CERN-2021-XXX

European Strategy for Particle Physics
Accelerator R&D Roadmap

Interim Report

Editor: D. Newbold

Published by CERN, CH-1211 Geneva 23, Switzerland

ISBN 978-92-9083-XXX-X (paperback)
ISBN 978-92-9083-XXX-X (PDF)

This volume should be cited as:

European Strategy for Particle Physics - Accelerator R&D Roadmap (Interim Report),
D. Newbold (ed.)

A contribution in this report should be cited as:

[Chapter editor name(s)], in European Strategy for Particle Physics - Accelerator R&D Roadmap (Interim Report), D. Newbold (ed.)
CERN-2021-xxx (CERN, Geneva, 2021), pp. [first page]–[last page],
http://doi.org/10.23731/CYRM-2021-XXX.[first page]

Corresponding editor: Y.XXXX@cern.ch.

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

Editor: D. Newbold

Section editors: R. Assmann, S. Bousson, M. Klein, D. Schulte, P. Vedrine

Abstract
This report ....

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

Contents

1 Introduction

I. Dawson
Queen Mary University of London, United Kingdom

This report documents the knowledge and experiences gained by the LHC experiments in running vertex and tracker detector systems in extreme radiation environments and concludes a series of workshops held at CERN [1–3].

References

[1] Radiation effects in the LHC experiments and impact on operation and performance, CERN, 11–12 February 2019, Indico.

[2] Radiation effects in the LHC experiments and impact on operation and performance, CERN, 23–24 April 2018, Indico.

[3] 31st RD50 Workshop, CERN, 20–22 November 2017, Indico.

2 High-field Magnets

B. Auchmann[a], A. Ballarino[b], B. Baudouy[c], L. Bottura[b], P. Fazilleau[c], M. Noe[d], S. Prestemon[e], E. Rochepault[c], L. Rossi[f], C. Senatore[g], B. Shepherd[h], L.-G. Tabares[i], P. Vedrine[c]

[b]PSI, Villigen, Switzerland
[a]CERN, Geneva, Switzerland
[c]CEA, Saclay, France
[d]KIT, Karlsruhe, Germany
[e]LBNL, Berkeley, California, USA
[f]INFN-LASA, Milano, Italy
[g]University of Geneva, Switzerland
[h]ASTEC, Daresbury, UK
[i]CIEMAT, Madrid, Spain

2.1 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, through HERA in 1991, RHIC in 2000 and finally the LHC in 2008, all frontier hadron colliders were built using superconducting (SC) magnets. All colliders listed above made use of the highly optimized superconducting alloy of Nb and Ti, 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.

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. These programs unfolded 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. On the EU side the first targeted EU-wide activities were initiated under the EU-FP6 CARE (Coordinated Accelerator Research in Europe) initiative, and in particular the Next European Dipole Joint Research Activity (NED-JRA). 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 magnet that still detains with 14.6 T the highest dipole field ever produced in a clear bore of significant aperture.

The fruit of the technology development sketched above is the High-Luminosity LHC upgrade (HL-LHC), presently at the forefront of technology and construction, with the highest field ever attained by accelerator magnets. The results achieved with the 11T dipoles and QXF quadrupoles demonstrate that Nb_3Sn has the ability to surpass the state-of-the-art Nb-Ti mentioned earlier.

The result of the efforts briefly outlined above can be appreciated graphically in Fig. 1, reporting the steady increase of field produced by dipole magnets built with Nb_3Sn over the past forty years. The data is a loose collection of results obtained with short demonstrator magnets (simple configurations

This contribution should be cited as: High-field Magnets, DOI: 10.23731/CYRM-2021-XXX.3, in: European Strategy for Particle Physics - Accelerator R&D Roadmap (Interim Report), Ed. D. Newbold,
CERN-2021-XXX, DOI: 10.23731/CYRM-2021-XXX, p. 3.

that lack an aperture for the beam and are not built with other constraints such as field quality), short model magnets (short version of magnets that are representative of the full-size accelerator magnets), and full-size accelerator magnets. Still, it gives a good impression of the timeline and state-of-the-art.

While Nb_3Sn is baseline for the high field magnets beyond HL-LHC, 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. To date, the result of these activities are small demonstrator magnets that have reached bore field in the range of 3 to 5 T in stand-alone mode.

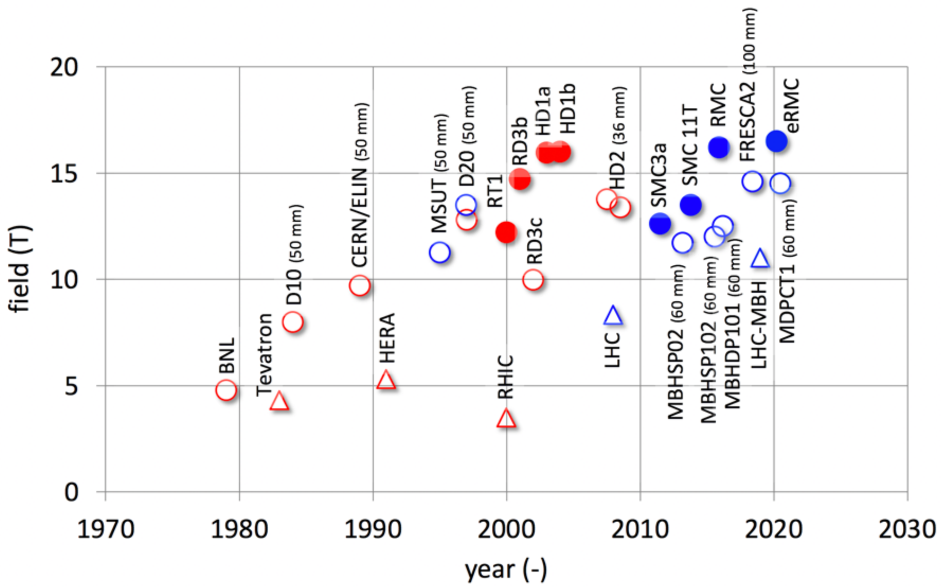

Fig. 2.1: Record fields attained with Nb_3Sn dipole magnets of various configurations and dimensions, and either at liquid (4.2 K, red) or superfluid (1.9 K, blue) helium temperature. Solid symbols are short demonstrator, i.e. "racetracks" with no bore, while open symbols are short models and long magnets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

To complement this simplified but interesting perspective, we observe that:

- Lead times for the development of high-field magnets are long, the cycle to master new technology and bring novel ideas into application has 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, one such research team needs considerable investment for its constitution and operates most effectively with continuity.

These considerations support 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.

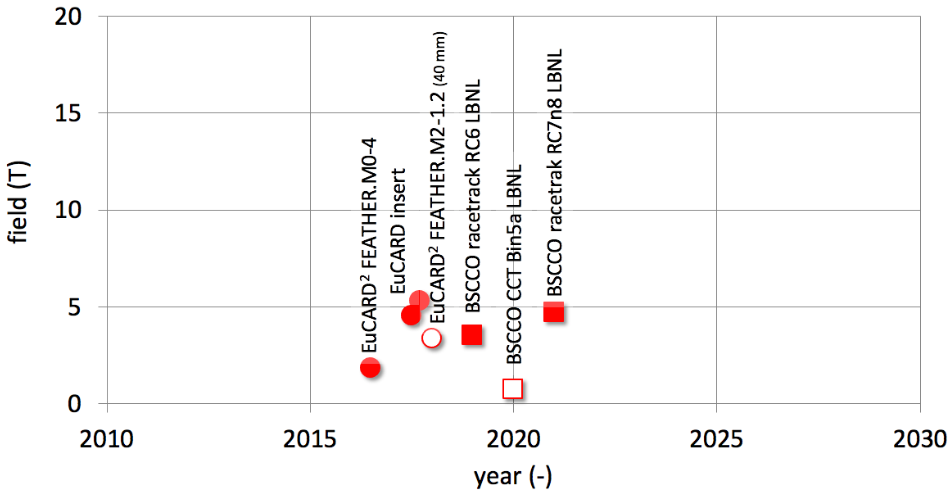

Fig. 2.2: Record fields attained with HTS short demonstrator magnets producing a dipole field. All tests performed in liquid helium (4.2 K). Solid symbols are magnets with no bore (e.g. racetracks), while open symbols are magnets with bore. Round symbols are magnets built with REBCO, square symbols with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

2.2 Panel Activities

HFM Expert Panel meetings held eleven meetings to date. All meetings are collected under an indico category containing the material presented and minutes (https://indico.cern.ch/category/13420/). Two open international workshops were organized and held virtually. Details on the workshops can be found at:

- "HFM State-of-the-Art" (SoftA workshop) took place April 14-16, 2021: https://indico.cern.ch/event/1012691/
- "HFM Roadmap Preparation" (RoaP workshop) took place June 1&3, 2021: https://indico.cern.ch/event/1032199/

The workshops included an expert evaluation of the state of the art in HFM for accelerators, topical reviews and technical roadmaps, and an overview of the strategic positioning of the main EU actors, including laboratories, universities and industry.

The proceedings of the workshops constitute the main body of the wide and open consultation of the community demanded by the LDG. A report is in preparation, based on the executive summaries provided by all contributors. Open consultation process is now completed. We expect to have 4. . . 6 more meetings of the Expert Panel in the coming 3 months to define the prioritized roadmap. A panel-only workshop is planned for Roadmap Implementation (RoaI) on September 15-16, 2021, with the goal of consolidating the final report containing the proposed HFM roadmap for November 2021.

2.3 State of the Art and Challenges of High Field Magnets

2.3.1 Superconductor

The prime challenge to achieve high magnetic fields of interest to HEP is to have a conductor with sufficiently high engineering current density, J_E, with good mechanical properties. A target of $J_E \approx 600$ A/mm^2 is appropriate to yield a compact and efficient coil design. The J_E 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 is mastered and controlled throughout all magnet fabrication and operation conditions.

In the case of Nb_3Sn the target of J_E , which enables construction of compact and affordable magnets, requires a minimum critical current density in the superconductor, J_C, of the order of 1500 A/mm^2 at the reference design conditions (i.e. at 16 T and 4.2 K). This target exceeds the performance of state-of-the-art HL-LHC Nb_3Sn wire. As a result of the R&D initiated with the FCC CERN Conductor Development Program, Nb_3Sn is reaching the upper limit of performance. Advances in composition and architecture need to be consolidated (laboratory), and made practical for large-scale production (industry), including considerations on all performance parameters (mechanics, magnetization – laboratory; homogeneity, unit length, cost – industry).

For HTS, the target J_E is actually common practice for the present production industrial standards of REBCO and BSCCO materials, so no effort is expected in the direction of increasing J_E. We witness spectacular electrical performance of HTS tapes, and the challenge is now to combine critical current with mechanical and protection properties. This may need some innovative thinking about tapes and cables (tape structuring, no transposition, no insulation), which may bring a revolution in magnet engineering. High temperature operation (20 to 65 K) is an interesting option (cryogenic efficiency, high radiation and thermal loads for muon collider), also driven for other fields (fusion and power machinery). Industry drive for high-field performance is independent of HEP (fusion and NMR, power applications for motors and generators at 50…65 K) and cost of HTS may decrease because of substantial investment from fusion and power applications.

