1 The ERL Project

1-1 Introduction

The energy recovery linac (ERL) is expected to be useful for carrying out innovative research in new areas of materials science. By illuminating a specimen with short-pulse, coherent nanometer-sized X-ray beams, scientists can conduct nondestructive measurements on rapidly evolving dynamical materials and organisms with submicron resolution. Multitudes of applications will be available in material, life, chemical and environmental sciences. Research studies on high-speed next-generation communication devices, drug discovery, subcellular imaging, catalysts for clean hydrogen energy systems, and efficient utilization of light energy are gaining interest.

The ERL Project Office was set up at KEK on April 1, 2006, for the development of the ERL. The office was assigned the task of forming the ERL Project Team, which currently includes several working groups, for the design and development of key components of the ERL. Accelerator scientists from KEK, JAEA(Japan Atomic Energy Agency), ISSP(The Institute for Solid State Physics), UVSOR(Outline of the Ultraviolet Synchrotron Orbital Radiation Facility), SPring-8, AIST(Advanced Industrial Science and Technology), Hiroshima University, and Nagoya University are part of this team. Furthermore, the office plays a major role in forming a collaboration between the present ERL project and other ERL projects around the world. For example, the Cornell Laboratory for Accelerator-Based Sciences and Education (CLASSE), Cornell University, and KEK signed an MOU in March 2007. These collaborations are summarized in Fig. 1

Since there is no GeV-class ERL in the world, it is necessary to construct a test accelerator (Compact ERL; energy: 35–245 MeV) that can be used for developing several critical accelerator components such as a high-brilliance DC photocathode electron gun and superconducting cavities for the injector and main accelerator. In the period 2006–2008, we concentrated on the design and development of such an ERL and its components and published the Conceptual Design Report (CDR) [1] for the Compact ERL in March 2008.

During the FY2008, several accelerator components have been fabricated and tested at a budget of approximately 230 million Japanese Yen, and hence, rapid progress has been made in the development of the accelerator components; these will be discussed in the next session. In addition, a supplementary budget of approximately 1.1 billion Japanese Yen has been sanctioned for infrastructure development, i.e., reconstruction of the East Counter Hall, setting up of electric power and cooling water supply systems, and development of a liquid helium cryogenic system. Thus, FY2008 marks the initial phase of construction of the Compact ERL.

The ERL Project Advisory Committee was set up on September, 16, 2008, for suggestions on the progress of the ERL project. The committee acknowledged that reasonable progress was being made in the development of the accelerator components and encouraged us to carry out further work in this direction. One of the important suggestions made by the committee was that the scientific cases of the final 5-GeV ERL should be brushed up much more clearly to promote the ERL project. Accordingly, we organized a meeting with the Chair Prof. Kazumichi Namikawa at Tokyo Gakugei University and invited suggestions on scientific cases of the ERL. The scientific case of the ERL was intensively discussed from November to December 2008; the decisions made during these discussions are summarized in Fig. 2.

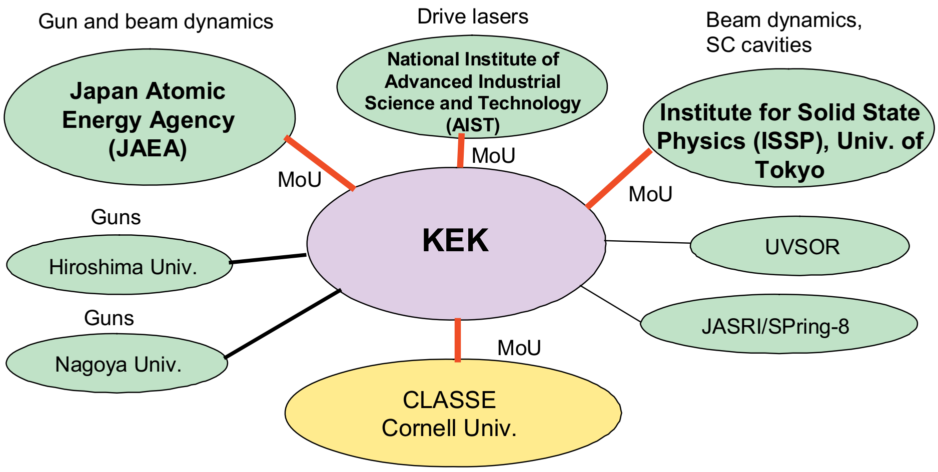

Figure 1
Collaborations for developing ERL technology.

