1 The ERL Project

1-1 Introduction

The energy recovery linac (ERL) at around 5 GeV will promote new sciences in synchrotron radiation community as well as support a large variety of general users. The new sciences will benefit from the sub-picosecond time duration and/or the spatial coherence of the synchrotron radiation. The emittance of the electron beam will be of the order of 10 pm-rad, which corresponds to the diffraction limit of a 10-keV photon. The bunch width will be of the order of 100 fs, which will promote the ultrafast science of the materials structure. In order to realize these ends, the ERL Project Office was started at KEK from April 2006. The mission of the office is to steer the ERL Project team, which currently consists of several working groups, to design and develop the key components of the ERL. The team comprises accelerator scientists from KEK, Japan Atomic Energy Agency (JAEA), Institute for Solid State Physics (ISSP), UVSOR, SPring-8, The National Institute of Advanced Industrial Science and Technology (AIST), Hiroshima University, and Nagoya University.

Since there is no GeV-class ERL machine in the world at present, it is necessary to construct a test facility. A compact ERL at 60~200 MeV will be an ideal platform for the research and development of several critical accelerator components. From 2006 to 2008, we have designed and developed the compact ERL and its components. The compact ERL will also facilitate studies of intense terahertz radiation, which is produced as a coherent synchrotron radiation (CSR) from short electron bunches, and/or laser inversed Compton X-ray source, which will be useful for studies with femtosecond X-rays and X-ray imaging using a fine point source. One of the most important achievements in 2007 was the publication of the Conceptual Design Report (CDR) [1] of the compact ERL.

Furthermore, the office is promoting collaboration with other ERL projects in the world and also publicizing the sciences with ERL. The office assigned an MOU between the Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE) of Cornell University and KEK in March 2007. The workshop on "Compact ERL and the Scientific Case" was held in July 2007 and the "1st Science Workshop" was held in March 2008 to disseminate information on the 5-GeV ERL.

The Compact ERL Workshop, at which 70 participants attended (Fig. 1), was focused on the scientific case by using highly intense terahertz (THz) radiation, and laser inversed Compton X-ray source from the compact ERL. The intensity of the CSR in the THz range is 7-8 orders of magnitude larger than that available from existing facilities. The THz CSR will provide deeper information on elementary excitation processes that are essential for material science. The examples include lattice and molecular vibrations, the plasma oscillation frequency in conduction carriers, and the behavior of strongly-correlated quasi-particles. Furthermore, it was proposed to use the THz source not only as a probe light source but also as an excitation light source. Examples include selective diffusion of doped atoms in semiconductor process by selective excitation of lattice oscillation mode, which draws attention of the relevant industries. The X-ray source provided by the laser inversed Compton scattering will provide a unique X-ray imaging apparatus based on a micron-order light source, which is excellent for X-ray phase contrast imaging including medical applications. It can also be used as a femtosecond X-ray pulse source for imaging ultrafast phenomena.

The ERL Science Workshop, at which 70 participants attended (Fig. 2), was focused on the scientific case based on the ERL at around 5 GeV."Coherence", "Nano-beam", and "Dynamics" are the major keywords of the 5-GeV ERL. The workshop was taken place for two days and organized as follows.

Figure 1
The Compact ERL Workshop (July 9-10, 2007 at KEK).

Figure 2
The ERL Science Workshop (March 16-17, 2008 at KEK).

1) Introduction (including the performance of the machine).
2) Experimental methodologies.
3) Scientific case on life science by using coherence and nano-beam.
4) Scientific case on material science by using coherence and nano-beam.
5) Scientific case on life science by using short pulses.
6) Scientific case on material science by using short pulses.

The workshop was assigned as one of a series of workshop for the ERL at around 5 GeV.

1-2 Progress in the ERL Project during 2007

Fabrication of accelerator components

Figure 3 shows an outline of the progress of the ERL Project during 2007. Prototypes and/or test devices of several key components such as super conducting cavities for the main accelerator and pre-accelerator, a DC electron gun, and a drive laser system have been fabricated. Some of them are briefly discussed in this report. Detailed information can be obtained from published papers [2,3]. Even though the report was in Japanese, the CDR for compact ERL [1] is expected to be a fundamental report to progress the construction of the compact ERL.

