3 cERL

3-1 cERL Overview

As described before, the aim of the cERL in the R&D program includes the development of critical components for the ERL, as well as the construction of a test accelerator. The design parameters of the cERL are shown in Table 1. In 2012, we could complete the construction of the radiation shielding to cover accelerator components for the cERL, as shown in Fig. 1. The key accelerator components, such as a photocathode DC electron gun, super conducting cavities for the injector and main linac, and an evaluation beamline for the injector electron beam, were successfully installed in the radiation shielding. An RF power test for each super conducting cavity was also completed by the end of the 2012 fiscal year, and the interlock systems for beam operation at the injector part were also completed. Beam operation of the injector part will start in April 2013.

Table 1: The design parameters of the cERL.

Parameter	Value
Beam energy (injector)	5 MeV
(return loop)	35 MeV
Beam current (initial goal)	10 mA
(future goal)	100 mA
Normalized beam emittance	< 1 mm·mrad
	(at 77 pC/bunch)
RMS bunch length (usual)	1–3 ps
(with compression)	< 150 fs
RF frequency	1.3 GHz

Figure 1: ERL project members in front of radiation shield for cERL.

3-2 High-brightness DC Photocathode Gun and Gun Test Beamline

A collaboration team, including the staff of Japan Atomic Energy Agency (JAEA), KEK, Hiroshima University, and Nagoya University, has developed a 500-kV DC photocathode gun to produce small-emittance electron beams with high average current. Their outstanding achievements included successful application of a high DC voltage up to 510 kV, as well as the production of an electron beam of 1.8 mA with applied voltage of 500 kV as show in Fig. 2 [1]. These achievements were done in the laboratory at the JAEA Tokai site. After confirming these performances, the DC gun has been installed in the cERL and is ready for operation. Beam characterization is important in evaluating the performance of the injector accelerator. Several components for the characterization beamline have been developed at the gun test facility, which is located in the PF-AR south experimental hall. The beamline has also been installed in the cERL by using components from the PF-AR south experimental hall. Figure 8 shows the injector part of the cERL with a 500-kV DC electron gun and super conducting cavity for the injector.

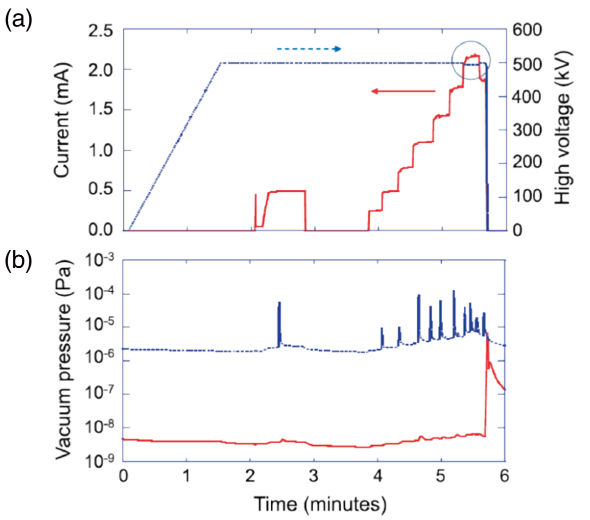


Figure 2: (a) Beam current (red solid line) and gun high voltage (blue dotted line) as a function of time. As shown the figure, 1.8mA with 500kV can be demonstrated.
(b) Vacuum pressures of gun (red solid line and beam dump (blue dotted line), respectively (after ref.[1]).

Figure 3: Photograph of the injector part of the cERL with 500-kV DC electron gun and super conducting cavity for injector.