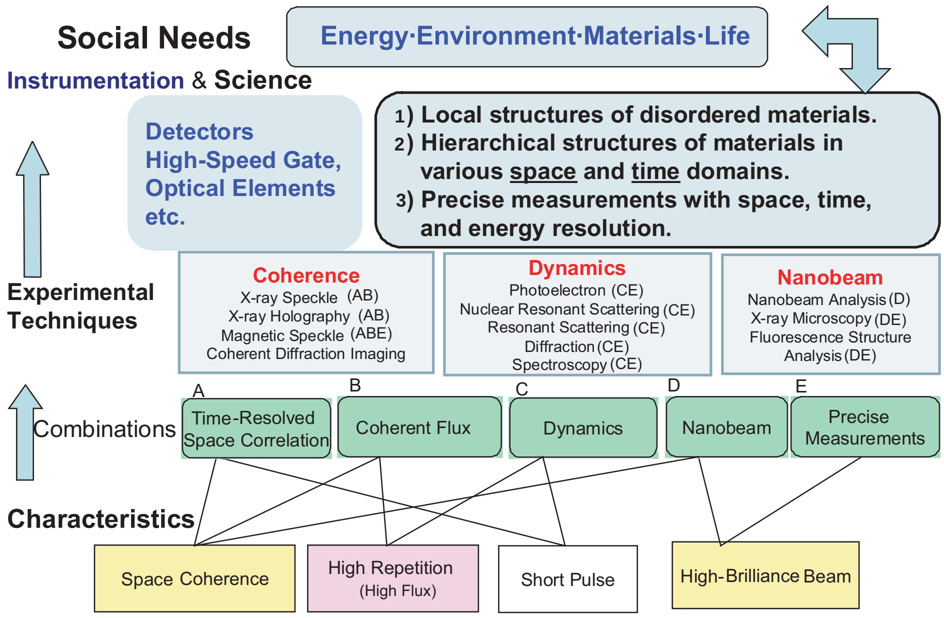

Figure 2
Summary of brainstorming meeting for scientific cases of ERL.

The discussion started from the picking up the characteristics of the synchrotron radiation from the ERL, such as space coherence, high repetition rate, short pulse, and high brilliance beam. Then, we analyzed the advantages and disadvantages of various possible combinations of the aforementioned characteristics; for example, a time-resolved space correlation effect would possibly be observed for beams with spatial coherence and a short pulse. The other combinations are coherent flux, dynamics, nanobeam and precise measurements. Then, we discussed experimental techniques based on the ERL characteristics and finally concluded that the unique science case based on the ERL were as follows:

1) Local structures in disordered materials
2) Hierarchical structures of materials in various space and time domains
3) Precise measurements with space, time, and energy resolution.

In the meeting, it was recommended that a science workshop be organized to familiarize researchers with the sophisticated instrumentation of the ERL and help them operate the synchrotron radiation source. Since February 2009, a series of science seminars and lunch-time seminars were organized, and an ERL science workshop will be held in July 2009. Details of the topics covered in this workshop will be presented in the next annual report.

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1-2 Accelerator Developments during 2008

Extensive R&D studies were carried out in 2008 for developing an ERL-based synchrotron light source. Top priority was given to the development of key accelerator components such as a high-brightness electron gun and superconducting RF cavities. Further, construction of a test accelerator (Compact ERL) was planned for demonstrating beam acceleration and beam recirculation using the above-mentioned key accelerator components.

