1 The ERL Project

1-1 Introduction

The feasibility of an energy recovery linac (ERL) as a future light source has been investigated for several years. It has been concluded that a 5-GeV class ERL should be the most promising candidate for making progress with new synchrotron radiation activities based on sub-picosecond pulses and/or spatial coherence, while at the same time supporting a large variety of user needs from VUV to X-rays. A conceptual layout of a 5-GeV ERL is shown in Fig. 1. The principal parameters are also shown in Table 1. In order to realize this kind of a light source, many new components need to be developed. Investigations into beam dynamics, energy recovery in RF cavities, beam stability, conservation of normalized emittance, and so forth are also essential. Therefore, we are planning to construct a 60–200-MeV class ERL (Compact ERL) to substantiate the principle of the ERL within several years. The compact ERL will also bring us characteristic scientific cases. It supplies a high intense coherent synchrotron radiation (CSR) in the THz region due to its short electron bunch length. With laser-inversed Compton scattering, a ~100-MeV class ERL will serve as an X-ray source; the short pulse width is essential for femtosecond time-resolved X-ray studies, and the fine point source supplies an opportunity of coherent X-ray imaging. The principal parameters of the Compact ERL are also shown in Table 1.

The headquarter of this project, the ERL Project Office at KEK started at the beginning of April, 2006. The organization structure of the ERL Project Office is schematically shown in Fig. 2. The ERL Project Office consists of members from KEK, JAEA (Japan Atomic Energy Agency), ISSP (Institute of Solid State Physics, the Univ. of Tokyo) and other facilities such as UVSOR (Institute for Molecular Science) and JASRI/SPring-8. The office organizes the ERL project team, which consists of several task forces to design and develop the key components of the ERL. We have exchanged official MOUs with JAEA and ISSP, concerning the collaboration for the development of accelerator components. The office also engages in international collaborations with other ERL projects around the world. The MOU starting from March 2007 between the Cornell Laboratory for

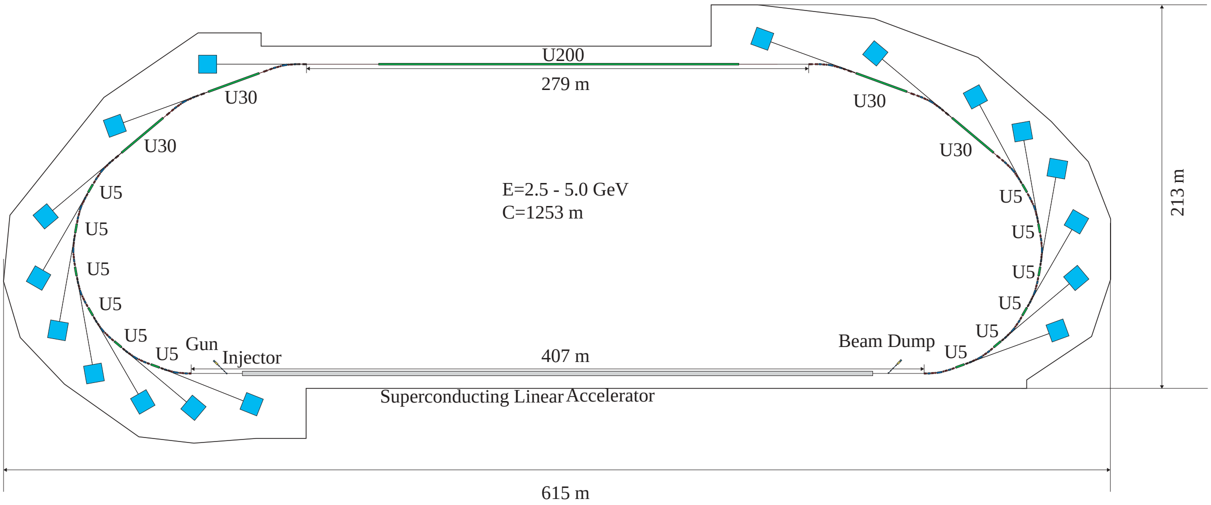

Figure 1
Conceptual layout of 5-GeV ERL.

Table 1 Principal parameters of the 5-GeV ERL and the Compact ERL.

