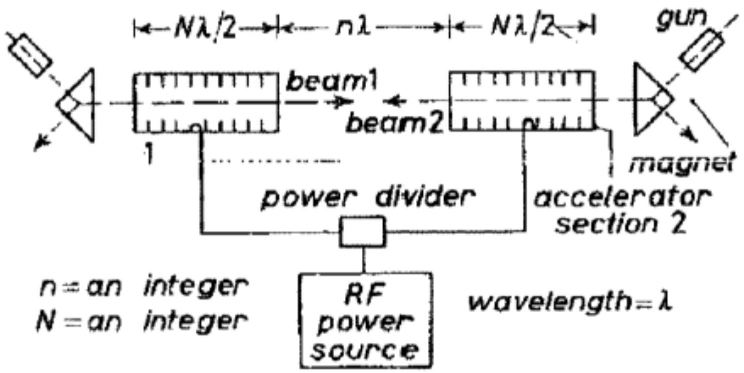
Development of Energy Recovery Linacs

Towards a European ERL Roadmap

Max Klein

UNIVERSITY OF LIVERPOOL



Following a 56 year old idea with the technology of today and tomorrow:

M Tigner A Possible Apparatus for Electron Clashing-Beam Experiments, N.Cim 10(1965)1228

For the ERL Roadmap Panel

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)

EPS Conference, Hamburg – on-line, 30.7.2021

Symposium on ERLs and its Applications, June 4, 21

LDG-XXX-YYY DRAFT 0.1 July 29, 2021

The Development of Energy Recovery Linacs

A Contribution to the European Strategy for Particle Physics

The ERL Study Group

Abstract (DRAFT)

Energy recovery linacs (ERL's) have been emphasised by the recent (2020) update of the European Strategy for Particle Physics as one of the most promising technology for the accelerator base of future high energy physics. They are indeed beginning to assert their potential as game changers in the field of accelerators and their applications. Their unique combination of bright, linac-like beam quality with high average current and extremely flexible time structure, unprecedented operating efficiency and compact footprint opens the door to previously unattainable performance regimes. This paper summarises the previous achievements on ERLs and the status of the field and its basic technology items. The main possible future contributions and applications of ERLs to particle and nuclear physics as well as industrial developments are presented. Many of the single resulting requirements will be or have been already met in the ongoing concerted effort, which will move the field forward with complementary facilities. A corresponding roadmap is established, describing major opportunities, new facilities, milestones, deliverables and necessary investments, as a coherent global effort to meet expectations in the next five years and further ahead. It thus is realistic to predict that a viable technical ERL base will originate in the not distant future serving as a reliable input to strategic high energy physics decisions to come.

The paper includes a vision for the further future, beyond 2030, as well as a comparative data base for the main existing and forthcoming ERL facilities. At hand is an unprecedented technology combining strongly enhanced performance of electron and photon beam based physics with sustainable power consumption, by using the decelerated beam for new acceleration, and with non-radiative waste, as the beam is dumped at injection energy. A series of continuous innovations, such as on intense electron sources or high quality superconducting cavity technology, will massively contribute to the development of accelerator physics at large. Industrial applications potentially are revolutionary and may carry the development of ERLs much further, establishing another shining example of the impact of particle physics on society and its technical foundation with a view on sustaining nature.

Long Write-Up on ERLs - in preparation

Activities

18 panel members from 11 facilities

← 250pp base paper about 50 authors

Regular meetings + reports to LDG

Symposium →

Subpanel on e^+e^-

Towards an ERL Roadmap - fall 21

for integration into Accelerator R&D 5-10 year plan

Interested in input

Chair: Bettina Kuske (HBZ, Berlin)

13:00 **Welcome by the Lab Directors Group** 10m
Prof. Dave Newbold (STFC R.Appleton Laboratory)

13:10 **Introduction** 10m
Max Klein (University of Liverpool)

13:20 **ERL Facilities** 25m
Andrew Hutton (Jefferson Laboratory)

13:45 **High Current Electron Sources** 15m
Boris Militsyn (STFC)

14:00 **SRF Developments for ERLs** 25m
Robert Alan Rimmer (Jefferson Laboratory)

14:25 **ERL Prospects for High Energy Colliders** 25m
Oliver Bruning (CERN)

14:50 **Coffee/tea Break** 10m

Chair: Olga Tanaka (KEK)

15:00 **Low Energy Physics with ERLs** 20m
Jan Bernauer (Stony Brook University)

15:20 **Industrial ERL Applications** 20m
Peter Williams (Daresbury Laboratory)

15:40 **Energy Recovery and Sustainability** 20m
Erk Jensen (CERN)

Chairs: Andrew Hutton and Max Klein

16:00 **Discussion** 55m

https://indico.cern.ch/event/1040671

Particle Physics: The Challenge Ahead

3.5.33-23.7.21

Principally new theories would be required to "turn the SM on its head" while, as Steven Weinberg also stated not long ago: "There isn't a clear idea to break into the future beyond the Standard Model" [15], it remains the conviction, as Gian Giudice described it in his eloquent "imaginary conversation" with the late Guido Altarelli, that "A new paradigm change seems to be necessary" [17] in the "Dawn of the post naturalness era".

[15] CERN Courier 10/17: SW Model Physicist
[17] GG in Book for Guido Altarelli, 1710.07663

The Development of ERLs. Draft paper

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

*) cf backup slide

High field magnets, SRF, ERL, Muon Collider, and Plasma Wakefield
The five acc. technology pillars identified last year and by Council/SPC/LDG.- we may learn about + use their interdependence

LHeC: Poster at EPS by Kevin Andre

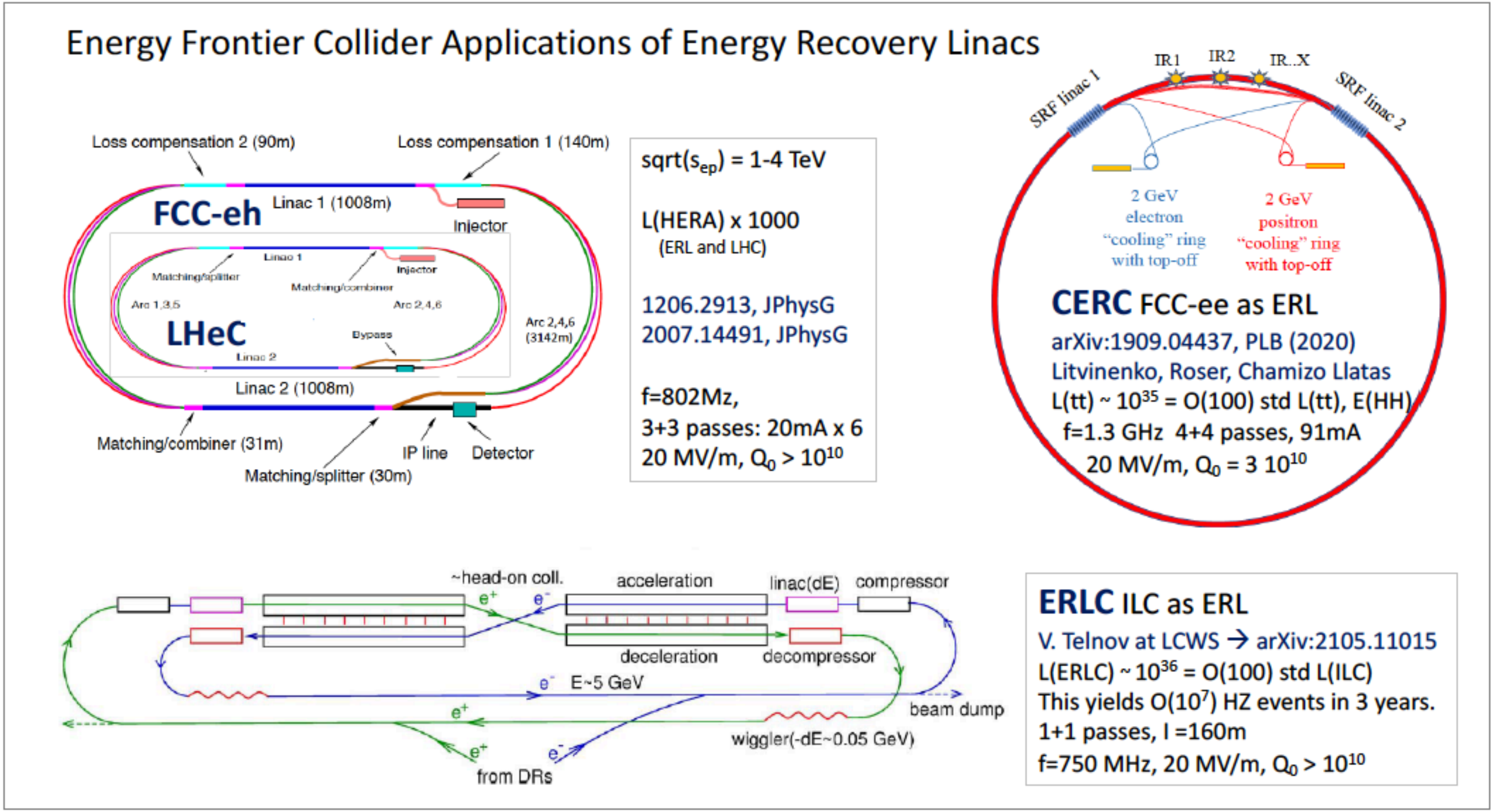


Figure 2: Sketch of possible future colliders based on ERLs: left top: LHeC and FCC-eh; right top: CERC; bottom: ERLC. For more information see the arXiv references displayed.

