# CURRENT STATUS AND FUTURE PERSPECTIVES OF ENERGY RECOVERY LINACS

R. Hajima*, JAEA, Tokai, Ibaraki 319-1195, Japan

## *Abstract*

Energy-recovery linac (ERL), which is able to generate an electron beam of high-average current and small emittance, is expected to realize future light sources in various photon energies from terahertz to X/$\gamma$-rays and also considered as a driver of high-energy physics applications. In this paper, we overview current R&D status and future perspectives of ERLs.

## INTRODUCTION

An energy-recovery linac (ERL) is a new class of electron accelerator to generate an electron beam of high-average current and small emittance. In an energy-recovery linac, an electron beam from an injector is accelerated by time-varying rf field stored in a superconducting linear accelerator and the beam is transported to a recirculation loop. In the recirculation loop, the beam is utilized for specific applications such as X-ray generation, cooling of ions. After the recirculation, the electron beam is injected again to the superconducting accelerator so that the electrons are decelerated. This deceleration can be accomplished by putting the electrons at the opposite phase to the acceleration. The energy of accelerated electrons is, thus, converted back into the rf energy and recycled to accelerate succeeding electrons.

The energy recovery technology has a great impact on modern accelerator applications, because the ERL is able to accelerate a high-power electron beam with rf generators of small capacity. Adding to this excellent conversion efficiency from the electric power to the electron beam power, the ERL has an advantage essential to generation of high-brightness electron beams. Since an electron bunch in an ERL goes to a beam dump after deceleration and another fresh electron bunch is accelerated every turn, the ERL is almost free from degradation of electron beam emittance. Beam brightness of an ERL can be increased by adopting a high-brightness injector such as a photocathode electron gun. The ERL is, therefore, quite different from a storage ring, in which emittance and temporal duration of electron bunches are determined by equivalent state of electron beam dynamics after bunch thermalization during a number of turns.

Now, the ERL is considered as an important platform of future light sources and a driver of high-energy physics applications.

## FACILITIES IN OPERATION AND UNDER CONSTRUCTION

So far, four ERL facilities have been constructed: JLAB [1], JAEA [2], BINP [3], Daresbury [4]. Adding to the above facilities, an injector test facility is in operation at Cornell Univ. [5] and a prototype ERL is under construction at BNL [6]. In these facilities, critical components for future ERLs, electron guns and superconducting linacs, are tested in detail. Beam dynamics issues are also investigated.

In Japan, the collaboration team of KEK/JAEA/ISSP and other institutes decided to build a test facility, the Compact ERL. The Compact ERL is designed to demonstrate all the technologies relevant to future ERL light sources, and will be a scale of 65-125 MeV and 10-100 mA [7].

## FUTURE ERL LIGHT SOURCES

### *Possible ERL Light Sources*

Accelerator-based light sources are the most significant application of ERLs, as we can see a historical fact that the ERLs have been developed for high-power FELs [1, 2, 3].

Emission of electro-magnetic waves from relativistic electrons is possible in various ways as listed in Table 1. Coherent synchrotron radiation from bunched electrons enables strong terahertz and millimeter waves. FELs can be operated in a wide range of photon energies from terahertz to X-ray. Synchrotron radiation from a bending magnet or an undulator is used for generation of VUV, soft X-ray and hard X-ray. Laser Compton scattering can generate X-ray and $\gamma$-ray beams.

Distinguished features of the ERL, high-average current, small emittance, short bunch availability, contribute directly to the reinforcement of these light sources in their flux, brilliance, and shor pulse availability. Future light sources based on the ERL technology are proposed in the world. We see proposals of X-ray and $\gamma$-ray light sources in the following sections.

### *X-ray Sources*

X-ray synchrotron light source is one of the most successful applications of high-energy electron accelerators. We can see in the world that more than 60 synchrotron light sources are now providing bright X-rays to many experimental users from scientific researches to industrial applications. All the synchrotron light sources are based on storage rings.