2.3.2 Forces and Stresses

Forces increases with the square of the bore field, making mechanics one of the main challenges of high field magnets. Length effects and electro-thermo-mechanics of Nb_3Sn magnets are also a crucial issue (11T experience), we need to find a way to address them. Model and prototypes developments need to be better integrated and supported by basic R&D. However, length effects can only be investigated with long coils.

Filament breakage caused by excessive transverse pressure or axial tension during assembly, cool-down, powering, quench , or WU-CD-powering cycle and irreversible change of pre-load or de-bonding, leading to excessive conductor motion could induce degradation of the critical current. Performance issues have been also identified like strain-dependent J_C-curve with a lack of knowledge of the actual strain status, instabilities at low field (in particular for the conductors in the low field area), training, coupling between longitudinal and transverse forces/strain, memory with thermal cycles.

An initial tentative to identify suitable design options for the various field levels targeted has yielded the following result:

- 2-layer cos-theta suitable up to 12 T
- 4-layers cos-theta or blocks for the 14-16 T range
- Common coils to resolve the issue of the end (to be demonstrated)
- CCT or other stress managed concept beyond 15-16 T

Industry would welcome early involvement in the R&D phase, participating in the whole process to gain early experience on a potential manufacturing phase and decrease risk. However, as for SC industry, it is unlikely that a large-scale manufacturing of HEP magnets would have direct spin-off to other fields.

2.3.3 Stored energy and Protection

Aiming at the range of 16 to 20 T, the stored energy increases proportionally to the square of the field. This yields a factor 4 o 10 with respect to the LHC, ranging from 1 to 3 MJ/m per aperture. This in itself may result in severe limitations on the powering of strings, both from the point of view of their inductance (voltage required to ramp the string of dipoles), as well as magnet protection (energy density and dump time).

In addition, the energy per unit volume, that drives the maximal temperature (hot-spot) during a quench, also increases, proportionally to the field. The LHC magnets have a stored energy density of 50 MJ/m^3. This will increase up to 80 to 100 MJ/m^3 for the HL-LHC Nb_3Sn magnets, with a design hot-spot limited to 350 K. Moreover, this value reaches 200 MJ/m^3 for the most compact 16 T FCC designs, increasing with a factor 4 with the LHC magnets as reference.

Electrical engineering considerations would favor 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 not a trivial matter. Furthermore, in order to keep the hot-spot temperature in the coil after a quench below reasonable 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 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 behavior 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.

2.3.4 Cost

Cost is the last main challenge faced by high-field magnets for a next step collider. We have identified 3 main cost drivers.

The conductor, among which the superconductor strand (round wire, or tape for REBCO) is the primary cost driver of HFM. In LHC, the Nb-Ti cost was about 25% of the total cost of the magnet (excluding the external services like power supply and other ancillaries). The Nb_3Sn cost for FCC-hh is projected to be half of the cost of the magnet system. Therefore, investing to reduce SC cost is a good return investment. Not only unit cost must be reduced but also use of Sc in the magnet: design must be assessed also based on the use of superconductor and we need to encourage solution that go in that sense.

The second biggest part is coil construction, in which winding remain the most expensive part. Today winding is basically a manually driven operation, with the help of some automation in the winding operation. Given the experience of more recent project, like ITER, and given the number of coils (20,000 coils all identical for the main FCC-hh dipoles) and investment in advanced robotics seems a crucial point to reduce winding cost.

The third cost driver is the mechanical structure. Here the community must make the choice among collars, bladder&key, yoke-as-restrain etc... Performance consideration put aside, they are not all equal in terms of cost: some operation seems more suitable to automation. To inject, aside the performance study also this type of study may be a good investment to take the right decision when time will come.

Robotization, is not only beneficial for reducing construction cost, but also for increasing construction quality and enhancing the uniformity of the production The main challenge is to find the optimum between performance and cost, including operational cost. High temperatures (4.2K for Nb_3Sn and 20 K for HTS) should be seriously considered, as it could result in a significant reduction of operation costs. We need to favor simpler designs with repeated operation that might be more suitable to automation, even if slightly less performant in terms of field.

Industry should be involved as soon as possible. However, industry will consider this seriously only if there is continuity (of budget and work assigned to Industry). Industry needs to make plans with at least 5 years horizon to be effective. The issue of IP is to be clarified. If not, better to involve Industry at a later stage because Industry will unlikely unveil their methods, or commit high-level engineering, if their IP is not suitably protected.

An important matter underlying the above considerations is that of 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 the future ones, shall be kept intentionally small (i.e. inserts in background field). An effective R&D program will hence include practical consideration of cost and will need to rely on a high degree of synergy.

2.3.5 Objectives of a High Field Magnets R&D Program

Based on the state-of-the-art and challenges described above, and the strong and precise statements encouraging a high-profile R&D activities on high field accelerator magnets contained in the 2020 upgrade of the European Strategy for Particle Physics, 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 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 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 limit is presently 16 T dipole field (the reference for FCC-hh). This field should be intended as a target, to be quantified and measured against the performance of a series of short demonstration and model magnets.
   (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 efforts, 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 applications, providing 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.

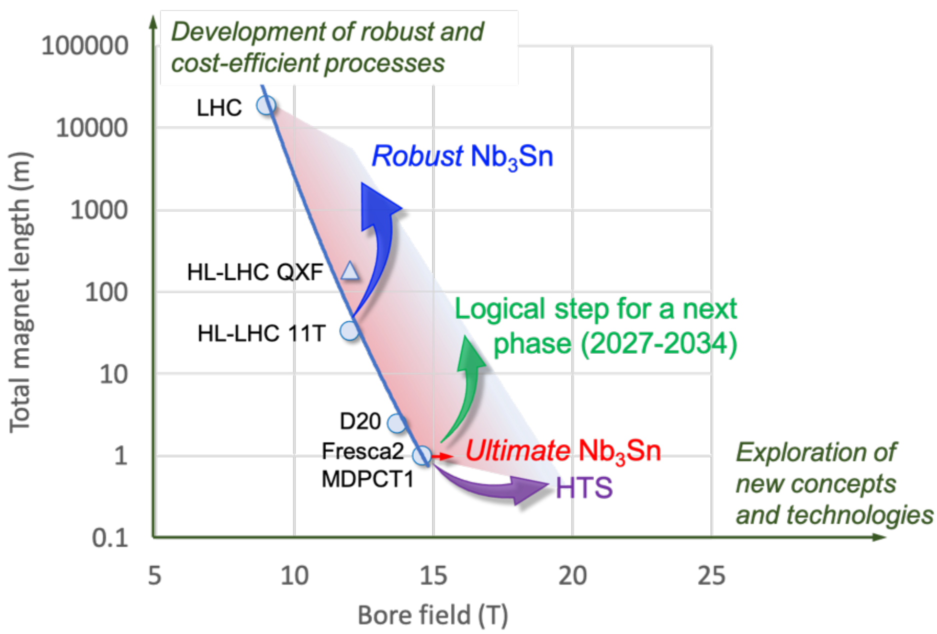

Fig. 2.3: Graphical representation of the objective of the HFM R&D program in this phase, 2021-2027. Both fronts of maximum field (red for Nb_3Sn, purple for HTS) and large-scale production (blue) are intended to be advanced at the same time. Also represented, in green, a possible evolution for the longer term, 2027-2034.

It is possible to represent graphically these main objectives in the form reported in Fig. 3, where we plot a length of dipole magnets produced (i.e. magnet length times the number of magnets) vs. the bore field. The direction of developments are represented by the arrows. The parallelism in the development is an important element of the program. We believe this is necessary to provide the requested significant advances within a five to seven years' time frame, i.e. responding to the notion of a mission-style R&D that needs to feed the discussion for the next upgrade of the European Strategy for Particle Physics with crucial deliverables.

The graphical representation of Fig. 3 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 magnet prototype, i.e. several meters of cumulated magnet length. This is represented by the green arrow in Fig. 3, 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. In the staged approach described here, they are also compatible with the allotted development time of the integrated FCC program. Indeed, the parallelism proposed has the advantage that it will provide options for an earlier decision on magnet technology towards the construction of the next hadron collider.

Given the ambitious scope, the long-term engagement, and the cost, one such program will have to be of collaborative nature, with strong partnership among national laboratories, universities and industry. Last 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 Key points of Roadmap

2.4.1 High Field Magnets R&D Program Drivers

Driven by the challenges outlined above, and in line with the main objectives set for the HFM R&D, 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 largely looking at 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 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 design 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 extend 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 cost ?

- Q9: What is the specific diagnostics, instrumentation and infrastructure required for a successful HFM R&D, taking into account present and projected needs, and 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 ?

2.5 Proposed Program Structure and Deliverables

2.5.1 Conductor development

Nb_3Sn

The main focus of this R&D line is threefold: (i) to advance 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 conductor 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 stemming from accelerator magnet construction and operation, with a target as declared in [ASC-2014]. Development is still needed, the following key objectives being put forth:

HTS

Activities in Europe are focusing on REBCO tapes. The focus 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, effect dog-bone shape of copper stabilizer. Feedback shall be given by the community to tape manufacturers to make them aware about 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 feasibility of long - 1 km target – unit lengths as required for magnet manufacturing. 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 others) the need for transposition.

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

2.5.2 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. compare different needs for high/low pre-stress compact coils, SM coils). 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 next ESPP update. And in the end all developments must constitute steppingstones 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. 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.

2.5.3 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 use above. Such a configuration requires the use of liquid helium as coolant (there are some concerns about using he-II with HTS, this has to be checked). However, there is a great opportunity to work at 20 K with JE 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).

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 (//c). The end design options (cloverleaf, CCT,. . .) is a crucial issue that needs to be addressed to mitigate the complexity of tape ratio aspect and hard way bending. Finally, screening currents effects (magnetization and time stability) need to be understood in detail, with ways to decrease/remove these effects (overshoot/vortex shaking/temperature increase)

2.5.4 Cross cutting technologies

Advances will be required in these fields that are common to both Nb_3Sn and HTS magnets (i.e. cross-cutting):

Materials, Cryogenic and Modeling

R&D programs on material development and characterization are already in place in the EU and the USA and must be reinforced. The global strategy to follow 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).

Magnet Protection and Powering

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 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 are safely within allowables. 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

2.6 Facilities and Infrastructure

The development of high field magnets requires, at the partners' laboratories, dedicated infrastructure suitable for R&D, at 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 of: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; 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 shared among all collaborators.

For test and measurement of magnets we need test stations the 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. This is a specific requirement for the qualification of HTS coils; 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 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 HFM R&D.

References

3 High-gradient Plasma and Laser Accelerators

A. Alici[a], M. Bomben[b], I. Dawson[c], J. Sonneveld[d]
[a]University of Bologna, Italy
[a]LPNHE & University of Paris, France
[c]Queen Mary University of London, United Kingdom
[d]Nikhef, Amsterdam, Netherlands

The Large Hadron Collider is a 26.7 km circular accelerator based on a twin aperture superconducting magnet design with a design proton beam energy of 7 TeV [1]. The four particle physics experiments ALICE, ATLAS, CMS, and LHCb are located at the positions indicated in Fig. 3.1.