[from a report to LDG 5/21]

Evaluation of ERL concepts for FCC-ee [CERC] and the ILC [ERLC]

Vladimir Litvinenko+ https://doi.org/10.1016/j.physletb.2020.135394 ;
Valery Telnov, https://arxiv.org/abs/2105.11015

The e^+e^- ERL Sub-Panel

The Sub-Panel is evaluating the technical and financial implications of the two novel concepts compared to the FCC-ee and ILC projects:

What are the technical advances, specifically in luminosity?

What are the technical solutions + obstacles requiring R&D?

How much time would that additionally require?

What is the rough cost implication (to about 10%)

Sub-Panel members

Chris Adolphsen (SLAC)	Reinhard Brinkmann (DESY)
Oliver Brüning (CERN)	Andrew Hutton (JLab) – Chair
Sergei Nagaitsev (Fermilab)	Max Klein (Liverpool)
Peter Williams (STFC)	Akira Yamamoto (KEK)
Kaoru Yokoya (KEK)	Frank Zimmermann (CERN)

Dates for the sub-Panel

Kick-off meeting held June 9, 2021

Completion by September 3, 2021

Deliverable:

A short report (~20 pages) detailing the conclusions of the evaluation, which should be agreed and supported by the entire sub-Panel and published as Appendix B to the full Panel report.

Had/have weekly meetings, initially with proponents

Very lively discussion and development of insight

Too early to summarise (30.7.21)

Recent (June, July) Ideas being incorporated

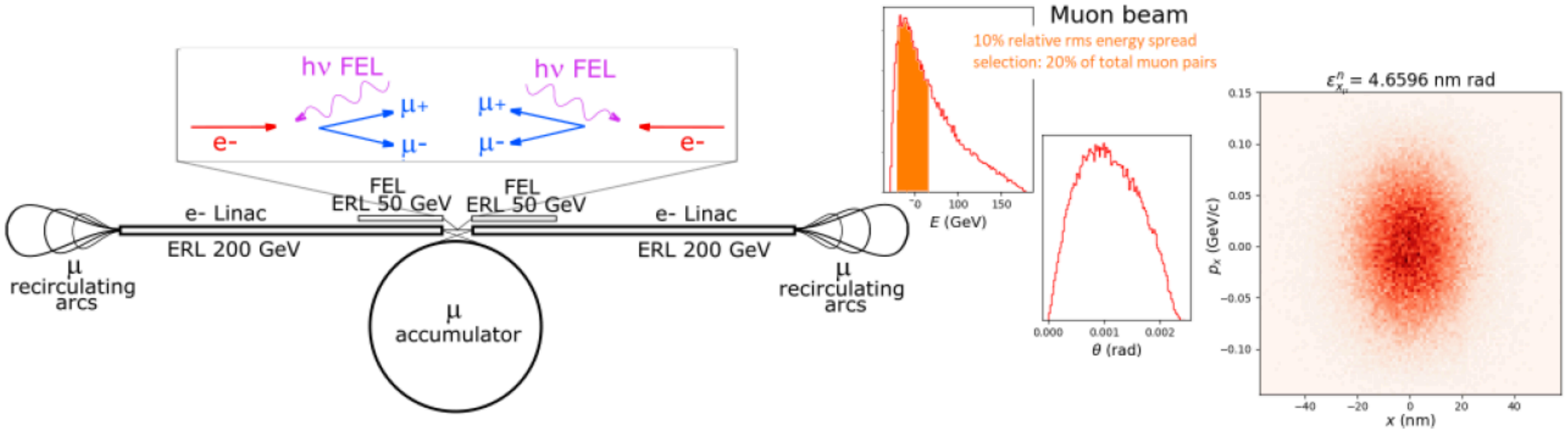
Electrons and X-rays to Muon Pairs (EXMP)

$E_e = 200$ GeV, $h\nu = 150$ keV, $E_{CM} \simeq \sqrt{4E_e h\nu + M_e^2} = 346$ MeV

- no target → no target handling, no cooling needed
- no beamstralung, no ring → very tight focus allowed

C. Curatolo, L. Serafini
arXiv:2106.03255

Evaluation not planned



Picosecond x-ray source with high (15 T) field magnet(s) on 1-GeV ERL. This option could intensify ERL activity, transforming, for example, test facility PERLE or ERL projects for x-ray lithography FEL, to unique user facility (storage rings can not provide so short x-ray pulses, and linacs can not provide average intensity).

Nikolay Vinokurov
Talk at ERL Panel 15.7.21

Sub-ps periodic X ray pulses for time resolved experiments → a 4th example for applications

Examples of Industrial Applications

- 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 exceeding that of the XFEL by orders of magnitude
- That could be a contribution for a decade of physics programme at CERN between the HL-LHC and the HE-LHC when time may be required for high field SC dipoles to be routinely available
- The industrial process of producing semiconductor chips comprises the placing of electronic components of nanometre scale onto a substrate or wafer via photolithography
- To advance 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
- ERLs might well reach into the EUV market, which in 2020 was 400B Euro, following initial surveys and design studies undertaken by industry

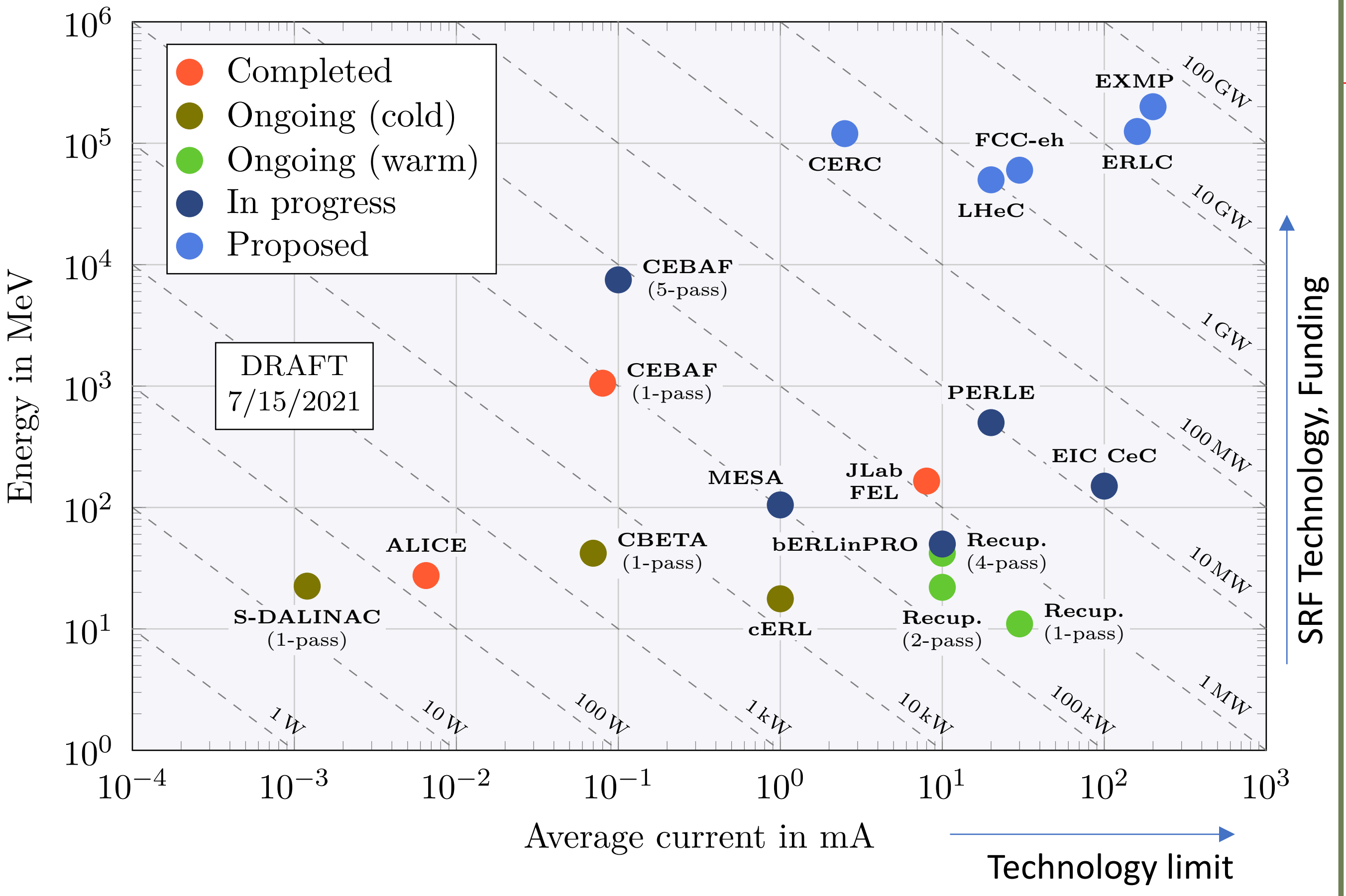
Andrew Hutton at Future Accelerator R&D Symposium for the HEP Community, July 7, 2021 - from ERL Long Write-Up, in preparation

