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PROSPECTS FOR FUTURE FACILITIES BASED ON ENERGY RECOVERY LINACS

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Abstract

Superconducting Energy Recovery Linacs (SC-ERLs) promise a step change in the capabilities, and sustainability, of electron accelerator based facilities. This was highlighted in the 2022 ECFA / CERN European Strategy for Particle Physics Accelerator R&D Roadmap. Potential beneficiary fields include high energy particle physics, free-electron laser (FEL) light sources for physical and life sciences and industry, and inverse Compton based gamma sources for nuclear science and industry. Here we explore contemporary theoretical and experimental progress in ERLs, discuss the ongoing technical challenges, and present the community roadmaps toward deployment of ERLs in facilities globally.

WHY ENERGY RECOVERY LINACS

ERLs are capable of providing nearly linac quality electron beams, with nearly storage ring beam powers.

By decelerating a spent beam within the same structures used to accelerate, the energy of the bunch can be returned to the structures and is available to accelerate subsequent bunches. This process overcomes the inherent inefficiency of conventional linear accelerators, without introducing the beam quality limitations imposed by stored beams. Because the beam power at high energy can be many times greater than the RF power required to sustain it, ERLs allow us to consider higher power applications that would otherwise be unaffordable. ERLs also allow superior radiation control as the recycled beam power never reaches a dump, thereby mitigating safety and environmental concerns. ERLs are therefore a sustainable path to GW-class electron beams.

The 2020 European Strategy for Particle Physics [1] recommended that, *the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies ... a roadmap should prioritize the technology....* Five areas were selected, of which one was ERLs. A panel was established which contributed sections to the summary accelerator R&D roadmap [2], and produced a longer report with status and recommendations [3]. These identify the technologies and test facilities required to take the next steps in energy and power. Subsequent to this European Process, a similar effort was undertaken as part of the US Snowmass planning exercise [4], building on the findings of the European reports.

ERLs were first proposed by Tigner in 1965, the first NC demo was at AEC Chalk River in 1977 and first SC demo at Stanford in 1987. The first "true" ERL, in the sense that the beam power exceeded the RF drive, was achieved at the Jefferson Lab series of FEL drivers from 1999. The first ERL in Asia was the JAERI FEL project - achieving kW lasing in 2000, and the first in Europe was the ALICE IR-FEL at Daresbury Laboratory, which ran a successful user programme from 2008 - 2016.

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THE POTENTIAL OF FUTURE ERL FACILITIES

The most established proposal applying ERL technology to particle physics is the LHeC / FCC-eh 50 / 60 GeV ERL to augment LHC into an e-A collider [5–7]. An ERL was selected over a storage ring in 2012 due to the higher achievable luminosity, primarily due to its superior disruption tolerance. During 2020 / 2021 a number of proposals were published exploring how ERLs could address e+e- colliders, and a sub-panel was established to look at the first two of these in detail. Figure 1 shows how these proposals fit in context of beam power of selected past and existing ERL facilities.

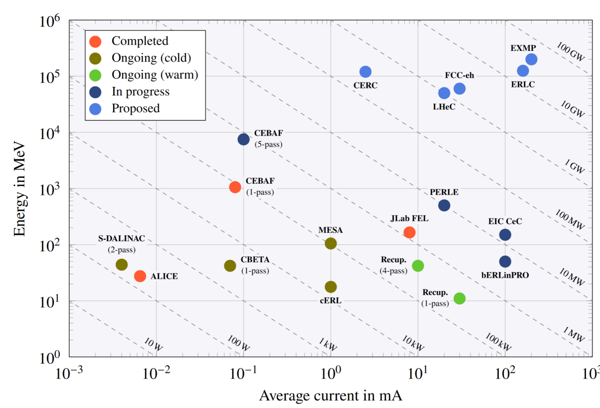

Figure 1: The landscape of past, present, and proposed ERLs. The dashed lines are contours of constant beam power.

CERC: Re-Imagining FCC-ee as an ERL

Litvinenko, Llatas & Roser [8] propose two 11 to 90 GeV SRF linacs in a 4-pass ERL configuration to fit within the proposed FCC 100 km tunnel, shown in Fig. 2. Choosing to fix the synchrotron radiation (SR) power loss to 30 MW (1/3 of FCC-ee), results in luminosity predictions exceeding FCC-ee substantially at all centre-of-momentum (CoM) values higher than the Z, see Fig. 3. The maximum CoM proposed is 600 GeV corresponding to $Ht\bar{t}$. Damping rings for both species provide emittance reduction and recycling of beams, and enable full beam polarization.