3-3 SC Cavities for the Injector

An injector for the cERL is required to accelerate continuous-wave (CW) electron beams of 10 mA from 500 keV to 5 MeV of beam energy. The injector cryomodule contains three 2-cell cavities equipped with two input couplers and five HOM couplers. In order to qualify the cavity performance, vertical tests of the three 2-cell cavities were conducted at KEK-STF (Superconducting RF Test Facility). The three 2-cell cavities attached to new types of RF feedthroughs achieved an accelerating gradient higher than 20 MV/m, which exceeds the operating gradient as a cERL injector. After this, the 2-cell cavities were sent back to a company for welding with a He jacket made of titanium. RF conditioning of six input couplers was performed with a high power RF source of CW-300 kW. The conditioning 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 a CW operation.

Assembly of the injector cryomodule began in April 2012. All components, including input couplers, beam tubes, RF feedthroughs, and vacuum parts were carefully rinsed. Six input couplers were mounted at the upper and lower ports of the three 2-cell cavities, and the string assembly was completed in a class-10 cleanroom (Fig. 4). Then, the attachment of a tuner system and the alignment of the three cavities were carried out. After a cold-mass assembly including a cooling pipeline of 2K-He, two reservoir panels of 5K-He, and thermal shields of 80K-N2, the string cavities were inserted into a vacuum vessel. The entire assembly of the injector cryomodule was completed in June 2012. The injector cryomodule was installed in a beamline and was connected to a cold valve box, as shown in Fig. 5.

The first set of cool-down tests for low RF power measurements was carried out in September 2012. The temperature distribution, static heat loads at 2K, and RF-coupling parameters such as the input coupler (Qin), HOM filter (QHOM), and monitor coupler (Qt) were measured. The tuner performance of the motor and piezo tuners was tested, and control of the resonant frequency was successfully confirmed, as shown in Fig. 6. The second set of cool-down tests for high RF power measurements was carried out in February 2013. The conditioning of an accelerating gradient in each individual cavity was initially started in a pulsed operation of 2 ms and 5 Hz (duty of 1%). After an accelerating gradient reached 15 MV/m, the duty factor was increased to 10 % (5 ms and 2 Hz). Finally, stable CW operation at 9 MV/m (7.5 MV/m in the specification) was confirmed. Measurement of Qo values by dynamic heat loads of 2K-He was carried out at 5 – 8 MV/m; however, the obtained Qo values in all three cavities were one order lower than expected (1×10^{10}) due to heat-up at the HOM RF feedthroughs. The improvement of the cooling system of HOM RF feedthroughs will be an important item in the future.

Figure 4: The assembly of the super conducting cavities for injector in a clean room.

Figure 5: Completed cERL injector cryomodule installed in beam line and connected with cold box.

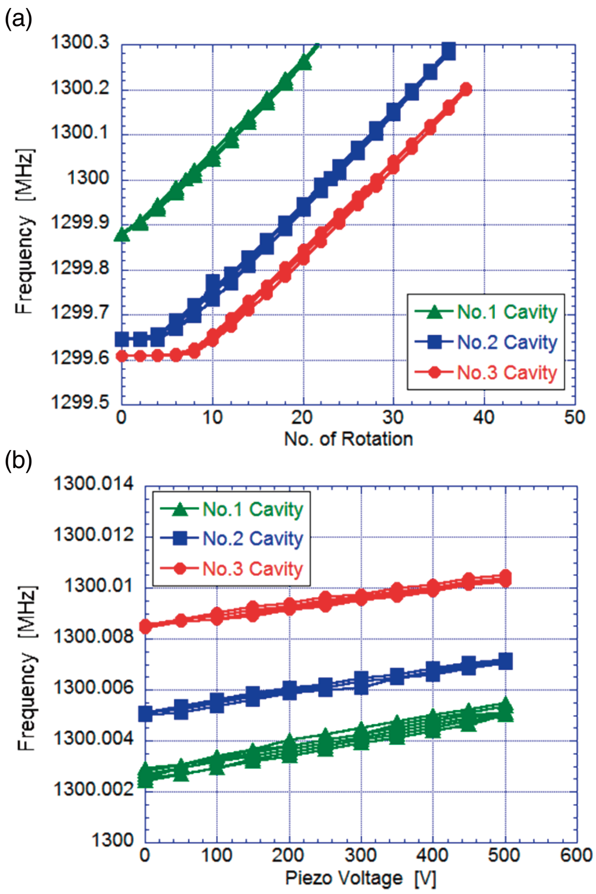


Figure 6: Measurement results of tuner performance in three 2-cell cavities; Coarse tuner by stepping motor (a) and fine tuner by piezo (b).

