4 cERL

4-1 Overview of the cERL Project

In order to establish key technologies for the ERL project, we are conducting extensive R&D efforts [1], including the development of high-brightness DC photocathode guns, superconducting (SC) cavities for both injector and main linacs, and some other technologies. To demonstrate the production, acceleration, and recirculation of ultra-low emittance beams using these key technologies, we are constructing the Compact ERL (cERL) [2] in KEK.

A plan for the cERL is shown in Fig. 1. The cERL will comprise a 5-MeV injector, a main SC linac, and recirculating loops, as well as some supporting facilities such as a liquid-helium refrigerator system, 1.3-GHz RF sources, and power supplies. Initial and final goals of the cERL are shown in Table 1. At the initial stage, we will produce low-emittance (normalized emittance: 1 mm•mrad) beams of 10 mA from the DC photocathode gun, accelerate them up to 35 MeV, and recirculate them for energy recovery. We will initially install a single cryomodule having two 9-cell cavities for the main linac. After its successful commissioning, we plan to upgrade the cERL by installing additional cryomodules for upgrading the beam energy and by constructing the second return loop for demonstrating the double-loop ERL configuration.

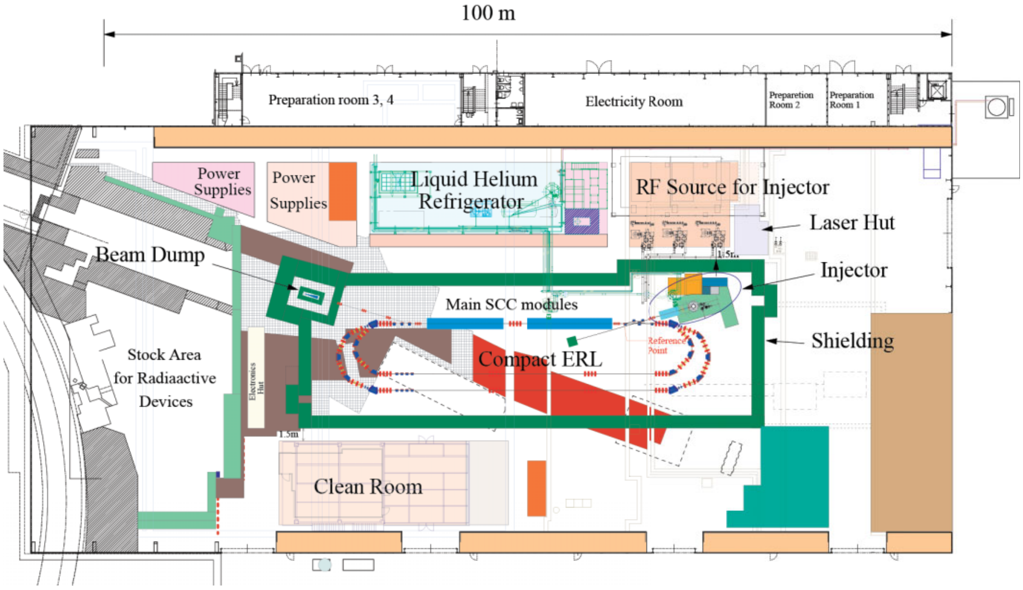

Figure 1
Plan of the Compact ERL.

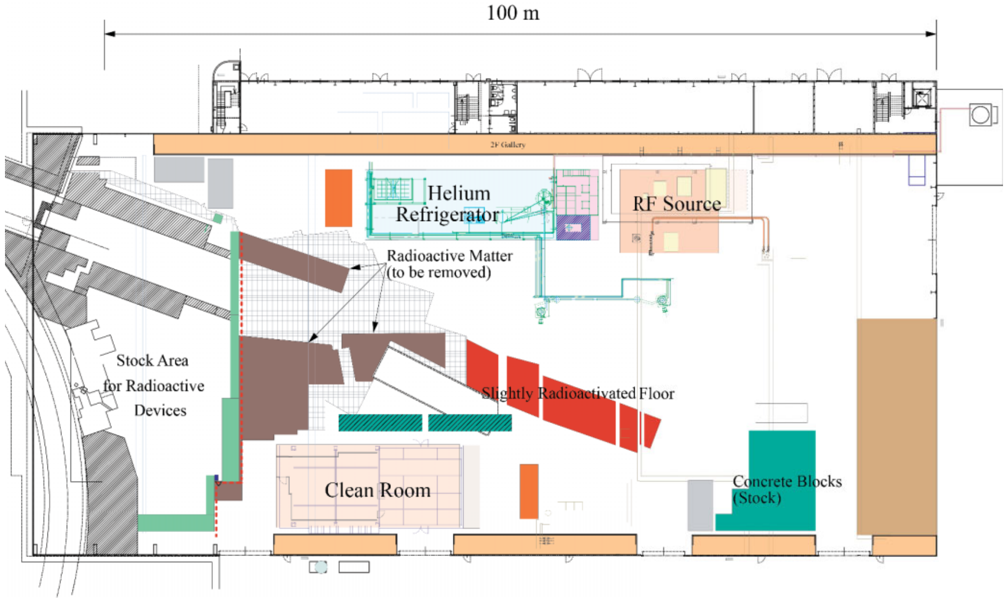

Figure 2
Current layout in the East Counter Hall.

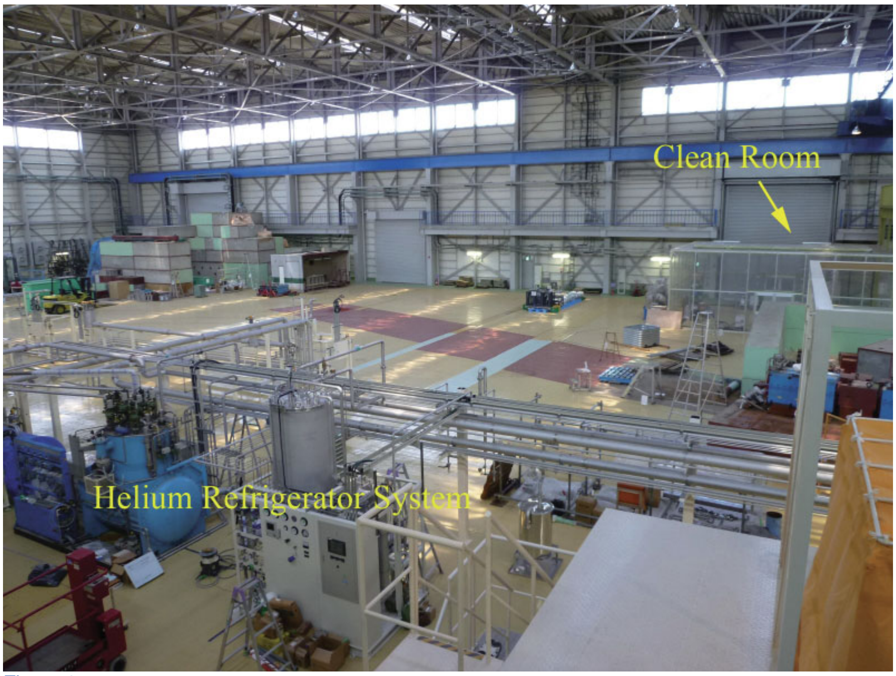

Figure 3
Picture taken in the East Counter Hall after its refurbishment.

Table 1 Goals of the Compact ERL.

