On the Road to PERLE

- Roadmap overview
- Colliders
- Status
- Technology
- bERLinPRO, CEBAF, CEIC
- PERLE timeline, organisation

Co-authors of ERL Roadmap Chapter

Energy-recovery linacs

Panel members: M. Klein[i,‡‡] (Chair), A. Hutton[x] (Co-Chair), D. Angal-Kalinin[qq], K. Aulenbacher[rr], A. Bogacz[x], G. Hoffstaetter[ss,jj], E. Jensen[a], W. Kaabi[c], D. Kayran[jj], J. Knobloch[tt,uu], B. Kuske[uu], F. Marhauser[x], N. Pietralla[vv], O. Tanaka[y], C. Vaccarezza[f], N. Vinokurov[ww], P. Williams[qq], F. Zimmermann[a]

Associated members: M. Arnold[vv], M. Bruker[x], G. Burt[d], P. Evtushenko[xx], J. Kühn[uu], B. Militsyn[qq], A. Neumann[uu], B. Rimmer[x]

Sub-Panel on CERC and ERLC: A. Hutton[x] (Chair), C. Adolphsen[w], O. Brüning[a], R. Brinkmann[e], M. Klein[i], S. Nagaitsev[nn], P. Williams[qq], A. Yamamoto[y], K. Yokoya[y], F. Zimmermann[a]

Roadmap submitted to CERN Council 25.11.21

Max Klein, PERLE Collaboration Meeting, online, 11.1.2022

European Strategy for Particle Physics - Accelerator R&D Roadmap

Editor: N. Mounet[a]

Panel editors: B. Baudouy[b] (HFM), L. Bottura[a] (HFM), S. Bousson[c] (RF), G. Burt[d] (RF), R. Assmann[e,f] (Plasma), E. Gschwendtner[a] (Plasma), R. Ischebeck[g] (Plasma), C. Rogers[h] (Muon), D. Schulte[a] (Muon), M. Klein[i] (ERL)

Steering committee: D. Newbold[h,*] (Chair), S. Bentvelsen[j], F. Bossi[f], N. Colino[k], A.-I. Etienvre[b], F. Gianotti[a], K. Jakobs[l], M. Lamont[a], W. Leemans[e,m], J. Mnich[a], E. Previtali[n], L. Rivkin[g], A. Stocchi[c], E. Tsesmelis[a]

Five major topics (HFM, RF, Plasma, Muon Collider and ERL). Intense work including an interim report and consultations with interested particle and accelerator physics community, for all of 2021.

https://indico.cern.ch/event/1040671 ← ERL Symposium, June 4, 2021

CERN Yellow Report to appear soon. Council mandated LDG to present a plan for implementation by March 22.

Abstract: The goal of the roadmap is to document the consensus in the field on the next steps for the R&D programme, and to provide the evidence base to support subsequent decisions on prioritisation, resourcing and implementation.

The implementation task

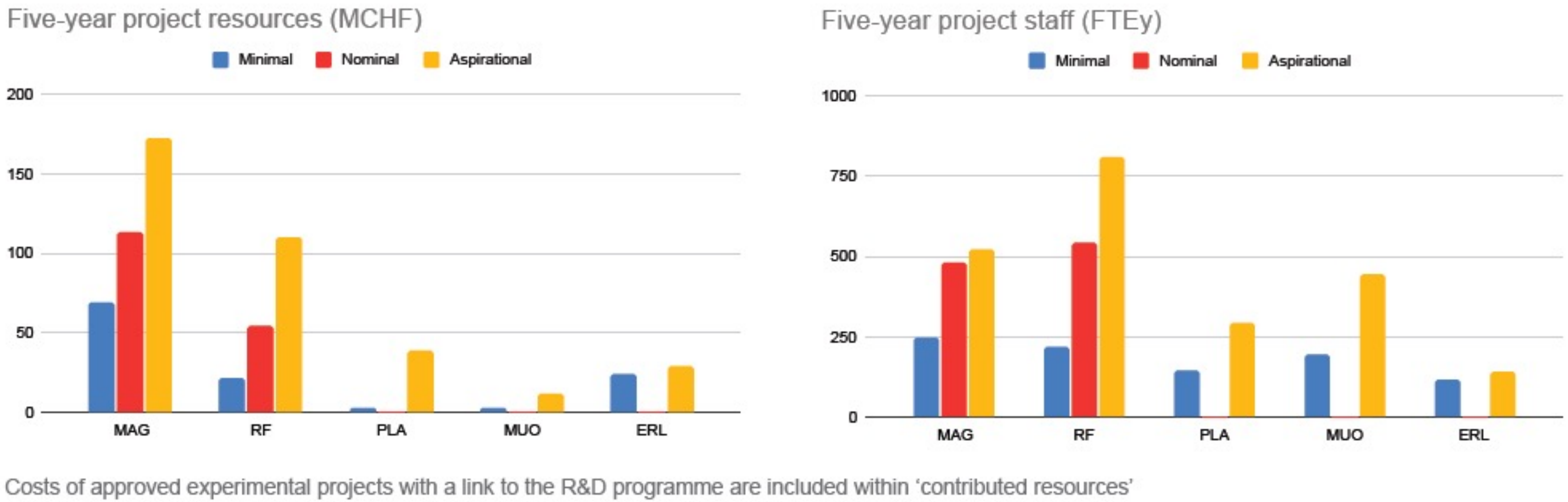


Fig. 9.1: Indicative cost of the R&D programme.

LDG to present an implementation plan to CERN Council by March 2022. Note focus is on the next 5 year.

Roadmap on Energy Recovery Linacs

5 Energy-Recovery Linacs

Editor: M. Klein[b]

Panel members: M. Klein[b,] (Chair), A. Hutton[a] (Co-Chair), D. Angal-Kalinin[c], K. Aulenbacher[d], A. Bogacz[a], G. Hoffstaetter[e,f], E. Jensen[g], W. Kaabi[h], D. Kayran[f], J. Knobloch[i], B. Kuske[i], F. Marhauser[a], N. Pietralla[j], O. Tanaka[k], C. Vaccarezza[l], N. Vinokurov[m], P. Williams[c], F. Zimmermann[g]*

Associated members: G. Burt[n], M. Bruker[a], P. Evtushenko[o], B. Militsyn[c], A. Neumann[i], [incomplete 29.10.]

