3 cERL

3-1 cERL Overview

The 3-GeV Energy Recovery Linac (ERL) has been proposed [1, 2] for a future project of the Photon Factory at KEK. To develop key technologies for our ERL project, we have been actively researching such components as the high-brightness electron guns and superconducting (SC) cavities since 2006. To demonstrate the production and recirculation of ultra-low emittance beams, we are constructing the Compact ERL (cERL) [3, 4] at KEK. The cERL will comprise a 5-MeV injector, a main linac, and a return loop, as well as RF sources, power supplies, and a cryogenic system, as shown in Fig. 1. The principal parameters of the cERL are given in Table 1. We plan to commission the cERL-injector in the spring of 2013, and the recirculating loop in the autumn of 2013.

In the following sections, we report the status of development and construction of each subsystem: the development of high-brightness electron guns and a drive-laser system are reported in Section 3-2, the design and optimization of the cERL lattice and beam optics in Section 3-3, and the production and measurement of magnets in Section 3-4. A superconducting cryomodule for the injector, containing three 2-cell cavities, has been assembled and installed in the cERL beamline, as described in Section 3-5-1. The other superconducting cryomodule for the main linac, containing two 9-cell cavities, is ready for assembly, as described in Section 3-5-2. Four of the five RF sources for the cERL have been installed, as also reported in Section 3-6. A cryogenic system for the cERL was installed and performance tests are under way step by step, as described in Section 3-7. Construction of radiation shielding for the cERL started in February 2012, and will be finished at the end of September 2012, as described in Section 3-8.

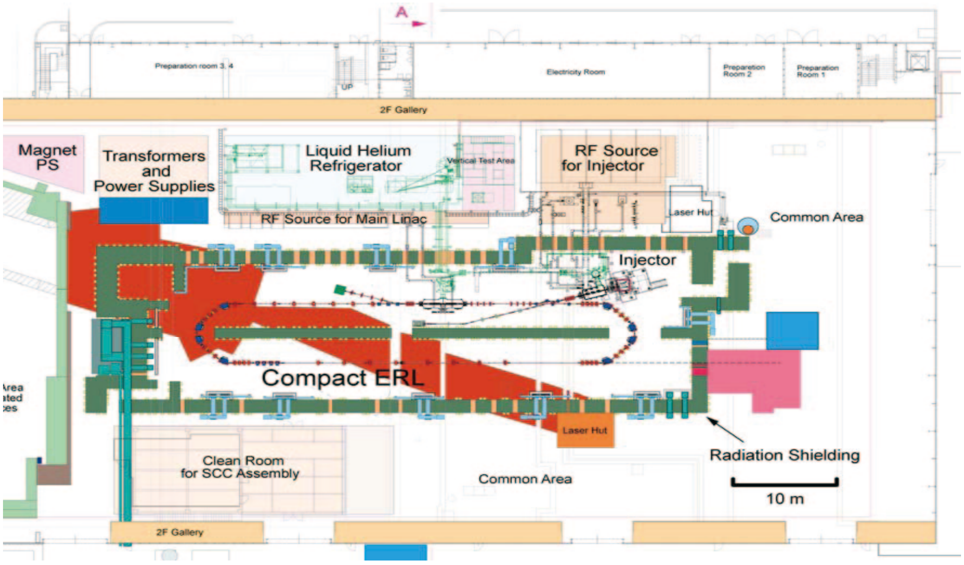

Figure 1
Planned layout of the Compact ERL (35 MeV version).

Table 1 Principal parameters of the Compact ERL.

Parameter	Value
Kinetic energy of electron beams (initial) (maximum)	35 MeV 245 MeV
Kinetic energy of electrons from the injector (initial)	5 MeV
Beam current (initial) (future goal)	10 mA (7.7 pC/bunch) 100 mA (77 pC/bunch)
Normalized emittance (at 7.7 pC/bunch) (at 77 pC/bunch)	0.3 - 1 mm·mrad 1 mm·mrad
RF frequency	1.3 GHz
Bunch length in rms (usual operation) (under bunch compression)	1–3 ps < 100 fs

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3-2 cERL Gun and Injector Beamline

Aiming for initial beam operation of the cERL in March 2013, two high-brightness photocathode DC electron-gun systems, a drive laser system, and an injector beamline are being developed to achieve normalized emittance of less than 1 mm·mrad, beam current of 10 mA, and a sufficiently long cathode lifetime.

For the first gun system, which is being developed at JAEA, high-voltage processing up to 526 kV with a cathode electrode and NEG pumps in place, and extraction of an electron beam of 5.7 μA with bias voltage of 300 kV have been achieved. A test for extracting a high beam current of 10 mA is scheduled for the summer of 2012. Thanks to the remarkable progress of the first gun system, we have selected it as the electron gun for the initial beam operation of the cERL, and it is due to be installed in the ERL development building in the autumn of 2012. Figure 2 shows the first gun system developed by JAEA.