DC electron gun

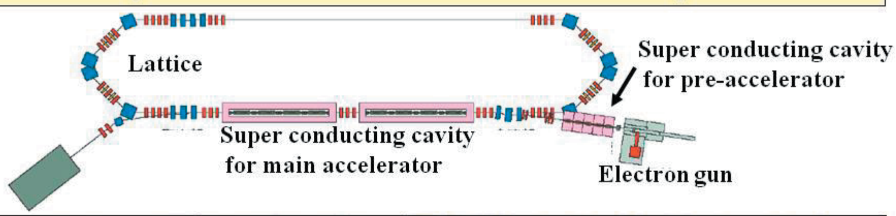
The ERL light source requires an electron gun to generate electron beams with high brightness and high average current; the electron gun is one of the most important components. A 250-kV, 50-mA photocathode DC electron gun has been developed at the JAEA. The fabrication of the gun is almost complete and the first photocurrent was obtained using a NEA-GaAs photocathode. Apparatuses for beam measurements are under installation. We plan to measure the transverse emittance of the beam emitted by the gun and its temporal profile by using a double-slit configuration and a deflecting cavity, respectively. The design of these apparatuses is described elsewhere [4]. On the basis of particle-tracking simulations, the normalized transverse emittances are expected to be 0.59 and 0.11 mm·mrad for bunch charges of 77 and 7.7 pC, respectively.

In addition to the development of the 250-kV gun, we have started the construction of a 500-kV gun, which will be installed in the compact ERL. A multiple-segmented cylindrical ceramic is designed for applying a 500-kV DC voltage to a high-voltage insulator. Studies on photocathode physics and ultrahigh vacuum in collaboration with JAEA, KEK, Hiroshima University, and Nagoya University are also underway in order to obtain a cathode that is capable of operating for long durations.

Drive laser for photocathode DC electron gun

In order to obtain a electron beam with high brightness (0.1 mm·mrad as the natural emittance) and high beam current (100 mA) for an NEA-GaAs photocathode, the requirements for the laser system are as follows: the laser beam should have a wavelength of around 800 nm for an average power of 15 W, a pulse width of 10–20 ps, and a repetition rate of 1.3 GHz. A Yb-doped fiber-amplifier (YDFA) system is the most promising [5,6]. The optical parametric amplifier system can realize a tunable wavelength of around 800 nm. The

Development of the accelerator components



Super conducting cavity for main accelerator	KEK, ISSP, JAEA	37MV/m Single cell model ⇒ 9 cell model ⇒ Cryo-module will be designed in 2009
Electron gun	JAEA, Hiroshima Univ., KEK, and Nagoya Univ.	Construction of electron gun of 250 kV and we start the designing of the electron gun of 500kV
Laser system for electron gun	AIST, ISSP, KEK	Yb fiber laser of ~100MHz oscillator ⇒ 1.3GHz oscillator
super conducting cavity for pre-accelerator	KEK	Test cavities have been completed.
High power RF source	KEK	300 kW Klystron will be ready until summer 2009.
Cryogenic systems	KEK	In progress
Designing of the lattice	KEK, ISSP, UV-SOR, JAEA	In progress
CDR of Compact ERL	All	published in March 2008

Figure 3
Outline of the progress of the ERL Project during 2007..

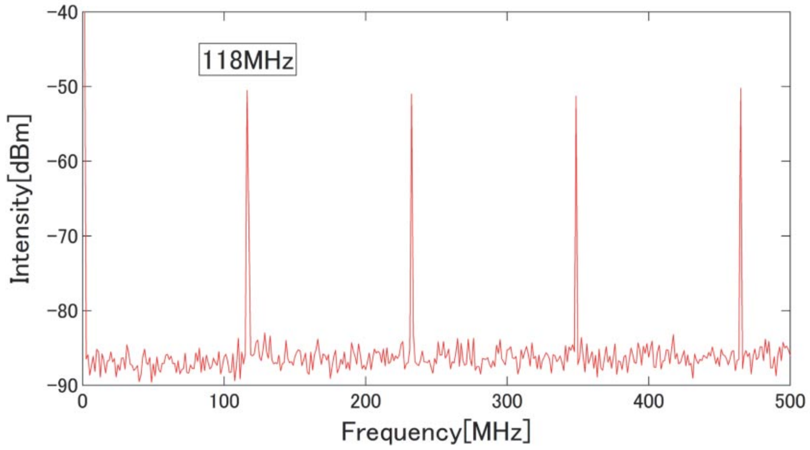


Figure 4
Output of the developed 118 MHz Yb-doped fiber laser oscillator.