Sub-Panel on CERC and ERLC: A. Hutton[a] (Chair), C. Adolphsen[p], O. Brüning[g], R. Brinkmann[q], M. Klein[b], S. Nagaitsev[r], P. Williams[c], A. Yamamoto[k], K. Yokoya[k] F. Zimmermann[g]

Max Klein, Andrew Hutton

in conjunction with Interim Report and our presentations to the LDG 30.9. + 12.10.21

LDG Meeting, November 2[nd], 2021

Long Write-Up on ERLs
For publication end of 21 to accompany ERL roadmap
~ 250 pages, ~50 authors

The Development of Energy Recovery Linacs

DRAFT

Contents

To be published …

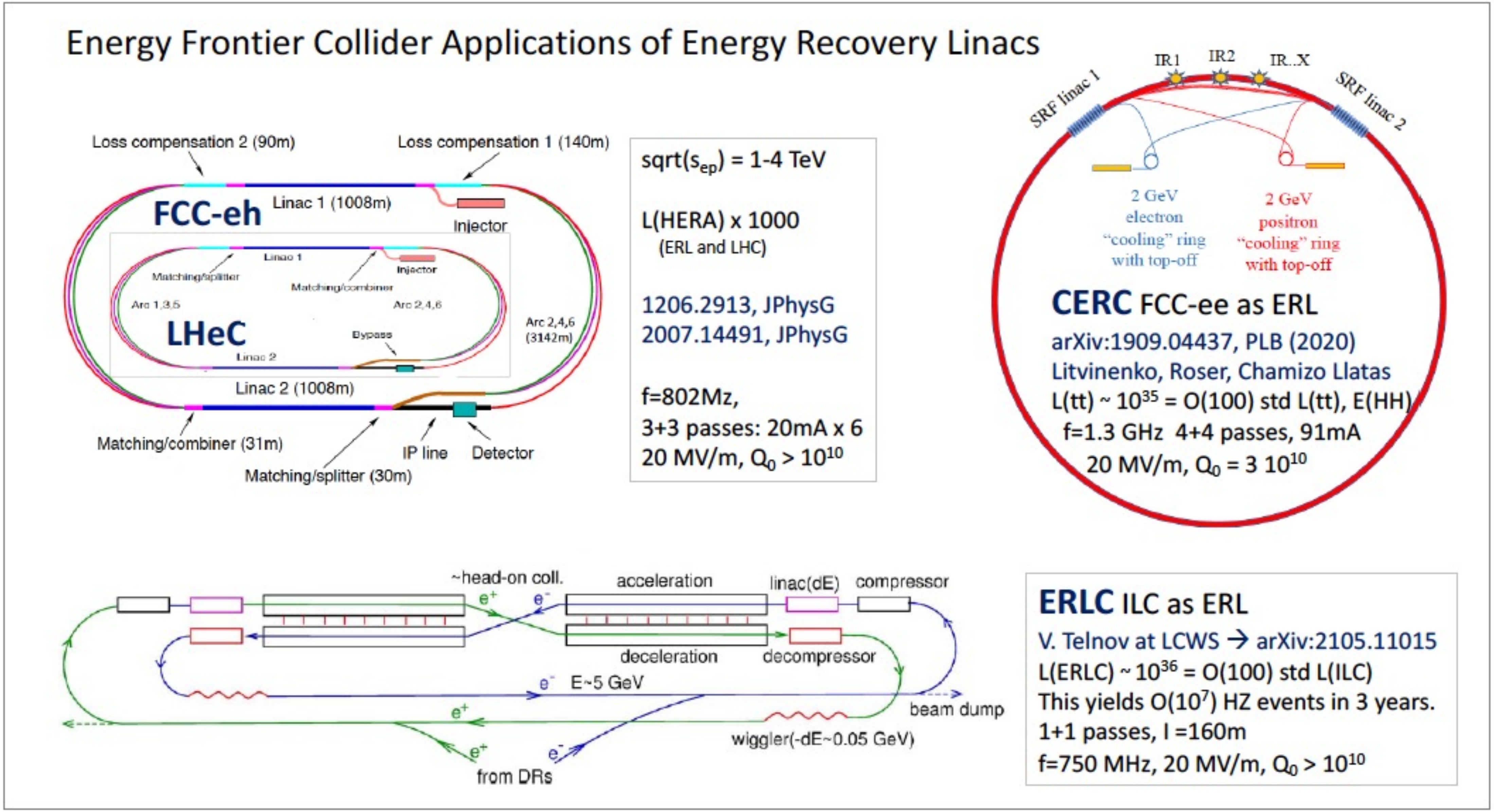
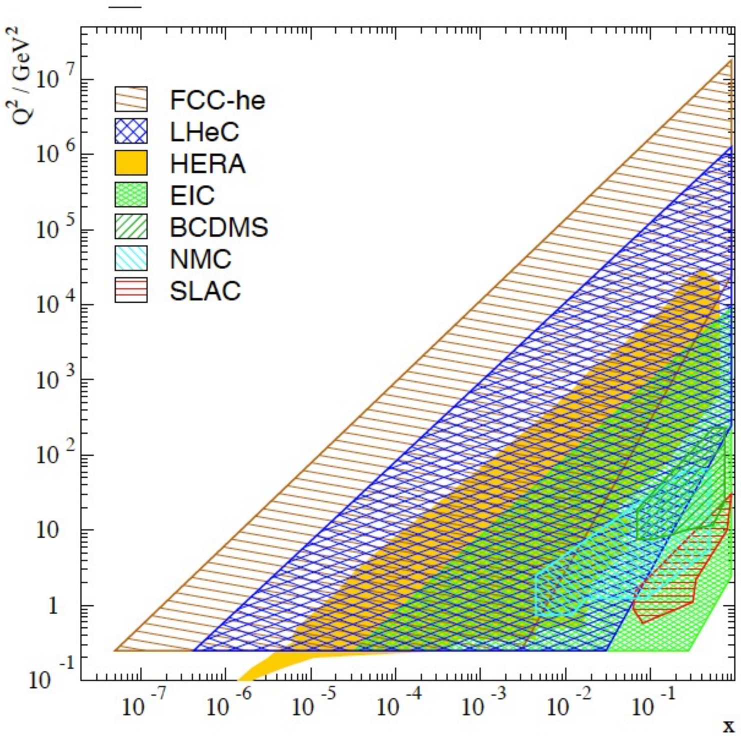


Figure 2: Sketch of possible future colliders based on ERLs: left top: LHeC and FCC-eh; right top: CERC; bottom: ERLC. For more information see the arXiv references displayed.