Photocathode DC gun

The ERL light source requires an electron gun that can generate electron beams with high brightness and high average current. The electron gun is one of the most important components of the ERL. A prototype 250-kV, 50-mA photocathode DC gun has been developed at JAEA. The assembly of the gun is almost complete, and the first photocurrent measurement has been performed using a negative-electron-affinity (NEA) GaAs photocathode. Preliminary measurements demonstrated that the 250-kV gun could produce low-emittance electron beams with a normalized emittance of approximately 0.13 mm·mrad at a low beam current of less than 1 μA [2].

In addition to the development of the 250-kV gun, we are involved in the construction of a 500-kV, 10-mA photocathode DC gun [3] (Fig. 3) under a collaboration between JAEA, KEK, Hiroshima University, and Nagoya University. An improved ceramic insulator equipped with guard rings is incorporated in this gun. With this new DC gun, it is possible to mitigate damages caused to the ceramic insulator during high-voltage operations; such damages have been observed in the case of some pioneering guns such as the gun at Cornell University [4]. In order to enhance the lifetime of the NEA surface, it is necessary to maintain the pressure at an extremely

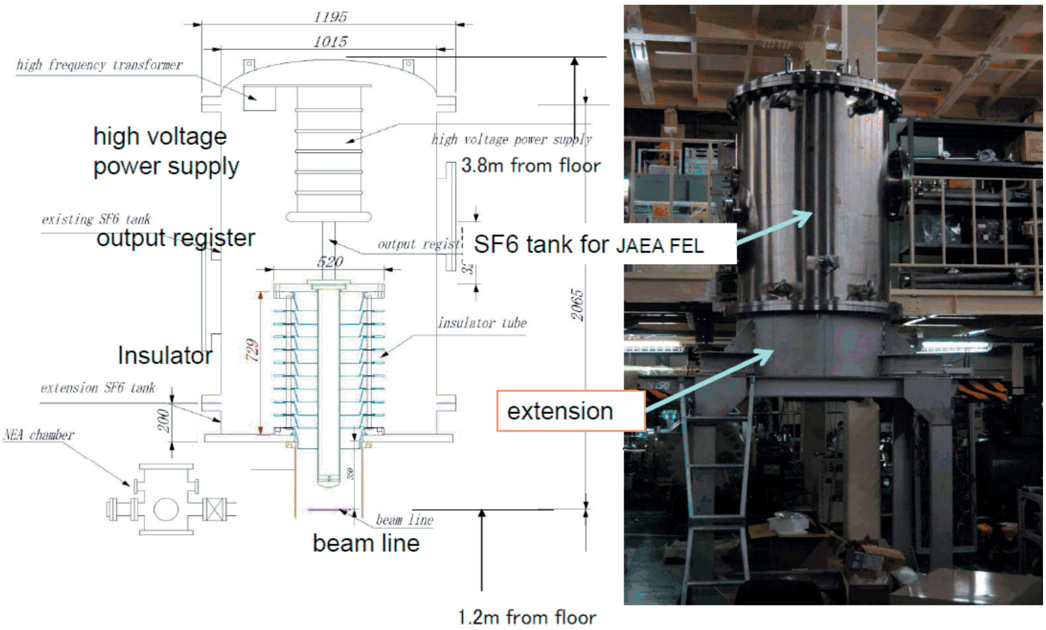


Figure 3
A 500-kV, 10-mA photocathode DC gun was assembled at the Japan Atomic Energy Agency (JAEA).

