HZB Helmholtz Zentrum Berlin

The European Energy Recovery Linac Roadmap

Andrew Hutton, Jefferson Lab,

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The LHeC/FCCeh and PERLE Workshop at Orsay

Oct 26 → Oct 28, 2022, Orsay, France

Towards sustainable accelerators for HEP

European Roadmap Process

- In 2020, the European Strategy Group recommended:
  - *The particle physics community should ramp up its R&D effort focused on advanced accelerator technologies [...]*
  - *The European particle physics community must intensify accelerator R&D and sustain it with adequate resources*
  - *A roadmap should prioritize the technology [...]*
  - *Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes*
- To achieve this, five Roadmap Panels were set up:
  - **Superconducting Magnets:** Pierre Vedrine (IRFU)
  - **Plasma Acceleration:** Ralph Assmann (DESY)
  - **RF:** Sebastien Bousson (IJCLab)
  - **Muons:** Daniel Schulte (CERN)
  - **ERL:** Max Klein (Liverpool)

All 'Jefferson Lab' transparencies are taken from Andrew Hutton's talk at the ERL 2022 workshop

Process

- Establish the Roadmap Panel
- Collect information on every ERL that is operating, or has ceased operation but still holds a record in some parameter, and proposed future projects
  - A spreadsheet was developed to facilitate this
- Request a status report from each of the facilities
- Seek input via a Symposium*
- Panel Members took responsibility for preparing Chapters of a long report with the status of all the projects
- Prepare a shorter report for integration with the other Roadmap panels

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

1:00 PM	→ 1:10 PM	Welcome by the Lab Directors Group	Speaker: Prof. Dave Newbold (STFC Rutherford Appleton Laboratory (GB))	LDG_Roadmap_Intr...	10m
1:10 PM	→ 1:15 PM	Introduction	Speaker: Max Klein (University of Liverpool (GB))	introSymp4621.pdf	5m
1:15 PM	→ 1:40 PM	ERL Facilities	Speaker: Andrew Hutton (Jefferson Laboratory)	ERLFacilities5.pdf; ERLFacilities5.pptx	25m
1:40 PM	→ 2:00 PM	High Current Electron Sources	Speaker: Boris Militsyn (STFC)	B.L. Militsyn High c...; B.L. Militsyn High c...	20m
2:00 PM	→ 2:25 PM	SRF Developments for ERLs	Speaker: Robert Alan Rimmer	SRF4ERLs_Rimmer....; SRF4ERLs_Rimmer....	25m
2:25 PM	→ 2:50 PM	ERL Prospects for High Energy Colliders	Speaker: Oliver Bruning (CERN)	ERL Symposium-V3....; ERL Symposium-V3....	25m
2:50 PM	→ 3:00 PM	Coffee/tea Break			10m
3:00 PM	→ 3:20 PM	Low Energy Physics with ERLs	Speaker: Jan Bernauer (Stony Brook University)	lowephys.pdf	20m
3:20 PM	→ 3:40 PM	Industrial ERL Applications	Speaker: Peter Williams (Daresbury Laboratory)	2021-06-04 PW ERL...; 2021-06-04 PW ERL...	20m
3:40 PM	→ 4:00 PM	Energy Recovery and Sustainability	Speaker: Erk Jensen (CERN)	Energy Recovery & ...; Energy Recovery & ...	20m
4:00 PM	→ 4:55 PM	Discussion			55m
4:55 PM	→ 5:00 PM	aob			5m

ERL Panel Members

- A team of experts was assembled in January 2021 to develop a Roadmap for ERLs
- The Panel had members from every laboratory that has, or has had, an ERL bringing a wealth of experience to the Panel

Deepa Angal-Kalinin (STFC)
Kurt Aulenbacher (Uni Mainz)
Alex Bogacz (Jefferson Lab)
Georg Hoffstaetter (Cornell)
Andrew Hutton (Jefferson Lab) – Co-Chair
Erk Jensen (CERN)
Walid Kaabi (IJCLab)
Dmitry Kayran (BNL)
Max Klein (Liverpool) – Chair

Jens Knobloch (Helmholtz-Zentrum Berlin)
Bettina Kuske (Helmholtz-Zentrum Berlin)
Frank Marhauser (Jefferson Lab)
Norbert Pietralla (Darmstadt)
Olga Tanaka (KEK)
Cristina Vaccarezza (INFN, Frascati)
Nikolay Vinokurov (BINP)
Peter Williams (STFC)
Frank Zimmermann (CERN)

Long Report

- The long report was completed in July 2022 – a marathon that took 18 months!
  - Editor: Max Bruker (Jefferson Lab)
  - 49 authors
  - 22 institutions
  - 270 pages
  - 58 figures
  - 419 references
- Available at https://arxiv.org/abs/2201.07895
- Accepted for publication in JINST

The Development of Energy-Recovery Linacs

Chris Adolphsen,[t] Kevin Andre,[d,i] Deepa Angal-Kalinin,[f] Michaela Arnold,[g] Kurt Aulenbacher,[j] Steve Benson,[o] Jan Bernauer,[m] Alex Bogacz,[o] Maarten Boonekamp,[l] Reinhard Brinkmann,[u] Max Bruker,[o] Oliver Brüning,[d] Camilla Curatolo,[p] Patxi Duthill,[k] Oliver Fischer,[i] Georg Hoffstaetter,[e,c] Bernhard Holzer,[d] Ben Hounsell,[k,i] Andrew Hutton,[o,1] Erk Jensen,[d] Walid Kaabi,[k] Dmitry Kayran,[c] Max Klein,[i] Jens Knobloch,[a,s] Geoff Krafft,[o] Julius Kühn,[a] Bettina Kuske,[a] Vladimir Litvinenko,[m] Frank Marhauser,[o] Boris Militsyn,[f] Sergei Nagaitsev,[v] George Neil,[o] Axel Neumann,[a] Norbert Pietralla,[g] Bob Rimmer,[o] Luca Serafini,[p] Oleg A. Shevchenko,[b] Nick Shipman,[d,q] Hubert Spiesberger,[j] Olga Tanaka,[n] Valery Telnov,[b,r] Chris Tennant,[o] Cristina Vaccarezza,[h] David Verney,[k] Nikolay Vinokurov,[b] Peter Williams,[f] Akira Yamamoto,[n] Kaoru Yokoya,[n] Frank Zimmermann[d]

