goal of 20 mA current corresponds to 500 pC bunch charge at 40 MHz frequency as prescribed by the LHC. Delivery of such high-charge electron bunches into the main loop of an ERL is challenging as the emittance, required to be below 6 mm mrad, has to be preserved. The beam dynamics were simulated using the code OPAL and optimised using a genetic algorithm and a three-dipole solution was chosen for the merger. Table 6.3 shows the requirements on the beam at the exit of the main linac after the first pass. For achieving such low emittance at high average

Table 6.3: PERLE injector specification

Parameter	**Values**
Bunch charge	500 pC
Emittance	$\leq$ 6 mm mrad
Total injection energy	7 MeV/c
First arc energy	89 MeV
RMS bunch length	3 mm
Maximum RMS transverse beam size	6 mm
Twiss β at 1st main linac pass exit	8.6 m
Twiss α at 1st main linac pass exit	–0.66

current, a DC-gun-based injector will be used, re-installing the ALICE gun delivered from Daresbury to Orsay. The complete injector will consist of a 350 kV photocathode electron gun, a pair of solenoids for transverse beam size control and emittance compensation, an 801.58 MHz buncher cavity, a booster linac consisting of four single cell 801.58 MHz SRF cavities, and the merger, Twiss matched to the loop optics, to transport the beam into the main ERL loop.

PERLE is a compact three-pass ERL project based on SRF technology, pushing as a new generation machine the operational regime for multi-turn ERLs to around 10 MW beam power level. Apart from the experiments it could host thanks to its beam characteristics, A summary of the design parameters is presented in Table 6.4. The bunch spacing in the ERL is assumed to be 25 ns; however, empty

Parameter	unit	value
Injection beam energy	MeV	7
Electron beam energy	MeV	500
Norm. emittance $\gamma\varepsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	24.95
RF frequency	MHz	801.58
Duty factor		CW

Table 6.4: PERLE Beam Parameters

bunches might be required in the ERL for ion clearing gaps. PERLE will study important ERL accelerator characteristics such as: CW operation, handling a high average beam current, low delivered beam energy spread and low delivered beam emittance.

The linac optics design minimises the effect of wakefields such that the beta function is minimised at low energy. The ERL is operated on crest in order to benefit from the maximum voltage available in the cavity. The spreaders/recombiners connect the linac structures to the arcs and route the electron bunches according to their energies. The design is a two-step achromatic vertical deflection system and features a specific magnet design in order to gain in compactness.

The three arcs on either side of the linacs are vertically stacked and composed of 6 dipoles instead of 4 dipoles with respect to the previous design [50], reducing the effects of CSR. Moreover, the arc lattice is based on flexible-momentum-compaction optics such that the momentum compaction factor can be minimised but also adjusted if needed. The low energy implies that the energy spread and emittance growth due to incoherent synchrotron radiation is negligible in the arcs.

The ERL lattice design provides a pair of low-beta insertions for experimental purposes, and the multi-pass optics optimisation gives a perfect transmission with the front-to-end tracking results including CSR. Multi-bunch tracking has shown that instabilities from HOM can be damped with frequency detuning. The optimal bunch recombination pattern gives some constraints on the length of the arcs. Furthermore, the arc with the low-beta insertions will provide the necessary shift to the decelerating phase in the RF cavities. There are two chicanes in the lattice, located at the entrance of a linac and symmetrically at the exit of the other linac structure. They are needed to allow injection and extraction through a constant field. PERLE has two linacs and 3 passes, which leads to a six-fold increase and subsequent decrease of the beam energy.

Prospect

PERLE will serve as a hub for the validation and exploration of a broad range of accelerator phenomena in an unexplored operational power regime. A vigorous R&D program is currently being pursued to develop a Technical Design Report for PERLE at Orsay until the end of 2022. To achieve this goal, the following sequence of accelerator design studies and hardware developments has been identified:

- Start-to-end simulation with synchrotron radiation, CSR micro-bunching
- Multi-pass wake-field effects, BBU studies
- Injection line/chicane design including space-charge studies at injection
- HOM design and tests of a dressed cavity
- bCOM Magnet Prototype
- Preparation of ALICE gun installation at Orsay
- Design of PERLE diagnostics
- Preparation of facility infrastructure

The collaboration is aiming at the PERLE Technical Design Report to be concluded by end of 2022, with the goal of achieving the first beam at PERLE by the mid-twenties. Important milestones will be the delivery and equipment of the JLEIC booster cryostat to Orsay and the production and test of the complete linac cavity-cryomodule, as the first linac for PERLE and the 802 MHz cryomodule demonstrator as part of the FCC-ee feasibility project. It is considered very desirable to integrate FRT microphonics control into this design as mentioned above, Sect. 6.6. Further details on the current design of PERLE can be found in Ref. [52].