[from a report to LDG 5/21]

Remarks on ERL based Colliders (eh, muons)



Energy frontier DIS has been part of HEP and is necessary for going beyond the SM. The EIC has obviously a different role.

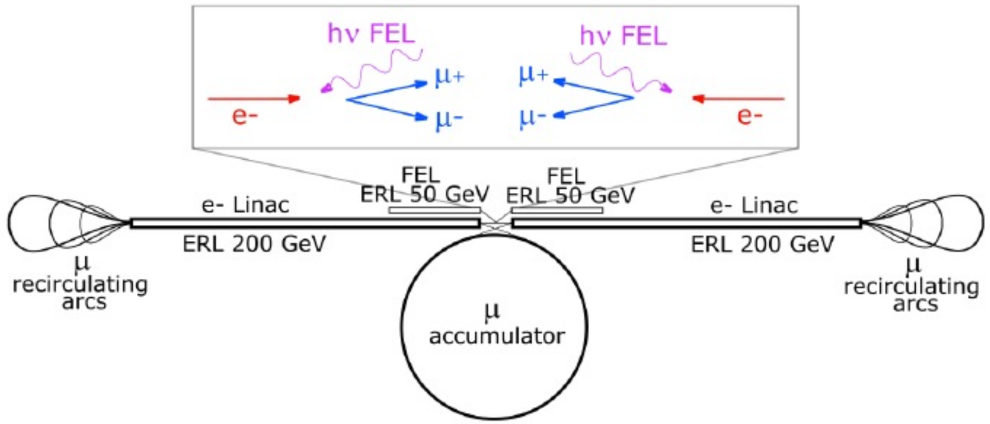
LHeC and FCC-eh are partners of LHC and FCC. The **cleanest high resolution telescopes world can build.** Rechecking the power economy of LHeC (100MW).

ERL technology concept of LHeC has wide range of HEP applications: γγ collider, FCCee injector, HE XFEL →

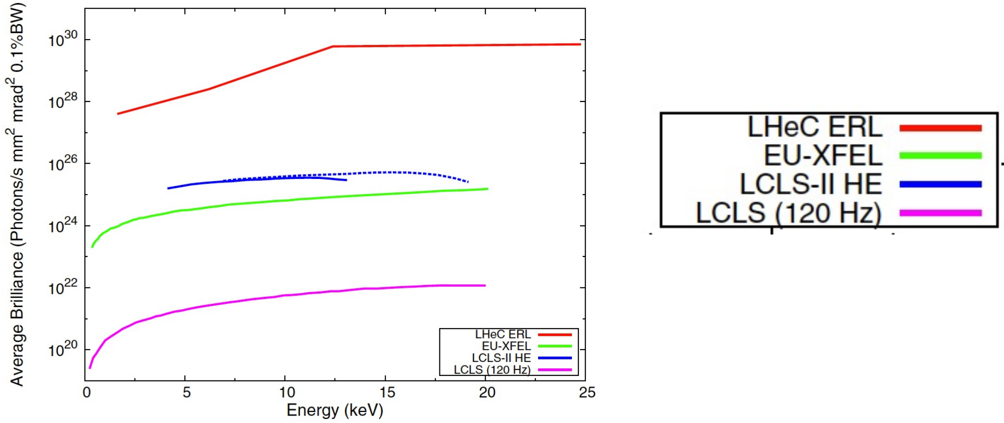
GeV muon beams with picometer-class emittance from electron-photon collisions

C. Curatolo[1,2] and L. Serafini[3]

arXiv:2106.03255



Bright Ångstrom and picometer free electron laser based on the Large Hadron electron Collider energy recovery linac



PHYSICAL REVIEW ACCELERATORS AND BEAMS **24**, 100701 (2021)

R&D Goals and Motivation as described in roadmap 28.10.

-- **Sustainability**: Limitation of power consumption despite orders of magnitude higher luminosity need in electron based colliders

-- **The near term 10 MW, 2K program**: 100 mA currents, Niobium SRF at optimum frequency, Q_0 3 10^{10} to 10^{11} , beam based

- **Next step in ERL technology**
- **Crucial development for Europe to stay as recognised partner for US, Russia and Japan**
- **Technology base for decision on LHeC and FCC-eh, 802 MHz cryomodule demonstrator for FCC-ee feasibility**
- **Low energy particle and nuclear physics: nuclear photonics, exotic isotope spectroscopy, elastic ep (p radius, weak i.a.), dark photons**
- **Industrial applications such as Photolithography at nm scale, FELs (low and high E), inverse gamma sources, pico-second Xray sources**

-- **The longer term 4.4K program**: R&D for power economy, 20 MV/m, 5 10^{10} Q_0: ambition comparable to high field magnet program

- **Next generation ERL technology: power (heat transfer) efficiency enhanced by factor of three: 300 → 100 MW**
- **Enabling a 500 GeV 10^{36} $cm^{-2}s^{-1}$ luminosity ERL based linear collider for per cent measurement of Higgs self-coupling [backup]**
- **Transfer of superconducting RF technology to smaller labs → revitalisation of the field and its industrial base**

3-fold Roadmap Structure (executive summary)

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

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

B) **A key technology R&D program** focused on high-current electron sources and high-power SRF technology and operation in the years ahead. Next generation ERLs lead to the major goal of being able to operate at 4.4 K cryogenic temperature [4] with high Q_0, and also including higher-order mode damping at high temperature, dual-axis cavity developments and novel means for high-current ERL diagnostics and beam instrumentation to deal with effects such as beam break-up or RF transients;