Parameter	Initial goal	Final goal
Beam energy at recirculation	35 MeV (single loop)	125 MeV (single loop) 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	15-20 MV/m	15-20 MV/m
Bunch repetition frequency	1.3 GHz	1.3 GHz
Normalized emittance	1 mm•mrad	1 mm•mrad (77 pC/bunch) 0.1 mm•mrad (7.7 pC/bunch)
Rms bunch length	~ 2 ps (usual operation) ~ 100 fs (compression)	~ 2 ps (usual operation) ~ 100 fs (compression)

The cERL is being built in an experimental hall (the East Counter Hall) at KEK. This hall had been used for high-energy physics experiments for about 35 years. In order to prepare for the construction of the cERL, we carried out the following works during FY2009: 1) clearing concrete blocks and old proton beamlines in the hall, 2) refurbishing the building, and 3) refurbishing a cooling water system and an electrical substation. We then installed some infrastructure such as: 1) a liquid-helium refrigerator system having a cooling capacity of 600 W at 4 K, 2) a part of the RF sources including a 300-kW klystron and some 30-kW Inductive Output Tubes (IOTs), and 3) a clean room for cavity assembly. Following these works, the hall is almost ready to construct the cERL. Figures 2 and 3 show the present layout and a picture of the hall, respectively.

During FY2010, some radioactive matter remaining in the hall will be removed. In parallel, photocathode DC guns and SC cavities are under development. During FY2011, the radiation shielding for the cERL will be constructed, and during FY2012, most of the components of the cERL will be installed. The cERL is planned to be commissioned at the end of FY2012.

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4-2 Renovation of the East Counter Hall for Constructing the compact ERL

The East Counter Hall (ECH) at KEK has been used for high-energy experiments and nuclear physics experiments, with proton beams from the 12-GeV Proton Synchrotron. Because these activities are shifting to J-PARC site, this hall starts to be used for developing pioneering accelerators, especially for constructing the compact ERL (cERL).

In FY 2008, we received budget for renovating the ECH and making its building earthquake-resistant. During FY 2009, a work on clearing about 10,000 tons of concrete shielding, as well as activated components from the old proton beam lines, was carried out in the ECH.

Both a cooling water plant and an electrical substation were also renewed as the infrastructure for the cERL. The cooling water system can provide 2,600 l/min of pure water and has a cooling power of 1.9 MW. The electrical substation supplies 4.1 MW of electrical power.

Renovation of the ECH has been completed and construction of the cERL is ready to proceed. According to the current schedule, we will construct the radiation shield in the ECH during FY 2011.

Figure 4
View of the East Counter Hall before the renovation.

Figure 5
View of the East Counter Hall after renewing and clearing the East Counter Hall.

4-3 High Brightness DC Photocathode Gun

To operate and test the photocathode guns before installation at the cERL injector, a gun test facility has been constructed in the PF-AR South Experimental Hall [3]. The gun test facility has two photocathode guns (a 200-kV gun developed at Nagoya University [4] and a new 500-kV gun, which is under development), a laser system to emit electrons from the photocathode surface, beam transport lines, and a beam diagnostics system. The diagnostics system consists of a double slit emittance measurement system, beam position monitors, transverse profile monitors, and a deflecting cavity to measure the bunch length and the longitudinal profile. Figure 6 shows the layout of the gun test facility.

For the cERL, two 500-kV DC gun systems are being developed individually at JAEA and KEK. The first reason for the two individual systems is that there are many development elements: how to avoid insulator breakage, how to produce extremely high vacuum of below 10^{-10} Pa, and how to suppress dark current from the electrodes in high electric fields. Especially, in order to achieve 100-mA beam operation, the R&D machine must overcome many problems, for example, high power laser development, cathode heating problem, and the very serious cathode lifetime problem. The second

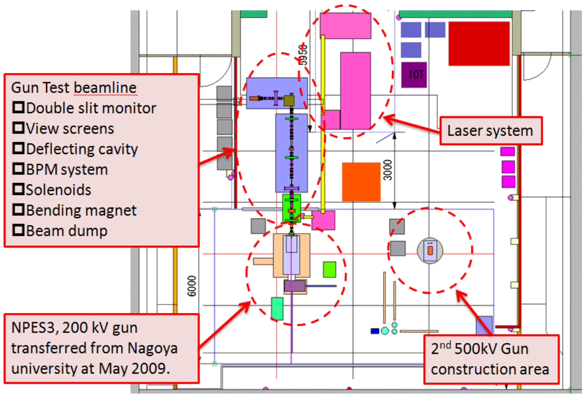


Figure 6
Layout of AR South Experimental Hall to develop and study the gun system.

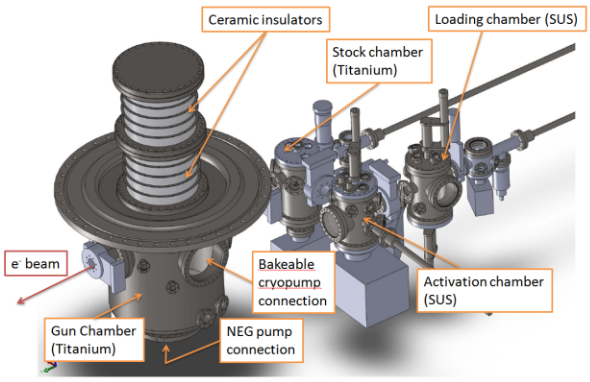


Figure 7
Second photo cathode 500-kV DC gun system.

reason is as a backup in case of serious damage to an installed gun system during operation. In this report as follows, the gun of JAEA is called the first gun, and the gun of KEK is called the second gun. Figures 7 and 8 show the second gun system, the concept of which is as follows. In order to achieve extremely high vacuum, we employed titanium for the material of the gun chamber. The second gun was designed in consideration of easy maintenance, extendibility, and compatibility with the first gun. For the vacuum pumping system, we employed a specialized bakeable cryopump. For the cathode preparation system, we are planning to develop a multiple cathode preparation system to decrease the cathode preparation duty. The target vacuum condition for each chamber is about 10^{-8} to 10^{-10} Pa or less. Several cathodes are fixed on a puck revolver and installed in the loading chamber. In the loading chamber, the cathodes are cleaned by atomic hydrogen and heating. Then, the cathodes are transferred to the activation chamber, and the negative electron affinity (NEA) surface is created by Cs and oxygen deposition. Then, the revolver is transferred to the stock chamber. In the stock chamber, the cathodes are preserved in extremely high vacuum to maintain high cathode quantum efficiency (QE). Then, one cathode is transferred to the gun. If the cathode QE decreases, we can quickly exchange it with another fresh cathode. This is the concept of our multi-puck system. The fabricating processes of the gun chambers were finished in March 2010. From April 2010, we will examine the vacuum chambers and construct the gun system.

A 1.3-GHz fiber laser system is being developed at the gun test facility, aiming for first injector commissioning of up to 1 mA. Figure 9 shows the laser system configuration. Commissioning of the drive laser at the gun test facility started in 2009. The requirements for the 10-mA operation of cERL are 1.3 GHz in repetition, 530 nm in wavelength, 20 ps in pulse duration, and 1.5 W in power. The system has been built based on commercial units (1.3-GHz oscillator, fiber amplifier, second harmonic generation, etc.). A second harmonic power of 100 mW has been achieved, which is sufficient for the first injector commissioning of up to 1 mA. Development of the high-power amplifier is progressing for a second harmonic power of over 1 W that can generate 10-mA beams. Pulse train shaping (a pulse train of 1000 bunches) has been introduced for a burst operational mode, which is for the commissioning phase of the ERL operation. In order to test the high bunch charge beams, a lower repetition rate, higher intensity Ti:sapphire laser system will be used. The laser transport line and input chamber are being made.