Three major features: Linac brightness at storage ring powers, Dump at injection, GW class beams unaffordable otherwise

Peter Williams at ERL Symposium June 6. 2021 [considered Free Electron Lasers and Inverse Compton Sources, in Long Write-Up]

Facilities

Electron beam energy [MeV] vs current [mA]



Main goals of development and study:

High current sources, SRF to take ~100 mA load and high Q_0
CSR, HOMs, small emittance, efficient multi-turn operation

Current and coming activities [from an Interim ERL report 7/21]

– S-DALINAC (TU Darmstadt)

- establishment of a multi-turn SRF-ERL with high transmission (up to 70 MeV and 20 μA);
- 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.

ERL Facilities *DRAFT 19.3.21*			**CEBAF 5-Pass**	**MESA**	**EIC Cooler**	**PERLE**
			Jefferson Lab, USA	U Mainz, Germany	BNL, USA	IJCLab, France
ERL	**Top energy**	**MeV**	**7584**	**105**	**22.3/54.1/150**	**500**
	Beam power	**MW**	**0.758**	**0.1**	**22.3/54.1/150**	**10**
Source	Gun Energy	keV	100	100	400	350/200
	Bunch charge	pC	0.06	1	1	500
	Current	mA	0.1	1	**100**	20
	Polarization		Yes	Yes	No	Yes & No
Injector	Beam energy	MeV	84	5	5	7
	Emittance (normalized)	μm	0.05	< 1	< 3	6
Acceleration	Energy gain/linac	MeV	2 x 750	2 x 50	17.3/49.1/145	2 x 82
	RF Frequency	MHz	1497	1300	591	801.58
	Bunch repetition rate					
	Total Linac current	mA	1	2	200	120
	Harmonic frequency	MHz	N/A	N/A	1773	N/A
	Macropulse length	μsec	CW	CW	CW	CW
	Bunch charge	pC	0.06	1	1	500
	Emittance	μm	0.05	<1	< 3	6
	Gradient	MV/m	12 - 17.5	12.5 MV/m	20	21
	Quality factor	x 10^{10}	1	>1.25		>1
	RF controls		Analog/digital	ITCA (digital)	TBD	
	Beam loss	nA		<10^-5	TBD	
Arcs	Multi-pass		**5 + 5**	1 + 1	1 + 1	**3 + 3**
	Optics design		Achromatic, isochronous	MBA	R56 canceling bending, Bates	Flexible Momentum Compaction
	Beam loss	%		<10^-3	TBD	
Interaction Region	βx, βy	cm	N/A	~1m	40/40	
	Beam size	μm	N/A	100	1330, 550/200	
	Beam Divergence	μrad	N/A	100	4	
	Magnets		N/A	Copper	Copper	
	Dump beam energy	MeV	84	5	5	7
Dump	Dump power	kW	8.4	5	500	140
	Max CW current recovered	mA	0.1	0.999mA		

New Facilities in the Twenties

CEBAF (JLab): high energy, 5-turn

MESA (Mainz): polarisation

Cooler (BNL) + bERLinPRO: high current

PERLE (Orsay): high power, 3-turn

Chapter 4 in the Long Write-UP
Key Challenges – **a Concerted Effort**

Studies:

DICE Darmstadt, DIANA Daresbury derived from PERLE; also IHEP Beijing

SRF Cavities

ERLs, being somewhere between linacs and storage rings, have unique requirements for their RF systems and therefore need optimised designs to achieve the full potential of the concept. Proposed new machines operating with about 100 mA of current, either in single or multi-pass mode, need cavities with cell shapes optimised to avoid strong beam excitation of longitudinal higher order modes (HOMs), to minimise the power extracted from the beam, and strong HOM damping of all monopole and dipole HOMs to avoid beam break up instabilities.

Bob Rimmer

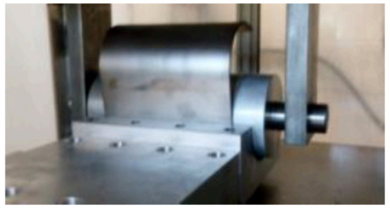
← f < 1 GHz

- We developed all tooling for cavity fabrication

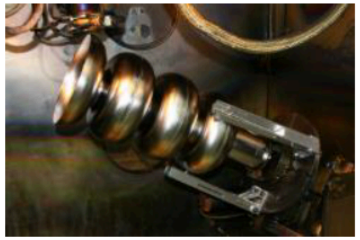
Frank Marhauser et al. at Jlab (FM talk at PERLE workshop)

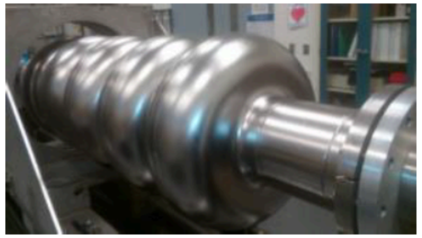

Fixture for female die with blank holder


Male die

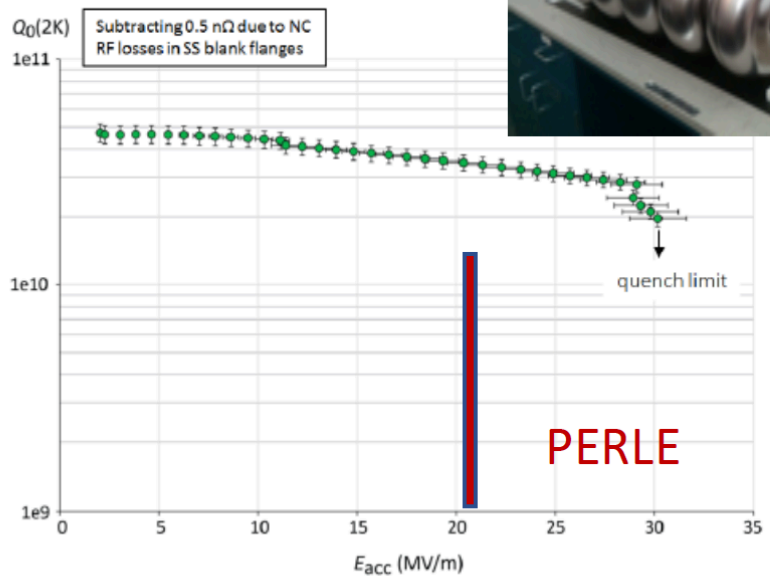

Beam tube rolling die

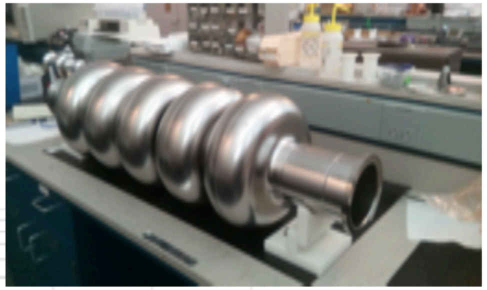

RF half cell/dumbbell measurements fixture


Five-cell cavity in EBW machine prepared for subsequent dumbbell and endgroup welding with both outside and inside welds in tilted position