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* e-mail: hajima.ryoichi@jaea.go.jp

The ERL with high-average current and high-brightness electron beams can realize future synchrotron light sources, which outperform the storage-ring light sources in their X-ray brilliance and short-pulse availability. The first proposal of ERL light source was given by a group of BINP at the 1st Asian Particle Accelerator Conference, which is "MARS – diffraction limited 4th generation X-ray source" [8]. The term "diffraction limit" means the condition that an electron beam has smaller divergence than the emitted photon beam, and given by $\varepsilon \leq \lambda/4\pi$, where $\varepsilon$ is geometrical emittance, $\lambda$ is radiation wavelength. It is known the geometrical emittance is reduced by linear acceleration, that is adiabatic damping of transverse phase space. If we have an electron beam of normalized emittance $\varepsilon_n = 0.1$ mm-mrad and accelerate the beam to 6 GeV, the beam becomes diffraction limit for hard X-rays of $\lambda = 0.1$ nm. X-ray radiation from a diffraction limited electron beam has superior coherence, i.e. brilliance, and is expected to promote a novel field of X-ray science such as coherent X-ray applications.

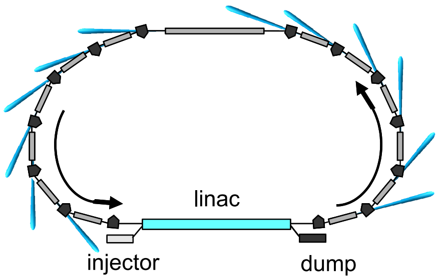

Figure 1: X-ray light source based on an ERL.

The ERL light source also drives ultrafast X-ray science by utilizing femtosecond electron bunches, which can be generated by well-established technique of electron bunch compression.

Proposals of future ERL light sources have been submitted by Cornell University [9] and KEK Photon Factory [10]. Adding to these two facilities, an ERL upgrade program is under consideration at ANL-APS [11] and an ERL project is proposed at Berlin [12].

Cornell University has a plan to build a 5 GeV ERL light source utilizing an existing CESR tunnel. They have developed an ERL injector targeting normalized emittance of 0.1 mm-mrad and average current of 100 mA, which fulfills requirements of the future ERL light source.

Table 1: Possible ERL light sources in various region of photon energy

| **photon energy** | **light source** |
|---|---|
| terahertz | FEL / coherent synchrotron radiation |
| infrared | FEL |
| VUV – X-ray | undulator / bending /<br>FEL / laser Compton scattering |
| $\gamma$-ray | laser Compton scattering |

In Japan, collaborative efforts towards future ERL light sources have been organized by KEK, JAEA, ISSP and other institutes [13]. Development of critical components, a photocathode DC gun and a superconducting accelerator, are carried on [14].

## *LCS X-ray and $\gamma$-ray Sources*

The combination of an energy-recovery linac and modern laser technologies brings unprecedented improvements in laser Compton scattering (LCS) X-ray and $\gamma$-ray sources.

ERL-based LCS sources show outstanding performance when it is equipped with a laser supercavity for the colliding laser. The supercavity consists of mirrors with high reflectivity and optical pulses from an external mode-locked laser are stacked in the supercavity to be high-average power. Supercavities having an enhancement factor of $10^3 - 10^4$ are under development [15].

In the Compton scattering, only a small fraction of electrons and photons contribute to the generation of high-energy photons, because the cross section of Compton scattering is very small. Thus, recycling of electrons and photons which do not contribute to the Compton scattering is necessary to obtain a high-flux LCS source. The combination of an ERL and a laser supercavity is an ideal device for such recycling of electrons and photons.

As an example of future LCS source based on an ERL, we present an ERL $\gamma$-ray source proposed for nuclear industrial applications [16]. Figure 2 shows a schematic view of an ERL $\gamma$-ray source. At the collision point, electron bunches circulating the ERL loop collide with laser pulses stored in a supercavity. Using 350 MeV electron beams and 500-1000 nm lasers, we can generate $\gamma$-rays with energy up to 4.5 MeV.

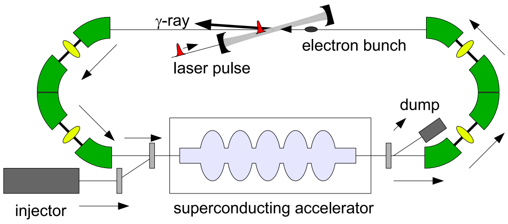

Figure 2: LCS $\gamma$-ray source based on an ERL.