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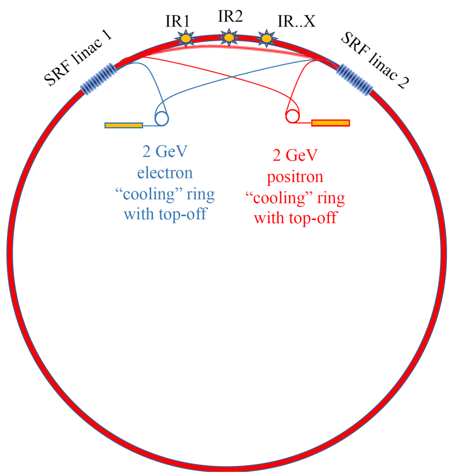

Figure 2: CERC: A re-imagining of FCC-ee as an ERL.

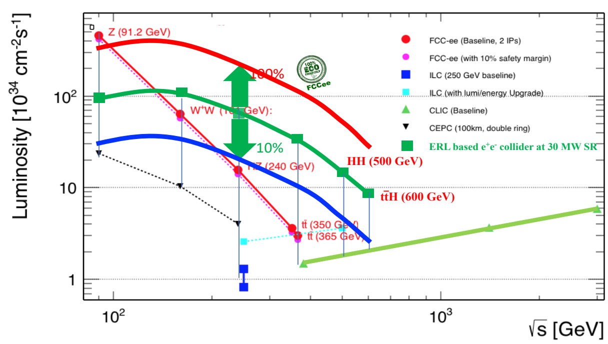

Figure 3: Luminosities for various options for a high-energy e^+e^- collider. The plot was taken from [9]. Three CERC luminosity curves are added in blue, green, and red added to it for levels of synchrotron radiation power of 10 MW, 30 MW, and 100 MW, respectively.

The main challenges identified by the panel were beamstrahlung, energy acceptance of the damping rings, the choice of bunch length, and microphonics within the SC structures. This led to further calculations and an iteration of some parameters by the proposers - this is to be expected in an early stage proposal. No obvious show-stoppers were found and the panel felt the concept deserves a dedicated expanded study.

Table 1 summarizes an estimate of the CERC power consumption. This assumes 1.25 kW of cryo-plant power per 1 W loss at 1.8 K in the SRF linac, including a 25 % overhead related to the cryogenic facility and liquid He transport system. A ratio of AC power to RF power for the RF amplifiers of 1.66 was assumed. For the damping rings, permanent magnets are assumed as these are now deployed in light sources. The same would be done for the transfer lines to and from the damping rings. The electric power consumption of the CERC is lower than that of the FCC-ee by about 100 MW over its energy range with much higher luminosities at the higher energies. The extension of CoM up to 600 GeV can be achieved without an excessive rise in power consumption. Power consumption could be further reduced with focused R&D, notably on SRF at 4K. Table 2 shows an estimate of the CERC construction cost normalized to FCC-ee cost. The ~ 40% increase over FCC-ee indicated by this points to the interesting possibility of starting the physics program at Z and WW with the FCC synchrotron, then upgrading beyond CoM of 150 GeV with the CERC ERL to take advantage of its superior luminosity.

ERLC: Re-Imagining ILC as an ERL

Telnov [10] proposes two parallel SRF linacs connected to each other with RF couplers such that the fields are equal at any time, shown in Fig. 4. This twin-axis approach avoids parasitic collisions. Damping is provided by wigglers at 5 GeV. Particles are recycled and damping rings are used on

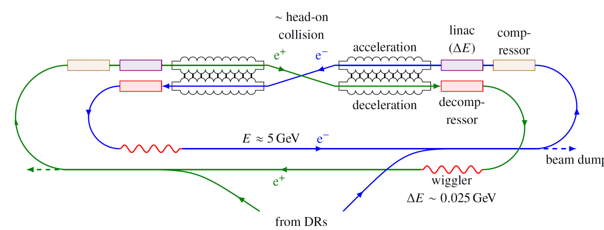

Figure 4: ERLC: A re-imagining of the ILC as an ERL.

injection / extraction. This combination of damping rings and large linacs is novel and the sub-panel came to the view that this aspect should receive dedicated beam dynamics studies. Luminosities are compared to ILC at CoM 250 GeV in Tab. 3 and 500 GeV (see [3]) for equivalent wallplug powers of 120 MW and 150 MW respectively and are found to be between one and two orders of magnitude greater, depending on the duty factor chosen.

