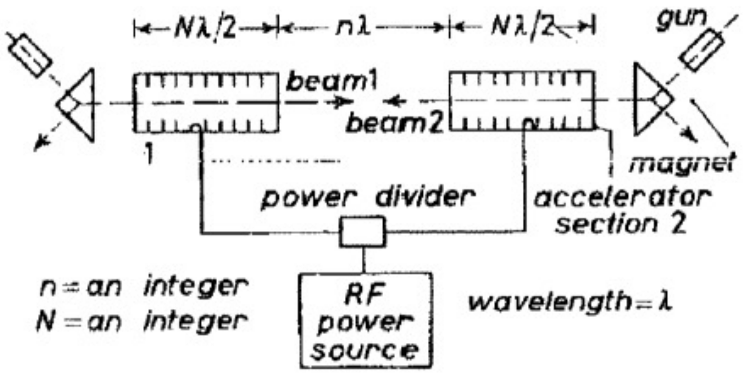
Towards a Roadmap on Energy Recovery Linacs

Max Klein — University of Liverpool

Andrew Hutton — Jefferson Lab, Thomas Jefferson National Accelerator Facility

As we progress, a roadmap emerges for main directions while detailed implementations are a next step.



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)

LDG Roadmap Meeting – on-line, 30.9.2021

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

EPS Status

30.7.21

Activities

18 panel members from 11 facilities worldwide

← 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

Symposium on ERLs and its Applications, June 4, 21

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

Interim Report on ERL

6.1 Executive summary of findings to date

The fundamental principles of energy recovery linacs (ERLs) have been successfully demonstrated across the globe. There can no longer be any doubt that an ERL can be built and achieve its goals. The panel has drafted a long write-up as an introduction to “The Development of Energy Recovery Linacs” and held an ERL Symposium . It is currently evaluating recent electron-positron collider ERL concepts and moves towards the development of a Roadmap on ERLs—to serve future colliders as well as low-energy particle and nuclear physics. ERLs promise a luminosity increase for physics applications by orders of magnitude at a power consumption comparable to classic, low-luminosity solutions, which is a necessary step towards the sustainability of high-energy physics, as interaction cross sections fall with rising energy. ERLs are also near utilisation in several industrial and other applications.

The novel high-energy ERL concepts targeted at energy-frontier electron-hadron, electron-positron and electron-photon colliders, as well as further physics and other applications, require the development of high-brightness electron guns and dedicated SRF technology as prime R&D objectives. Moreover, “it needs a facility comprising all essential features simultaneously: high current, multi-pass, optimised cavities and cryomodules and a physics-quality beam eventually for experiments" (Bob Rimmer).

Europe’s next endeavours are MESA at Mainz, a polarised beam facility for experiments, bERLinPRO, an accelerator R&D facility at Berlin with the potential to reach 100 mA of electron current, and a dedicated high-power, multi-turn facility, PERLE at Orsay, which is being developed by a large international collaboration. Moderate investments, compared to other accelerator R&D projects, will be required to have this programme adequately supported. Globally, ERLs deserve coordinated cooperation, with the developments of high-current ERL facilities at BNL, BINP and KEK, with a forthcoming high-energy experiment at CEBAF as well as plans for next-generation facilities. High-current ERL operation causes major challenges, such as beam breakup instabilities or RF transients, requiring collaborative efforts across the various facilities. In summary, the panel notes with much interest that the ERL technology is close to its high-current and high-energy application, requiring dedicated and coordinated R&D efforts, with the stunning potential to revolutionise particle, nuclear and applied physics as well as key industry areas, at a time where caring for energy resources is a prime necessity for this planet, not least big science. ERLs are therefore primed for inclusion among the grand visions our field has been generating, and for dedication of adequate support to it for this unique potential to bear fruit.

[delivered end of July]

Follow,
Extend,
Update
Interim

Roadmap for the Development of Energy Recovery Linacs

Authors are ERL Panel and others

DRAFT STATUS AS OF TUESDAY NIGHT

Panel Meeting on 27.9. : Build on three, interlinked parts

A (4.) – Facilities in progress including technology developments
[sDALINAC, MESA + cBETA, cERL, Recuperator]

B (8.1) – New Facilities – towards high current and power
[bERLinPRO , PERLE multi-turn + CEBAF5, eCooler]

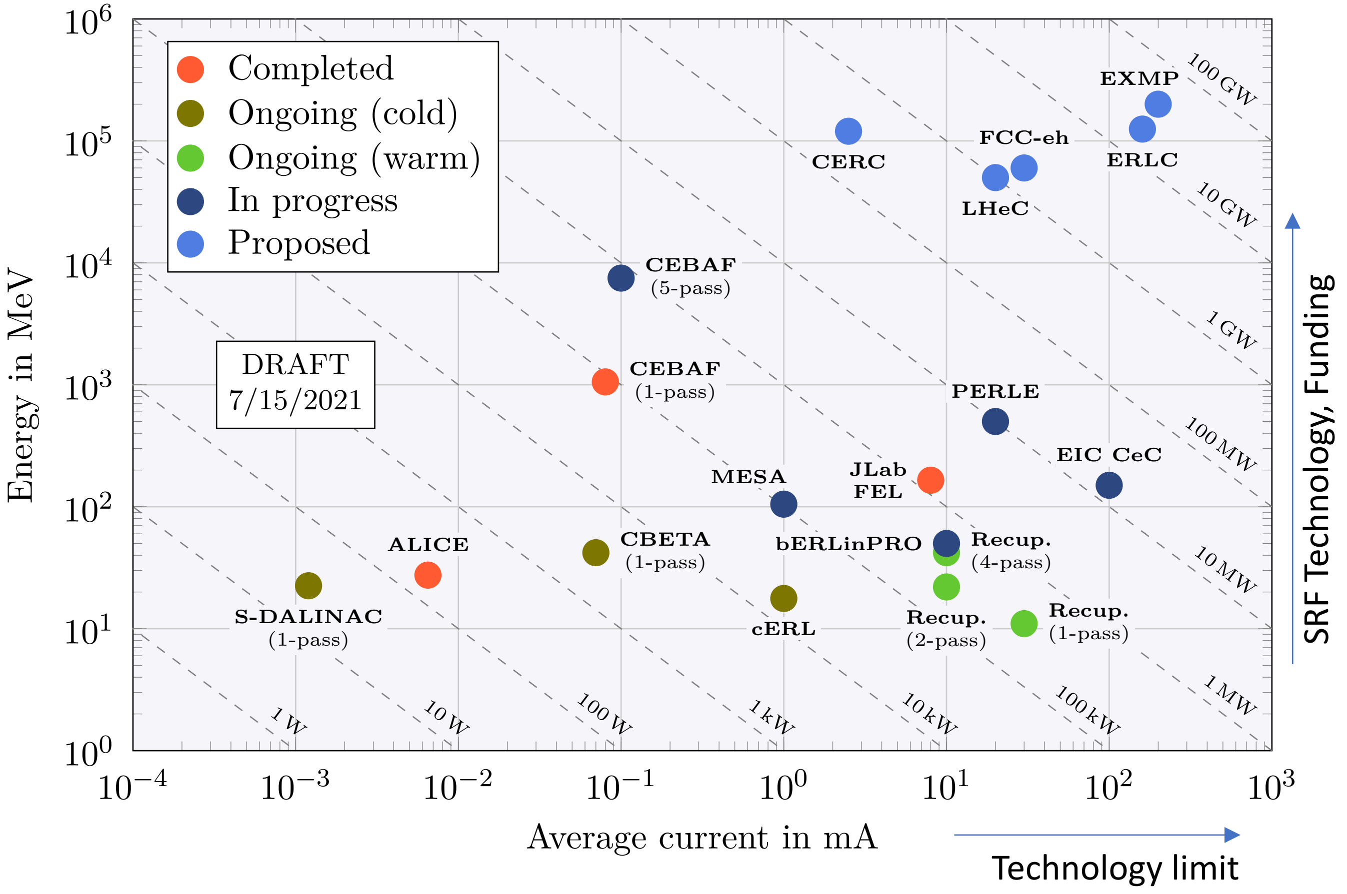
C (8.2) – Key Technology R&D Program – next generation ERLs

This is work in progress and not fully reflected yet in the ToC
Funding estimates and milestones are being worked on

A

Facilities

Electron beam energy [MeV] vs current [mA]



Notice: 10 MW frontier. Energy > 100 GeV needs 4.4K

Next ERL workshop will be held at Cornell (BNL, Jlab) 21-24. June 22

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

Text being extended, but rely and refer to long write up

- 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 countermeasures;
  - Characterisation of potential operating points of individually recirculating ERLs.
- MESA
  - Improving electron beam polarimetry to an accuracy of $dP/P \leq 0.5\,\%$ 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 higher-order mode (HOM) damping capabilities, for instance by coating of the HOM antennas by layers of material with a high critical temperature.
- 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.
- cERL (KEK)
  - Development of a 10 kW-class powerful ERL-based EUV-FEL;
  - Realisation of 100 % energy-recovery operation with a beam current of 10 mA at cERL and FEL light production experiment;
  - Development of an irradiation line for industrial applications (carbon nanofibers, polymers and asphalt production) based on 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.
- 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.

A-C Supportive Technology

(5.3. in Interim Report)

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 ..