3-4 SC Cavities for Main Linac

A prototype module of the cERL main linac was assembled and cooled. The module contained two 9-cell cavities of 1.3 GHz. The cavities were connected to each other with three HOM absorbers and fixed in a 5K shield titanium frame. A cross-sectional view is shown in Fig. 7 In October, after assembly, the module was installed in the cERL (Fig. 8). The first 2K cooling test was performed for one month, beginning in the middle of November. The first half of this period was used to determine the fundamental performance of the modules, such as cooling speed, temperature distribution, heat loss, cavity alignment, and low-level RF measurements including frequency tuners. Acceptable results of these tests allowed us to execute the RF high-power test in the second half of the testing period. The accelerating gradient of both cavities reached 16 MV/m; however, strong field emission was observed at the gradient of more than 10 MV/m, which limited the CW to operating below 14 MV/m because of the limitations of the X-ray shield and the cryogenic power capacity.

A beam commissioning of the injector section will be followed by the construction of the return loop, which is scheduled for the summer of 2013. Preparation of a low-level RF and other operation systems of the main linac is in progress, aiming for total beam commissioning of the cERL in December 2013.

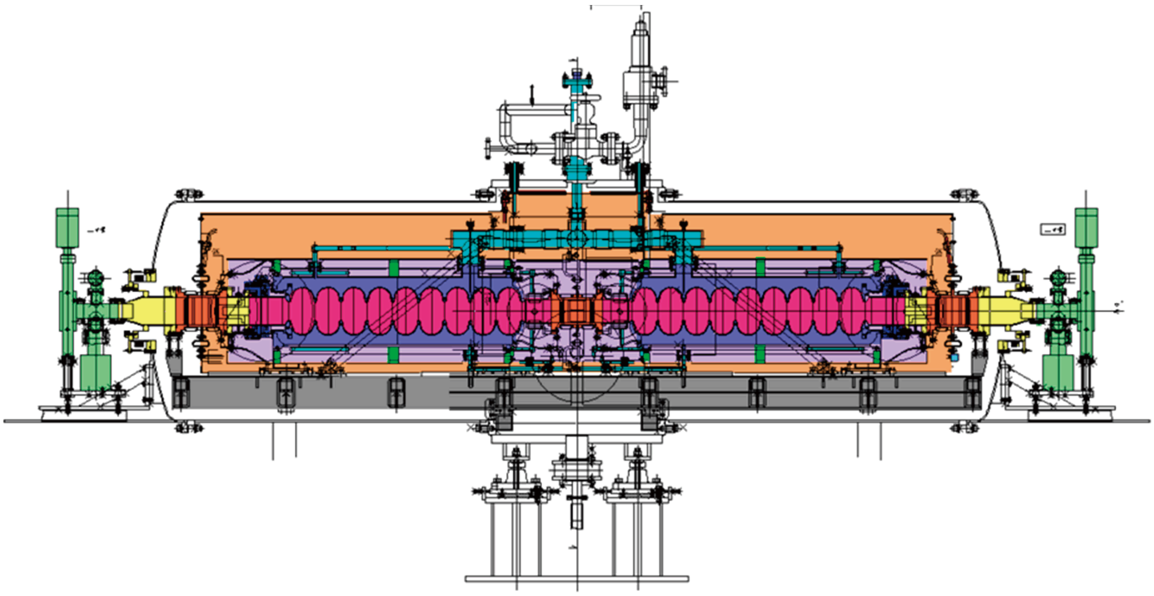


Figure 7: A cross-sectional view of the main linac module. Two 9-cell Nb cavities (red) dressed in the Ti-jacket (blue) are connect each other with HOM absorbers (orange). This structure is supported by the Ti-frame (violet) which has a magnetic shield and work as the 5K shield.

