R&D EFFORTS FOR ERLS

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Abstract

Even though the first conceptual idea of an energy recovery linac (ERL) dates back almost 50 years, it took many years to foster the interest in these unique devices. The last few years have seen extensive R&D for ERLs, with several prototype facilities now under construction or in operation. The article reviews the world-wide progress made towards the construction of a large scale energy recovery linac with some focus on the Cornell ERL R&D program that has reached major achievements recently.

INTRODUCTION

The original paper from Tigner dates back to 1965 [1], where he suggested that a beam, being accelerated to a certain energy is decelerated again after interaction, with the energy being recovered in the RF field of the accelerating cavity (see Fig. 1).

At first sight, the concept seems to be a smart way to increase the efficiency of particle accelerators. As we know of today, the energy recovery linac concept if far more as it allows you to combine the advantages of a synchrotron with these of a linear accelerator.

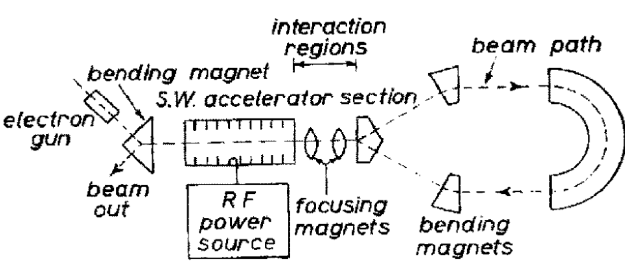

Fig. 3.

Figure 1: The concept of an Energy Recovery Linac (ERL), taken from the the first publication [1].

While todays storage rings usually are operated at high currents (several 100 mA) with high bunch repetition rates (sometimes GHz), the beam parameters are less favourable for future applications: the bunch length of those machines is more in the order of 10 ps, the energy spread is mostly fixed around 10^{-3} relative and moreover, the equilibrium emittance is determined by the ring lattice.

Linear accelerators can provide beams with excellent energy spread (sometimes below 10^{-4}), the bunch length is tunable down to the 100 fs region and they can provide small emittance beams being mainly defined by the emittance of the particle source. However, their limitation comes from the operating cycle being pulsed: linacs have usually low average currents (but can have high peak currents), and, when pushed towards cw operation, they become a huge power consumer.

Energy recovery linacs now allow you to combine the beneficial parameters of both machines. As the energy of the beam is almost fully recovered there are now power limits on the duty cycle- which allows you to ramp up the average current- assuming one is able to provide the beam by a source. As a matter of fact, an energy recovery linac, which is based on superconducting RF, is a very interesting option for future synchrotron radiation sources [2]. They open up new paths for future x-ray science as they are able to deliver defraction limited photon beams that can hardly be achieved with existing machines.

The basic principles of ERL operation were demonstrated in the late 1980's [3] and first applied to a low-energy dedicated machine at the Thomas Jefferson National Accelerator Facility (JLab) in the last half of the 1990's [4]. Since then, the last few years have seen extensive R&D for ERLs, with several prototype facilities now under construction or in operation. They address the challenges of ERL operation, which mainly fall into three categories: generating high current and high charge bunches, getting and conserving small emittance beams and ensuring a highly efficient acceleration with superconducting cavities while keeping beam driven excitations (BBU) controlled and small.

In addition, possible applications of ERL concepts have expanded which includes light source design, beam cooling applications and collider or thin target applications for nuclear physics.

ERL FACILITIES

FEL/ERL @ JLab

Jefferson Lab has been pioneering in ERL operation. Since the late 90' the JLab FEL has been pushing the limits, achieving ultra-fast (~150 fs), ultra-bright (10^{23} photons/s/mm^2/mrad^2/0.1%BW) laser beams. Being the first high current ERL the machine produced a 14 kW average power IR beam.

