LDG-XXX-YYY DRAFT 0.1 June 28, 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

…

The ERL Study Group

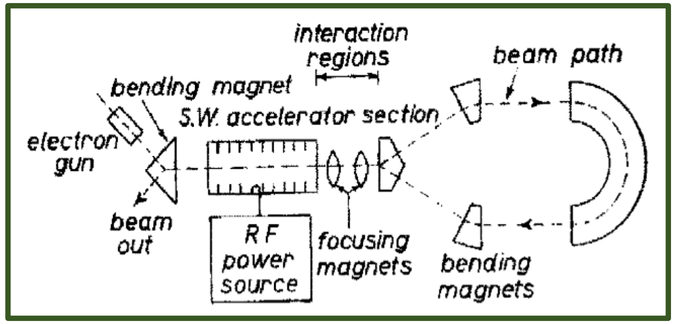
ERL Panel Members

Deepa Angal-Kalinin[6], Kurt Aulenbacher[10], Alex Bogacz[15], Georg Hoffstaetter[5], Andrew Hutton[15] (Co-Chair), Erk Jensen[4], Walid Kaabi[11], Max Klein[9] (Chair), Bettina Kuske[1], Frank Marhauser[15], Dmitry Kayran[3], Jens Knobloch[1], Olga Tanaka[14], Norbert Pietralla[7], Cristina Vaccarezza[8], Nikolay Vinokurov[2], Peter Williams[6], Frank Zimmermann[4]

Guest Authors

Michaela Arnold[7], Steve Benson[15], Jan Bernauer[13], Maarten Boonekamp[12], Oliver Brüning[4], Max Bruker[15], Patxi Duthill[11], Oliver Fischer[9], Bernhard Holzer[4], Geoff Krafft[15], Julius Kühn[1], Boris Militsyn[6], George Neil[15], Axel Neumann[1], Vladimir Litvinenko[13], Bob Rimmer[15], Oleg A. Shevchenko[2], Nick Shipman[4], Hubert Spiesberger[10], David Verney[11], Valeri Telnov[2], Chris Tennant[15] and others

incomplete



Performance of a 55 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

Status Report for TIARA

with a remark on PERLE

Max Klein (U.Liv) & Andrew Hutton (Jlab)

for the ERL Roadmap Panel

TIARA Meeting, June 29, 2021

A long Write-up on ERLs for Publication

Science base for input to Roadmap.

Status: Write-up drafted

ERL Symposium

Next:
PP Symposium
EPS Conference
→ Roadmap

Today: Observations

Contents

Figure 3: Draft table of contents of the about 250 pages paper in preparation describing the ERL developments and prospects [1]. A similar order of topics will be used for the shorter roadmap input, complemented by chapters on milestones, cost and options for the ERL future.

