REVIEW OF ERL PROJECTS AT KEK AND AROUND THE WORLD*

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Abstract

Energy-recovery linacs (ERLs) are being developed over the world to realize future light sources and other applications. This paper describes the 3-GeV ERL-based light source project and the compact ERL project at KEK and also reviews ERL-based accelerator projects around the world.

INTRODUCTION

Energy recovery linacs (ERLs) are expected to provide high-current and low-emittance electron beams for a number of applications. Several existing ERLs are already operated as Free Electron Lasers (FELs) and some kind of photon sources. In ERLs, electron beams can achieve extremely low emittances reaching the X-ray diffraction limit and very short electron bunches with flexible bunch structure. These characteristics are very suitable for future light sources that provide synchrotron radiation (SR) with extremely high brightness and/or ultra-short pulse length. Small energy spreads of ERL beams help to make most of long undulators. Furthermore GeV-class ERLs can be easily extended to short-wavelength FELs with excellent electron-beam quality produced by ERL technologies.

KEK has a project to construct a 3-GeV ERL-based light source with an X-ray free-electron-laser oscillator (XFEL-O) as the successor of two operational SR sources at the Photon Factory, the 2.5-GeV PF ring and the 6.5-GeV PF-AR[1]. In order to demonstrate excellent ERL performances toward the 3-GeV ERL project, the compact ERL (cERL) project is on going[2]. The Japanese collaboration team is making efforts for R&D on key components such as high-current superconducting cavities and high-brightness electron gun.

In this paper, the two ERL projects at KEK will be described including the present status of R&D activities. Furthermore ERL projects around the world will be briefly reported.

3-GEV ERL LIGHT SOURCE PROJECT AT KEK

The schematic view of the ERL-based light source is shown in Fig. 1. In the first stage of the project, we will construct a 3-GeV ERL, which consists of an injector, a superconducting main linac and a return loop. In the return loop, we will install about 30 undulators and provide super-bright and/or ultra-short SR in the vacuum ultra-violet (VUV) to hard X-ray range. In the second stage, an XFEL-O will be constructed. In the XFEL-O operation, an electron beam from the injector is accelerated twice by the main linac of the 3-GeV ERL without energy recovery and fed to the XFEL-O after the acceleration up to 6 GeV (or 7 GeV with an upgrade in the main linac). Typical operational modes and their parameters of the 3-GeV ERL are given in Table 1.

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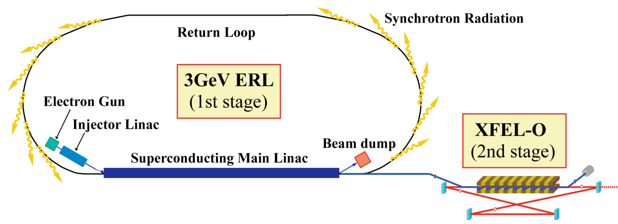

Figure 1: Schematic view of the ERL-based light source at KEK, a 3-GeV ERL and a 6-7 GeV XFEL-O.

Table 1: Beam Parameters for Typical Operational Modes for the ERL Light Source at KEK

	HC†1	HF†2	UL†3	US†4	XFEL-O
Energy	3 GeV	3 GeV	3 GeV	3 GeV	6-7 GeV
Current	10 mA	100 mA	100 mA	77 μA	10 μA
Charge	7.7 pC	77 pC	77 pC	77 pC	10 pC
Repetition	1.3 GHz	1.3 GHz	1.3 GHz	1 MHz	1 MHz
Norm. emittance	0.1 mm·mrad	1.0 mm·mrad	0.1 mm·mrad	-	0.2 mm·mrad
Energy spread	$2x10^{-4}$	$2x10^{-4}$	$2x10^{-4}$	-	$5x10^{-5}$
Bunch length	2 ps	2 ps	2 ps	< 100 fs	1 ps

†1 HC: High Coherence mode, †2 HF: High Flux mode, †3 UL: Ultimate mode, †4 US: Ultra-Short Pulse mode