For the second gun system, which is being developed by KEK, work is continuing on developing the vacuum system to achieve the extreme-high vacuum of 1×10^{-10} Pa and the high-voltage power supply system of up to 600 kV. To achieve the extreme-high vacuum, the outgassing rate and pumping speed of the system are critical aspects. The total outgassing rate of the second gun vacuum system, which consists of a titanium chamber, ceramic insulators and guard ring electrodes, was precisely measured to be 1.0×10^{-10} Pa m^3/s by the rate-of-rise (RoR) method, which is two orders of magnitude lower than that of the conventional SUS chamber. The pumping speed of a 4 K bakeable cryopump was measured using a standard conductance element developed by AIST, and the preliminary results are shown in Fig. 3. The measured pumping speed was about 1000 L/s for CH_4, N_2, CO and CO_2 at vacuum pressure of 1×10^{-9} Pa. Since the conductance of the pumping port was limited in the measurements, the pumping speed of the gun system, which has larger conductance, is estimated to be three times larger than the measured value. The high-voltage power supply system has been improved to fix the discharge in the circuit, and high-voltage processing is scheduled to start in the summer of 2012.

As the drive laser of the photocathode gun, a high-average-power laser amplifier based on a Yb-doped photonic-crystal fiber has been developed [5], and 70 W output power with a 1.3 GHz repetition rate at 1064 nm wavelength has been demonstrated. This will be converted to the second harmonic of 532 nm, and then will be delivered to the cathode. The achieved laser power is sufficient to generate an electron beam of 10 mA.

Tests of the injector beamline, which connects with the photocathode gun, are continuing in the PF-AR south experimental hall. The laser chamber and screen chambers have been modified to reduce outgassing and to increase the pumping speed. After the beamline has been tested in the PF-AR south experimental hall, it is scheduled to be transferred to and constructed in the ERL development building in the winter of 2012. In the initial beam operation, the injector diagnostic beamline, which connects with the injector in a straight line, will be used to measure the quality of the injector beam. It is also scheduled to be constructed in the winter of 2012.

Development of the photocathode is a key part of developing the gun system. In the ultimate mode of the ERL light source, the cathode requires low emittance, a fast time response, and robustness. The initial emittance and the time response were measured using the gun test beamline for thickness-controlled GaAs sam-

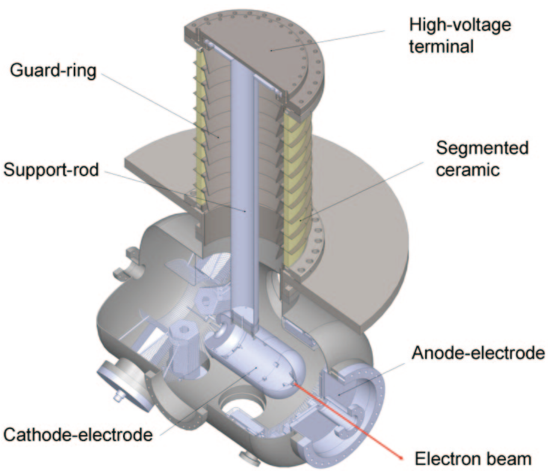

Figure 2
The first DC electron gun system developed at JAEA.

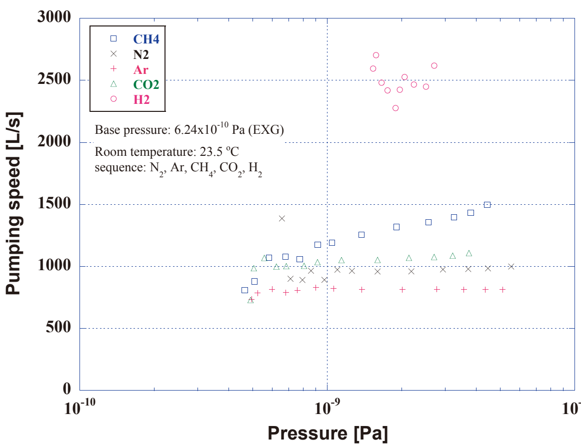

Figure 3
Preliminary results of pumping speed measurement for 4 K bakeable cryopump.

ples and GaAs/GaAsP superlattice [6, 7]. No clear dependence on cathode thickness was seen for cathodes with thicknesses of 100 and 1000 nm, indicating that conduction electrons are mostly relaxed within a range of 100 nm in the crystal.

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3-3 cERL Lattice and Optics

The cERL initially comprises a 5-MeV injector, a superconducting 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 a second return loop [8].

Figure 4 shows the latest design of the 35-MeV single-loop configuration [9]. The lattice and optics from the injector to the main linac have been designed by simulation including space charge effects for the first cERL commissioning [10]. By modifying the arrangement of eight quadrupole magnets between the merger and the main linac, the horizontal and vertical normalized emittances just after the main linac were improved to less than 0.3 mm·mrad for the bunch charge of 7.7 pC (beam current of 10 mA), as shown in Fig. 5. Figure 6 shows the betatron and dispersion functions from after the main linac to the beam dump in the normal operation mode. The two arc sections with non-zero dispersion have the same isochronous optics in the normal operation mode and are designed so that the normalized emittance is well preserved against the CSR effects.

In the bunch compression mode, the first arc section has non-isochronous optics with a positive momentum compaction factor and the second arc section with a negative one. The bunch is accelerated off-crest by the main linac, compressed after the first arc and decompressed after the second arc. Four sextupole magnets for each arc section are used to compensate second-order momentum compaction. The simulation result shows that the bunch can be compressed to about 150 fs for the bunch charge of 77 pC and the injection bunch length of 1–2 ps, as shown in Fig. 7. In order to guarantee the momentum acceptance for the bunch compression mode, the physical aperture of the beam pipe has an octagon-like shape with the horizontal and vertical half widths of 35 mm (H) and 20 mm (V) in the two arc sections, while it basically has a round shape with radius of 25 mm in the straight sections.