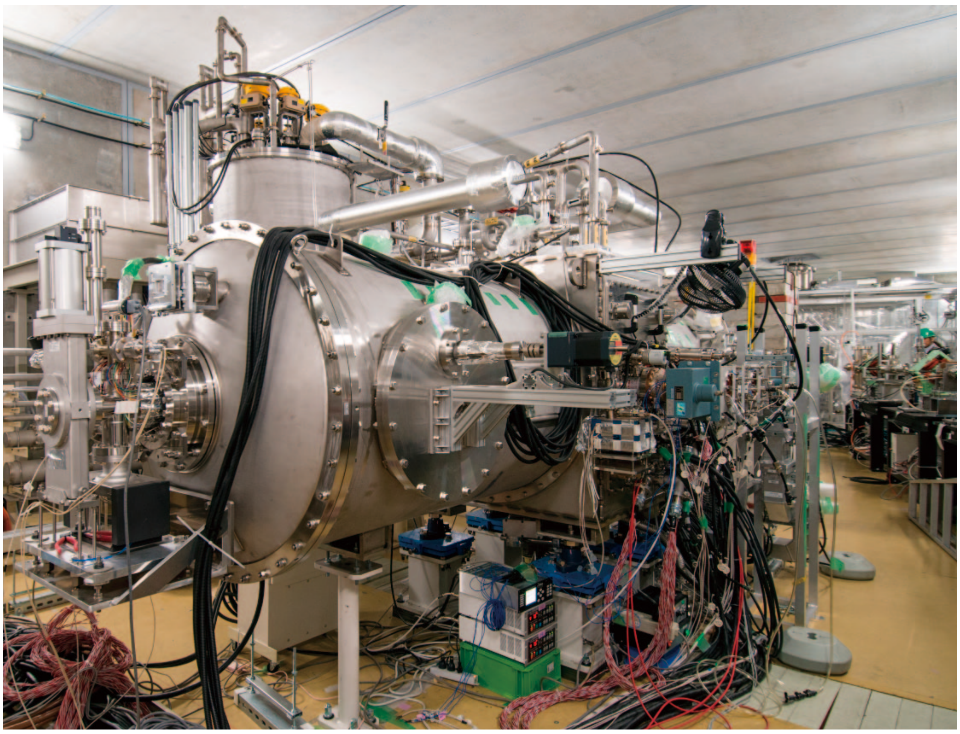


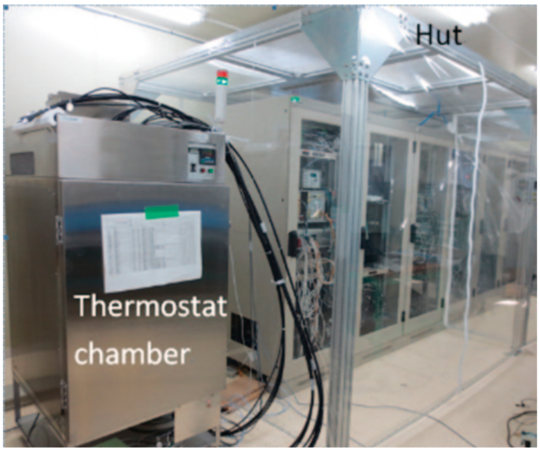
Figure 8: Prototype module of a main linac installed in the cERL shield room.