The lattice and optics design of the 3-GeV ERL was recently started[3]. The main linac consists of more than two hundred of 9-cell cavities to accelerate the electron beam up to 3 GeV with a moderate accelerating gradient of 15 MV/m or less. The return loop of the 3-GeV ERL has about 30 TBA(Triple Bend Achromat) cells with 6-m or 30-m long straight sections for insertion devices. The bending radius of the bending magnet is sufficiently long to suppress emittance growth and energy spread increase due to the incoherent synchrotron radiation effects. The optics of the main linac is designed so that the betatron function is well suppressed for achieving a high BBU threshold current. Figure 2 shows the preliminary result of the optical functions for the main linac and the return loop of the 3-GeV ERL. Figure 3 the tentative layout of the ERL light source in the KEK Tsukuba campus.

The 3-GeV ERL provides SR with the maximum brightness of 10^{22} - 10^{23} phs/s/mm^2/mrad^2/0.1%b.w. in the VUV and X-ray region. The 6-7 GeV XFEL-O generates fully coherent X-rays with the averaged brightness of about 10^{26} phs/s/mm^2/mrad^2/0.1%b.w.[4]. For the future development, one 300-m long straight section is reserved in the middle of the return loop. This section has large

ISBN 978-3-95450-115-1

potential for (1) 300-m class undulator with the spectral brightness up to 10^{23} - 10^{24} phs/s/mm^2/mrad^2/0.1%b.w., (2) 3-GeV XFEL-O using the higher harmonics [5], (3) EEHG(Echo-Enabled Harmonic Generation) including attosecond pulse generation[6,7] and so on.

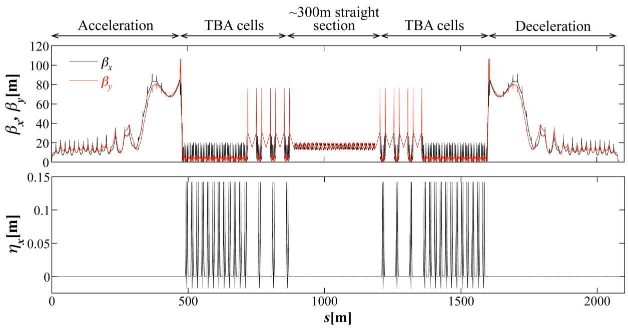

Figure 2: Betatron (upper) and dispersion (lower) functions of the main linac and the return loop for the 3-GeV ERL.

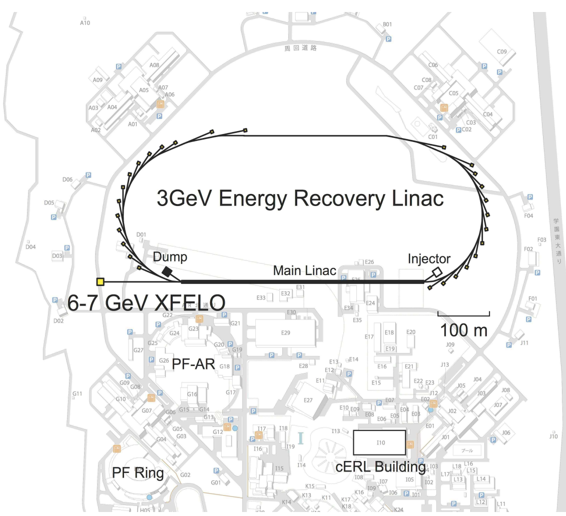

Figure 3: Tentative layout of 3-GeV ERL light source with an XFEL-O at KEK Tsukuba campus.

THE COMPACT ERL PROJECT AT KEK

The layout of the cERL is shown in Fig. 4. The cERL building that had been originally used for the experiments of the proton synchrotron was refurbished for the cERL. The cERL parameters are listed in Table 2. The cERL will initially comprise a 5-MeV injector, a main linac with two 9-cell cavities in a cryomodule and a single return loop. The first target of the cERL is the normalized emittance of 1 mm·mrad for the beam current of 10 mA at the beam energy of 35 MeV. The beam energy can be increased up to 125 MeV by increasing the number of cavities and can be doubled to 245 MeV by installing the second return loop. The cERL is under construction and the commissioning is scheduled to start in 2013.