Beam loss due to residual-gas scattering was calculated and as a result the beam pipe radius at the beam dump line was increased to about 50 mm from 25 mm because the beam loss can be significant after the deceleration by the main linac. The space charge effects after the main linac to the beam dump are being studied and the lattice and optics for a laser-Compton scattering X-ray experiment in the straight section opposite to the main linac are being designed.

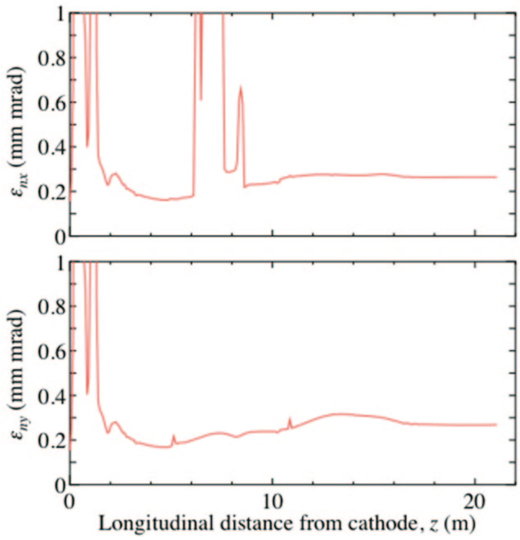

Figure 5
Simulation results for horizontal (upper) and vertical (bottom) normalized emittances from the DC photocathode gun to the main linac.

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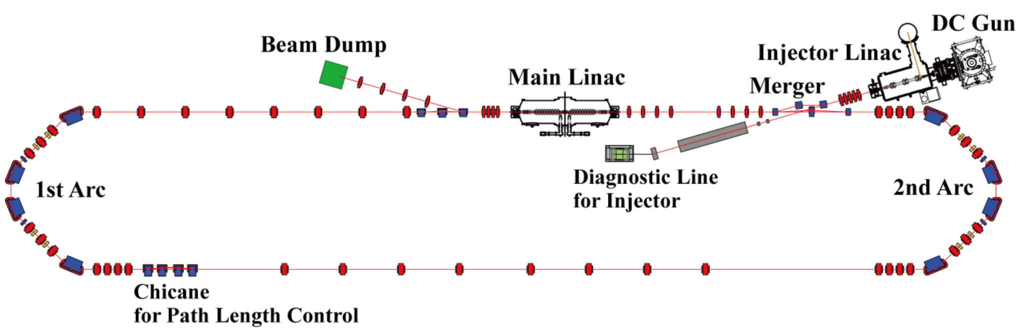

Figure 4
Latest design of the 35-MeV single-loop configuration.

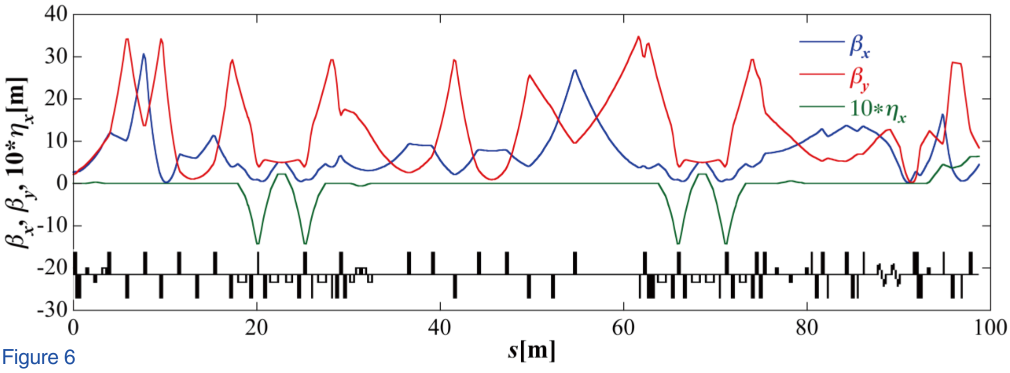

Figure 6
Betatron and dispersion functions of the cERL from after the main linac to the beam dump.

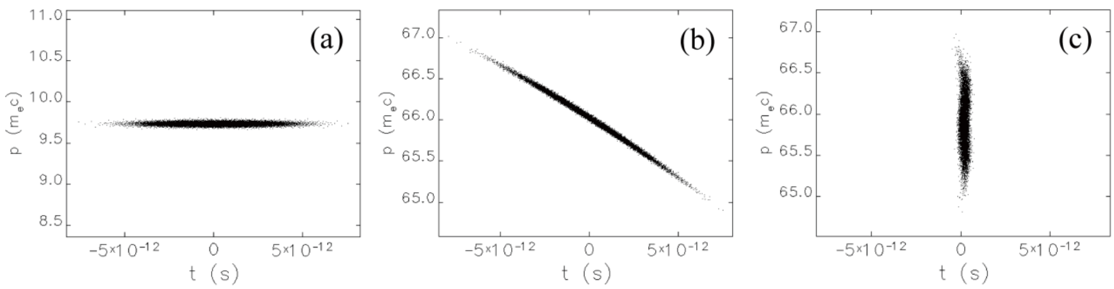

Figure 7
Simulated temporal and momentum distributions of an electron bunch (a) before and (b) after the main linac and (c) after the first arc section in the bunch compression mode.