3-5 RF Sources

RF stabilities of 0.1% in amplitude and 0.1 deg. in phase are required for the cERL. In order to satisfy these requirements, we adopted a digital low-level RF (LLRF) system, which is located inside the temperature-controlled hut in the LLRF control room on the 2nd floor. This hut has been used for the KEKB injector linac and the temperature inside is regulated by controlling the ventilating fans on the roof. The temperature stability of the hut is about 0.2 °C. An RF source (RF; 1.3 GHz), local oscillator (LO;1.31 GHz), and clock generator are installed inside the thermostat chamber, which operates using a Peltier device. Figure 9(a) shows the thermostat chamber and the temperature controlled hut. The phase drift of the cavity probe signal can be the dominant error of the RF stability because no air conditioners are installed in the ERL test hall. In order to realize stable RF signals, RF cables were packed inside the water-cooled cable duct between the LLRF control room and the radiation shield inside, as shown in Fig. 9(b).

Concerning the high-power RF system (HPRF), a total of 5 RF sources will be installed in the cERL. An IOT (Inductive Output Tube; 20 kW) will drive a normal conducting buncher cavity. An Injector 1 superconducting (SC) cavity will be driven by a 30-kW klystron. Injector 2 and 3 cavities will both be driven by a 300-kW klystron. All the power distribution waveguides (including circulators and power splitters) were installed in the injector linac. Each injector SC cavity has two RF couplers. The RF input phase is adjusted by the waveguide phase shifter located inside the radiation shield, as shown in Fig. 10.

(a)



(b)

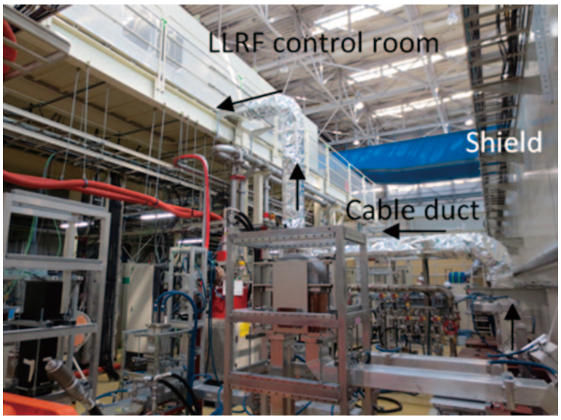


Figure 9: (a) Thermostat chamber and temperature controlled hut. (b) Water cooled rf cable duct.

Figure 10: Variable waveguide phase shifter for adjusting the cavity input phase.

3-6 Cryogenic Systems

In FY2012, both the injector cryomodule and the main linac cryomodule were installed in the cERL and connected to each 2K helium cryogenic system. In June 2012, before the installation of these cryomodules (Fig. 11), the performance of the cryogenic system, including two 2K refrigerator cold boxes and transfer lines for the cryomodules, was measured. We produced 2K superfluid helium in the two 2K refrigerator cold boxes and measured static heat loads to the cryogenic system. The response of the cryogenic system to the heat load variations was also measured using electric heaters in the 2K refrigerator cold boxes to simulate dynamic heat loads from superconducting RF cavity cryomodules.

In July 2012, the injector cryomodule was connected to one of the 2K refrigerator cold boxes as shown in Fig. 12(a). A connection transfer line was specially designed to minimize the ambient heat load to the cryogenic system. The cryogenic system, including the injection cryomodule, was inspected by the Ibaraki prefecture under the High Pressure Gas Safety Act in August 2012 and passed its completion inspection. The injector cryomodule was successfully cooled down to 2K, and performance of the superconducting RF cavities was measured in September 2012. The main linac cryomodule was connected to another 2K refrigerator cold box in October 2012, as shown in Fig. 12(b), following the first cryogenic test of the injector cryomodule, and it passed the completion inspection by the Ibaraki prefecture in early November 2012. The cryogenic test of the main linac cryomodule was carried out with high RF power in November and December 2012. The injector cryomodule was cooled down again in January and February 2013 for cryogenic testing of the cavities with high RF power.

