# ERL-BASED LIGHT SOURCE CHALLENGES

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*Abstract*

The challenges of the design and technology for the future Energy Recovery Linac (ERL) based light source are reviewed. The developments of a high-brightness electron source, including the drive laser, and the CW high gradient superconducting cavities for both injector and main linac as key components of the accelerator are described. In addition, the status of the compact ERL (cERL) for R&D which is going to be constructed at KEK is presented.

## INTRODUCTION

The Energy Recovery Linac (ERL) is a future X-ray light source based on state-of-the-art superconducting linear accelerator technology, which will offer far higher performance than the existing storage ring. The high repetition rate, short pulse, high spatial coherence and high brightness will enable the filming of ultrafast atomic-scale movies and determination of the structure of heterogeneous systems on the nano-scale. These unique capabilities of ERL will lead to a distinct paradigm shift in X-ray science from static and homogeneous systems to dynamic and heterogeneous systems, in other words, from time- and space-averaged analysis to time- and space-resolved analysis. In short, ERL will be an unprecedented tool that will bridge the critical gaps in our understanding of material science and technology [1].

In addition, continuous improvements in linear accelerator technology may result in dramatic progress in X-ray science in the future, such as the realization of a fully coherent X-ray free-electron laser. Although self-amplified spontaneous emission X-ray free-electron lasers (SASE-XFELs) are in use around the world, the X-ray beam from SASE-XFEL is essentially not fully coherent in the temporal domain. By configuring a Bragg diamond cavity for lasing in the X-ray region, it may be possible to create an X-ray free-electron laser oscillator (XFEL-O) by taking full advantage of the unprecedented electron beam quality of ERL [2-4]. Construction of the XFEL-O is planned in the second stage of the ERL project.

KEK established the ERL Project Office in April 2006. Because a GeV-class ERL machine has not been constructed anywhere in the world, it is first necessary to construct a compact ERL (cERL) with an energy of 35 MeV that can be used for developing several key accelerator components such as a high-brilliance DC photocathode electron gun and superconducting cavities for the injector and main linac. During 2011, such main accelerator components were successfully developed and operation of the beam will start at the end of March 2013.

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In this conference, the development of high-brightness electron sources and superconducting cavities, which are key accelerator components for the ERL, and construction of the compact ERL for R&D at KEK, will be mainly presented.

## DESIGN CONCEPT OF THE 3-GEV ERL AT KEK

For the future project of the KEK Photon Factory, we propose constructing a 3-GeV ERL that can be upgraded to become the XFEL-O [5-7]. A conceptual layout of the 3-GeV ERL is shown in Fig. 1. In the first stage of the project, a 3-GeV ERL which comprises an injector linac, a superconducting main linac, and a return loop will be constructed. In the return loop, 20–30 insertion devices which are used to emit synchrotron radiation will be installed. Using state-of-the-art undulator technology, a broad spectrum of synchrotron radiation from vacuum ultra-violet (VUV) to hard X-rays will be covered.

In the second stage of the project, an XFEL-O system which comprises a long undulator and an X-ray resonator will be built. To deliver high-energy beams for the XFEL-O system, the path length in the return loop by a half rf wavelength of 115.3 mm will be adjusted. Under this configuration, the beams are firstly accelerated to 3 GeV through the main linac and pass through the return loop. The beams are then accelerated again (without energy recovery) through the main linac up to 6 GeV. Finally, the beams are used to drive the XFEL-O, and dumped without energy recovery.

Target parameters of the 3-GeV ERL are given in Table 1. Since the ERL is a very flexible light source, this table shows some typical operational modes. For the major users requiring highly brilliant SR, we provide high-coherence or high-flux modes of operation. Among these modes, the high-flux mode imposes a greater challenge for the lifetime of the photocathodes. The "ultimate" mode requires both very-low emittance and high currents; this imposes much greater challenges for the accelerator physics and engineering, and thus is a long-term goal. In the ultra-short-pulse mode, we compress the electron bunches down to a hundred femto-seconds or shorter. In this mode, the beam emittances are largely influenced by the coherent synchrotron-radiation in the return loop. Then, bunch charges in this mode will be chosen by balancing the SR intensity and the beam emittance.

