CONSTRUCTION OF CERL CRYOMODULES FOR INJECTOR AND MAIN LINAC

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Abstract

The Compact ERL (cERL) project is advanced in Japan. Its aim is to demonstrate the circulation of 100 mA electron beams with energy of 35-200 MeV. Superconducting cavities are key components for realizing ERL and used for injector part and main linac part. Critical issue for the injector part is the development of input power coupler. Prototype input couplers were fabricated and high power test was performed. Cooling ability of HOM coupler is also important for CW operation of cavity. At main linac part, HOM damped 9-cell cavities are applied to avoid BBU instabilities. Prototypes were fabricated for the cavity, the input coupler and the HOM absorber. Their performance was investigated. For both parts, cryomodules are under construction and will be completed in 2012.

THE COMPACT ERL PROJECT

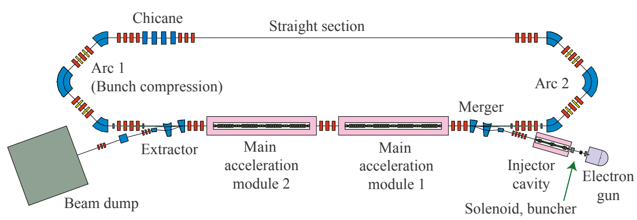

Figure 1: Conceptual layout of the Compact ERL.

Compact ERL (cERL)[1, 2] is a test facility, which is now constructing on the ERL Test Facility in KEK. Its aim is to demonstrate technologies needed for future 5-GeV class ERL. One of critical issues for ERL is development of superconducting cavities, which are applied for both the injector linac and the main linac.

Table 1: Main parameters for cERL project

Beam energy	35 – 245 MeV
Beam current	10 – 100 mA
Normalized emittance	0.1 – 1 mm mrad
Bunch length	1 – 3 ps (usual) 100 fs (bunch compression)

Main parameters of the cERL project are appeared in Table 1 and conceptual view of cERL is shown in Figure 1. At the first stage of cERL, minimum version of ERL will be constructed. Only two 9-cell cavities will be installed into one main linac cryomodule. Achievable beam energy is 35MeV. Beam current is also expected to be around 10 mA.

At the ERL Test Facility, a 2K refrigerator system and a class-10 clean room were already constructed. A plan is that both cryomodules will be constructed, assembled and tested during 2012. After that, beam operation is awaited.

CRYOMUDULE FOR INJECTOR LINAC

At the injector linac [3, 4], 100 mA of electron beam is accelerated up to 10 MeV. Thus, total of 1MW RF power should be passed to the beam. The injector linac consists of three 2-cell cavities and each cavity is fed RF power by twin couplers. Still, one input coupler should pass the high power of 167 kW. This is most challenging task in the injector part.

Another important issue is cooling of HOM coupler. It is well known that original TESLA-type HOM coupler has a heating problem in the CW operation [5]. Design of HOM coupler was modified [6] and also cooling ability was strengthened.

Main parameters for injector cavity are summarized in Table. 2.

Table 2: 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 / cavity
Coupler power	167 kW / coupler
Coupler coupling	3.3×10^5
Number of HOM coupler	5 / cavity
Operating temperature	2 K

Two-Cell Injector Cavity with HOM coupler

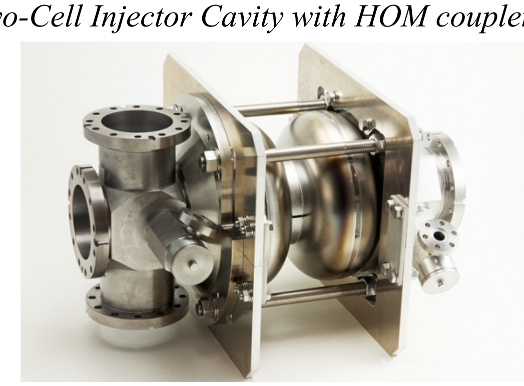

Figure 2: Prototype of injector 2-cell cavity.

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Figure 2 shows the prototype of injector 2-cell cavity. As described above, two input coupler ports can be seen on the picture. Suppression of coupler kick is also important for the injector linac, since low energy electron pass through the cavities. Cell shape is based on TESLA shape, while larger beampipe is applied for strong coupling needed for the input coupler.

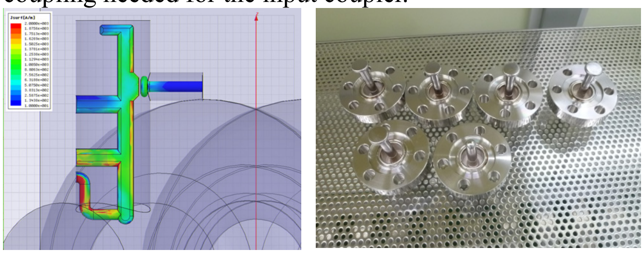

Figure 3: (left) Magnetic field distribution of HOM coupler. (right) Pickup probes for HOM coupler.