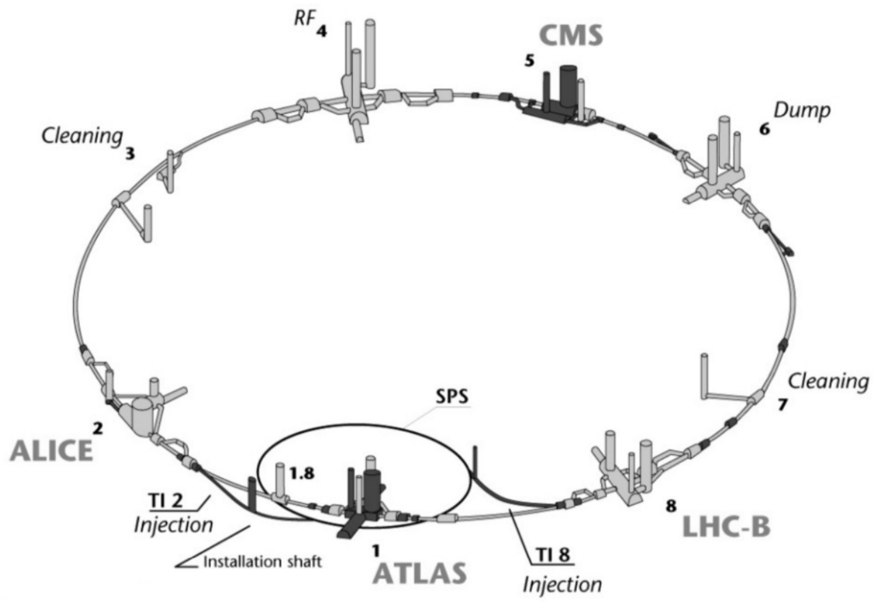

Fig. 3.1: The LHC layout

The LHC was first operated with beams for short periods in 2008 and 2009. In 2010, a first experience with the machine was gained at a beam energy of 3.5 TeV, with moderate beam intensities of 1.1×10^{11} protons per bunch (ppb) and up to ~200 bunches. In 2011, the beam intensity was increased to ~1400 bunches of 1.4×10^{11} ppb, while 2012 was dedicated to luminosity production with higher bunch intensities (1.6×10^{11} ppb) and a beam energy of 4 TeV. The running years 2010–2013 are commonly referred to as Run 1. In early 2013 beam operation was stopped for a 2 year long shutdown (LS1) to complete work on the magnets in view of reaching the design beam energy. Beam operation resumed in 2015 with beam energies of 6.5 TeV following a dipole training campaign that took place at the end of LS1 [2]. The LHC experiments had expressed a strong preference for beams with 25 ns bunch spacing, as opposed to the 50 ns spacing used in 2011–2012, as this would result in too many inelastic collisions per crossing (pile-up). On the machine side, this posed additional challenges, so 2015 became a learning

This contribution should be cited as: High-gradient Plasma and Laser Accelerators, DOI: 10.23731/CYRM-2021-XXX.15, in: European Strategy for Particle Physics - Accelerator R&D Roadmap (Interim Report), Ed. D. Newbold, CERN-2021-XXX, DOI: 10.23731/CYRM-2021-XXX, p. 15.

year dedicated to preparing the machine for full luminosity production in 2016–2018 (Run 2). Further details of machine operation during Run 2 can be found in Ref. [3].

In addition to the proton beams, one month per year is dedicated to running with heavy ions, providing either Pb–Pb or p–Pb collisions. The first two years of Run 1 provided Pb–Pb collisions to the experiments, and the final year was dedicated to p–Pb. Run 2 (2015–2018) again saw a mix of Pb–Pb and p–Pb set-ups, except in 2017- when Xe–Xe collisions were provided for the first time to the experiments.

3.1 Luminosity delivered to the experiments

The main driver of radiation backgrounds in the experiments is from the collisions, although beam backgrounds can play a role too. The rate of collisions R in an experiment is given simply by the product of the particle interaction cross-section σ_{int} and the instantaneous luminosity L:

$$R = L \times \sigma_{int}, \qquad L = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*} F\,, \tag{3.1}$$

where k is the number of colliding bunch pairs, N the particle number of each bunch, and f is the LHC revolution frequency (= 11.25 kHz). Here, σ_x^* and σ_x^* are the horizontal and vertical beam sizes at the interaction point and F (≤ 1) is a geometric reduction factor which takes into account the reduced luminosity due to beam crossing angles at the interaction point.

The situation for ATLAS is similar. The gaps in the measurements correspond either to machine winter technical stops or the long shutdown LS1 (2013–2014). The total integrated luminosities delivered to experiments for pp, p–Pb, and Pb–Pb collisions are given in Table 3.1.

Table 3.1: Total integrated luminosities delivered to each of the experiments for the different particle collisions

	pp ($\mathbf{fb^{-1}}$)		**Pb–Pb ($\mathbf{nb^{-1}}$)**		**p–Pb ($\mathbf{nb^{-1}}$)**	
	Run 1	**Run 2**	**Run 1**	**Run 2**	**Run 1**	**Run 2**
ATLAS	28.0	157.0	0.176	2.37	31.2	183.8
CMS	29.4	162.9	0.184	2.49	36.14	188.3
LHCb	3.47	6.35	-	0.24	2.14	34.1
ALICE	0.015	0.067	0.153	1.34	31.9	43.3

3.2 The large LHC experiments

3.2.1 ATLAS

The ATLAS detector [4] was built and installed at the LHC interaction point 1 in the years 2000 to 2008.

References

[1] M. Mangano, *Physics at the FCC-hh, a 100 TeV pp collider*. CERN Yellow Reports: Monographs. CERN, Geneva, 2017. https://cds.cern.ch/record/2270978.

[2] Planck Collaboration, P. A. R. Ade et al., *Planck 2015 results. XIII. Cosmological parameters*, Astron. Astrophys. **594** (2016) A13, arXiv:1502.01589 [astro-ph.CO].

[3] I. Esteban, M. C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni, and T. Schwetz, *Global analysis of three-flavour neutrino oscillations: synergies and tensions in the determination of* $\theta_{23}, \delta_{\mathrm{CP}}$*, and the mass ordering*, JHEP **01** (2019) 106, arXiv:1811.05487 [hep-ph].

[4] F. Capozzi, E. Lisi, A. Marrone, and A. Palazzo, *Current unknowns in the three neutrino framework*, Prog. Part. Nucl. Phys. **102** (2018) 48–72, arXiv:1804.09678 [hep-ph].

4 High-gradient RF Structures and Systems

A. Alici[a], M. Bomben[b], I. Dawson[c], J. Sonneveld[d]
[a]University of Bologna, Italy
[a]LPNHE & University of Paris, France
[c]Queen Mary University of London, United Kingdom
[d]Nikhef, Amsterdam, Netherlands

The Large Hadron Collider is a 26.7 km circular accelerator based on a twin aperture superconducting magnet design with a design proton beam energy of 7 TeV [1]. The four particle physics experiments ALICE, ATLAS, CMS, and LHCb are located at the positions indicated in Fig. 4.1.

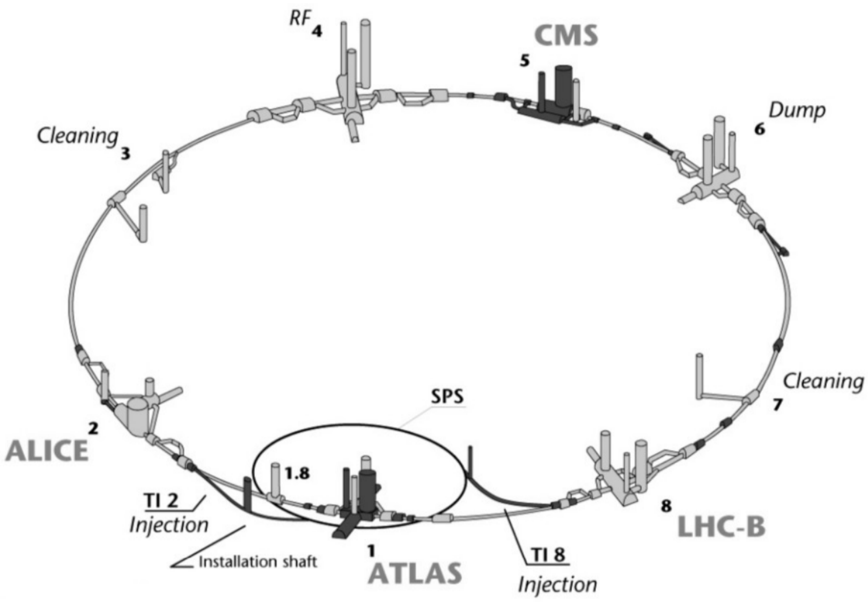

Fig. 4.1: The LHC layout

The LHC was first operated with beams for short periods in 2008 and 2009. In 2010, a first experience with the machine was gained at a beam energy of 3.5 TeV, with moderate beam intensities of 1.1×10^{11} protons per bunch (ppb) and up to $\sim$200 bunches. In 2011, the beam intensity was increased to $\sim$1400 bunches of 1.4×10^{11} ppb, while 2012 was dedicated to luminosity production with higher bunch intensities (1.6×10^{11} ppb) and a beam energy of 4 TeV. The running years 2010–2013 are commonly referred to as Run 1. In early 2013 beam operation was stopped for a 2 year long shutdown (LS1) to complete work on the magnets in view of reaching the design beam energy. Beam operation resumed in 2015 with beam energies of 6.5 TeV following a dipole training campaign that took place at the end of LS1 [2]. The LHC experiments had expressed a strong preference for beams with 25 ns bunch spacing, as opposed to the 50 ns spacing used in 2011–2012, as this would result in too many inelastic collisions per crossing (pile-up). On the machine side, this posed additional challenges, so 2015 became a learning

This contribution should be cited as: High-gradient RF Structures and Systems, DOI: 10.23731/CYRM-2021-XXX.19, in: European Strategy for Particle Physics - Accelerator R&D Roadmap (Interim Report), Ed. D. Newbold, CERN-2021-XXX, DOI: 10.23731/CYRM-2021-XXX, p. 19.

year dedicated to preparing the machine for full luminosity production in 2016–2018 (Run 2). Further details of machine operation during Run 2 can be found in Ref. [3].

In addition to the proton beams, one month per year is dedicated to running with heavy ions, providing either Pb–Pb or p–Pb collisions. The first two years of Run 1 provided Pb–Pb collisions to the experiments, and the final year was dedicated to p–Pb. Run 2 (2015–2018) again saw a mix of Pb–Pb and p–Pb set-ups, except in 2017- when Xe–Xe collisions were provided for the first time to the experiments.