In 2009, we started constructing the gun test beamline. The purpose of the test beamline is to gain experience of operating the low energy beam, to evaluate the performance of the DC guns by an additional diagnostic line for measuring emittance and bunch length, and to develop a new 500-kV gun and the injector line to be used at cERL. Now, a 200-kV gun developed at Nagoya University for a polarized electron source of the International Linear Collider [4] is under beam operation. This gun was transferred from Nagoya University in May 2009. Until the mid 2011, we will use the 200-kV gun to test the beam diagnostic system. After construction of the 500-kV gun, we will switch from the 200-kV gun to the 500-kV gun. Figure 10 shows the layout of the gun test beamline. The beamline consists of three sections. The first section has the same layout as the

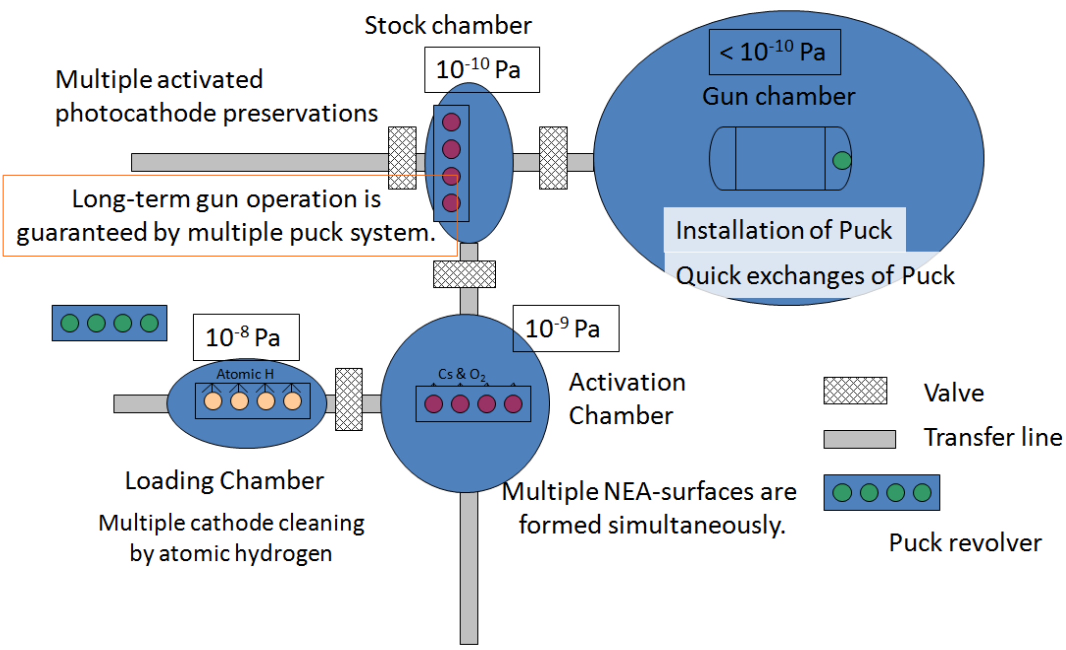
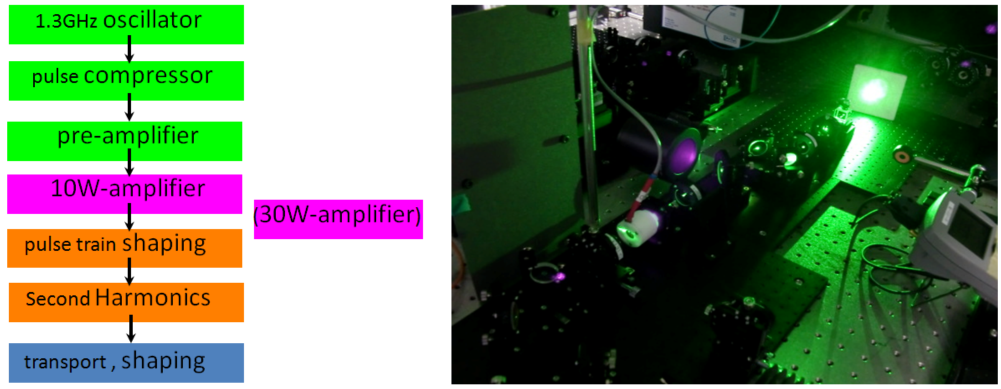


Figure 8
Outline of second photocathode 500-kV DC gun system.



(a) Outline of fiber laser system **(b) Photograph of laser**

Figure 9
Configuration and photograph of the fiber laser system.

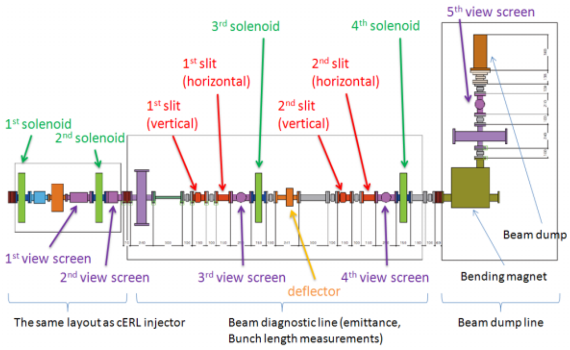


Figure 10
Layout of the gun test beamline.

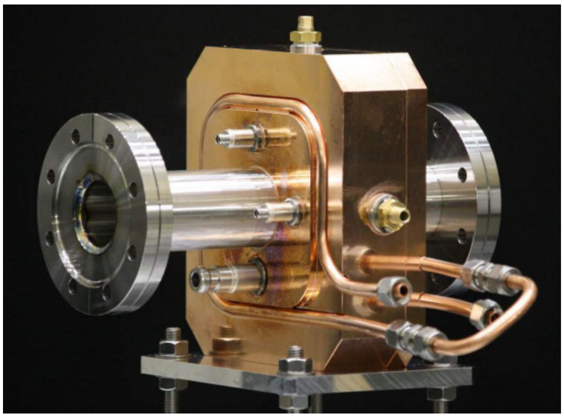


Figure 11
Photograph of the deflecting cavity to measure bunch length.

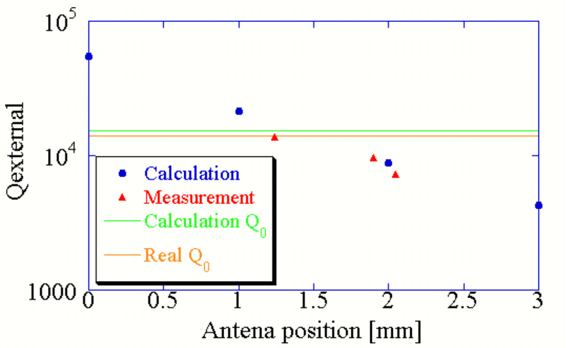


Figure 12
Q-external of deflecting cavity versus head of antenna position from cavity wall. The positive position is the direction of intrusion into the cavity.

cERL injector. After this section, we connect a beam diagnostic line, which has a double-slit emittance measurement system and a deflecting cavity to measure bunch length. The third section has a beam dump. We are constructing the gun test beamline with the 200-kV gun in the gun test facility.

Some of the photocathodes have slower response time, which generates a longer beam tail compared with the laser pulse width. The slower cathode response affects the beam parameter generated by the DC gun. For example, the emittance growth is caused by both the longer tail and space charge effect. Therefore, since the beam parameter depends on the property of the photocathodes, the cathode properties required to generate high-quality beams must be investigated. The cathode response can be measured by measuring the bunch length. In order to observe bunch length and longitudinal beam profile, we have designed a single-cell deflecting cavity with a 2.6-GHz dipole mode [5]. The cavity consists of two main bodies, beam pipe, coupler, probes, tuners, pipes for water cooling, and flanges. Figure 11 shows a photograph of the cavity. The power input test and vacuum test of the cavity have been finished. As an input coupler, a coaxial type antenna having an inner conductor of 3 mm diameter and outer conductor of 7 mm diameter is used. The calculated and measured Q-externals of this coupler are shown in Fig. 12. The deflecting cavity will be installed in the gun test beamline.

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4-4 Superconducting Cavities

4-4-1 Superconducting Cavities for the Injector

In the injector linac of the cERL, three superconducting (SC) cavities are used to accelerate beams from the DC photocathode gun up to a kinetic energy of 5 MeV. The two-cell cavity, a high-power input coupler, and a cryomodule are under development [6]. Considering the higher injection energy of 10 MeV that is required for the future 5-GeV ERL, we set the goals of an accelerating gradient of 14.5 MV/m and transmission power through each coupler of 170 kW.