3-4 cERL Magnets

A prototype of the main sector bending magnet was designed and manufactured in 2010. The remaining seven magnets were manufactured in 2011, as shown in Fig. 8. The magnetic measurements are conducted for the prototype, as shown in Fig. 9.

Fifty-six quadrupole magnets were manufactured (Fig. 10). Twelve of them having a core length of 10 cm are used for the low energy (5 MeV) part while the other 44 magnets having a core length of 20 cm are used for the high energy part (≥ 35 MeV). For the 35-MeV operation, 280-turn coils of electric wire are used.

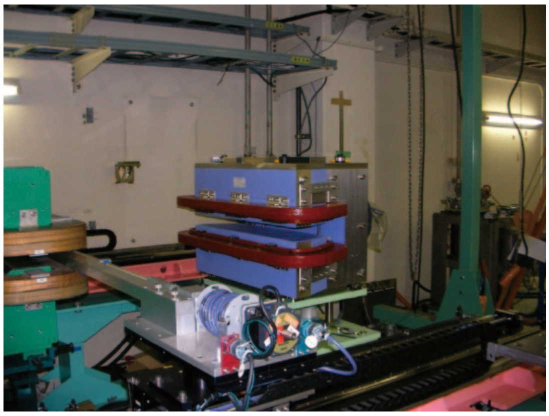

Figure 9
Magnetic measurement of the bending magnet.

Figure 8
Sector-type bending magnets.

Figure 10
Quadrupole magnets.

3-5 Superconducting Cavities

3-5-1 Two-cell Cavities for the Injector

In the injector cryomodule for the cERL, electron beams of 10 mA are accelerated from the beam energy of 500 keV to 5 MeV. The injector cryomodule containing three 2-cell cavities was designed, as shown in Fig. 11 [11]. Each cavity is driven by two input couplers to reduce the required RF power handling capacity and also to compensate for coupler kick. The 2-cell cavities are dressed with a helium (He) jacket made of titanium, and magnetic shields are put inside the two-Kelvin (2K) He jacket. A higher-order-mode (HOM) coupler scheme was chosen for HOM damping, and five loop-type HOM couplers are attached on both beam pipes of each cavity. Efficient cooling of RF feedthroughs for HOM pick-up antennas is an important issue. A slide-jack tuner with a pair of piezo elements is attached at the thick titanium base-plates for the frequency tuning system. RF input couplers are a critical component in a high-power application of superconducting cavities. A coaxial coupler with a single disk-type ceramic window is used for the continuous-wave (CW) input couplers.

The limitation on cavity performance in the 2-cell cavities was not only thermal quenching at defects on the RF surface in the cells, but also the drop in Q_o values due to heating-up at the niobium (Nb) antenna tip of the HOM pick-up probe. New RF feedthroughs with more efficient cooling performance were developed, as shown in Fig. 12 [12]. An Nb antenna was joined with a center conductor made of Kovar by a screw in the original RF feedthrough (Type-0). In Type-I feedthroughs, the Nb antenna was joined by brazing, and the material of the center conductor was changed to molybdenum (Mo) to increase the thermal conduction. Furthermore, the material of the outer conductor was changed from Kovar to copper to improve the cooling efficiency by liquid-He (Type-II). Finally, a male pin for connecting the center conductor was applied in the Type-II feedthroughs. These new RF feedthroughs were tested in the vertical tests of the 2-cell cavities. The final vertical test results in each cavity are shown in Fig. 13. In the No. 4 cavity test with five Type-I feedthroughs, the obtained maximum accelerating gradient (E_{acc}) was limited by the drop of Qo values due to heating-up of the Nb antenna tip. On the other hand, the limitation in cavities No. 3 and No. 5 with Type-II feedthroughs was thermal quenching at the cell without heating at the Nb antenna. All cavities achieved an accelerating gradient (E_{acc}) of higher than 20 MV/m, which exceeds the operating gradient in the cERL injector.

Conditioning of six input couplers for the injector cryomodule was carried out by using a newly developed 300 kW CW klystron. The high-power RF test stand used for conditioning a pair of input couplers is shown in Fig. 14. A water cooling channel was inserted inside the inner conductor of the input couplers. The coaxial line between an RF window and a doorknob-type transition was cooled by nitrogen gas flow. The outer surface of the test stand was cooled by air blown from two electric fans. Conditioning of these input couplers was carefully carried out up to 200 kW in a short pulsed operation with a duty of less than 1%, and 30–40 kW in CW operation [13].