4.1 Luminosity delivered to the experiments

The main driver of radiation backgrounds in the experiments is from the collisions, although beam backgrounds can play a role too. The rate of collisions R in an experiment is given simply by the product of the particle interaction cross-section σ_{int} and the instantaneous luminosity L:

$$R = L \times \sigma_{int}, \qquad L = \frac{kN^2 f}{4\pi\sigma_x^* \sigma_y^*} F\,, \tag{4.1}$$

where k is the number of colliding bunch pairs, N the particle number of each bunch, and f is the LHC revolution frequency (= 11.25 kHz). Here, σ_x^* and σ_x^* are the horizontal and vertical beam sizes at the interaction point and F (≤ 1) is a geometric reduction factor which takes into account the reduced luminosity due to beam crossing angles at the interaction point.

The situation for ATLAS is similar. The gaps in the measurements correspond either to machine winter technical stops or the long shutdown LS1 (2013–2014). The total integrated luminosities delivered to experiments for pp, p–Pb, and Pb–Pb collisions are given in Table 4.1.

Table 4.1: Total integrated luminosities delivered to each of the experiments for the different particle collisions

	pp ($\mathbf{fb^{-1}}$)		**Pb–Pb ($\mathbf{nb^{-1}}$)**		**p–Pb ($\mathbf{nb^{-1}}$)**	
	Run 1	**Run 2**	**Run 1**	**Run 2**	**Run 1**	**Run 2**
ATLAS	28.0	157.0	0.176	2.37	31.2	183.8
CMS	29.4	162.9	0.184	2.49	36.14	188.3
LHCb	3.47	6.35	-	0.24	2.14	34.1
ALICE	0.015	0.067	0.153	1.34	31.9	43.3

4.2 The large LHC experiments

4.2.1 ATLAS

The ATLAS detector [4] was built and installed at the LHC interaction point 1 in the years 2000 to 2008.

References

[1] M. Mangano, *Physics at the FCC-hh, a 100 TeV pp collider*. CERN Yellow Reports: Monographs. CERN, Geneva, 2017. https://cds.cern.ch/record/2270978.

[2] Planck Collaboration, P. A. R. Ade et al., *Planck 2015 results. XIII. Cosmological parameters*, Astron. Astrophys. **594** (2016) A13, arXiv:1502.01589 [astro-ph.CO].

[3] I. Esteban, M. C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni, and T. Schwetz, *Global analysis of three-flavour neutrino oscillations: synergies and tensions in the determination of* $\theta_{23}, \delta_{\rm CP}$*, and the mass ordering*, JHEP **01** (2019) 106, arXiv:1811.05487 [hep-ph].

[4] F. Capozzi, E. Lisi, A. Marrone, and A. Palazzo, *Current unknowns in the three neutrino framework*, Prog. Part. Nucl. Phys. **102** (2018) 48–72, arXiv:1804.09678 [hep-ph].

5 Bright Muon Beams and Muon Colliders

T. Arndt[a], *A. Chance*[b], *J. P. Delahaye*[c], *A. Faus-Golfe*[d], *S. Gilardoni*[c], *P. Lebrun*[c], *K. Long*[e,f], *E. Metral*[c], *M. Palmer*[g], *N. Pastrone*[h], *L. Quettier*[i], *T. Raubenheimer*[j], *C. Rogers*[f], *D. Schulte*[c], *M. Seidel*[k], *D. Stratakis*[l], *A. Yamamoto*[m]
[a] Karlsruhe Institute of Technology (KIT) and Institute for Technical Physics (ITEP)
[b]CEA Saclay, France
[c]CERN, Switzerland
[d]University of Valencia, Spain
[e]Imperial College London, United Kingdom
[f]STFC Rutherford Appleton Laboratory, United Kingdom
[g]Brookhaven National Laboratory, United States of America
[h]INFN Torino, Italy
[i]CEA Lorraine, France
[j]Stanford University, United States of America
[k]Paul Scherrer Institute, Switzerland
[l]Fermi National Accelerator Laboratory, United States of America
[m]KEK, Japan

This contribution should be cited as: Bright Muon Beams and Muon Colliders, DOI: 10.23731/CYRM-2021-XXX.23, in: European Strategy for Particle Physics - Accelerator R&D Roadmap (Interim Report), Ed. D. Newbold, CERN-2021-XXX, DOI: 10.23731/CYRM-2021-XXX, p. 23.

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 [1–3].

The Muon Beam Panel has confirmed that the muon collider is a promising path to high energy 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 3 TeV collider accumulating 1 ab^{-1} would present a facility that, given sufficient resources, could be constructed by 2045, making it suitable to follow on from the end of the HL-LHC. A 10-14 TeV muon collider, accumulating 10-20 ab^{-1} respectively, has a physics reach comparable to a 100 TeV hadron collider. Studies for staging between these facilities seem promising.

Maintaining an option for a collider by 2045 requires R&D to begin now. 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 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 facility to demonstrate the muon production and cooling will be required. 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 and help to ensure a timely implementation of the demonstrator facility. 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 5 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.

1. Neutrino flux from muon decays in the collider and accelerator rings leads to slightly increased levels of radiation far from the collider. A proposed mitigation scheme can reduce the impact of the flux to a level similar to the LHC by moving magnets to change the beam direction; it requires detailed studies of beam physics and engineering.
2. Beam-induced background in the detector can be mitigated using masks and advanced detector design. Initial studies indicate that even the most challenging physics measurements can be performed. Further optimisation of the detector design and collider ring must be performed in concert to provide a full understanding of the potential detector performance and assess physics reach.
3. The collider ring and the acceleration after the muon cooling have not been designed for 10 or more TeV and more detailed and integrated studies are also required for 3 TeV to ensure that the desired performance can be achieved.
4. The production of a high-quality muon beam is required to reach satisfactory luminosity. Previous studies developed a number of designs that, together, come close to reaching the desired beam quality through muon ionisation cooling but further integration and optimision is required. The Muon Ionisation Cooling Experiment (MICE) demonstrated the novel cooling principle. The panel

deems it necessary to demonstrate, with beam, an engineered solution suitable for a muon collider. It appears possible that this demonstrator facility could be leveraged to contribute to a cutting-edge physics programme.

5. High-performance superconducting solenoids are needed in the muon production and cooling, a few of them requiring the use of HTS. The high-energy complex uses high-field dipoles and combined function magnets with performances close to the HL-LHC goal for 3 TeV and significantly more ambitious for 10 TeV. The magnets roadmap will be the basis for their development but dedicated design effort is required for the muon collider. The acceleration system requires special fast-ramping magnets with efficient powering systems.
6. High-field superconducting cavities are employed in the acceleration complex and will profit from the RF roadmap. Specialised, low-frequency, high-gradient normal-conducting cavities operating in a high magnetic field are used in the muon cooling. The principle has been demonstrated and it is necessary to continue this R&D to systematically assess the breakdown rates, push the gradient limits and to move toward production cavities.

Further details are given below.

5.2 Motivation

The current muon collider baseline concept was developed by the Muon Accelerator Program (MAP) collaboration [4], which conducted a focused program of technology R&D to evaluate its feasibility. Seminal measurements have been performed by the Muon Ionization Cooling Experiment (MICE) collaboration, which demonstrated the principle of ionisation cooling that is required to reach sufficient luminosity for a muon collider [5]. The MAP scheme is based on the use of a proton beam to generate muons from pion decay and is the baseline for the collider concept being developed by the new international collaboration. An alternative approach (LEMMA), which uses positrons to produce muon pairs at threshold, has been explored at INFN [6].

5.2.1 Potential of the Muon Collider

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.

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 [7]. 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. The growing interest of the theory community in muon colliders has been expressed in the context of the ongoing Snowmass21 initiative [8,9]. Several sensitivity projection studies have been completed during the last two years, and summarised at three Workshops [10–12] and at regular meetings on the muon collider physics potential [13]. 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. The most obvious aspect is the moderate land use thanks to the relative compactness of the accelerator complex: for a collision energy per elementary constituent in the few TeV range, 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.

A second, decisive advantage concerns the energy efficiency, and more precisely the beam power, and hence the specific electrical power consumption per unit of luminosity. The luminosity that can be achieved per wall-plug 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. While for electron/positron colliders Beamstrahlung dominates the uncertainty of collision energy, such radiation effects are not relevant for collisions of muon beams. Here the limitation is rather 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 summarized in the following scaling formula:

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

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

From this relation the advantageous scaling of efficiency with energy is evident. However, the absolute value of the power consumption for a certain center of mass energy has not been studied or optimized 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.

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.

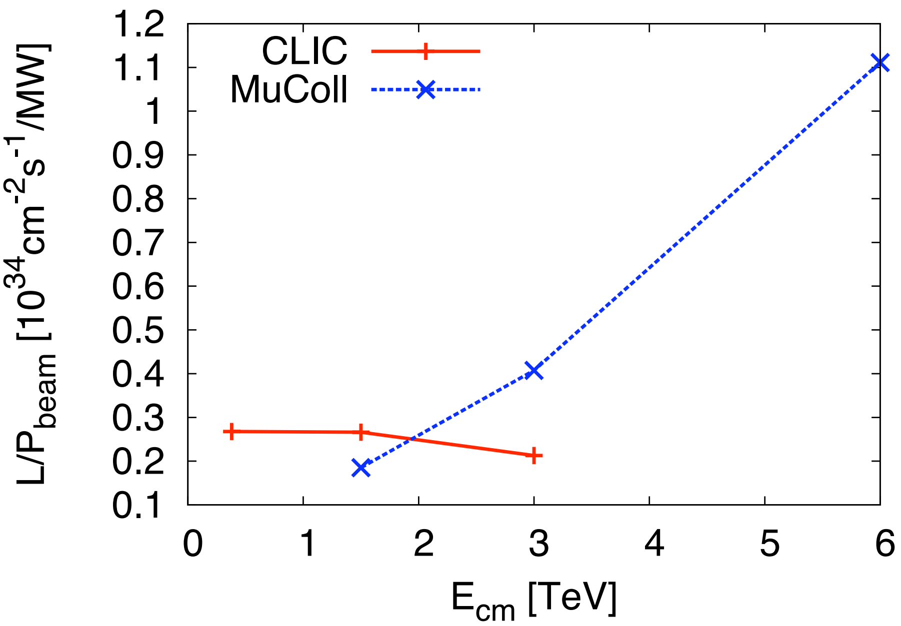

Fig. 5.1: Luminosity of the muon collider compared to CLIC per MW of beam power, compared with the centre of mass energy at the collision point.

5.3 Muon Beam Panel Activities

The muon beam panel is employing three principal tools to develop the input for the roadmap:

– closed, fortnightly meetings of the panel to organise the work and to use the expertise of the members,
– the meetings of the muon collider collaboration, which address the R&D and
– dedicated community meetings and workshops that draw on the world-wide expertise.

Three community meetings have been held in 2021 and at least one more is planned.

– A workshop, held on March 24–25 to assess the testing opportunities for the muon collider, helped to arrive at a first definition of the scope of the demonstrator.
– A community meeting took place on May 20–21 with nine working groups. These working groups, coordinated by an international group of conveners, identified the key R&D challenges across the project.
– A community meeting, held on July 12–14, completed the formulation of the list of R&D challenges and prepared a set of proposals to address the key challenges that must be addressed before the next ESPPU.
– A community meeting in September will discuss the proposed roadmap and will provide feedback to the panel for the preparation of the final report.