The electron energy can be up to 135 MeV with up to 135 pC pulses at a repetition rate of 75 MHz. Currently, proof of principle experiments are conducted to simulate high-power ERL operation with an internal gas target to address dark light search. In order to controlling power

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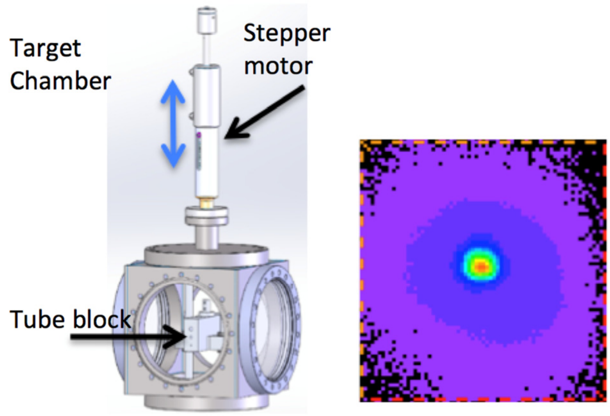

Figure 2: Set-up at JLab to testing high current ERL operation, investigating beam halo, impedance and wake field effects. The gaussian fit to the beam size yielded σ_x=50 μm; σ_y=52μm.

deposition from beam loss and impedance/wake effects from both beam core and halo components through a 12.5 cm long small aperture (6, 4, or 2 mm diameter) [5].

ERL @ Budker

The Budker institute of Nuclear Physics (BINP) in Novosibirsk operates an ERL based on normal conducting cavities [6]. Accelerated by 16 180.4 MHz single cell cavities the maximum achievable energy gain is 12 MeV. A world record beam current of 30 mA has been recycled. The machine is used to address splitter/ merger concepts as well as staging ERLs.

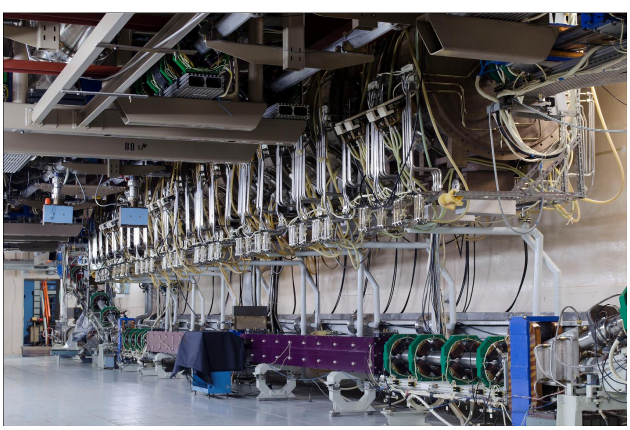

Figure 3: Energy Recovery Linac at the Budker institute. The normal conducting RF cavities are suspended from the ceiling and the return arc is bolted to the ground.

Alice @ Daresbury

The ALICE facility is an energy recovery test accelerator at Daresbury Laboratory [7]. The main energy-recovery loop is designed for 26 MeV beam energy. Acceleration is provide by a superconducting linac module, shown in Fig. 4, that was built on basis of an international collaboration formulated in 2005 (with partners from DESY, Rossendorf, Cornell, LBNL, TRIUMF and Stanford). After an initial conditioning the cw gradients

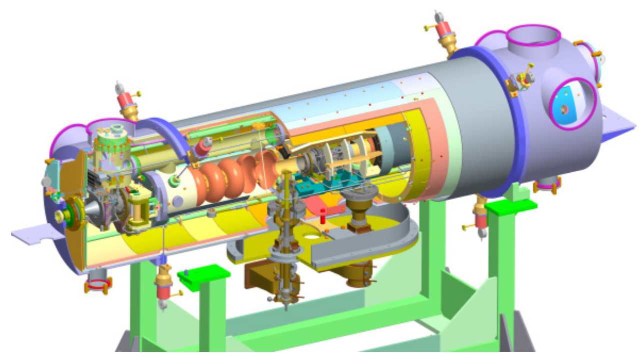

Figure 4: The international ERL cryomodule put into operation at Daresbury.

reached 10.8MV/m and 12.5 MV/m. No field emission was observed but limitations due to microphonics were discovered.

IHEP ERL Test Facility

The ERL proposed at the IHEP, Beijing consists of an 5 MeV injector, based on a 500 kV DC gun followed by an SRF module [8]. The main linac will provide 30 MeV energy gain, supplied by two 7-cell cavities. At a bunch charge of 77 pC a normalized emittance of below 2 mm·mrad is projected. A wiggler in the straight section will be used to produce coherent THz radiation.