This choice of duty factor was felt by the sub-panel to be the key determinant of the proposal. CW operation is more attractive than pulsed, not only for cryogenic efficiency, but also due to the reduced particle replacement rates compared to ILC. For CW operation the demand on the positron source is reduced by an order of magnitude over ILC. However, achieving this cost effectively necessitates R & D to deploy 4K SRF operation, the increasing of cavity Q_0 to 10^{11} and extraction of higher-order modes to high temperature (or somewhat equivalently, lowering RF frequency from 1.3 GHz to e.g. 650 MHz). Without these advances, the sub-panel estimates that build cost would be more than twice ILC (Tab. 4) and AC power consumption up to an order of magnitude greater (Tab. 5). Of course the cost and power consumption *per unit luminosity* is still at least one order of magnitude better than ILC, but the sub-panel settled on the view that the absolute cost was also an important consideration. In summary, the ERLC proposal deserves development into a detailed facility design. The technical R & D topics stated above should be undertaken concurrently and will each make this interesting proposal even more attractive.

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Table 1: Estimation of the AC power consumption of the CERC.

Mode	Z	W	HZ	$t\bar{t}$	HHZ	$t\bar{t}H$
Beam energy (GeV)	45.6	80	120	182.5	250	300
Synchrotron radiation (MW)	30	30	30	30	30	30
Microphonics (MW)	1.6	2.9	4.5	7.0	10.1	13.4
Higher-order modes (MW)	0.1	0.2	0.3	0.2	0.1	0.0
Total RF power (MW)	31.7	33.1	34.8	37.2	40.2	43.4
Magnets (MW)	2.0	6.2	13.9	32.0	60.1	86.6
1.8 K cryo load (kW)	5	10	15	23	34	45
Cryo plant AC power (MW)	6.25	12.5	18.75	28.75	42.5	56.25
Total AC power (MW)	61	74	90	123	169	215

Table 2: Cost estimate for the CERC accelerator relative to FCC-ee for the case of 365 GeV ($t\bar{t}$ machine).

Item	Estimated fraction of total FCC-ee cost
Civil engineering (no new straight tunnels assumption)	47 %
Technical infrastructure	17 %
Damping rings (2 GeV / 8 GeV) and injector	3 % / 6 %
Collider arcs (16 beam lines)	39 %
Main RF system & cryo	24 %
Harmonic RF system & cryo	1 %
Other	4 %
Total	138 %

EXISTING FACILITY STATUS

Established at Cornell, NY, USA, as a test facility for the Electron Ion Collider, the Cornell-BNL Electron Test Accelerator, CBETA, became the first SRF machine to demonstrate multi-pass energy recovery in 2020 [11]. Comprising a DC photoinjector holding the record of 70mA for sustained beam current, a SC linac module incorporating HOM dampers specifically for ERL operation, and a unique ns-FFA beam transport system, CBETA proved many key technologies for ERLs. There remains opportunity to explore higher current operation with CBETA in the short term, were funding to become available.

The compact ERL - cERL [12] at KEK, Ibaraki, Japan completed construction in 2013 with the goal of demonstrating low-emittance, 10 mA beam for a future multi-GeV ERL light source. In 2016 it successfully achieved simultaneous low emittance and 1 mA operation. After a short hiatus, cERL is now dedicated as a testbed for a future EUV semiconductor lithography FEL. The goal of 10 mA operation has been resumed and will now drive a high average power IR FEL for industrial R & D.

S-DALINAC [13, 14] at TU Darmstadt, Germany is a twice recirculating SC electron linac that has operated for nuclear physics experiments since 1991. In 2016 a new beamline was installed to enable thrice recirculation, and energy recovery (in different modes). In 2017 ER was demonstrated in once-reciculation mode, and in 2021 ER in twice-recirculating mode was acheived. This became the first demonstration of ER measured by reduced RF power draw in a multi-pass ERL. S-DALINAC will continue to be exploited both scientifically and for training needs, TU Darmstadt are also considering a possible replacement ERL facility.