Five-cell cavity on tuning bench

PERLE/LHeC (20 x 6 mA) and FCC-ee 802MHz Nb Cavity

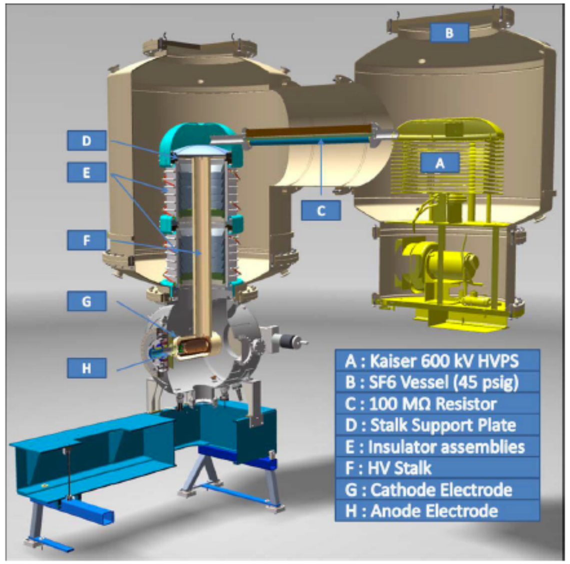




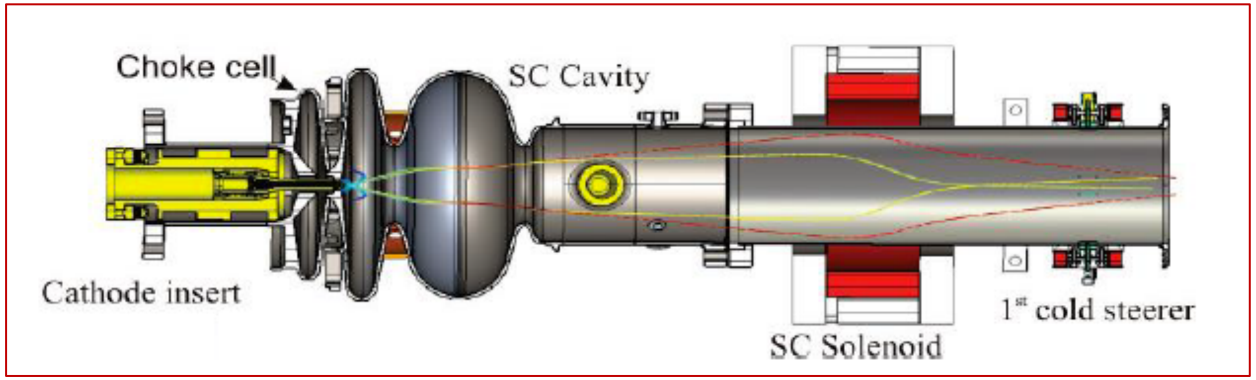
High Current Electron Sources

- DC photocathode guns operated with Sb-based photocathode and thermionic guns can demonstrate at the moment unpolarised current of as high as 100 mA
- Potential to reach this current also have photocathode guns equipped with Sb photocathodes
  - QWR SRF gun
  - QWR NCRF gun
  - Elliptical cavity SRF gun
- There is no operational injector which can demonstrate 100 mA of polarised current, it's limited by photocathode lifetime
- Potential to deliver this current, in case of success of the program on improving GaAs lifetime by activation with Cs-alkali metal layer,
  - DC photocathode guns
  - SRF photocathode guns

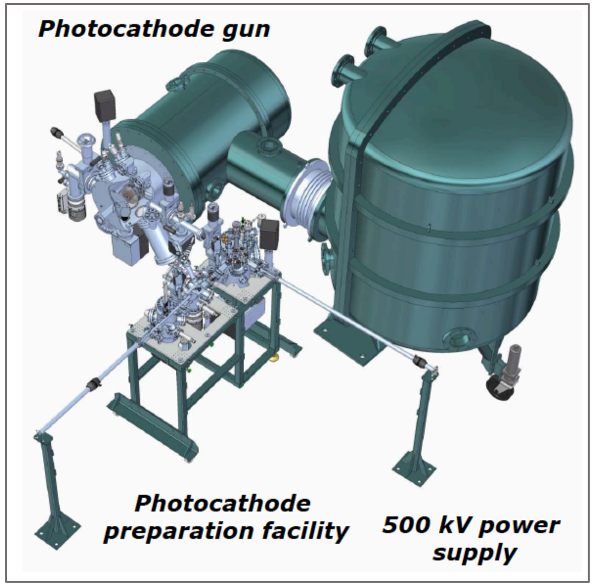
Boris Militsyn (ERL symposium)



DC photocathode gun: 70mA (Cornell)



SRF elliptical cavity gun at bERLinPro (HZB) – upgradeable to 100 mA



ALICE (upgrade 20mA) → Orsay

Associated Technology

three examples

1. Diagnostics and Beam Operation

Large beam power

beam loss, halo diagnostics, radiation detection

Small emittance preservation

view screens, CSR, microbunch instability..

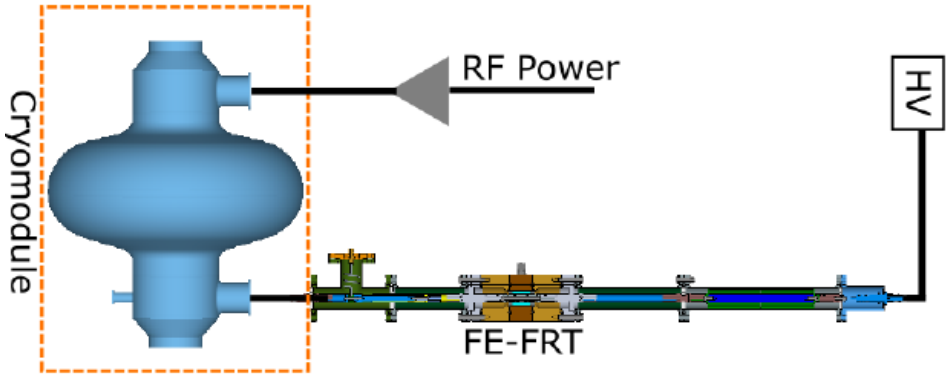
Energy match

arrival time monitors, alignment ..

2. Simulation Software and Training

- Wakefields and beam break up in multi-turns
- Longitudinal match
- Front-end simulations, beam profile
- CSR, microbunching
- Lattice design (momentum compaction…)
- Higher order components
- 3D simulation for the electron coolder

challenging software developments
attractive accelerator physics - education

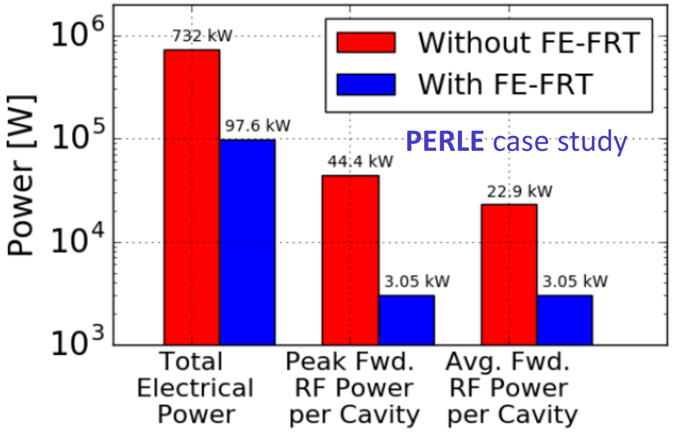


LHeC Workshop (9/18)
IPAC, May 2021
SRF Symposium (7/21)
Nick Shipman et al.