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

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

First presented to LDG 30.9.21

5.5 State of the art and Facility plans—Roadmap Part A

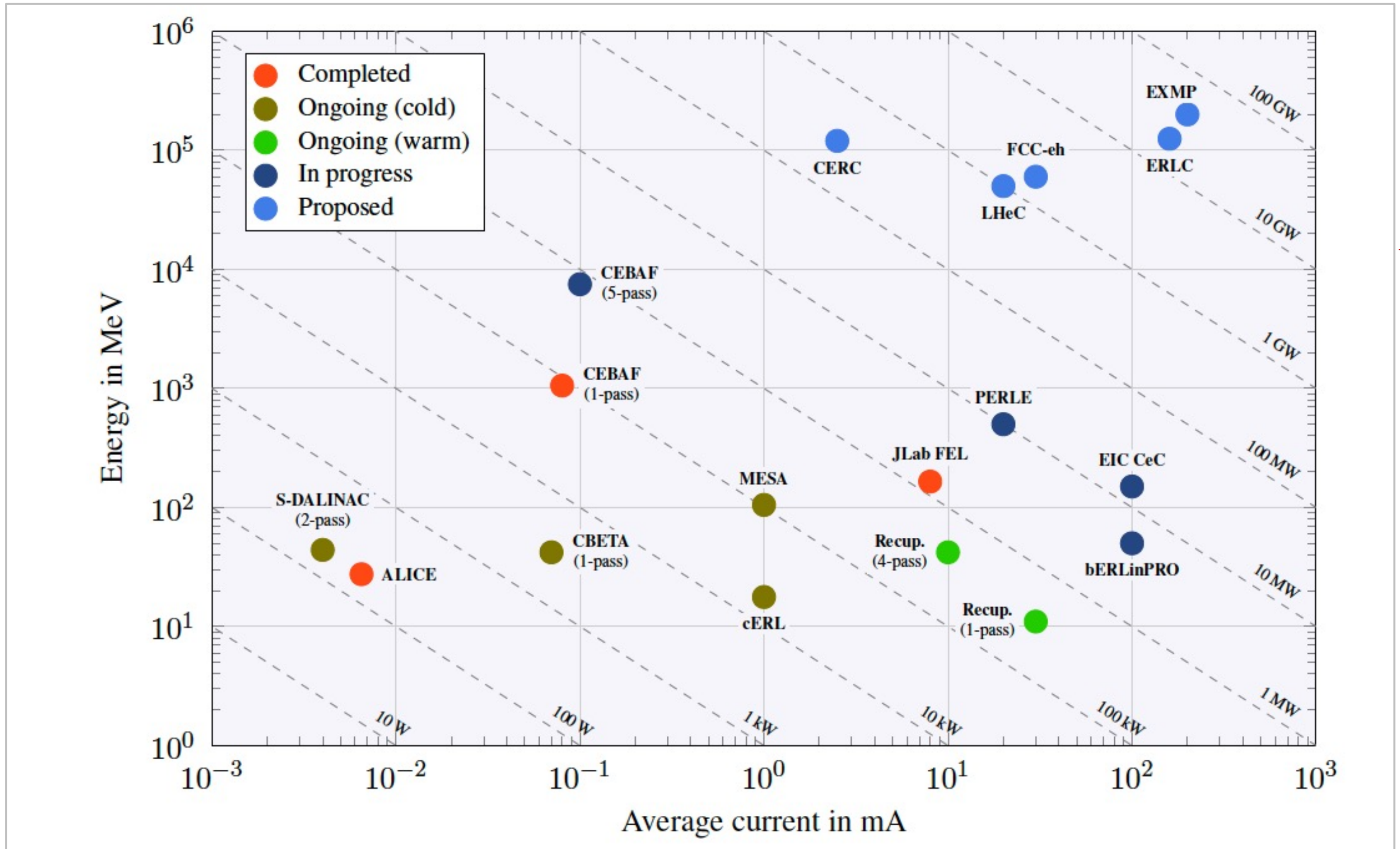


Fig. 5.1: Electron energy E vs. electron source current I for classes of past, present and possible future ERL facilities as are introduced in the text. Dashed diagonal lines are equi-power lines, $P[\mathrm{kW}] = E[\mathrm{MeV}] \cdot I[\mathrm{mA}]$. A brief account of the ERL history is presented in Sect. 5.2.1.

A challenging international ERL development program (no roadmap resource required).

Ongoing/forthcoming facilities

Training, operation — S-DALINAC - Darmstadt

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

Support EIC CeC — CBETA - Cornell

After achieving all Key Performance Parameters of CBETA's NYSERDA-funded construction and commissioning phase, operation was interrupted in the spring of 2020. The accelerator is now available to test single-turn and multi-turn ERL technology. Especially tests for the 100 mA hadron-cooling ERL of the EIC are of interest, as several key design parameters of CBETA's main components match that future accelerator well.

Exps, polarised, HOM — MESA- Mainz (from 2024)

It will represent a sustained infrastructure for such experiments but also be available for further research on ERLs for a long time to come. The civil construction for the new machine will be finalised in 2022. Following the installation and commissioning of the machine, first ERL tests are expected in 2025. External-beam experiments are expected to start somewhat earlier. The ERL

– **Improving the higher-order mode damping capabilities** of the cavities.

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

Industry, 10mA, Nb_3Sn — cERL – KEK (50 years..)

– Realization of energy-recovery operation with 100 % efficiency at a beam current of 10 mA at cERL and the FEL light production experiment.
– Development of an irradiation line for industrial applications (carbon nanofibers, polymers, and asphalt production) based on the CW cERL operation.
– Realization of a high-efficiency, high-gradient Nb_3Sn accelerating cavity to produce a superconducting cryomodule based on the compact freezer. We are targeting a general-purpose compact superconducting accelerator system that that can be operated at universities, companies, hospitals,

90MHz, FEL — Recuperator – BINP (warm)

The current of the Novosibirsk ERL is now limited by the electron gun. A new RF gun was built and tested recently [41]. It operates at a frequency of 90 MHz. An average beam current of more than 100 mA was achieved. In brief, the following work is planned for the next years:

– Installation of the RF gun in the injector, while the existing electrostatic gun will be kept there. The RF gun beamline has already been manufactured and assembled in the test setup. It includes an RF chopper for the beam from the electrostatic gun.

See roadmap and long write-up for much more info.

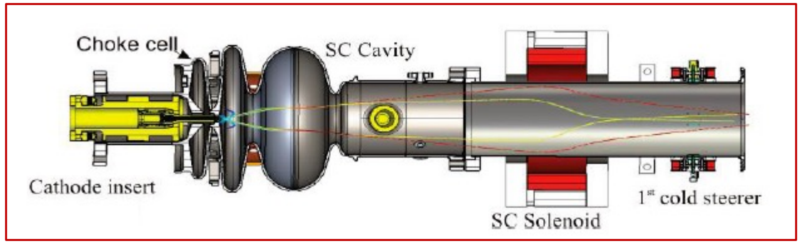
5.6 R&D objectives - Key technologies - ERL Roadmap Part B

