COMPACT ERL LINAC

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Abstract

Construction of the Compact ERL is planned in KEK, in order to test the key technology to realize a future ERL based X-ray light source. The operation of 60-200 MeV beam energy and 100 mA beam current are proposed. The superconducting cavity is one of the key components and applied for the injector part and the main linac part. At the injector part, most challenging issue is an input coupler, which has to handle more than 300kW input power per cavity. On the other hand, strong HOM damping is required for the main linac, in order to avoid beam instabilities and large heat load at cryomodules. Status of cavity developments, together with cryomodule developments, including input couplers and HOM couplers/absorbers, are described in this paper.

INTRODUCTION

Although 5-GeV class ERL is anticipated as a future light source, which provides super-brilliant and/or ultra-short pulse X-rays, many issues have to be solved. Most important tasks are the electron gun, emittance conservation scheme and superconducting cavities.

The compact ERL [1, 2] is a test facility to demonstrate performance of such components and its potential as a light source. Injector design is basically same with the one for 5-GeV ERL. Since beam quality of the ERL is dominated at the injector part, it is important to show ultra-low emittance beam can be operated with beam current of 100 mA. Achieving to ultra-short pulse of 100 fs is also another interest.

For the superconducting cavity, CW operation is a key point. At the injector cavity, each cavity has to handle more than 300 kW of input power. At the main linac, suppression of HOM is essential to avoid BBU (beam breakup) instability. The cavities are operated at 2K. Stable operation of the cryogenic system is another important issue.

THE COMPACT ERL PROJECT

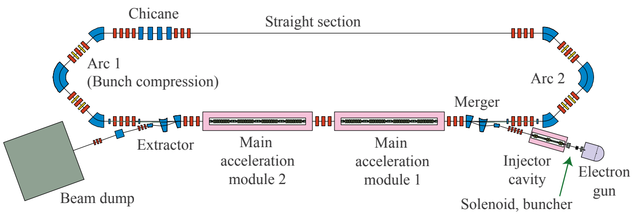

Figure 1: Conceptual layout of the Compact ERL.

Figure 1 shows conceptual layout of the Compact ERL. It will be planned to be constructed at the East Counter Hall on KEK.

Electron beams injected from the electron gun pass through the solenoid magnets and buncher cavity, and accelerated up to 5-10 MeV by the injector linac. Beams are further accelerated at the main linac part, radiate synchrotron light at the arc section, come back to the main linac and decelerated, and dumped to the beam dump. Operation frequency is 1.3 GHz. Beam energy is 60-200 MeV, after acceleration. Design goal is an emittance of 0.1-1.0 mm mrad with beam current of 100 mA. Total of eight 9-cell cavities are considered for the main linac. A 2-turn lattice is under discussion to achieve 200 MeV. Multi-turn lattice has difficulty against beam instabilities and emittance conservation. It has merits, however, that size of the ring can be reduced and also cryogenic loss can be reduced for main linac part.

INJECTOR LINAC

The injector linac [3] accelerates 100 mA beam up to maximum of 10 MeV. Total of 1 MW is needed to compensate the beam-loaded power. It was decided to use three 2-cell cavities for injector linac, after discussing necessary accelerated gradient and possible input power for input couplers.

Two-Cell Injector Cavity

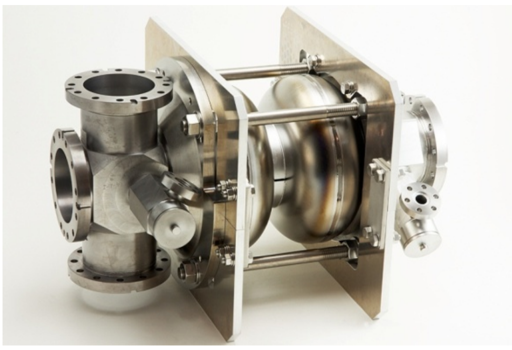

Figure 2: Proto-type of injector 2-cell cavity.

Figure 2 shows a proto-type of injector 2-cell cavity. Two input ports and four HOM couplers are mounted. Its cell shape is same with STF-BL cavity, i.e. TESLA-like cavity, which is developed for the ILC project. The diameter of the beampipes is enlarged to 88 mm, in order to take adequate coupling for the input ports. Main parameters for the injector cavity are shown in Table 1.