Assembly of the injector cryomodule was started in April 2012 [14]. All components such as input couplers, beam tubes, RF feedthroughs and vacuum parts were carefully rinsed, and were dried in a class-10 clean room. All of the RF feedthroughs for HOM couplers were replaced with new Type-II feedthroughs, as shown in Fig. 12. Six input couplers were mounted in the upper and lower ports of three 2-cell cavities. Three cavities

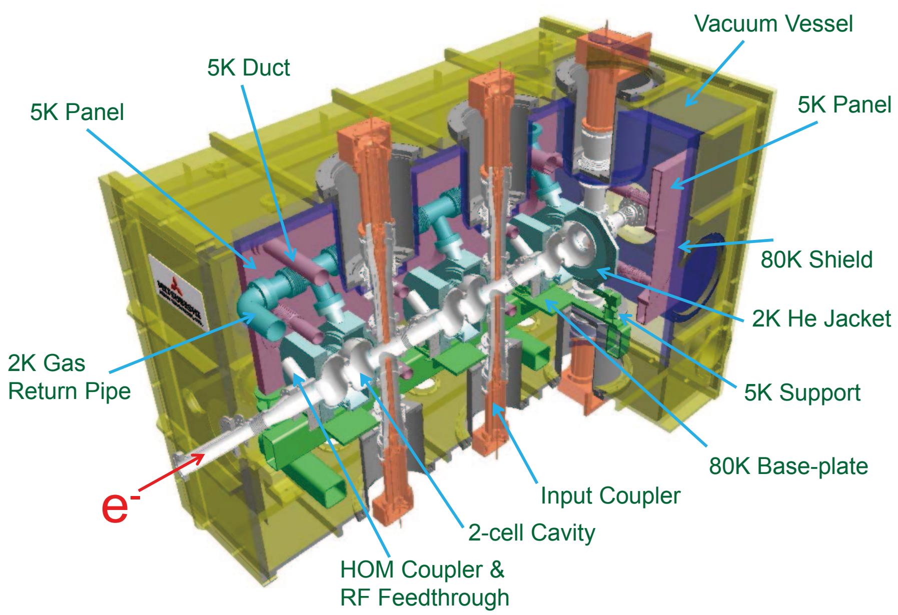

Figure 11
Injector cryomodule for cERL.

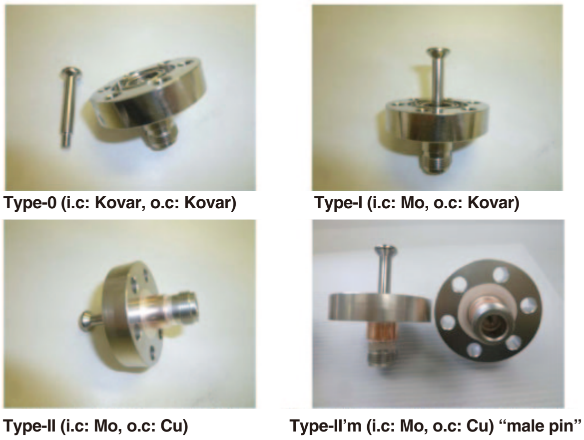

Figure 12
Four types of RF feedthrough with HOM pick-up antenna made of niobium; material of inner conductor (i.c) and outer conductor (o.c).

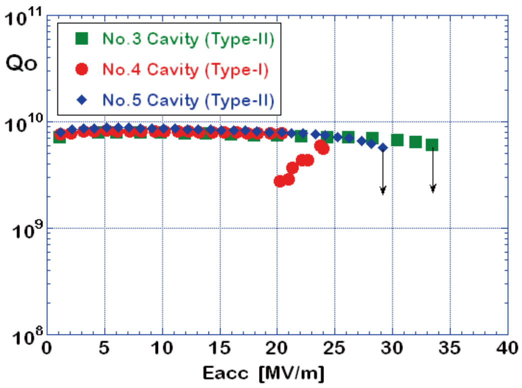

Figure 13
Final vertical test results of three 2-cell cavities attached with five RF feedthroughs at the five HOM couplers.

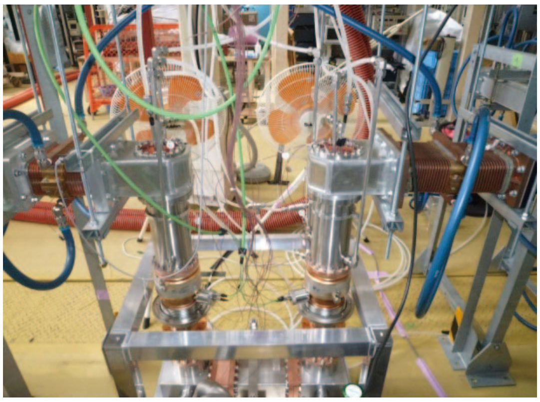

Figure 14
High power RF test stand for conditioning a pair of input couplers.

Figure 15
String assembly of three 2-cell cavities with six input couplers in a class-10 clean room.

were stringed with two interconnected bellows, and two beam tubes were attached to both ends. The completed cavity string assembly is shown in Fig. 15. Attachment of the frequency tuner system and alignment of three cavities were carried out. After cold mass assembly such as the cooling pipeline of 2K-He, two reservoir panels of 5K-He and thermal shields of 80K-N_2, the string cavities were inserted into the vacuum vessel. The whole assembly of the injector cryomodule was completed by the end of June 2012, and the cryomodule was installed in the beam line. The first cool-down test of the cryomodule is scheduled for September 2012.

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3-5-2 Nine-cell 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 cERL main linac are now being manufactured. Cold tests of the two 9-cell cavities were carried in a vertical cryostat, and a maximum accelerating gradient of 25 MV/m was achieved (Fig. 16). Field emission at 15 MV/m was sufficiently low and Q value of >1×10^{10} was obtained. After the performance test, each cavity was filled with Ar gas and was welded in the titanium He vessel.