The multi-turn, high-current, small-emittance configuration and the time line of PERLE make it a central part of the roadmap for the development of energy-recovery linacs which has attracted experienced partners from outside Europe. PERLE includes two important goals for completion beyond the first 5 years of the roadmap: a) the preparation of two experiments which will be on exotic isotope spectroscopy and possibly inverse photon scattering physics or/and ep scattering for proton radius, dark photon or electroweak measurements for which a polarised gun would be required, and b) the mid-term development of a first warm 802 MHz cavity-cryomodule as is described in Sect. 6.6.

The total effort for the 250 MeV PERLE, based on essential in-kind deliveries (gun, booster and one linac cryomodule) is estimated to require about 14 MCHF, and NN FTEs for the period of 2022 to 2025, and another 12 MCHF for the following phase (2026-2030). This includes IJCLab infrstracture provisions one roughly may estimate to amount to 10 MCHF besides considerable technical and personnel effort. A graphic breakdown of the effort and funding requirements over time is provided below in Sect. 6.8.

6.8 Delivery Plan for European ERL R&D

The ERL roadmap comprises three main and interlinked elements: **A)** the continuation and development of the various facility programs, summarised in Sect. 6.5, for which no funds are requested. For Europe these are SDALINAC in Darmstadt and MESA in Mainz (both in Germany); **B)** a number of key technologies to be developed as characterised in Sect. 6.6. Some of these, such as electron sources of high brightness (reaching the 100 mA electron current regime), FRTs and, for longer term, the development of an 802 MHz 4.4 K cavity-cryomodule have been integrated in the plans for bERLinPRO and PERLE as all require beam operation [11]. Two other items of strategic importance deserve separate support and are included here, the HOM damping at high temperature and the development of twin cavities; **C)** the timely upgrade of bERLinPRO and built of PERLE at Orsay as the necessary steps to move ERLs forward to their introduction to collider developments, possibly mid-term and long term. This regards electron-hadron, electron-positron and may be muon collider developments as explained above. Ahead is a new era of high power ERL operation R&D, high intensity low energy experiments and industrial applications.

Here follow the charts for HOM at high T, Twin cavities, bERLinPRO and PERLE with only scarse explanations for these had been given above. Please take note of the long write-up of ERLs that the panel together with about 30 other authors is about to publish [3] for further detailed information. Please also take note of the Interim Roadmap report for a brief, provisional summary of the panel's findings in summer 2021.

6.8.1 Higher order mode damping at high temperature

Dynamic higher order mode losses appear proportional to the beam intensity squared and to the number of cavities which for ERLC reaches about 10^4. This dynamic load leads to a heat transfer related to a power "amplification" factor $\propto T/(300-T)$. The power requirement for compensating dynamic HOM losses is therefore the smaller the higher the temperature T is, as has been sketched in the key technology section 6.6. The diagram below summarises the sequence of steps and estimated effort for developing this area further.

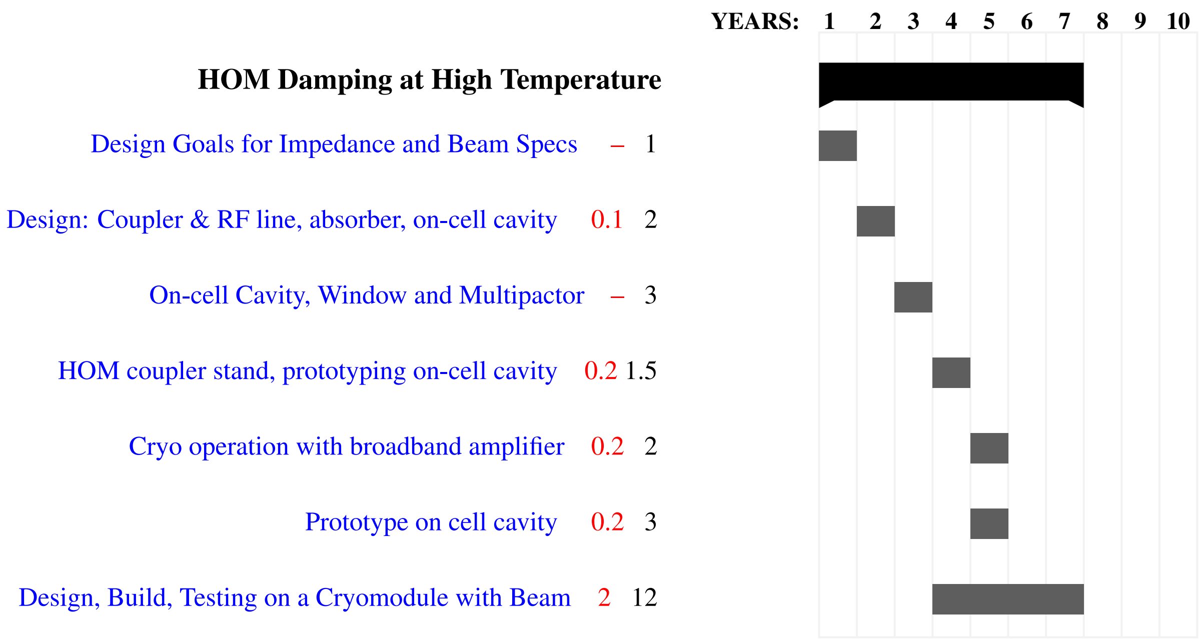

Chart 1: Development of HOM damping technology for high temperature. Funding 2.7 MCHF (red

[11] Basic infusion and sputtering 4.4 K technology developments are covered in the SRF R&D roadmap albeit being much supported by the results of this panel and the prospects for future colliders as well as small lab innovations leading to novel industrialisation of warm(er) cavity technology.

column) over 6 years, 24.5 FTEs (black). Year 1 for this development is chosen to be 2023 for giving time for interested laboratories to embark on it.