Due to the twin-coupler system, input power per coupler can be reduced to 167 kW. It is, however, still

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challenging to handle such large CW input power. Electron beam travelling at the injector part has low energy of ~500 keV. Therefore, it is rather easy to receive effect of perturbation, such as transverse kick. Another merit of the twin-coupler is cancellation of the coupler kick.

Table 1: Main parameters for injector cavity

Frequency	1.3 GHz
Number of cell	2 cell
R/Q	205 Ω
Operating Gradient	14.5 MV/m
Number of input coupler	2
Coupler power	167 kW/coupler
Coupler coupling	3.3×10^5
Number of HOM coupler	4~5
Operating temperature	2 K

At present, one cavity has four or five HOM couplers to suppress the HOM impedance. Two types of, loop-type and antenna-type, HOM couplers are used for the proto-type injector cavity [4].

At the injector part, the HOM field could be the source of the transverse kick, against the low energy beam. It was checked that the HOM impedances were enough suppressed, by low power measurements.

It is known that TESLA-type HOM coupler has heat problem when used at high accelerating gradient with CW mode, because of the magnetic field of the fundamental mode [5]. The HOM couplers used for the injector cavity are the modified one, which is designed to avoid such problem, by putting additional stub.

Vertical Test Results

Two proto-type injector cavities were fabricated. One of them was prepared for vertical testing, with the following surface treatment procedure; CP(20μm), 750 degree annealing, final EP(100 μm), H_2O_2 rinsing, hot bath rinsing, HPR, assembly and baking.

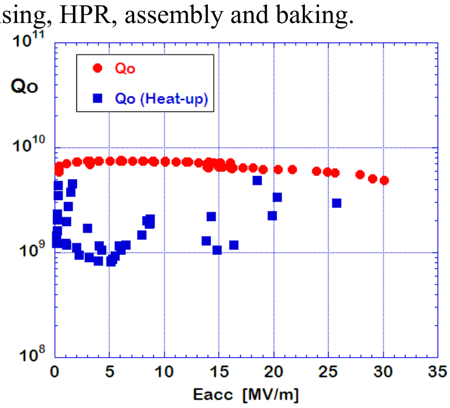

Figure 3: Vertical test results of 2-cell injector cavity. Blue points show values with the heating problem.

Figure 3 shows the results of vertical testing at 2K temperature. Low Q_0 value comes from heat loss of SUS flanges mounted on both ends of the beampipes, since the beampipes are not long enough. Cavity surface does not have any problem.

Accelerating gradient reached to maximum of about 30 MV/m. At relatively high accelerating gradient, Eacc > 16 MV/m, however, Q_0 value was dropped, because of heating at one of the antenna-type HOM coupler. The heating problem happened after keeping the field with high Q_0, for several seconds to several ten minutes. Higher the field, the duration of the field became shorter. The blue points in Figure 3 are the measured values with such HOM coupler heating. There was a tendency that the heating was somewhat processed. Careful surface treatment of HOM couplers may be helpful to avoid the problem.

To confirm the long-term stability at operation gradient, the field was kept at Eacc = 15 MV/m. It was possible to keep the field more than ten hours, without any special problems.

Cryomodule Design

Cryomodule design was almost completed. Figure 4 shows the cryomodule design. Three 2-cell cavities with six input couplers are installed into one cryomodule, which is operated at 2K.

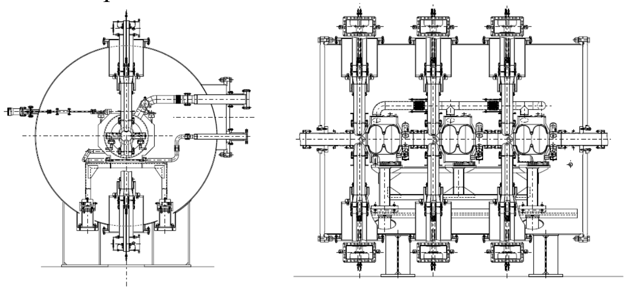

Figure 4: Cryomodule system for injector part.