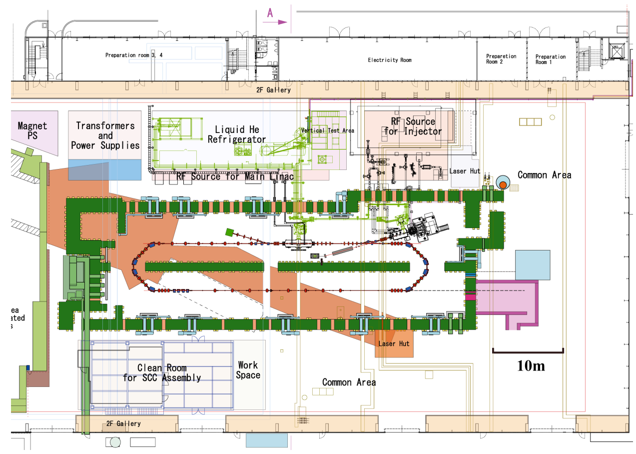

Figure 4: Layout of the compact ERL (cERL).

Table 2: Parameters for the cERL

Beam energy	35 - 125 MeV (single loop) 245 MeV (double loop)
Injection energy	5 MeV
Average current	10 mA (100 mA in future)
Acc. gradient	15 MV/m
Normalized emittance	0.1 mm·mrad (7.7 pC) 1 mm·mrad (77 pC)
Bunch length	1 - 3 ps 100 fs (with bunch compression)
RF frequency	1.3 GHz

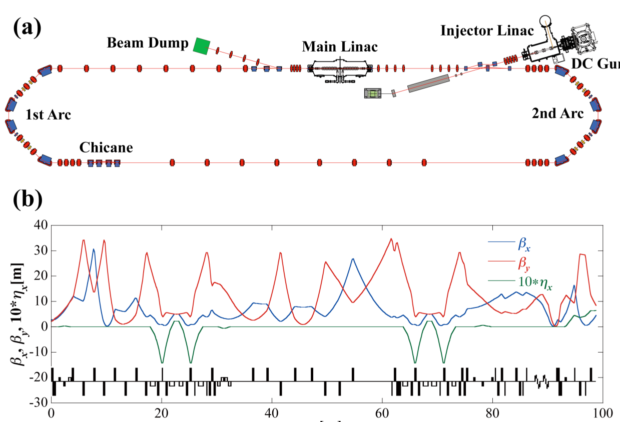

Figure 5: (a) Lattice and (b) optics of the cERL.

Lattice and Optics

Figure 5a shows the latest design of the single-loop configuration. The lattice and optics from the injector to the main linac have been designed with simulation including space charge effects for the first cERL commissioning[8]. The simulation shows that the normalized emittances just after the main linac can be sufficiently lower than 1 mm·mrad for the bunch charge

ISBN 978-3-95450-115-1

of 7.7 pC (the beam current of 10mA). Figure 5b shows the beam optics from the quadrupole magnet just after the main linac to the beam dump. Two isochronous arc sections are identical and designed so that the normalized emittance is well preserved against the CSR effects. The optics of eight quadrupole magnets before the first arc is optimized for matching between the main linac and the first arc. The lattice and optics for the laser-Compton scattering γ-ray experiment[9] in the straight section opposite to the main linac is being designed.

DC Photocathode Gun and Drive Laser

The 1st DC photocathode gun with segmented insulator has been developed at JAEA. The gun already demonstrated 8-hour operation at 510 kV for a stem electrode with a dummy cup[10]. Next the cathode electrode and NEG pumps were installed in the HV chamber and HV processing was performed up to 526kV. However 550 kV has not reached yet because of a local radiation problem, which is under investigation and needs to be solved. Gas conditioning and installation of a new cathode electrode are being performed to remove the field emission site. The gun is scheduled to be installed in the cERL beamline at KEK by October 2012.

The 2nd DC photocathode gun developed at KEK was produced so that it can achieve an extreme high vacuum of below 1×10^{-10} Pa to preserve a Negative Electron Affinity (NEA) state on the cathode for a long time. The gun consists mainly of two segmented insulators made of special ceramic material(TA010, Kyocera) and a large titanium vacuum chamber. Measurement of the outgassing rate of the gun and the pumping speed of a bakeable cryopump was performed[11]. A 600-kV power supply for the gun is being developed.