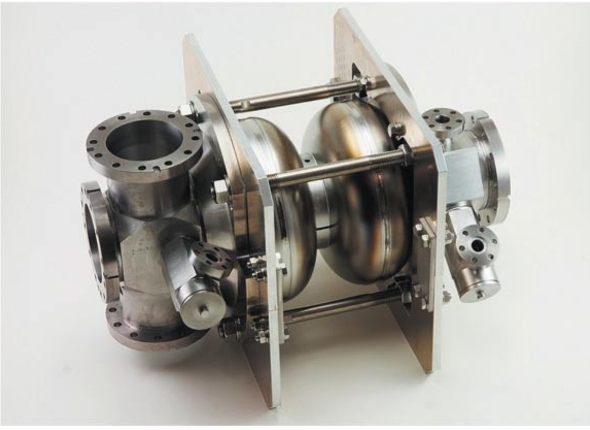


Figure 5
Two-cell superconducting cavity developed for the pre-accelerator.

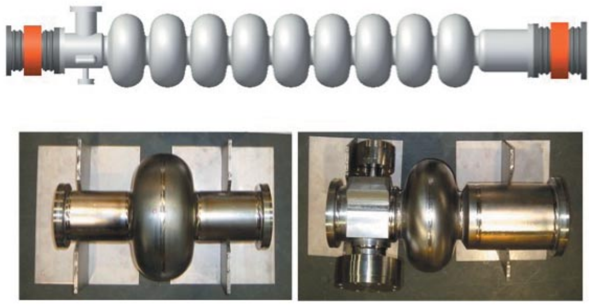


Figure 6
Schematic diagram of the nine-cell cavity (upper) and two prototype cavities, C-single (left) and E-single (right) for ERL..

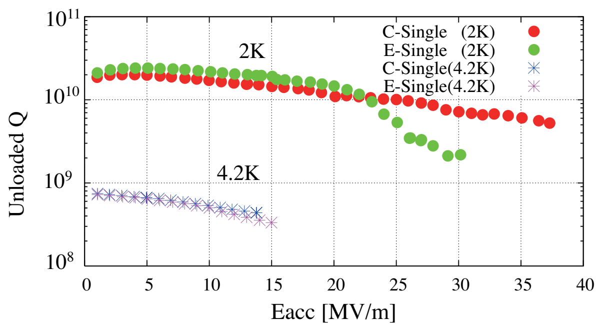


Figure 7
Results of the vertical tests of the prototype single-cell cavities.

required average power for the YDFA system is about 200 W. The National Institute of Advanced Industrial Science and Technology (AIST) has developed a laser with an average power of 30 W, a repetition frequency of 80 MHz, and with pulse widths of a few picoseconds. By using this technology, we are developing a master oscillator and a power amplifier system in collaboration with ISSP and KEK at AIST. A 118-MHz Yb-doped fiber laser oscillator has successfully been developed. Figure 4 shows an output of the developed oscillator. The next challenge is to upgrade its repetition rate to 1.3 GHz.

Superconducting cavities

• *Superconducting cavity for pre-accelerator*

The pre-accelerator for a 5-GeV-class ERL should have the capability to accelerate electron beams of 100 mA up to a beam energy of about 10 MeV without energy recovery. This means that a power of 1 MW has to be provided to the beam in CW operation. The pre-accelerator has been designed as a set of three two-cell cavities, each of which has two power couplers to reduce the power per coupler; the pre-accelerator is also designed to maintain a symmetric field configuration around the coupler ports. Figure 5 shows the prototype of the two-cell cavity prepared in March 2008.

• *Superconducting cavity for main accelerator*

A nine-cell cavity has been designed for the main accelerator so as to damp higher-order modes (HOMs). The diameters of both irises and beam pipes in the cavity are chosen to be large in order to reduce the transverse impedances for its dipole modes. Furthermore, one of the beam pipes has a mode converter called eccentric fluted beam pipe (EFB) in which the quadrupole modes can be partially transformed into dipole modes; the transformed modes can then propagate through the beam pipe. Details of the mode converter can be found in refs. [7,8].

Figure 6 shows the prototypes of two single-cell cavities called C-single and E-single. C-single has the same cell shape as that of the central cell of the nine-cell cavity, while E-single has the shape of the end cell that is equipped with beam pipes for the nine-cell cavity.

We have examined the method of fabrication, surface treatment processes, and performance of these cavities. Figure 7 shows the Q-E plot obtained from vertical cold tests. Both the cavities satisfy the specification of 20 MV/m for an unloaded Q of 1×10^{10}, which corresponds to the target value for the nine-cell cavity of the main accelerator of the ERL Project. We have already started the fabrication of the prototype of the nine-cell cavity.

Design of the compact ERL and its performance as light sources

We have completed the conceptual design [1] of the compact ERL, which is a test facility planned to be built in the East Experimental Hall in KEK; the design is shown in Fig. 8. Table 1 shows the principal parameters of the compact ERL together with those of an ERL-based light source to be developed in the future. The main purpose of constructing the compact ERL is to demonstrate the reliable operation of the key components of the ERL as well as to investigate topics in accelerator physics that are critical to build an ERL for the light source.