6.8.2 Dual axis cavity developments

Twin axis cavities are required when the accelerating and decelerating beams are traveling in opposite directions through long linacs. Initial developments have been done at JLab and the John Adams Institute a few years ago. For cost efficiency of a new generation e^+e^- linac the availability of high Q_0 twin cavities is considered to be an important economy factor. The roadmap thus includes the design and production of a multi-cell twin cavity followed by a complete cryomodule.

Chart 2: Development of dual axis cavity and cryomodule technology. Funding 3.5 MCHF (red column) over 6 years, 12.5 FTEs (black). Year 1 for this development is chosen to be 2023 for giving time for interested laboratories to embark on it.

6.8.3 bERLinPRO

The facility bERLinPRO has been recognised as a most suitable ERL accelerator to achieve 100 mA electron beam current in a few years time for performing necessary, evolved high current operation studies. All ERL based HEP collider concepts, elder or recent, aim to reach high luminosity through such high intensity. For this goal to be achieved, bERLinPRO requires two steps leading beyond their default 10 mA study: a) to build and install a new 100 mA SRF gun, essentially a development based on the existing 10 mA gun, and b) introduction of a new 1.3 GHz linac module into the completed racetrack, equipped with FRTs in order to study their effect in single-pass ERL beam operation. This program will lead to further collaboration with other Helmholtz centers such as Rossendorf and with CERN. It will also help establishing more intimate connections to MESA or SDALINAC in Germany and be supportive to the development of PERLE as was outlined in Sect. 6.7. The following shows two charts: for the 100 mA (a) and the completion of the programme (b). It is obvious that the so upgraded and completed bERLinPROP facility will provide further important R&D opportunities of particular interest to the Berlin Helmholtz center.

