The European Energy Recovery Linac Roadmap

Andrew Hutton, Jefferson Lab,

Max Klein, Liverpool University,

Bettina Kuske, Helmholtz-Zentrum Berlin for the ERL-panel Team

IPAC 2022, Bangkok, Thailand

Towards sustainable accelerators for HEP

Since **2005** the CERN council mandates the

“European Strategy for Particle Physics” *

“… a broad consultation of the grass-roots particle physics community, actively soliciting the opinions of physicists from around the world, … in close coordination with similar processes in the US and Japan in order to ensure … optimal use of resources globally.”

2019/2020 update: CERN Council mandates the Laboratory Directors Group (LDG) to define and maintain a prioritised accelerator R&D roadmap towards future large-scale facilities for particle physics.

LDG defined 5 areas of interest:

- High-field magnets
- High-gradient RF structures and systems Plasma
- High-gradient plasma and laser accelerators
- Bright muon beams and muon collider
- Energy-recovery linacs (chair: Max Klein, U-Liverpool),
  e+e- collider subpanel (chair: Andrew Hutton, JLab)

18 Panel members: Deepa Angal-Kalinin, Kurt Aulenbacher, Alex Bogacz, Georg Hoffstaetter, Andrew Hutton (Co-Chair), Erk Jensen, Walid Kaabi, Max Klein (Chair), Bettina Kuske, Frank Marhauser, Dmitry Kayran, Jens Knobloch, Olga Tanaka, Norbert Pietralla, Cristina Vaccarezza, Nikolay Vinokurov, Peter Williams and Frank Zimmermann. The editor was Max Bruker.
In addition, numerous guest authors contributed to their specific fields of experience.

ERL Symposium, June 4th, 2021:
joint consultation with the particle and accelerator physics communities,
discussed the basis, status, impact, technology, and prospects of the field of ERLs. https://indico.cern.ch/event/1040671/

*: https://europeanstrategy.cern/european-strategy-for-particle-physics

Underlying conviction: 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 for industrial applications

ERLS are 'green(er)':

- recycle the kinetic energy of the used beam (significantly reduced power consumption)
- utilize the high brightness of modern injectors (avoid emittance blow up)
- dump the beam at injection energy (less radiation hazard)

This broad effort, conducted in 2021, resulted in a document
"European Strategy for Particle Physics"
published in Jan. 2022: http://arxiv.org/abs/2201.07895 or https://doi.org/10.23731/CYRM-2022-001

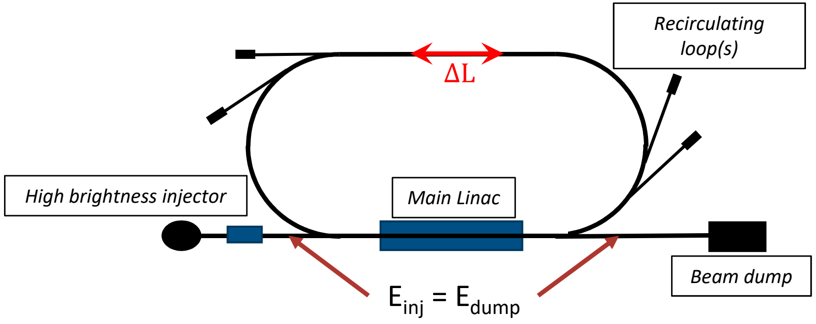
Executive summary (ERL)*: *"The panel notes with much interest that the ERL technology is close to high-current and high energy application … with the stunning potential to revolutionise particle, nuclear and applied physics, as well as key industry areas."*

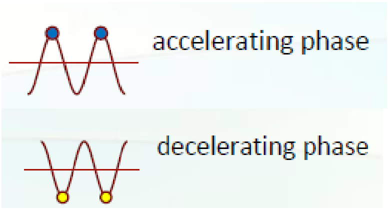
*: European Strategy for Particle Physics - Accelerator R&D Roadmap, N. Mounet (ed.), CERN Yellow Reports: Monographs, CERN-2022-001 (CERN, Geneva, 2022), https://doi.org/10.23731/CYRM-2022-001
Extended ERL, covering all of the panels findings - to be published soon

The layout of the talk:

- Brief introduction to ERL
- Next generation accelerators for HEP
- European operational facilities
- Power consumption conventional versus ERL colliders
- **Key challenges ahead and the Roadmap's strategy**
- Status

Energy Recovery - a technique in accelerator construction





$\Delta L = 1/2\ \lambda_{RF}$: electrons are decelerated on second turn in linac and deposit their energy back into the RF cavities to accelerate further bunches.