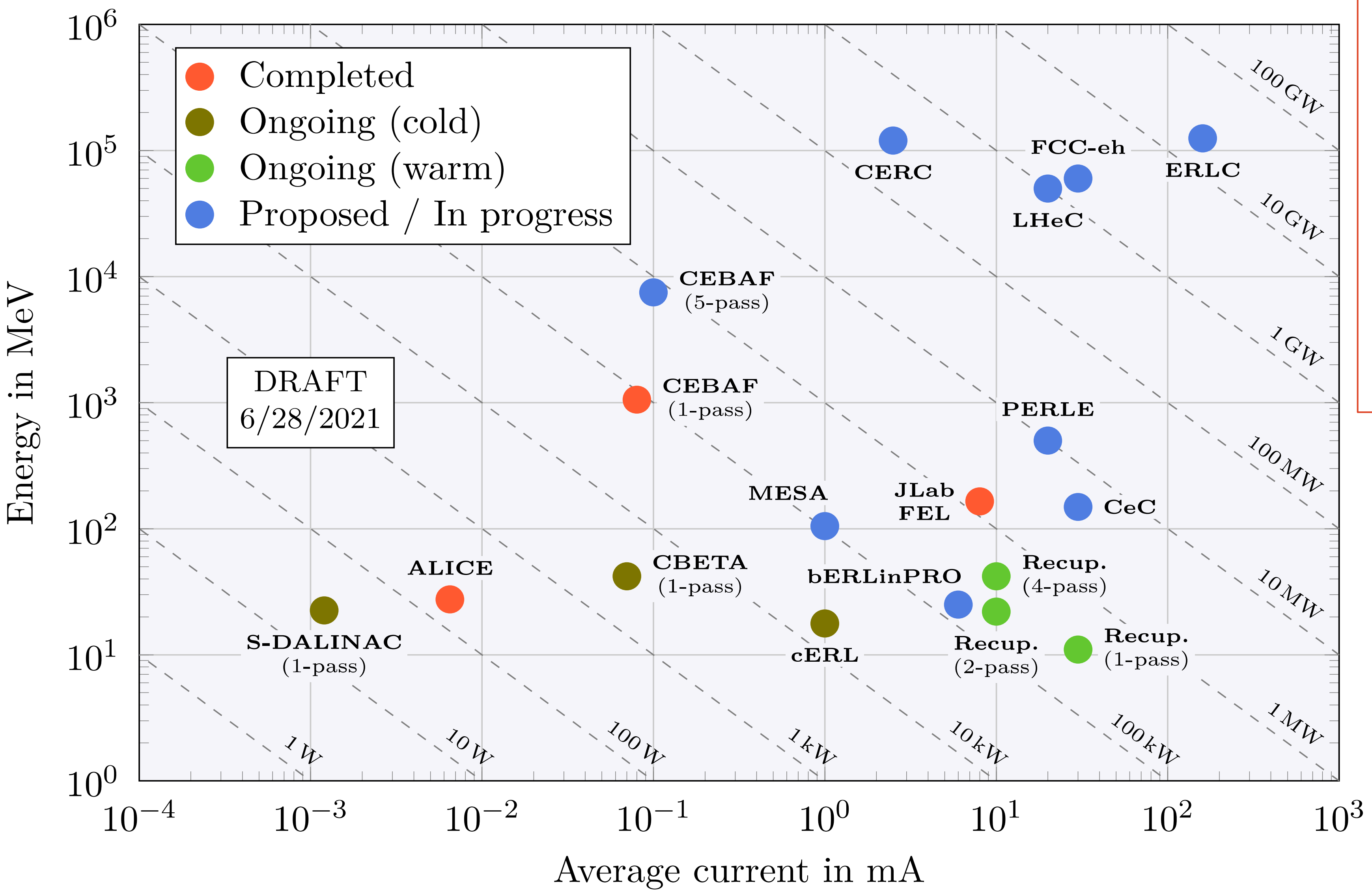
[from report to LDG]

Energy Frontier: ERL concepts now for ep, e^+e^-, γγ + muon colliders

Very recent: $e\gamma \rightarrow e\mu/\mu$ concept of 100 GeV eERL with X ray FEL as base for muon collider
10pmrad emittance

arXiv:2106.03255
Curatolu, Serafini

A selection of past, present and proposed **ERL facilities**: Power = $E_e I_e$



ERL Features:

Very high luminosity through high electron current and small preserved injector emittance. Economic use of power $P_o/(1-\eta)$ through recovery in multiple linac passing (recirculator or head-on). Non-radiative beam dump at injection energy. → orders of magnitude improved performance at same or reduced power, **a new era for accelerator, HEP, NP and applications**

"The ERL concept is well proven and the technology is well developed. Many demonstrator facilities exist worldwide with increasing sophistication. 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 at ERL Symposium, June 4, 2021)

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	MTCA (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): high current