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

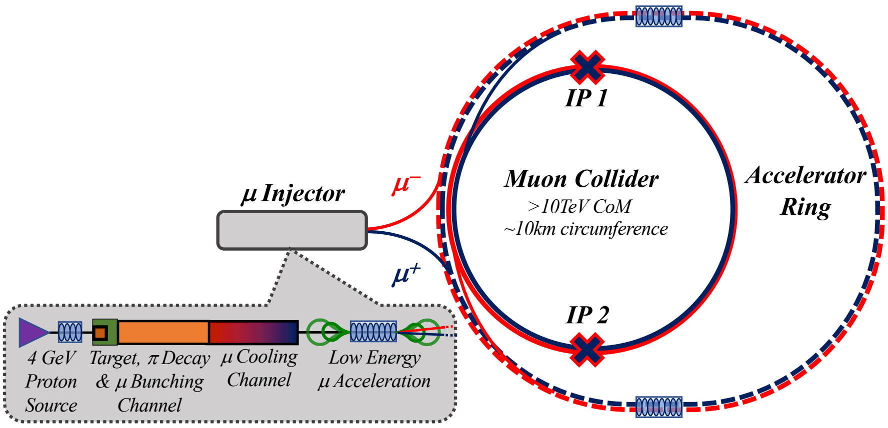

Fig. 5.2: A conceptual scheme of the muon collider.

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. An injector complex produces a high-current positron beam. The positrons impact a target with an energy of 45 GeV, sufficient to produce muon pairs by annihilating with the electrons of the target. This scheme can produce small emittance muon beams. However, it is difficult to achieve a high muon beam current and hence competitive luminosity. Novel ideas are required to overcome this limitation.

5.4.1 Status of the Concept

The MAP Collaboration focused on an evaluation of the feasibility of the key sub-systems required to deliver an energy frontier collider [14]. Several issues were identified as part of the MAP Feasibility

Assessment that had the greatest potential to prevent the realization of a viable muon collider concept. These issues were:

- Development of a 6D cooling lattice design consistent with realistic magnet, absorber, and RF cavity specifications;
- Operation of RF cavities in high magnetic fields in the front end and cooling channel;
- A direct demonstration and measurement of the ionization cooling process;
- Development of very high field solenoids to achieve the emittance goals of the Final Cooling system;
- Demonstration of fast ramping magnets to enable RCS capability for acceleration to the TeV-scale.

While other machine design and engineering conceptual efforts were pursued to develop the overall definition of a muon collider facility, research in the above feasibility areas received the greatest attention as part of the MAP effort.

An important outcome of MAP was that progress in each of the above areas was sufficient to suggest that there exists a viable path forward. 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 [15, 16]; a 6D cooling lattice was designed that incorporated reasonable physical assumptions to meet the 6D cooling targets [17]; a Final Cooling Channel design, which implemented the constraint of a 30 T maximum solenoid field, came within a factor of $\sim$2 of meeting the transverse emittance goal for a high energy collider [18] and current development efforts appear poised to deliver another factor of $\sim$1.5 improvement; while further R&D is required, fast-ramping magnet concepts [19] do exist that could deliver muon beams to the Terascale. Following the end of MAP, acceleration in a recirculating linear accelerator with a FFA arcs was demonstrated by CBETA [20].

In Europe, significant investment into muon accelerator R&D was made in neutrino factory design through the EuroNu and neutrino factory International Design Study [21]. 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 [5]. Rapid acceleration in a fixed field accelerator was demonstrated by EMMA [22]. Schemes for high power targetry using liquid metal [23] and fluidised powder jets [24] were demonstrated, indicating potential for managing proton beam powers even beyond those required for the 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.

In particular, the study will focus on the designs of two machines with centre-of-mass energies of 3 TeV and 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 integrated luminosities of 1, 10 and 20 ab^{-1} within 5 to 10 years, respectively. This increase in luminosity compensates the decrease of the s-channel cross sections.

A staged scenario can be developed by constructing additional acceleration stages that would accelerate 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

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	$\mathcal{L}$	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	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

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.

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 10 TeV lepton collider is uncharted territory and poses a number of key challenges:

- The collider can potentially produce a high neutrino flux that might lead to increased levels of radiation far from the collider. This must be mitigated and is a prime concern for the high energy option.
- The Machine Detector Interface (MDI) where beam induced background might limit the physics reach and the detector and machine needs to be simultaneously optimised. This study is shared with the physics and detector effort.
- The collider ring and the acceleration system that follows the muon cooling can limit the energy reach. These systems have not been studied for 10 TeV or higher energy. The collider ring impacts the neutrino flux and MDI.
- The production of a high-quality muon beam is required to achieve the desired luminosity. Optimisation and improved integration are required to achieve the performance goal, while maintaining low power consumption and cost. The source performance also impacts the high-energy design.

Integrated accelerator design of the key systems is essential to evaluate the expected performance, to validate and refine the performance specifications for the components and to ensure beam stability and quality.

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. Using formulae from [25], one finds 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 [26]. 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 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 [27]. Studies performed so far demonstrate that, given reasonable assumptions of detector performance, it will be possible to perform the most challenging physics measurements [28]. 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 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. **Designs for an accumulator and compressor system should be developed, taking into account existing H^- ion sources and capability of H^- stripping systems for injection into the ring.**

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. The baseline design concept in MAP assumed a 6.75 GeV H^- linac with accumulator and buncher rings to properly format the proton beam with a final combiner system to bring multiple proton bunches simultaneously onto the target for pion production. The proton energy was chosen in order to facilitate a neutrino factory but, in the 5-15 GeV proton energy range, the muon production rate is proportional to the beam power and exhibits only a weak dependence on the beam energy so other energies in this range are suitable [29].

The Front End systems begin with a multi-MW target enclosed in a high-field, large-bore solenoid magnet to enable simultaneous capture of both positive and negative species [30]. A tapered solenoid section matches into a decay channel where the pions produced at the target decay into muons. RF cavities capture the muons into a bunch train and then apply a time-dependent acceleration to decrease the energy spread of the muons [31].

The bunched muons from the Front End must be rapidly cooled to achieve the required emittances for a collider before the unstable muons can decay. In the MAP scheme, an Initial Cooling channel [32], 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 [33] into parallel 6D cooling channels to continue reducing the beam emittance to the levels required for luminosity production in a collider. This emittance reduction for the individual species occurs in 4 distinct steps: 1) 6D cooling of the bunch train that is delivered from the Charge Separator; 2) a Bunch Merge stage to combine the bunch trains into a single bunch of each species [34]; 3) a second 6D Cooling section to reduce the emittance of the individual bunches; and 4) a Final Cooling section that trades the longitudinal emittance for improved transverse emittance of the beam. In the MAP studies, the best 6D cooling performance achieved was based on the so-called Rectilinear Cooling Channel [17] while the performance of the baseline Final

Cooling Channel [18] was limited by the maximum achievable B-field that was assumed for the solenoid magnets in the design.

A solid target might be able to handle 2 MW beam power, but evaluations of the stress and heating must be performed. The short proton bunch length and 5 Hz operation result in a large instantaneous power. A liquid metal [35] or a fluidised tungsten target [24] are alternative solutions in case a solid target cannot withstand the 2 MW or start-to-end studies indicate that the muon survival is insufficient and higher production rates are required.

The system of high-field solenoids around the target and downstream is challenging. At the target the field of a 15 T superconducting solenoid is boosted to 20 T with an inner copper solenoid. An alternative 15 T solution has also been explored by the MAP collaboration and may have sufficient performance [30]. The large 1.2 m aperture of the superconducting solenoid provides space for shielding from the target debris to avoid quench and radiation damage. The magnet design, with associated proton dump, and the radiation environment are key for overall machine performance. **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. Alternative solutions, for example using liquid metal, should be considered to manage the large instantaneous power.**

While subsystem designs exist that indicate the cooling performance required to deliver the required luminosity, they have not been integrated and further optimisation is expected to yield significant performance improvements.

The accelerating cavities are key to cooling efficiently and with limited loss of muons. They need to provide a high gradient in a strong magnetic field and the two approaches considered in MAP, high-pressure hydrogen filled cavities and beryllium end-caps are unconventional technology. **The accelerating cavities should be developed experimentally so that they can be properly integrated into a cooling demonstrator**.

The baseline final cooling uses high field solenoids to minimise the beam emittance. Pushing their field beyond the current state-of-the-art, around $\sim$30 T, would improve the collider performance and appears feasible given the rate of progress in magnet R&D. The luminosity increases roughly linearly with the field and the high energy systems could potentially have smaller apertures, which can simplify their design. **The current and expected availability of high field solenoids should be examined and appropriate magnet options should be incorporated into the muon collider design.**

The overall design has to be optimised to improve the transverse emittance by a factor two and achieve the target performance; 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**.

5.5.6 High-energy complex

Cooled muons are accelerated through a sequence of accelerators. The MAP scheme envisioned an initial LINAC followed by a recirculating LINAC (RLA) that could provide 5 GeV muons for neutrino factory applications [36]. A second RLA would then take the beams to 63 GeV to enable an s-channel Higgs Factory option. To reach the TeV-scale, a series of Rapid Cycling Synchrotrons would be used to reach beam energies of 750 GeV, 1.5 TeV, and 3 TeV, depending on the choice of collider energy by the community.

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 [37]. 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.**

5.5.7 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 facility with beam is required to demonstrate the ability of the muon collider to deliver the requisite luminosity. 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 6 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. Preliminary studies indicate that construction of a junction cavern may be required in the next long shutdown in order to meet the timeline of the muon collider. **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

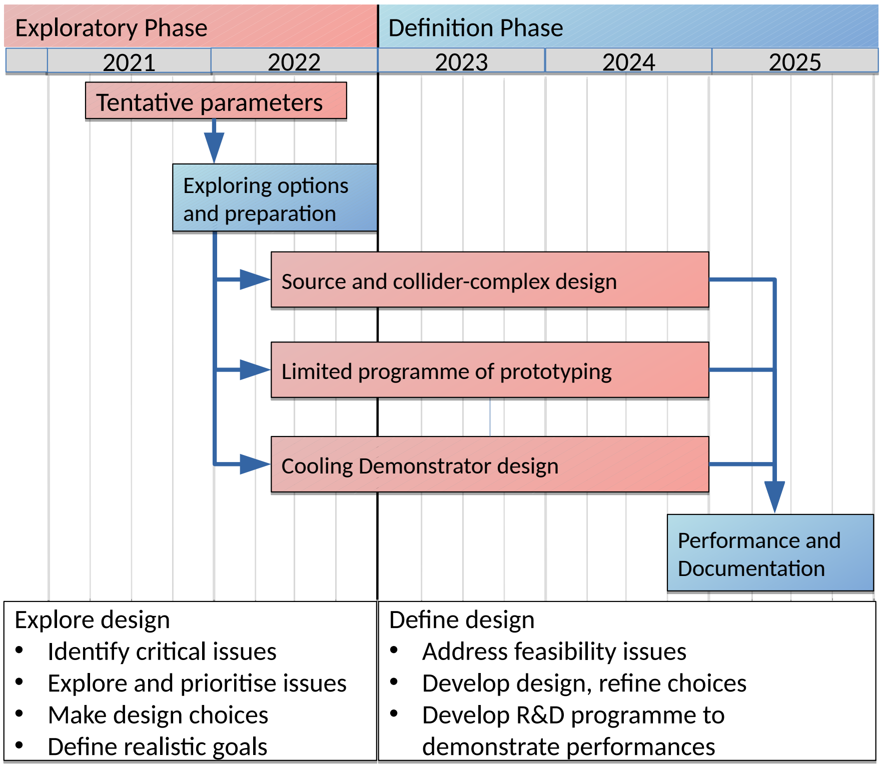

Fig. 5.3: A timeline for muon collider R&D leading to the next ESPPU.