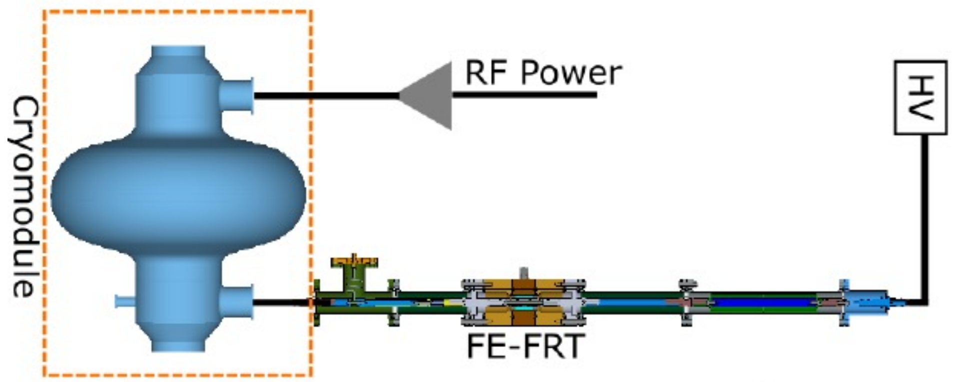
[also in B for facilities and C for very high current]

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 physicists - education

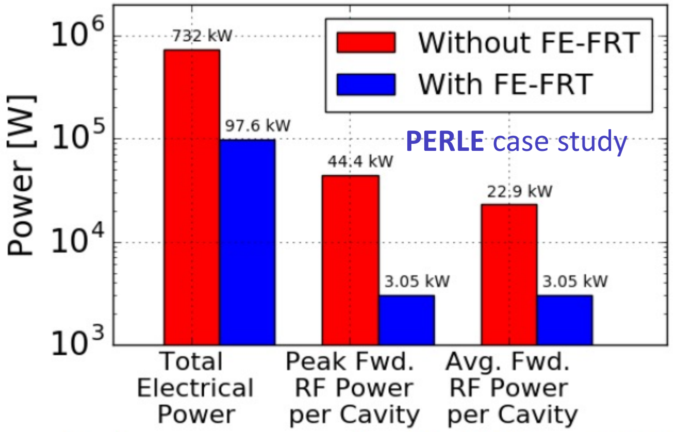


LHeC Workshop (9/18)
IPAC, May 2021
SRF Symposium (7/21)
Nick Shipman et al.

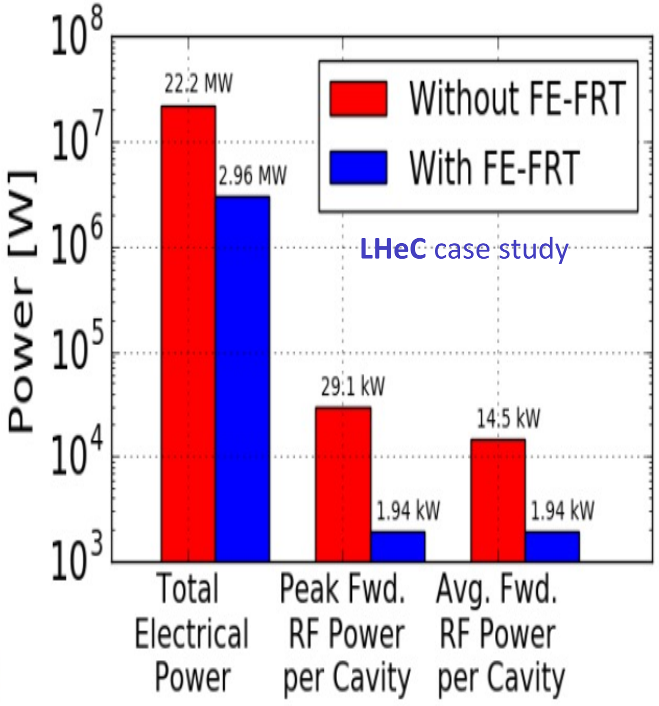
Considering FRTs for bERLinPRO + PERLE in collab. with CERN

3. Fast Reactive Tuners

contra microphonic resonance detuning



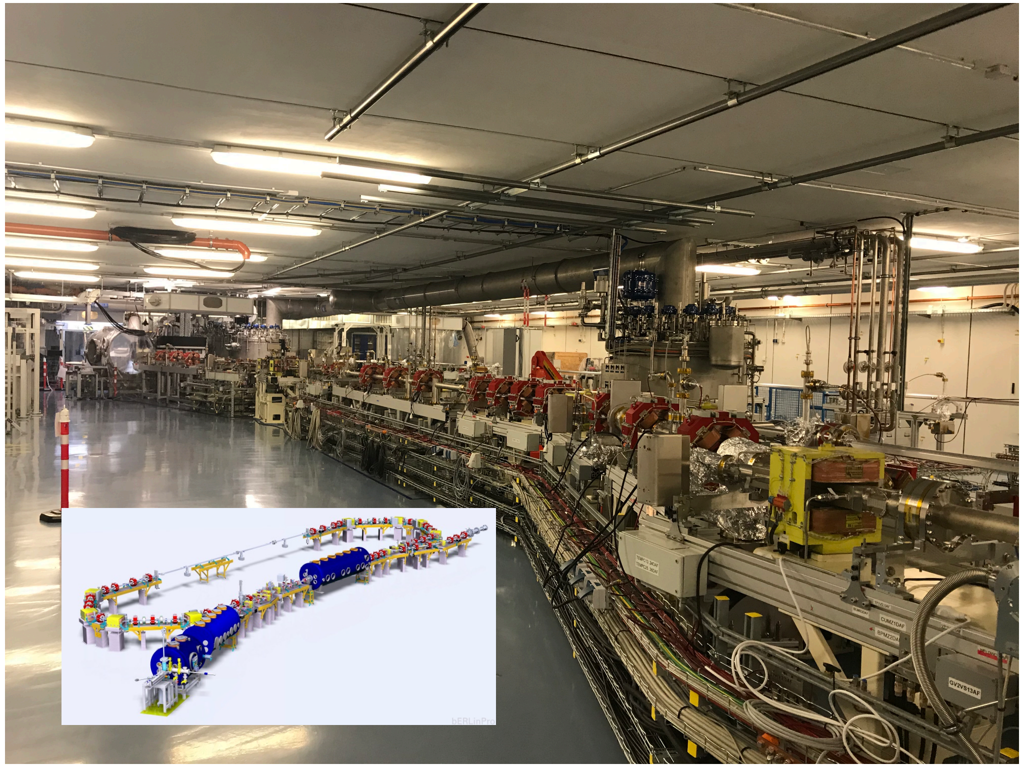
- Peak power per cavity 44.4 kW → 3.05 kW



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.

B

bERLinPRO



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

Draft timeline and cost table

Option	min. invest	optimum	time
	gun		
high current 100 mA gun	1 cavity, 2 Canon couplers	2nd module, solenoid, 4 Canon couplers, 2 cavities, 1 FTE engineer	2-3 y
cathode research: QE preserving transport optimization	Dispenser material for additional cathodes beyond bERLinPro program		
	booster		
high current 100 mA Booster	work and small parts		6 m
	linac		
linac bERLinPro design	3 cavities, auxilliaries, cryomodule	5 cavities, auxiliaries, cryomodule	3 y
alternative: linac with FRTs	3 cavities, auxiliaries, cryomodule	5 cavities, auxiliaries, cryomodule	3-4 y
	complete program		
			4 y
additional personnel	4y × 2 FTE	4y × 4 FTE	

Jens Knobloch, Bettina Kuske, Axel Neumann

Racetrack closed
600kW Dump, 100mA cryogenics
RF transmitter all there.

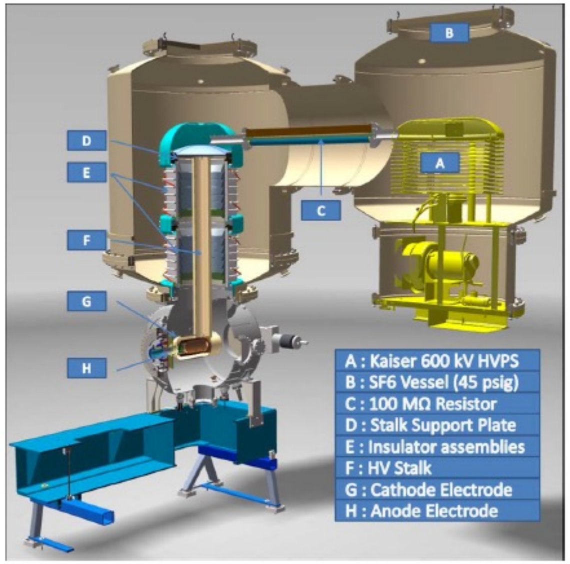
Possibility to upgrade SRF gun to 100 mA (currently power coupler limited)
Adding cavity-cryomodule, equipped with FRT, to complete the facility.
R&D on stability, emittance preservation, beam loss, bunch length..