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[b] *Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia*
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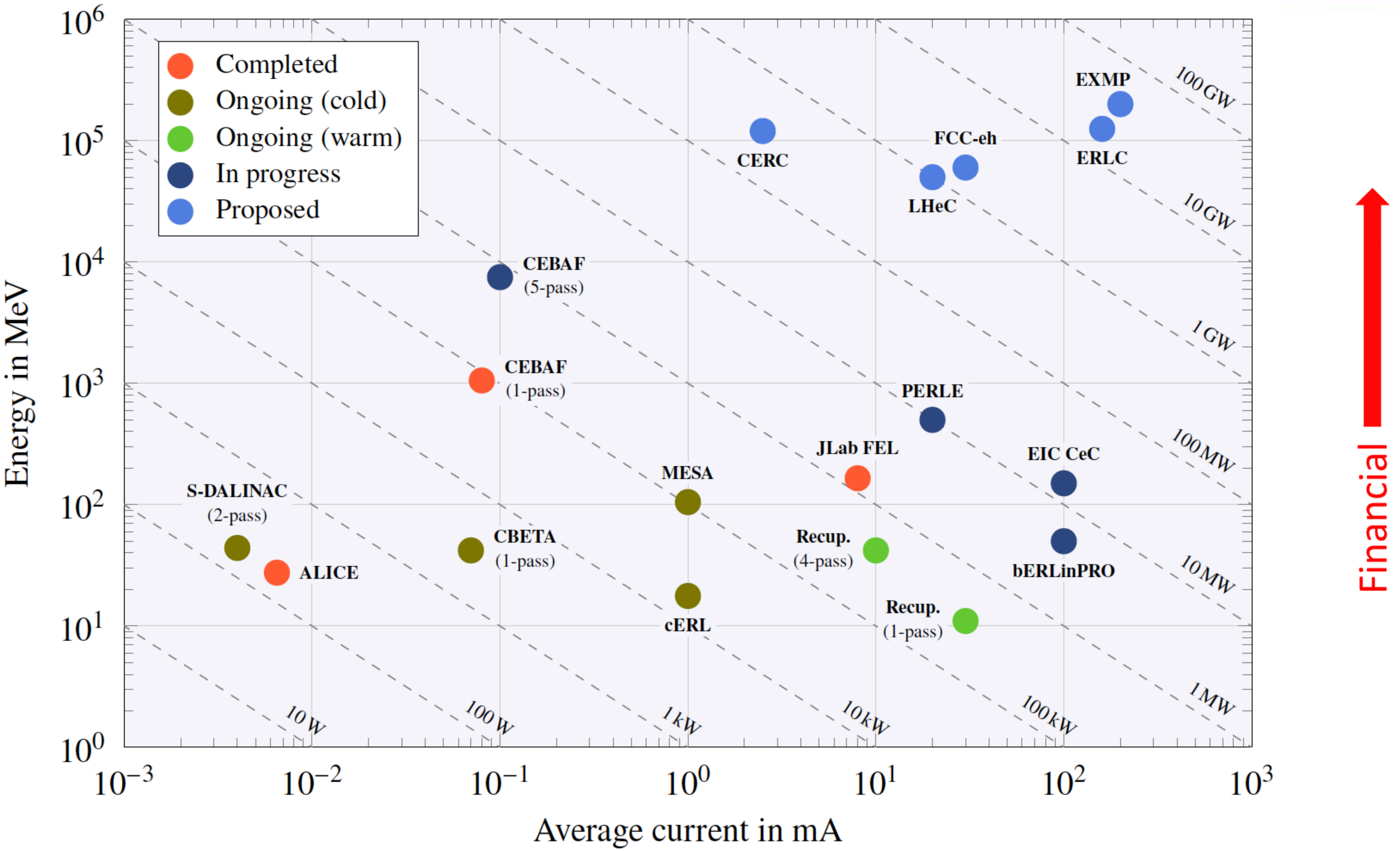
[r] *Novosibirsk State University, 630090, Novosibirsk, Russia*
[s] *University of Siegen*
[t] *SLAC*
[u] *DESY*
[v] *Fermilab*

Overview of ERL Facilities



Technology

Appendix A: Completed and Ongoing Facilities

Table A.1. Completed facilities.

		ALICE	JLab FEL	CEBAF 1-pass
Top energy	MeV	27.5	165	1045
Beam power	kW	0.18	1300	104.5
Injector / Dump				
Gun energy	keV	350	100	100
Bunch charge	pC	60	270	0.06
Current	mA	5	8.5	0.1
Polarization		No	No	No
Beam energy	MeV	6.5	9	25 / 45
Emittance (norm.)	µm	2.5	8	0.05
Dump energy	MeV	< 10	11	25 / 45
Dump power	kW	30	100	4.5
Acceleration				
Energy gain per linac	MeV	20	156	2×500
RF frequency	MHz	1300	1497	1497
Bunch repetition rate	MHz	81.25		
Total linac current	mA	10 (peak)	17	0.2
Macropulse length		100 µs	CW	CW
Emittance (norm.)	µm	3	10	0.05
Average gradient	MV/m	11	12	12
Quality factor	$\times 10^{10}$	0.5	1	1
RF controls		analog / DLLRF	analog	analog
Beam loss		not measured	100 nA	
Arcs				
Passes		1	1	1
Optics design			Bates bends	achromatic, isochronous
Beam loss		2 %	$< 10^{-4}$	
Interaction region				
β_x / β_y	cm	20	≈ 6	n/a
Beam size	µm	50	50	n/a

Table A.2. Ongoing facilities (parameters achieved).

		S-DALINAC 1-pass / 2-pass	bERLinPro	cERL	Recuperator	CBETA 1-pass / 4-pass
Top energy	MeV	22.5 / 41	25	17.6	40	42 / 150
Beam power	kW	0.027 / 0.3	150	20	200	2.9 / 0.3
Injector / Dump						
Gun energy	keV	125 / 250	< 3500	500	300	350
Bunch charge	pC		77	0.77	1500	5
Current	mA	0.0012 / 0.007	100	0.9	10	$0.07 / 2 \times 10^{-6}$
Polarization		Yes / No	No	No	No	No
Beam energy	MeV	2.5 / 4.5	6	3	1.5	6
Emittance (norm.)	µm		≤ 1	0.29 / 0.26	20	0.3
Dump energy	MeV	2.5 / 4.5	6	3	1.5	
Dump power	kW	0.003 / 0.032	< 60	2.7	15	0.42 / 0.012
Acceleration						
Energy gain per linac	MeV	20 / 18	43	14.6	10	6
RF frequency	MHz	2997	1300	1300	180	1300
Bunch repetition rate	MHz	2997			5.6 / 7.5 / 3.8	
Total linac current	mA	0.0024 / 0.028	200	1.8	10 / 30 / 70	$0.28 / 8 \times 10^{-6}$
Macropulse length		CW	CW	CW	CW, copper	CW
Emittance (norm.)	µm		≤ 1	0.42 / 0.26	20	0.3
Average gradient	MV/m	< 5	18	5.8–8.3	0.4	16
Quality factor	$\times 10^{10}$	0.3	1	0.25–0.6	4×10^{-6}	
Beam loss			$< 10^{-5}$	$< 10^{-4}$	$< 10^{-2}$	
Arcs						
Passes		1 / 2	1	1	1 / 2 / 4	1 / 4
Optics design		MBA	DBA	180° achromatic	180° achromatic	FFAG
Beam loss					$< 10^{-4}$	< 1 %

Appendix A: Facilities in Progress

Appendix B addresses two proposals: CERC and ERLC, discussed later

Table A.3. Facilities in progress (target values).

