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THE EUROPEAN ERL ROADMAP*

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Abstract

Following the European Strategy process in 2019, five Roadmap Panels were set up to prepare the technologies needed for future accelerators and colliders: high-field magnets, SRF, muon colliders, plasma wakefield accelerators and Energy Recovery Linacs (ERLs). The ERL Roadmap Panel, consisting of ERL experts from around the world, first developed an overview of current and future ERLs. From this it was possible to carry out a gap analysis to see what R&D would be needed, from which the roadmap could be developed. The European ERL Roadmap [1] focused on three main aspects: 1) the continuation and development of facility programs for which no additional funds are needed, S-DALINAC in Darmstadt and MESA in Mainz; 2) technology development for room-temperature HOM damping and twin-axis SRF cavities; 3) the timely upgrade of bERLinPro for 100 mA current and the construction of PERLE at Orsay as a dedicated 10 MW power multi-turn facility. The roadmap entails a vision of a future energy frontier electron-positron and electron-hadron collider and describes a high-quality ERL program for 4.4 K SRF technology at high Q_0.

INTRODUCTION

Future HEP colliders will require revolutionary advances in technology for both accelerators and detectors, and complementary facilities will be required, as has been shown in the past decades. In addition, energy efficiency and other sustainability aspects will be important factors in the design of a new facility. ERLs, which recycle the kinetic energy of a used beam for accelerating a newly injected beam to minimize the power consumption, and avoid the emittance growth of storage rings, are set to become the technology of choice for the next generation of HEP colliders. This will require R&D to extrapolate the excellent results obtained in small facilities. The ERL Roadmap Panel was charged with developing a coherent plan, which is described in this paper.

COMPLETED FACILITIES

The landscape of past, existing and future ERLs is shown in Figure 1 [1]. Only those ERLs that still hold a record for at least one parameter have been retained.

ALICE [2] in Daresbury was the first European ERL. It operated successfully for a decade until 2019, when it was decommissioned to provide space for a medical facility.

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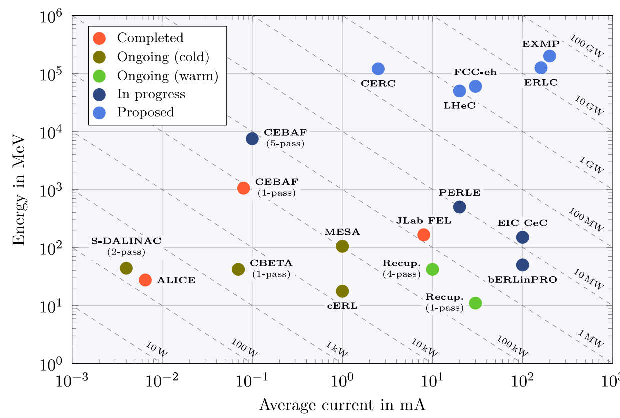

Figure 1: Landscape of past, present and proposed ERLs. of past, present, and proposed ERLs. The dashed lines are contours of constant beam power.

The Jefferson Lab FEL [3-6], which closed when it lost funding, still holds records for maximum beam current recirculated in a superconducting ERL (8.5 mA), and maximum beam power (1.3 MW). The maximum power into the building is 650 kW, underlining the energy efficiency of ERLs.

An experiment was successfully carried out at Jefferson Lab on CEBAF [7] to recirculate beam once around the facility, which at that time had 39 cryomodules, demonstrating that there were no unforeseen issues.

ONGOING ACTIVITIES

CBETA at Cornell was built as the first multi-pass ERL using an FFAG lattice for all four beams, both accelerating and decelerating [8]. All of the key performance indicators were successfully met, showing that this concept is viable for other facilities [9].

The Compact Energy-Recovery Linac (cERL) has been operating since 2013 at KEK as a test accelerator operating with a 1 mA average beam current and excellent beam quality [10], and is now being developed for industrial applications.

The Recuperator at BINP, Novosibirsk is a normal conducting ERL [11], and includes three FELs operating in the terahertz, far-, and mid-infrared spectral ranges. The facility holds the record for the highest bunch charge (1.5 nC), and several records for FEL output power at different wavelengths.

The S-DALINAC has been in operation in Darmstadt since 1991 [12]. Initially built as a twice-recirculating machine, but a new recirculation beam line was installed allowing for the operation as an ERL. In August 2017, once-recirculating ERL operation was demonstrated and twice recirculating ERL mode was achieved in 2021 [13].