Table 1: Target Parameters of the 3-GeV ERL Integrated with the X-Ray Free-Electron-Laser Oscillator (XFEL-O)

| Operation modes | High-coherence mode | High-flux mode | Ultimate mode | Ultra short-pulse mode | XFEL-O mode |
|---|---|---|---|---|---|
| Beam energy ($E$) | 3 GeV | 3 GeV | 3 GeV | 3 GeV | 7 (6) † GeV |
| Average beam current ($I_0$) | 10 mA | 100 mA | 100 mA | Typically, 77 mA (flexible) | 20 mA |
| Charge/bunch ($q_b$) | 7.7 pC | 77 pC | 77 pC | Typically, 77 pC (flexible) | 20 pC |
| Repetition rate of bunches ($f_{rep}$) | 1.3 GHz | 1.3 GHz | 1.3 GHz | Typically, 1 MHz (flexible) | 1 MHz |
| Normalized beam emittances ($\varepsilon_{nx}$, $\varepsilon_{ny}$) | 0.1 mm·mrad | 1 mm·mrad | 0.1 mm·mrad | To be investigated (typically, 1-10 mm·mrad) | 0.2 mm·mrad |
| Beam emittances at full beam energy ($\varepsilon_x$, $\varepsilon_y$) | 17 pm·rad | 170 pm·rad | 17 pm·rad | To be investigated (typically, 1 - 10 nm·rad) | 7 pm·rad |
| Energy spread of beams; in rms ($\sigma_E/E$) | $2\times10^{-4}$ | $2\times10^{-4}$ | $2\times10^{-4}$ | To be investigated | $5\times10^{-5}$ |
| Bunch length; in rms ($\sigma_t$) | 2 ps | 2 ps | 2 ps | 100 fs | 1 ps |

† Parameters for the XFEL-O at a beam energy of 7 GeV [2-4] are shown. Parameters at a lower beam energy of 6 GeV are under investigation.

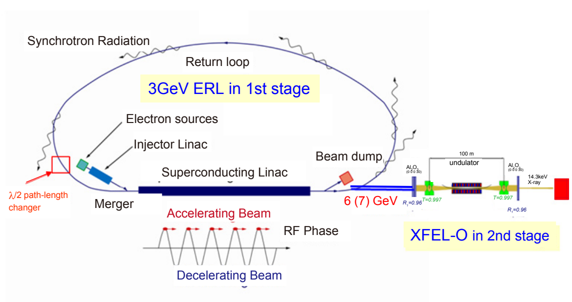


Figure 1: Conceptual layout of 3-GeV ERL plan integrated with an X-ray free electron-laser oscillator (XFEL-O).

## DEVELOPMENT OF KEY COMPONENTS FOR ERL

### *High-Brightness DC Photocathode Gun and Gun Test Beamline*

Two high-brightness photocathode DC electron guns are under development at the Japan Atomic Energy Agency (JAEA) and KEK site to meet the requirements for the Energy Recovery Linac (ERL) of a normalized emittance of less than 1 mm·mrad and a sufficiently long cathode lifetime. To suppress the increase in emittance induced by the space-charge effect, the gun voltage must be 500 kV or higher. An extreme high vacuum of the gun chamber is required to preserve the negative electron affinity (NEA) surface of the cathode. All of the vacuum components in the gun system (a titanium chamber, ceramic insulators, guard rings, etc.) should have a low outgassing rate, and the pumps should function under the extreme high vacuum.

The first gun developed at JAEA has successfully extracted an electron beam of 10 mA with a voltage of 180 kV and has applied a high voltage of up to 500 kV with a cathode electrode and NEG pumps in place. The pressure of the gun chamber reached $6\times10^{-10}$ Pa ($N_2$ equivalent) with 18000 l/s NEG pumps after baking at 180ºC for 50 h. The 1/e static lifetime of the NEA GaAs cathode is 1000 h in a cathode preparation chamber.