B High Current Electron Sources (5.1. in Interim)

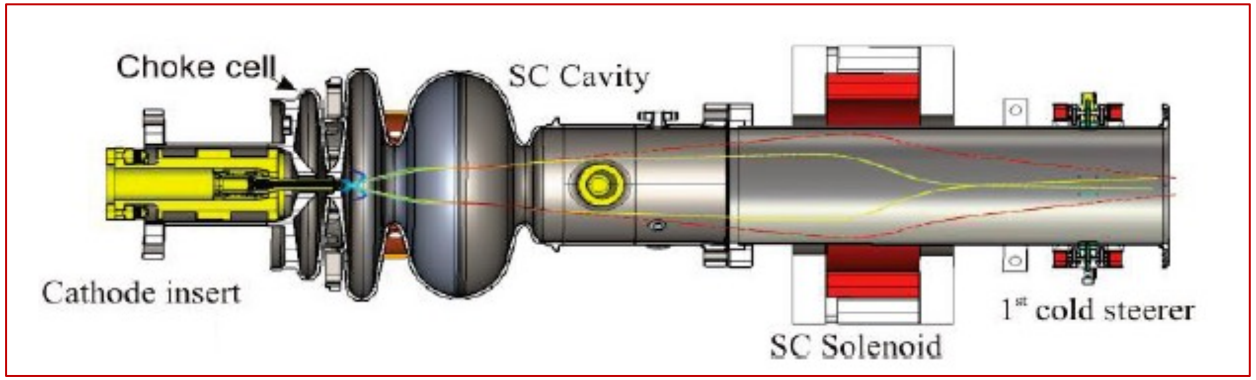
Linked to facility progress and developed at other places

- 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

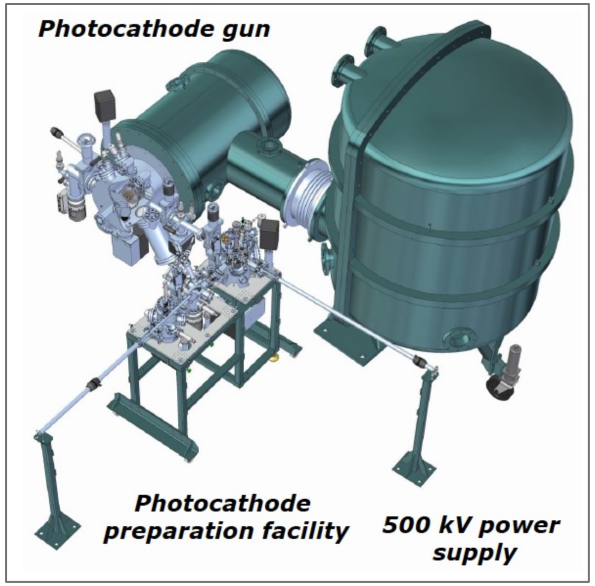
Boris Militsyn (ERL symposium)



DC photocathode gun: 70mA (Cornell)



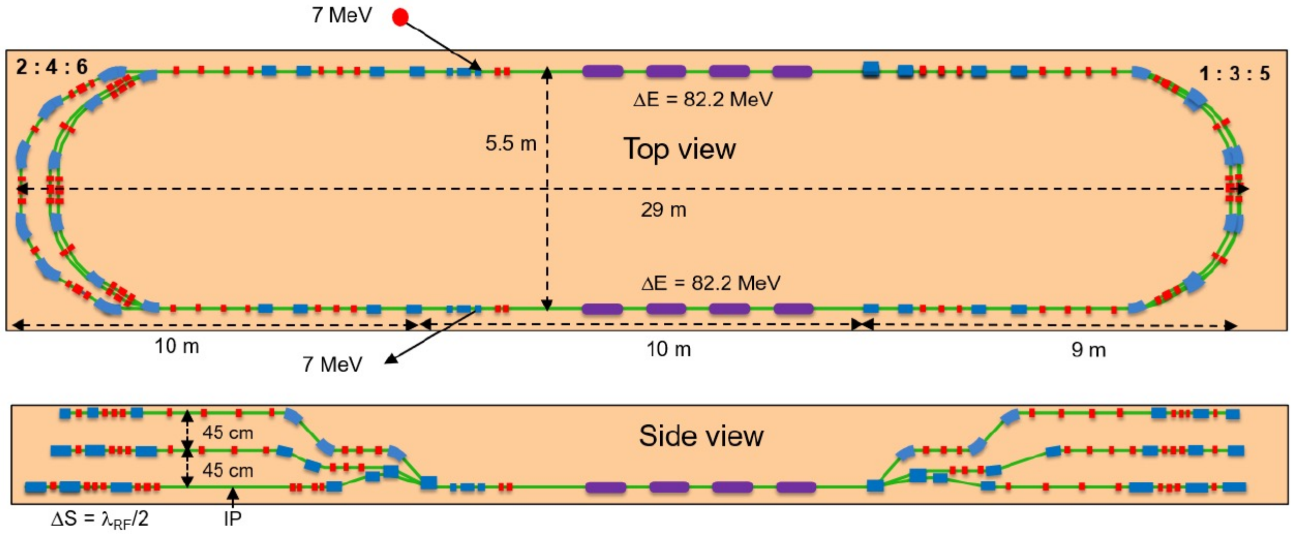
SRF elliptical cavity gun at bERLinPro (HZB) – upgradeable to 100 mA



ALICE (upgrade to 20mA) → PERLE

B

Key Tasks for PERLE

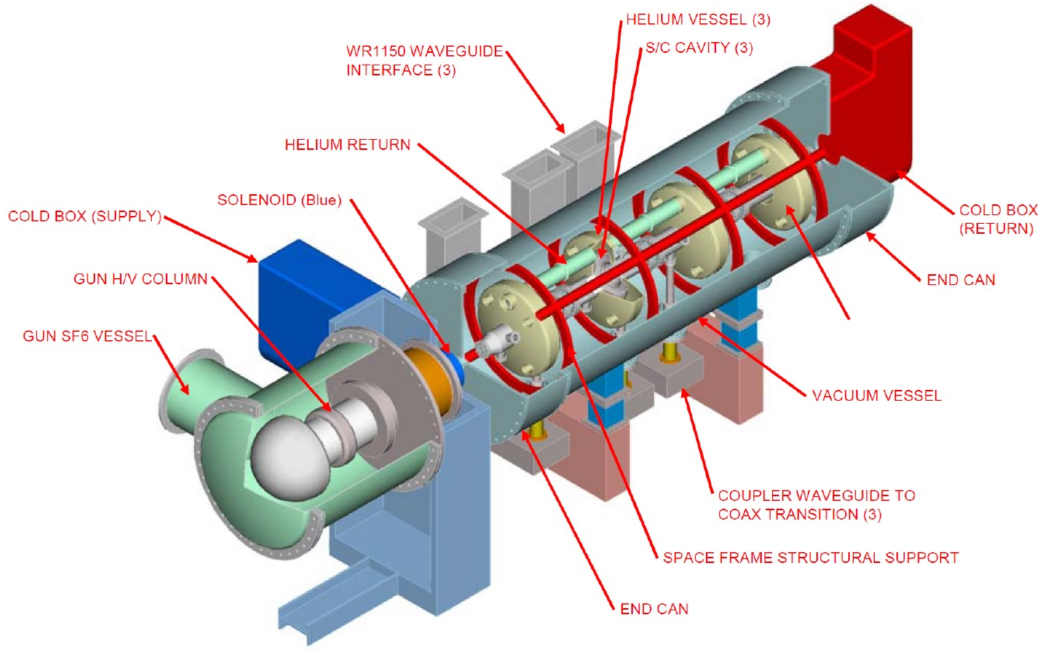


- Installation of ALICE Gun at IJCL Orsay
- Adapting JLab/AES Booster to 802 MHz
- Dressed cavity design (HOM, power) and build of 4 cavities
- Adapting SPL Cryomodule to house 4 cavities (also for FCC-ee)
- Build "B com" magnet prototype → all magnets
- Preparation of Cryo- and Power-Infrastructure
- Prepare for Physics (e-isotope scattering, igs, dark ys – tbc)

CERN, Cornell, Daresbury, Jefferson Lab, Liverpool, Novosibirsk, IN2P3 : IJCLab Orsay (Host), Grenoble PERLE Collaboration

JLab Booster for PERLE – under evaluation

	JLab/AES Booster	PERLE
Booster exit energy	7MeV	7MeV
Bunch charge	133pC	500pC
Bunch repetition rate	748.5MHz	40.1MHz
Cavity Fundamental Frequency	748.5MHz	802MHz
Average current	100mA	20mA
RMS bunch length	3mm	3mm
Emittance	<5mm mrad	<6mm mrad
Uncorrelated energy spread		< 10keV



Fay Hannon

B

SRF Cavities (5.2. in Interim)

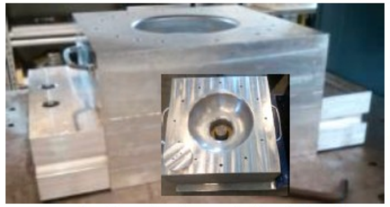
ERLs, being somewhere between linacs and storage rings, have unique requirements for their RF systems and therefore need optimised designs to achieve the full potential of the concept. Proposed new machines operating with about 100 mA of current, either in single or multi-pass mode, need cavities with 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