5.6.2 SRF Technology and the 4.4 K Perspective

Near-Term 2 K Developments

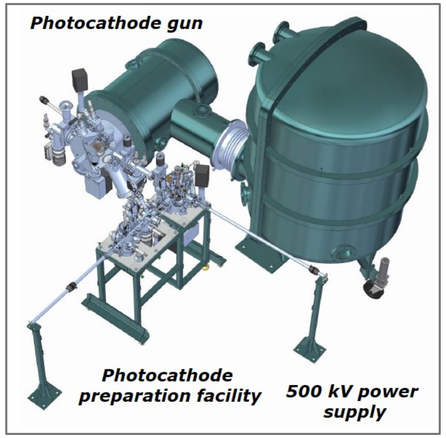
- Operation at 20 MV/m with $Q_0 > 3\ 10^{10}$
- Extraction of HOM power from Helium bath
- Damping of HOMs to prevent beam break up
- Reduction of RF power via Fast Reactive Tuners (FRT)
- 100mA sources (SRF and DC photocathode)

5.6.1 High-Current Electron Sources



SRF elliptical cavity gun at bERLinPro: new 100mA module

ALICE (20mA) PERLE:



Roadmap integrates high current current source and 2K developments into the two facilities (part C):

bERLinPRO: 1.3 GHz, 100mA, 1-pass & PERLE: 802 MHz, 20mA, 3 passes

Towards 4.4 K

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

$$P = \frac{V_{\mathrm{acc}}^2}{(R/Q) \cdot Q_0} \cdot N_{\mathrm{cav}} \cdot \eta_T \qquad (5.1)$$

where V_{acc} is the acceleration of a cavity, R/Q the shunt impedance, Q_0 the cavity quality factor, N_{cav} the number of cavities and η_T the heat transfer, i.e. combined technical and Carnot, efficiency, which is proportional to the ratio of the cryo temperature, T, and its difference to room temperature, 300 K − T.

Boost cryogenic efficiency and chill cavities with cryocoolers, no lHe

- Nb_3SN coating via vapour infusion, sputtering or ALD
- Evaluation of other superconductors as NbN, NbTiN, V3S
- Cavity tuners to avoid detachment of coating

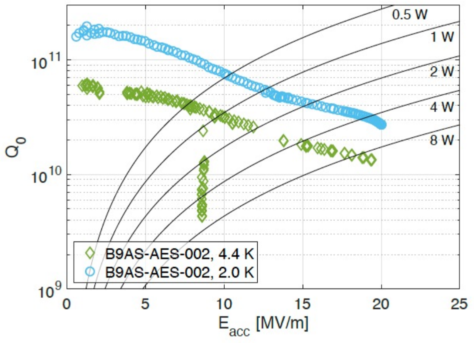


Fig. 13: Performance of 650 MHz single cell cavity B9AS-AES-002. The multipacting at 9 MV/m was processed during the test.

arXiv:2008.00599

In parallel: nitrogen diffusion and doping to reach 10^{11}

Roadmap: long term cavity R&D towards 4.4K: SRF Panel ERL: full module in beam test (2030?) PERLE or bERLinPRO

bERLinPRO

C

(2022-2025+)

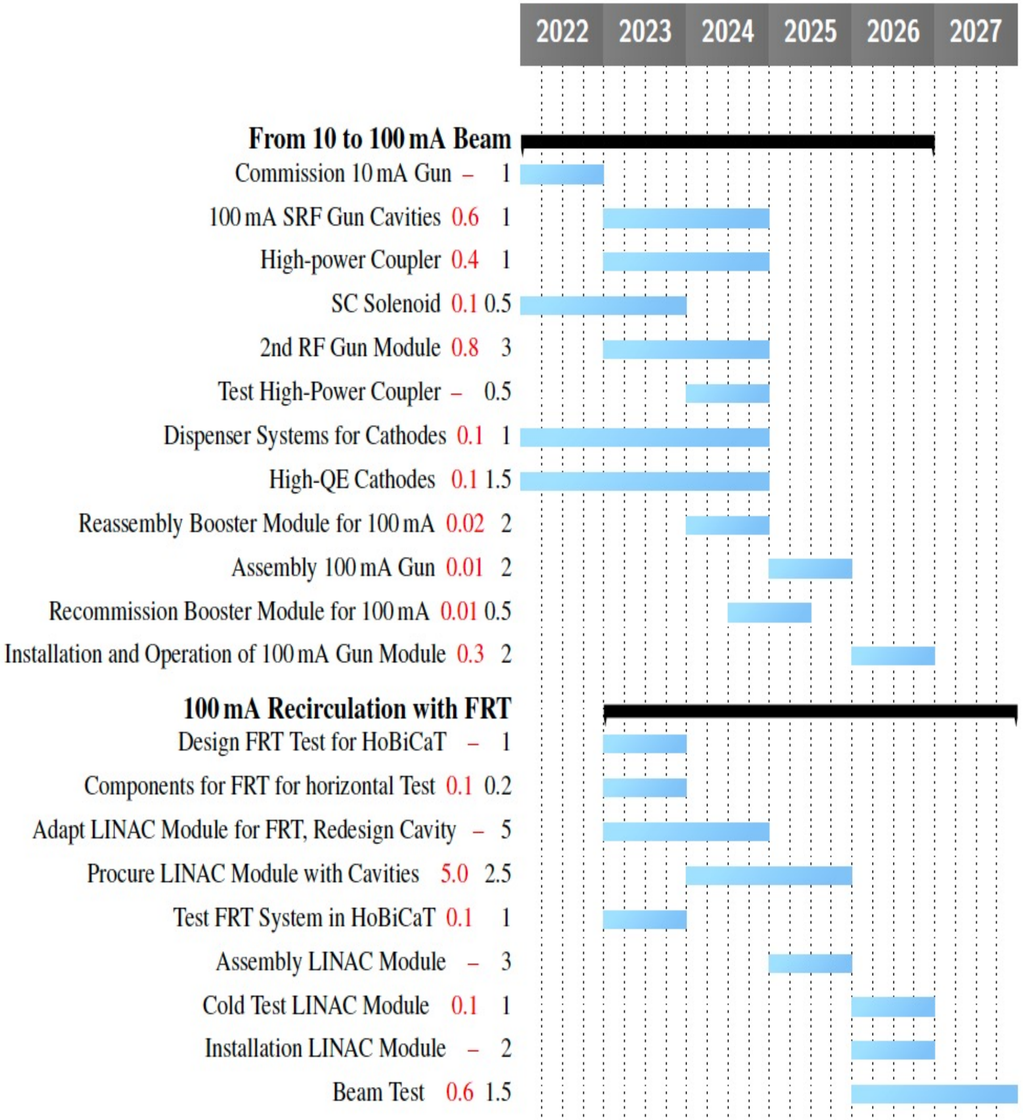
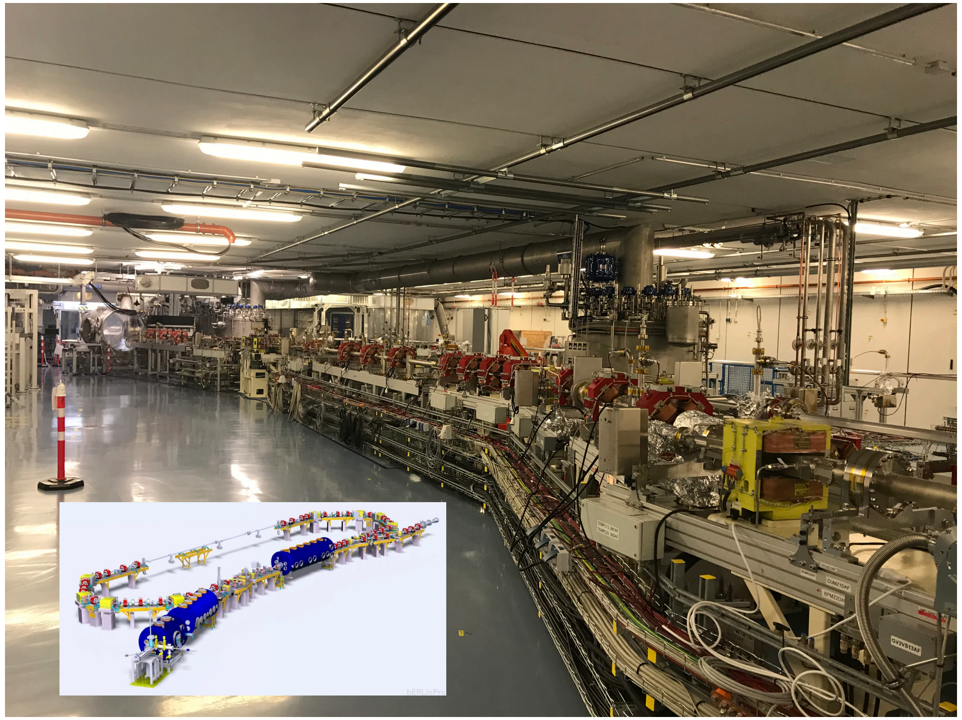