Design of the input coupler for the injector cavity and proto-type models are shown in Figure 5 [6]. Design is based on the one for KEKB superconducting cavity and coaxial disk type ceramic window is used. Cooling is very critical, since it has to handle 167 kW CW power. Inner conductor is cooled by water cooling system. Thermal design is also important. It is designed to reduce cryogenic loss, using 80K and 5K thermal anchors. Preparation of high power test stand is under way. First high power test, using 1.3 GHz 300 kW klystron, is scheduled in this autumn.

The Slide-Jack tuner is used for frequency tuning. This tuner is the one used for STF-BL cryomodule.

The injector cryomodule will be completed in 2012.

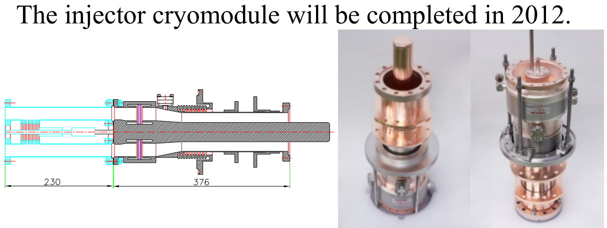

Figure 5: (Left) Design of the input coupler. (Right) Proto-type of input coupler.

MAIN LINAC

In ERL, acceleration and deceleration beams pass through the main linac part. Thus, requirement for HOM damping is stringent. Required features are following:

- Frequency 1.3 GHz
- Accelerating gradient 15~20 MV/m
- CW high current beam operation (> 100 mA)
- Energy recovery should work

Higher accelerating gradient may be generally desirable. In the case of ERL, however, higher gradient leads to more enormous cryogenic heat loss, since the loss increases with square of the gradient. It is considered that around 15 MV/m is adequate for the main linac.

There are two requirements against HOMs. One is suppression for the dipole and quadrupole HOMs. They can induce BBU and quadrupole BBU instabilities, which cause the current limit and/or emittance growth. Another is requirement for monopole HOMs. They lead to heat loss at the HOM absorbers. In order to achieve strong HOM damping, we decided to use beampipe HOM absorbers, which are mounted with RF absorber, as shown in Figure 6. These HOM absorbers are located inside cryomodule, at temperature of 80 K. Frequencies of monopole HOMs should be selected not to be close to the integral multiples of beam frequency. When applying 2-loop lattice, the requirements against HOMs become more severe.

KEK-ERL Model-2 Cavity

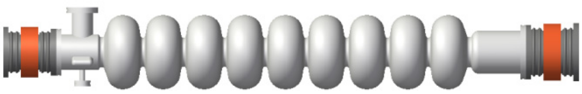

Figure 6:Schematic view of the KEK-ERL model-2 cavity.

As mentioned above, sufficient HOM suppression is required for the ERL main linac. To meet such conditions, we optimized cavity cell shapes and designed KEK-ERL model-2 cavity, whose schematic view is shown in Figure 6 [7,8]. Points of design are following.

(1) Cell shapes were optimized to HOM suppression. Diameter of iris was chosen to be 80 mm. The HOMs can easily propagate between cells.

(2) Diameters of beampipes were selected to be 100 and 120 mm. All monopole and dipole HOMs can propagate to beampipes and are damped by the RF absorbers.

(3) EFB (Eccentric fluted beampipe) was applied, in order to damp quadrupole HOMs. The EFB acts as mode converter from quadrupole to dipole mode, due to its asymmetric structure [9].

As a result, impedances of HOMs can be enough damped, while keeping 9-cell structure. Current threshold against BBU instability is estimated to be several 100 mA from computer calculations [10].

Table 2: Parameters for KEK-ERL model-2 cavity

Frequency	1.3GHz	Coupling	3.8 %
Rsh/Q	897 Ω	Geom.Fac.	289 Ω
E_{peak}/E_{acc}	3.0	H_{peak}/E_{acc}	42.5Oe/(MV/m)

Main parameters are listed in Table 2. Cell-to-cell coupling becomes large due to large iris diameter. This is a merit to keep the field profile. It is less sensitive to variation of cell frequencies. The value Rsh/Q becomes around 900 Ω. A demerit is increase of Epeak/Eacc, which is 3.0. Enough suppression of field emissions are experimental issue.

Vertical Test Results

Figure 7: Proto-type of KEK-ERL model-2 cavity for main linac.