ERL Facility @ BNL

Brookhaven is currently setting up an ERL facility to become an ampere class 20 MeV superconducting ERL [9]. The machine consists of an SRF photoemission injector, an SRF accelerating cryomodule, a recirculating loop, and a beam dump. Its purpose is testing of concepts relevant for high-energy coherent electron cooling, electron-ion colliders, and high repetition rate Free Electron Lasers. One of the challenges addressed is the SRF gun. Commissioning is underway. For the first beam test, a Cs_3Sb cathode was fabricated and the quantum

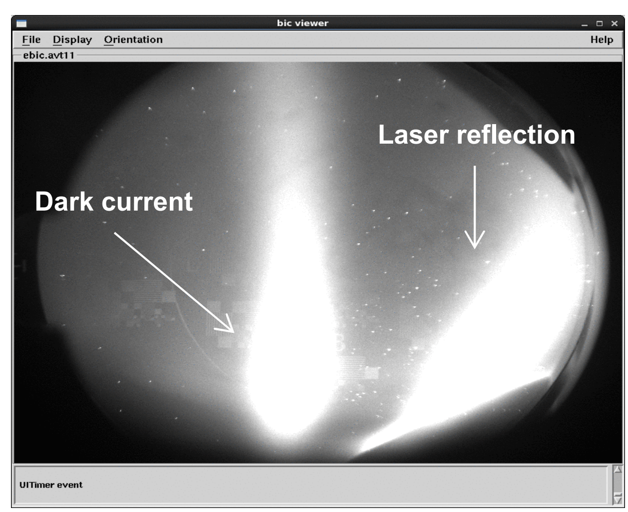

Figure 5: Dark current image taken at beam profile monitor during energy measurement at gun voltage setting of 1.2 MV, taken at the BNL SRF gun.

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efficiency (QE) has been measured at 0.25%. During the cathode insertion into the gun and initial start of RF power, there were several instances of vacuum spiking to 10^{8} torr range, significantly reducing the QE of the cathode to the level, where it became impossible to measure the photoemission current.

However, a dark current was observed on a YAG screen, shown in Fig. 5, and measured by the Faraday cup (1.4 µA at a cathode field of 15 MV/m). The low power beam testing will continue after some improvements are made to the cathode deposition chamber and transport cart. In 2015, after completion of the beam line, it is planed to demonstrate energy recovery with high charge per bunch and high beam current.

cERL @ KEK

Purpose of the Compact ERL (cERL) currently under commissioning at KEK is to demonstrate the generation and recirculation of ultra-low emittance beams as well as to show reliable operations of all ERL components such as the photocathode gun and the superconducting cavities [10]. The initial goal is to achieve an emittance of 1 mmmrad with 7.7 pC bunches (corresponding to 10 mA beam current).

After the installation was completed, depicted in Fig. 6, commissioning took place in February 2014. A 19.9 MeV, 24 µA peak current beam was successfully recirculated and energy recovered. Future plans will be to generate compton scattering x-rays beams and coherent THz radiation.

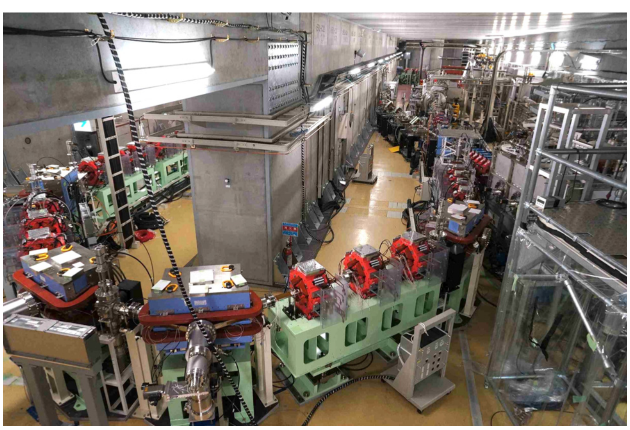

Figure 6: Picture of the ERL vault of the compact ERL at KEK commissioned in February 2014

bERLinPro @ HZB

bERLinPro is designed as a test facility to study ERL related accelerator physics questions [11]. It has received funding in 2011 and will eventually concept next-generation light source applications of ERLs. The layout beam with an emittance of below 1 mm mrad (normalized) will be accelerated to 1.5 MeV inside the is given in Fig. 7: based on an SRF photon-gun, a 100 mA gun cavity and then boosted to 6 MeV by 3 modified Cornell 2-cell cavities. The linac module will house 3 7-cell cavities

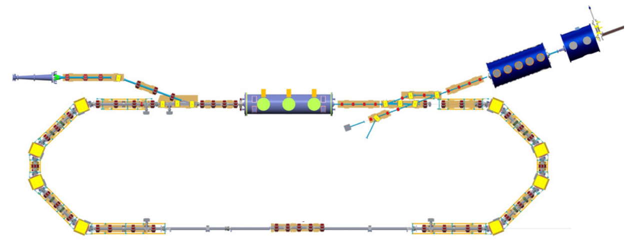

Figure 7: Layout of the bERLinPro ERL at the Helmholtz Zentrum Berlin.

to yield 50 MeV electrons. Currently, the SRF gun is under testing.