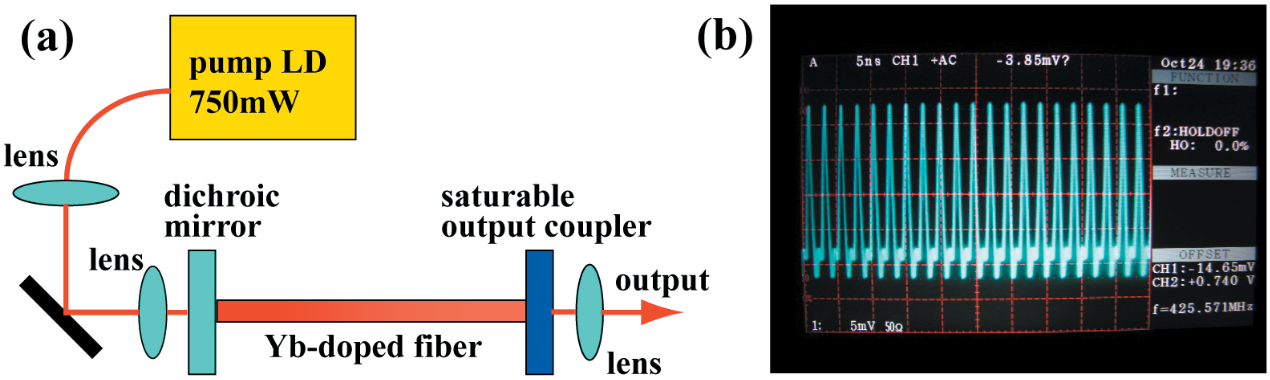
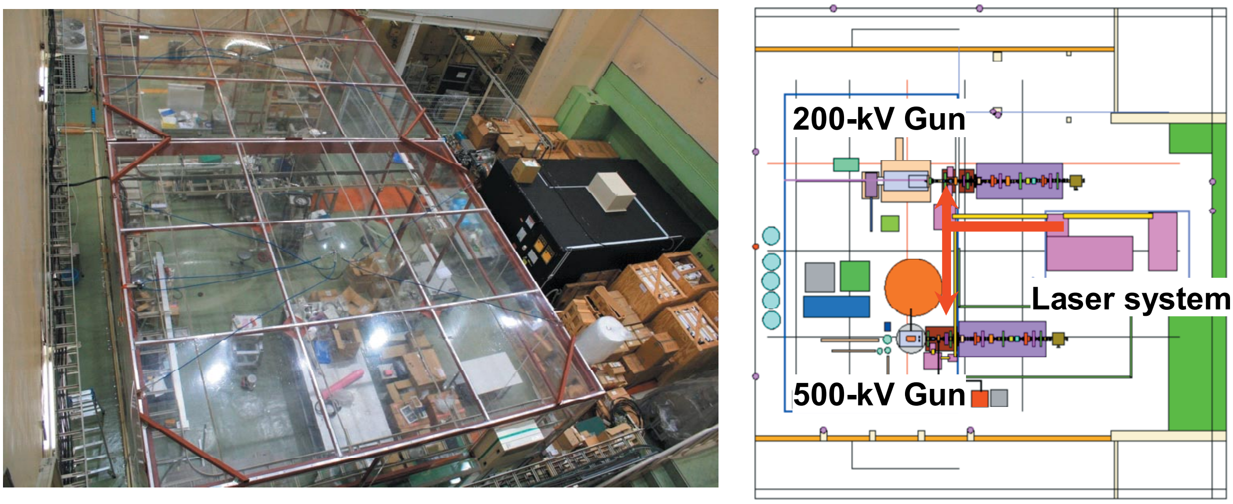


Figure 4
A Yb-fiber laser oscillator. (a) Layout of a linear-cavity fiber laser oscillator, (b) output of a 425-MHz pulse train.



(a) (b)

Figure 5
ERL gun development area in the South Hall of the storage ring PF-AR. (a) Photograph of present area, (b) planned layout.

low value, i.e., at approximately 10^{-10} Pa. For this purpose, all the vacuum chambers are manufactured using a titanium alloy that has a very low outgassing rate, and the chambers are equipped with powerful pumps (NEG pumps of 18000 liters/s and an ion pump of 500 liters/s). The ceramic insulator, vacuum chambers, and a Cockcroft-Walton high-voltage power supply have been delivered, and high-voltage testing will soon be commenced.

Drive laser for the gun

The photocathode DC gun is driven by a special laser system. The drive laser provides laser pulses at a high repetition rate of 1.3 GHz. The principal requirements of this laser system are as follows: 1) wavelengths of around 800 nm, 2) an average power of 15 W, and 3) pulse widths of 10–20 ps. We are developing the drive laser in a stepwise manner, as such a laser system is not commercially available. We believe that a Yb-doped fiber amplifier (YDFA) system is the most promising candidate for the above-mentioned laser system [5, 6].