Five loop-type HOM couplers are mounted on each cavity, in order to strongly damp the field of HOMs. Magnetic field distribution of HOM coupler is shown in left of Figure 3. In order to reduce strength of magnetic field at antenna tip, second stub and a boss are added to original TESLA HOM coupler. Right of Figure 3 shows pickup probes. Tip of the pickup probe antenna, which is made from niobium, is a place where heating occurs.

Two prototype cavities (cavity #1 and #2) and three operation cavities (cavity #3, #4 and #5) were fabricated.

Results of Vertical Tests

Vertical tests were performed for cavity #1, #2 and #3. Figure 4 shows the results of vertical test for cavity #2. Cavity performance was very nice and reached to around 40 MV/m. It was difficult, however, to keep at high accelerating field. After keeping field during some period, heating problem happened on the HOM coupler. In order to simulate the condition inside a cryomodule, RF power was fed with the condition that the cavity was cooled by He, but the HOM coupler was out of He. Maximum field was 13 MV/m, under CW operation. Vertical test results for cavity #1 were also similar with those for cavity #2. Details of measurements are found at elsewhere [4, 7].

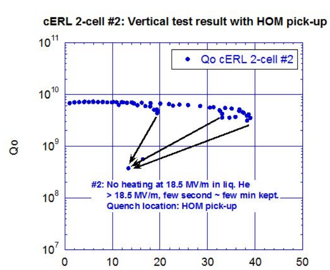

Figure 4: Results of vertical test for cavity #2

For vertical tests of cavity #3, several improvements were applied to increase cooling efficiency of pickup prove. Setup of vertical test is shown in left of Figure 5. As seen in the picture, HOM pickup connectors were attached to thermal anchor and cooled by 2K He. Outer part of HOM couplers were also cooled through thermal anchors, as seen in right of Figure 5. Furthermore, tip of antennas were carefully polished. Then the antennas were screwed into feedthroughs using indium seal, to improve thermal connection.

Figure 5: Setup for vertical test of cavity #3. (left) Thermal anchor around HOM pickup connector. (right) Cooling for HOM couplers.

Figure 6 shows the vertical test results for cavity #3. This time, cavity performance was limited to 30 MV/m by thermal quenches due to a defect. But this is enough for ERL operation. As same with cavity #2, CW performance of the HOM coupler was tested, by simulating the cryomodule condition. Accelerating field of 25 MV/m was successfully kept under CW operation. The results satisfied the specifications for ERL injector linac.

Vertical tests for cavity #4 and #5 are planned from this autumn. More efficient cooling methods will be tried. Some modifications are also planned about feedthroughs.

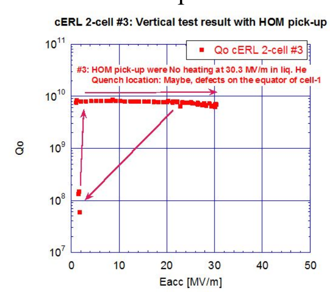

Figure 6: Vertical test results for cavity #3.

Input coupler

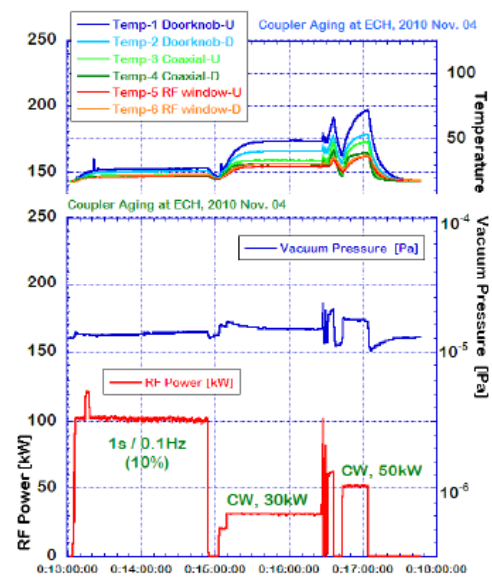

Figure 7: Results of high power tests for prototype input couplers. Plots for (top) temperature and (bottom) for vacuum and RF power.

As already mentioned, input coupler is critical component for injector linac. Coaxial coupler with single disk type ceramic window is applied [8]. Inner conductor is cooled by water. Two prototype input couplers were fabricated and high power test stand was prepared at KEK, using 300 kW CW klystron. Setup of high power test is found in elsewhere [9]

Figure 7 show the performance, during high power tests. For pulse mode with 10% duty, 120 kW of RF power could successfully pass through. For CW mode, 50 kW of power could be feed for 30 minutes, accompanied by some temperature rise.

The performance of input couplers was enough for the first stage of cERL operation with 10 mA electron beam. But, for the future with 100 mA operation, further enhanced cooling is essential.

Cryomodule

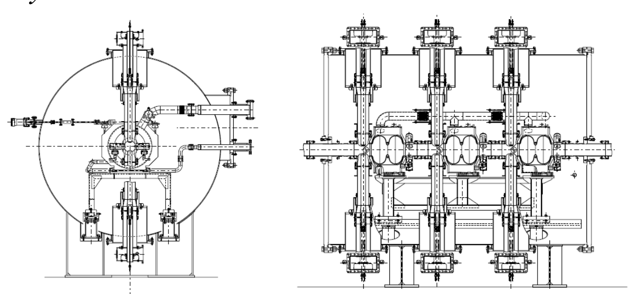

Figure 8: Cryomodule system for injector part.