A technically limited timeline for the muon collider R&D programme proposed for the next 5 years is outlined in fig. 5.3. Two phases have been identified: the Exploratory Phase and the Definition Phase. The execution of the proposed R&D will enable a 3 TeV muon collider to be constructed in 2045, given a significant resource uplift following the next ESPPU.

In the Exploratory Phase existing studies will be identified and early stage design work will be performed leading to a tentative parameter set. A technology baseline will be established 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 for a demonstrator 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.

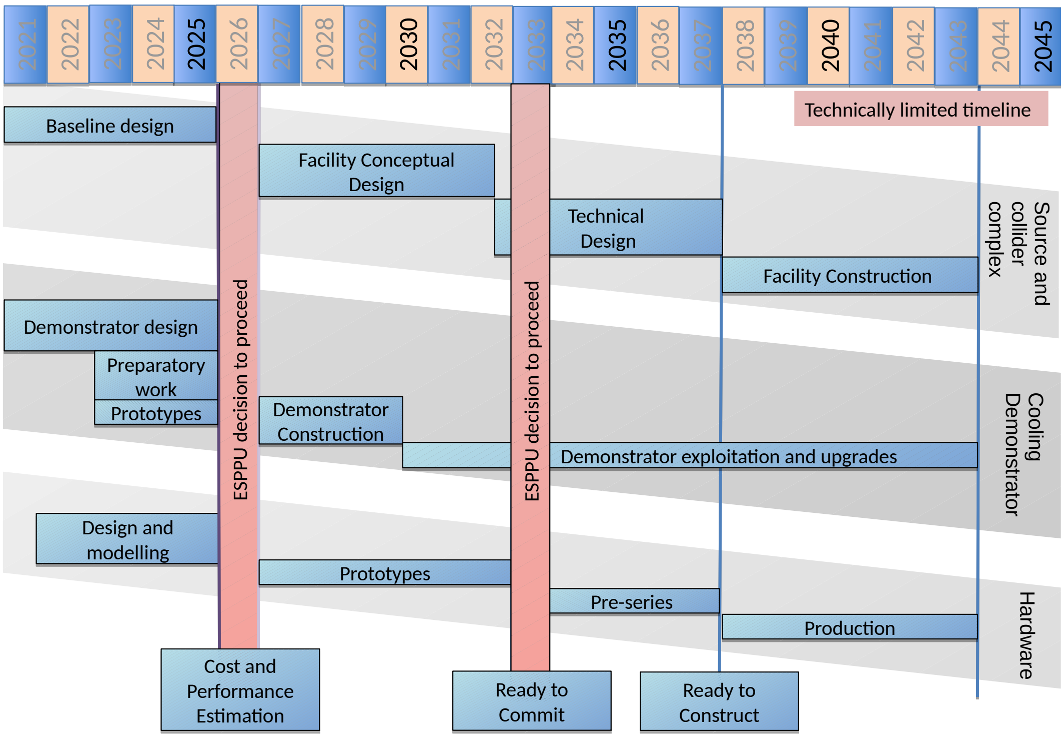

Fig. 5.4: A technically limited timeline for the muon collider R&D programme.

The programme timeline leading to construction of a 3 TeV muon collider is outlined in fig. 5.4. Following the next update of the European strategy, and subject to the prioritisation made at that point, the project would 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. The demonstrator facility will be constructed and exploitation would begin. This will enable a technical design phase to begin in the early 2030s and construction of a 3 TeV collider by 2045.

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. 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 allow the next ESPPU to make fully informed decisions. It will also benefit equivalent strategy processes in other regions. Based on these decisions a significant ramp-up of resources could be made to accomplish construction by 2045 and exploit the enormous potential of the muon collider.

5.8.1 Acknowledgement

We would like to thank the conveners of the community meetings as well as the speakers and participants of the community meeting, the meeting on muon collider testing opportunities and of the regular muon collider meetings. Special thanks go to Andrea Wulzer and Donatella Lucchesi for valuable comments on the physics and detector. We would also like to thank Alexej Grudiev and Roberto Losito for valuable contributions.

References

[1] J. P. Delahaye et al. Muon colliders. *arXiv*, 1901.06150, 2019.

[2] European Large National Laboratories Directors Group (LDG). Minutes of the LDG meeting on July 2, 2020.

[3] http://muoncollider.web.cern.ch.

[4] https://map.fnal.gov/.

[5] M. Bogomilov et al. Demonstration of cooling by the muon ionization cooling experiment. *Nature*, 578, 2020.

[6] D. Alesini et al. Positron driven muon source for a muon collider, 2019.

[7] P. Roloff et al. The Compact Linear e^+e^- Collider (CLIC): Physics Potential. 12 2018.

[8] A. Wulzer et al. Letter of interest: Muon collider physics potential. *Submission to Snowmass21*.

[9] H. Al Ali et al. The Muon Smasher's Guide. *ArXiv*, 2103.14043, 2021.

[10] https://indico.cern.ch/event/1037447/.

[11] https://indico.cern.ch/event/969815/.

[12] https://conference.ippp.dur.ac.uk/event/967/.

[13] https://indico.cern.ch/category/12792/.

[14] J. P. Delahaye M. Boscolo and M. Palmer. The future prospects of muon colliders and neutrino factories. *RAST*, 10, 2019.

[15] B. Freemire et al. The experimental program for high pressure gas filled radio frequency cavities for muon cooling channels. *JINST*, 13, 2018.

[16] D. Bowring et al. Operation of normal-conducting RF cavities in multi-tesla magnetic fields for muon ionization cooling: A feasibility demonstration. *PRAB*, 23, 2020.

[17] D. Stratakis and R.B. Palmer. Rectilinear six-dimensional ionization cooling channel for a muon collider: A theoretical and numerical study. *PRSTAB*, 18, 2015.

[18] H. Sayed et al. High field - low energy muon ionization cooling channel. *PRSTAB*, 18, 2015.

[19] J.S. Berg and H. Witte. Pulsed synchrotrons for very rapid acceleration. *AIP Conference Proc.*, 1777, 2016.

[20] A. Bartnik et al. CBETA: First Multipass Superconducting Linear Accelerator with Energy Recovery. *Phys. Rev. Lett.*, 125(4):044803, 2020.

[21] M. Bogomilov et al. Neutrino factory. *PRSTAB*, 17, 2014.

[22] S. Machida. Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA. *Nature Physics*, 8, 2012.

[23] I. Efthymiopoulos et al. The MERIT (nTOF-11) high intensity liquid mercury target experiment at the CERN PS. *Proc. European Particle Accelerator Conference*, 2008.

[24] O. Caretta et al. Proton beam induced dynamics of tungsten granules. *PRAB*, 21, 2018.

[25] B. King. Neutrino radiation challenges and proposed solutions for many-TeV muon colliders. *BNL - 67408*, 2000.

[26] N. V. Mokhovy and A. Van Ginneken. Neutrino induced radiation at muon colliders. *Proc. of the Particle Accelerator Conference*, 1999.

[27] F. Collamati et al. Advanced assessment of beam induced background at a muon collider. *ArXiv*, 2105.09116.

[28] N. Bartosik et al. Detector and physics performance at a muon collider. *JINST*, 15, 2020.

[29] M. Zisman. Proton beam requirements for a neutrino factory and muon collider. *Proc. of the Workshop on Applications of High Intensity Proton Accelerators*, LBNL-2932E, 2009.

[30] X. Ding et al. Carbon and mercury target systems for muon colliders and neutrino factories. *Proc. of the International Particle Accelerator Conference*, 2016.

[31] D. Neuffer et al. Front end for a neutrino factory or muon collider. *JINST*, 12, 2017.

[32] Y. Alexahin. Helical FOFO snake for initial six-dimensional cooling of muons. *JINST*, 13, 2018.

[33] C. Yoshikawa et al. A charge separation study to enable the design of a complete muon cooling channel. *Proc. of the Particle Accelerator Conference*, 2013.

[34] Y. Bao et al. Conceptual design and modeling of a six-dimensional bunch merging scheme for a muon collider. *PRAB*, 19, 2016.

[35] K. Tsujimoto et al. Research and development program on accelerator driven subcritical system in jaea. *Journal of Nucl. Sci. and Tech.*, 44(3), 2007.

[36] S.A. Bogacz. Muon acceleration concepts for numax:dual-use linac and dogbone rla. *JINST*, 13, 2018.

[37] Y. Alexahin et al. Muon collider lattice concepts. *JINST*, 13, 2018.

6 Energy Recovery Linacs

Deepa Angal-Kalinin (STFC Daresbury), Kurt Aulenbacher (Mainz), Alex Bogacz (Jlab), Georg Hoffstaetter (Cornell/BNL), Andrew Hutton (Co-Chair, Jlab), Erk Jensen (CERN), Walid Kaabi (IJCLab Orsay), Max Klein (Chair, Liverpool), Bettina Kuske (HZB Berlin), Frank Marhauser (Jlab), Dmitry Kayran (BNL), Jens Knobloch (HZB Berlin), Olga Tanaka (KEK), Norbert Pietralla (TU Darmstadt), Cristina Vaccarezza (INFN Frascati), Nikolay Vinokurov (BINP Novosibirsk), Peter Williams (STFC Daresbury), Frank Zimmermann (CERN)

6.1 Executive summary of findings to date

The fundamental principles of energy recovery linacs (ERLs) have been successfully demonstrated across the globe. There can no longer be any doubt that an ERL can be built and achieve its goals. The panel has drafted a long write-up, as an introduction to “The Development of Energy Recovery Linacs" [1], and held an ERL Symposium [2]. It currently evaluates recent electron-positron collider ERL concepts and moves towards the development of a Roadmap on ERLs - to serve future colliders, but as well low energy particle and nuclear physics. ERLs promise a luminosity increase for physics applications by orders of magnitude, at a power consumption comparable to classic, low luminosity solutions, which is a necessary step towards the sustainability of high energy physics, as interaction cross sections fall with rising energy. ERLs are also near utilisation in several industrial and other applications.

The novel high energy ERL concepts, for 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 cryo-modules and a physics quality beam eventually for experiments" (Bob Rimmer in [2]).