As the first step, we are developing a Yb-fiber laser oscillator that could be operated at a high repetition rate of up to 1.3 GHz. We attempted to develop the following two systems: (1) a 100-MHz ring-cavity fiber laser combined with a 1.3-GHz external cavity; (2) a linear-cavity fiber laser oscillator [7]. In the former case, we could generate 1.3-GHz laser pulses; however, neither the power nor the stability was sufficiently high in this case. In the latter case, we could generate a pulse train with a fundamental repetition rate higher than 400 MHz, as shown in Fig. 4. In addition, we plan to develop a ring-cavity fiber laser oscillator with 1.3-GHz electro-optic (EO) modulation.

In order to develop an electron gun and a drive laser before installation in the Compact ERL, we have designed a test area in the South Hall of PF-AR. Figures 5(a) and 5(b) show the photograph and layout of the test area used for the electron gun. In this area, two DC electron guns will be installed, as shown in Fig. 5(b). One is a 200-kV spin-polarized electron gun developed at Nagoya University and transferred to KEK, and the other is a 500-kV DC electron gun that will be developed for installation in the Compact ERL. Construction of a diagnostic beamline and a laser system for 10-mA beams is in progress.

Superconducting cavities

• *Superconducting cavity for injector linac*

In the injector linac of the Compact ERL, high-current (maximum current: 100 mA) electron beams will be pre-accelerated to an energy of 5 MeV before they are injected to the main linac. For this purpose, three two-cell superconducting (SC) cavities with an RF frequency of 1.3 GHz are used. The three cavities will be housed in a single cryostat. The most important requirements for these cavities are as follows: (1) feasibility of use in CW operation, (2) high unloaded Q of approximately 10^{10} with a moderate accelerating gradient of 10–15 MV/m, (3) high power capability for input couplers, and (4) efficient higher-order-mode (HOM) damping.

To develop these cavities, we first constructed a prototype cavity having two large ports for input couplers and four HOM couplers. In order to use this cavity for CW operations, we improved the design of the HOM couplers from those for the TESLA-type cavity, where heat losses due to the fundamental modes could be reduced. Figure 6 (left) shows a photograph of the prototype cavity assembled for the vertical test. In the first vertical test carried out on this cavity [8], we could successfully maintain a high field gradient of 15.2–15.8 MV/m for 580 min under CW operation at temperatures of 1.6–2 K. The Q values measured in the test are indicated by red circles in Fig. 6 (right).

A cryostat that can house three two-cell cavities is

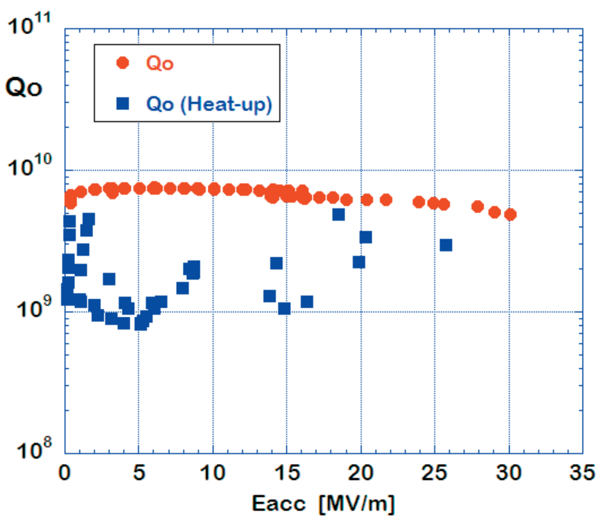


Figure 6
Prototype superconducting cavity for the injector (left) and result of vertical test carried out on the cavity (right).

also being designed. An input coupler for the injector cavities, each of which can transmit a high RF power of approximately 170 kW, is also under development.

Figure 7
Preparation for vertical testing of the nine-cell superconducting cavity.