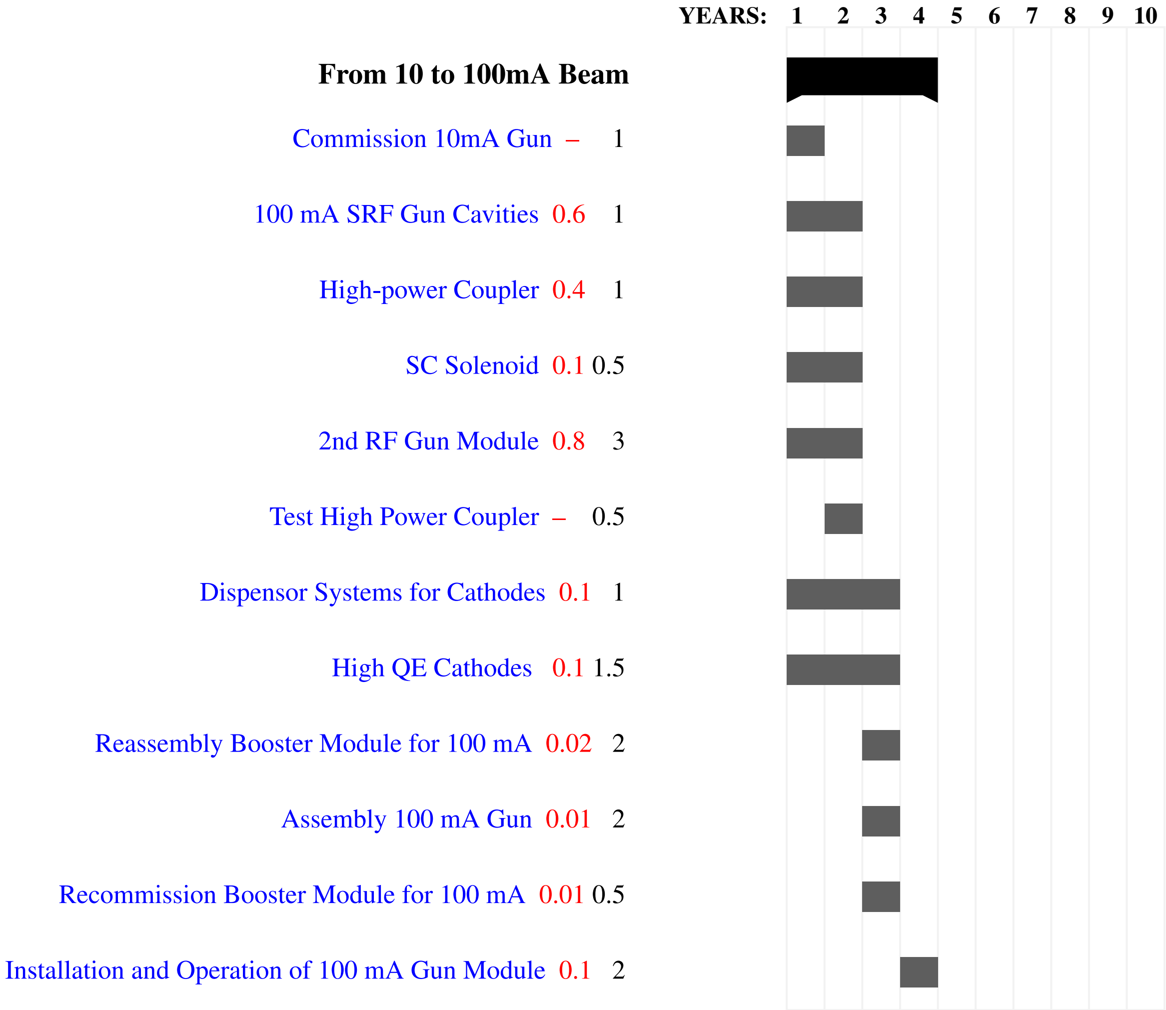

Chart 3a: Upgrade of bERLinPRO to 100 mA electron current operation. Funding 2.2 MCHF (red column) over 4 years, 16 FTEs (black). Year 1 for this development is 2022 for the program to succeed by 2025.

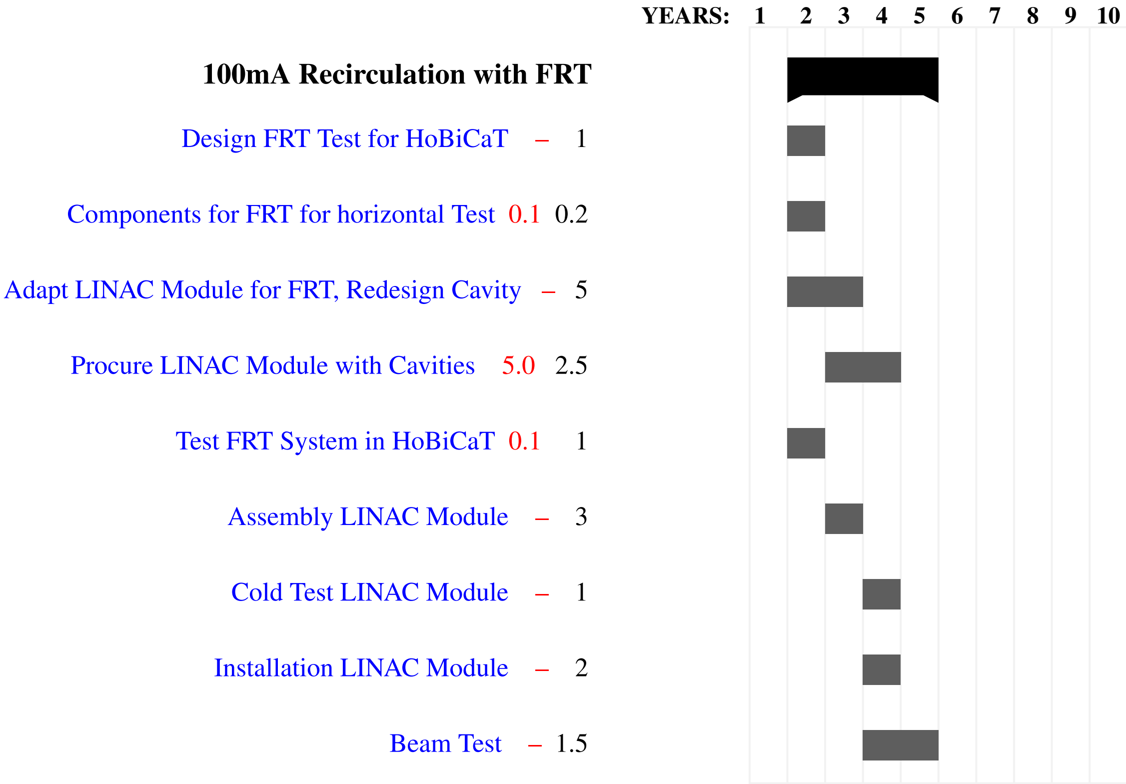

Chart 3b: Completion of bERLinPRO with a 1.3 GHz cavity-cryomodule. Funding 5.2 MCHF (red column) over 4 years, 17 FTEs (black). Year 1 for this development is 2023, a year after part a) started, for the program to succeed by 2025/6.