Among the main components, a pair of input couplers was completed, and mounted in a cleanroom onto the power test assembly as shown in Fig. 17. Power conditioning up to 20 kW will be performed before fitting the couplers to the cavity.

Fabrication of the two types of HOM dampers is under way, that is, the small beam pipe (SBP) and the large beam pipe (LBP). A ferrite cylinder of IB004 is bonded to the copper pipe by the hot-isostatic-pressing (HIP) method. Figure 18 shows a completed one which is connected to the LBP of the cavity. Movement of a frequency tuner was tested on the prototype tuner, which is based on the slide-jack structure developed for the ILC cavities. A few micro-meters of movement is smoothly obtained by a piezo tuner to compensate the cavity frequency with a response of 300 Hz/μm.

The main linac module (Fig. 19) is scheduled to be assembled in the summer of 2012, which will be followed by a cold test in the autumn. The clean environment and tools for the final assembling are now being prepared.

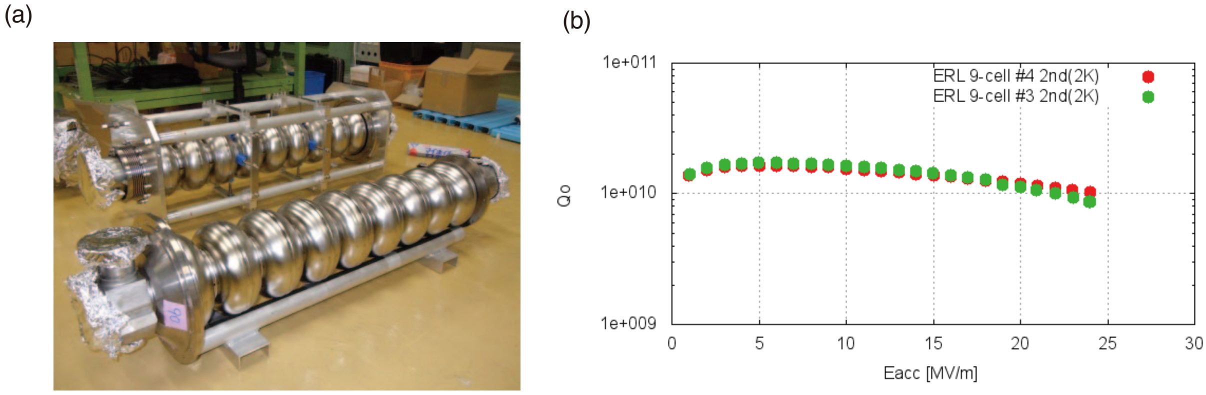

Figure 16
(a) A pair of 9-cell Nb cavities for the cERL main linac. The cavities were annealed, frequency-tuned and electro-polished before the cold performance test in a vertical cryostat. After warming, the test cavities were filled with pure Ar gas and welded to a titanium helium vessel.
(b) The Q-E plot of the 9-cell cavities for the cERL main linac module.

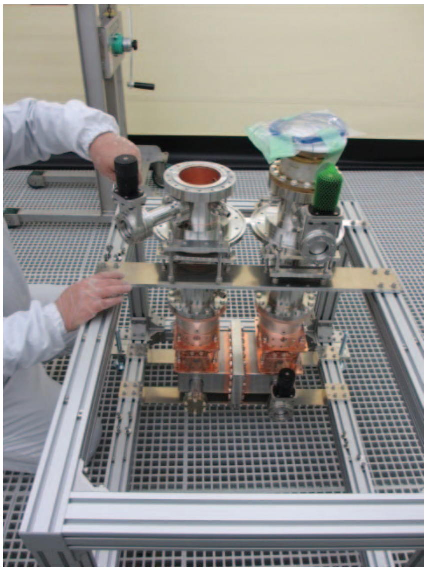

Figure 17
A pair of input couplers was completed, and mounted onto a power test assembly in a clean room. Each coupler has double ceramic windows, cold and warm, to allow the couplers to be assembled in a cryostat without opening the cavity. The ceramics are protected by the interlocks of both the arc detector and vacuum pressure. Thermal anchors of the outer conductor and a nitrogen gas flow in the inner conductor make it possible to feed CW-RF power of 20 kW in full reflection mode. These couplers are to be processed up to 20 kW soon.

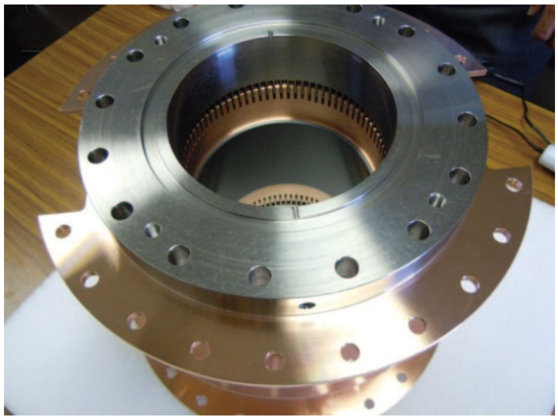

Figure 18
A HOM damper with a ferrite absorber. The cERL module contains two LHOM dampers and one SHOM damper. A cylinder of IB004 ferrite is bonded to the inner surface of a copper beam pipe by the HIP method and absorbs HOM power. A short bunched beam of 77 pC induces a wide-range HOM of 150 W in a 9-cell cavity, which is cooled by LN2. A pair of vacuum bellows with a comb-type RF shield is used to isolate the damper thermally from the 2K cavity.