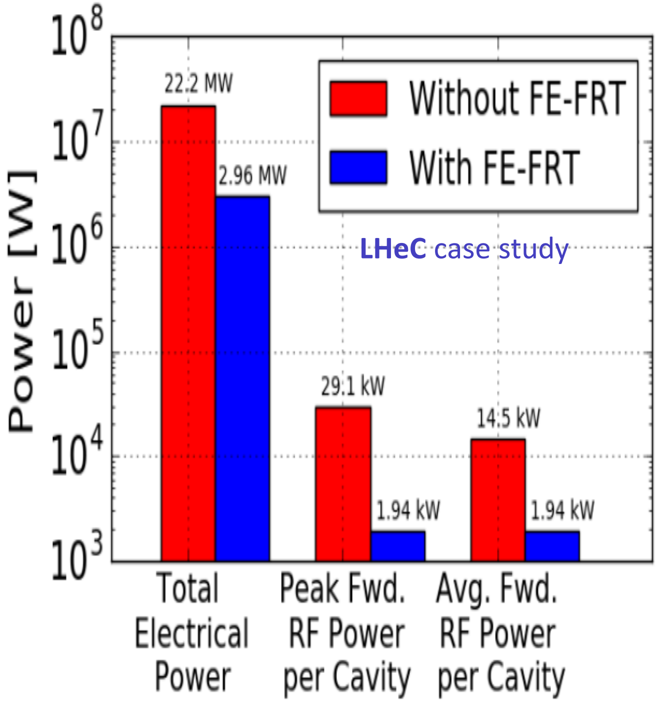
Considering FTRs for bERLinPRO + PERLE

3. Fast Reactive Tuners

contra microphonic resonance detuning

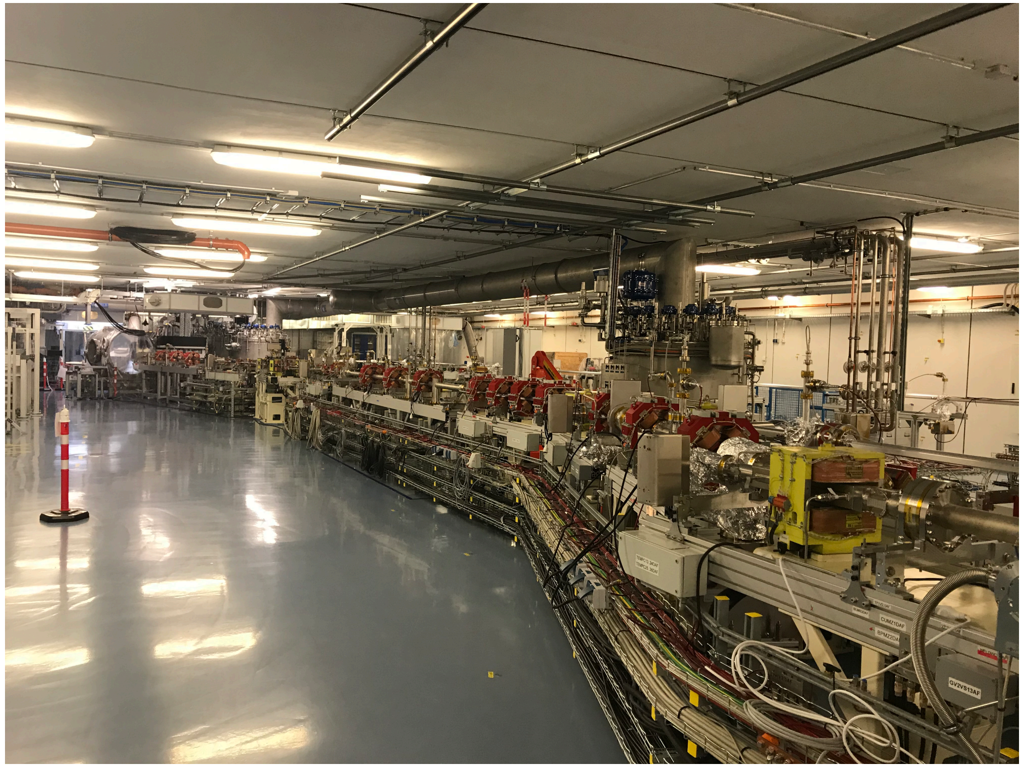


- Peak power per cavity 44.4 kW → 3.05 kW

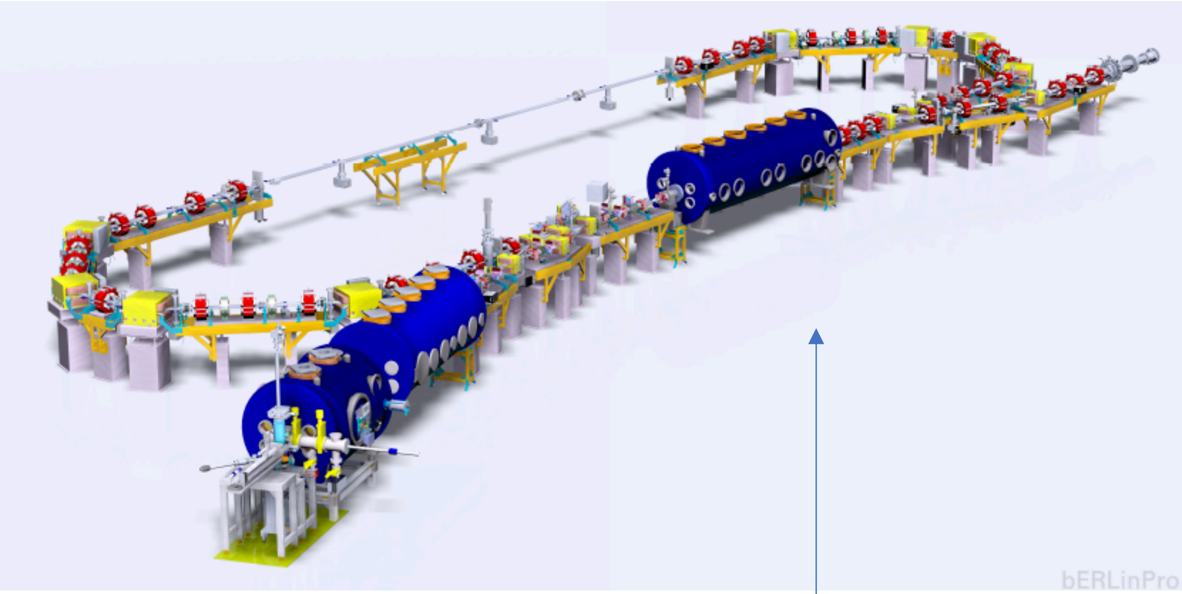


continuously readjusts the cavity resonance. Piezo-electric tuners have been investigated for some time and more recently, very promising ferro-electric $BaTiO3 - SrTiO3$-based fast reactive tuners are under development. Their suitability and longevity with full SRF systems without and with beam must be demonstrated to capitalise on their enormous potential.

bERLinPRO



Single-turn, 10mA, 1.3 GHz - at Helmholtz Zentrum Berlin



Racetrack closed
Dump, 100mA cryogenics
RF transmitter all there.