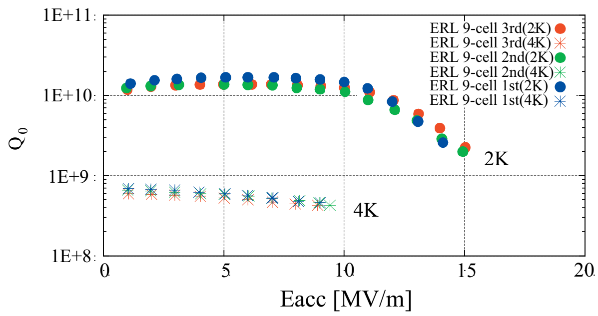


Figure 8
Results of the first vertical test carried out on of the prototype nine-cell cavity.

• *Superconducting cavity for the main linac*

Nine-cell SC cavities for the main linac are under development. Essential issues on these cavities are as follows: (1) feasibility of use in CW operation, (2) high accelerating gradient of 10–20 MV/m with Q values higher than 10^{10}, (3) efficient HOM damping, and (4) reliable input couplers that can withstand a moderate RF power of up to 20 kW/coupler. For this purpose, we have designed a nine-cell cavity [9] where harmful higher-order-modes can be extracted by large beam pipes.

We first fabricated two single-cell cavities whose cells were similar to those of the designed nine-cell cavity in shape and tested them successfully [10]. We then fabricated a prototype nine-cell cavity and carried out vertical tests [11]. Figure 7 shows a photograph recorded when preparations were being made for the test.

The results of the first vertical tests are shown in Fig. 8. We successfully tested the cavity under field gradients of up to 15 MV/m at 2 K; we also achieved an unloaded Q of higher than 10^{10} at a field gradient of 10 MV/m. However, we found that when the field gradient exceeded 10 MV/m, the Q value decreased because of field emissions. To resolve this problem, we plan to finish a suspicious spot of the cavity and retest it.

Along with the above-mentioned cavity fabrication and surface processing studies, we are involved in the design of a prototype cryostat that can house two nine-cell cavities.

The Compact ERL

In order to demonstrate the production and recirculation of ultra-low-emittance beams using the above-mentioned key components, we plan to construct a test accelerator named Compact ERL [1]. Compact ERL will be built in the East Counter Hall at KEK, and the old building (dimensions: 100 m × 50 m) will be refurbished

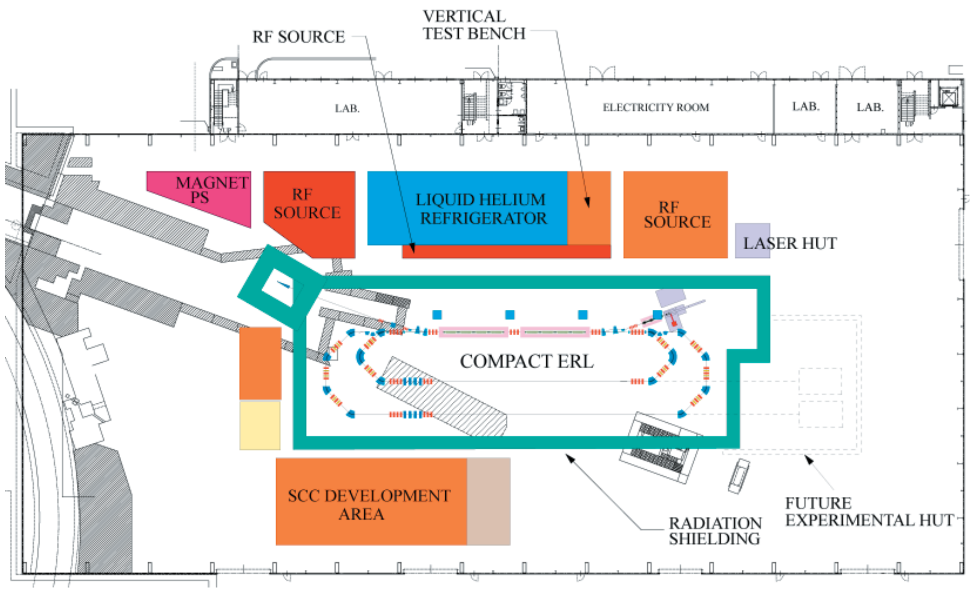


Figure 9
Planned layout of the Compact ERL in the East Counter Hall.

for this purpose.