The second gun developed at KEK has been constructed with a gun chamber and a pair of ceramic insulators with guard ring electrodes fixed inside as shown in Fig. 2. In order to understand the actual performance of the vacuum system, we have precisely measured the outgassing rate by the rate-of-rise method. The gun system was baked at 150–200ºC for 100 hours. After the baking process, a total outgassing rate of $1.0\times10^{-10}$ Pa m$^3$/s ($H_2$ equivalent) was measured.

To study the properties of the cathode, the initial beam emittance and temporal response have been measured by using a 200-kV gun and a beam diagnosis system. The 200-kV gun was originally developed at Nagoya University and the beam diagnosis system, which has a RF deflector, a double slit system, solenoids and screen monitors, was constructed at KEK. Typical results for the temporal response of photocathodes with different thickness of active layer are shown in Fig. 3. The measured photoemission response depends on the thickness of the active layer [8].

### *Drive Lasers*

A drive laser system that has a repetition rate of 1.3 GHz, pulse duration of 20 ps, and average power of 15 W is required for 10 mA beam operation in cERL. The wavelength was originally specified to be ~800 nm to minimize the emittance, however, our studies on the emittance and time response of photocathodes have




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shown that ~500 nm is a better choice. A stable oscillator that can be synchronized to the accelerator timing system, a high-power amplifier, and a wavelength conversion system are the main components of the laser system. Various other issues related to beam operation include spatial and temporal shaping, various operational modes of pulse structure, delivery to the gun, position and intensity control, and fast interlock system.

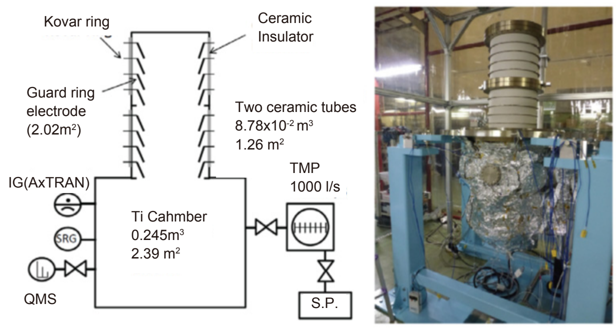


Figure 2: Layout of the vacuum system for the 2nd gun at KEK (left), and a photograph of the system (right).

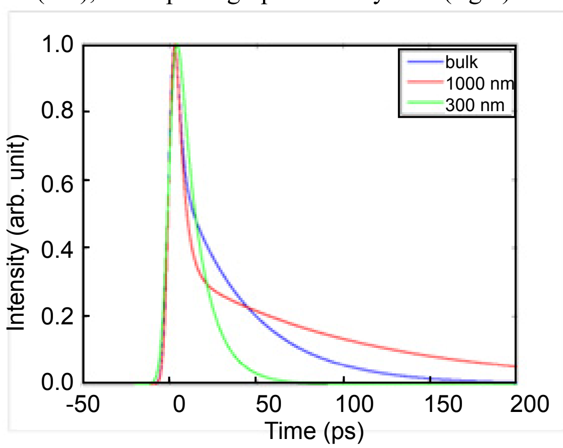


Figure 3: Temporal response of NEA GaAs photocathode by irradiation of short laser pulses (~ ps, $\lambda$ = 785 nm) to a thickness of 300 nm, 1000 nm and bulk sample.

Work on developing the drive laser system has been under way since 2007. Various schemes for the 1.3 GHz oscillator have been tried and a 10 W-class fiber amplifier has been demonstrated, but the results were not sufficient to achieve the above target values.

We have therefore introduced a commercially available 1.3-GHz laser oscillator and a fiber amplifier in a gun test stand, and have studied the performance of the oscillator. Although the long-term stability is still questionable, we confirmed that it could operate in a mode-lock state synchronized to the given RF reference. In order to improve the wavelength conversion efficiency, a new scheme utilizing an enhancement cavity has been proposed and tested as shown in Fig. 4.