A fiber laser system has been developed for the photocathode gun. At KEK, a Yb fiber laser amplifier successfully produced 37.9 W of 1064 nm output at 1.3 GHz with a $Nd:YVO_4$ mode-locked oscillator and more recently a multi-stage Yb-fiber amplifier system demonstrated output power of 70 W at the same wavelength[12]. High-efficient wavelength conversion system is also being developed to provide a high-power second harmonic light enough for 10-mA operation of the cERL photocathode gun.

SC Cavities for Injector and Main Linacs

Superconducting(SC) cavities for the cERL injector linac[13] have a TESLA-like cell shape and a larger beam pipe aperture of 88 mm. Three 2-cell cavities to be installed in the cERL injector cryomodule were already fabricated. Each of them is equipped with two input couplers and five loop-type higher-order-mode(HOM) couplers. The HOM coupler had a heating problem at high fields and limited the cavity performance. Recently a new RF feedthrough of the HOM pick-up antenna was developed to increase the thermal conduction. The new RF feedthroughs were tested in the final vertical test of the injector cavities and a high accelerating gradient of more than 25 MV/m was successfully achieved without heating of the HOM pick-up antenna. The completed six input couplers were conditioned at a high-power test stand and successfully processed up to 30 - 40 kW in CW operation. This means the input couplers sufficiently satisfy the requirement of 10-mA operation. Water-cooling channels may be added to the warm part to achieve the required input power of 170 kW for future 100-mA operation. Assembly of the cERL injector cryomodule was started from April 2012 and will be completed in June 2012. The first cooldown test of the cryomodule is scheduled in July 2012.

A 9-cell cavity that has a large iris with diameter of 80 mm and two large beam pipes with diameters of 100 and 123 mm has been developed for the cERL main linac[14]. The beam pipes with HOM dampers absorb the HOM power of 150 W at the maximum beam current of 200 mA and have an eccentric-fluted structure to suppress the quadrupole HOMs. Two 9-cell cavities to be installed in the cERL were fabricated and in the vertical test of the two cavities the accelerating gradient up to 25 MV/m was achieved with the target specification, the Q-value of more than 1×10^{10} at 15MV/m. The onsets of field emission were measured to be 14 MV/m and 22 MV/m for these cavities. Each cavity was already dressed with a Helium jacket and is waiting for installation in the cryomodule. Design and prototyping of the input coupler were completed. In high power tests of the prototype, the input power reached to 25kW in standing wave condition and feeding 20kW power could be kept for 16 hours. Fabrication of two more input couplers to be installed in the cERL was completed and the RF conditioning is being performed. The structure test of a HOM damper model has finished and HOM dampers with ferrite absorbers (IB004, TDK) are being fabricated. The cryomodule is also being constructed.

Other Components

A normal-conducting RF buncher for the cERL injector is being produced. Two CW klystrons (30 kW and 300 kW) for the injector linac, two 30-kW IOTs for the main linac, and a 20-kW IOT for the buncher were already installed in the cERL building. To control RF voltages very precisely, a digital low-level RF(LLRF) system is being developed. A liquid-helium refrigerator system with a cooling capacity of 600 W at 4 K was already installed and tested. Eight bending magnets and fifty-six quadrupole magnets were completely delivered. Gate valves, pumps and gauges for the vacuum system and monitors for the injector were also delivered. The rest of magnets, vacuum components and monitors will be produced and delivered in FY2012. Construction of the cERL radiation shield was started from March in 2012 and will be finished this autumn.

ERL PROJECTS AROUND THE WORLD

The number of ERL-based accelerator projects is steadily increasing in the world. Statuses of almost all the ERL projects are briefly described here.