MESA @ U of Mainz

MESA at the university of Mainz is going to be a production accelerator [12]. In contrast to the other ERL facilities, the focus of which is more to do machine studies and investigate radiation physics aspects, MESA is supposed to provide beam for electron scattering nuclear physics experiments. Two operation options are foreseen, the ERL option with an internal experiment and the resirculating linac mode with the beam extracted (see Fig. 8). It is designed to accelerate electrons to a maximum energy of 155 MeV at a current of 150 µA in external beam mode or up to 10 mA at 105 MeV in energy-recovering mode.

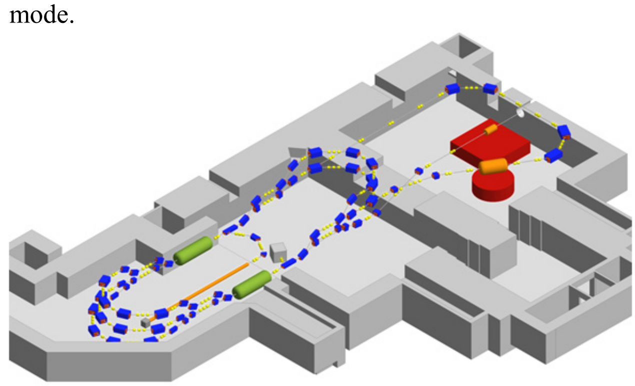

Figure 8: The planned Mesa facility at Mainz University-allowing internal nuclear physics experiments with full energy recovery as well as extracted beam operation in a recirculating linac configuration.

LHeC ERL @ CERN

LHeC at CERN is a proposal to add an energy recovery linac to the existing LHC to allow e-p collisions (see Fig. 9). For kinematic reasons, the energy of the ERL has to be 60 GeV which results in a multi-pass layout for the machine. Based on BBU considerations as well as synergy arguments with existing CERN RF systems, a lower frequency (802 MHz) was chosen.

A preliminary design of the cavity and the cryomodule exist and the design of an ERL test facility has started [13], which might also serve as a more general beam facility.

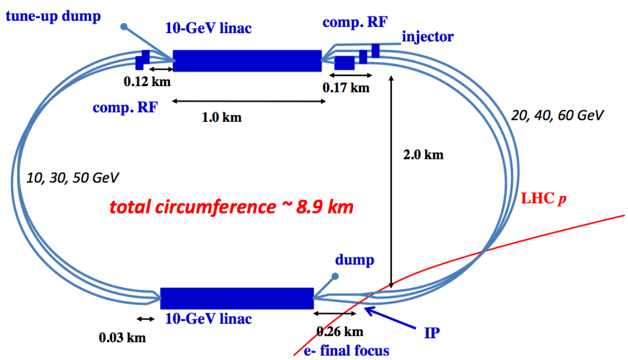

Figure 9: LHeC ERL under conceptual design at CERN.

CORNELL ERL

The Cornell ERL is a proposed upgrade plan for the existing CESR facility, transforming it into a 4^{th} generation light source which would eventually delivering a diffraction limited x-ray beam [14]. With an energy of 5 GeV and 100 mA beam currents, an emittance of 8 pm is targeted. Given the short bunch length (2ps) combined with the high current, HOM power per cavity is expected to be 200 W, in average.

To make this CW machine economical in operation, high quality factors of the SRF cavities are needed. Cornell has chosen to design for $2x10^{10}$ at 1.8 K and a gradient of 16 MV/m resulting in 10 W dissipated power per cavity.

Proving these design figures resulted in a 10 year R&D phase, pushing as well as testing the limits in the fields listed below.