In the design example, the following parameters were assumed: electron beam energy 350 MeV, bunch charge 100 pC, repetition 130 MHz, normalized emittance (x/y) 2.5/1.0 mm-mrad, electron beam size at the collision (x/y) 37/24 $\mu$m, laser wavelength 1064 nm, pulse energy 1.8 $\mu$J, enhancement of the supercavity 3000. The $\gamma$-ray flux is calculated to be $1\times10^{13}$ph/s in total, and spectral density is to be $6.8 \times 10^9$ph/s/keV for 2 MeV $\gamma$ rays, which exceeds the performance of existing facilities by several orders of magnitude. Such high-flux $\gamma$-ray source can be used for many scientific and industrial applications. Nondestructive assay of radio-nuclides by using nuclear resonance fluorescence will be a valuable tool for management of radioactive wastes [17]. Other possible applications under proposal are the testing of a semiconductor Compton telescope [18], studies of the materials science with the magnetic Compton scattering [19], and studies of the nuclear parity nonconservation via the nuclear resonance fluorescence [20].

## MACHINE DEVELOPMENT

### *Electron Guns*

An electron gun to produce small emittance electron beams with high-average current is an essential device for an ERL to exploit its full advantages, acceleration of high-power high-brightness electron beams. The ERL X-ray sources under proposal are based on electron beam parameters: average current of 10-100 mA, normalized emittance of 0.1-1 mm-mrad, bunch repetition of 1.3 GHz. These parameters are beyond the established technologies such as photocathode RF guns for SASE-FELs. Therefore, we need to develop an ERL electron gun in a different approach from the SASE-FEL guns.

Now, two types of electron guns are developed for ERLs. One is a photocathode DC gun and the other is a photocathode SRF gun, both of which can be operated in a CW-mode with high-average current. Here we summarize the current status of the ERL gun development.

A photocathode DC gun is able to generate an electron beam of ultra-small initial emittance, when it is equipped with a semiconductor photocathode having a negative electron affinity (NEA) surface. This type of electron gun is under development in JLAB, Cornell and JAEA.

In a photocathode DC gun, higher DC voltage is suitable for suppressing the space-charge induced emittance growth. From numerical simulations, it was found that DC voltage higher than 500 kV is required for future ERL injectors [21]. For this purpose, high-voltage DC guns have been constructed, but stable operation over 500 kV has never been demonstrated. This is because that the DC voltage is limited by field emission from a supporting rod located within a ceramic insulator. The electrons emitted from the supporting rod is intercepted by the inner surface of the ceramic and penetrate into the ceramic body. If the ceramic has high resistivity, these electrons cause a concentration of charges in a small area and may lead to a punch-through failure of the ceramic. In order to avoid such failure, ceramic insulators with a finite bulk resistivity and a finite surface resistivity have been tested [22].

A segmented ceramic insulator with guard rings was designed and fabricated in JAEA. This type of ceramic insulator is expected to be tolerant to the field emitted electrons. The insulator consists of multiple ceramics stacked in series, and a Kovar electrode is sandwiched between two ceramics and blazed. Guard rings are attached to the Kovar electrode at both inner and outer sides. The number of segmentation and the shape of guard rings were optimized to minimize the surface electric field. Trajectories of field emitted electrons from the rod were also taken into consideration in order to guard the ceramic surface from the field emitted electrons from the supporting rod. A high-voltage test of the ceramic insulator tube up to 550 kV will be started soon [23].

An inverted ceramic insulator tested in JLAB has a completely different style. The inverted insulator has no supporting rod, which is the dominant source of the field emission [24].

It is known that tailoring three-dimensional distribution of an electron bunch generated from a photocathode can effectively reduce the space-charge emittance growth. Thus, shaping of a drive laser pulse has been an intrinsic technology in photocathode RF guns, and it is also applicable to photo cathode DC guns. In the scheme of three-dimensional pulse shaping, the transverse direction is controlled by laser spatial shaping, and the longitudinal direction is achieved by laser temporal shaping. For the temporal shaping, a photocathode must have temporal response fast enough, typically less than a few ps. In an experiment at Cornell revealed that such fast temporal response can be obtained by appropriate combination of cathode material and laser wavelength. In the experiment, a photocathode of GaAs illuminated by 520 nm laser showed temporal response faster than 2 ps [25], which is much faster than that for illumination with near band-gap wavelength ($\sim$800nm). The faster response at 520 nm is attributed to wavelength dependence of optical absorption constant of GaAs.