MESA [15] at JGU Mainz, Germany, is a fully instrumented ERL facility for low energy nuclear and particle physics experiments. It is approaching the final stages of installation, with beam commissioning commencing in Summer 2023. MESA will perform two-recirculation ERL operation reaching 105 MeV at 10 mA. The ER beam will impinge on a low density gas target within a dedicated detector, MAGIX, a spectrometer for nuclear physics. The experimental programme is planned to start in 2025. An upgrade to 10 mA operation is foreseen and infrastructure has been specified to enable this.

NEW FACILITIES IN THE 2020s

bERLinPro

Originally funded and built as a light source test facility, bERLinPro is a fully constructed ERL situated in a new building at Helmholz Zentrum Berlin [16, 17]. Designed for 100 mA operation, it is fully aligned to the European Strategy goal of demonstrating and developing high power ERLs, and is capable of this in the short term. The SRF photoinjector is under commissioning at the time of writing, with all subsystems on track to allow first beam in Summer 2023. The RF, cryogenics system, and beam transport are fully commissioned and under vacuum. The main linac however is not yet funded, options are being explored to rectify this in a timely fashion. In the interim, R&D will concentrate on injector beam dynamics and transport, and applications in electron diffraction and coherent THz production.

EIC Cooler

The Electron-Ion Collider at Brookhaven National Laboratory, USA, will use the existing RHIC hadron ring, and a new electron storage ring to produce e-A collisions at

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Table 3: Parameters of ERLC and ILC, $2E_0$ = 250 GeV.

	unit	ERLC	ERLC	ERLC	ERLC	ILC
Beam mode		pulsed	pulsed	contin.	contin.	
Cavity material		Nb	Nb	Nb3Sn	Nb3Sn	Nb
Cavity temperature	K	1.8	1.8	4.5	4.5	1.8
RF frequency	GHz	1.3	0.65	1.3	0.65	1.3
Energy $2E_0$	GeV	250	250	250	250	250
Luminosity $\mathcal{L}_{tot}$	10^{36} cm^{-2} s^{-1}	0.39	0.75	0.83	1.6	0.0135
P (wall) (collider)	MW	120	120	120	120	129 (tot.)
Duty cycle, D		0.19	0.37	1	1	n/a
Accel. gradient, G	MV/m	20	20	20	20	31.5
Cavity quality, Q	10^{10}	3	12	3	12	1
Length L_{act}/L_{tot}	km	12.5/30	12.5/30	12.5/30	12.5/30	8/20
N per bunch	10^9	1.13	2.26	0.46	1.77	20
Bunch distance	m	0.23	0.46	0.23	0.46	166
Rep. rate, f	Hz	2.47×10^8	2.37×10^8	1.3×10^9	6.5×10^8	6560
$\epsilon_{x,n}/\epsilon_{y,n}$	μm	10/0.035	10/0.035	10/0.035	10/0.035	5/0.035
β_x^*/β_y at IP	cm	2.7/0.031	10.8/0.031	0.46/0.031	6.8/0.031	1.3/0.04
σ_x at IP	μm	1.05	2.1	0.43	1.66	0.52
σ_y at IP	nm	6.2	6.2	6.2	6.2	7.7
σ_z at IP	cm	0.03	0.03	0.03	0.03	0.03
$(\sigma_E/E_0)_{BS}$ at IP	%	0.2	0.2	0.2	0.2	~ 1

Table 4: ILC-250 and ERLC (DF =1/3) cost estimate comparisons, assuming the HOMs directly extracted to ≥ 100 K, at each ILC-type 9-cell, but twin-cavity end, with 9 cavities per cryomodule.

Item	Relative ILC cost	Factor	relative ERLC cost (normalized to ILC)
Civil engineering	19 %	×2	38 %
Tech. infrastructure	14 %	×2	28 %
Main Linac & SRF:			
Cavity & module	27 %	×2.6	70 %
RF	7 %	×1	7 %
Cryogenics	8 %	×6	54 %
Other sub-systems:			
Sources, DR & LE	21 %	×1	21 %
BDS	4 %	×1.5	6 %
Sum	100 %		224 %

E_{CM} = 20 GeV −140 GeV. In order to satisfy its ultimate luminosity goal of 10^{34} cm^{-2} s^{-1}, the hadron beam must be cooled both during injection, and during collisions at high energy. The latter requires a high brightness, high current and low noise electron beam that will cool using the principle of Coherent Electron Cooling (CeC). CeC is analogous to conventional stochastic cooling, but uses the electron beam itself as the detect-amplify-kick medium. The baseline method of amplification is to invoke the microbunching instability, and it is this which imposes that the beam properties can only be provided by a beyond-the-state-of-the-art ERL. This EIC cooler is presently being designed by a joint Jefferson Lab / BNL team [18].