The Compact ERL comprises the injector, the main linac, a return loop, and a beam dump. The ERL injector produces high-brightness electron beams and accelerates them to an energy of 5 MeV. The beams are then merged into the main linac and further accelerated to the final beam energy. The beams are recirculated through the return loop, deccelerated in the main linac for energy recovery, and finally dumped. Figure 9 shows the planned layout of the Compact ERL. The principal parameters of the Compact ERL are listed in Table 1.

The injector linac comprises a 500-kV photocathode DC gun, two solenoids, a buncher, three SC cavities, five quadrupole magnets, and a merger. To preserve the extremely low emittance from the photocathode gun, it is necessary to optimize the injector design. We carried out this optimization [12] using a multiobjective method [13]. In this method, we used a computer code GPT and carried out a number of tracking simulations to each set of several (at present, nineteen) parameters corresponding to the injector. Using a genetic algorithm, we attempted to find an optimized set of parameters that would give the minimum beam emittance for a given bunch length at the merger exit. The injector design and optimization results are shown in Figs. 10 and 11, respectively. At present, the normalized emittance is calculated to be 0.58 mm·mrad for an rms bunch length of 0.6 mm and beam energy of 7 MeV.

Table 1 Objectives for the Compact ERL.

Beam energy [1]	35 - 245 MeV
Injection energy	5 MeV
Maximum beam current	10 - 100 mA
Charge per bunch	7.7 - 77 pC
Normalized emittance	0.1 - 1 mm·mrad
RF frequency	1.3 GHz
Rms bunch length	0.1 – 3 ps

1) To be upgraded by stages.

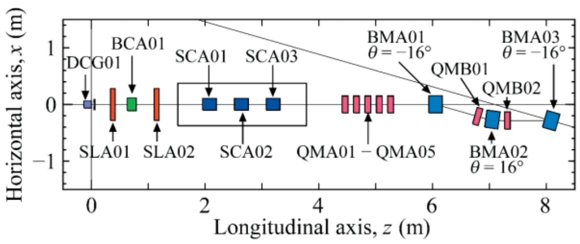


Figure 10
Design of the Compact ERL injector. In this design, the merger comprises rectangular bends and quadrupoles. Merger angle is 16°.

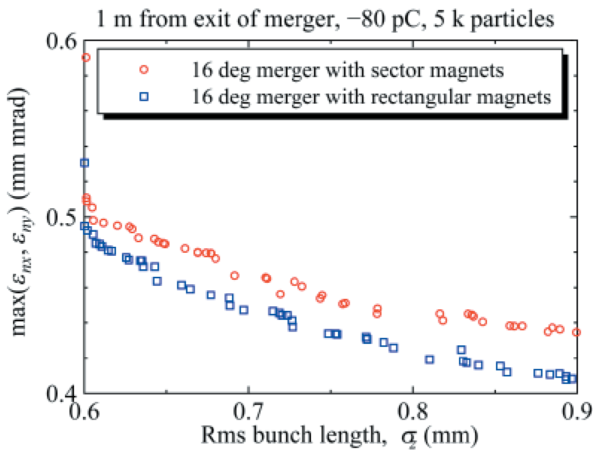


Figure 11
Normalized beam emittance as a function of bunch length after optimization. Simulation results for two types of mergers (one shown in Fig. 10 and the other using sector magnets) are shown. The beam emittances and bunch lengths are calculated at a point 1 m downstream of the merger exit. Beam energy at the exit is 7 MeV.

In the main linac, we can install two cryomodules, each of which can accommodate four nine-cell cavities. At a typical accelerating gradient of 15 MV/m, a maximum beam energy of 125 MeV can be achieved. We are currently considering three operation modes: a high-current (77 pC/bunch, 1 mm·mrad) mode, a low-emittance (7.7 pC/bunch, 0.1 mm·mrad) mode, and a bunch compression (>77 pC/bunch at a low repetition rate) mode. We have optimized the beam optics for the above-mentioned three operation modes [14].