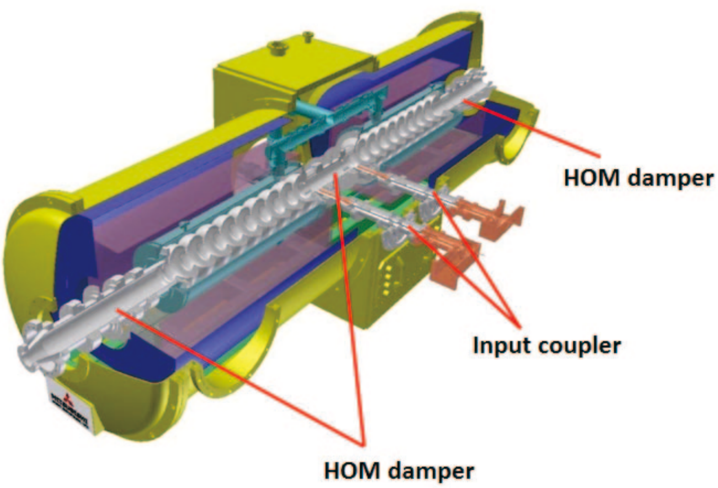

Figure 19
A sketch of the prototype module of the cERL main linac. A pair of 9-cell cavities is connected with HOM dampers which are cooled by LN2.

3-6 RF Power Supply

A total of five RF sources such as klystrons and inductive-output-tubes (IOTs) will be used at the cERL. The RF configuration is summarized in Table 2. Four RF sources have been installed in the ERL development building. After the Great East Japan Earthquake, the minimum recovery work was carried out at a 300 kW klystron and the klystron was used for the coupler conditioning as shown in Fig. 20. A 30 kW IOT and a 30 kW klystron have also been tested. Figure 21 shows the test assembly of a 30 kW klystron.

RF stability of 0.1% in amplitude and 0.1 deg. in phase is required for the low-level RF system (LLRF) of the cERL. In order to satisfy these requirements, it is especially important to minimize the drift of the amplitude and the phase. Since the experimental hall (outside the radiation shield) has no air-conditioner, a diurnal temperature range of more than 10ºC is expected. According to the phase measurements of RF cable at various temperatures, phase drift of 0.5 deg./ºC/100m is obtained, which means that the cable temperature should be regulated to within 0.5ºC for 40 m (to regulate 0.1 degree in phase). Temperature regulation inside the cable ducts is planned to suppress changes in atmospheric temperature. Figure 22 shows a cable duct with water cooling channel. Two channels will be combined and heat insulation will cover the duct. It has been confirmed that this configuration will suppress temperature drift within 0.1ºC.

Table 2 RF configuration at cERL.

Item	Unit	Buncher	Inj-1	Inj-2	Inj-3	ML-1	ML-2
Power required	kW	4.5	10	37	37	11	11
Power output	kW	6.2	17	122		11	11
RF source		IOT	Klystron	Klystron		IOT	IOT
Power available	kW	20	30	300		>15	>15

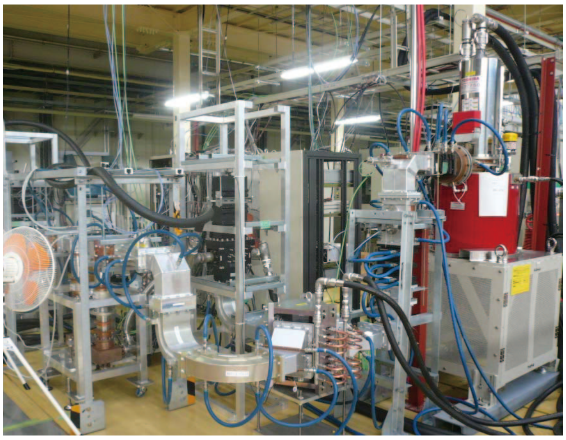

Figure 20
Coupler test stand with 300 kW klystron.

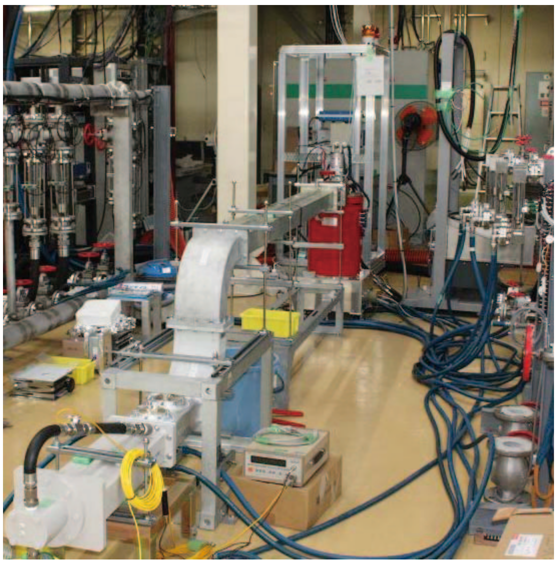

Figure 21
Evaluation of the 30 kW klystron.