6.8.4 PERLE

The novel high-energy ERL concepts targeted at energy-frontier electron-hadron, electron-positron and electron-photon colliders, as well as further physics and other applications, require the development of high-brightness electron guns and dedicated SRF technology as prime R&D objectives. Moreover, “it needs a facility comprising all essential features simultaneously: high current, multi-pass, optimised cavities and cryomodules and a physics-quality beam eventually for experiments" (Bob Rimmer in [3]). PERLE has been founded as a Collaboration by several institutes to explore the 10 MW regime with a 3-pass ERL facility. It will be hosted by IJCLab Orsay and be built in two stages, with first one and then a second linac module. Its main features are the 802 MHz frequency, a DC photocathode gun based on ALICE to reach 20 mA, a classic booster using the JLab/AES booster cryomodule, a linac cryomodule, using the SPL module provided by CERN, housing four 5-cell Niobium cavities, three return arcs, spreaders and combiners of roughly 200 short dipoles and quadrupoles etc. It is considered for later phase B to possibly add a polarised 20 mA gun and to test a 4.4 K 802 MHz cryomodule in the PERLE accelerator, subject to progress on 4,4 K technology developments. The main task of PERLE is to demonstrate high current multi-turn operation, later for experiments, and to develop 802 MHz technology also as part of the FCC-ee feasibility study.

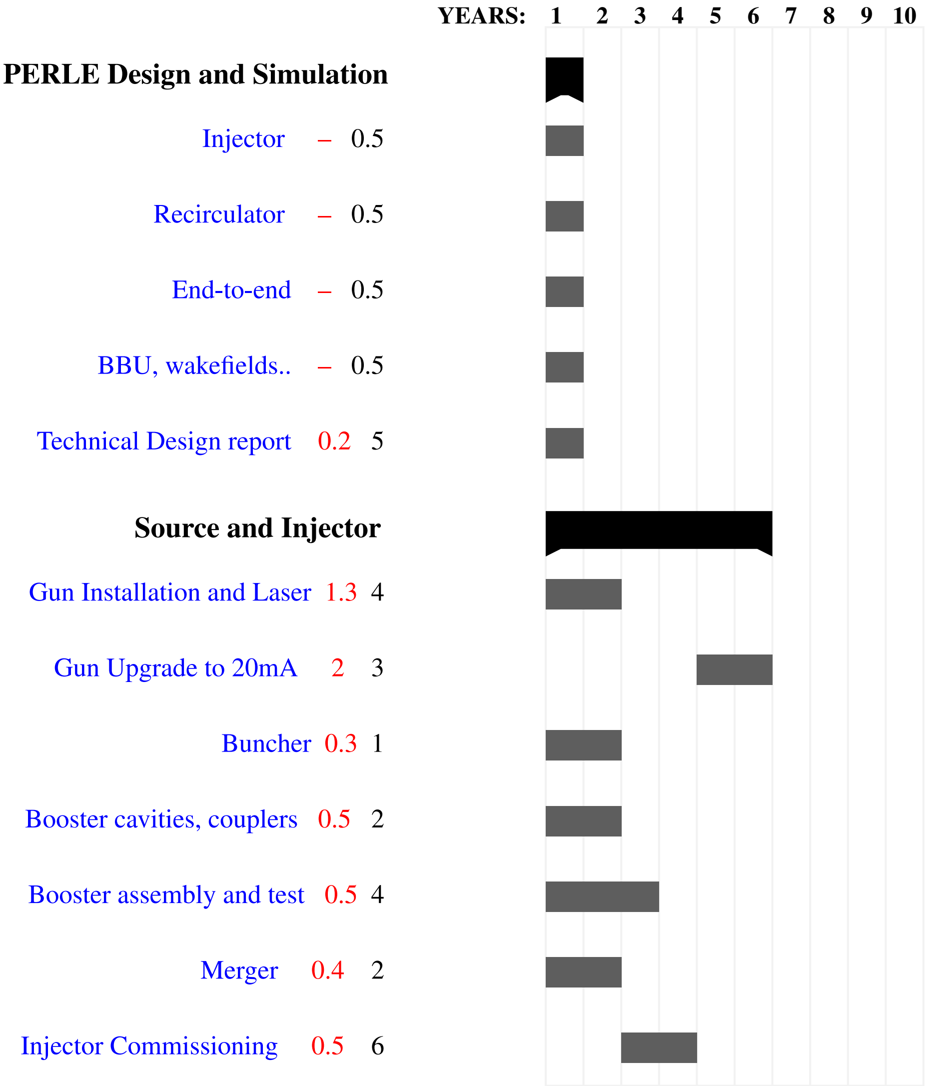

Chart 4a: The path to the PERLE technical design report and commissioning of the injector including the gun upgrade to full current. Funding 3.7 MCHF (red column) over 4 years plus 2 MCHF for the gun upgrade in the following two years, 29 FTEs (black). Year 1 for this development is 2022.