	5-GeV ERL	Compact ERL	
Beam energy	2.5–5.0	0.06–0.2	GeV
Injection energy	5–10	5–10	MeV
Circumference	1253	68.8	m
Beam current (Max.)	100	100	mA
Normalized emittance	0.1–1	0.1–1	mm·mrad
Energy spread (rms)	5×10^{-5}	–	
Bunch length	1–0.1	1–0.1	ps
RF frequency	1.3	1.3	GHz
Accelerating gradient	10–20	10–20	MV/m

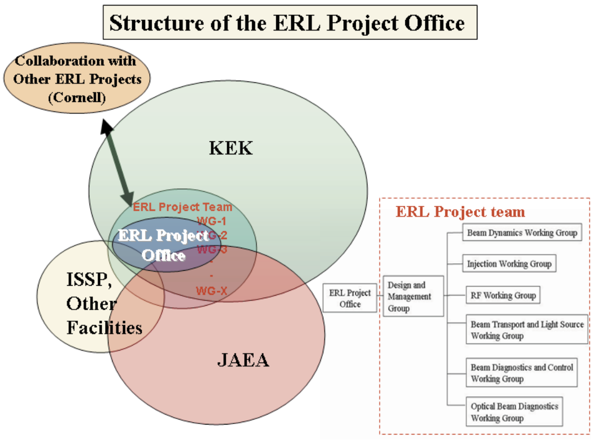

Figure 2
The organization structure of the ERL Project Office.

Figure 3
Photograph at the occasion of the mini-workshop for ERL under the collaboration meeting between CLASSE and KEK, which was held on March 12, 2007.

Accelerator-based Sciences and Education (CLASSE) of Cornell University and KEK was also exchanged. Figure 3 shows a photograph at the occasion of the mini-workshop for ERL under the collaboration meeting between CLASSE and KEK, which was held on March 12, 2007.

1-2 Why the ERL is the Most Promising Candidate for the Future Light Source

In 2005, we concluded that the energy recovery linac (ERL) with 5-GeV acceleration energy is the most suitable candidate as the next-generation synchrotron-radiation source, because the horizontal emittance and pulse length of the electron beam in linac-based light sources can be improved beyond the limitation in storage rings, by optimizing the performance of the electron gun.

Through our preliminary investigations, the performance of the ERL was estimated as shown in Figs. 4 and 5. Figure 4 shows the estimated average brilliance spectra expected from undulators of various periods and total lengths, installed in the ERL, operated with the parameters summarized in Table 2. Note that the horizontal emittance of the electron beam is equal to the vertical emittance in ERLs. The brilliance in the X-ray region can be almost 1 to 2 orders of magnitude higher than those of present-day 3rd-generation storage rings. As shown in Fig. 5, the coherent fraction of synchrotron radiation is expected to be ~10% with a 5-m undulator (λ_u = 16 mm, N = 312). As a result, the coherent flux from the 5-GeV ERL will be two orders of magnitude higher than the currently available 25-m undulator at SPring-8.

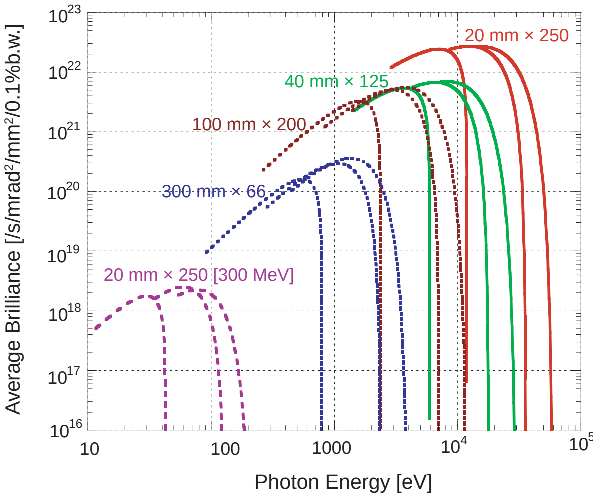

Figure 4
Estimated brilliance spectra from 5-m and 20-m undulators. Solid and dotted lines are calculations for a 5-GeV ERL while dashed lines are for the 300-MeV Compact ERL. The length and number of the periods for each undulator are denoted in the figure.