Fig. 6.8: Top: upgrade of bERLinPro to 100 mA electron current operation (**ERL.PRO.PR1**). Resources required are 2.4 MCHF (red) plus 16 FTEy (black). Bottom: completion of bERLinPro with a 1.3 GHz cavity-cryomodule in the beam **ERL.PRO.PR2**. Resources required are 5.9 MCHF (red) plus 17 FTEy (black).



Jens Knobloch, Bettina Kuske, Axel Neumann (Berlin HZB), **Orsay seminar by AN Dec 21**

First ERL Facility to operate 100mA in single turn ERL with FRT control

A - Build SRF gun for 100 mA (currently power coupler limited)

B - Adding 1.3 GHz module, equipped with FRT, to complete facility.

→ R&D on stability, bbu, emittance preservation, beam loss, halo ..

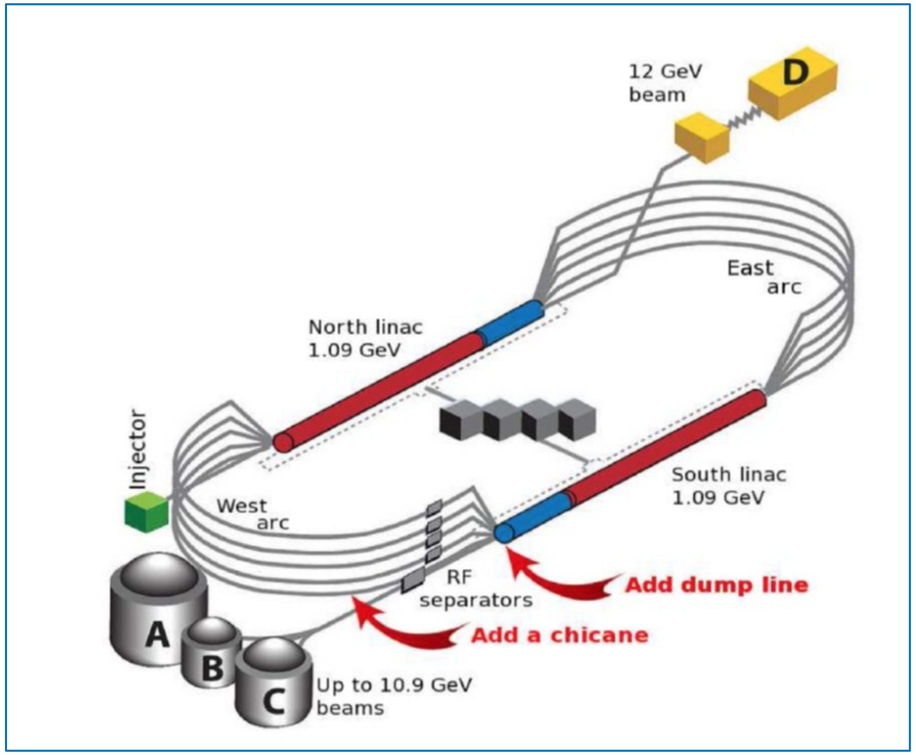
→ Test of FRT concept in high current beam operation.