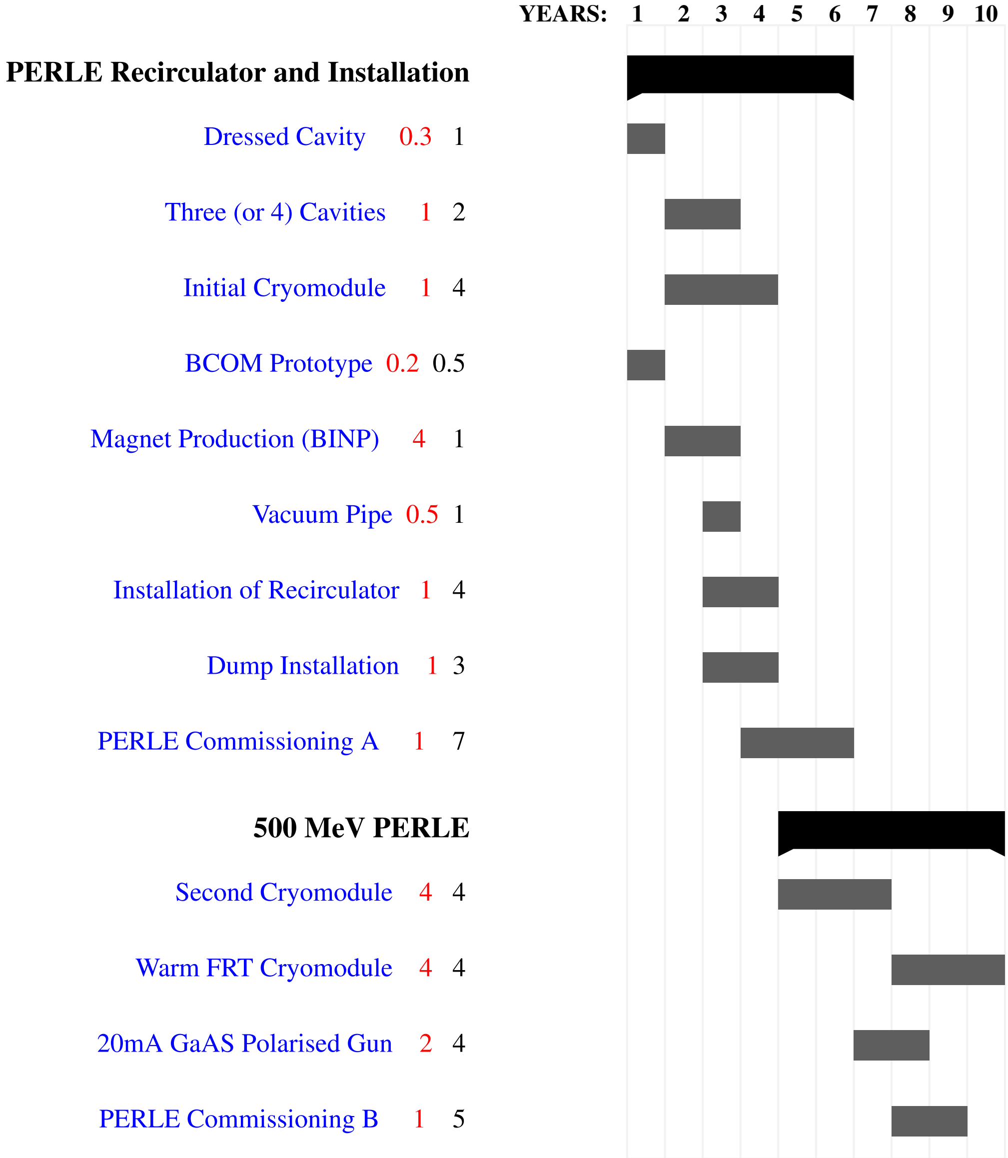

Chart 4a: PERLE completion in two steps, the 250 MeV phase with beam in the mid twenties will be followed by the 500 MeV stage towards the end of the twenties. Funding of the first part 10 MCHF (red column) over 4 years, 24 FTEs (black), and 11 MCHF for the second part , 17 FTEs. Year 1 for this development is 2022 although the second part, as illustrated begins only in 2025 about.

6.8.5 High current operation and diagnostics

ERLs have specific diagnostics needs because of the large beam power, the small emittance that is to be preserved, and the low beam loading that needs to be maintained in the main linac cavities. The large beam power can lead to continuous beam losses that can easily damage vacuum components, magnets, and electronics; and it can create dark current in accelerating cavities. Halo diagnostics and radiation detection in critical regions is therefore essential. While existing ERLs have developed solutions, e.g., high-dynamic-range halo monitors at the JLab FEL or continuous radiation monitors along both sides of the beam pipe in CBETA, solutions for larger beam powers still have to be developed. This leads to a plan described above in Sect. 6.6 and the following work plan:

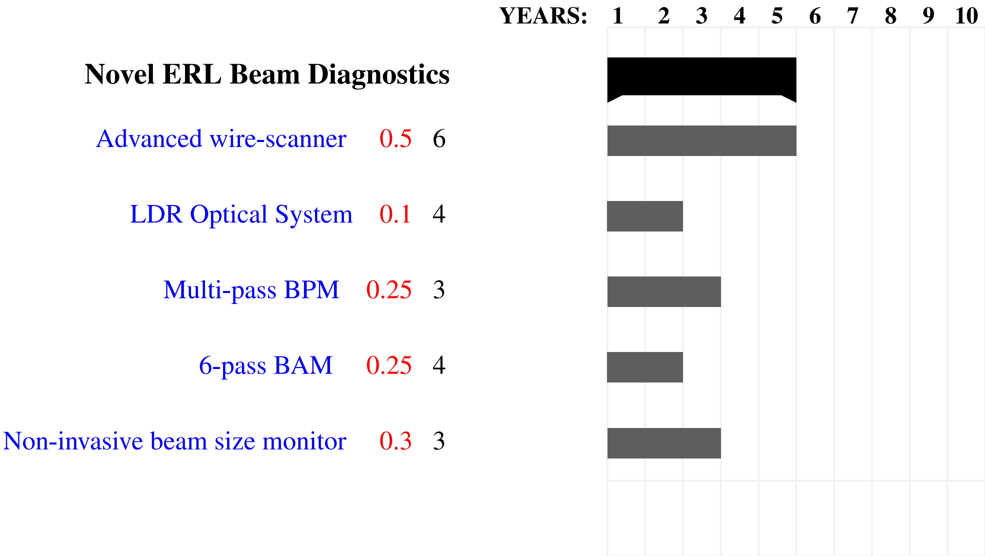

Chart 5: Development plan for high current ERL beam diagnostics. Funding 1.4 MCHF (red column) over 5 years, 20 FTEs (black). Year 1 for this development is set to 2023 for interested parties to organise.

6.9 Collaboration and organisation

The development and application of ERL technology has been a global effort as, not least, the authorlist and panel composition of this roadmap illustrate. A combination of generic R&D efforts in various laboratories with complete ERL facilities, in the US, Russia, Japan and Europe, as here described, has advanced the field so much that one can now consider its application to energy frontier particle physics in various types of colliders involving electron beams.

This roadmap describes a threefold strategy based on (A) the further development of existing ERL facilities, (B) the implementation of a nearer and long term R&D program on key technologies and (C) the operation of new facilities at higher current and/or energy, notably bERLinPRO (HZB Berlin) and PERLE (IJCLab Orsay) in Europe as well as CEBAF5 (Jefferson Lab) and the EIC electron Cooler (BNL) in the US. The panel is convinced that pursuing these interlinked developments will advance ERLs in a major way, not least since they enable new generation low energy experiments, approach HEP colliders and promise striking applications for industry and related science developments. Implementation of such a program, in Europe and on a global scale, would much profit from a more intimate world-wide coordination and intensified exchange of personnel, technology and experience.

The success of such a coordination, and the ERL field in general, will rely on its community and material support, not least the inclusion of ERL developments into CERN's Medium Term Plan as a document of influence on the accelerator future for and beyond Europe. It will also rely on timely progress in the main existing and future facilities. As these develop, a tendency becomes clear of stronger collaboration of several institutes around ERL facilities, and main technology developments. PERLE is the first, large institutional collaboration for building and operating an ERL facility. Its success will be related to the personal, technical and financial contributions of the collaborating partner institutes given the clear decision of IN2P3 and its Irene Joliot Curie Laboratory to realise this machine soon. PERLE comprises accelerator, particle and nuclear physicists, and its collaboration structure is just emerging as probably a balance between particle physics experiment collaboration models and a host facility oriented one.

Globally, ERL experts meet in accelerator conferences such as IPAC and have an annual dedicated ERL workshop, from Berlin 2019 to Cornell 2022, interrupted by the Covit pandemic. They have been in close contact and jointly been working on facilities and projects, as, for example, the recent commissioning of the CBETA facility has demonstrated.

The next step of this roadmap development will be its implementation, subject to CERN Council's endorsement and acceptance by a wider community. This will give time, in a further consultation process, to develop an appropriate organisation of ERL developments, recognising and possibly combining local, regional and continental capacities and interest with the achievement of midterm and further goals as we tried to here describe. ERLs are one of the not many ways for innovation of future accelerators, a technology with stringent advantages and the opportunity to eventually and experimentally lead particle physics indeed beyond its Standard Model. Their general physics and impact potential is outstanding. They are surely worth the most sincere efforts.

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7 Sustainability considerations *(∼8 pages)*

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CERN Yellow Reports: Monographs, CERN-2021-XXX, DOI: 10.23731/CYRM-2021-XXX, p. 113.