We have produced two prototype 2-cell cavities for investigating their performance. The latest cavity (No. 2) has two input-coupler ports and five loop-type HOM couplers. Under performance tests in a vertical cryostat (see Fig. 13), this cavity achieved an accelerating gradient of higher than 40 MV/m without connecting HOM pickups.

We have also produced two prototype input couplers, as shown in Fig. 14. We constructed a high-power test bench and carried out tests for the prototype couplers. These couplers were successfully conditioned under pulsed high-rf power. Typical conditions in the tests were a peak power of 130 kW, pulse width of 1 s, and repetition frequency of 0.2 Hz (average power: 26 kW). We plan to test them under higher power after making some improvements to the cooling mechanism.

Design of an injector cryomodule which can house three 2-cell cavities is also under way.

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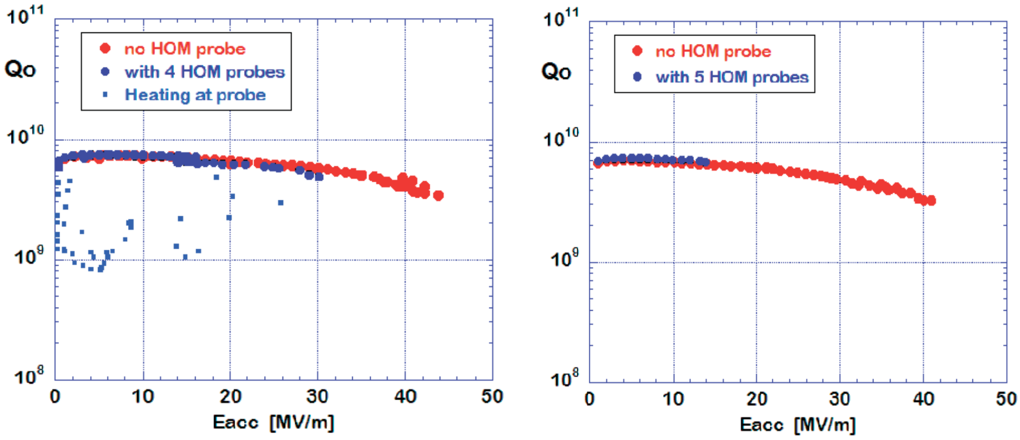

Figure 13
Results of the performance tests on the prototype 2-cell cavities [6]. Measured unloaded-Q values at the temperature of 2K are shown as a function of the accelerating gradient.

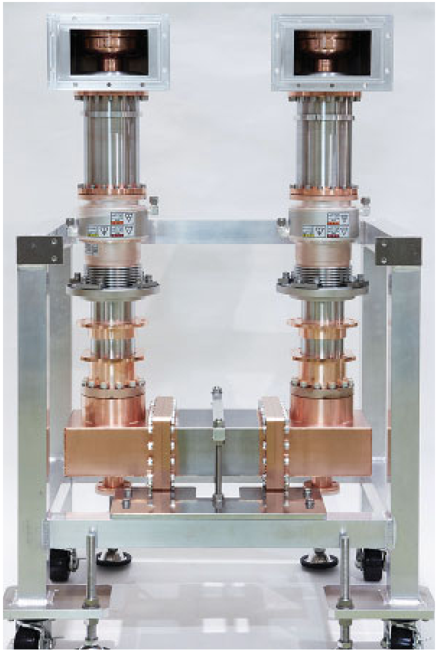

Figure 14
Picture of the prototype input couplers.

4-4-2 Superconducting Cavities for the Main Linac

In order to obtain the technology needed for the ERL main linac, a great deal of effort was put into developing critical components, for example, the cavity, input coupler and Higher Order Mode (HOM) absorber. Design of a cryomodule, which contains two 9-cell cavities, is also under way.

Nine-cell superconducting cavity

We have designed the KEK-ERL model-2 cavity, which is optimized for ERL operation, especially for HOM damping. It has a large iris diameter of 80 mm and large beampipes with diameters of 100 mm and 120 mm [7]. An accelerating gradient of 15–20 MV/m is required for ERL cavities. To verify this cavity design, a prototype of the 9-cell cavity was manufactured, and a series of surface treatment procedures was applied to it.

Several vertical tests were carried out to investigate the performance of the cavity. Figure 15 shows the Q-E curves obtained from the 1st to 7th vertical tests [8]. In all cases, field emissions limited the cavity performance up to 15–17 MV/m. Even the initial state of the 7th test was fine and could reach 25 MV/m without hard field emissions. Unfortunately, however, X-ray bursts happened during pass-band measurements, and the final state of the cavity was limited to 10 MV/m.

In order to investigate the behavior of field emissions, we have developed the rotating mapping system [9]. X-ray trajectories and temperature mapping can be obtained using Si PIN diodes and carbon resistors, respectively. Figure 16 shows an example of the X-ray mapping, which was obtained at Eacc = 13.9 MV/m in the 4th vertical test. A sharp X-ray peak can be seen at 330 degrees (in angular coordinates) of the 8–9 iris, and broad X-ray peaks can be seen at around 150 degrees of the irises of 1–5 cells. After the vertical tests, the inner surface of the cavity was observed using an inspection camera. As seen in the right figure of Fig. 16, a small tip was found at 150 degrees of the 8–9 iris. It is considered most probably to be the source of the field emissions.

We are working to suppress field emissions to improve cavity performance.

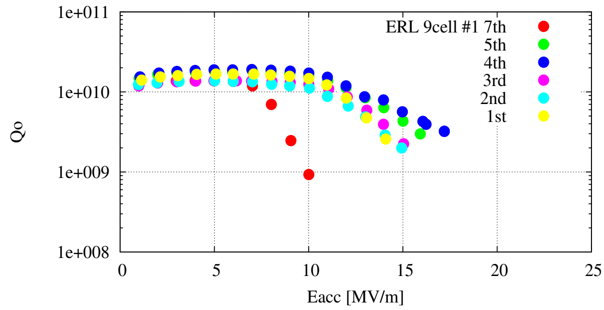

Figure 15
Qo-Eacc curves of vertical tests.

Input coupler

A coaxial type power coupler with double ceramics has been designed for the ERL main linac input coupler [10]. A maximum RF power of 20 kW with standing wave is required. To reduce dynamic losses of the RF power, HA997 ceramic is used.

In order to confirm the performances of components such as ceramics and bellows, we constructed a high-power test stand using 30-kW IOT, at JAEA, as shown in the left of Fig. 17. Unfortunately, the first model of window could not pass enough RF power; even at less than 10 kW, unexpected RF losses and temperature rises happened and finally the ceramic windows broke, as shown in the right of Fig. 17. Through low-level measurements and computer simulations with HFSS and MW-studio, it was found that the dipole resonance existed close to 1.3 GHz [11].

In order to avoid the dipole resonance from an operation frequency of 1.3 GHz, a second model of the ceramic window was fabricated with thinner HA997 ceramic, and the frequency of the dipole mode was shifted about 30 MHz. A high-power test was performed and successfully passed a CW standing wave of 27 kW without any abnormal temperature rises.

The bellows of the inner conductor is another important component. Applying air cooling by an air flow of 90 l/min, its temperature rise was suppressed to an adequate level.