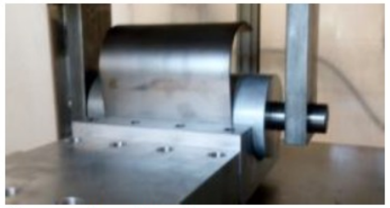
← f < 1 GHz

- 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

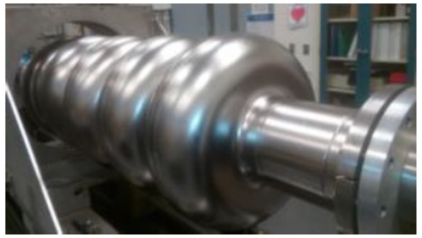

Male die


Beam tube rolling die

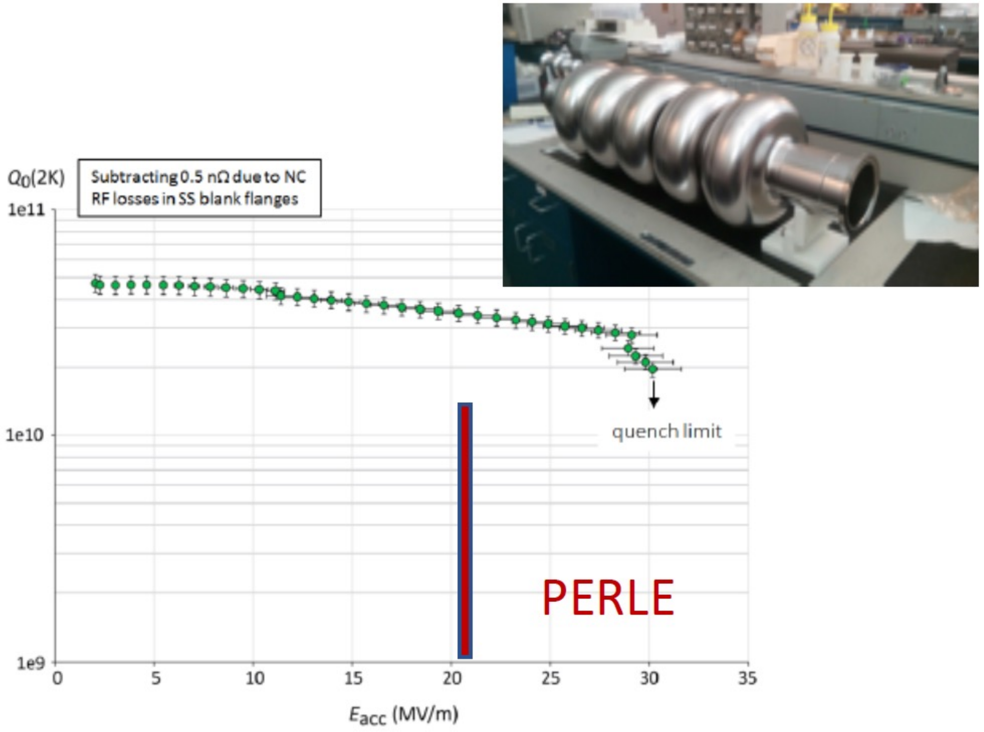

RF half cell/dumbbell measurements fixture



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

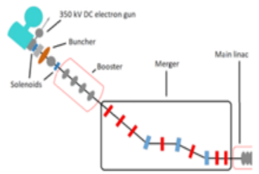


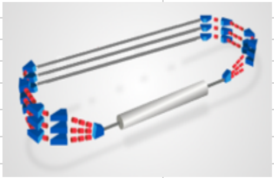
DRAFT timeline of PERLE: Design, Injector, SRF, Magnets, Infrastructure, Experiments, Safety/Integration

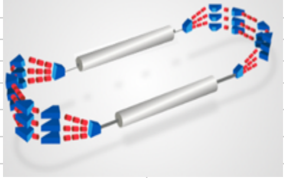
Work Package	Task	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
		TDR Phase (2021–2022)		PERLE-Phase 0: Injection line (2023–2025)							
				PERLE-Phase 1: PERLE @ 250 MeV (2023–2027)							
				PERLE-Phase 2: PERLE @ 500 MeV- 10MW (2023–2030)							
WP2: Accelerator Design	T2.1: Lattice and Optics	Linear Lattice optimisation									
		Momentum acceptance & longitudinal match (2021–2022)									
		Correction of nonlinear aberations with multipole magnets (2021–2022)									
		Injection line design (2021–2022)									
		Merger study and design (2021–2022)									
	T2.2: Beam Dynamics	End to End Multi particle tracking studies, error effects & halo formation (2021–2022)									
		End-to-End simulation with CSR & micro-bunching (2021–2022)									
		Space charge studies at injection (2021–2022)									
			Impedance analysis & wakefield effect mitigation (2022–2023)								
			Beam Breack-Up instability (2022–2023)								
WP3: e- source & injector	T3.1: DC gun installation preparation	Gun installation preparation	Starting gun installation	Testing DC gun	Injector Installation	Injector commisioning		DC gun upgrade and operation (2027–2028)			
	T3.2: Buncher & Booster design		Buncher cavity design	Buncher cavity production							
			Single cell booster cavities design	Single cell booster cavities production							
		Booster needs identification (2021–2022)		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 (2023–2024)				5-cell cavities production and test (2027–2028)			
	T4.2: Power coupler design and prototyping	Adaptation of SPL power coupler and RF conditioning (2021–2022)									
	T4.3: Cryomodule	Design SPL Cryomodule completion (2021–2022)			Completion of SPL Cryomodule and test (2024–2025)						
				New cryomodule design (2023–2025)				Completion and test of the 2nd cryomodule (2027–2029)			
	T4.4: Fast reactive tuner design and protyping	Feasibility study & integration on cavity (2021–2022)									
	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 (2023–2024)		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 (2021–2022)		Cryoplant design and production (2023–2024)		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 (2023–2025)						IP ingration for experiments	
WP8: Safety & integration	T8.1: Facility Administratif Classification (ASN)	Classification study and Preparation of ASN Document (2021–2023)									
	T8.2: Radioprotection & shielding studies	Radioprotection studies (2021–2022)		Personnel safety system (PSS) & machine safety system (MSS) design and implementation (2023–2025)							
	T8.3: Preliminary studies of the site	Site investigations (ground, available Area, ancelleries) (2021–2022)		Required infrastructure work							
	T8.4: PERLE footprint	Specifications & implementation design (2021–2022)									

2026–2027: Complete installation of PERLE @ 250 MeV, 4 mA, 3-turn and starting the commisioning

2030: Complete installation of PERLE @ 500 MeV, 20 mA, 3-turn and starting the commisioning







Principally endorsed by PERLE CB, June 2021

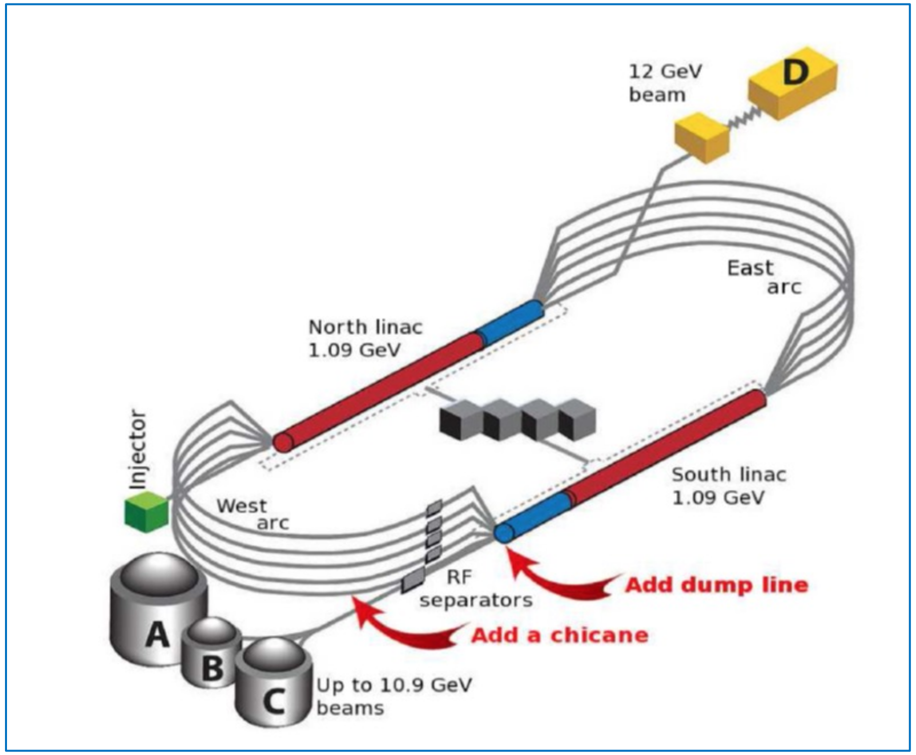
Walid Kaabi et al, 28.6.2021

Cost being drafted (in-kind, different costings, ..)