PERLE (Orsay): high power, 3-turn

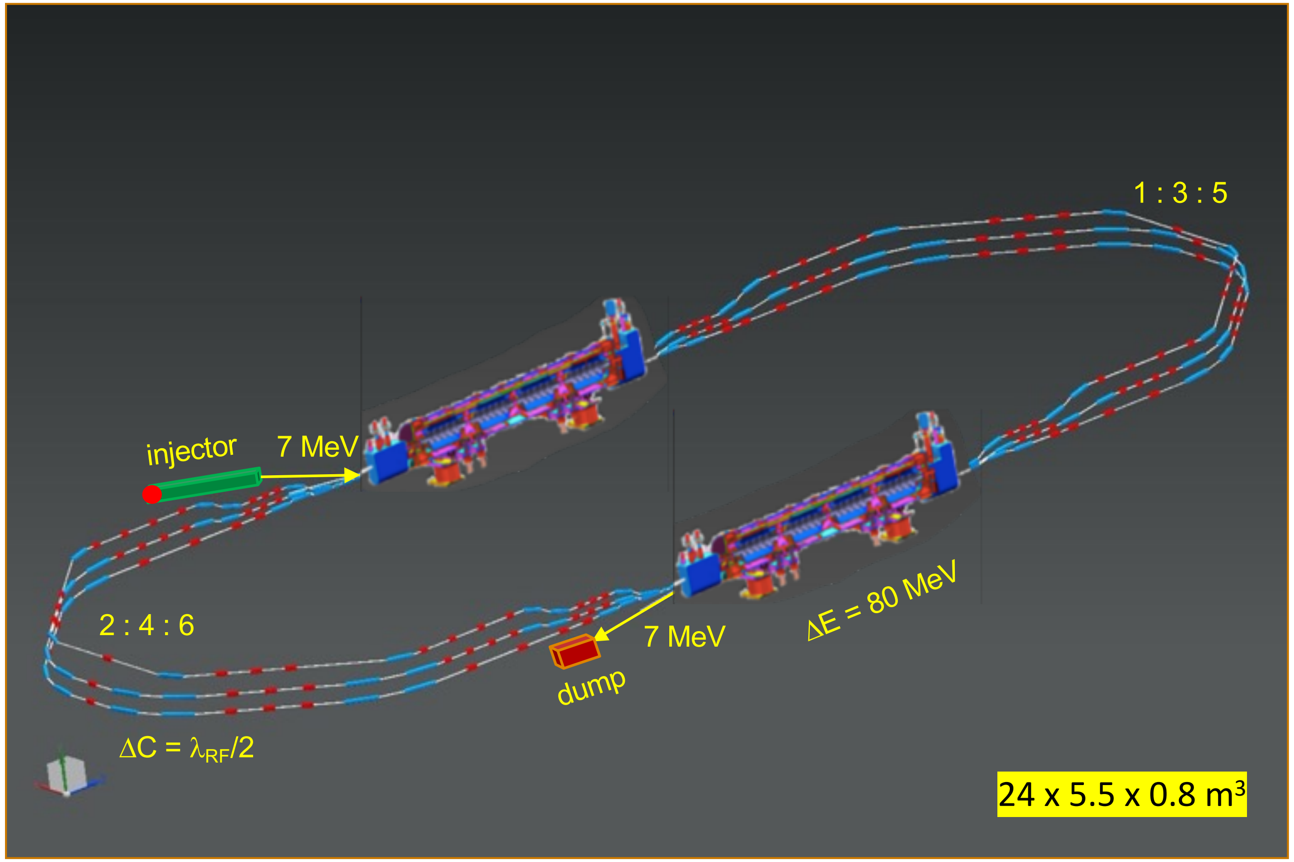
Chapter 4
Key Challenges – **a Concerted Effort**

Studies:

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

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 +

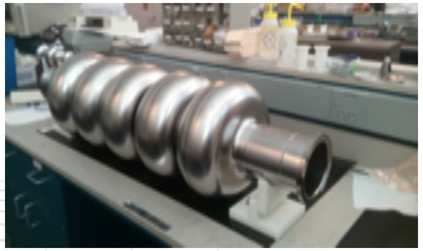
* PERLE. Powerful energy recovery linac for experiments. Conceptual design report