### *SC Cavities for the Injector*

The injector for the cERL is required to accelerate CW electron beams of 10 mA from the beam energy of 500 keV to 5 MeV. An injector cryomodule, which contains three 2-cell cavities equipped with two input couplers and five HOM couplers, was designed as shown in Fig. 5. Three 2-cell cavities and six input couplers for installing into the cryomodule were fabricated in 2011. Vertical tests to confirm the cavity performance were carried out

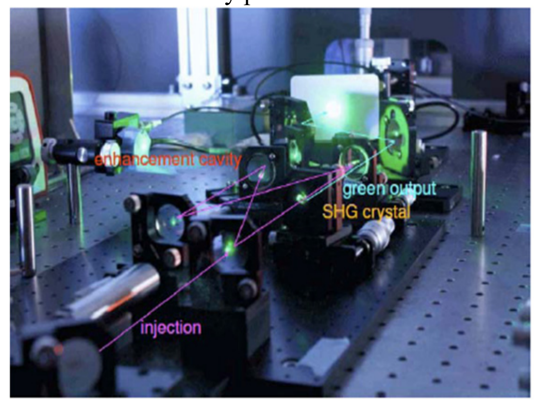


Figure 4: Laser system with cavity wavelength conversion.

at KEK-STF (Superconducting RF Test Facility), and RF conditioning of the input couplers with a CW high-power RF source were performed at KEK-ETF (ERL Test Facility).

The vertical tests investigated not only the high gradient performance of the cavities but also the thermal properties of several types of RF feedthrough for the HOM couplers. The final vertical test results of three 2-cell cavities are shown in Fig. 6. After confirming the cavity performance, the 2-cell cavities were sent back to the manufacturer in order to weld with a He jacket made of titanium. As shown in Figure 5, a high-pressure gas examination of the 2-cell cavities covered with the He jacket and two He panels made of stainless steel was carried out in compliance with the Japanese law concerning the safety of high-pressure vessels. The main components of the injector cryomodule were delivered to KEK in March of this year and assembly work was started in April. The injector cryomodule was completed in June, and has already been connected with the cold-box for cool-down. The first cool-down test of the injector cryomodule will be started by this September.

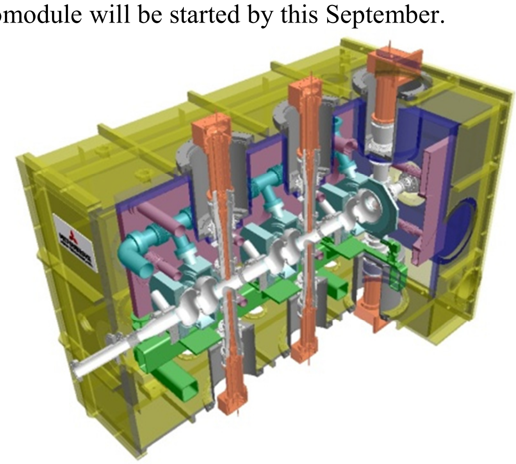

Figure 5: Schematic drawing of the injector cryomodule containing three 2-cell cavities and six input couplers.

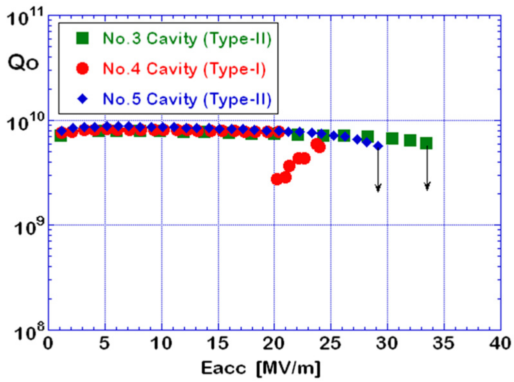


Figure 6: Final vertical test results of three 2-cell cavities with five RF feedthroughs (Type-I or Type-II) for five HOM couplers.