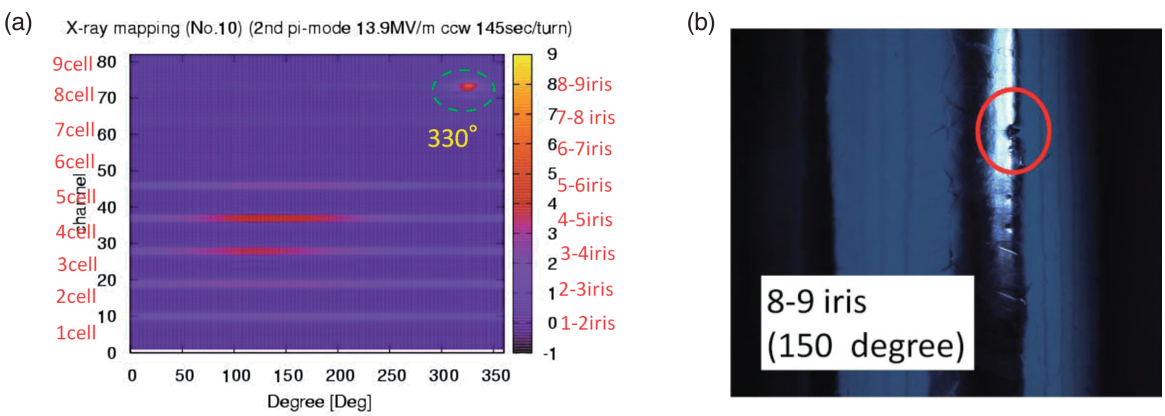

Figure 16
(a) X-ray mapping data at Eacc = 13.9 MV/m. (b) Picture of inner surface of cavity. A tip was found at the iris between 8-cell and 9-cell.

HOM absorber

A new IB004 ferrite was selected as a material for the HOM absorber, after investigating its absorption property at a low temperature of 80 K. A schematic view and a picture of the prototype HOM absorber without ferrite are shown in Fig. 18. A ferrite cylinder with a thickness of 2 mm will be bonded onto the inner surface of a Cu beam pipe by hot isostatic pressing.

Cooling tests of the prototype HOM absorber without ferrite are now in progress at the Institute of Solid State Physics, University of Tokyo [12].

Cryomodule design

The first main linac cryomodule for the cERL project is being designed [13]. It contains two 9-cell cavities as shown in Fig. 19. Each cavity is covered with a Ti-jacket of diameter 300 mm. They are aligned on Ti frames and connected with each other through the HOM absorber. A slide-jack tuner and a piezo tuner are used for frequency tuning.

Two cavities will be fabricated in FY2010, and module assembly will be completed in FY2011.

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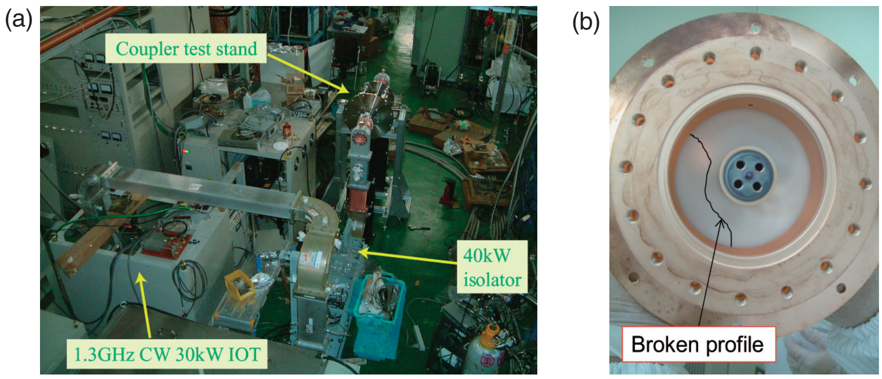

Figure 17
(a) Setup of the coupler test stand. (b) Picture of the cold window with broken profile.

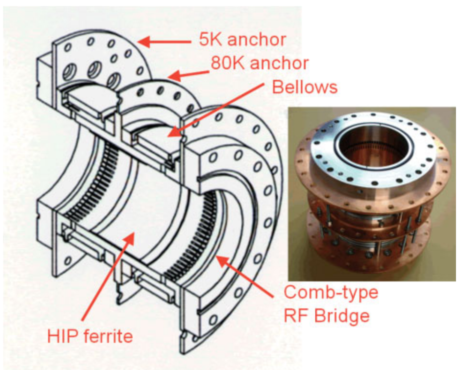

Figure 18
Schematic view and prototype HOM absorber.

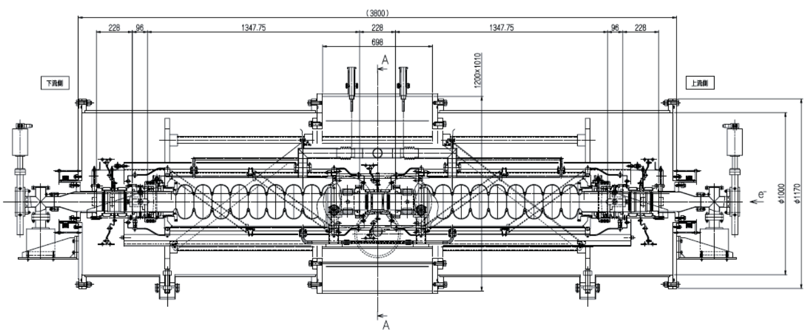

Figure 19
Design of the prototype module for the cERL main linac.

4-5 Cryogenic System

The 2K cryogenic system was designed and constructed to cool the cERL 1.3-GHz superconducting RF cavities. The layout and flow diagram of the 2K cryogenic system are shown in Fig. 20 and Fig. 21, respectively. This 2K cryogenic system consists of the following four main components:

1) A helium liquefier/refrigerator,
2) High-performance helium transfer line,
3) Two 2K helium refrigerator cold boxes and helium gas pumping system,
4) Cryomodules of superconducting RF cavities for injector and main linac.

Helium liquefier/refrigerator

The cold box of the helium refrigerator TCF200 (cooling power of 500 W at 4.4 K or liquefaction rate of 250 l/h) was installed beside the cERL in the experimental hall to make the helium transfer line as short as possible. The screw type helium compressor is installed in the existing compressor building used for the helium refrigerator operated for the previous physics experiments. This helium refrigerator was previously used at the National Institute for Materials Science (NIMS) for more than ten years as a liquefier. After it ceased being used at NIMS due to system renewal, this refrigerator (cold box and compressor unit) was transferred to KEK.

In this 2K cryogenic system, the helium liquefier/refrigerator is operated mainly as a liquefier to make the liquid helium needed for the 2K refrigerators, and also operated as a refrigerator to cool the 4K heat load at the transfer line and the cryomodules. In the 2K cooling, which is the so-called liquefier mode, the cold vaporized gas from the 2K refrigerator is warmed up to room temperature and sent back to compressor suction without utilizing cooling capacity. In the 4.4K cooling, which is the so-called refrigerator mode, cold vaporized gas used for cooling is sent back to the cold box through the transfer line, and its cooling capacity recovers.

High-performance helium transfer line

The liquid helium liquefied and stored in the 3000L liquid helium Dewar is sent to the 2K refrigerator by the high-performance vacuum insulated multi-channel transfer line. As shown in Fig. 21, the multi-channel transfer line has a helium flow line to supply the liquid helium to the 2K refrigerators and a cold helium gas return line to recover cold helium gas to the refrigerator, and flow and return liquid nitrogen lines to cool the 80K thermal shield of the cryomodules. In this transfer line design, the helium lines are thermally guarded by the 80K shield cooled by liquid nitrogen to reduce the heat loss to lower than 0.1 W/m.

The liquid nitrogen required for cooling the 80K thermal shield of the transfer lines and cryomodules is supplied by a liquid nitrogen circulation system. The cooling power of this circulation system is provided by the liquid nitrogen supplied from the liquid nitrogen storage tank. The configuration of this circulation system is very simple; it consists of a commercially available air compressor, heat exchanger, and J-T valve, and has no expander to make the cooling power. By adopting this liquid nitrogen circulation system we can supply liquid nitrogen economically to many lines in parallel to cool the 80K shield.