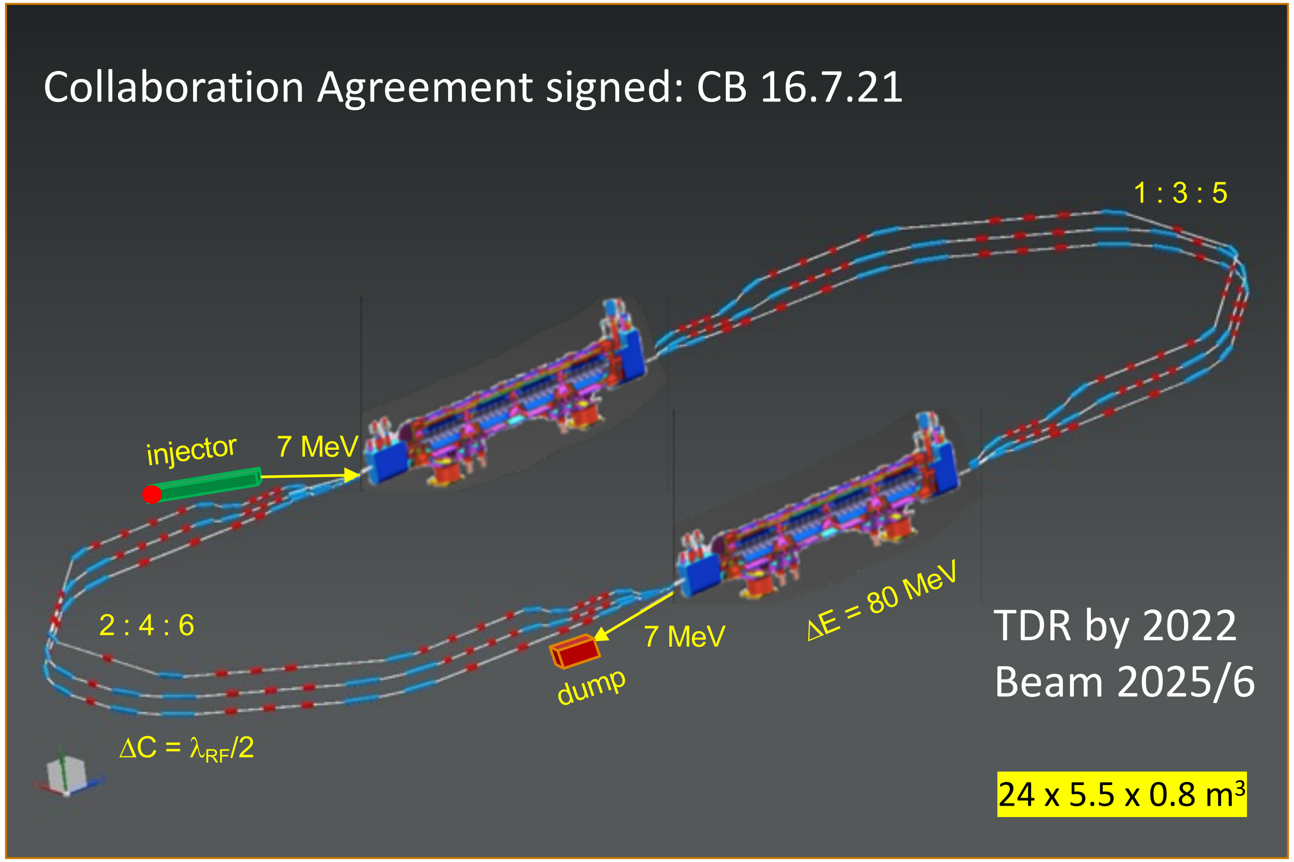
Well suited for ERL R&D
with 2 x 100 mA load:

Missing LINAC cryomodule

Possibility to upgrade SRF gun to 100 mA (currently power coupler limited)
Adding cavity-cryomodule, possibly equipped with FRT, to complete the facility.
R&D on stability, emittance preservation, beam loss, bunch length..

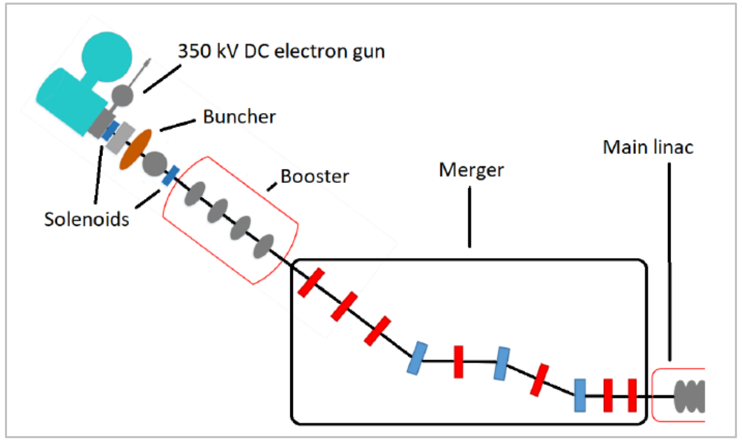
PERLE * (ERL R&D → Physics [NP, PP])

ALICE DC Photocathode, JLEIC Booster and SPL Cryomodule – in kind



CERN, Cornell, Daresbury, Jefferson Lab, Liverpool, Novosibirsk, IJCLab Orsay (Host) Collaboration, growing: Grenoble, GANIL +

* PERLE. Powerful energy recovery linac for experiments. Conceptual design report
Published in: *J.Phys.G* 45 (2018) 6, 065003 e-Print: 1705.08783 [physics.acc-ph]



Injector design (ALICE gun, 3Dipole merger - tentative)

Linac: Cavity (Nb, 802 MHz) designed, built, tested
Full [SPL] cryomodule by 2024 for FCCee, PERLE and LHeC

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

PERLE characteristics

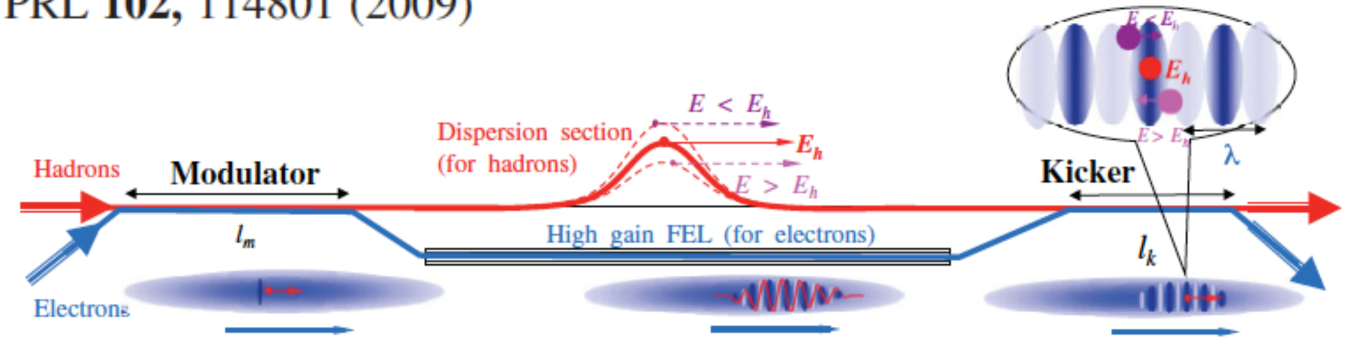
More information: EPS: Poster by Ben Hounsell
LHeC (and PERLE, FCC-eh) paper: 2007.14491
Alex Bogacz: DIS21 proc.; Long Write-Up on ERLs

Coherent Electron Cooling

Vladimir N. Litvinenko[1,*] and Yaroslav S. Derbenev[2]

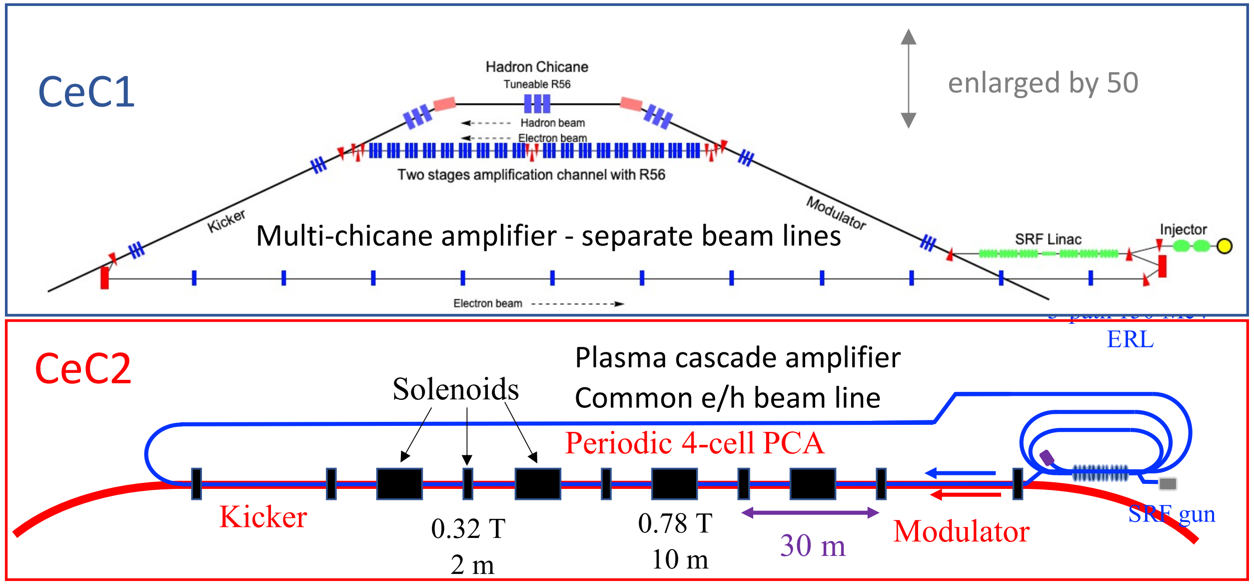
EPS talk on EIC by F Willeke 27.7.