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MESA is a new facility being built in Mainz [14]. The magnet system is arranged in double-sided fashion with an accelerating cryomodule on each side. The MAGIX experiment will employ windowless gas-jet targets. Because of the low areal density, the interaction of the beam with the target is minimal, so energy recovery of the beam is efficient and higher luminosities can be achieved with a given installed RF power. This will be the first ERL designed to operate with an experimental interaction region.

NEW FACILITIES IN THE TWENTIES

The bERLinPro project at Helmholtz-Zentrum Berlin (HZB) started in 2011 [15] and is partially built and ready to accept a cryomodule with the latest fundamental power couplers to dynamically match the loaded cavity to the klystron (Fig. 2). With an upgraded gun and a new cryomodule, bERLinPro aims for a recirculated single-pass current of 100 mA. This enables a detailed study of high current phenomena, as the cryomodule will see a current of 200 mA, more than is planned for LHeC, so this is an important step for future large ERL facilities.

Figure 2: Schematic of bERLinPro. From bottom left to top right: SRF photoinjector, booster module, merger, main linac module, and beam dump.

PERLE@Orsay is a three-pass ERL facility that is being prepared at IJCLab by a large international collaboration [16]. The parameters were chosen to match those of a future LHeC machine, providing a bridge to the future of HEP in Europe. This will be the first three-pass high current ERL in the world and will be able to test all of the technologies that will be needed.

CEBAF 5-Pass Energy Recovery Experiment [17] will accelerate beams five times through 50 cryomodules and then decelerate them back to the injection energy where the beams will be dumped. This test is important as it will demonstrate that energy recovery is possible with a large number of cryomodules, as will be required for a high energy ERL.

The EIC at Brookhaven National Lab is currently under construction, based on the existing RHIC collider. In order to reach the desired luminosity (>10^{34}cm^{-2}s^{-1}) Coherent Electron Cooling is proposed, which uses an electron beam to perform all functions of a stochastic cooler [18]: the pick-up, the amplifier, and the kicker. The required energy (150 MeV) and the desired current (100 mA) means that an ERL is an absolute requirement. The parameters of this facility are the most stringent of all the proposed ERLs.

KEY CHALLENGES

The electron gun must reliably produce 20 mA (and up to 100 mA for bERLinPro and the EIC Cooler) beams with low emittance (less than 5 mm mrad) and high bunch charge (500 pC). This can be produced by thermionic guns [18, 19], DC guns [20, 21], RF guns [22] and SRF guns [23-26]. This research is proceeding, and does not need to be specifically addressed in the ERL Roadmap.

SRF cavity and cryomodule development has made great progress over the last decade and this can be expected to continue. However, there some areas which are specific to ERLs which still need R&D; system designs compatible with high beam currents and the associated HOM excitation; handling of transients and microphonic detuning that otherwise require a large RF overhead to maintain RF stability; enhanced cryogenic efficiency of SRF modules, notably operation at 4.5 K. All of these items are included in the ERL R&D Roadmap and should continue to be pursued.

Multi-turn studies will be carried out at CEBAF [17] and at PERLE [16], but simulation packages should be developed and, in particular, new diagnostic should be developed to separate beams on successive turns.

APPLICATIONS

The Roadmap focused on the future HEP colliders where they have a bright future. But ERLs are also a natural fit for high-power FELs, which is why Jefferson Lab adopted an ERL for their FEL program [3-6]. The advantages are obvious: high-power electron beams, which are needed for high-power FELs, would be prohibitive in electrical power and cost if the energy is not recycled. Since up to 5% of the energy is used for the FEL, the arc(s) for the spent beams must have a large energy acceptance. In addition, the electron beam must be carefully manipulated to ensure that the beam losses are minimal. Now that these conditions can be achieved, the commercial and research potential of ERLs is set to explode in EUV lithography, e.g. [27], and Inverse Compton Scattering [28].

SUSTAINABILITY

In any new accelerator proposal, sustainability issues will be heavily scrutinized, be that in electricity and water use, the overall efficiency of the facility, including reusing the heat for other purposes (space heating, biogas production, etc.) or energy recycling. ERLs bring a new dimension. Directly returning the unused energy of the beam into RF that can be used for acceleration is a unique feature of ERLs. While not all of the energy can be recovered, the overall efficiency of the process is extremely high, which leads to a reduction in the RF power needed for acceleration, which translates into smaller RF sources and their associated power transformers (reducing the resources needed for their production), and less electric power and water cooling required (reduced operating costs as well as a reduced carbon footprint). ERLs have a special place in future colliders, given the importance of sustainability and the reduction of electrical power and water consumption.