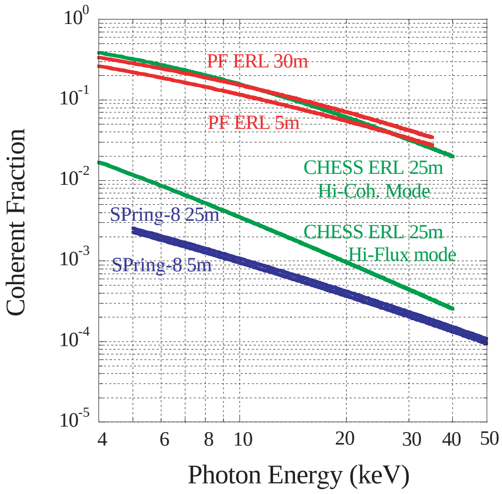

Figure 5
Coherent fraction spectra from the 5-GeV ERL compared with other light sources.

Table 2 Parameters for the 5-GeV ERL.

Acceleration energy	5 (GeV)
Beam current	100 (mA)
Emittance	10 (pm-rad)

These features are compatible with the required specifications for the next-generation synchrotron radiation facility, except for the difficulty in obtaining a wide energy-range coverage from VUV to X-rays. As mentioned before, it will be necessary to construct a Compact ERL with energy of 60–200 MeV. This can be converted into a regularly operating light source for the VUV photon energy region, when the operation energy is raised up to ~300 MeV. For example, the expected brilliance spectra from a 5-m undulator on the Compact ERL operated at 300 MeV with the electron beam emittance of 170 pm·rad are shown in Fig. 4. About 10^{18} photons/s/mrad^2/mm^2/0.1%b.w. can be obtained in the photon energy range of 30–100 eV.

It is worth comparing the ERL with the Self Amplified Spontaneous Emission (SASE) Free Electron Laser (FEL). Several projects to construct a SASE-FEL, such as the LCLS at SLAC, the TESLA project at DESY, and the SCSS at RIKEN/SPring-8 are already in progress. Table 3 summarizes the comparison between the 5-GeV ERL and the SASE-FEL. The average brilliance of the 5-GeV ERL is comparable to that of the SASE-FEL, and is almost 2~3 orders of magnitude higher than that of a typical 3rd generation synchrotron radiation source. There is a remarkable difference in the values of peak brilliance. The peak brilliance of the SASE-FEL is expected to be extremely high, in the order of 10^{33} photons/s/mrad^2/mm^2/0.1%b.w. because of the low repetition rate of 100 Hz~1 kHz. These remarkable features of SASE-FEL bring us a wonderful experimental tool based on one-shot measurement, which will open a new science field.

On the other hand, the peak brilliance of the ERL is at a moderate value of the order of 10^{26} photons/s/mrad^2/mm^2/0.1%b.w. because of the high repetition rate of 1.3 GHz. These remarkable features enable “non-perturbed measurement” without any problem due to Coulomb explosion of the irradiated materials. In materials science experiments, it is important to keep the samples under well controlled experimental conditions (temperature, pressure, magnetic field, electric field, etc.) to investigate the electronic structures, atomic structures and charge densities under particular experimental conditions. In this respect, the ERL will provide a “probing light”, which has been one of the most important usages of synchrotron-radiation sources.

1-3 Design of the Compact ERL and Development of Key Components

Lattice and Beam Dynamics Issues of the Compact ERL

The Compact ERL consists of a DC photoinjector, a superconducting (SC) injector linac, one or two cryomodules for the main linac, and a return loop and a beam dump. The injection energy will initially be 5 MeV, and then be upgraded to 10 MeV. The maximum beam energy will be 60–200 MeV, depending on the number of superconducting cavities in the main linac and on their accelerating gradient (10–20 MV/m). A maximum beam current of 100 mA is anticipated.

We used an injector design made by the JAEA group as our starting point. The design consists of a 500-kV DC photocathode gun, two solenoids, (temporarily) five three-cell cavities, some quadrupoles and a three-dipole merger. Normalized emittances were predicted to be approximately 1 and 0.1 mm·mrad under bunch charges of 77 and 7.7 pC, respectively, at the end of the merger. Further optimization of this design is underway.

In order to prove successful operations of SC cavities for the main linac under high beam currents, as well as to verify some predictions of accelerator physics issues, a return loop is necessary. Figure 6 shows our current design. A triple-bend achromat (TBA) lattice was adopted for two arcs because a similar lattice will be used for the later 5-GeV ERL. Two cryomodules will finally be installed in one of the straight sections, and a test undulator will be installed in the other straight section in order to evaluate the quality and stability of the emitted photon beams. Figure 7 shows typical optical functions calculated with the computer code SAD.