### *SC Cavities for the Main Linac*

Development of the basic technologies of the main components has finished and the components for the prototype module of the main linac are now being manufactured. Cold tests of two 9-cell cavities were carried in a vertical cryostat and a maximum accelerating gradient of 25 MV/m was achieved, as shown in Fig. 7. Field emission at 15 MV/m was sufficiently low and a Q value of $>1\times10^{10}$ was obtained.

As main components, a pair of input couplers was completed and assembled in a clean room to the power test station. Power conditioning up to 20 kW will be performed before installing the couplers in the cavity. Fabrication of the two types of HOM dampers is now under way. A ferrite cylinder of IB004 is bonded on the copper pipe by the hot-isostatic-pressing method. Movement of the frequency tuner was tested on a prototype tuner, which is based on the slide-jack structure developed for the ILC cavities. Movement of several micro-meters was smoothly obtained by a piezo tuner to compensate the cavity frequency response of 300 kHz/mm.

The main linac module as shown in Fig. 8 is going to be assembled, which will be followed by a cool test in autumn.

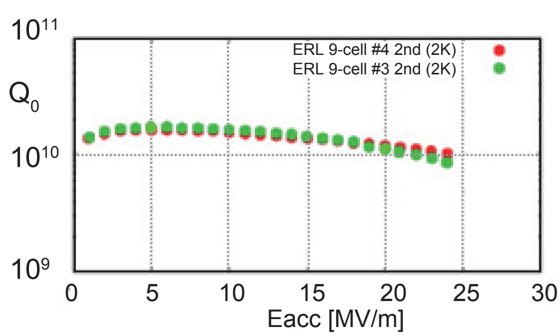


Figure 7: Q-E plot of the 9-cell cavities for the cERL main linac module.

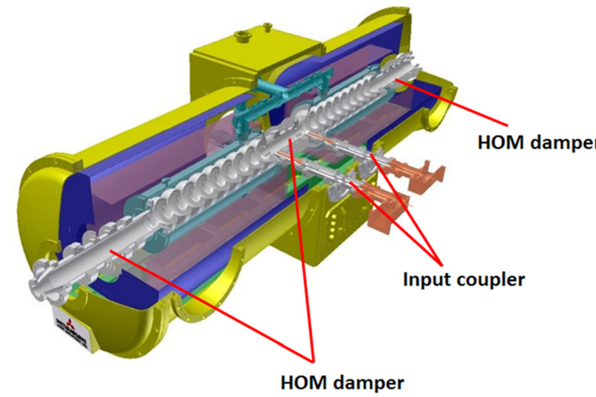


Figure 8: Schematic drawing of the prototype module of the cERL main linac. A pair of 9-cell cavities is connected with $LN_2$-cooled HOM dampers.

## COMPACT ERL PROJECT

### *Overview of cERL*

Figure 9 shows the current plan of the cERL for the first stage of commissioning [9]. It will comprise a 5-MeV injector including a 500-kV DC photocathode gun and three 2-cell superconducting (SC) cavities, a main SC linac having a single cryomodule, a single return loop of 35 MeV, and supporting facilities. The principal parameters of the cERL are shown in Table 2.

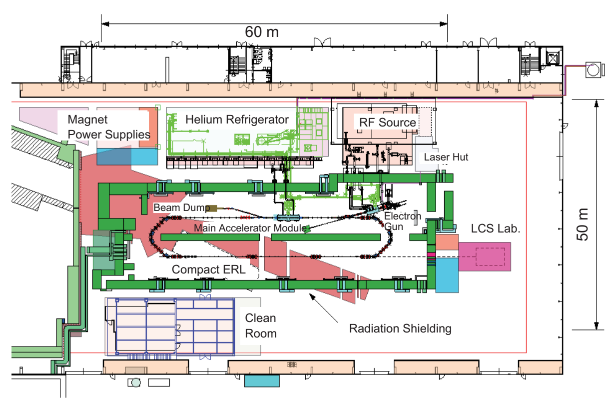


Figure 9: Current plan of the Compact ERL for commissioning.