B

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

CEBAF 5 pass



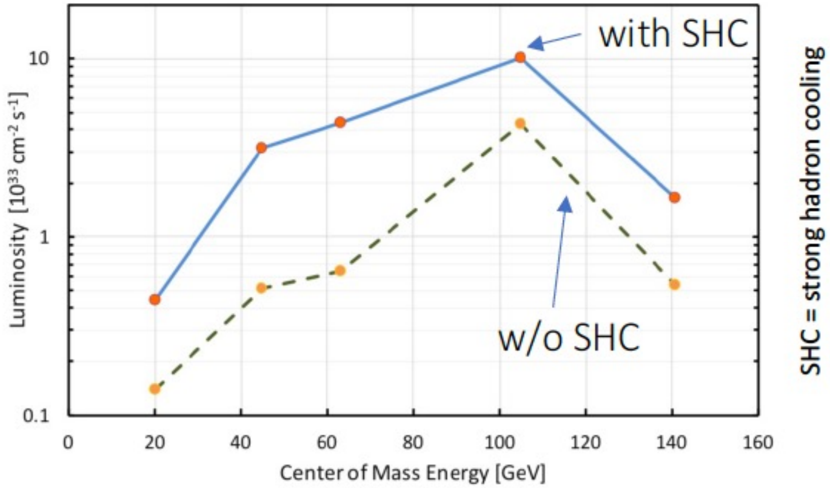
12 GeV (11 passes) beam to Hall D, 11 GeV to A,B,C

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

Electron Cooler for EIC

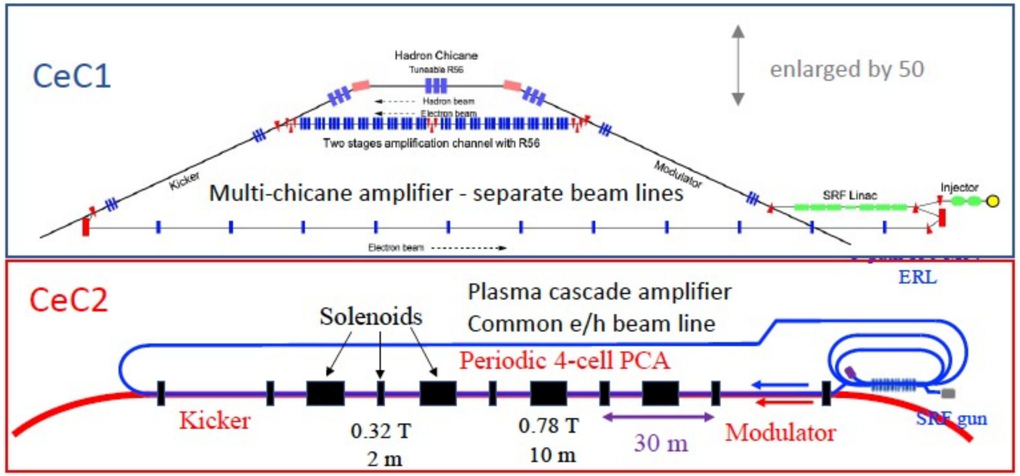
Decision expected with CD2

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

C

Key Technology R&D longer term

4.4K and Nb_3SN program

Motivation

Technology perspective (long recognized, envisaged applications in waste water treatment or medical isotope production)
increase T from 2K to 4.4K which makes technology widely accessible - leads to Nb_3Sn or other superconductor instead of pure Niobium
Nb: T_c 9K → high Q_0 and small heat dissipation [but few 10^8 at 4K]. Nb_3Sn: T_c 18 K potentially higher Q_0

HEP Collider perspective:
single pass electron energy accelerator in ERL mode with E > 100 GeV costs few 100 MW of cryopower, i.e. loose the energy recovery gain
4.4 K has 3 times better performance than 2K, lower frequency than ILC (not too low for size), higher Q_0
→ Then reach 500 GeV with 10^{36} $cm^{-2}s^{-1}$ and O(100) MW total power, the ERL design of **a next generation e^+e^- collider**

Requirements

4.4 K cryo-cavity technology for 600-800 MHz frequency. Aim at Q_0 ~ 5 10^{10} and gradients about 20 MV/m

Tri-Linear Higgs Coupling in e^+e^-

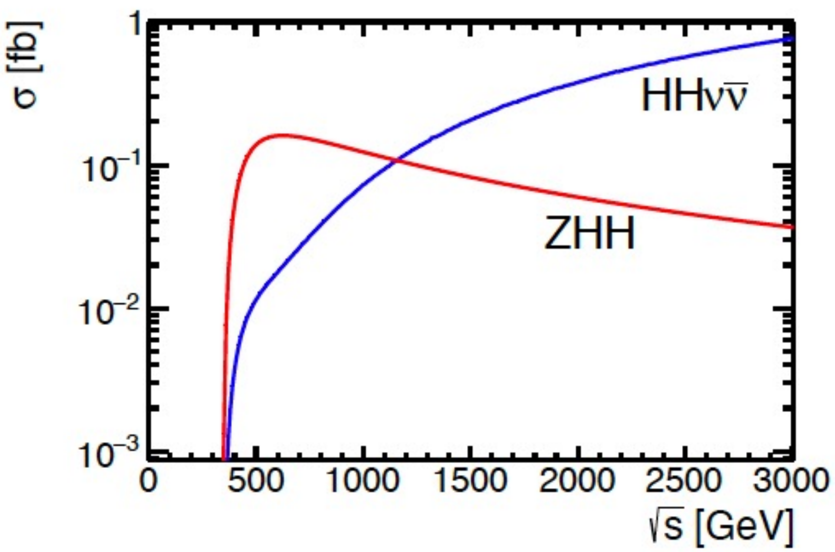


Fig. 1 Cross section as a function of centre-of-mass energy for $e^+e^- \to ZHH$ and $e^+e^- \to HH\nu\bar{\nu}$ production for a Higgs boson mass of $m_H = 126$ GeV. The values shown correspond to unpolarised beams including initial state radiation but not including the effect of beamstrahlung [16].

arXiv:1901.05897

CLIC: 1.4 TeV 2.5 ab^{-1} and 3 TeV 5 ab^{-1}
10% error on tri-linear H-HH coupling
[-29 - +67% for 1.4 TeV alone]

Kinematic limit of e e → Z H H : M(Z) + 2 M(H) = 341 GeV

ZHH unpolarised cross section maximum at 500 GeV: O(0.1) fb

O(10^{34}) $cm^{-2}s^{-1}$ luminosity gives 1 ab^{-1} in ten years: 100 events (A=1)

O(10^{36}) $cm^{-2}s^{-1}$ luminosity should produce 10 000 events → few %
and 300 fb * 100 ab^{-1} = 3 10^7 ZH events,
→ opens rare H decay channel programme in e^+e^-

<u>This is a strong case for a next generation linear ee collider</u>

Gradient 20*f MV/m: two 25/f km linacs:

It needs: Twin cavities, 4.5K, Nb_3SN, Q_0 towards 10^{11}

On CERC and ERLC: cf slides shown to LDG 8.9., subpanel report imminent: neither of the two concepts is ready to “just” replace the canonical FCC-ee or ILC designs → leads to a known R&D program.

C

Advances in Nb_3Sn superconducting radiofrequency cavities towards first practical accelerator applications

S. Posen[1a)], J. Lee[1,2], D.N. Seidman[2,3] A. Romanenko[1], B. Tennis[1], O. S. Melnychuk[1], D. A. Sergatskov[1]
[1]*Fermi National Accelerator Laboratory, Batavia, IL, 60510, USA*
[2]*Department of Materials Science and Engineering Northwestern University, Evanston, IL, 60208, USA*
[3]*Northwestern University Center for Atom-Probe Tomography (NUCAPT), Evanston, IL, 60208, USA*

arXiv:2008.00599 and many references therein

Single cell tests with gradient > 20 MV/m and high Q_0

1.3 GHz

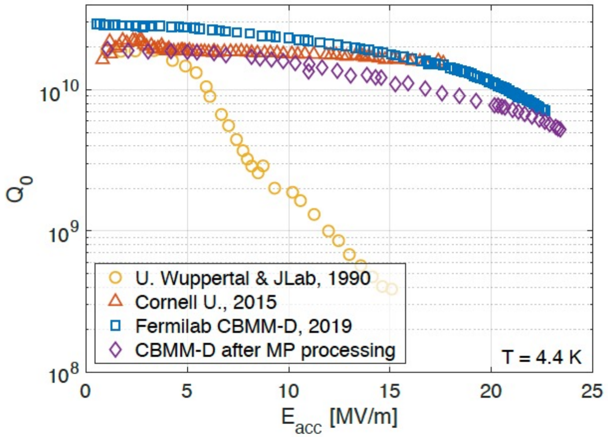


Fig. 12: Performance of 1.3 GHz single cell cavity CBMM-D before and after processing (top) and comparison to a selection of previous 1.3-1.5 GHz single cell cavities (data from [23], [32]) at 4.4 K (bottom).

650 MHz

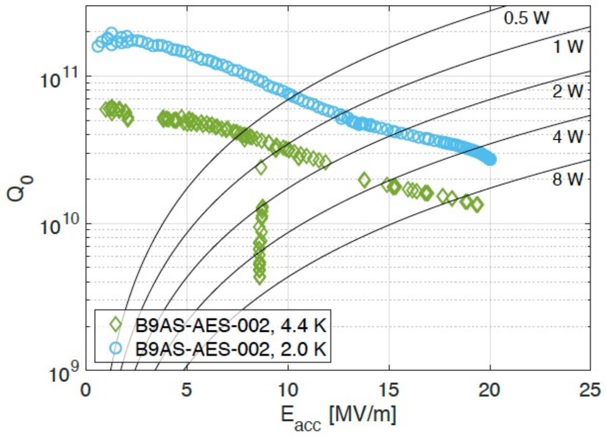


Fig. 13: Performance of 650 MHz single cell cavity B9AS-AES-002. The multipacting at 9 MV/m was processed during the test.