Published in: *J.Phys.G* 45 (2018) 6, 065003 e-Print: 1705.08783 [physics.acc-ph]

Paramater	Unit	Value
Frequency	MHz	801.58
Number of cells		5
active length l_{act}	mm	917.9
loss factor	V pC^{-1}	2.742
R/Q (linac convention)	Ω	523.9
$R/Q \cdot G$ per cell	Ω^2	28788
Cavity equator diameter	mm	327.95
Cavity iris diameter	mm	130
Beam tube inner diameter	mm	130
diameter ratio equator/iris		2.52
E_{peak}/E_{acc}		2.26
B_{peak}/E_{acc}	mT/(MV/m)	4.2
cell-to-cell coupling factor k_{cc}	%	3.21
TE_{11} cutoff frequency	GHz	1.35
TM_{01} cutoff frequency	GHz	1.77

Table 10.15: Parameter table of the 802 MHz prototype five-cell cavity.

LHeC Design Update
2007.14491
J.PhysG, 21



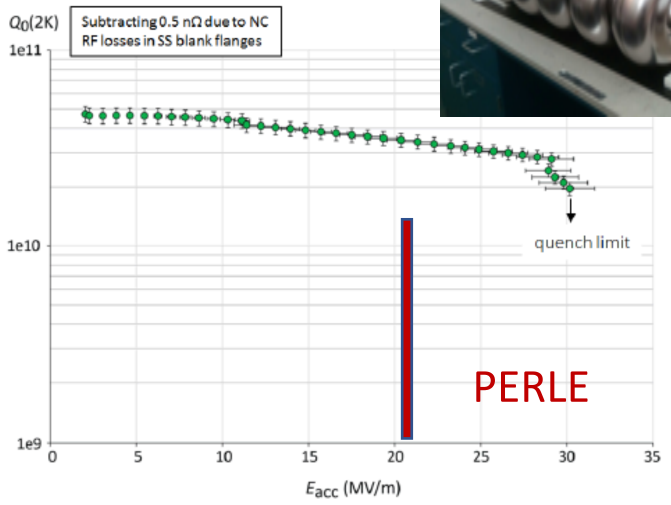
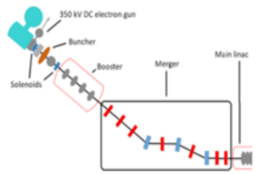
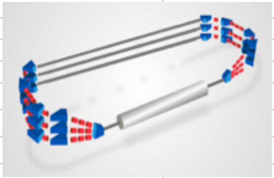


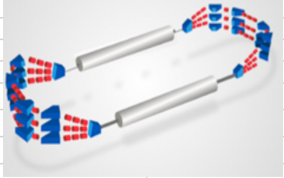
Figure 10.20: Vertical test result of the five-cell 802 MHz niobium cavity prototype.

DRAFT timeline of PERLE: Design, Injector, SRF, Magnets, Infrastructure, Experiments, Safety/Integration