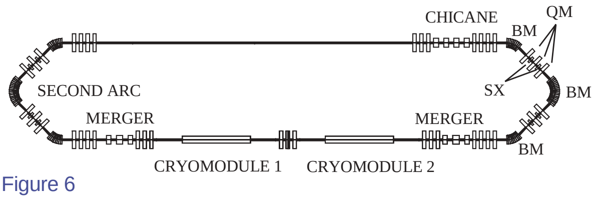

Figure 6
A prototype design of the return loop for the Compact ERL.

Table 3 Comparison between the 5-GeV ERL and SASE-FEL.

	Average brilliance	Peak brilliance	Repetition rate	Coherent fraction	Bunch width (ps)	Number of BLs	Remark
5-GeV ERL	~$10^{22\text{-}23}$	~10^{26}	1.3 GHz	~20%	0.1~1	~30	Non-perturbed measurement
SASE FEL	~$10^{22\text{-}23}$	~10^{33}	100 Hz~1 kHz	100%	0.1	~1	One-shot measurement

(Brilliance : photons/mm^2/mrad^2/0.1%/s @ 10 keV)

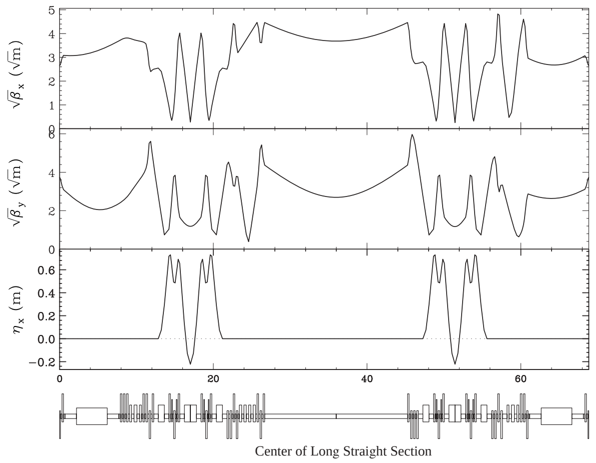

Figure 7
Typical optical functions along the return loop. Periodic condition was assumed.

Photocathode DC Gun

The combination of a DC gun and a photocathode should be the optimum electron source, which fulfils the requirement for ERL light sources, electron beams of high average current and ultra-low emittance. To demonstrate the quality of electron beams satisfactory for the ERL, a photocathode DC gun is going to be developed at JAEA. The gun consists of a main chamber for DC electrodes, an negative electron affinity (NEA) surface preparation chamber, and a load-lock system for transporting a photocathode between these chambers. A ceramic insulator for the gun and a high voltage stack of 250 kV - 50 mA power supplies are located side-by-side in a pressure vessel, containing SF_6 at 2 atm. A high-voltage test without a beam load has been completed successfully, and the load-lock system is now being assembled. We are proposing a superlattice semiconductor for the photocathode, which realizes high quantum efficiency and low thermal emittance simultaneously. As the first step of the photocathode development, we have fabricated several types of bulk samples, which are GaAs and AlGaAs with different aluminum content. Measurements of quantum efficiency and life-time of these samples have indicated that AlGaAs offers twice the quantum efficiency and almost an order of magnitude longer life-time than GaAs.

The Drive Laser

An ideal laser system for the gun driver must provide enough power to generate electron pulses of 100 mA at a wavelength corresponding to the band-gap energy of the NEA GaAs photo-cathode. These pulses have a repetition rate of 1.3 GHz, pulse widths of 10–20 ps, and must be synchronized to a reference RF signal. By assuming a quantum efficiency of 1% at a wavelength of 800 nm, the required average power amounts to 15 W. To minimize the emittance, the possibility to tune the laser wavelength is necessary. The mode-locked Ti:Sapphire laser is one of the candidates for the drive laser because of its wavelength tunability. However, CW operation under high average power is challenging. From the viewpoint of high average power, the ytterbium (Yb) fiber laser is an attractive solution. Several laser systems for the ERL driver employing this new technology have been proposed, and the design is now being optimized.

Superconducting Cavity

Two types of 1.3-GHz superconducting (SC) linacs are under investigation, namely the injector linac and the main linac. The choice of 1.3 GHz allows us to use the SC cavity technology that has been developed for an international linear collider project.

• Injector Linac

At a total RF voltage of 10 MV, the injector linac delivers the RF power of 1 MW to the beam of 100 mA in CW mode. Therefore, the most difficult part of the injector linac is the input power couplers. To reduce the power of each coupler, a couple of SC cavities with two- or three-cell structure and double input couplers is considered as a candidate for the injector linac. Cavity design and fabrication of a prototype cavity have started.