		MESA	PERLE	CEBAF 5-pass	EIC CeC
Top energy	MeV	105	500	7584	22.3 / 54.1 / 150
Beam power	MW	0.21	10	0.758	2.2 / 5.3 / 14.7
Injector / Dump					
Gun energy	keV	100	350 / 200	100	400
Bunch charge	pC	1	500	0.06	1000
Current	mA	2	20	0.1	98.5
Polarization		Yes	Yes / No	Yes	No
Beam energy	MeV	5	7	84	5.6
Emittance (norm.)	µm	< 1	6	0.05	< 3
Dump power	kW	5	140	8.4	551.6
Acceleration					
Energy gain per linac	MeV	2×25	2×82	2×750	17.3 / 49.1 / 145
RF frequency	MHz	1300	801.58	1497	591
Bunch repetition rate	MHz				98.5
Total linac current	mA	8	120	1	197
Harmonic frequency	MHz	n/a	n/a	n/a	1773
Macropulse length		CW	CW	CW	CW
Emittance (norm.)	µm	< 1	6	0.05	< 3
Average gradient	MV/m	12.5	20	12–17.5	20
Quality factor	$\times 10^{10}$	> 1.25	> 1	1	
RF controls		MTCA (digital)		analog/digital	TBD
Beam loss		10^{-5}			TBD
Arcs					
Passes		2	3	5	3
Optics design		MBA	flexible momentum compaction	achromatic, isochronous	R_{56}-canceling bending, Bates
Beam loss		10^{-3}			TBD
Interaction region					
β_x / β_y	cm	≈ 100		n/a	40 / 40
Beam size	µm	100		n/a	1330 / 550 / 200
Beam divergence	µrad	100		n/a	4

Accelerator R&D Roadmap

- A compendium of the five Roadmap Panels has been published as a CERN Report
  - https://e-publishing.cern.ch/index.php/CYRM/issue/view/146
  - arXiv:2201.07895

- The ERL Roadmap section contains the recommendations of the ERL panel for future R&D

1965 M. Tigner
"A possible apparatus for electron clashing-beam experiments"

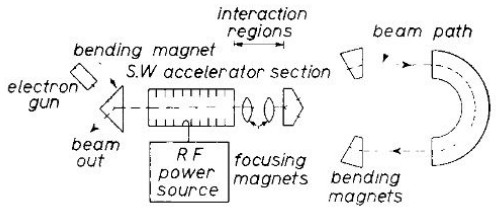


Fig. 3.

1987 High Energy Physics Lab Stanford University
SRF cavities, proof of principal experiment

1987 Los Alamos
FEL-operation, nc,
coupled acc/dec cavities

2000
Jefferson Lab
"Front End Test"
SRF, first CW recovery

2002
Jefferson Lab
"IR-Demo"
SRF, 5mA, 48MeV,
2.1kW beam power IR
2003
CEBAF, 1 GeV, single turn
2007 Upgrade:
9mA, 150MeV
1.1MW beam power
with ~300kW RF power

2002 JEARI, Japan
FEL, SRF, 700kW beam power

2004 BINP, Russia
FEL-operation
normal conducting RF,
30 mA
2007: 4-passes

2005 Daresbury Lab, GB
"Alice", SRF, 26MeV, versatile
10-year user program

2013 KEK, Japan
"cERL", prototype
ERL light source

2020, Cornell
cbeta, FFA-arc
4-pass ERL
(80mA injector, ε = 0.3mm mrad)

under construction:
MESA, Germany
particle physics application

PERLE, France
testfacility (FCC-ee)

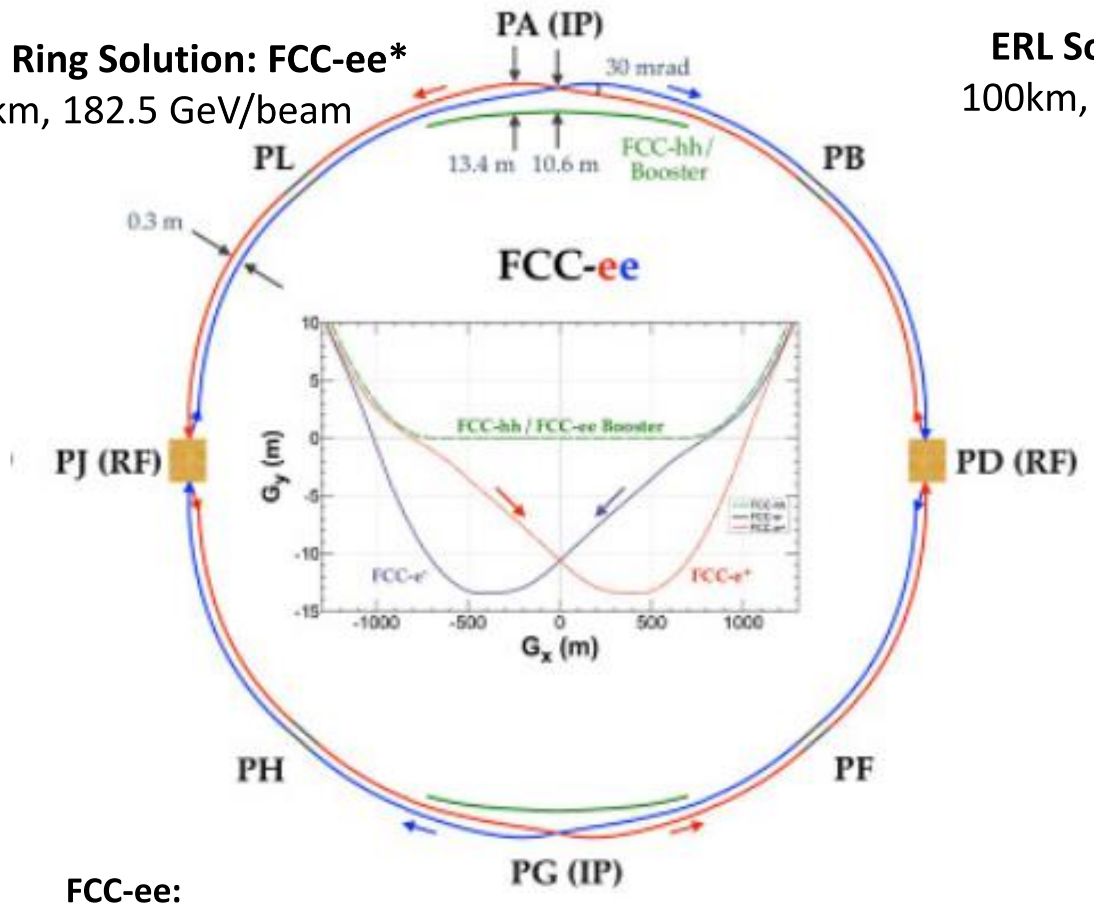
bERLinPro, Germany
SRF/ERL technology test facility