2K helium refrigerator cold box and helium gas pumping system

The 2K super-fluid liquid helium used to cool the superconducting RF cavities is generated at the 2K refrigerator cold box by pumping the helium gas in the 2K pot to a pressure lower than 0.03 bar. Figure 22 shows the detailed flow of the 2K refrigeration for cERL. The

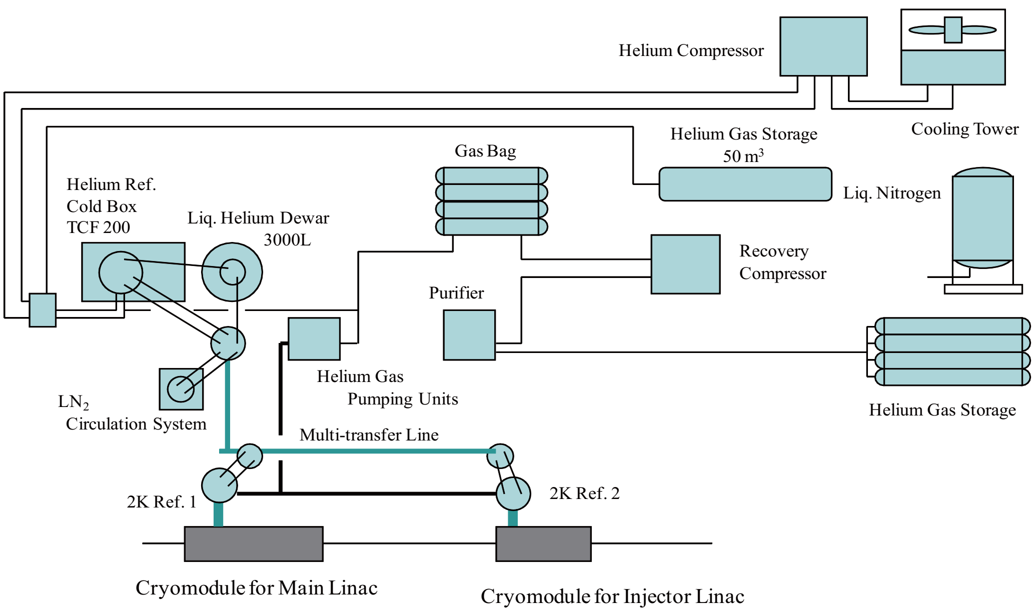

Figure 20
Layout of the 2K cryogenic system for cERL.

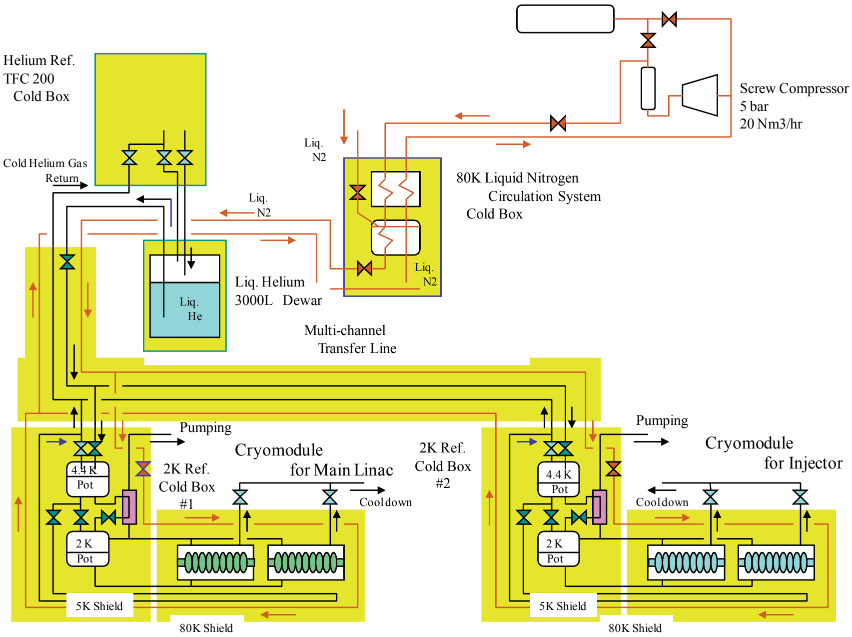

Figure 21
System flow diagram of the 2K cryogenic system for cERL.

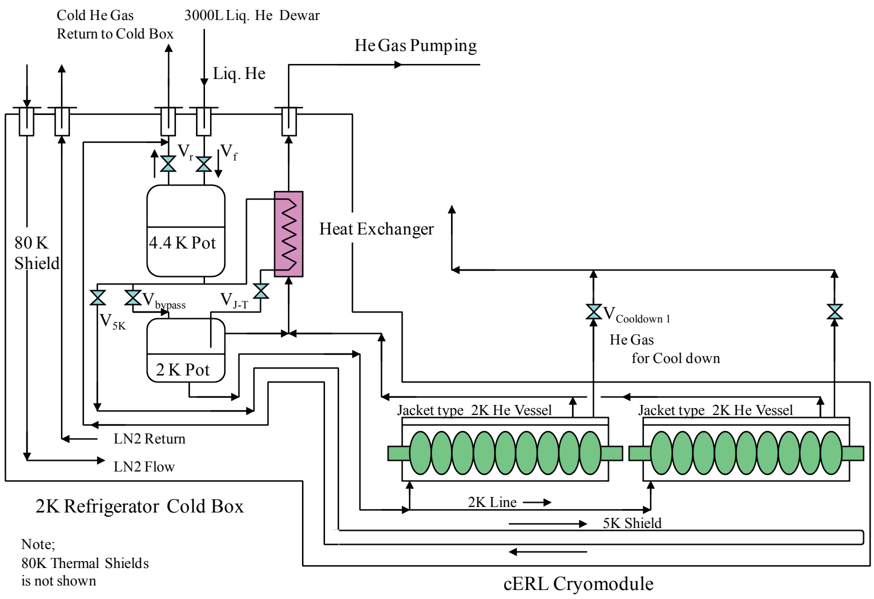

Figure 22
Detailed system flow diagram of 2K refrigerator and cryomodule for cERL.

liquid helium of about 1.2 bar in the 4.5K helium pot is sent to the 2K J-T heat exchanger and cooled by 2K return helium gas, and expands into the 2K pot of 0.03 bar through the J-T valve.

In this 2K refrigerator, the vaporization heat of liquid helium is used to produce 2K cooling power. We must vaporize about 1.5 l/hr of liquid helium to obtain cooling power of 1 W. Therefore, for cooling power of 100W at 2K, we must supply about 150 l/hr of liquid helium to the 2K refrigeration system, and pump out the same amount of helium gas at the pressure of 0.03 bar. In the case of long-term steady operation, the maximum cooling capacity of these 2K refrigerators is limited by the liquefaction rate of the refrigeration system. But by operating the 2K refrigerator intermittently, the cooling capacity can be increased by consuming extra liquid helium stored in the 3000L Dewar liquefied during low-power operation of the 2K cooling system.

For pumping the vaporized helium gas from the 2K pots and the cryomodules, room-temperature pumping units are used. These pumping units are mounted on rubber vibration isolators to prevent vibration of the pumping unit from transmitting to the superconducting cavities. The pumping unit is a combination of a mechanical booster pump and rotary pump in tandem. Two pumping units were installed for a cooling capacity of about 50 W at 2 K, which can be increased by adding more pumping units in future upgrades.

Cryomodules of superconducting RF cavities

The superconducting RF cavities installed in the jacket-type 2K helium vessel are assembled into the cryomodule and cooled by 2K liquid helium as shown in Fig. 22. These 2K components are thermally guarded by 5K and 80K shields cooled by liquid helium and liquid nitrogen, respectively. The cryomodule is connected to the 2K refrigerator cold box by a multi-channel transfer line. The liquid helium stored in the 2K pot is supplied to the 2K helium vessel to cool the superconducting RF cavity by the 2K piping of the multi-channel transfer line. The vaporized gas in the 5K shield is sent back to the refrigerator cold box through the return helium line of the multi-channel transfer line.

Construction of the cryogenic system for cERL

The design study of the 2K cryogenic system for cERL was started in 2006. In designing the cERL 2K refrigeration system, for the base line design, we adopted the Superconducting Test Facility (STF) 2K 40W refrigerator system which was designed, constructed, and operated to cool the cryomodule of the International Linear Collider (ILC) prototype superconducting RF cavities. Because the required cooling power of the cERL 2K refrigerator is 80 W for each 2K refrigerator, which is twice that of the STF 2K refrigerator, we must pump out two times more cold gas through the 2K heat exchanger. We developed a new large-size heat exchanger to accommodate this requirement. Two 2K refrigerator cold boxes are constructed for the injector cryomodule and the main linac cryomodule.