### *Construction of the Radiation Shield for the cERL*

The KEK-ETF was selected as the construction site for the cERL. This hall was fully renovated in 2009, at which time we removed large amounts of concrete blocks and radioactive components from the old proton beamlines. In 2010, remaining radioactive matter, such as radioactive iron plates attached to the floor and a lot of polyethylene shielding stuffed in the floor pit, was removed. In parallel with cleaning the hall, we started designing the radiation shielding for the cERL. After checking the maximum safety load of the floor, the structure of the radiation shielding was designed. The shielding will be made of




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reinforced concrete, and the thickness of the surrounding walls and ceiling blocks are 1.5 m and 1.0 m, respectively. The ceiling blocks can be removed when large instruments are installed in the shield. Calculations for the structure, assuming both horizontal and vertical loads (acceleration) of 0.25 G, were carried out, and it was confirmed that the structure was sufficiently strong. Soon after finishing the radiation shielding design, the Great East Japan Earthquake struck on 11 March 2011. Fortunately no one was working in the building, there were no injuries, and there was no serious damage to the building. However, the specifications of the shielding needed to be changed: the limit of horizontal and vertical excitation force was raised from 0.25 G to 0.5 G for resisting a similar large earthquake.

Construction and installation of the radiation shield in ETF started in February and will be completed by the end of this September.

Table 2: Principal Parameters of the Compact ERL

| Parameter | Initial goal | Final goal |
|---|---|---|
| Beam energy at recirculation | 35 MeV (single loop) | 125 MeV (single loop)<br>245 MeV (double loops) |
| Injection energy | 5 MeV | 5 MeV |
| Average beam current | 10 mA | 100 mA |
| RF frequency | 1.3 GHz | 1.3 GHz |
| Accelerating gradient of main SC cavities | 15 MV/m | 15 MV/m |
| Bunch repetition frequency | 1.3 GHz | 1.3 GHz |
| Normalized emittance | 1 mm·mrad | 1 mm·mrad (77 pC/bunch)<br>0.1 mm·mrad (7.7pC/bunch) |

### *Construction and Commissioning Schedule*

The schedule for constructing the cERL is shown in Fig. 10. Fabrication of the accelerator components such as the injector part, superconducting cavities, RF sources and He cryogenic systems will be completed by the end of next March. Then, beam commissioning for the injector part will be started and will continue until mid-July 2013. Then, the recirculation loop will be installed in the summer of 2013 and commissioning will be started in October 2013. To avoid radiation problems from the cERL, the beam current will be carefully increased and the beam quality of the cERL, including unwanted beam loss, will be examined during 2014. The beam current of 10 mA with the normalized emittance of 1 mm·mrad will be achieved as the first stage, and then the emittance will be gradually reduced to 0.3 mm·mrad with 7.7 pc/bunch. In addition, the emittance of 1 mm·mrad with a higher bunch charge of 77 pc is also expected.

Commissioning of the beam at cERL will yield much important information on whether the components need to be improved as well as information on the drawbacks of the design of the 3-GeV class ERL.

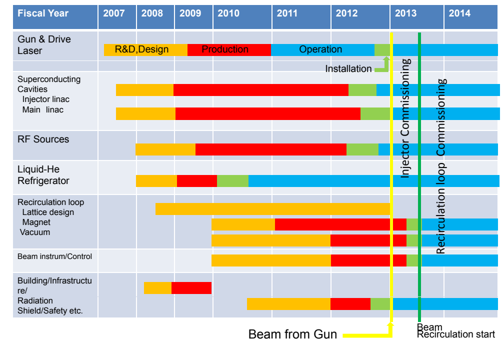


Figure 10: Construction and commissioning schedule of cERL.

## ACKNOWLEDGMENT

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