SRF High Q Cavities and HOM Damping

The Cornell ERL cavities have 7-cells with optimized cell geometry with respect to the BBU limit and the HOM properties [15]. Operating at 1.3 GHz the envisaged quality factor seemed to be very ambitious at the time of the decision, leading to an extensive prototyping and a series of tests conducted in a short horizontal test cryostat, (HTC I through HTC III) in which a Q of $6x10^{10}$ could be demonstrated, finally [16].

Within one of these tests, a 40 mA was run through the cavity being equipped with two HOM absorbers (details are described in [17]). We observed extremely good HOM damping, no charge-up effects of the material and heating effects less than predicted.

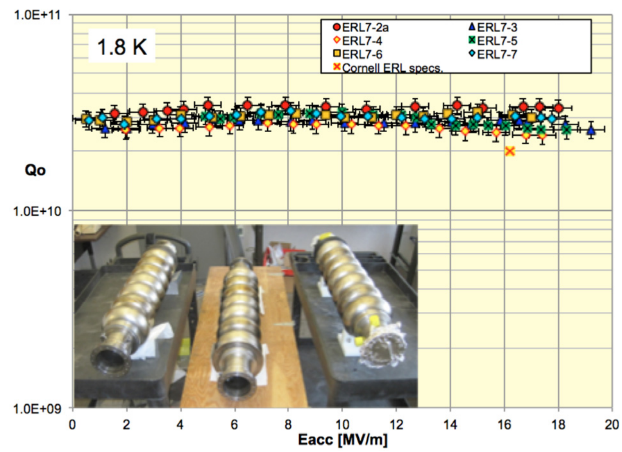

Figure 10: Quality factors of the 6 ERL cavities built at Cornell. All cavities surpass the design specifications.

For the prototype of a full scale Main Linac Cryomodule (MLC) [18], 6 more cavities have been produced in-house. The recipe for the cavity preparation is rather simple, though being modified with experience: the damage layer is removed by bulk buffered chemical polishing (BCP, 140 µm). Hydrogen degassing is done at 650 C for 4 days while we monitor the hydrogen residual gas inside the furnace. Studies showed that a higher temperature (800 °C) seems to remove more hydrogen but would slightly soften the cavity still being acceptable. One cavity has been treated such, showing a slightly higher Q. Subsequently, another 10 µm layer is removed, a 120 °C bake performed as well as an HF rinse.

During the cavity production, we improved the mechanical tolerances in the cavity forming and welding, leading to a mean length deviation of the last 3 cavities by only 0.2 mm [19]. The SRF properties of the 7-cell main Linac cavity were characterized at several stages before completing the assembly. Figure 10 shows the Q data from vertical tests of all 6 cavities. It should be noted that for we observed higher Qs horizontally in our HTC test compared to the same cavity being tested vertically.

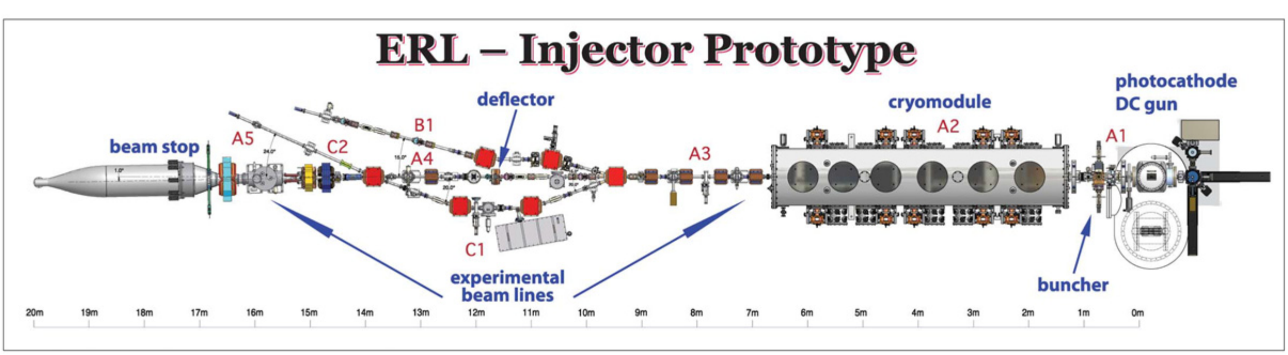

Figure 11: The Cornell ERL photo-injector, consisting of an 350 kV DC gun holding a high QE, high current photo cathode, followed by an SRF injector module based on 5 2-cell cavities, a merger section with adequate diagnostics and a beam dump.