- The niobium cavity substrates were given electropolish treatment (as opposed to buffered chemical polish) to achieve a smooth surface prior to coating
- The niobium substrates were anodized to 30 V in ammonia prior to coating (recommended previously, e.g. [22] and [23])
- To encourage high vapor pressure, the Sn heater was driven with maximum power available (measured ~1300°C in thermocouples in heater coil, expect somewhere between 1200°C-1250°C in Sn crucible based on previous calibration)
- To encourage high vapor pressure, a relatively large crucible diameter was used (~15 mm or larger)
- To prevent condensation of Sn droplets on the surface due to a high vapor pressure in a closed volume, one or more ports of the cavity were kept open to the chamber (similar to the Cornell setup [1])
- The nucleation step was substantially modified, to have a rapid ramp to high temperatures ~1000°C – this will be discussed in detail below
- A nitrogen infusion step was added at the end of the coating process – this is also discussed in detail below

High end technology requiring long term expertise
Sn Vapor diffusion: FNAL, JLab, Cornell. Not in EUK

Sputtering technology

- Magnetron sputtering allows for good stoichiometry control
- Compatible with other substrates (e.g., Cu)
- Can be rapidly be adapted to other superconductors (e.g. NbTiN)
- So far only sample measurements (QPR)
- Europe (CERN and IFAST Collaboration) leading, some effort in USA.

CERN, Nb_3Sn deposited on copper, magnetron sputtering & HiPIMS
STFC Daresbury, Nb_3Sn on Cu and multilayers
INFN Legnaro, Nb_3Sn by dipping/annealing, by magnetron sputtering -

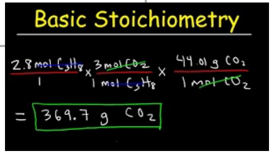
Single cell → multi-cell → module → industry

A decade of developments.
Very promising but demanding (cf backup)

Should Europe invest in diffusion ?

One of the many questions we will discuss.

Involves industrialization prospects etc.



Sputtering

DRAFT 27.9.

Task	Invest (TEUR)	FTE Total	'E Cost (MEU	Total cost	Sample recipe development	Miulticell Sputtering Setup	Single cell development	Multicell development
	1.875	**23**	**3.668**	**5.543**	1.253	1.489	1.128	1.673
Produce 5 QPR Samples	75		0	75	1			
Produce RaSTA	200	1	163	363	1			
QPR Sample testing		1	163	163	1			
Sample production in IFAST		1	163	163	1			
6 GHz cavity testing in IFAST		1	163	163			1	
Design new multicell sputtering		1	163	163		1		
Sample production		2	326	326	1			
1.3 GHz cavity production to support IFAST		1	163	163			1	
Procure 5 copper single cell cavities	150		0	150			1	
Install multicell sputtering system	1000	1	163	1163		1		
RaSTA and QPR Sample Testing		1	163	163	1			
Cavity Testing		0,5	81,5	81,5			1	
Optimization of single cell coating		1	163	163			1	
Commission multicell sputtering system		1	163	163		1		
Procure 5 copper multicell cavities	450		0	450				1
RaSTA and QPR Sample Testing		0,5	81,5	81,5			1	
Cavity testing		0,5	81,5	81,5			1	
Single-cell/Multicell coating		2	326	326			0,5	0,5
Cavity testing		1	163	163			0,5	0,5
Multicell coating		2	326	326				1
Cavity Testing		1	163	163				1
Multicell coating		2	326	326				1
Cavity Testing		1	163	163				1

A tentative schedule - Jens Knobloch

C

HOM damping to room T

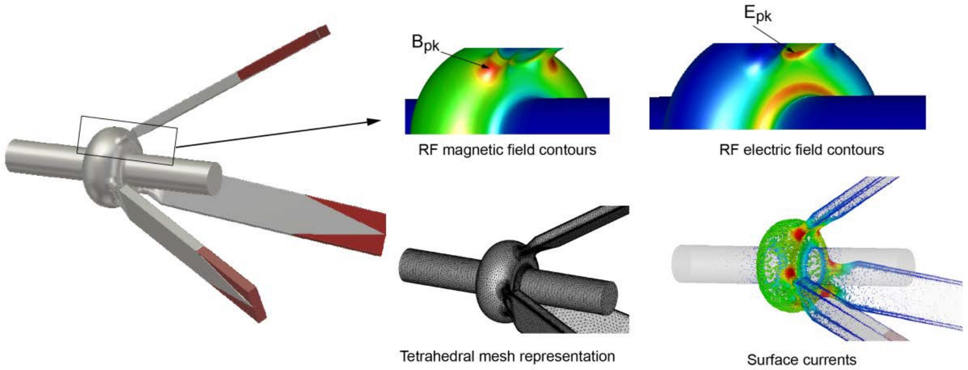
HOM power is usually extracted from the cavities and brought out to ~50K to reduce the thermal load

About 7% of the power is dissipated at 2K in the ILC

For high-current ERLs, this would be unacceptable

R&D Goal: >99% of HOM power transferred to room temperature

Possible technique: on-cell damping



Frank Marhauser: http://dx.doi.org/10.1088/1361-6668/aa6b8d

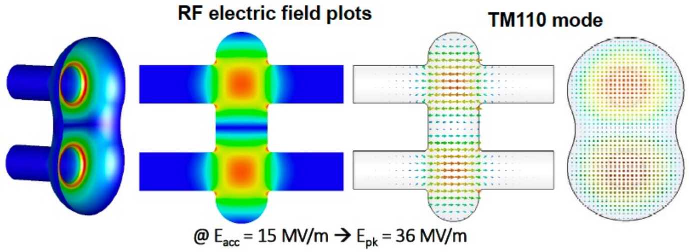
Input to roadmap being written, link to LHC:

Extract 1kW per HOM coupler at 400 MHz to warm via RF

Higher may need waveguide (Graeme Burt)

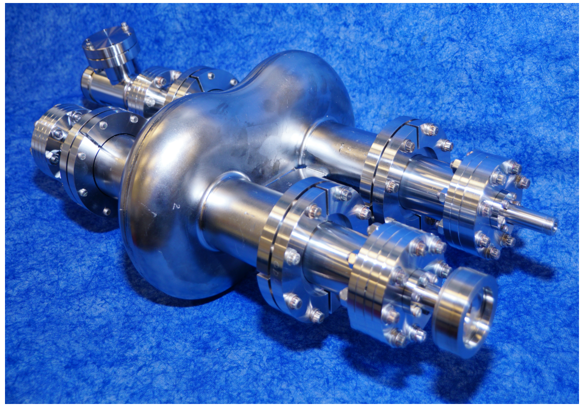
Twin Cavities

HyeKyoung Park
SRF2017 Lanzhou



"compatible with Nb_3SN vapor deposition process"

1.5 GHz twin axis Nb cavity



7-cell cavity in Al

H. Park, S. De Silva, J. Delayen, A. Hutton and F. Marhauser, "Development of a Superconducting Twin Axis Cavity, doi:10.18429/JACoW-LINAC2016-THPLR037.

V. Konoplev, K. Metodiev, A. J. Lancaster, G. Burt, R. Ainsworth and A. Seryi, "Experimental studies of 7-cell dual axis asymmetric cavity for energy recovery linac", Phys. Rev. Accel. Beams 20 (2017) no.10, 103501.

Reduce bbu, cost, ..: R&D for a decade for cryomodule

Experience at Jlab + Old Dominion U and John Adams + Cockcroft

Tentative Conclusions

- What R&D needs to be done towards future facilities? What are the priorities? *)

  Priority is the 10 MW frontier: bERLinPRO fully equipped and PERLE 250 MeV, both by ~2026
  → new generation of low energy experiments, technology for medium energy (50 GeV) ERL for ep, impact on industry and ERL itself
  Next generation of High Energy (> 100 GeV) electron accelerators (e^+e^-, HE FCC-eh) needs key technologies to be developed
  → Nb_3SN and 4.4 K (sputtering Europe/CERN, thin film rather US), high T HOM damping, high(er) current OP and diagnostics, Twin cavities

- How long might it take? What is the fastest technically limited schedule?

  A facilities are operational but have important programs, MESA (polarized) coming up; **B** beam by 2026; **C** 2032
  Note that A,B,C are all interlinked.

- How much will it cost?

  A operational facilities: sDALINAC, MESA in Europe, cBETA (US), Recuperator (Ru), cERL (J). European facilities basically covered
  B new facilities and their technology: bERLinPRO (m MEuro) and PERLE (nn MEuro – cost + time reduced by in kind components)
  C 4.4K and Nb_3SN (cost depends on technology chosen [m sputtering, n Sn vapor diffusion]); high T HOM damping (?); diagnostics (?); twin cavity (depends on whether there will be a European development –JAI?)

- What different options and trade-offs exist?

  The field, especially in Europe, needs funding, coordination and inclusion. The genuine sustainability development we have.

- What are the linkages between activities?

  A,B,C and developments at other places (e.g. HZ Rossendorf) are much interlinked. ERLs are global (missing China, so far)
  ERLs are required for high E+L ep, yy, e^+e^-, muon? colliders. Links exist to SRF, Plasma, Muons. Technology for FCC-ee, …

- What science can be done using demonstrators, or intermediate-scale facilities?