For the practical operation of future ERL light source, a photocathode must provide electron charge over 10000 C (100 mA, 1 day). Life of NEA cathodes remains a critical issue to be resolved. A surface of negative electron affinity is created by coadsorption of Cs and $O_2$ (or $NF_3$) on a wafer of p-doped GaAs. Since the NEA surface is easy to destroy by collision of residual gas molecules or back-bombarding ions, keeping good vacuum is necessary to obtain long-life NEA cathodes. DC photocathode guns are, thus, equipped with a vacuum chamber made of material having low out-gassing rate and large capacity of NEG pumps.

In the Cornell DC gun, stainless steel with heat treatment in air at 400°C is used for the vacuum chambers to obtain out-gassing rate of $3 \times 10^{-11}$Pa m/s [26]. The main chamber is equipped with NEG pumps, 20000 litter/s in total.

In JAEA, they fabricated vacuum chambers made of titanium which has out-gassing rate of $6 \times 10^{-13}$Pa m/s. The main chamber of JAEA DC gun accommodates 18000 litter/s NEG pumps and a 500-litter/s ion pump [23].

Off-center illumination of a drive laser is also effective for longer life of NEA cathodes. This is because the back-bombarding ions hit the center of photocathode, a different position from the electron emission area. In the JLAB FEL gun with off-center illumination, they obtained cathode lifetime (1/e life) of 550 C at 5-mA operation [24].

Optimization of electrode geometry to preserve small beam emittance during the off-center illumination remains to be studied.

Superconducting photocathode guns are under development at BNL and Germany. The BNL gun is designed to generate a 500-mA, 2-MeV (1 MW) electron beam from a half-cell 703 MHz cavity. A multi-alkali photocathode ($K_2CsSb$) driven by 355-nm laser is used. A high acceleration field in the SRF cavity allows relatively large bunch charge with keeping a small emittance. The design value is normalized emittance of 2.3 mm-mrad for a 1.4 nC bunch [27]. The gun is under fabrication and will be commissioned soon.

A 3.5-cell L-band SRF gun equipped with a $Cs_2Te$ photocathode has been developed by German collaboration team (BESSY, DESY, MBI and FZD). The gun was operated at ELBE and produced a low-current beam (50 pA) for the first test [28].

### *Superconducting Linacs*

Superconducting cavities optimized for a high-average current ERL are under development. Research issues in these development are high-power input couplers, strong damping of higher-order modes (HOM), cryomodules with small microphonics, and so on.

In BNL, a 5-cell 703 MHz superconducting cavity to accelerate beam current over 500 mA is ready for commissioning [27]. The cavity is designed to extract HOMs through a beam pipe having a large aperture and damp the HOMs by on-axis ferrite absorbers at room temperature.

In the Japanese collaboration team (KEK/JAEA/ISSP), they are developing superconducting cavities for future ERL light sources. They have chosen a 9-cell 1.3-GHz structure and obtained a cavity design to achieve HOM-BBU threshold current over 600 mA in a 5-GeV ERL. The cavity has optimized cell shape and enlarged beam pipes for efficient damping of HOMs. HOMs excited in the cavity are extracted through the beam pipes and damped by on-axis HOM absorbers installed at both ends of the cavity [29].

## FUTURE DIRECTIONS

As presented in the previous section, the R&D efforts are now intensively carried out towards the specific programs of future ERLs such as X-ray light sources, high-power FELs and an e-cooler. Adding to these proposals, we can pursue a wide range of applications, which exploit the advantage of ERLs, acceleration of high-average current and small-emittance beams with saving RF power. We overview possible future directions of ERL applications in the following.

### *XFEL Oscillator*

A FEL oscillator operated in hard X-ray region (X-FELO) is one of the possible extensions of future multi-GeV ERLs [30]. The X-FELO looks an attractive and promising option, because it realizes fully coherent hard X-ray pulses by small modification of an X-ray ERL light source. X-ray pulses having a good temporal coherence will be a ground-breaking light source for X-ray applications such as inelastic X-ray scattering experiments. In order to obtain lasing in a hard X-ray FEL oscillator, an electron beam must be “diffraction limit”, that is smaller emittance than optical diffraction. This requirement is completely equivalent to the targeting value of the future ERL X-ray light sources.