Europe’s next endeavours are MESA at Mainz, a polarised beam facility for experiments, bERLinPRO, and accelerator R&D facility at Berlin with the potential to reach 100 mA of electron current, and a dedicated high power, multi turn facility, PERLE at Orsay, which is being developed by a large international collaboration. Moderate investments, compared to other accelerator R&D projects, will be required to have this programme adequately supported. Globally, ERLs deserve coordinated cooperation, with the developments of high current ERL facilities at BNL, BINP and KEK, with a forthcoming high energy experiment at CEBAF as well as of plans for next generation facilities. High current ERL operation causes major challenges, such as beam breakup instabilities or RF transients, requiring collaborative efforts across the various facilities. In summary, the panel notes with much interest that the ERL technology is close to its high current and 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 resource is a prime 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 for this unique potential to bear fruit.

This contribution should be cited as: Energy Recovery Linacs, DOI: 10.23731/CYRM-2021-XXX.41, in: European Strategy for Particle Physics - Accelerator R&D Roadmap (Interim Report), Ed. D. Newbold,
CERN-2021-XXX, DOI: 10.23731/CYRM-2021-XXX, p. 41.

6.2 Motivation

6.2.1 *Sustainability*

Energy Efficiency and sustainability have received a lot of attention over recent years. The concerns about climate change and global warming have to be taken especially seriously, also by the accelerator community. To quote F. Bordry [3]: "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 prime goal for the panel to evaluate the power economy of ERLs and to emphasise techniques being developed to further minimise the use of power. The accelerator community drives research and development at the cutting edge of technology for a greater purpose than just making the next accelerator better: Society expects a return from the investment in this research, which includes other applications of accelerators and further spin-offs. Innovation in accelerator technology, often linked to energy frontier physics, has been a prime attraction to new talents, training of whom is an important part of the sustainability program here followed.

6.2.2 *Accelerator Development*

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 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 beam for colliding against hadrons (eh), positrons (e^+e^-) or photons ($e\gamma$). They all rely on the provision of high electron currents (of I_e up to $\sim 100\,\mathrm{mA}$) and high quality cavities ($Q_0 > 10^{10}$).

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 [4]. 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.

6.2.3 *ERL based Physics Prospects*

ERLs provide a maximum luminosity through a high brightness source, and high energy through possibly multi-turns and high power, which is recovered in the deceleration of a used beam. It is most remarkable, that following the LHeC design from 2012 [5] (updated in 2020 [6]), all these avenues have been followed: for $\gamma\gamma$ collisions [7], further for eh with the FCC-eh in 2018 [8], for e^+e^- in 2019 (an ERL concept for FCC-ee termed CERC [9]) and in 2021 (an ERL version of the ILC termed ERLC [10]) and very recently a concept for the generation of muon pairs through high energy and current $e\gamma$ collisions [11].

A common task for these colliders are 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 corners of phase space.

At low energies, the luminosity is similarly crucial for several physics applications, such as polarised ep scattering for weak interactions, elastic form-factor measurements or dark-photon searches as are planned for MESA and had been pursued at Jlab. Very high ERL intensity may permit to use internal targets which avoids external target acceptance uncertainties. In backscattered photon scattering, the luminosity available exceeds that of ELI by few orders of magnitude paving the way to nuclear photonics, an area possibly comparable with the appearance of lasers in the sixties. A further fundamental interest regards the exploration of unstable nuclear matters with intense electron beams of O(500) MeV energy as is characteristic for PERLE and envisaged for GANIL in France. This follows 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".

6.2.4 Industrial and other Applications

The range of further applications, beyond particle and nuclear physics, is very remarkable. It is briefly presented in the ERL paper [1], using high power lasers, photo-lithography and the use of inverse Compton scattering (ICS) as examples. 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 orders of magnitude higher than that of the XFEL.

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 a few nm dimension, 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 EUV. 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, presented in [1] for its nuclear physics but also exotic medical isotope generation and transmutation applications, 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-tuneable, artificial gamma-ray beams. They will enable quantum-state selective excitation of atomic nuclei along with a yet-unexploited field of corresponding applications.

6.3 Panel activities

The ERL Roadmap Panel was recruited and its membership endorsed by the LDG in early 2021. It has 18 members, representing leading institutions and major ERL facilities (past, operational 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 [1], from which a Roadmap would naturally emerge in a second phase of activity. Today, a draft of 220 pages exists citing 350 references, which is being completed in the coming weeks. The write-up, besides the panel, currently has about thirty further authors for covering the field with the necessary expertise.

On Friday 4^{th} of June, an extended Symposium on the Development of Energy Recovery Linacs was held [2], introduced by Dave Newbold for the LDG. With up to 100 participants, and including an hour long discussion, this was an important consultation with a community of interested accelerator, particle and nuclear physicists. Max Klein was invited to present to a TIARA meeting (29.6.21), while Andrew Hutton talked at the subsequent Particle Physics Symposium [12] (9.7.21).

While the panel started to work, the ERLC concept was put forward to 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 to configure the FCC-ee as a circular energy recovery collider, with very high luminosity extending to large cms energy, maximally 600 GeV. This caused the formation, in agreement with the LDG, of a sub-panel [1] to evaluate the luminosity prospects, the involved R&D, schedule and cost consequences for both ERL based e^+e^- collider options. It is intended to document the findings of the sub-panel in an Appendix to the ERL baseline paper, which will be published in early autumn 21.

The panel is moving towards the genuine ERL Roadmap document, based on its insight from the long ERL write-up [1] and corresponding to its mandate.

6.4 State of the art

6.4.1 Current Status

A long way has been paved since the first SRF ERL [13] at Stanford, as is described in the panel's write-up [1]. Key parameters of an ERL are the electron beam current I_e ($\propto$ luminosity) and energy E_e. The beam power is simply $P = I_e E_e$. 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 $10^{34}\,\mathrm{cm^{-2}s^{-1}}$ luminosity for which without energy recovery a GW of beam power would be required. 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 reached the highest energy so far, of 1 GeV, 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 SC facilities (dark green) currently operational, S-DALINAC at Darmstadt, CBETA at Cornell and the compact ERL at KEK in Japan.

Five facilities in progress, of which three are in Europe, marked in dark blue, 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 single pass. MESA at Mainz will serve a number of low energy experiments, the only facility with polarised beams so far. PERLE is designed for high current (20 mA), 3-turn operation leading to 500 MeV beam energy.

Fig. 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 (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. 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 3-turns) and, in a single pass, of an upgraded bERLinPRO and the CeC at BNL in its most challenging configuration.

6.4.2 Plans for the Next Years - Operational Facilities

The existing and forthcoming facilities have specific development plans which are listed here and detailed in the long write-up [1]. These activities and plans underpin to quite some extent the common, main R&D objectives which are detailed in Section 6.5.

– S-DALINAC (TU Darmstadt)
  - establishment of a multi-turn SRF-ERL with high transmission (up to 70 MeV and 20 μA);

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

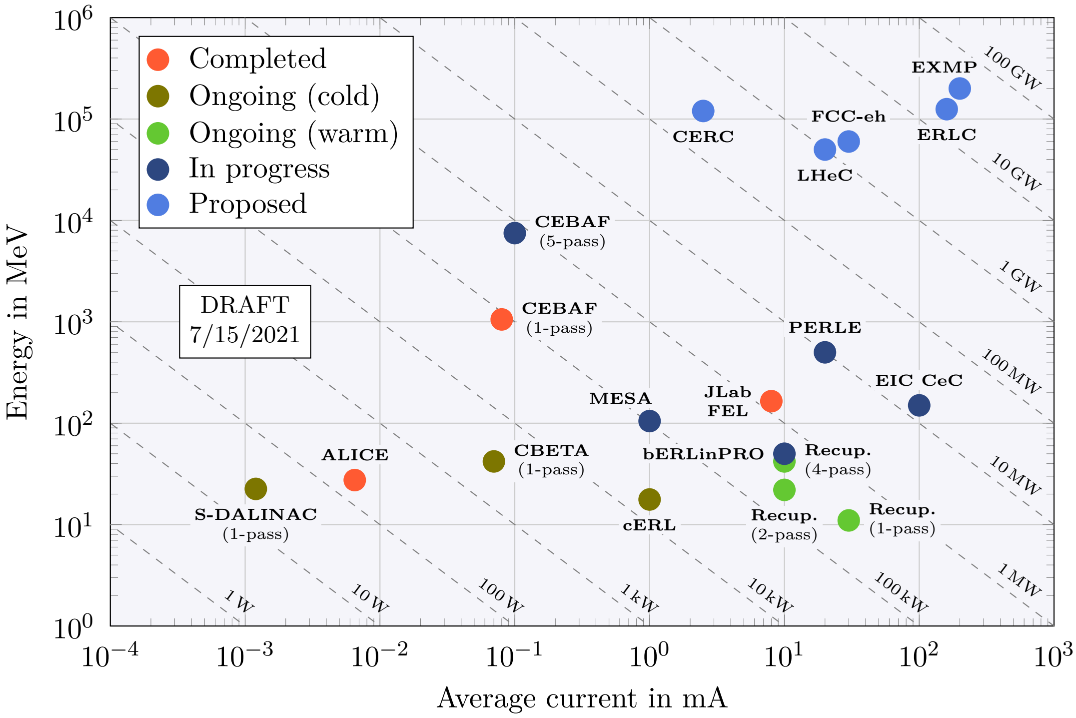

Fig. 6.1: Electron energy vs current for ERL facilities, draft plot from [1], see text.

- quantification of phase-slippage effects in multi-cell-cavity-ERLs and counter-measures;
- characterisation of potential working points of individually-recirculating ERLs.

– Recuperator (BINP Novosibirsk)
- The current of the Novosibirsk ERL is now limited by the electron gun. A new RF gun was built and tested recently. It operates at a frequency of 90 MHz. An average beam current of more than 100 mA was achieved;
- Plans are to install this 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. The beam parameters were measured after the first bending magnet and at the beamline exit.

– CBETA (Cornell)
- 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.

– bERLinPRO (HZB Berlin)
- Present activities are focused on the high-current SRF photoinjector and associated technologies. A dedicated diagnostic line capable of handling 10 mA is installed to characterise the beam;
- Following the upcoming booster installation, the beam can be transported through the merger to the high-power beam dump following the splitter section, allowing studies of emittance preservation, beam loss, and bunch length manipulation.

– cERL (KEK)
- Development of 10kW class powerful ERL -based EUV-FEL;
- Realisation 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;
- Further, planning to develop a high efficiency high gradient Nb_3Sn acceleration cavity to realise a superconducting cryomodule based on the compact freezer.

– MESA
- Improving electron beam polarimetry to an accuracy $dP/P \leq 0.5\%$ in order to support the first physics measurements of electroweak observables, possibly including Hydro-Moeller polarimeter;
- Installing a second photo-source at the MESA injector with the potential to provide bunch charges > 10 pC with good beam quality;
- Improving the cavity HOM damping capabilities, for instance by coating of the HOM antennas by layers of high TC-material.

6.5 R&D objectives

As the state of the art section above indicates, the development of ERLs has been a complex challenge regarding several interrelated technology issues. The panel identified three key research and development objectives of particular importance: i) the provision of electron beams of high brightness, ii) the development of high quality SRF technology designed for ERL use and iii) the development of supportive technology including software and simulation techniques. It is characteristic for the field that its eventual progress relies on complete ERL facilities, for which a new generation is forthcoming, presented in Sect. 6.7.