  Huge opportunities with very high intensity (PERLE = 1000 ELI) and small emittance: MESA (> 2024), PERLE (>2027)
  Weak interactions, dark matter, nuclear photonics through IGS, exotic isotope spectroscopy, …

*) Questions posed by Dave Newbold in ECFA Newsletter No 7 (28.9.21)

backup

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]

The e^+e^- ERL Sub-Panel (since 9.6.21)

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 Sub-Panel 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)

Deliverable

Short reports (2x10 pages) detailing the conclusions of the evaluation, which should be agreed and supported by the entire sub-Panel and is intended to be published as Appendix B to the full Panel report (tbc)

Had/have weekly meetings, initially with proponents

This has developed into sincere work and study.

Needs 4-6 weeks to conclude, comments next pages

Overall and tentatively: neither of the two concepts is ready to "just" replace the canonical FCC-ee or ILC designs. Their clear potential invites further study and dedicated R&D, which will be sketched in the subpanel reports, e.g. 4K operation, Nb_3Sn coating – cavity developments (link to RF group). The timeline of the conclusions is for the roadmap, not the interim report. It is now imminent (meeting yesterday 29.9.).

LHeC: Poster at EPS by Kevin Andre

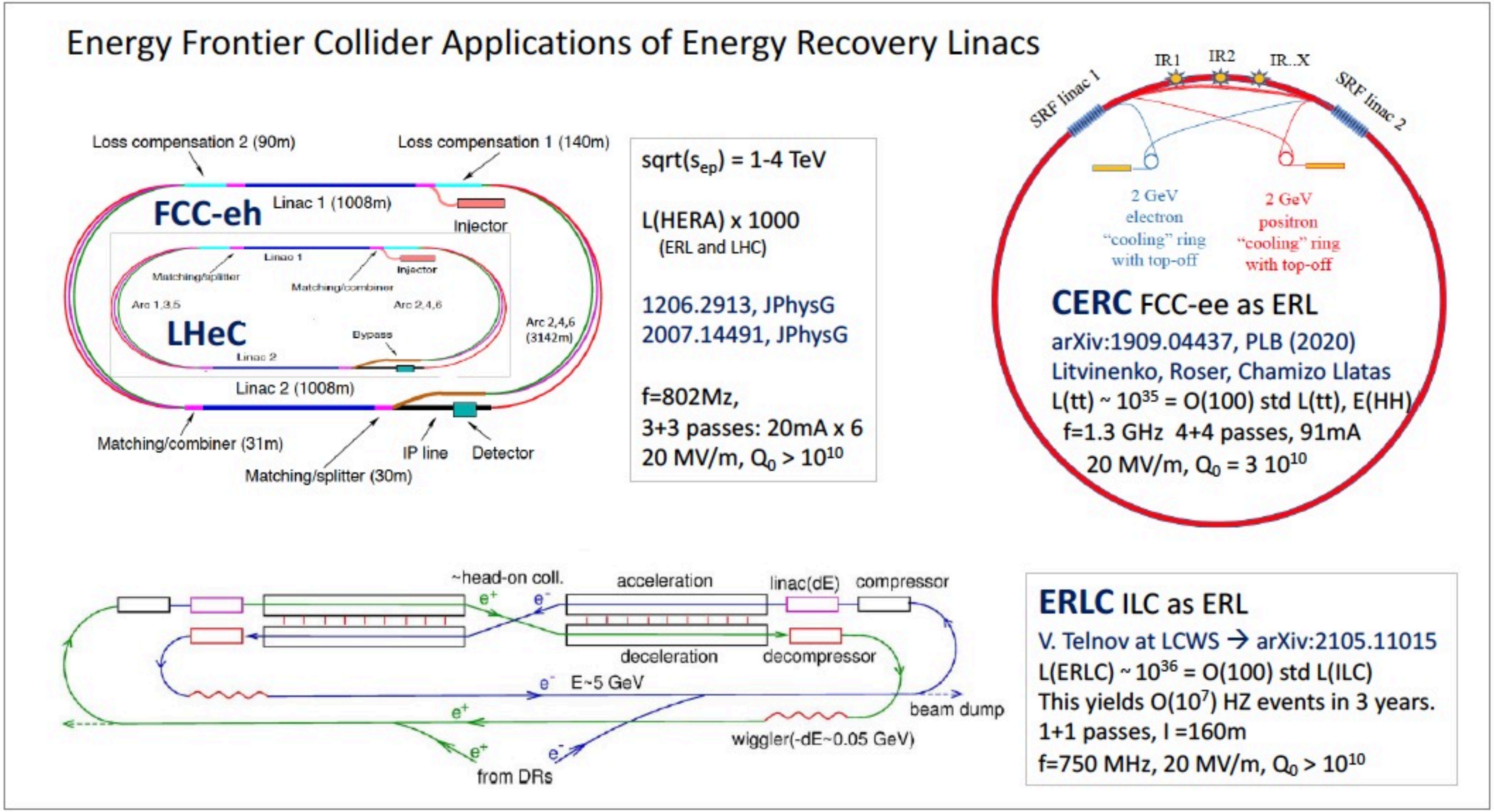


Figure 2: Sketch of possible future colliders based on ERLs: left top: LHeC and FCC-eh; right top: CERC; bottom: ERLC. For more information see the arXiv references displayed.

[from a report to LDG 5/21]

CERC ERL configuration of FCC-ee

ERL applied to a circular collider configuration

Questions under current discussion

- Luminosity vs beam parameters
- Bunch length vs long beam line and DR acceptance
- Energy of damping rings (2→ 8 GeV)
- Power consumption through damping rings
- Cost through instrumented arcs and their technology
- Shape of tunnel for CERC vs FCC-hh
- Upgrade of FCC-ee
- …

Future High Energy Circular e^+e^- Collider using Energy-Recovery Linacs

Vladimir N Litvinenko[1,2], Thomas Roser[2] and Maria Chamizo Llatas[3]

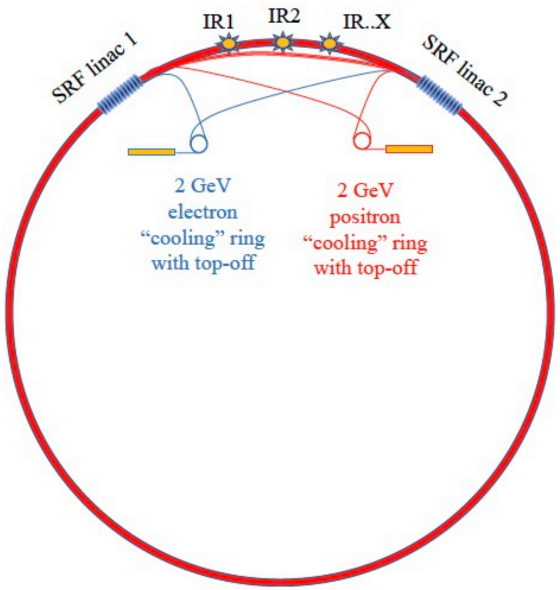
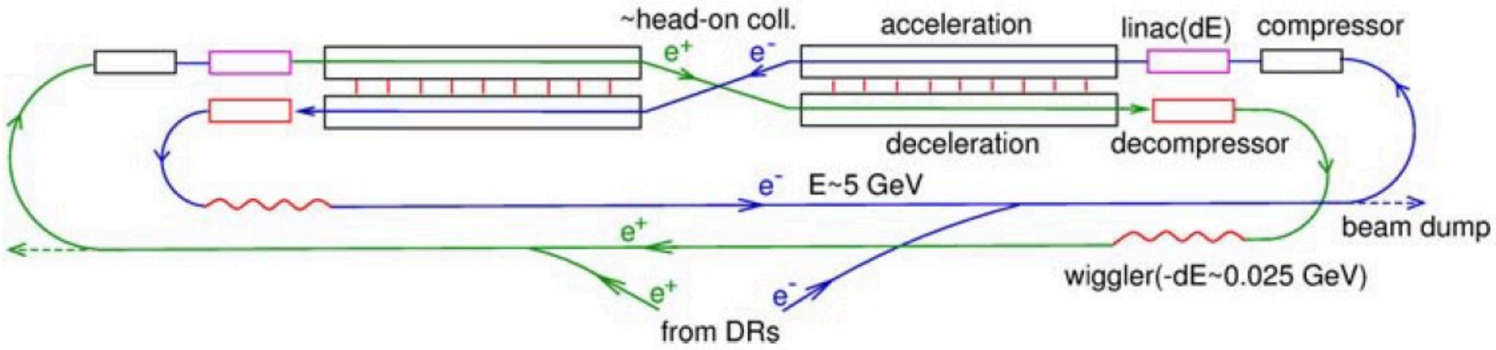


Fig. 2. A possible options of an ERL-based FCC ee collider with linacs separated by 1/6th of the FCC circumference.

ERLC ILC as an ERL



V Telnov
2105.11015

The ERLC is not a linear collider with damping rings. Because the bunches are returned to the damping rings after each acceleration-collision-deceleration cycle, it must be considered as a loop - a sort of extended ring.