C

Two ERL facilities in progress in the US
Important for, but not part of this Roadmap

Electron Cooler for EIC

CEBAF 5 pass

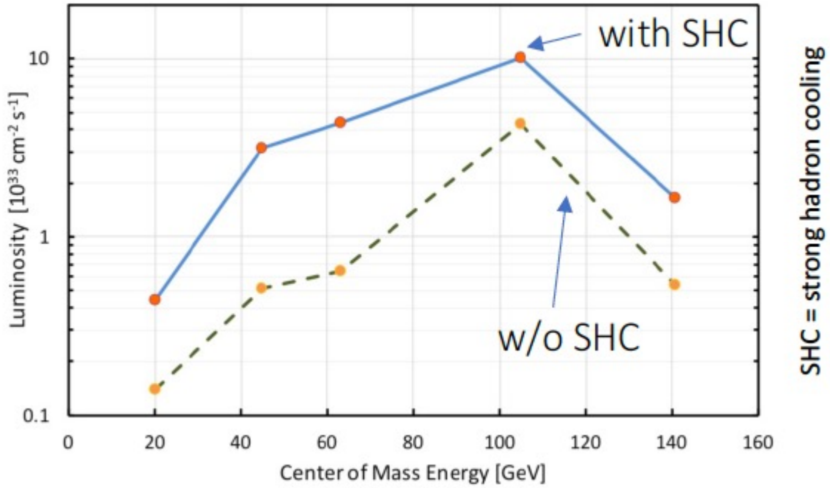


12 GeV (11 passes) beam to Hall D, 11 GeV to A,B,C

Experiment Run schedule for 2024
Important test of ERLs for high energy application

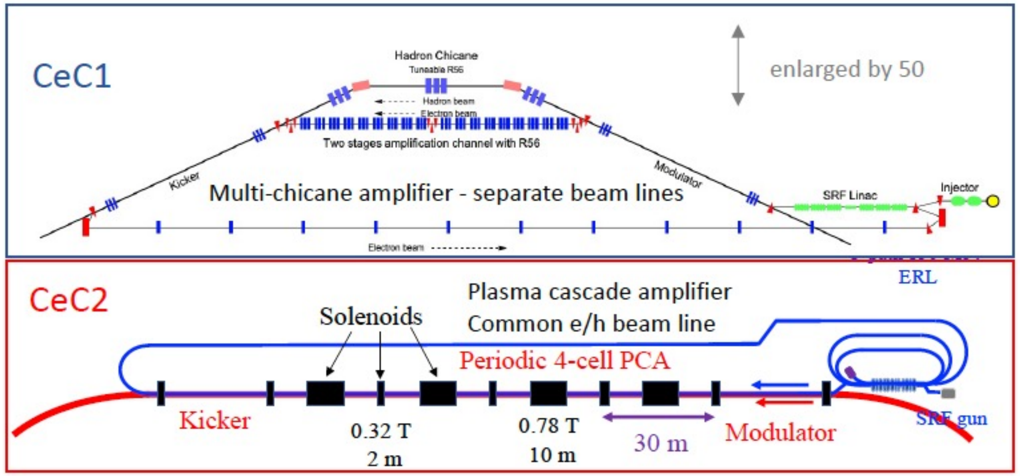
Decision expected with CD2

PRL **102,** 114801 (2009)
Derbenev, Litvinenko



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

Decision expected with CD2



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

Fig. 6.9: The path to the PERLE technical design report and commissioning of the injector. Resources required are 3.9 MCHF (red), 31 FTEy (black).

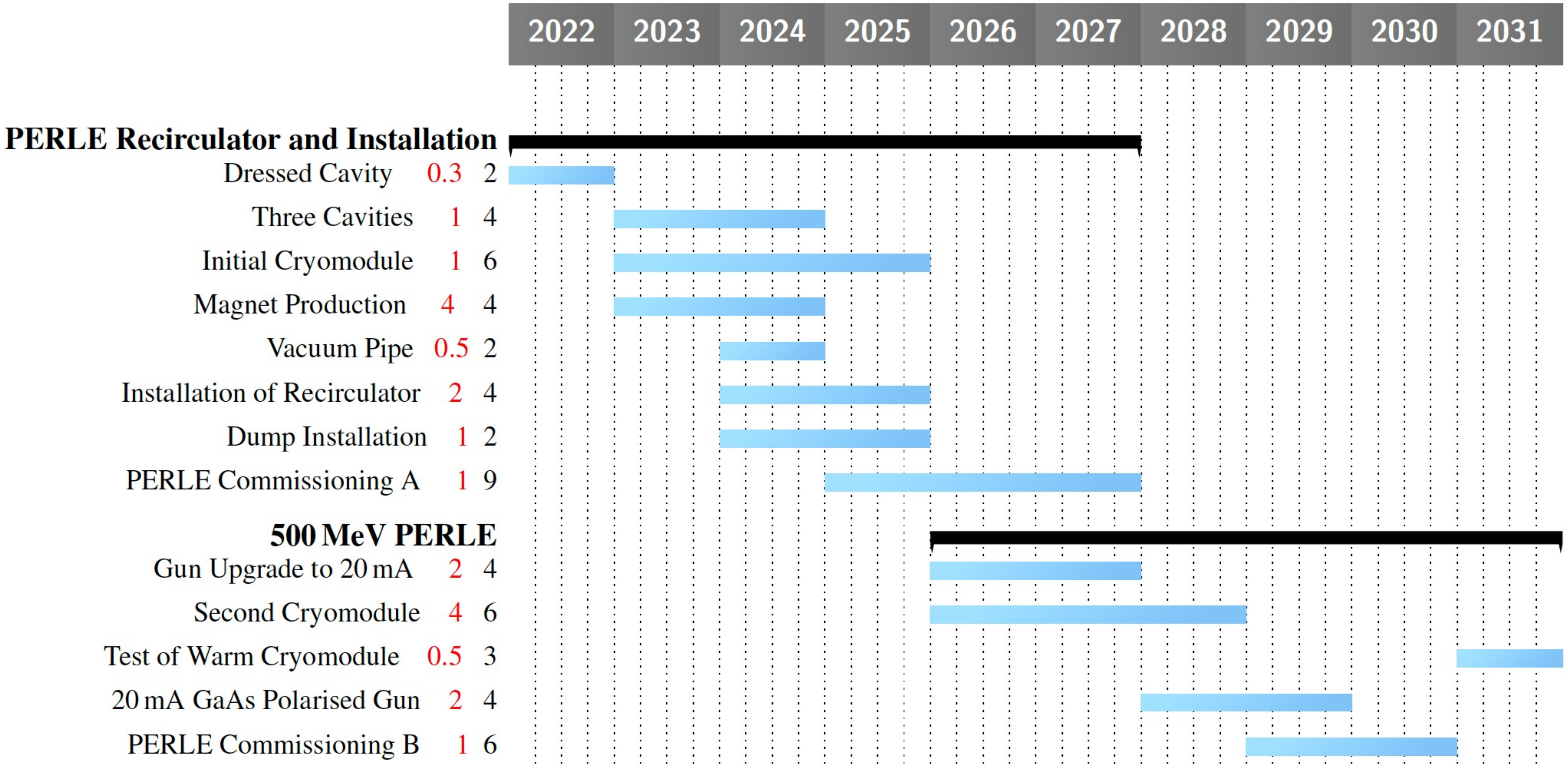


Fig. 6.10: PERLE completion in two steps: The 250 MeV phase with beam in the mid-twenties (**ERL.PER.PE1**); and the 500 MeV stage towards the end of the decade (**ERL.PER.PE2**). Resources for the first part, including funding of the TDR and injector phase: 14.6 MCHF (red), 64 FTEy (black). Resources for the 500 MeV stage: 9.5 MCHF, 23 FTEy.