Proposals:

- ERL-based generation of picometer-emittance-class **muon beams** by electron-photon collisions*
- ERL-based **linear collider**** ⇔ILC
- ERL-based **circular collider***** ⇔ FCC-ee
- HH500****: energy-efficient, ultra-high-luminosity (~10^{36} $cm^{-2}s^{-1}$) 500 GeV ERL-based **electron-positron collider**

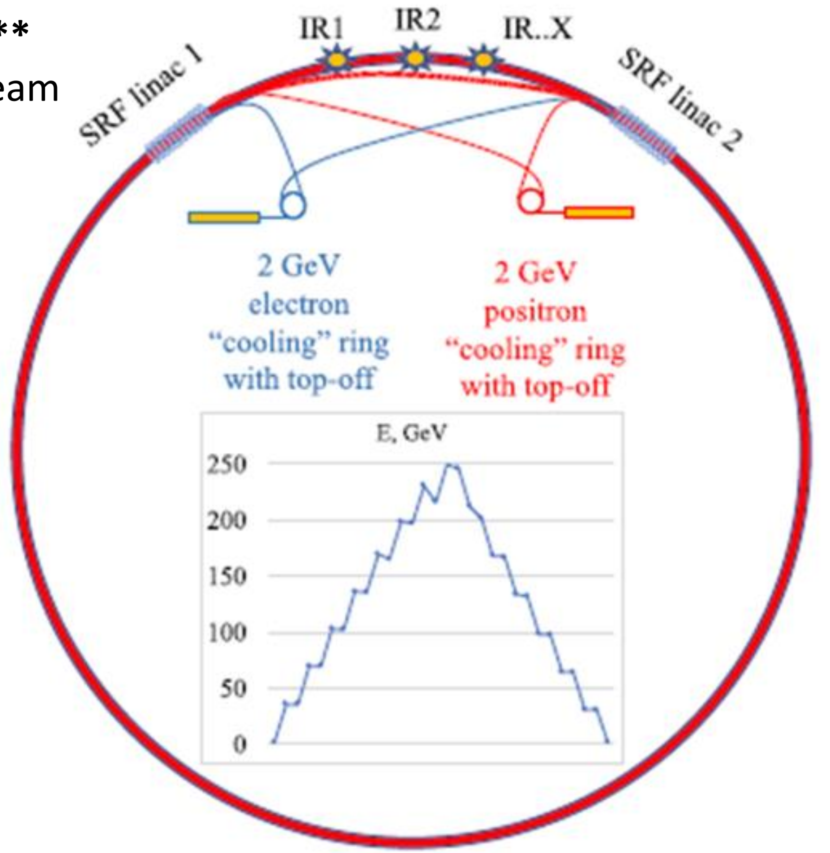
**   C. Curatolo and L. Serafini. Appl. Sci. (2022), 12(6), 3149*
***   V. I. Telnov. Journal of Instrumentation 16 (2021) P12025*
**** V. N. Litvinenko, T. Roser, and M. Chamizo-Llatas. Phys. Lett. B, 804:135394, 2020*
***** V. N. Litvinenko, N. Bachhawat, M. Chamizo-Llatas, Y. Jing, .F Mét, I. Petrushina,, T. Roser, https://arxiv.org/pdf/2203.06476.pdf*

Storage Ring Solution: FCC-ee*
100km, 182.5 GeV/beam



FCC-ee:
6 GeV NC pre-injector linac
6-20 GeV pre-booster
Main booster in collider tunnel 182.5 GeV (green)
Storage ring, top-up operation

ERL Solution, CERC**
100km, 182.5 GeV/beam



CERC:
2 beam sources, 2 linacs 2GeV
damping rings (top-up), emittance reduction, and beam recycling
4 turns up, 4 turns down (16 beamlines in tunnel)
2 main linacs (~23GeV)
=> reusage of particles and reusage of energy

*: https://link.springer.com/content/pdf/10.1140/epjst/e2019-900045-4.pdf
**: https://doi.org/10.1016/j.physletb.2020.135394

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POWER NEEDS FOR ACCELERATION: FCC-ee AND ERL BASED e+e – CIRCULAR COLLIDER

	Storage Ring - FCC-ee* / ttbar operation	**ERL – CERC****
Luminosity [10^{34} / cm² / s]	**1.55**	**35** (no reuse of beam after collision, lower restriction for beam-beam tune shift)
SR losses [MW]	100 (∝ E^4) (collider rings)	30 (incl. DR)
RF power injector [MW]	**10** pre injector **8** Booster (RF & Cryo)	**8.1** (damping rings) ***
RF power linac [MW]	**123**	**41.9** *** (no HOM, no beam-beam losses)
50% RF efficiency [MW]		**100*****
85% RF efficiency [MW]	**145** (**60%** of total)	**59**
Cryoplant [MW]	**46** Thin film Niobium on copper, 4.5 K, Q=3 10^9	**153** *** (**56%** of total; 85% RF eff.) 2K, Q = 2 10^{10}, BNL-ERL 5-cell cavity +20% thermal shield and power coupler cooling
Utility power [MW] (cryoplant and RF)	**37**	**63** ***
Total power consumption acceleration	**246MW** (total incl. magnets, data center. etc: **359MW**)	**275MW** @ 85% RF eff. (316MW *** @50%)

*: F Zimmermann, FCC Week 2019 Brussels, 24 June 2019
**: ERLC: https://doi.org/10.1016/j.physletb.2020.135394
***: http://arxiv.org/abs/2201.07895 :Appendix B. ERL High-Energy e+e– sub-Panel Report

	Storage Ring - FCC-ee* / ttbar operation	**ERL – CERC****
Luminosity [10^{34} / cm² / s]	**1.55**	**35** (no reuse of beam after collision, lower restriction for beam-beam tune shift)
SR losses [MW]	100 (∝ E^4) (collider rings)	30 (incl. DR)
RF power injector [MW]	**10** pre injector **8** Booster (RF & Cryo)	**8.1** (damping rings) ***
RF power linac [MW]	**123**	**41.9** *** (no HOM, no beam-beam losses)
50% RF efficiency [MW]		**100*****
85% RF efficiency [MW]	**145** (60% of total)	
Cryoplant [MW]	**46** Thin film Niobium on copper, 4.5 K, Q=3 10^9	**153** *** (56% of 85% RF eff. total) 2K, Q = 2 10^{10}, BNL-ERL 5-cell cavity +20% thermal shield and power coupler cooling
Utility power [MW] (cryoplant and RF)	**37**	**63** ***
Total power consumption acceleration	**246MW** (total incl. magnets, data center. etc: **359MW**)	**275MW** @ 85% RF eff. (316MW *** @50%)

physics

technology

*: F Zimmermann, FCC Week 2019 Brussels, 24 June 2019
**: ERLC: https://doi.org/10.1016/j.physletb.2020.135394
***: http://arxiv.org/abs/2201.07895 :Appendix B. ERL High-Energy e+e− sub-Panel Report

"Progress should be based on several medium-scale projects underway around the world, with complementary goals in different aspects of the technologies involved."