The Compact ERL will initially be constructed with a single return loop, and it can be upgraded in future by installing a second return loop [15]. After the upgradation, we can carry out studies on issues such as emittance preservation in two-loop ERLs and double the beam energy. This study is expected to be highly beneficial, as the use of the two-loop ERL would help reduce the construction cost of future large-scale ERLs.

The proposed budget for refurbishing the East Counter Hall, including reinforcement of the building and renovation of the cooling water plant and an electrical substation, has been sanctioned. We also received funds for installing a liquid helium refrigerator (cooling capacity: approximately 600 W at 4 K) and a part of high-power RF sources for the Compact ERL. Design of these components is underway. Thanks to the staff of the Institute of Particle and Nuclear Studies at KEK, efforts for clearing 10,000 tons of concrete shield material and activated proton beamlines are underway in the East Counter Hall.

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1-3 Time Schedule of the ERL Project

The tentative schedule of the ERL Project is shown in Fig. 12. By April 2010, evacuation of the East Counter Hall as well as infrastructure development for the Compact ERL will be complete. Installation of the accelerator components will commence after April 2010 and will hopefully be completed by mid 2012. Then, commissioning of the Compact ERL will be carried out at a beam energy of 35 MeV. The results of the beam test will provide information that can be used for making improvements to the accelerator components that are necessary for designing components for the final 5-GeV ERL.

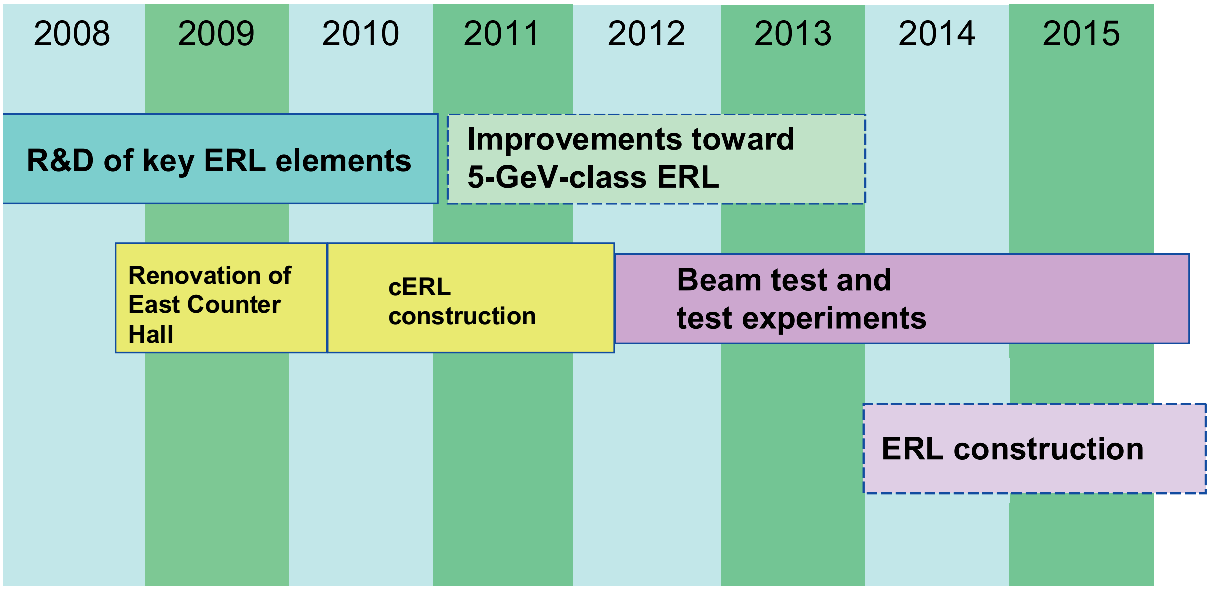

Figure 12
Tentative schedule of the ERL project.