Organisation

PERLE is the first large institutional collaboration for building and operating an ERL facility. Its success will rely on the intellectual, technical, and financial contributions of the collaborating partner institutes, built around given the clear decision of IN2P3 and its Irène Joliot Curie Laboratory to realise this machine soon. PERLE comprises accelerator, particle and nuclear physicists, and its collaboration structure is emerging as a balance between the particle physics experiment collaboration model and a host-facility-oriented one.

From Roadmap report

Collaboration Board and Host Laboratory (IN2P3/CNRS)

PERLE Project

Scientific Responsible: A Stocchi
Technical Responsible: W Kaabi

Spokesperson M Klein

Management Board

A Bogacz, P Duthil, F Gerigk
W Kaabi, M Klein (chair), B Militsyn
D Reynet, B Rimmer , A Starostenko
A Stocchi, P Williams

Project Engineer: Denis Reynet

WP1 WP2 WP3 WP11

Evolving tentative structure of the PERLE Project and Collaboration

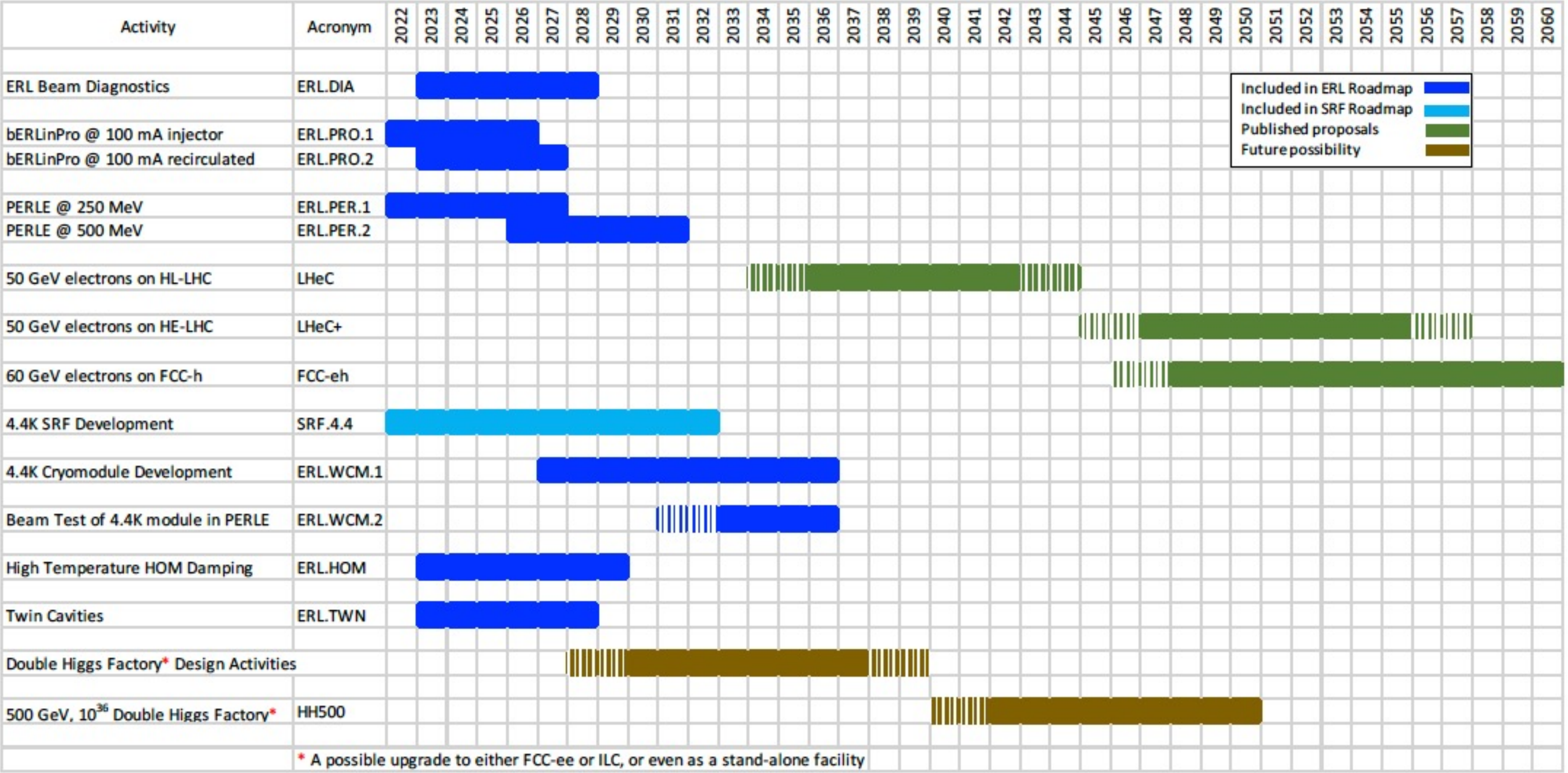


Fig. 6.12: Long-term vision for the ERL Roadmap showing how the activities in the next five to ten years lead to multiple options for future HEP Colliders.

Conclusion

Unprecedentedly high beam intensities open new fields of low energy physics such as nuclear photonics, elastic ep scattering, dark photon searches and exotic isotope spectroscopy. This technology also has a significant future in other fields such as FELs, EUV Lithography, Inverse Compton Scattering, etc. ERL technology is inherently energy-sustainable, which will be an important requirement for all future accelerator projects. As an innovative field, it is bound to attract new generations of accelerator physicists and engineers.

The year 2021 was a very important milestone year for energy recovery linacs, leading to much hope and high expectations. As part of a global development, with CEBAF, CEIC in the US, cERL in Japan and the Recuperator in Russia, Europe's ERL future goes with MESA, the upgrade of bERLinPro and PERLE, which has a key role as a high current, multi-turn facility. The support of CNRS/IN2P3/IJCLab and a very experienced collaboration offer the unique chance to open a new chapter, not least for linear accelerators at Orsay. This opportunity poses severe demands on all of us, as the ESP process is set to progress based on results by the mid twenties.