Work Package	Task	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
		TDR Phase		PERLE-Phase 0: Injection line							
				PERLE-Phase 1: PERLE @ 250 MeV							
				PERLE-Phase 2: PERLE @ 500 MeV- 10MW							
WP2: Accelerator Design	T2.1: Lattice and Optics	Linear Lattice optimisation									
		Momentum acceptance & longitudinal match									
		Correction of nonlinear aberations with multipole magnets									
		Injection line design									
		Merger study and design									
	T2.2: Beam Dynamics	End to End Multi particle tracking studies, error effects & halo formation									
		End-to-End simulation with CSR & micro-bunching									
		Space charge studies at injection									
			Impedance analysis & wakefield effect mitigation								
			Beam Breack-Up instability								
WP3: e- source & injector	T3.1: DC gun installation preparation	Gun installation preparation	Starting gun installation	Testing DC gun	Injector Installation	Injector commisioning	Complete installation of PERLE @ 250 MeV, 4 mA, 3-turn and starting the commisioning		DC gun upgrade and operation		Complete installation of PERLE @ 500 MeV, 20 mA, 3-turn and starting the commisioning
	T3.2: Buncher & Booster design		Buncher cavity design	Buncher cavity production							
			Single cell booster cavities design	Single cell booster cavities production							
		Booster needs identification		Booster completion							
WP4: RF Systems	T4.1: Cavity & HOM design and Prototyping	HOM study and HOM coupler design	Endgroups integration into existing cavity & test	5-cell cavities production and test				5-cell cavities production and test			
	T4.2: Power coupler design and prototyping	Adaptation of SPL power coupler and RF conditioning									
	T4.3: Cryomodule	Design SPL Cryomodule completion			Completion of SPL Cryomodule and test						
				New cryomodule design				Completion and test of the 2nd cryomodule			
	T4.4: Fast reactive tuner design and protyping	Feasibility study & integration on cavity									
	T4.5: Tuner system										
	T4.6: LLRF										
	T4.7: RF power sources need										
WP5: Magnets and vacuum chambers	T5.1: Magnets	Magnet Specifications	B-Com magnet design and prototype								
	T5.2: Vacuum chambers design		Magnets & vacuum chambers design	Magnet & vacuum chambers production		Recirculator installation (arcs & swithyards)				Recirculator installation (additional swithyards)	
WP6: Instr. & diagnostics	T5.2: Beam diagnostics		Defining beam diagnostics needs	Beam diagnostics for injector							
	T5.3: Beam dump design		Dump design	Dump production							
	T5.4: Vacuum systems		Defining vacuum needs for injector	Defining vacuum needs for main loop							
	T5.5: Cryogenics	Need definition & cryoplant specification		Cryoplant design and production		Cryoplant installation & commisionni					
WP7: Experiments	T7.1: PERLE user identifaction	Potential experiment constrains									
			Fixation of Experiment program								
	T7.2: Experiment integration design			Experiment integration study						IP ingration for experiments	
WP8: Safety & integration	T8.1: Facility Administratif Classification (ASN)	Classification study and Preparation of ASN Document									
	T8.2: Radioprotection & shielding studies	Radioprotection studies		Personnel safety system (PSS) & machine safety system (MSS) design and implementation							
	T8.3: Preliminary studies of the site	Site investigations (ground, available Area, ancelleries)		Required infrastructure work							
	T8.4: PERLE footprint	Specifications & implementation design									