6.5.1 High Current Electron Sources

Injectors for high energy physics ERLs, which require high average current in combination with complicated beam temporal 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 antimonids, or GaAs based systems for polarised beams, in combination with a photocathode drive laser and extra high vacuum accelerating structure.

The quality of the photocathode is relevant for the performance of the photo-injector 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 photo-injectors 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 system 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 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 antimonit 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.

6.5.2 Superconducting RF Technology

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. 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 a linear collider is 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. Presently, operation at moderate gradients (around 15 - 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 higher-order mode (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 O(100) 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.

For CW operation, dynamic losses ($\propto E_{acc}^2$) dominate the cryogenic load and pragmatically limit the gradient. In recent years a big improvement with Nb cavities was demonstrated with novel techniques such as nitrogen doping, effectively doubling the (typically) 2-K operating Q_0. A promising approach looks at the possible use of so-called A15 materials (like Nb_3Sn) or V_3Si with higher T_c. First relevant tests with Nb_3Sn-coated cavities, which can be operated at higher temperature (4.2 K) and thus with significantly less power consumption for cryogenics, have reached encouraging results.

6.5.3 Supportive Technology, Simulations and Training

There are several important technology and development items to accompany the facilities in operation and those forthcoming. We provide here a non-exhaustive list of examples, which deserve further attention.

Fast Reactive Tuners

ERL cavities are essentially free of beam loading and in theory could be operated with a negligible RF power. However, beam transients and the constant microphonic detuning of the resonance requires one to operate with an increased coupling and RF power overhead that can exceed the theoretical value by an order of magnitude and more. Most of the power is reflected and dumped. A side effect is that the RF stability and hence beam stability also suffers. This waste can be avoided if one can rapidly and continuously readjusts the cavity resonance. Piezo-electric tuners have been investigated for some time and more recently, very promising ferro-electric $BaTiO3 - SrTiO3$-based fast reactive tuners are under development. Their suitability and longevity with full SRF systems without and with beam must be demonstrated to capitalise on their enormous potential.

Diagnostics developments

ERLs have specific diagnostics needs because of (a) the large beam power, (b) the small emittance that is to be preserved, and (c) the low beam loading that needs to be maintained in the main linac cavities. (a) 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. Once loss regions have been identified with these devices, their sources can be addressed, e.g. by collimation of the beam at low energies. (b) The small emittances of ERLs have to be preserved to high energy. While the energy is subsequently recovered, the beam size has to remain small enough to keep loss rates low. View screens can be used when setting up the accelerating paths, but only in those return-loop regions where the accelerating beams of all turns can be separated. One source of emittance dilution can be Coherent Synchrotron Radiation (CSR) which may cause a micro-bunching instability. Such micro bunching has been observed at CBETA and will have to be monitored to avoid the resulting emittance growth. Novel diagnostics that does not interrupt the beam has to be used for the decelerating passes. Effects that occur only at large beam currents, e.g. wake effects and beam-ion interactions also require non-interrupting diagnostics that is yet to be developed. (c) In each cavity, the energy during all accelerating turns must match the energy that is recovered during all decelerating turns. Only then can each cavity be operated by the low drive powers installed in ERLs. This balance can only be maintained when the time for each accelerating and decelerating path is closely monitored by precise arrival time monitors.

Simulation Studies and Education

Before a facility may advance and hardware be built, it requires reliable simulations, based on collaborative efforts, 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 requiring considerable CPU power. One can list a few specific beam dynamics studies related to ERLs:

- Study of CSR leading to micro bunching and ultimately to beam quality degradation and emittance dilution. Simulations are instrumental in developing mitigation measures to suppress micro-bunching 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 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 ability to transport the bunch in the decelerating passes.

The above selection of beam dynamics studies illustrate 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 Key points of roadmap

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 development is that it needs operational facilities with complementary parameters and tasks to be successful. The global landscape of existing ERL facilities, including S-DALINAC in Europe, which are under further development, is rich, as has been sketched in Section 6.4.

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 6.5, 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. MESA at Mainz will provide crucial insight in the handling of high beam polarisation in an ERL.

Four developments of high energy and current facilities, presented in Section 6.7, are expected to provide major progress for the ERL field and a base for decisions due in the twenties on next generation HEP colliders, and their further development. For Europe, a roadmap focus will be on the utilisation of bERLinPRO for 100 mA developments and on a timely realisation of PERLE as a hub for accelerator developments and low energy physics. These and further considerations will be the base for the European ERL Roadmap to be worked out in detail henceforth.

With appropriate financial support and enhanced attention to the European plans, complemented by the developments in the US and Asia, the road to powerful ERLs for application in energy frontier colliders, as well as for new generations of intense particle and nuclear physics experiments, can be timely followed with considerable confidence.

6.7 Facilities and infrastructure

The ERL roadmap is about R&D on key technology items and their use in complete facilities. The ERL development is reaching higher energies and currents in facilities which allow the in depth study of associated technology and operation phenomena as are described in [1]. Several facilities are in progress with programs as here sketched and design parameters as indicated in Fig. 6.1:

– CEBAF 5-pass (ER@CEBAF Jefferson Lab)
  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 8 GeV, where effects such as coherent synchrotron radiation will notably occur. For the coming 4 years, the project has the following plans, also in collaboration with the University of Brussels and STFC Daresbury:
  - Engineering design for a half-lambda delay chicane;

- install dipoles for the delay chicane and the extraction dump;
- Continue ongoing beam dynamics studies;
- Finalising the Optics design, including sextupoles;
- Develop a step-by-step experiment run schedule (2024).

– bERLinPRO Upgrade (Helmholtz Zentrum Berlin)
The beam transport and technical infrastructure for 100 mA, 50 MeV ERL operation has been set up at the HZB. The facility is dedicated to SRF accelerator research, including ERL operation. It is nearly complete, including all RF power and cryogenics infrastructure and diagnostics for extensive beam studies, while the 1.3 GHz linac has been partially designed but isn't funded so far but leaves room for adaptation to accommodate new developments. bERLinPRO, being a part of the HZB SupraLab SRF test infrastructure, can, for example, be used to explore the use of Fast Reactive Tuners with beam or to further develop high-current SRF guns. A first high-current SRF gun, delivering up to 10 mA with an emittance better than 1 mm mrad, will be re-commissioned in 2022 (see above) and could be upgraded to 100 mA. The underground building with massive shielding is laid out to handle up to 30 kW continuous beam loss at 50 MeV.

– EIC electron Cooler CeC (Brookhaven Nation Lab)
Coherent Electron Cooling (CeC) 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 an average power of 15 MW or 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. Alternatively, the second CeC design is based on a plasma-cascade microbunching amplifier. Both CeC designs require an ERL operating with parameters beyond the state of the art.

– PERLE (Irène Joliot Curie Laboratory, Orsay)
PERLE is a compact three-pass ERL project using SRF technology, pushing as a new generation machine the operational regime for multi-turn ERLs to around 10 MW beam power. PERLE will serve as a hub for the validation and exploration of a broad range of ERL accelerator phenomena in a so far unexplored operational regime serving for the development of ERL technology for future energy and intensity frontier machines. Particularly, the PERLE facility targets the LHeC configuration by featuring a 3-turn acceleration and 3-turn deceleration racetrack configuration, an 802 MHz SRF system and beam currents of up to 20 mA (corresponding to a 120 mA cavity load). A first Nb cavity, realised at Jlab in collaboration with CERN for FCC-ee and LHeC, had a high Q_0 of $3 \cdot 10^{10}$ up to a gradient of nearly 30 MV/m. The facility initially uses in-kind deliveries: of the gun (from ALICE at Daresbury), the booster cryostat (from Jlab, using the module designed for JLEIC) and the main linac cryostat (from CERN adapting the SPL module). The Collaboration (BINP, CERN, U Cornell, IJClab Orsay, Jlab, U Liverpool, STFC Daresbury, with others expressing interest), has recently established an ambitious plan for first beam operation in the mid twenties. A second linac module, likely including FRT technology, and several electron-scattering experiments are in the early phase of planning.

References

[1] Deepa Angal-Kalinin et al. The Development of Energy Recovery Linacs. *A Contribution to the European Strategy, to be published*, 2021.

[2] Symposium on ERLs. https://indico.cern.ch/event/1040671/. June 2021.

[3] Frederick Bordry. Introduction to the fifth Workshop on Energy for Sustainable Science, PSI,Switzerland. *unpublished*, November 2019.

[4] M. Tigner. A possible apparatus for electron clashing-beam experiments. *Nuovo Cim.*, 37:1228–1231, 1965.

[5] J. L. Abelleira Fernandez et al. A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector. *J. Phys.*, G39:075001, 2012.

[6] P. Agostini et al. The Large Hadron-Electron Collider at the HL-LHC. *J. Phys. G to appear, arXiv:2007.14491*, 2020.

[7] S. A. Bogacz, J. Ellis, L. Lusito, D. Schulte, T. Takahashi, M. Velasco, M. Zanetti, and F. Zimmermann. SAPPHiRE: a Small Gamma-Gamma Higgs Factory. *arXiv:1208.2827*, 2012.

[8] A. Abada et al. FCC-hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3. *Eur. Phys. J. ST*, 228(4):755–1107, 2019.

[9] Vladimir N. Litvinenko, Thomas Roser, and Maria Chamizo-Llatas. High-energy high-luminosity e^+e^- collider using energy-recovery linacs. *Phys. Lett. B*, 804:135394, 2020.

[10] V. I. Telnov. A high-luminosity superconducting twin e^+e^- linear collider with energy recovery. *arXiv:2105.11015*, 2021.

[11] C. Curatolo and L. Serafini. GeV muon beams with picometer-class emittance from electron-photon collisions. *arXiv:2106.03255*, 2021.

[12] Symposium on Accelerator R&D. https://indico.cern.ch/event/1053889/. July 2021.

[13] R. Rohatgi, H. A. Schwettman, and T. I. Smith. A Compact energy recovered FEL for biomedical and material science applications. *Conf. Proc. C*, 870316:230, 1987.

7 Conclusion

The LHC experiments have been running successfully and taking data since 2010. Much experience has been gained in running detector systems in challenging radiation conditions, and the impact on operation and performance has been assessed in this report. In general, we find the impact of the radiation effects to be in accordance with initial design expectations. While some unexpected effects have been observed with challenging consequences, these were in general successfully mitigated against.

We showed the many measurements related to radiation damage performed by the experiments. A variety of probes have resulted in a detailed diagnostic information that can be used for modifying models, guiding operation and upgrades, as well as improving the quality of offline reconstruction. For leakage current, existing models that were mostly developed at independent irradiation facilities describe the existing data reasonably well, while other probes like depletion voltage are less well modelled. Expanding and enhancing this measurement program into Run 3 and the HL-LHC will be critical for preserving and possibly enhancing physics analysis as radiation damage becomes even more prominent. Further developments of the existing models will be required to make the most use of future measurements and the existing data may provide powerful constraints on these models, including estimating uncertainties.