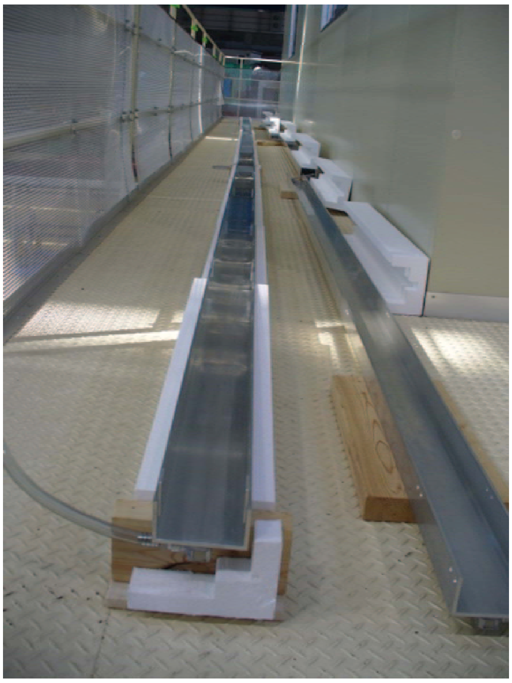

Figure 22
Cable shield for temperature regulation. It consists of an aluminum shield with water cooling channel and plastic thermal insulator.

3-7 Cryogenic System

Operation of the cryogenic system for the compact ERL was officially approved by Ibaraki prefecture under the High Pressure Gas Safety Act in the summer of 2010. Before the cryomodules of the superconducting RF cavities for the injector and the main linacs are connected to the two-Kelvin (2K) helium-refrigerator cold boxes of the cryogenic system, the performance of the cryogenic system on its own should be measured at the temperature of liquid helium and also at the operating temperature of the superconducting cavities, i.e. at 2K. Figure 23 shows the two 2K helium refrigerator cold boxes under cold tests in the ERL development building. A helium liquefier/refrigerator, a 3000L liquid helium storage vessel and a helium gas pumping system are located behind radiation shield walls. The cold box on the right, shown in Fig. 24, is for the cryomodule of the injector linac superconducting RF cavities, and the one on the left, shown in Fig. 25, is for the main linac. Both of the boxes are connected with a high-performance transfer line to reduce the heat load on the cryogenics system.

The cold test for the cryogenic system was carried out step by step. The static heat load to each 2K refrigerator cold box, which means no heat load from the superconducting RF cavities to the cold box, was found to be about 1 W for each, as expected from our experience. The cooling power of the cryogenic system is mainly dependent on the pumping capacity of the helium gas pumping system of the cryogenic system. One pair of rotary oil pump and mechanical booster pump employed in the helium gas pumping system can evacuate helium gas at the flow rate of about 10 m^3/h at room temperature, which corresponds to a cooling power of about 10 W at 2K. We have installed four units of the combined vacuum pumps, and so the cooling power is expected to be about 40 W at 2K. An electric heater in the 2K refrigerator cold box was used to simulate the dynamic heat load from the superconducting RF cavities. The results of the cryogenic test of the two cold boxes under operation among the four pump units showed that one cold box had cooling power of about 20 W at 2K, while the other cold box was kept at 2K without any dynamic heat load. It is concluded that each cold box has cooling power of about 20 W, and thus with four vacuum pumps, the cryogenic system can absorb heat load of about 40 W at 2K in total.

In fiscal 2012, it is planned that both of the cryomodules of superconducting RF cavities for the injector and main linacs will be connected to the cryogenic system with high-performance connection lines under the High Pressure Gas Safety Act. Though we will increase the number of units to eight next fiscal year and then the cooling power will be enhanced up to about 80 W at 2K, it is still necessary to estimate precisely the total heat load to the cryogenic system from the two cryomodules for the injector and main linacs.

Figure 23
2K helium refrigerator cold boxes which will be connected with cryomodules of superconducting RF cavities for injector and main linacs.

Figure 24
2K helium refrigerator cold box for injector linac under cold test.

Figure 25
2K helium refrigerator cold box for the main linac under cold test.

3-8 Status of Construction

In the ERL Test Facility (renamed from the East Counter Hall), construction of the radiation shield for the cERL started in February 2012. The radiation shield consists of about 300 concrete blocks, amounting to 4,800 tons. Before these blocks were installed, the hall was surveyed in order to prepare a flat base for setting the blocks. After installing the wall part blocks, ceiling blocks were mounted in order. The radiation shield will be completed in September 2012, and the cERL components will be installed by the end of March 2013 (Fig. 26).

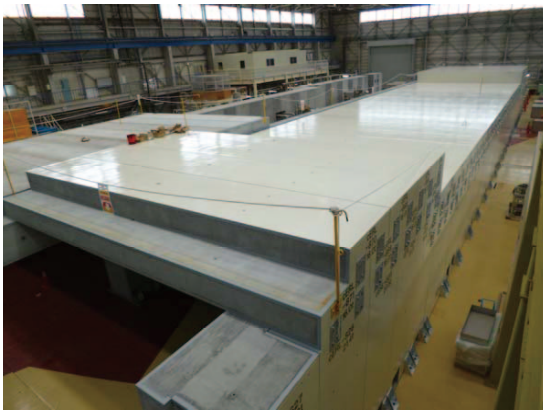

Figure 26
Construction of the cERL radiation shield.