ERL properties:

- single pass device (no emittance blow up)
- bunch properties defined by the source
  flexible bunch parameters, bunch patterns

} linac - like

- usage of return arc(s) for experiments
- RF needed beyond injection: compensation of SR and losses

} storage ring - like

ERL efficiency* :

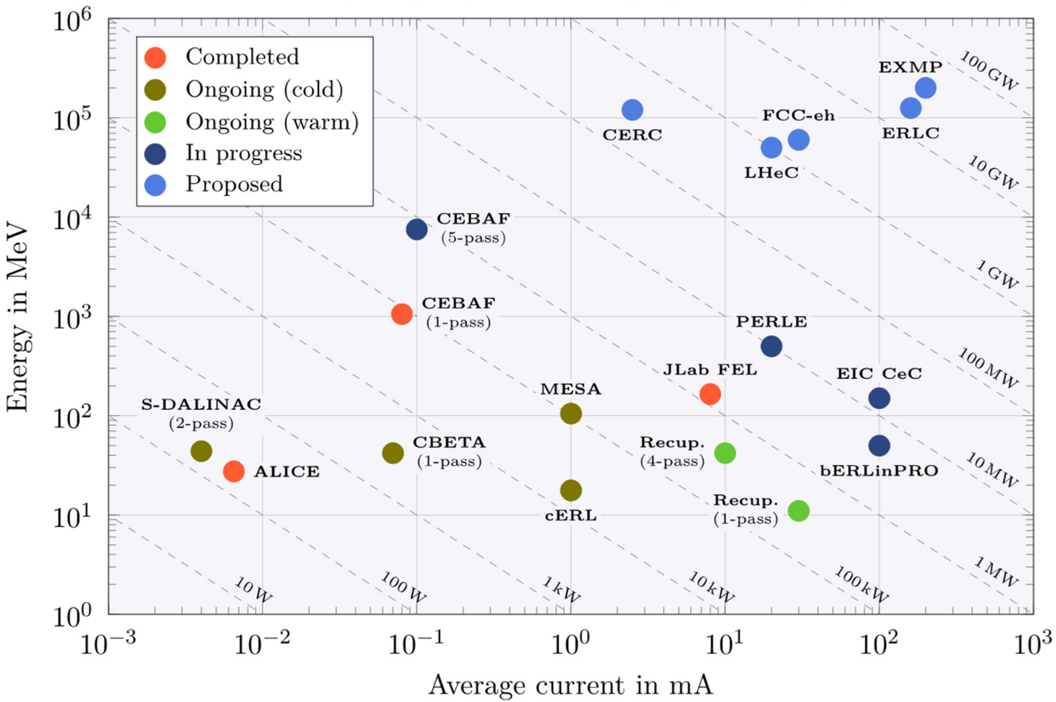
$$\frac{P_b}{P_{RF}} = \frac{I_b E_f}{I_b E_{inj} + P_{ramp\ up(+losses)}}$$

As the main accelerating energy is recovered…

ERLs are efficient for high beam power:

- high energy (multi-turn)
- high current

Landscape of past, present and proposed ERL projects



*: Merminga et al., HIGH-CURRENT ENERGY-RECOVERING ELECTRON LINACS, doi: 10.1146/annurev.nucl.53.041002.110456

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Efficiency of recovery process ⇔ SRF technology

cavity	R_s surface resistance	Q_0 quality factor	Frequency
Normal conducting	1	$\sim 10^4$	<500MHz
Super conducting	10^{-6}	$> 10^{10}$	0.7-1.3 GHz