Figure 7 shows the proto-type of KEK-ERL model-2 cavity. Following surface treatment procedures were applied; EP(130μm), annealing at 750 degree, final EP(20 μm), hot bath rinsing, HPR, assembly and baking. Left picture of Figure 8 shows the installation of 9-cell cavity to the cryostat.

For the cavity diagnostics, many carbon resisters and Si PIN diodes are used to monitor temperature and X-rays. Right picture of Figure 8 shows a part of rotating X-ray mapping system. Array of Si PIN diodes rotates 360 degree around the cavity surface and observes X-ray traces. Total of 82 Si PIN diodes are mounted for monitoring nine cells. One data can be taken with a few minutes.

Total of five vertical tests have been performed. The first test was aimed to check the vertical test system. After the first test, only baking was done and the second test was performed. Additional HPR was applied after the second test. After the third measurement, additional EP removed 50 μm of surface. Hot bath rinsing, HPR, assembly and baking were done. After the fourth test, nothing was done, since aim of the fifth test was to obtain detailed X-ray mapping data.

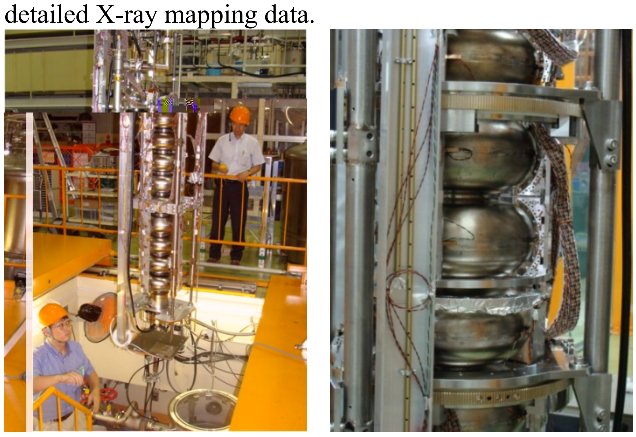

Figure 8: (Left) Installing 9-cell cavity to cryostat. (Right) A part of the rotating mapping system.

The results of vertical tests are shown in Figure 9. The Q_0-Eacc curves are plotted for 2K and 4K measurements.

Generally speaking, at all vertical tests, field emission started around Eacc = 10 MV/m and fields were limited at 15~17 MV/m. The reasons of field limitation were heating due to field emissions.

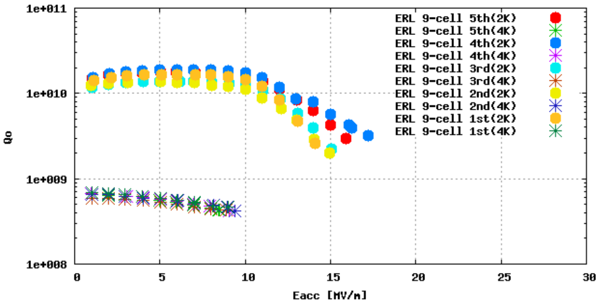

Figure 9 : Results of vertical tests for KEK-ERL model-2 cavity.

The Q_0-Eacc curves, shown in Figure 9, seem almost same for all measurements. However, it is noted that details of emission and temperature rise are much different each other, if looking at additional data, such as, X-ray signals, place of temperature rise and results for pass-band measurements. Only the fifth test was well reproduced the details of the fourth vertical test.

Figure 10 shows an example of X-ray mapping. This data was taken at Eacc = 13.9 MV/m at the fourth test. In the figure, “1 cell” is the cell which is close to the input port and “9 cell” is opposite side. The X-ray signal is strong at around iris parts. There are two characteristic signals. One is a very strong and sharp peak, observed at 330 degree at iris between 8-cell and 9-cell. Another is a broad signals, observed at around 150 degree, opposite side of sharp peak, at irises from 1-cell to 6-cell. These signals appeared at the same time around Eacc = 10 MV/m. Larger the accelerating gradient, these signals became stronger.