This means that it is necessary to define some additional parameters;

* Transverse tune
* Momentum compaction factor
* Synchrotron frequency
* Head-tail modes that lead to beam break-up

We also think that there are effects that will add up over 400 turns, but are unsure whether they add up linearly or some weaker dependence.

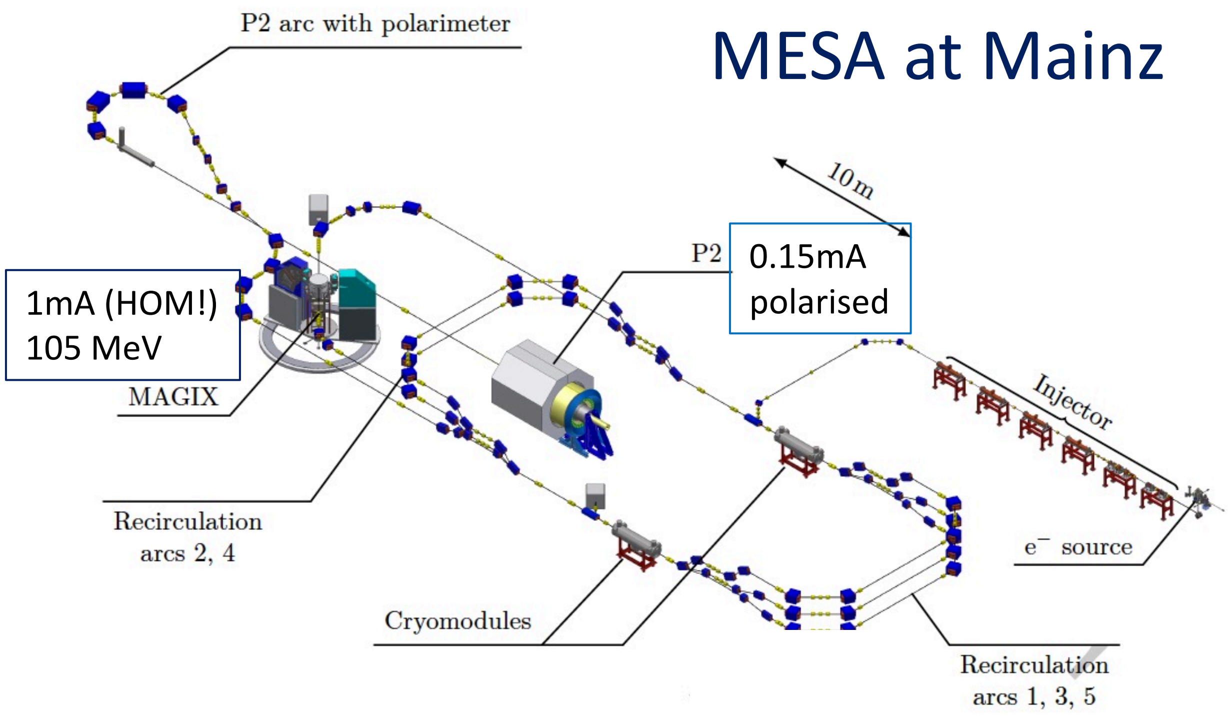
Questions/comments to VT, 8/21

R&D: Twin cavities, 4K development to lower cryogenic load, higher Q_0

Low Energy Physics with ERLs

Three examples from Long Write-UP

MESA at Mainz

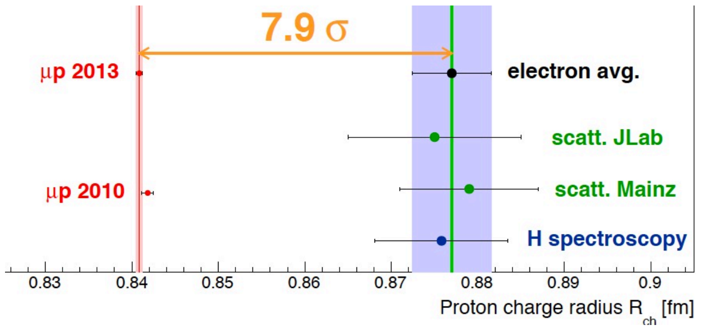


- 1.3 GHz, two ELBE type cryomodules, up to 3 passes
- New building, beam by 2024
- Polarimetry to 0.5% precision
- Current upgrade (unpolarised to 10 mA)

P2 – external target sin^{2}O, 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

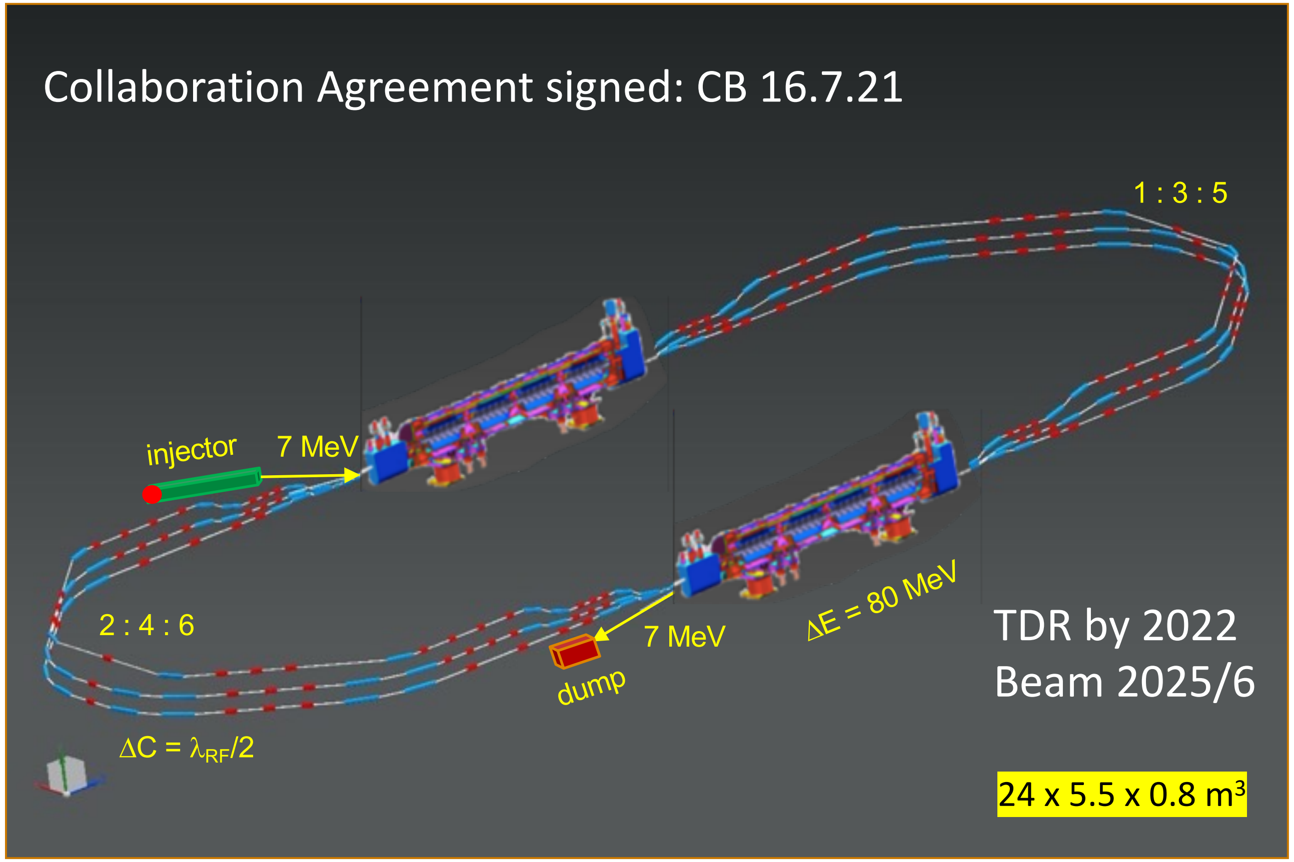
also: IGS: nuclear security, novel medical isotope research

Electrons Probing Exotic Nuclei

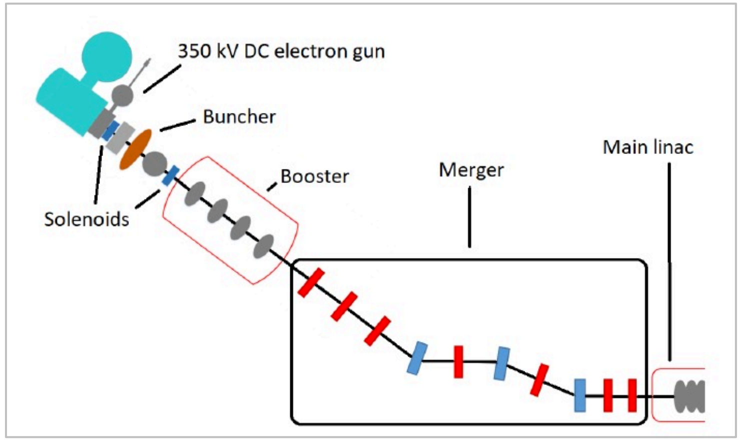
New field, pioneering: SCRIT@RIKEN, PRL 118, 2017
PERLE 500 MeV, 20mA, DESTIN project at Orsay
Outlook: eRI facility at GANIL (Caen, F) 200mA, ~2040

B 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 +



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

* 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]