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THE ERL ROADMAP

ERLs represent a unique, high-luminosity, green accelerator concept for energy-frontier HEP colliders, for major developments in lower-energy particle and nuclear physics, and for industrial applications. This is an innovative area with far-reaching impacts on science and society. With strongly enhanced performance, achieved with power economy and beam dumps at injection energy, ERLs are a vital contribution to the development of a sustainable science.

A peculiarity of the ERL roadmap and development is that it needs operational facilities with complementary parameters and tasks to be successful. The rich global landscape of ongoing ERL facilities, including S-DALINAC and soon MESA in Europe, which are under further development, has already been discussed.

A crucial next step towards the application of ERLs in high-energy physics and elsewhere is to conquer the ~10MW beam power regime with higher energy and/or high currents. This step requires addressing key technology challenges, in particular for bright electron sources, dedicated ERL cavity and cryomodule technology ($Q_0 > 10^{10}$), as well as associated techniques. These technologies are partially available and under development in the existing and forthcoming generation of ERL facilities. The regime of high currents, in the range of 100mA load to SC cavities, will be developed at BNL (EIC cooler CeC), KEK (cERL), possibly HZB Berlin (bERLinPro), and BINP Novosibirsk with normal-conducting, low-frequency RF. An order-of-magnitude increase in beam energy, to 10 GeV, is the goal of a new experiment at CEBAF. PERLE is the only facility designed to operate at 10MW in a multi-turn configuration and the only one proceeding in a large international collaboration.

The ERL roadmap for this decade comprises three interlinked elements (Fig. 3):

1. The continuation and development of the various facility programs, for which no funds are needed from the particle physics field. For Europe these are S-DALINAC in Darmstadt and MESA in Mainz (both in Germany).
2. A number of key technologies to be developed. Some of these, such as electron sources of high brightness (reaching the 100mA electron current regime), FRTs (Fast Reactive Tuners) and, for longer term, the development of an 802 MHz, 4.4K cavity-cryomodule have been integrated in the plans for bERLinPro and PERLE as all require beam operation
3. The timely upgrade of bERLinPro and the construction of PERLE at Orsay are the necessary steps to move ERLs forward to be ready for integration into large high energy collider projects such as LHeC, FCC-ee and FCC-eh. Ahead is a new era of high-power ERL operation R&D, high-intensity low-energy experiments, and industrial applications.

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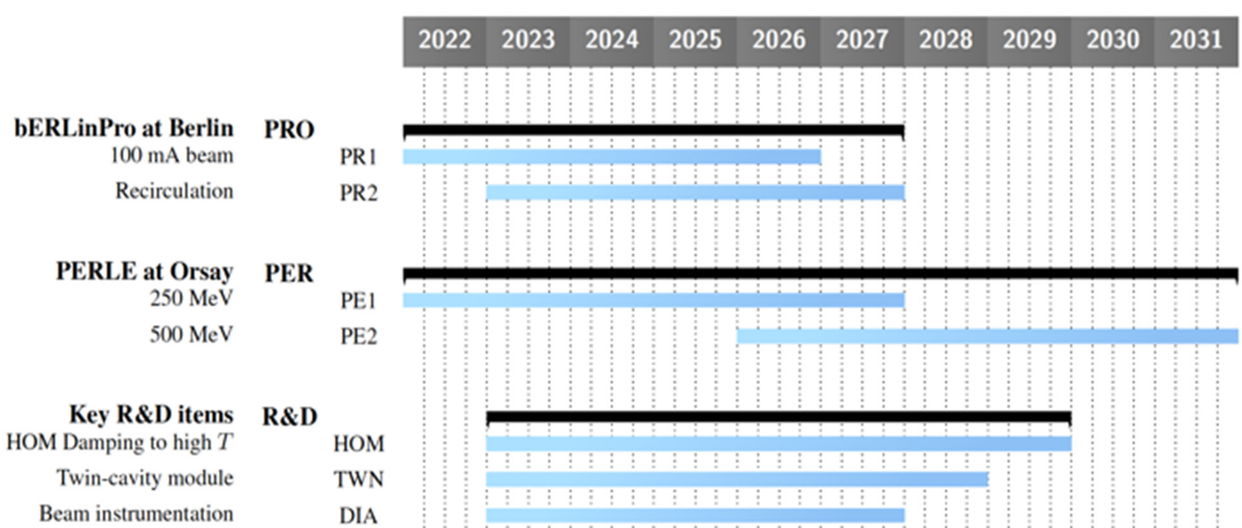

Figure 3: Time Lines of Key ERL Roadmap Components.

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