Because the helium refrigerator used for the cERL 2K cryogenic system is old, we were very concerned about the contamination of compressor oil into the heat exchanger of the helium refrigerator. Before starting the new operation for cERL, we opened the cold box and inspected the inside of the 80K charcoal filter which was installed in the flow line of just after the first heat exchanger. We found that the charcoal filter was contaminated by oil, so we cleaned the flow line of the first heat exchanger using solvent for oil and replaced the charcoal with a new one.

The helium refrigerator system and the main part of the two cERL 2K refrigerators and multichannel transfer line system were completed by the end of FY2009. Figure 23 shows a bird's-eye view of the completed whole cERL cryogenic system installed in the experimental hall. The cold box of helium refrigerator TCF200 (center), the 3000L liquid helium Dewar (left), and the helium purifier (right) can be seen in the front of the picture. The multi-channel transfer line and 2K refrigerator cold boxes can also be seen behind the cold box. Figure 24 shows the 2K refrigerator cold boxes for the main linac (left) and injector linac (right). Figure 25 shows the pumping unit for vaporized helium gas from the 2K refrigerator system installed under the helium gas bag.

After completion of the whole cryogenic system, an inspection test was performed by the local government in August and we received permission for operation.

The helium refrigeration system is scheduled to be commissioned in September 2010, and the cooling capacity and liquefaction rate of the helium refrigerator will be measured. The commissioning of the 2K refrigerator and helium transfer line without the cryomodule will be carried out, and the 2K cooling capacity will be checked.

Summary

The cERL 2K cooling system, which consists of helium refrigerator TCF200, two 2K refrigerators with helium gas pumping system, and multi-transfer line, was proposed and designed in 2008. The main components of the system were constructed and installed in the experimental hall of the cERL by the end of FY2009, and commissioning of the helium refrigerator will be started in September 2010.

Figure 23
The 2K cryogenic system for cERL installed in the experimental hall.

Figure 24
2K refrigerator cold boxes for injector and main linac cryomodules.

Figure 25
Pumping units for vaporized helium gas from the 2K refrigerator.

4-6 RF Source

Here we report the progress of the RF source of the compact ERL in FY2009. A 300-kW CW klystron and an associated power supply for an injector linac, an IOT, and a 35-MW CW klystron were developed. The key waveguide components such as the 150-kW circulator were also developed. The test stations required for processing the couplers for superconducting (sc) cavities have been in operation since 2009. The plan to develop the RF test station at the new site is now in progress.

We developed the 300-kW CW klystron of the injector linac to agree with the original Conceptual Design Report (CDR) plan [2], and ordered it to Toshiba Corp. in 2009. This klystron (Toshiba E37750) achieves an output power of 305 kW with an efficiency of 63% at a voltage of 49.5 kV and a beam current of 9.75 A. This klystron has been used for processing a pair of couplers with a 150-kW power level since March 2010 at the PF Power Supply Station. From June, the test station will be moved to the East Counter Hall in KEK where the cERL is to be constructed.

The power supply for the 300-kW CW klystron was manufactured in FY2009. The main specifications of the power supply are as follows: maximum output voltage of 52 kV, maximum output current of 11 A, output voltage ripple of less than 0.5% (peak-to-peak), and output voltage stability of less than 0.5% (peak-to-peak). Stabilization was achieved by the well-established thyristor phase control. For protection of the klystron, a fast Insulated Gate Bipolar Transistor (IGBT) switch goes active when it has an arcing to maintain an energy of less than 10 J in the tube.

We prepared the components of the WR650 waveguide system to be similar to those of STF since the operating frequency was the same. In FY2009, we developed a circulator with three ports; this circulator has the capability of the CW 150-kW klystron since the original CDR employs two couplers in one cryomodule that consists of two sc cavities. For compactness, the ferrite

Figure 26
Test Station in PF Power Supply Hall.

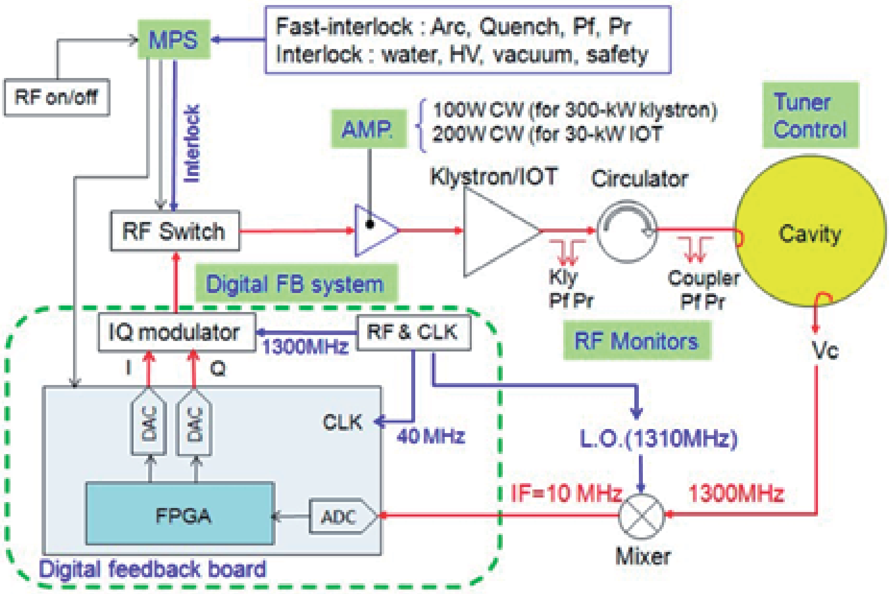

Figure 27
Block diagram of LLRF.

parts consist of four layers. An insertion loss of less than 0.3 dB and an isolation of more than 20 dB were achieved. This circulator has been used for the coupler test stand since the end of FY2009.

We prepared two types of RF source for the main linac: one is a 35-kW IOT (VKL-9130, CPI), and the other is a 35-kW klystron (E3750, Toshiba). Even though the E3750 had a good efficiency of 60% at the saturation points, when these two sources were operated in the unsaturated power range under low-level radio frequency (LLRF) feedback, the operating efficiency of an IOT was expected to be higher than that of a klystron. We will compare the performance of the two sources and make a choice for the future project. We obtained all the power supplies for these two sources. One was manufactured in FY2009, and the other two power supplies were transferred from the Japan Atomic Energy Association (JAEA). These will be installed and tested in FY2010 at the East Counter Hall in KEK.

In order to perform the high-power test of the injector couplers, which have a transmission power of 150 kW, before all components are manufactured, we developed a test bench to evaluate the coupler in the PF Power Supply Hall by utilizing the old power supply of the PF klystron. Figure 26 shows the test station of the couplers. The power transmission test of up to 150 kW of a pair of couplers was successfully performed in May 2010. This station will be closed soon, and all high-level radio frequency (HLRF) components except for the old power supply will be moved to the East Counter Hall where the cERL will be constructed.

The cERL will be constructed at the East Counter Hall in KEK. The layout of the entire cERL is shown in the CDR. In accordance with the energy reduction from the original design value, all power supplies and RF sources are gathered near the injector section. In addition, the two coupler-test stands for the injector linac and the main linac coupler are located next to the power supplies. There are some ambiguities since the structure of the radiation shield is not precisely designed.

The stability requirements are an rms amplitude of 0.1% and a degree phase of 0.1 at the cERL. In order to satisfy these requirements, a digital LLRF system has been developed. The block diagram of the LLRF is shown in Fig. 27. The LLRF consists of a digital control, an RF amplifier, an RF monitoring system, a tuner control, and a component safety system (MPS). Because of the budget limitation, we built the RF amplifier, the RF monitoring system, and the MPS, which is the same as the J-Parc one, in FY2009.