The compact ERL can also be used as (i) an intense terahertz radiation source producing a CSR and (ii) an ultrashort or a high-intensity X-ray source employing laser inverse Compton scattering. We anticipate a photon flux density of about 10^{17} photons/s/mrad^2/0.1%b.w. [9] at a photon energy of about 10 meV (~2.4 THz) from compressed bunches with pulse widths of 59 fs (rms) at a beam energy of 155 MeV. The compact ERL can also provide ultrashort X-ray pulses with pulse widths of about 110 fs. With a 90° Compton-backscattering configuration, we anticipate a photon flux of 3.5×10^3 photons/pulse/3%b.w. [1] at a beam energy of 60 MeV, a bunch charge of 100 pC, and a laser pulse energy of 10 mJ/pulse.

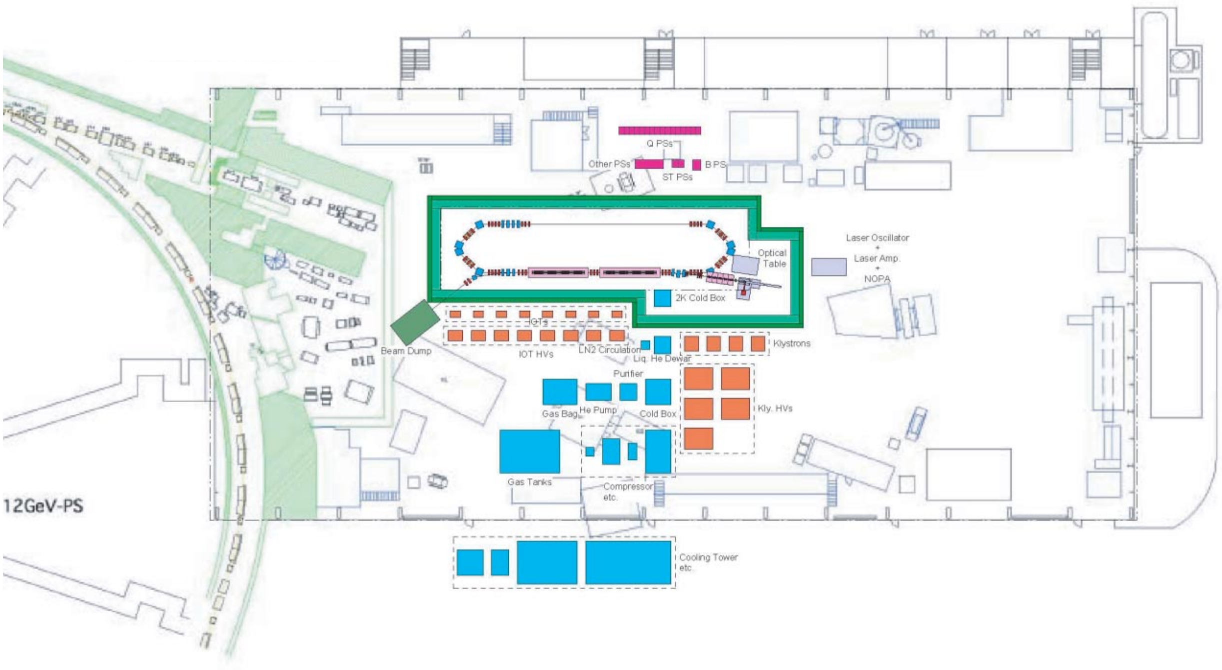


Figure 8
Compact ERL to be built in the East Experimental Hall at KEK.

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

	Compact ERL	5GeV ERL
Beam energy (GeV)	0.065–0.2	5
Injection energy (MeV)	5	~10
Path length (m)	70	1253
Beam current (mA)	10 - 100	10 - 100
Charge per bunch pC	7.7 - 77	7.7 - 77
Normalized emittance (mm·mrad)	0.1–1	0.1–1
Bunch length (ps)	0.1 – 3	0.1 – 3

1-3 Time Schedule of the ERL Project

The time schedule of the ERL Project is shown in Fig. 9. By the start of FY2010, we expect to complete the evacuation and construction of the infrastructure for the compact ERL, e.g., arranging for the supply of electricity, cooling water, and a cryogenic system for the superconducting cavities at the site where the East Experimental Hall is under construction. Actual work on the alignment of the accelerator components will start at the beginning of fiscal year 2010 and be completed at the end of 2011. The beam operation will start at the beginning of 2012. The beam test will provide important information on whether further improvement of the components is necessary and also on the drawbacks in the design of the 5-GeV ERL.