8 FCCee-specific R&D programme *(∼4 pages)*

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– Summary of the status of the programme, and the R&D / design work anticipated over the next five to ten years
– Reflections on where the R&D objectives outlined in the document are particularly relevant to the programme
– Any comments on where the work already planned may overlap with the R&D programme, or where there will be a legacy of training or facilities relevant to future R&D

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9 ILC-specific R&D programme *(∼4 pages)*

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– Summary of the status of the programme, and the R&D / design work anticipated over the next five to ten years
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10 CLIC-specific R&D programme *(∼4 pages)*

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- Summary of the status of the programme, and the R&D / design work anticipated over the next five to ten years
- Reflections on where the R&D objectives outlined in the document are particularly relevant to the programme
- Any comments on where the work already planned may overlap with the R&D programme, or where there will be a legacy of training or facilities relevant to future R&D

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11 Conclusion

11.1 Summary of findings

This report documents the initial findings of the expert panels, based upon six months of community consultation and input. Each of the panels has completed the first part of its remit, and attention has now turned to the definition of concrete R&D objectives and the plan to deliver them. A summary of the priority areas identified is as follows.

1. The **High-Field Magnets** group has identified the need for continued and accelerated progress on both Nb_3Sn and HTS technology. This should encompass not just developments in the materials, but place strong emphasis on their inclusion into practical accelerator magnet systems, with a wide range of associated engineering challenges. Considerations of both production and operations cost are taken into account, meaning that the parameters and design of the final magnets may have to reflect a compromise between ultimate performance and ease of manufacture, testing and operation.
2. The **High-gradient RF Structures and Systems** group finds that work is needed on the basic materials and construction techniques for both superconducting and normally conducting RF structures. There are significant challenges in improving efficiency beyond the accelerating structures themselves, since couplers and RF sources may be limiting elements. There is the need for the development of specialised and automated test, tuning and diagnostic techniques, particularly where large-scale series production is needed.
3. The **High-gradient Plasma and Laser Accelerators** group has focused on developments needed specifically for particle physics applications of the rapidly-developing dielectric acceleration technology. This includes the further development of existing techniques for high charge, low emittance, and improved efficiency; acceleration of positrons; and the staging together of accelerating stages in a coherent and realistic design for a future collider. The goal here will be to produce by 2026 an evidenced statement of the basic feasibility of such a machine, informing decisions on future investment into larger scale R&D.
4. The **Bright Muon Beams and Muon Colliders** group has examined the choice of parameters for a future muon collider concept, arriving at the concept of an ultimate 10 TeV machine with a 3 TeV intermediate scale facility. They have considered the challenges to be met in the construction of such a machine targeted for around 2045, and the immediate feasibility studies that must be carried out in the next five years. The goal for 2026 will be to demonstrate that further investment is scientifically justified, and to have developed concrete plans for an intermediate-scale technology demonstrator with scientific utility in its own right.
5. The **Energy-Recovery Linacs** group has gathered input from many of the medium-scale projects now under way in this area around the world, with complementary goals in different aspects of the technology. In addition, a sub-panel continues to work to consider the direct application of ERL technology in the long-term to electron-positron colliders. The next practical step is to approach the 10 MW power level for such machines based on progress on high current sources, high quality cavity technology and multi-turn operation.

Cross-cutting issues identified by the panels include:

- The necessity of moderating the electrical power consumption of future machines, in order that they are sustainable. This includes the power consumed by cryogenic plant in addition to that by RF efficiency or other direct losses.
- The requirement to design for reasonable manufacturing cost, throughput and efficiency for series-produced machine elements, including the automation and robotisation of both production and tuning for reduced cost.

- The need for investment in specialised large-scale facilities for development and testing of accelerator systems, up to and including dedicated beam facilities or demonstrator machines. The cooperative use of specialised medium-scale facilities, without competition or duplication of resources, is mandatory.
- The strong need for international cooperation and collaboration in all aspects of accelerator R&D.
- The need for continuity in the R&D programme, in terms of support for facilities, but also the career support and training of the next generations of researchers and engineers with specialised skills.

11.2 Planning of the Roadmap

Planning of the final Roadmap is now under way. Each expert panel is working towards development of multiple delivery plans, designed to encompass a range of funding scenarios. This is necessary, since it is clear that a ‘maximum rate of progress’ scenario in any one of the five areas (also bearing in mind other current demands on the human and financial resources) could exhaust the capacity of the field. Each delivery plan will include:

- a set of concrete deliverables, including technology demonstrators, over the next ten years
- first estimates of the human and capital resources required for delivery
- specification of the large- and medium-scale facilities required for delivery
- a statement of the linkage to work planned in other fields or for non-particle-physics facilities
- requirements for corresponding detector or instrumentation developments, and any scientific benefits foreseen in the short to medium term.

In essence, the Roadmap should seek to answer some fundamental questions, both immediately, and then in much greater detail by the time of the next strategy updates:

- What R&D remains to be done towards future facilities? What are the priorities?
- How long might it take? What is the fastest technically limited schedule?
- How much will it cost?
- What different options and trade-offs exist?
- What are the linkages between activities?
- What science can be done using demonstrators, or intermediate-scale facilities?

In addition, consideration will be given to how such R&D programme should be approved, organised and governed, including both those aspects which intrinsically fall under the responsibility of a given host laboratory, and those which do not. This will form the input into a more general set of recommendations on how the Roadmap as a whole should be implemented and overseen.