PRL 102, 114801 (2009)

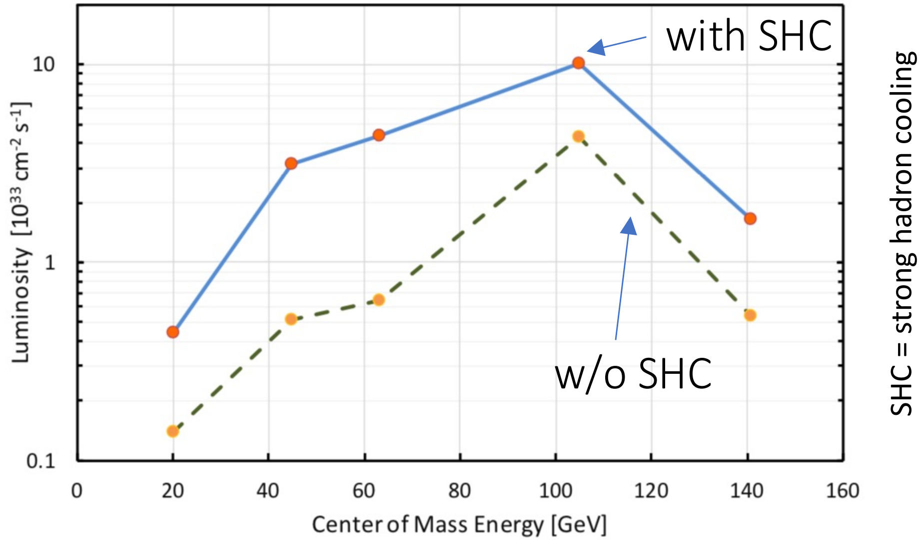


The CeC works as follows: *In the modulator*, each hadron (with charge Ze and atomic number *A*) induces a density modulation in an electron beam that is amplified *in the high-gain FEL*; *in the kicker*, the hadrons interact with the electric field of the electron beam that they have induced, and receive energy kicks toward their central energy. The process reduces the hadrons' energy spread, i.e., cools the hadron beam.

Decision expected with CD2

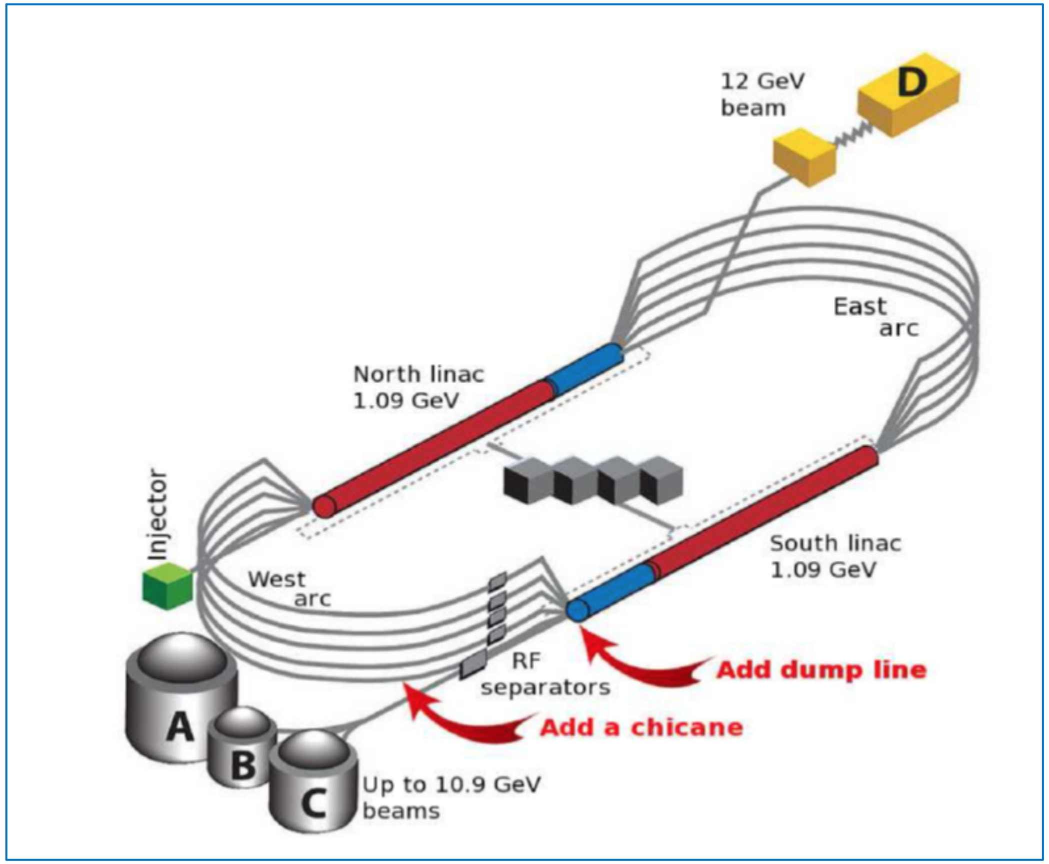


0.4 (1.5) MeV DC gun, 100 mA I_e, 149 MeV : 15 MW. 1 (3) path facility



L vs cms energy $\sqrt{s} = 2\sqrt{E_e E_p}$; HERA 319 GeV

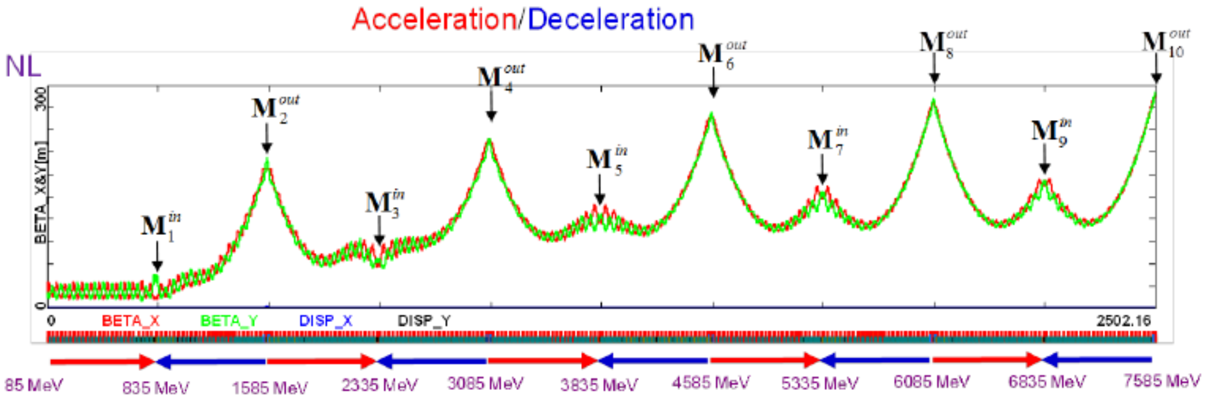
CEBAF 5 pass



12 GeV (11 passes) beam to Hall D, 11 GeV to A,B,C

JLab project to study Coherent Synchrotron Radiation (8 GeV beam energy) in an ERL CEBAF 5 pass configuration

Two additions:
- pathlength chicane to gain half wavelength, four 3m dipoles
  (initial bunch suppression, control momentum compaction M56..)
- low power dump line at the south linac end