High-power sustainable Superconducting RF (SRF) technology

- **Higher quality factors:** $Q_0 \sim 10^{11}$; involves **new cavity material** (Nb_3Sn, NbN, NbTiN…)
- **4.4K operating temperature:** option to use cryo-coolers* (no cryogenic liquids) ***=> power reduction by factor 3***
- **Efficient HOM power absorbers** at the highest possible temperature
- **Fast reactive tuners** (FRT):** new technology to compensate transients and microphonics; (based on new ferroelectric material)

High current electron sources:

- **Guns**: high cathode field & extremely high vacuum (DC, SRF, NCRF)
- **Photocathodes:** new cathode materials promise a longer lifetime, higher quantum efficiency
  - **Secure transport** of photocathodes (vacuum < 10^{-10})
- **Photo cathode laser:** elliptical temporal profile for high charge, ultra-low emittance

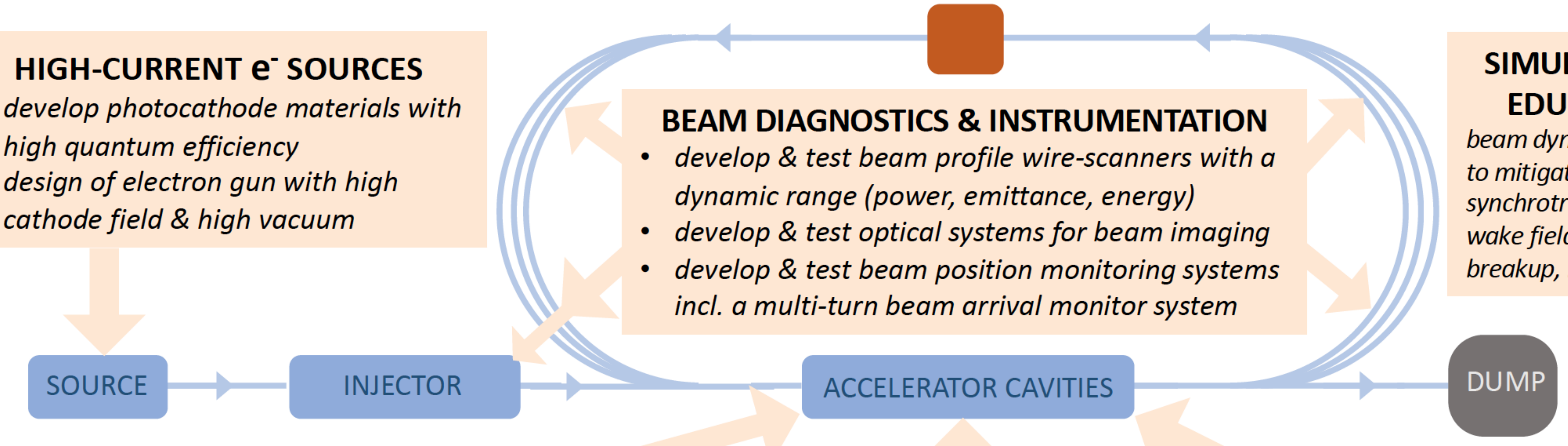
Diagnostics: high beam power, non-Gaussian bunch profiles, multiple beams, high dynamic range

Simulation: Coherent **S**ynchrotron **R**adiation, **B**eam **B**reak **U**p, longitudinal matching, S2E calculations

***** : Ram C. Dhuley: "Cryocooler conduction-cooled SRF cavities for particle accelerators", Cockcroft Institute Seminar, 08 September 2020
****:** N. Chipman et al,," **A Ferroelectric Fast Reactive Tuner for Superconducting Cavities**"
19th International Conference on RF Superconductivity, Dresden, Germany, DOI: 10.18429/JACoW-SRF2019-WETEB7

Main R&D objectives for Energy Recovery

HIGH-CURRENT e^- SOURCES
- *develop photocathode materials with high quantum efficiency*
- *design of electron gun with high cathode field & high vacuum*



BEAM DIAGNOSTICS & INSTRUMENTATION
- *develop & test beam profile wire-scanners with a dynamic range (power, emittance, energy)*
- *develop & test optical systems for beam imaging*
- *develop & test beam position monitoring systems incl. a multi-turn beam arrival monitor system*

SIMULATION & EDUCATION
beam dynamics studies to mitigate coherent synchrotron radiation, wake fields, beam breakup, …

HIGHER-ORDER MODE DAMPING
- *understand HOM powers for cryomodules*
- *design of HOM (on-cell) couplers*
- *modelling of high-frequency wakefield*

Most R&D objectives part of the bERLinPro and PERLE programs

HIGH-POWER SRF TECHNOLOGY
- *SRF system design for very high beam currents*
- *develop & test Fast Reactive Tuners (FRT)*
- *deploy in beam-test facilities*
- *towards 4.4K operation reduces the capital investment for the cooling plant (*)*
- *coating SC compound materials on substrates (*)*

(*) part of the RF R&D program

strategic

DUAL AXIS CAVITIES
- *advance both options: single cavity with two beam tubes and two cavities joined by a power bridge*
- *packing the cavity in cryomodule*
- *connecting dual axis cryomodules*
- *integrate HOM couplers in design*

The ERL roadmap has three major, interrelated elements

A) Current facilities, including crucial technological developments and operational experience