A micro-TCA system is adopted, and the new Field Programmable Gate Array (FPGA) board (AMC module) has four 16-bit ADCs and four 16-bit DACs. Down-converted RF signals (IF: ~10 MHz) are connected to the ADCs. Simple PI feedback with feed-forward will be applied inside the FPGA on the basis of the previous experiences at STF in KEK. The cavity detuning control will also be carried out by this new FPGA board. The FPGA board will be an Experimental Physics and Industrial Control (EPICS) Input/Output Controller (IOC), and all the controls and data acquisition will be via EPICS. The fast arc detector employs an optical fiber with a diameter of 0.6 mm and a photo-diode/multiplier system. The control board for the digital control was manufactured in FY2009. The AMC module is employed in the LLRF of ERL since this module is widely used in the field of telecommunications.

4-7 Lattice Design

In order to achieve high energy with limited space, the electron beam is accelerated twice by the same superconducting cavity with the double loop recirculation path as shown in Fig. 28. Figure 29 shows the step-by-step method of designing the linear optics, which includes only linear beam dynamics. In the first step, the optical function of the main linac section is designed by using the dummy loops, which consist of only quadrupole magnets and drift spaces. For the arc section, the triplets composed of three quadrupole magnets between the main bending magnets are optimized to make simultaneously achromat and isochronous optics in which the energy spread does not affect the beam emittance and bunch length at the following straight section in the linear beam dynamics. Finally, four quadrupole magnets between the main linac and arc sections are used to match their optics (matching section). To simplify the lattice design, the magnetic fields of all quadrupole magnets are fixed symmetrically. The optical functions for accelerating and decelerating beams can be close to a mirror symmetrical shape in spite of the imperfect symmetrical lattice. Figure 30 shows an example of the linear optics designed by the simulation code, elegant.

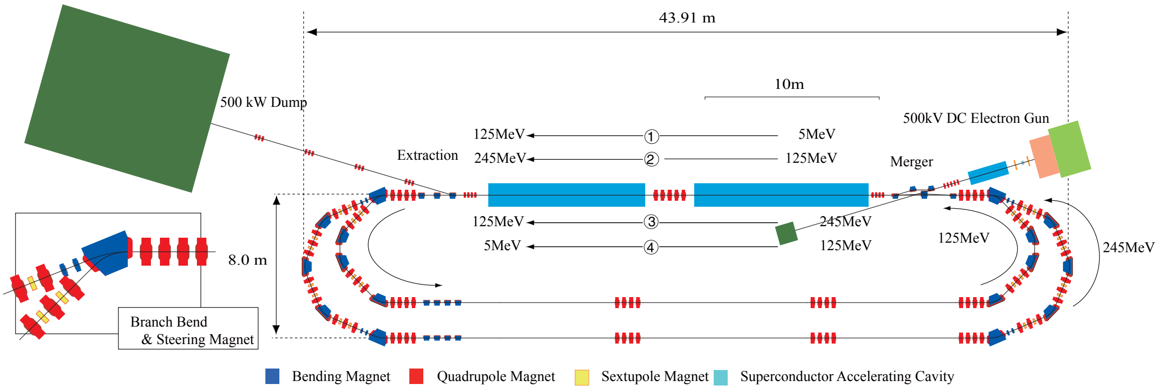

Figure 28
Lattice design of cERL.

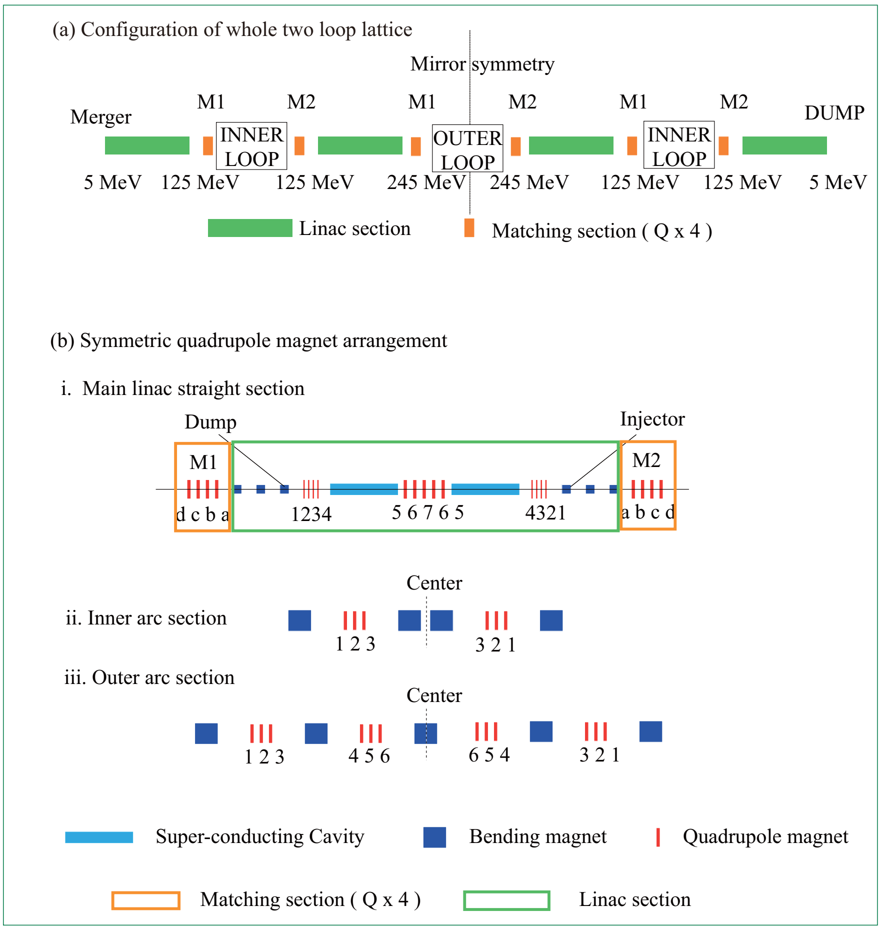

Figure 29
Optics design strategy.

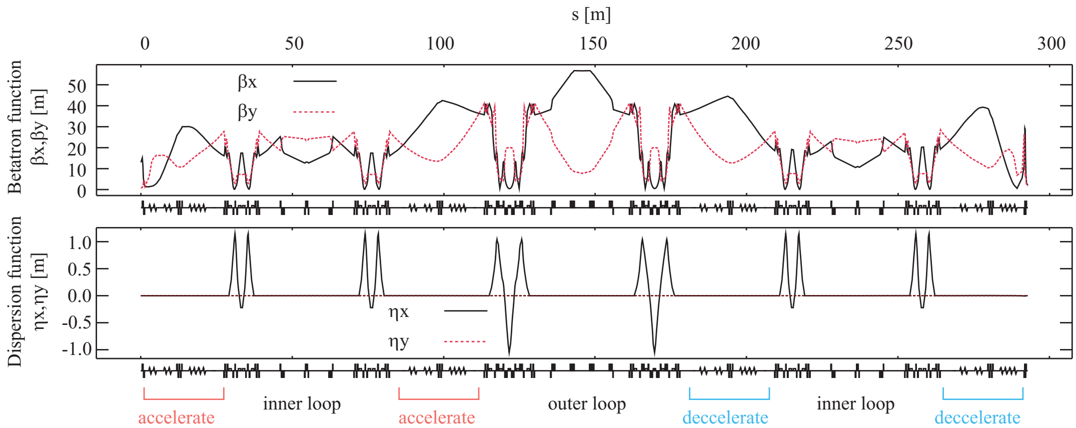

Figure 30
Example of quasi-symmetrical optical function. Optical function at the merger point to the injector (s =0) is (β_x, α_x, β_y, α_y, η_x, $\eta_{x'}$) = (13 m, -2, 0.7 m, 0 ,0, 0). Maximum horizontal beta function β_x is 57 m.