TJNAF(J-Lab)

The J-Lab FEL-ERL has pioneered potential of ERLs for high average current linacs and high-power FELs with low energy loss[15]. The 135-MeV ERL provides electron bunches up to 135 pC of less than 10 mm·mrad emittance at repetition rates of up to 74.85 MHz to either of two FEL (IR and UV) lines in the return loop[16]. The IR FEL line with a 5.5-cm period wiggler can lase in the infrared at high power (>10kW) and is used for user experiments. In 2010 the UV FEL line with a 3.3-cm period wiggler was commissioned and has lased with very high gain at wavelengths near 700 nm and 400 nm. The 10-eV third harmonic light was successfully obtained from the FEL and is planned to be used in user experiments this summer. The ERL has been also used as a test-bed for studying CSR, LSC, and BBU, resistive wall heating, as well as RF loading and magnet quality issues. J-Lab has an upgrade plan for an FEL oscillator in the VUV to soft X-ray spectral range[17].

BINP

BINP has a unique ERL for FELs at Novosibirsk[18]. This ERL uses a normal conducting linac and a thermionic gun. The first stage of the Novosibirsk ERL, a single-turn 11-MeV ERL in the vertical plane with a THz FEL, is in operation for almost 10 years and has demonstrated the maximum average current of 30 mA (world record for ERLs). The THz FEL provides radiation with average power up to 500 W and wavelength 120 - 240 microns for users. The second stage is a 4-turn 40-MeV ERL (first in the world multi-turn ERL) in the horizontal plane with two additional FELs. The first and second loops with the second FEL at a bypass is in operation and the third and fourth loops with an IR FEL under construction. Experiences obtained from the ERL can be used in the design of future machines such as a multi-turn ERL X-ray source, MARS[19].

Daresbury Laboratory

The ALICE accelerator is an operating ERL at Daresbury Laboratory for accelerator R&D tests and several different applications[20,21]. It generates bunches of up to 100 pC by the DC gun and accelerates them up to 27.5 MeV by the injector and main SC linacs. The bunch repetition rate within a bunch train of up to 100 μs can be varied up to 81.25 MHz and the train repetition rate is 1-10 Hz. An IR-FEL achieved the first lasing in 2010 and then demonstrated SNOM(Scanning Near-field Optical Microscope) experiments in 2011. The ALICE THz radiation was transported to a dedicated tissue culture laboratory (TCL) for the biological experiments. ALICE also serves as an injector of EMMA, the world's first proof of principle non-scaling FFAG machine, which achieved beam acceleration in 2011. The ceramic HV insulator of the DC gun was recently replaced by a new one to increase the gun voltage of 230 kV and the DC gun is currently operated at 325 kV.

Cornell University

The Cornell ERL project is to construct a 5-GeV X-ray light source as extension of CHESS on the campus. Research and development on DC gun, injector and main linac cryomodules, undulator and beam dynamics have been intensively performed for realizing the ERL X-ray source[22,23]. The injector prototype R&D has made great progress. The maximum beam current of 52 mA with a GaAs cathode was demonstrated and the beam current of 20 mA with a CsK_2Sb cathode was maintained for 8 hours. The minimum normalized emittance at 80 pC was 0.7 mm·mrad for the whole bunch and 0.3 mm·mrad for the bunch core. The injector prototype has already achieved beam sufficient for an ultra-bright X-ray ERL. Furthermore the maximum coupler power of 60 kW and the maximum accelerating gradient of 13 MV/m was achieved for the injector SRF cavity. Design of the main linac cryomodule is underway and fabrication of the cavity optimized for high current and efficient operation has started. Construction and test of one cavity test module are planned in 2012. The Project Definition Design Report (PDDR)[24] was recently completed and is ready for submission to the NFS.

HZB

Motivation of B*ERL*inPro (the Berlin Energy Recovery LINAC Project)[25] at HZB is to develop the ERL concept and technology for a wide variety of applications including next-generation light sources. The 50-MeV ERL consists of a 6 MeV injector with a 1.5 – 2.0 MeV SRF photocathode gun and three 2-cell SC cavities and a ~50m long racetrack shaped recirculator including the main linac with three 7-cell SC cavities. B*ERL*inPro aims to produce the beam current of 100 mA for the normalized emittance of 1 mm·mrad. The designs of SC cavities and beam optics have been studied for the high current goal. The SRF gun will be developed in a 3-stage approach. This project was started in 2011 and the first electron beam in the injector and the recirculation path is expected in 2015 and 2018 respectively.