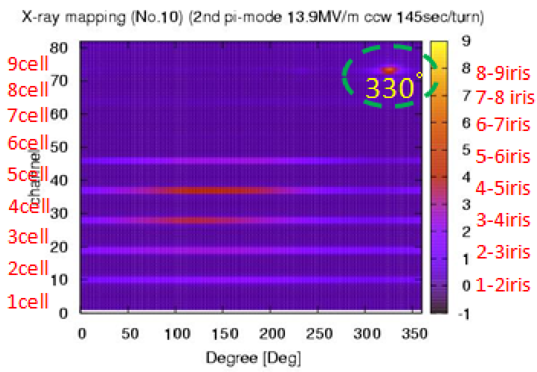

Figure 10: Observed X-ray mapping at Eacc = 13.9 MV/m at the fourth vertical test.

After the fifth measurement, inner surface of the cavity was observed using an inspection camera, so called Kyoto camera system [11]. A big tip was found, as shown in Figure 11, at 150 degree at the iris between 8-cell and 9-cell. Its size is several hundred μm diameter and several ten μm height. The surface inspection was also done after the third vertical test, but no such tip was observed.

It is very interesting that the tip was observed at just opposite side of the sharp X-ray peak observed on mapping. Most probably, this tip was the source of the field emission for the fourth and fifth vertical tests.

Figure 11: Inspection of cavity inner surface. A tip was found at iris between 8-cell and 9-cell.

This tip will be removed by grinding. Then the cavity will be electro-polished again and performed vertical testing.

Cryomodule Design

Design of cryomodule is ongoing for the Compact ERL project. Figure 12 shows schematic view of the main linac cryomodule. The proto-type cryomodule, which is now discussing, contains two 9-cell cavities, although the design for future ERL modules include probably from 4 to 8 cavities. Peripheral equipments have been also developed. The input couplers [12] have variable coupling mechanism and have double-windows, cold and warm windows. The HOM absorbers [13] are located at the beampipes of both ends of the cavities. Heat load at the RF absorbers are cooled down by using 80 K thermal anchors. For tuners, Slide-Jack tuner is applied. There are many issues to be studied, for example, stability of CW RF operation, HOM damping, thermal performance, alignment, module assembly, microphonics and so on. The cryomodule for the main linac is scheduled to be completed at 2012.

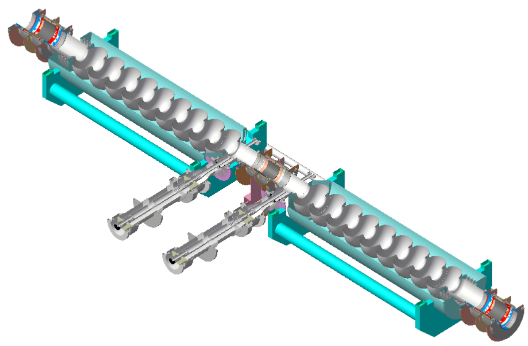

Figure 12: Schematic view of cryomodule for main linac.

Input Coupler Development

Schematic design of the input coupler is shown in Figure 13. It has cold and warm windows to avoid contamination of dust into cavity. For ceramic window, HA997 is selected to lower the dynamic loss. Bellows are adequately placed to allow the variable coupling, between the ranges of Qext from $5x10^6$ to $2x10^7$. Left picture of Figure 14 shows the proto-type of the warm and cold windows.

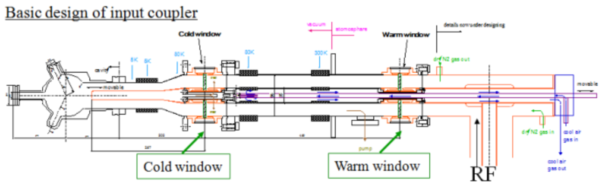

Figure 13: Schematic design of input coupler.

At the ERL main linac, beam loading becomes almost zero, because of the energy recovery. Necessary maximum input power can be estimated from the amount of detuning due to the microphonics and the maximum operating gradient. We estimated that 20 kW input power was needed for the operation of the cavity at Eacc = 20 MV/m.

To verify the components, such as ceramic windows and bellows, a high power test stand was constructed at JAEA. It is shown in Figure 14. RF power is fed by 1.3 GHz 30 kW IOT.