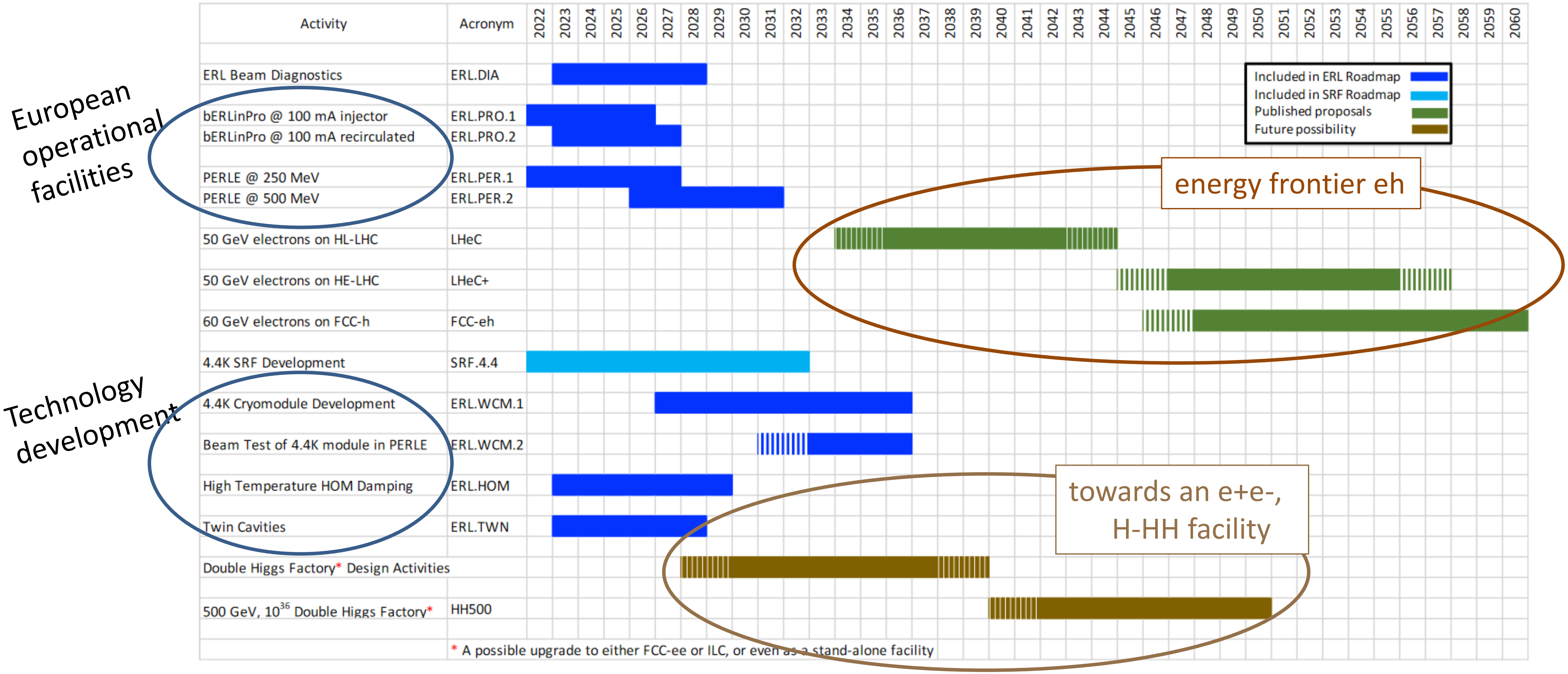
- S-DALINAC (TU Darmstadt, Germany), MESA (U Mainz, Germany), CBETA (U Cornell and BNL, US), cERL (KEK, Japan) and the normal-conducting, lower-frequency Recuperator facility (BINP Novosibirsk, Russia)

B) A key technology R&D program

C) New ERL facilities in preparation for reaching higher currents and electron beam energies at minimum power consumption

- In Europe:
  - bERLinPro (Berlin, Germany) with the goal to operate a 100 mA, 1.3 GHz facility
  - PERLE IJCLab (Orsay, France) as the first multi-turn, high-power, 802MHz facility with novel physics applications
- In the US:
  - ERL operation near 10 GeV with CEBAF5 (Jefferson Lab, Newport News)
  - Develop a challenging 100mA electron cooler for hadron beams at the EIC (BNL, Brookhaven)

Roadmap Timetable for the next Five to Ten Years



Leads to multiple options for future HEP Colliders

Total Support Requested

- Total effort for the R&D program on energy recovery linacs as presented in this roadmap, providing the total number of FTE years and MCHF for the duration as indicated
- The table does not include in-kind and infrastructure contributions nor further investments in ongoing facilities

Label		Description	FTEy	MCHF	Start	End
ERL.RD	sum	Key R&D Items	57	7.6	2023	2029
	HOM	Damping to high T	24.5	2.7	2023	2029
	TWN	Twin cavity module	13.5	3.5	2023	2028
	DIA	Beam instrumentation	19	1.4	2023	2027
ERL.PRO	sum	bERLinPro at Berlin	33	8.3	2022	2027
	PR1	100mA beam	16	2.4	2022	2026
	PR2	Recirculation	17	5.9	2023	2027
ERL.PER	sum	PERLE at Orsay	87	24.1	2022	2031
	PE1	250 MeV	64	14.6	2022	2027
	PE2	500 MeV	23	9.5	2026	2031
Total			**177 FTEy**	**40 MCHF**		

CONCLUSION

A detailed *European roadmap* – including timelines and costs – has been developed for the further developments of ERLs towards the next generation of HE accelerators.

ERLs are a very active field with many emerging *technological novelties*.

The wide scope of technologies involved can only be met by intense *international cooperation*.

ERLs have a *high TRL* (technological readiness level).

To recover the energy of particles after their usage in experiments is indispensable to ensure further development in HEPs accelerators.

Thank you for your attention

Back up slides

Funding Profile for Twin Cavities and Diagnostics

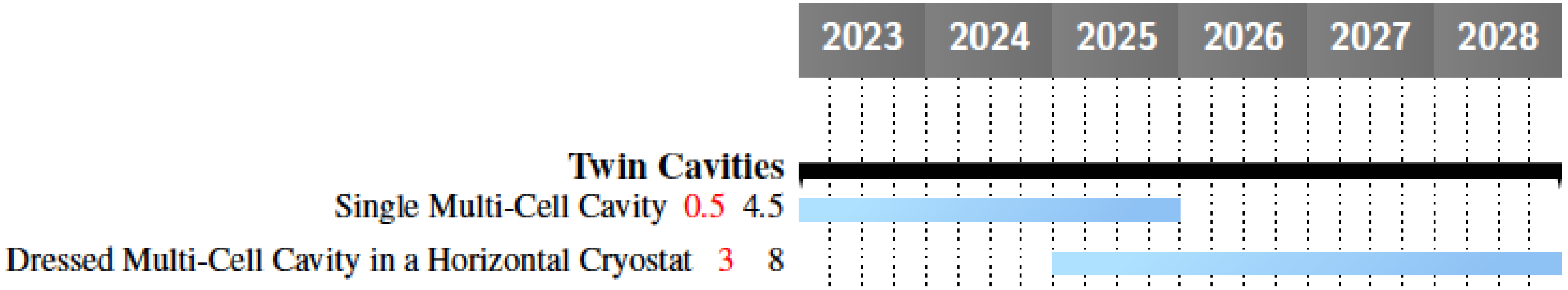


Fig. 6.6: ERL.RD.TWN: Development of dual-axis cavity and cryomodule technology. Resources required are 3.5 MCHF (red) over six years plus 12.5 FTEy (black).