We have conducted cryogenic tests of the cryomodules with 4 sets of rotary oil pumps and mechanical boosters in the helium gas pumping system of the 2K helium cryogenic system. For the injector cryomodule, it was found the current cooling power at 2K of the cryogenic system could sustain all heat loads from the cryogenic system itself and from the cryomodule. On the other hand, for the main linac cryomodule, the cooling power of the cryogenic system was slightly insufficient to sustain the heat loads. Considering the results of the cryogenic tests with high RF power into the cryomodules, we have increased the number of rotary oil pumps and mechanical boosters to 8 sets of pumps in order to increase the cooling power at 2K, since the cooling power at 2K depends directly on the pumping capacity of the helium gas pumping system in the 2K helium cryogenic system.

Figure 11: 2K refrigerator cold boxes and transfer lines for cryomodules.

(a)

(b)

Figure 12: (a) and (b) show the connections of injector (main linac) cryomodules and 2K refrigerator cold boxes, respectively.

3-7 cERL Magnet Systems

Almost all of the magnets and girders required for 35 MeV operation were manufactured until the end of the 2012 fiscal year. In 2013, three of the four girders for the quadrupoles and sextupoles of the arc section, and two girders for the LCS (laser Compton scattering) matching section, will be made. The eight sextuple magnets and four steering magnets will be manufactured in the future as well. In 2012, the 167 bipolar power supplies of 5 A and 60 V for the quadrupole magnets were manufactured. The four power supplies for the injection, extraction, and path length control chicanes will be made in 2013. Figure 13 shows the girders and power supplies, ready for the construction of the recirculation path. The prototype of the quadrupole and sextupole magnet girder of the arc section was manufactured on the basis of the optimized design from the static and dynamic structure analysis shown in Fig. 14.

Figure 13: The girders and power supplies at the ERL Hall.

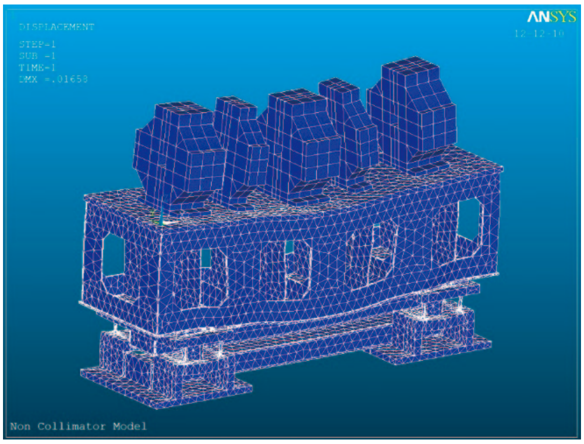


Figure 14: The sample of the distortion analysis of the girder.

3-8 Schedule

Fabrication of the accelerator components such as the injector part, super conducting cavities, RF sources, and He cryogenic systems was completed by the end of the 2012 fiscal year. We will start the beam tests of the injector parts at the beginning of the 2013 fiscal year. These tests will characterize the beam quality at the injector and will be performed until the end of July 2013. Then we will install the recirculation loop from the summer to November 2013 and begin the ERL operation in December 2013. We will carefully increase the beam current to avoid radiation problems from the cERL and will check the beam quality of the cERL in 2014. The target values during the first stage are a beam current of 10 mA and a normalized emittance of 1 mm mrad. Finally, we will check for normalized emittances of 0.3 mm mrad with 7.7 pc/bunch and 1 mm mrad with 77 pc/bunch. The beam test will provide important information on whether further improvement of the components is necessary, as well as information on the drawbacks of the design of the 3-GeV-class ERL.

REFERENCE

[1] N. Nishimori, R. Nagai, S. Matsuba, R. Hajima, M. Yamamoto, T. Miyajima, Y. Honda, H. Iijima, M. Kuriki, M. Kuwahara, *Appl. Phys. Lett.* **102** (2013) 234103.