Principally endorsed by PERLE CB, June 2021

Walid Kaabi et al, 28.6.2021

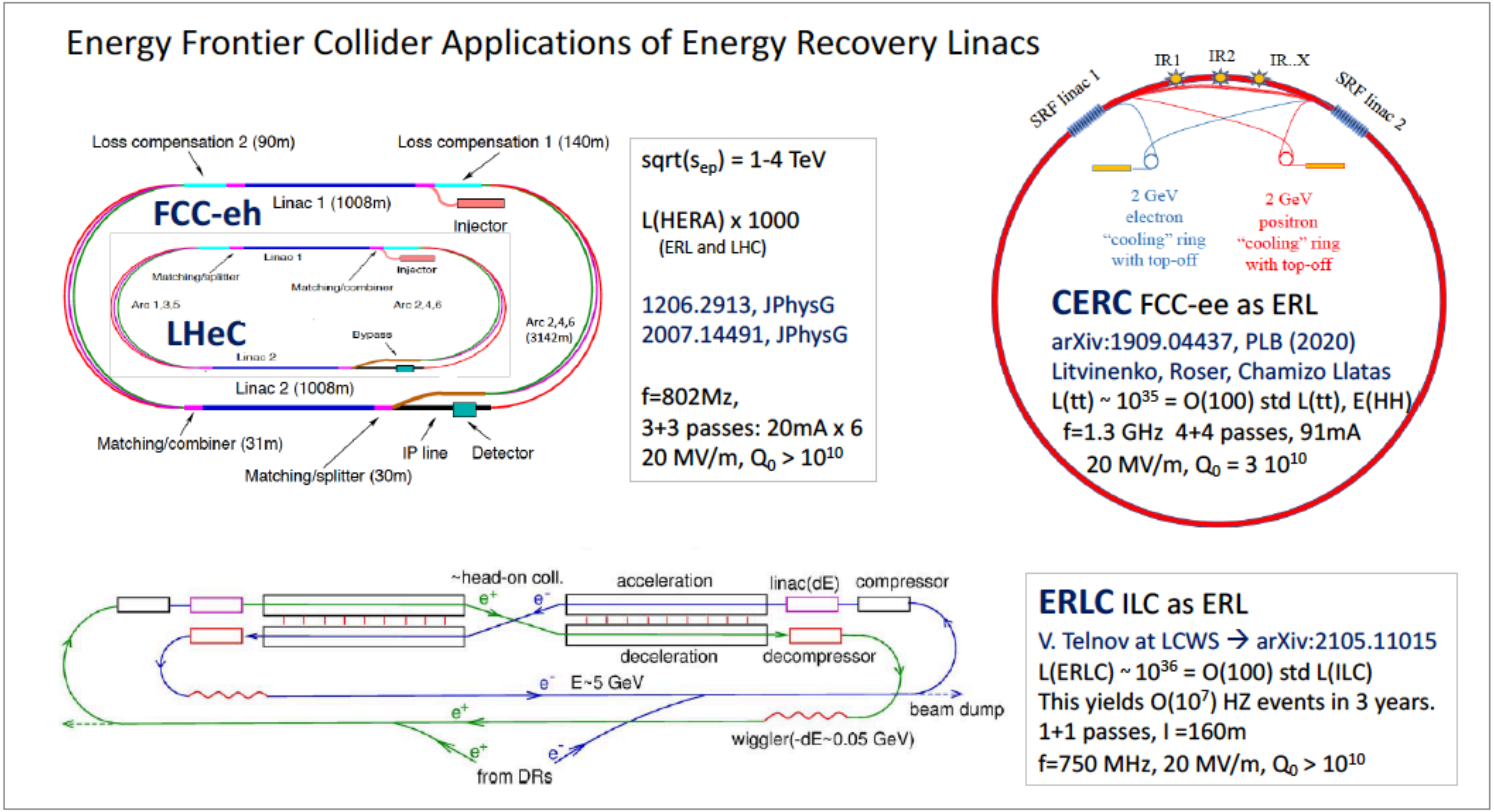


Figure 2: Sketch of possible future colliders based on ERLs: left top: LHeC and FCC-eh; right top: CERC; bottom: ERLC. For more information see the arXiv references displayed. [from report to LDG]

The e^+e^- ERL Sub-Panel

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 Sub-Panel should evaluate 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.

Methodology: Sessions with proponents to begin with. Sessions open to other ERL panel members