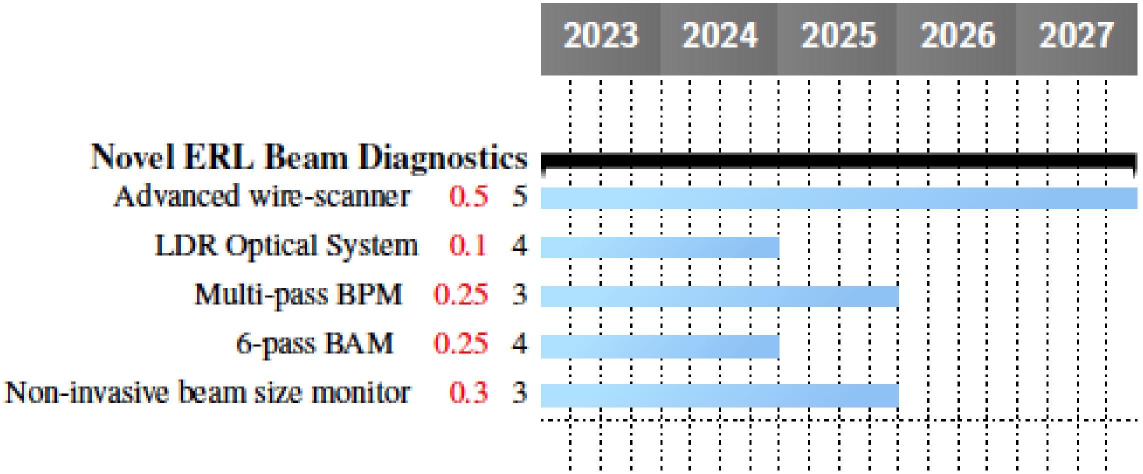


Fig. 6.7: ERL.RD.DIA: Development plan for high-current ERL beam diagnostics. Resources required are 1.4 MCHF (red) plus 19 FTEy (black).

bERLinPro Funding Profile

- bERLinPro has two separate projects:
- Develop a 100 mA SRF Gun
- Test recirculation at 100 mA

- PERLE and LHeC propose 3-pass 20 mA = 120 mA in the linacs
- bERLinPro test recirculation will demonstrate that HOM damping is adequate
- It will also test Fast Reactive Tuners (FRTs)

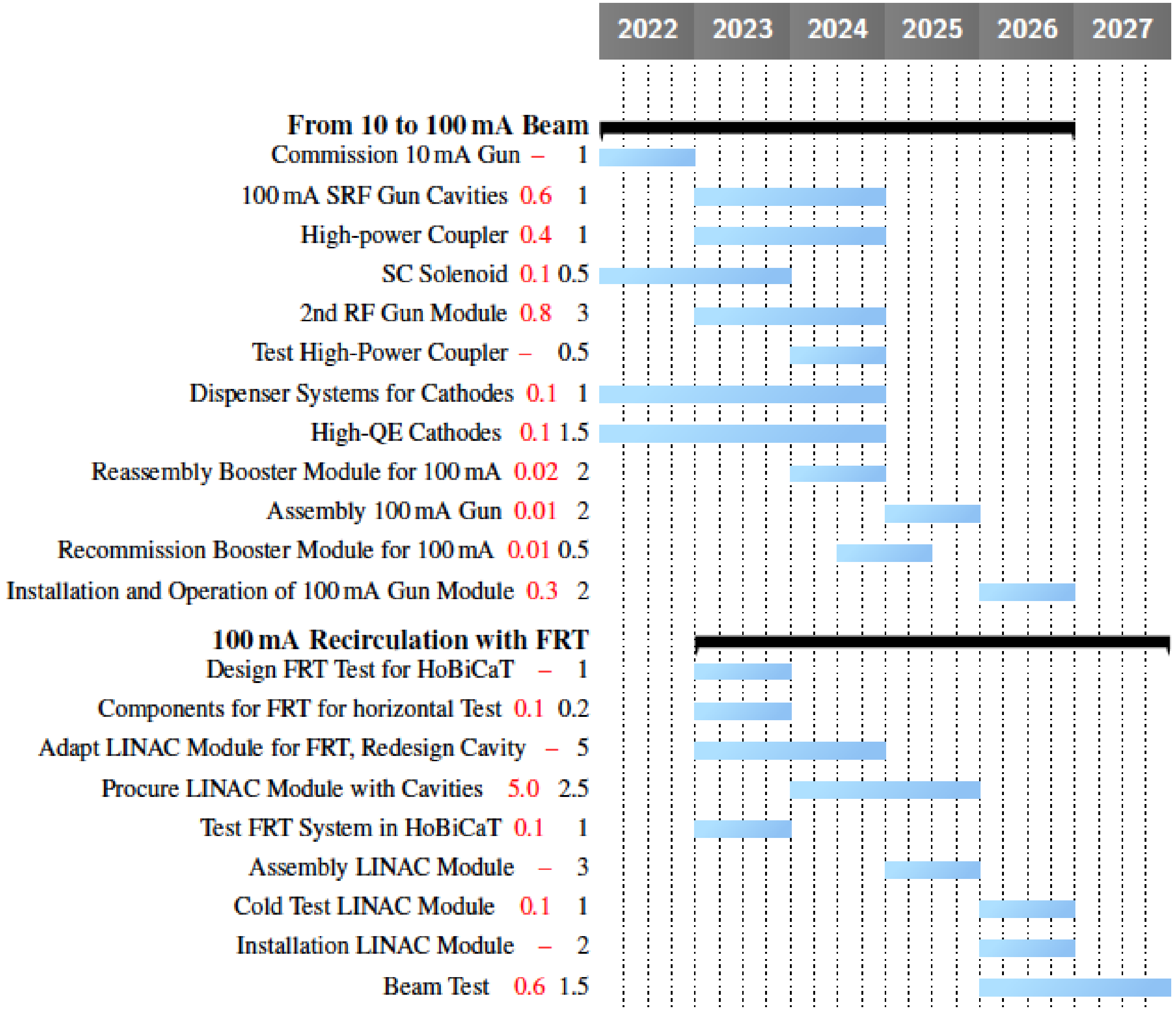
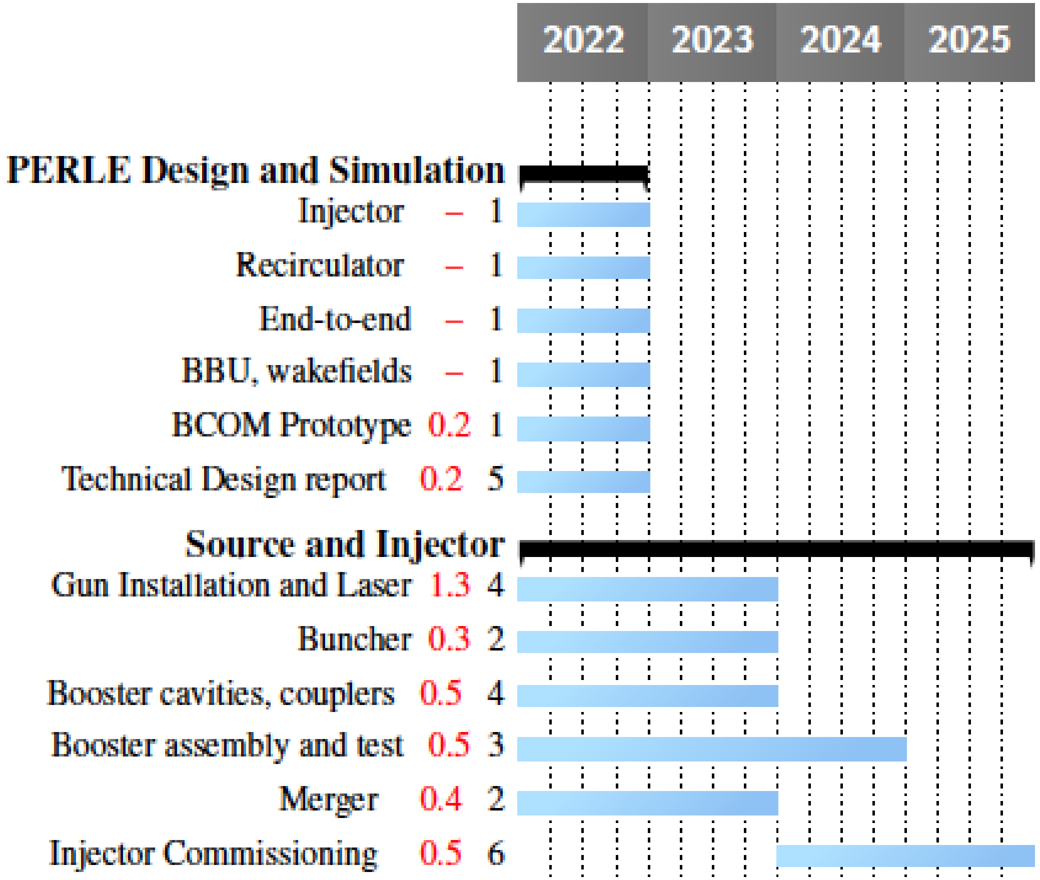