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High Current Generation

The Cornell ERL photo-injector was designed to provide the full ERL current at a 1.3 GHz repetition rate, which corresponds to a bunch charge of 77 pC. The layout is given in Fig. 11. It allows high current runs as well as emittance studies before and after the merger section. Based on a 350 kV DC gun and a high quantum efficiency photocathode, the Cornell injector achieved an average current of 65 mA (see Fig. 12) and up to 75 mA in shorter runs [19].

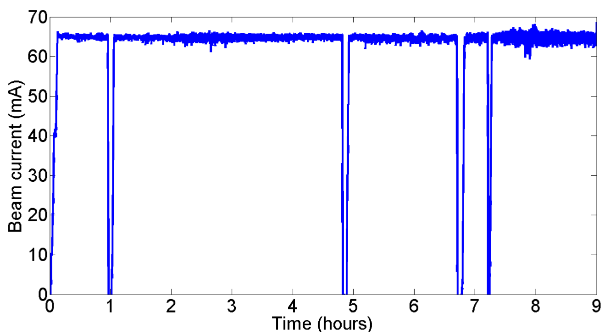

Figure 12: Electron beam current during an 8 hour run of the Cornell photo-injector.

Low Emittance Studies

To ensure high brightness, extensive emittance measurements and optimizations were performed in the Cornell injector, especially behind the merger section. The settings of the machine for these measurements were determined using a multi-objective genetic algorithm and a complete model of the injector with the 3D space charge code GPT. Depending on the two operation scenarios with bunch charges of 19 pC and 77 pC, two optimized settings were calculated and the machine was tuned accordingly [20].

In order to avoid damaging the emittance measurement system, a 50 MHz pulsing to the drive laser was applied. The normalized horizontal and vertical projected phase

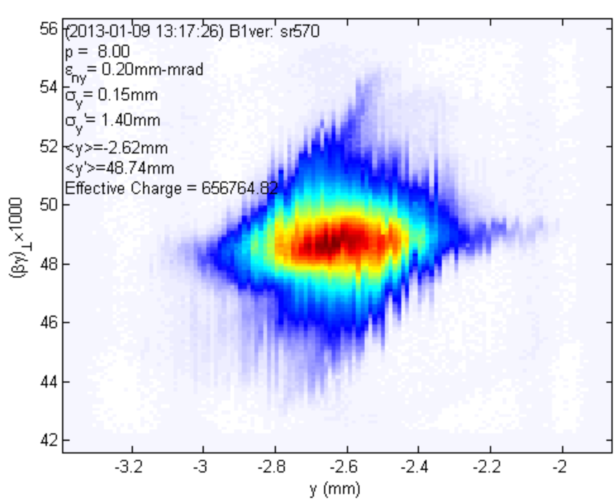

Figure 13: Vertical phase space emittance, measured at the Cornell photoinjector at a beam energy of 8 MeV.

Table 1: Emittance Results from the Cornell Photoinjector (all values were measured with a bunch length of less than 3 ps, and with an energy spread of approx. 10^{-3})

	Horizontal (mmmrad)	**Vertical (mmmrad)**
19 pC	0.23 (90 %)	0.14 (90 %)
	0.14 (67 %)	0.09 (70 %)
77 pC	0.51 (90 %)	0.29 (90 %)
	0.28 (64 %)	0.19 (70 %)

spaces were directly measured at both bunch charges. Figure 13 gives the vertical emittance as an example.

In addition, the time-resolved horizontal phase space was measured to get the bunch current profile and the rms bunch length. The values, summarized in Table 1 show vertical emittances getting close to the thermal values.

If accelerated to 5 GeV- which would be the final ERL energy, the normalized (90 %) horizontal emittances would become a geometric emittance of 24 pmrad (19 pC case) or 52 pmrad (77 pC case). Comparing this to emittance found in third generation light sources (PETRA III: 1 nmrad at 6 GeV, APS: 3 nmrad at 7 GeV) demonstrates the advantage of ERL concepts over traditional storage rings.

SUMMARY

ERLs have become a realistic concept for future accelerators. Combining high currents with excellent beam parameters make these devices attractive as light sources or for collider/ thin target experiments. There is a worldwide effort in pushing the limits with test facilities planed or operational in almost every continent. Recent results have confirmed the readiness for building a full size accelerator.

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