Multi-pass linac optics – A. Bogacz

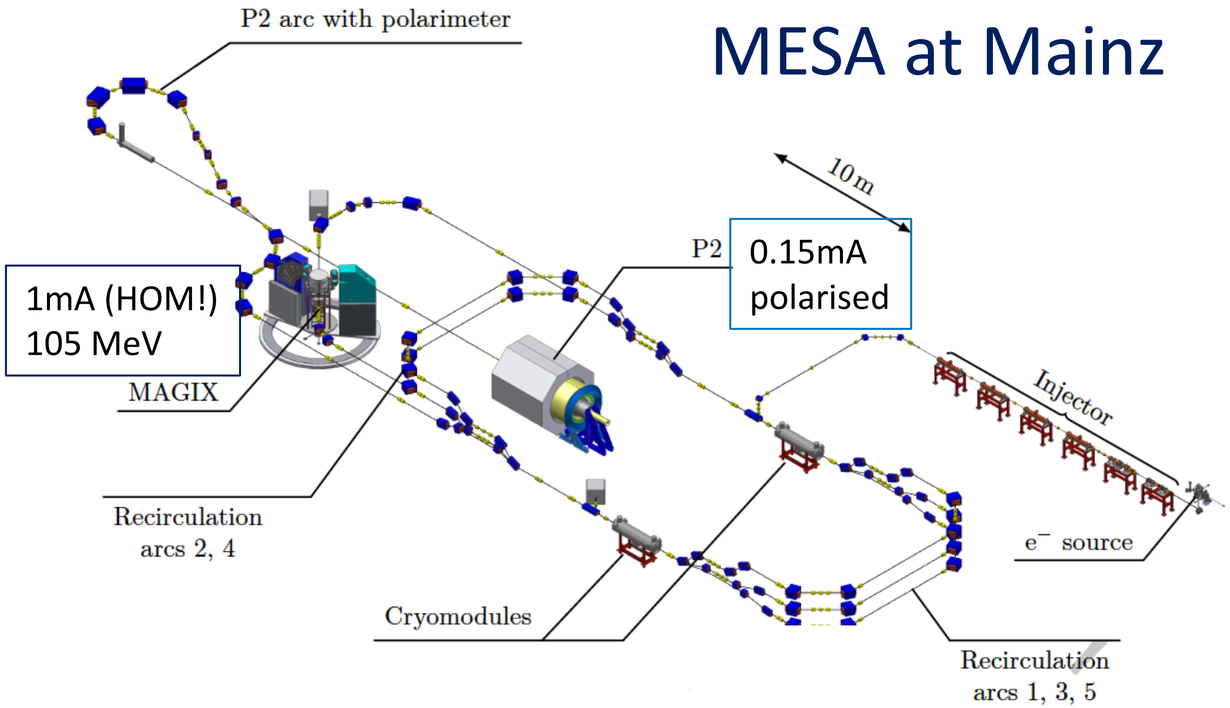
Experiment Run schedule for 2024

Important test of ERLs for high energy application

Low Energy Physics with ERLs

Three examples from Long Write-UP

MESA at Mainz

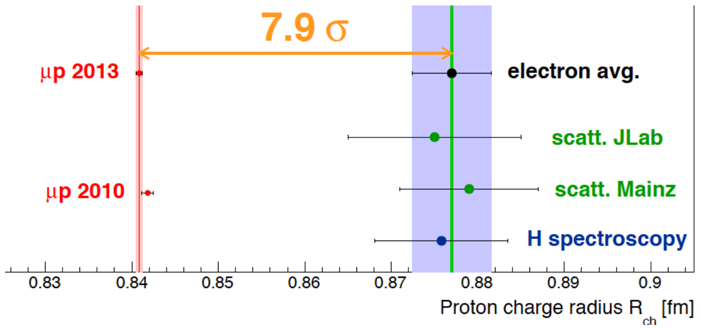


- 1.3 GHz, two ELBE type cryomodules, up to 3 passes
- New building, beam by 2024
- Polarimetry to 0.5% precision
- Current upgrade (unpolarised to 10 mA)

P2 – external target $\sin^2\Theta$, w/o energy recovery ("EB")
MAGIX – gas jet internal target, dark photons, p radius ("ER")

doi:10.18429/JACoW-ERL2019-MOCOXBS05

Proton Radius Puzzle [role for high intensity ERL, Jan Bernauer ERL Symposium 6/21



AMBER (CERN), MUSE (PSI), PRAD (Jlab), ULQ2 (Tohoku), Mainz .. ??

Nuclear Photonics [inverse γ's: L(PERLE) = O(10^3) L(ELI)]

Photonuclear reactions - from basic research to applications

A. Zilges[1], D. L. Balabanski[2], J. Isaak[3], N. Pietralla[3]

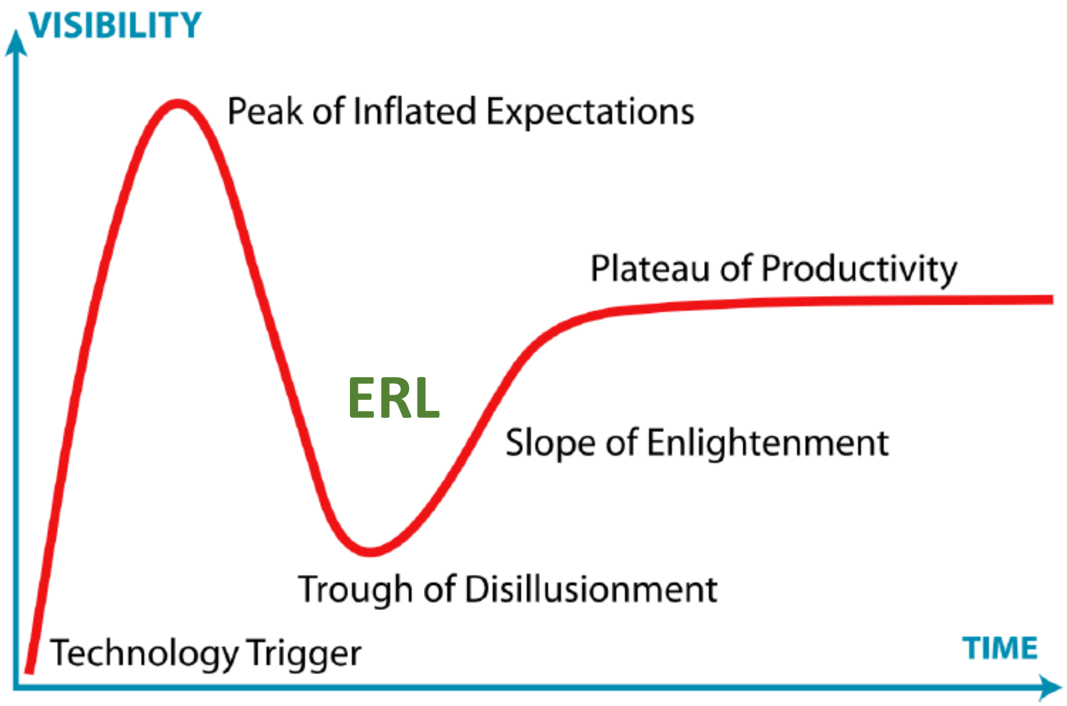
June 17, 2021, to appear

also: IGS: nuclear security, novel medical isotope research

Electrons Probing Exotic Nuclei

New field, pioneering: SCRIT@RIKEN, PRL 118, 2017
PERLE 500 MeV, 20mA, DESTIN project at Orsay
Outlook: eRI facility at GANIL (Caen, F) 200mA, ~2040

In summary: ERLs - a Progressing, Revolutionary Technology



The hype cycle is a branded graphical presentation developed and used by the American research, advisory and information technology firm Gartner to represent the maturity, adoption, and social application of specific technologies.

Olga Tanaka (KEK)

Based on decades of SRF, FEL, ERL, Facility.. developments*) :

The debate now is about the conditions for ERLs to reach their productivity plateau and the demands on R&D, financial, intellectual and technical support – Roadmap early fall 21

An initial observation (not only) by the panel:

ERLs are more than an appealing technology:

They (cor)respond to A NEW ERA in particle and several other fields of physics, industry, accelerators .. in a world that cannot proceed without renewed care for our planet.

Europe's key R&D development prospects:
PERLE (3-turn, 10 MW), bERLinPRO (100 mA)
Concerted global effort (cERL, CEBAF5, etc.)
Including developments outside ERL facilities

*) e.g. Ilan Ben-Zvi 2016 *Supercond. Sci. Technol.* **29** 103002
Chris Tennant, ERLs, in "Challenges and Goals for Accelerators in the XXI Century", O Bruening, S Myers, World Scientific, 2019

Many thanks to the ERL community and to Herwig Schopper for his view on how to recover energy..

Future of Particle Physics

much now resembles the fifties - theory provides questions, but no firm answers. Specifically, the SM has known, fundamental deficiencies: a proliferation of too many parameters, a missing explanation of the repetitive quark and lepton family pattern, an unresolved left-right asymmetry in the neutrino sector related to lepton-flavour non-conservation, an unexplained flavour hierarchy, the intriguing question of parton confinement and others. The Standard Model carries the boson-fermion asymmetry, it mixes the three interactions but has no grand unification, the proton is stable, it needs experiment to determine the parton dynamics inside the proton, has no prediction for the existence of a yet lower layer of substructure, and it does not explain the difference between leptons and quarks. Moreover, the SM has missing links to Dark Matter, possibly through Axions, and Quantum Gravity, while string theory still resides apart. The Standard Model is a phenomenologically successful theory, fine tuned to describe a possibly metastable universe [16].