PERLE

PERLE, to be based at the Irene Joliot-Curie Laboratory, Orsay, France, is a testbed to explore and validate a broad range of accelerator phenomena and technical choices on the pathway to the LHeC and other new frontier machines. It is aiming to be the first to demonstrate 10 MW beam power [19]. The project is in a technical design phase and the full facility comprises a 3-turn ERL of 164 MeV / turn with two linacs each of four 5-cell 802 MHz SC cavities for compatibility with LHC bunch rate. An inital stage will use one linac and acheive half the energy, but with full current. The photoinjector will build upon the Daresbury ex-ALICE gun, upgrading this to enable higher bunch charge extraction. Applications of the high power beam in nuclear physics are being actively explores and two user stations are presently envisaged, one for internal target experiments, and one for gamma generation via inverse Compton scattering.

CEBAF-5

Not a facility, but a proposed experimental programme augmenting the existing CEBAF multipass linac with transport to enable 5-pass energy recovery. This requires the addition of a path length adjustment chicane at the end of the fifth pass, an ER dump, and a small number of additional sextupoles within the injector and first arc. All components exist and are ready to install. CEBAF-5 will, in the medium term, provide the first multi-pass ERL demonstration at energies where synchrotron radiation losses and beam degradation become important. It is therefore an essential step

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Table 5: Wall-plug power comparisons of ILC with ERLC, including HOM load extraction at 100 K, and DF 1/3 (Case A) and DF 1 (Case B), the latter two having been estimated by the sub-Panel. Identical structures, frequency and 2K operation assumed.

	Unit	ILC	ERLC		
		ILC-250 estimate	Proposal estimates	Case A	Case B
Operating parameters:					
Electric field gradient	$MV\,m^{-1}$	31.5	20	20	20
Q_0 at operating temperature	10^{10}	1	3	3	3
Beam current	mA	⟨0.021⟩	⟨53.3⟩	⟨53.3⟩	53.3
Duty factor (for beam)		0.0037	1/3	1/3	1
Number N of e^+ / e^- per bunch	10^9	20	5	5	5
Distance between bunches	m	166	1.5	1.5	4.5
HOM absorber temperature	K	2, 5, 60	(300)	100	100
Linac AC power: (1)					
RF systems (2):					
RF to keep cavity gradient	MW	24	—	26	79
HOM energy-loss compensation	MW	—	30	23	23
Cryogenic loads:	MW		92		
Cavity dynamic (3)	MW	5.1	—	96	289
HOM dynamic (4)	MW	0.7	—	134	134
Power coupler dynamic & static	MW	1.6	—	~ 7	~ 7
HOM static	MW	(small)	—	33	33
Other static loads (5)	MW	8.3	—	30	30
Utilities (6)	MW	10.5	n/a	86	147
Linac AC power totals	MW	50	122	428	734
(Total collider AC power) (7)		(111)	(130 + n/a)		
Luminosity	$10^{34}\,cm^{-2}\,s^{-1}$	1.35	48	48	48

in proving feasibility of high energy ERL proposals. It can also test flexibility in longitudinal matching relevant to both colliders and XFELs [20–22].

THE 2030s, RECOMMENDATIONS & CONCLUSIONS

Looking beyond the immediate new ERL facilities into the 2030s there is opportunity to bridge the gap in power apparent in Fig. 1. For example the UK-XFEL [23] proposal will have at its heart an ~ 8 GeV SC linac and sustainability will be a key consideration in its development. An intriguing possibility to maximise the utilisation of this infrastructure would be to ERL-enable part of this linac to provide a high-flux gamma source based on inverse Compton scattering, and potentially also a high average power EUV / soft X-ray FEL. Such sources will provide new opportunity for nuclear physics and industry. These ideas are under active development, with a conceptual design to be published in 2025.

ERLs are a highly promising technology that will be key to ensuring sustainability in discovery science and societal applications in the coming decades. The European Strategy sub-panel on ERLs studied two early-stage proposals for e+e- colliders and found them to be important, worthy of serious consideration and further development. In order to realise the potential of ERLs, investment should be made in the short term into existing and new ERL facilities, and into underpinning technologies - most notably thin film SRF to enable high Q_0 at 4K.

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