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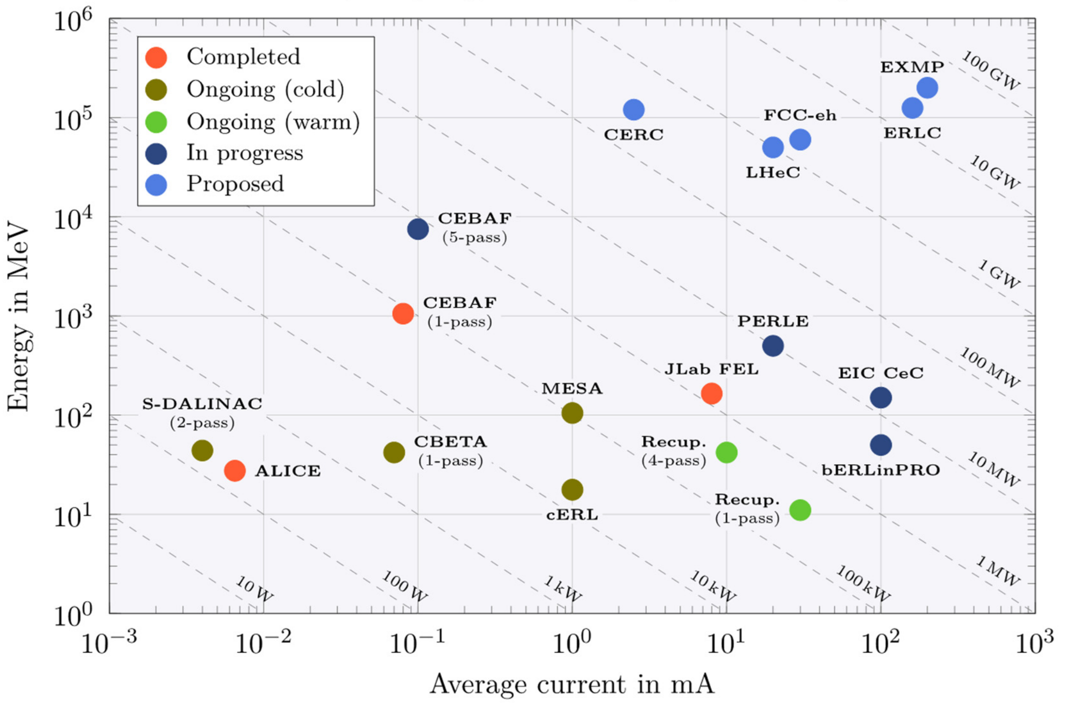

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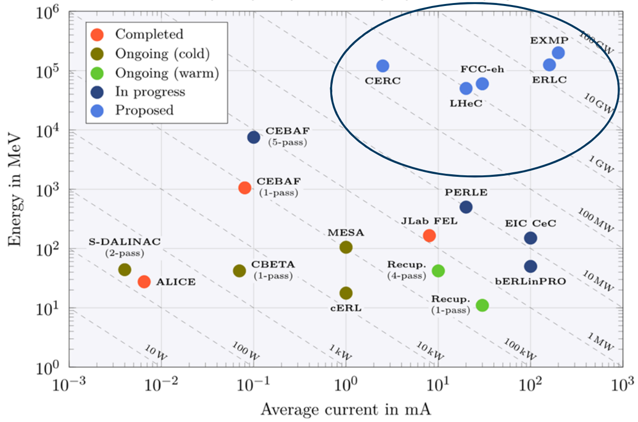


three-turn ERL

LHeC:
provides an intense,
high-energy electron beam for
collisions with the LHC beam.
50 GeV, 20/50mA
4.5km racetrack
(2012, 2020)

FCC-eh:
provides an intense,
high-energy electron beam for
collisions with the FCC beam.
60 GeV, 20mA
9km racetrack
(2018)

4-turn ERL

CERC:
ERL-version of FCC-ee
182.5 GeV, 1.01mA
100km, 4-turn circular
(2020)

single-pass ERL,
twin-axis cavities

EXMP – Muon source
Based on electron-photon collision
200 GeV, 200mA

ERLC
ERL-version of ILC
125GeV, 44.7mA
(2021)

Common demand:
SC cavities to tolerate 10 - 400 mA current load

Two European medium-scale facilities with exactly that goal:

PERLE, IJCLab, Orsay, France
3 turn ERL
Goal: 500MeV, 20mA, 10MW

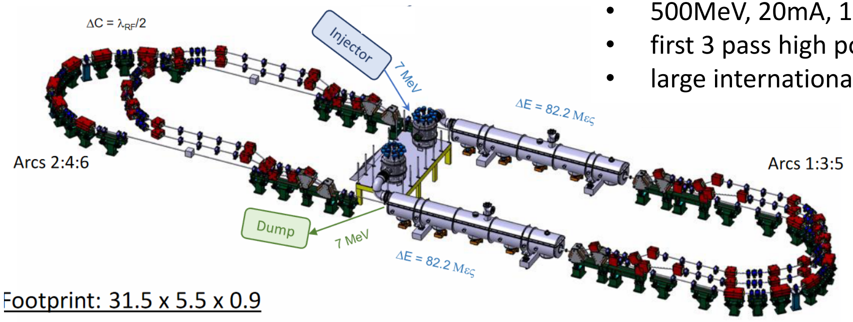
bERLinPro, HZB, Berlin, Germany
single-pass ERL
Goal: 50MeV, 100mA, 5MW

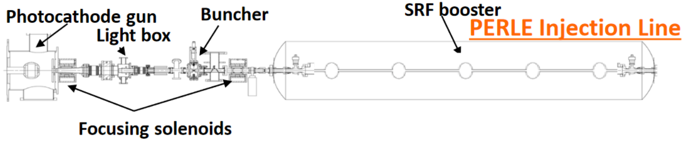
PERLE, IJCLab, Orsay, France

Large international collaboration

Test-bed for future high-power ERL facilities, specifically LHeC and FCC-ee technologies, ***in preparation***

- 500MeV, 20mA, 10MW
- first 3 pass high power/ high energy ERL
- large international collaboration





- Electron source to booster optimization meets specifications
- Merger studies
- First Nb 801.58MHz 5-cell elliptical cavity fabricated at Jlab with Q_0=3 10^{10}
- HOM-damping studies ongoing

Test facility SRF/ERL technology

Basically operational, the warm machine, and all facilities ready:

=> most rapidly accessible facility

- 10mA SRF gun – commissioning 2022/23
  - Assembly of cold string
  - HP coupler successfully tested
  - Extension to 100mA feasible in the same SRF module
- Ongoing R&D programs (UED application, industry coupler tests)
- Needs linac for recirculation

PERLE, IJCLab, Orsay, France

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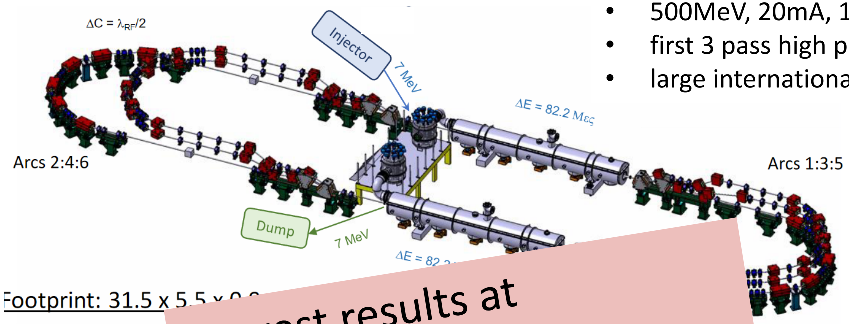

Footprint: 31.5 x 5.5 x 0.

Newest results at
- Linac 2022
- ERL Workshop 2022

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- Merger studies
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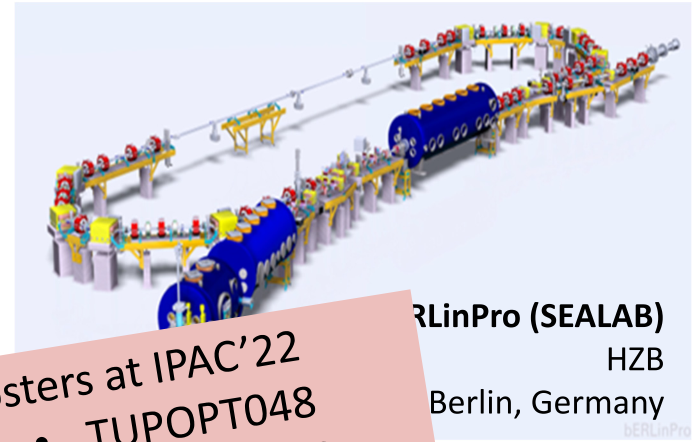