REFERENCES

[1] R. Hajima, N. Nakamura, S. Sakanaka and Y. Kobayashi, *KEK Report 2007-7/JAEA-Research 2008-032* (2008) [in Japanese].

[2] S. Sakanaka et al., *Proc. 2008 European Particle Accel. Conf.*, (2008) 3946-MOPC061.

[3] T. Kasuga, T. Agoh, A. Enomoto, S. Fukuda, K. Furukawa, T. Furuya, K. Haga, K. Harada, S. Hiramatsu, T. Honda, K. Hosoyama, M. Izawa, E. Kako, H. Kawata, M. Kikuchi, Y. Kobayashi, M. Kuriki, T. Mitsuhashi, T. Miyajima, T. Naito, S. Nagahashi, T. Nogami, S. Noguchi, T. Obina, S. Ohsawa, M. Ono, T. Ozaki, S. Sakanaka, H. Sasaki, S. Sasaki, K. Satoh, M. Satoh, T. Shioya, T. Shishido, T. Suwada, M. Tadano, T. Takahashi, Y. Tanimoto, M. Tawada, M. Tobiyama, K. Tsuchiya, T. Uchiyama, K. Umemori, S. Yamamoto, R. Hajima, H. Iijima, N. Kikuzawa, E. J. Minehara, R. Nagai, N. Nishimori, M. Sawamura, A. Ishii, I. Ito, H. Kudoh, N. Nakamura, H. Sakai, T. Shibuya, K. Shinoe, H. Takaki, M. Katoh, A. Mochihashi, M. Shimada, H. Hanaki and H. Tomizawa, *Proc. 2007 Particle Accel. Conf.*, (2007)1016.

[4] N. Nishimori R. Hajima, H. Iijima, R. Nagai, *Proc. ERL07* .

[5] H. Tomizawa for LAAA, *LAAA Note/ERL-Report-003*, 2006 [in Japanese].

[6] J. Itatani and Y. Kobayashi, "Laser for ERL photo-cathode", project proposal submitted to KEK-JAEA ERL project, 2007 [in Japanese].

[7] K. Umemori et al., *Proc. 2007 Asian Particle Accel. Conf.*, (2007)570.

[8] M. Sawamura et al., *Proc. 2007 Particle Accel. Conf.*, (2007)1022.

[9] K. Harada, M. Shimada and R. Hajima, *Infrared Phys. Tech.* **51** (2008) 386.

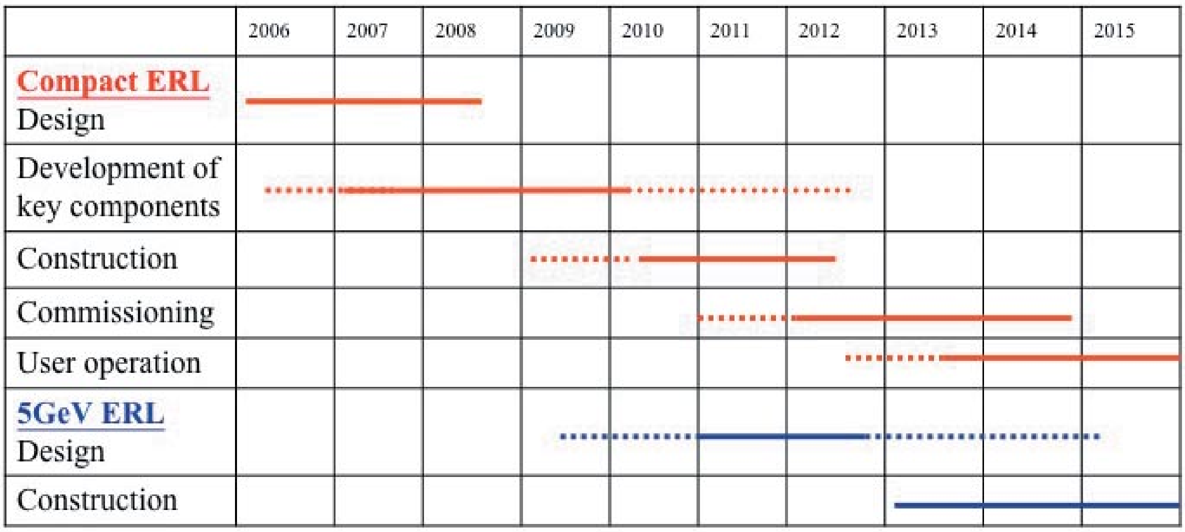


Figure 9
Time schedule of the ERL Project.