Procedure agreed with the proponents

Valeri Telnov and Vladimir Litvinenko, Tomas Roser

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

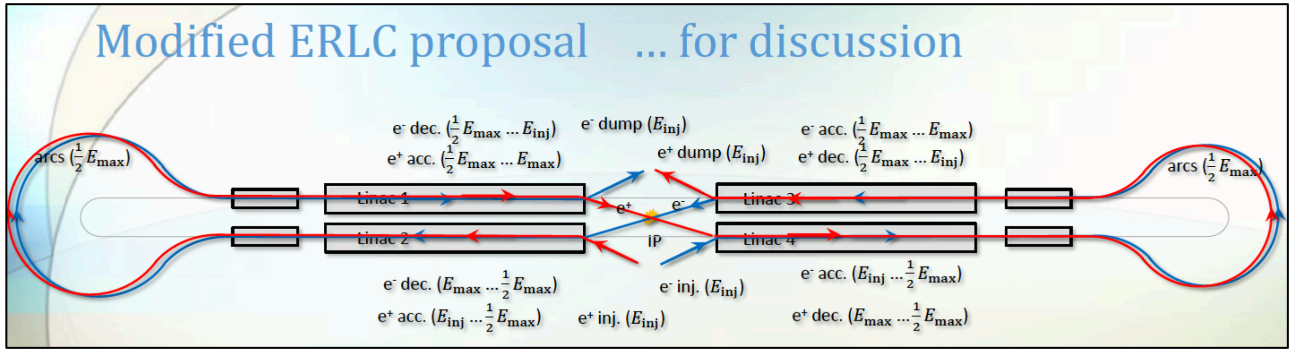
ERL Symposium

Friday 4.6. 1-5pm CEST

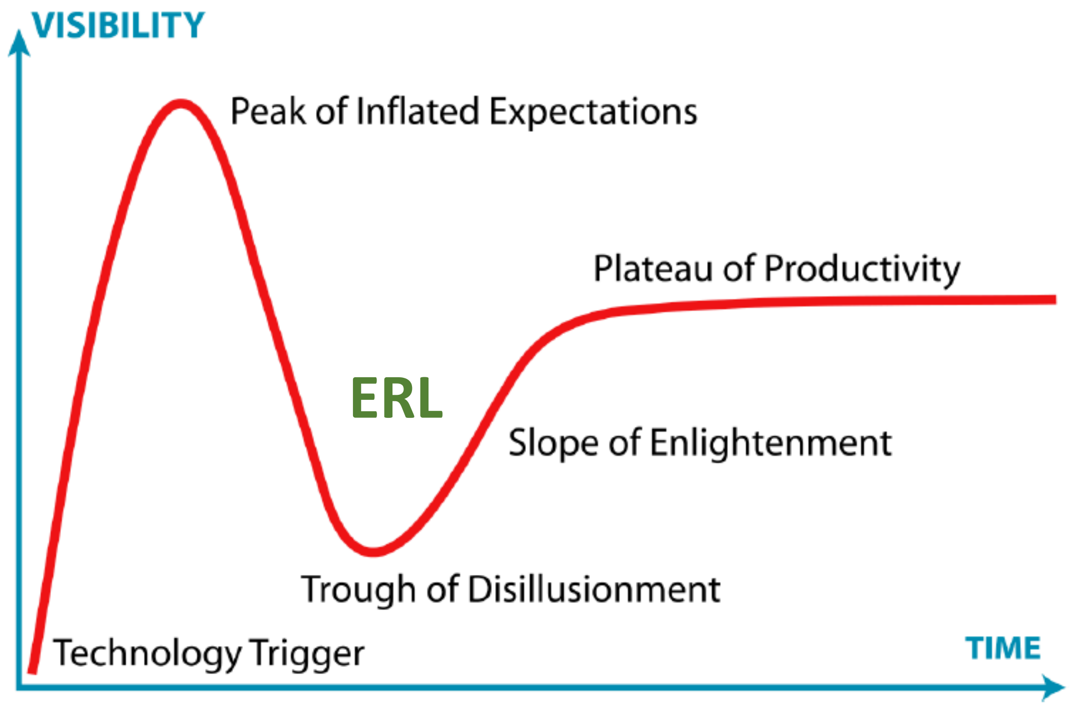
https://indico.cern.ch/event/1040671/

The symposium was an important event for information, consultation and formation of a more coherent R&D ERL effort.

→



Current 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)

*) 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

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 implied on R&D, financial, intellectual and technical support.

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.

ERLs, as came out at the Symposium, are technologies with far reaching impacts on science + society.

Next: Working towards the ERL Roadmap