### *FEL-based Coherent Electron Cooling*

Another interesting proposal of ERL-based FEL is coherent electron cooling of hadron beams [31]. The coherent electron cooling is conducted in three steps: a modulator, a high-gain FEL and a kicker. (1) in the modulator, each hadron induces a density modulation in a co-propagating electron beam, (2) the density modulation in the electron beam is amplified in the high-gain FEL, (3) in the kicker, the hadrons interact with the electric field of the electron beam that they have induced, and receive energy kicks toward their central energy. After these interactions, the hadron beam reduces its energy spread, that is cooling of the hadron beam. It is shown that the 7-TeV proton beam at LHC can be efficiently cooled by electron beam of 3.8 GeV ERL, and a proof-of-principle demonstration can be made at RHIC and the test ERL at BNL.

### *Time-Reversal Configuration*

Development of ERLs at affordable prices is also an important aspect to promote the ERL light source in a wide area of users including both scientific and industrial applications. Small-size laser Compton X-ray sources and infrared/THz FELs will be candidates of such ERL light source, which is a scale of 10-20 MeV. For realizing these ERLs at affordable prices (machine cost and operation cost), it is necessary to reduce the cost of injector and refrigerator. In a high-energy ERL, an injector is a relatively small part of the total facility. In a small ERL, however, the injector accounts for a large part of total cost.

One possible solution to downsize an ERL injector is utilizing the time-reversal configuration. In the time-reversal configuration, the spent electron beam is decelerate by SCA in the opposite direction to the accelerating beam. The electron beam is decelerated down to the energy of the electron gun by SCA or further decelerated down to almost zero kinetic energy by additional DC deceleration field [32]. Elimination of the power-consuming injector by time-reversal configuration realizes the reduction of initial cost and operation cost of the ERL.

### *Possible Use of Spoke Cavities*

Recently, superconducting electron accelerators consisting of spoke cavities, 350 MHz cavities operating at 4.5 K, were proposed for a laser Compton X-ray source [33] and a high-power FEL [34]. Utilization of spoke cavities is a possible option for ERLs at affordable price. The spoke cavity was originally developed for a medium-$\beta$ ion linac and has advantages compared with elliptical-cell cavities as follows. The transverse dimension of a spoke cavity is of the order of a half of RF wavelength. Thus, it has about half the transverse size of elliptical-cell cavities. It means that the spoke cavity can be operated at about half the frequency of elliptical-cavity of the same transverse size. The spoke cavity operating at lower frequency reduces the capacity of refrigerator and has potential to operate at higher temperature. Adding to the cryogenic aspect, large cell-to-cell coupling and easy installation of HOM couplers on the side of a spoke cavity are excellent advantages for high-current ERLs.

### *Multi-Loop ERLs*

As the HOM BBU threshold is increased by improvement of cavity performance, a multi-loop configuration becomes a practical option of an ERL light source. If a multi-GeV ERL light source is built in a 2-loop configuration, construction and operation costs of the linac, the refrigerator and the RF system can be reduced to a half of 1-loop configuration. Thus, the 2-loop ERL is attractive from an economic viewpoint, but we need detail investigation of electron beam dynamics in the 2-loop ERL before adopting the 2-loop configuration. In a previous study, HOM-BBU threshold current and growth of emittance and energy spread due to CSR in a 2-loop 5-GeV ERL consisting of the newly designed ERL cavities were investigated by particle simulation [35]. It was found that the 2-loop ERL can accelerate a 100 mA beam with keeping enough margin of safety for HOM-BBU, and is competent for future ERL light sources.

A 4-loop ERL is under construction at BINP and they have already demonstrated a successful operation in 2-loop recirculation [36]. The Japanese collaboration team plans to extend their facility, the Compact ERL, into 2-loop configuration in future [7]. In these facilities, studies of multi-loop ERL will be conducted in detail from beam dynamics issues to hardware compatibility.

## SUMMARY

We have overviewed the present status and the future perspectives of the energy-recovery linac. The ERL is a promising device to generate an electron beam of high-average current and small emittance, thus, it plays an important role in the research of future light sources and high-energy physics. As for the future light sources, the ERL has potential to improve the flux and brilliance of radiations from electrons significantly due to high-average current and small emittance of the ERL beam. This improvement is possible in a wide range of photon energies from terahertz to X/$\gamma$-rays via various kind of photon radiation methods. Extensive R&D's including construction of test facilities are underway in the world. In the near future, these efforts will result in realization of the ERL facilities under proposal. Future developments will also include both exploration of new concepts and persuasion of affordable-price ERLs.

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