• Main Linac

A nine-cell structure with sufficiently damped HOM has been optimized to achieve a stable accelerating gradient of 10–20 MV/m under the beam of 100 mA. The large iris diameter of the cells and large beam pipes on both ends can propagate out of the HOMs from the cavity to the absorbers, which is the way that has been successfully used in the KEKB SC cavity. Furthermore, an eccentric-fluted beam pipe has been proposed and adopted to take out the quadrupole modes. Figure 8 shows the cavity with absorbers on both ends. A Cu-model and full-scale Nb cavities are being fabricated.

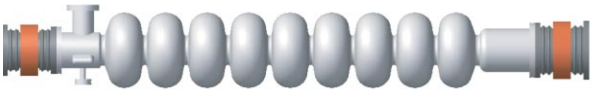

Figure 8
A nine-cell cavity for the main linac. HOM absorbers are on both sides.

The Site

We were planning to construct the compact ERL in the experimental hall which was used for cold neutron science at the KEK Tsukuba campus. However, in the design study, we found that the hall was not large enough to house a 200-MeV class machine. It is almost impossible to equip VUV beamlines around it, and it is also difficult to construct sufficient radiation shields. Meanwhile, the KEK 12-GeV Proton Synchrotron (PS) was closed, and research using the PS is moving to the J-PARC project. In the near future, the experimental halls around the PS will be available for new activities of KEK, so that we are now discussing the possibility of changing the site for the Compact ERL. Figure 9 shows the temporary layout of the Compact ERL which fits the east experimental hall of the PS.

1-4 Schedule

The development schedule of the Compact ERL is summarized in Table 4.

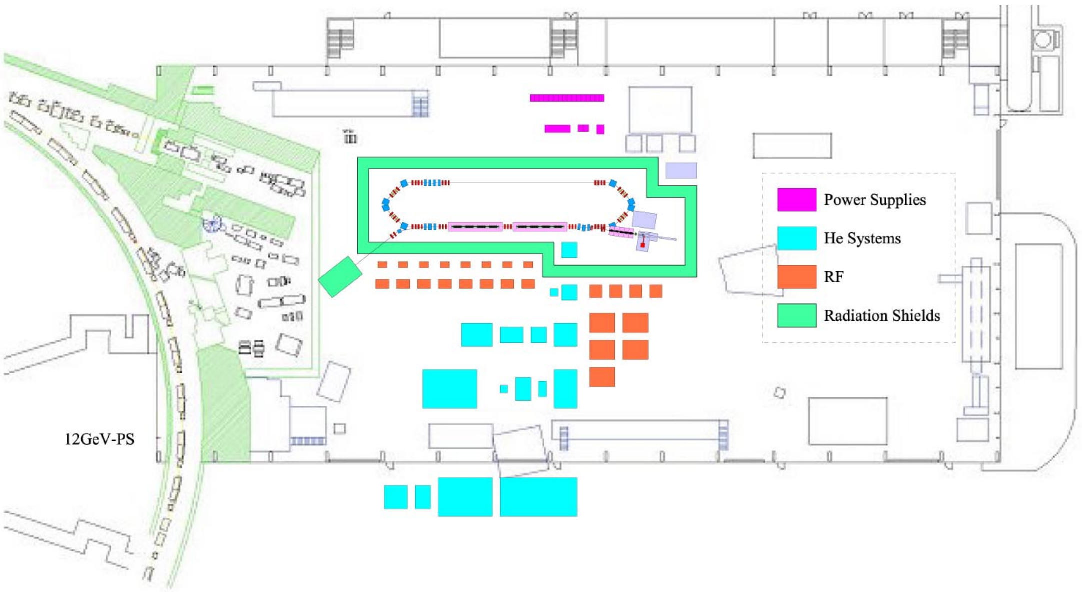

Figure 9
A temporary layout of the Compact ERL which fits the East Experimental Hall of the 12-GeV PS.

Table 4 Timetable of development of the Compact ERL.

2006	"ERL Project Office" started. Design study, R&D (SC RF cavity, gun)
2007 2008	Design study and R&D for SC RF cavity, gun, beam diagnostics, etc.
2009 2010	Fabrication/test of components Cryogenic system
2011	Installation (in east experimental hall of PS)
2012	Commissioning, machine development
2013	Operation, machine development Construction of 5-GeV ERL