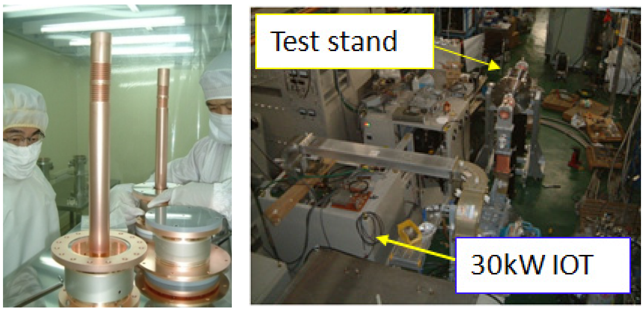

Figure 14: (Left) proto-type of warm and cold windows. (Right) High power test stand constructed at JAEA.

HOM Absorber Development

The HOM absorber will be installed inside the cryomodule and used at 80 K. The RF absorbers, used for HOM damping, should have enough absorption capability, at 80 K, for broadband frequency range.

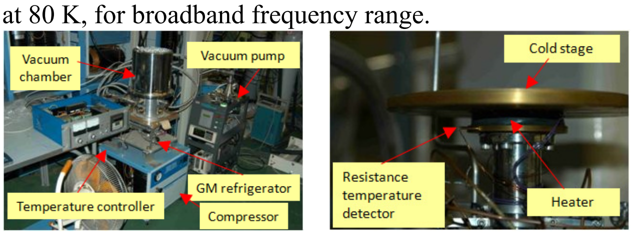

Figure 15: (Left) Low temperature measurement system. (Right) Cold stage set inside the vacuum chamber.

To measure the characteristics of materials even below 80 K, a low temperature measurement system was prepared, as shown in Figure 15. Coaxially manufactured samples of RF absorbers were installed inside a coaxial line and set on the cold stage in the vacuum chamber. The cold stage was connected to the GM refrigerator and the sample can be cooled down. While changing the temperature by controlling a heater, temperature dependences of complex permeability and permittivity were measured, at the range from room temperature to 40 K.

Measurements were carried out for around 10 samples. One of the measurement results is shown in left plot of Figure 16. Temperature dependences of μ" of ferrite IB004 are plotted for the frequency range from 2 to 6 GHz. It seems that IB004 can be used at 80K, at least up to around 10 GHz. The ferrite IB004 is a material used for HOM dampers of KEKB superconducting cavities. But it is located at room temperature. From this result, we decided to use IB004 as an absorber for the ERL main linac.

The design of the HOM absorber is in progress. The thickness, length and location of the ferrite were carefully optimized. Right of Figure 16 shows the schematic view of the HOM absorber. The proto-type of it is now under construction. Cooling tests and HOM measurements will be performed. Cooling ability of about 100 W heat load, under vacuum circumstance, should be verified. Characteristics of HOM damping are measured at low-power. Its damping ability should be confirmed.

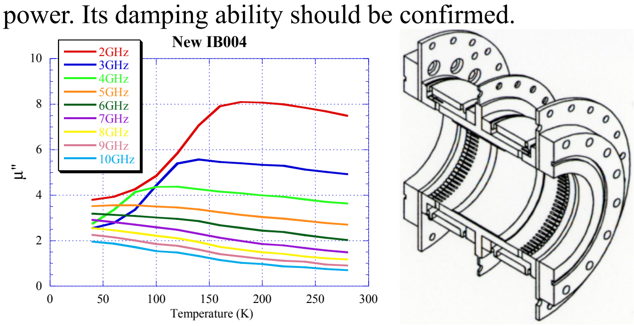

Figure 16: (Left) Temperature dependence of ferrite IB004. (Right) Schematic view of the HOM absorber.

SUMMARY

The Compact ERL project has started at KEK.

The proto-type of injector cavity was fabricated. It could reach to 30 MV/m at the vertical test. Although heating problem of the HOM coupler occurred at relatively high acceleration gradient, it was possible to keep 15 MV/m for 11 hours. The input couplers for injector cavity were fabricated and will be tested soon. Design of the injector cryomodule is almost completed.

For the main linac, the proto-type of nine-cell cavity was fabricated and vertical tests were performed several times. At present, the cavity was suffered from field emissions. The rotating X-ray mapping system was constructed and worked well. Design of the cryomodule is under way for the main linac. Coupler components were high-power tested at the test stand constructed at JAEA. Temperature dependent characteristics of RF absorbers were measured for several samples. The proto-type of HOM absorber is now under construction.

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