RLinPro (SEALAB)
HZB
Berlin, Germany

Posters at IPAC'22
- TUPOPT048
- WEPOTK060
- THPOPT019

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Basically ... cilities ready:
=> most r
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CERC (Circular Energy Recovery Collider)
FCC-ee parameters : 100km, 182 GeV/beam
V. Litvinenko, T. Roser, M. Llatas
Physics Letter B 804 (2020) 135394

ERLC (Energy Recovery Linear Collider)
ILC parameters : 125 GeV/beam
V. Telnov
arXiv:2105.11015v4 [physics.acc-ph] 28 Nov 2021

e+e- sub-Panel (-> report in roadmap)

- Not complete, no fully coherent parameter set yet
- Problems identified & updates exist
- no showstopper so far

Both promise luminosities 10^2 -10^3 higher than FCC / ILC proposals at comparable energy consumption

Circular ERL:
Lower restrictions on beam-beam tune shift, beam gets dumped after collision

Linear ERLS:
Much higher current:
44.7mA ⇔ 0.021mA

Conventional Colliders

		power for acceleration
FCC*	Storage ring	RF: 60%, ~145MW
		100MW synchrotron radiation
ILC**	Linear accelerator	AC-power main linac: 106MW
		"accelerate and dump"

Physics

Assuming 85% RF efficiency in both cases
* F. Zimmermann, FCC Week 2019 Brussels, 24 June 2019
** https://linearcollider.org/files/images/pdf/Executive%20Summary.pdf

ERL based Colliders

	power for acceleration
CERC#	Cryogenics: 56%, ~153MW
	2K, Q = $2x10^{10}$, BNL-ERL 5-cell cavity, +20% thermal shield and power coupler cooling
ERLC##	Cryogenics: 110MW
	0.19 duty cycle to cope with RF heat load in cavities (44.7mA)

Technology

\# Physics Letter B 804 (2020) 135394
\## arXiv:2105.11015v4 [physics.acc-ph] 28 Nov 2021

Total power consumption prediction for future HEP machines: ~300MW
>50% cryo & RF
>50% of cryo due to RF heat load

For more details:

*** Kaoru Yokoya: "Energy Recovery Versions of ILC and FCCee", ILC Camp, 2021/09/24, https://agenda.linearcollider.org/event/9312/contributions/48614/attachments/37188/58228/ERconceptForColliders-v3.pdf
Bettina Kuske: "Sustainability Aspects of Energy Recovery Linacs", https://engage.aps.org/dpb/meetings/meeting-presentations

Key challenges to achieving GW-level of beam power (high energy / high current):

- **SRF cavity and cryomodule development – sustainability centered**
  - much development ongoing worldwide (independent of ERLs)
  - ERLs: system design compatible with high beam current / HOM excitation
  - enhanced cryogenic efficiency, reduced RF power and cryogenic load due to RF losses
    - ⇒ operation at 4.4K
    - ⇒ higher quality factors (new cavity material: Nb_3Sn, NbN, NbTiN…)
    - ⇒ handling of transients and microphonic detuning (Fast Reactive Tuners)
    - ⇒ HOM power absorbers at the highest possible temperature
- **multiturn studies:** replace expensive linac with cheaper transport beamlines
- **reliable simulation software:** experimental benchmarking (CSR, BBU, longitudinal matching, S2E)
- **diagnostics:** separation of beams on successive turns, high beam power, non-Gaussian bunch profiles, high dynamic range

Addressed by ERL Roadmap

- **High current: electron gun** (thermionic, DC, RF and SRF guns)
  - current: reliably 20 mA to 100 mA
  - emittance: <1 mm mrad to 5 mm mrad
  - charge: 77 pC to 500 pC

research proceeding worldwide (bERLinPro, BINP, BNL, Daresbury, PERLE) re-enforced by roadmap process

European Accelerator R&D strategy:

Progress is necessarily based on the many medium-scale operational facilities **around the world**

High current – up to 100mA (gun & load to SRF cavities)

- bERLinPro@HZB, BINP (NC, low frequency), CeC-EIC@BNL, cERL@KEK

10MW beam power in multi-pass configuration

- PERLE@IJCLab Orsay, broad int. collaboration

Test of **F**ast **R**eactive **T**uners:

- bERLinPro@HZB

HOM damping:

- bERLinPro@HZB, PERLE@IJCLab Orsay, CeC-EIC@BNL (required, if I > 1mA)