IHEP

A compact ERL test facility (ERL-TF) is proposed at IHEP, Beijing to study ERL key technologies[26]. In this ERL, a 5-MeV injector beam is accelerated to 35 MeV by two 7-cell SC cavities with the normalized emittance of 1-2 mm·mrad for the beam current of 10 mA (bunch charge of 77 pC at the bunch frequency of 130 MHz for 1.3-GHz RF frequency). A wiggler installed in the straight section will produce a coherent THz radiation. A 500-kV DC photocathode gun is completely designed and its construction will be started soon. The design of a CW 7-cell cavity was preliminarily done and some beam physics issues such as space charge, CSR and BBU are being studied. In the test facility, an FEL beam that is separately generated in a different 20-MeV injector with an RF gun is also accelerated to ~45 MeV by the same SC cavities.

ISBN 978-3-95450-115-1

Peking University

Peking University has a plan to construct a superconducting ERL test facility to demonstrate energy recovery, ERL-based FEL and radiation sources, a high-brightness DC SRF photo-injector and SC cavities[27]. The maximum beam energy is 30 MeV and the normalized emittance is 4 mm·mrad for the bunch charge of 60 pC. The bunch length and energy spread are 4 ps and 0.3 % at entrance of a wiggler, which works for a 10-μm FEL. A 2-K cryogenic system with cooling capacity of 58 W was put into operation in 2010. RF and beam experiments of a 3.5-cell cavity DC-SRF injector is being carried out by using a 20-kW RF source and a test beamline. The accelerating gradient of 11 MV/m and the beam energy of 2.5 MeV were so far achieved by the experiments. The optics design for the ERL has been updated according to the expected characteristics of the photo-injector and acceleration module.

BNL

eRHIC is a future electron-hadron collider at the RHIC facility in BNL for exploring the internal structure of nucleons and nuclei[28]. The design is based on one of the existing RHIC hadron rings and a 6-turn ERL with two 2.45-GeV SC linacs completely placed in the RHIC tunnel to accelerate electrons up to 30 GeV and the target luminosity is 10^{33} – 10^{34} $cm^{-2}s^{-1}$. At present the ERL-based design and related R&D items such as SRF cavities and compact magnets are intensively developed. eRHIC will also employ an ERL to cool hadron beams by coherent electron cooling, of which a proof-of-principle experiment will be conducted at RHIC in 2014 - 2016. Furthermore a 20-MeV ERL facility is under construction to demonstrate CW operation with average current of 0.1 – 1 A. The first beam from the 703-MHz SRF gun is scheduled in September 2012 and the first ERL beam in May 2013[29].

CERN

The Large Hadron and electron Collider (LHeC) is proposed at CERN to collide a 7-TeV proton beam in the LHC with a high-energy lepton beam (60 GeV at least) [30]. The main target performance is the electron-proton luminosity at least 10^{33} $cm^{-2}s^{-1}$ with the total electrical power of less than 100 MW for the electron branch. The LHeC has the Linac–Ring (LR) option with a racetrack-shape 3-turn ERL, which is exactly one third of the LHC ring in total circumference and has two 10-GeV SC linacs. The other option is the Ring-Ring (RR) option, which has a new lepton ring in the LHC tunnel together with a 10-GeV injector. The LR option has advantages over the RR option in higher luminosity potential up to 10^{34} $cm^{-2}s^{-1}$, decoupling from the LHC operation and infrastructure, higher polarization degree of electrons, and reusable SC cavities for many other projects. The CDR draft was completed in 2011 for review of external referees.

SUMMARY AND OUTLOOK

The 3-GeV ERL light source project is promoted as a future project at KEK and expected to achieve a super-bright VUV and X-ray source and future upgrades to XFEL-O and other FELs, which will enhance brightness, coherence and temporal resolution. The on-going ERL projects in the world including the cERL project at KEK have made significant progress in ERL technologies and operational experiences for a few years and encourage us to work for further ERL development that can realize future ERL-based projects.

ACKNOWLEDGMENT

I would like to thank the Japanese ERL collaboration team and those from J-Lab, BINP, Daresbury Lab, Cornell U., HZB, IHEP, Peking U., BNL and CERN who provided material for this paper.

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