Fig. 6.8: Top: upgrade of bERLinPro to 100 mA electron current operation (**ERL.PRO.PR1**). Resources required are 2.4 MCHF (red) plus 16 FTEy (black). Bottom: completion of bERLinPro with a 1.3 GHz cavity-cryomodule in the beam **ERL.PRO.PR2**. Resources required are 5.9 MCHF (red) plus 17 FTEy (black).

PERLE Injector Funding Profile

- Goal is to rebuild ALICE gun and build a booster
  - ALICE gun is currently being assembled at IJCLab
  - Booster is a collaboration between CERN, Jefferson Lab and IJCLab



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

PERLE Recirculator Funding Profile

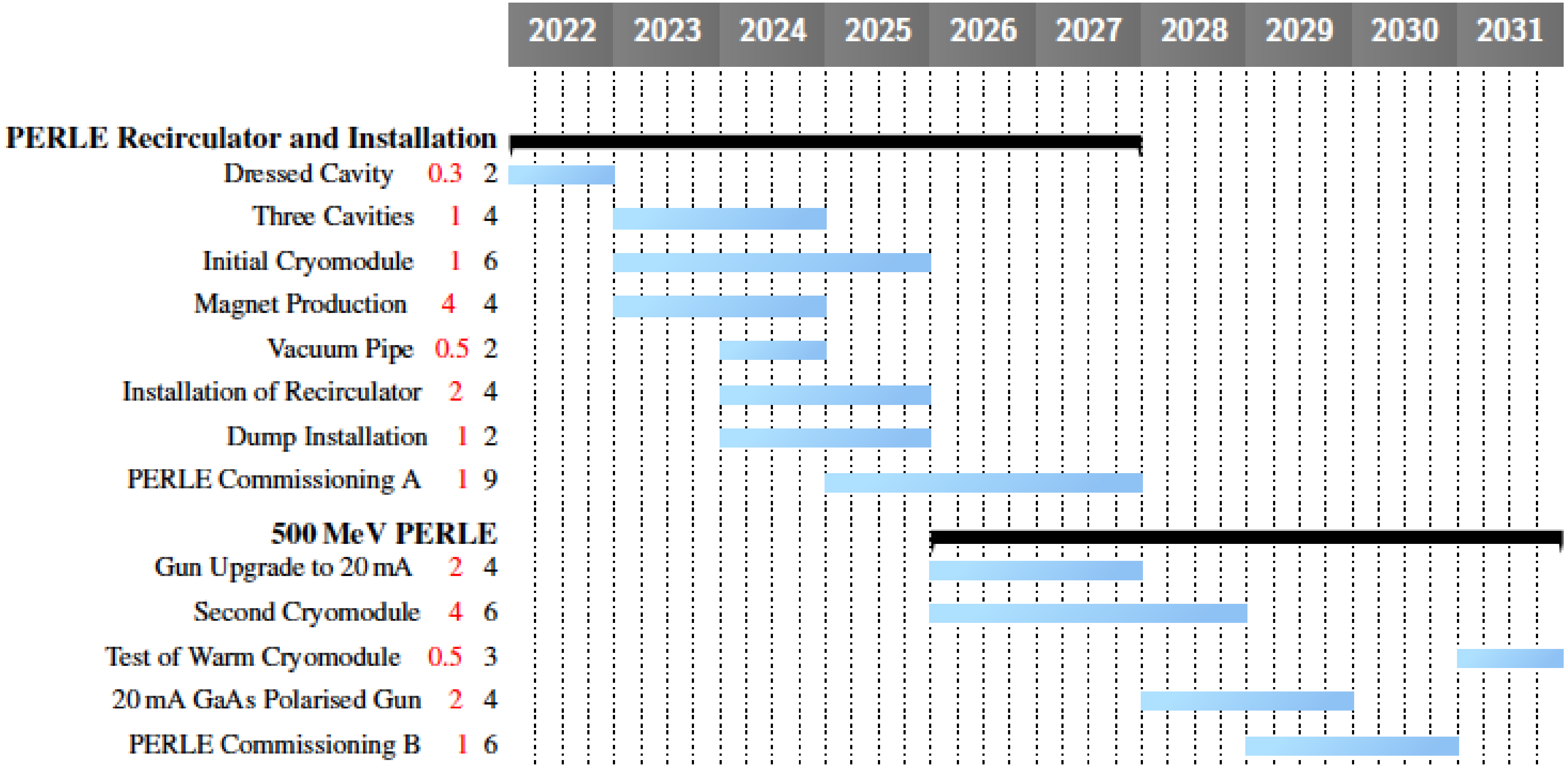


Fig. 6.10: PERLE completion in two steps: The 250 MeV phase with beam in the mid-twenties (**ERL.PER.PE1**); and the 500 MeV stage towards the end of the decade (**ERL.PER.PE2**). Resources for the first part, including funding of the TDR and injector phase: 14.6 MCHF (red), 64 FTEy (black). Resources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