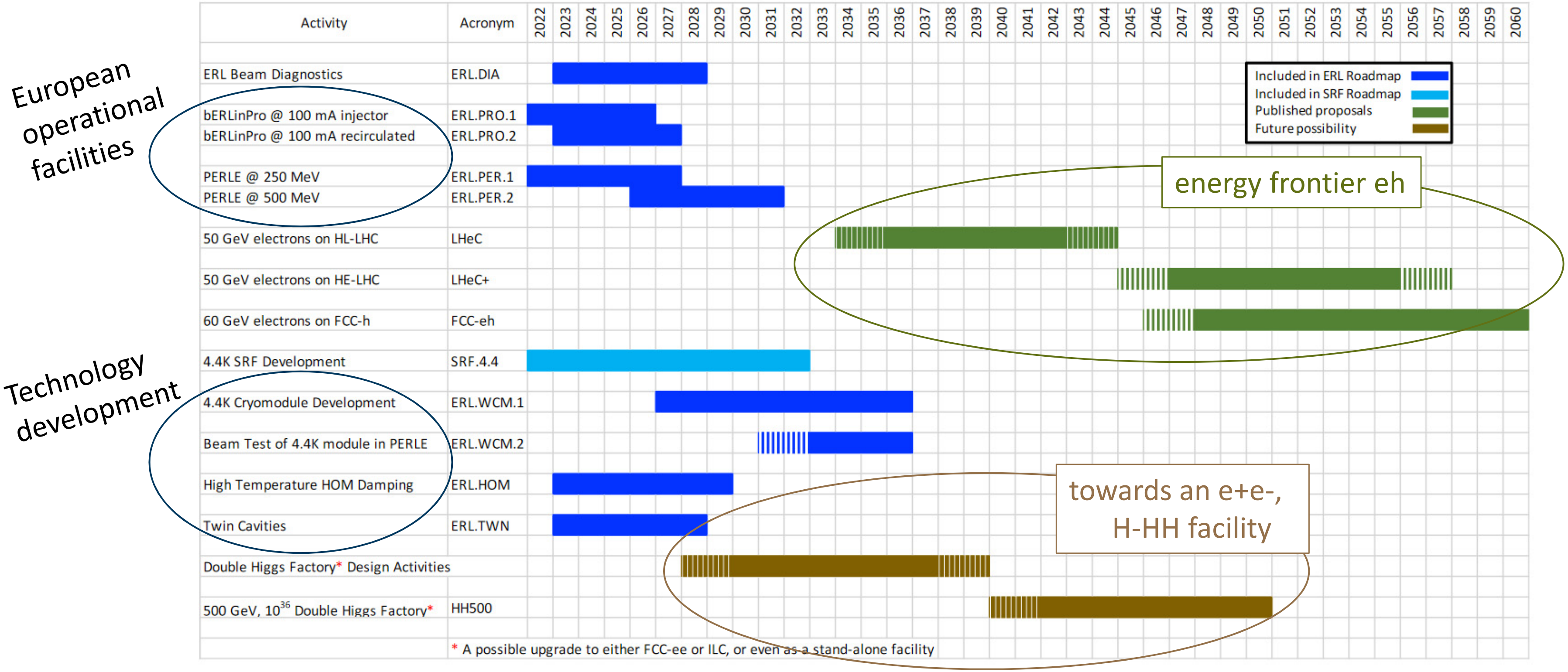
Energy increase to 10GeV in 5 passes (=> SR)

- ER@CEBAF, Jlab (&STFC Daresbury, U-Lancaster, U-Brussels)

Operational experience:

- S-DALINAC (TU Darmstadt, Germany), MESA (U Mainz, Germany), CBETA (U Cornell and BNL, US), cERL (KEK, Japan), and the NC Recuperator facility (BINP Novosibirsk, Russia).

Roadmap proposes funding for activities in the next five to ten years that lead to multiple options for future HEP Colliders



CURRENT STATUS

- The roadmap has been endorsed

  by CERN Council and the group of large HEP laboratories (LDG)
- It provides a reference for the “ERL implementation steering group”
- Intense work is continuing at Berlin and Orsay and around the world

International ERL workshop :
3-6 October 2022 in person at Cornell University https://indico.classe.cornell.edu/event/2018/

Frederick Bordry*: “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”.

Thank you for your attention

* CERN’s Director for Accelerators and Technology 2014-2021