Cryomodule design is shown in Figure 8. Three 2-cell cavities are installed into one cryomodule. Twin couplers are mounted on each cavity. Slide-Jack and piezo tuners, which have been developed for STF cavities, are used for frequency tuning. Figure 9 shows fabricated three 2-cell cavities and six input couplers, which will be installed into a injector cryomodule. These cavities, cavity #3, #4 and #5, will have vertical tests during autumn, and input couplers will have coupler aging from autumn to winter. A cryomodule assembly will be planned around spring. Then cooling tests and high power tests will be followed.

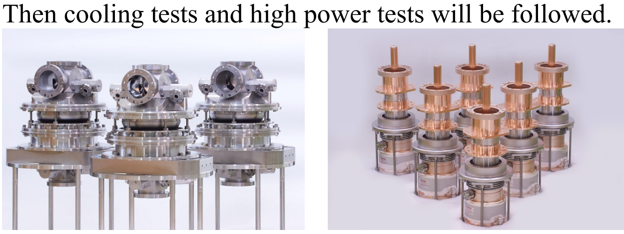

Figure 9: Fabricated (left) three 2-cell cavities and (right) six input couplers for cERL operation.

CRYOMODULE FOR MAIN LINAC

Most important issue for main linac is strong damping of HOMs to avoid BBU (beam-breakup) instability, to circulate high beam current of more than 100 mA. On the other hand, moderate accelerating field of 15 – 20 MV/m is required. Smaller field emission is desirable for CW operation of cavities. Our cavity, KEK-ERL model-2 cavity, is designed, focused on HOM damping [10]. Beampipe HOM absorbers are applied for efficient HOM damping. Development of HOM absorber is also important R&D issue. Table 3 shows main parameters for the main linac cavity.

Table 3: Main parameters for main linac cavity

Frequency	1.3 GHz
Number of cell	9 cell
R/Q	897 Ω
Operating Gradient	15 MV/m
Number of input coupler	1 / cavity
Coupler power	Max 20 kW/coupler
Coupler coupling	1 - 4 x 10^7
Number of HOM coupler	3 / two cavities
Operating temperature	2 K

Nine Cell Main Linac Cavity

KEK-ERL model-2 cavity is designed with large iris diameter of 80 mm for efficient HOM damping. This design increased E_{peak}/E_{acc} ratio to be three. Overcome of field emission is essential for our cavities.

We fabricated two prototype cavity, cavity #1 and #2, and other two cavities, #3 and #4, for cERL operation. The cavity #1 is a prototype to investigate the designed cell shape and the eccentric fluted beampipe structure. The cavity #2 is prototype model, which is considered to be installed into a cryomodule, with satisfying Japanese high pressure low. As shown in Figure 10, He jacket end plates and stiffener rings are manufactured. Niobium thickness is increased for both half of end cells. For vacuum sealing, Helicoflex is applied.

The cavity #3 and #4 are almost same with the cavity #2, but minor modification was applied, considering final cryomodule design.

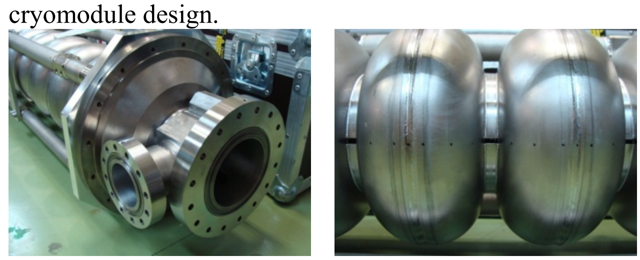

Figure 10: prototype 9-cell cavity #2. (left) titunium end plate for He jacket and flanges and (right) stiffener rings.

Vertical Test Results

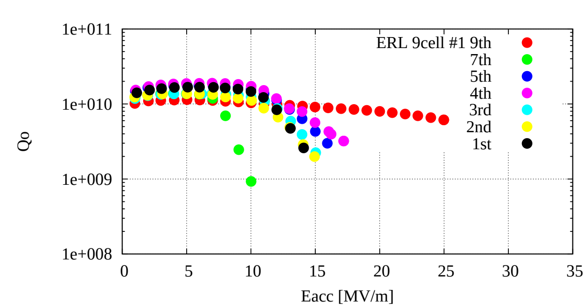

Figure 11; Vertical test results for prototype main linac 9-cell cavity #1.

Cavity performance was investigated by vertical tests for cavity #1 and #2. Cavity #3 and #4 are under surface treatment and performance will be tested at autumn.

Figure 11 shows vertical test results for cavity #1 [11, 12]. From the 1st to 8th measurement, the cavity was suffered from field emissions. After optimizing EP parameters, careful cavity assembly and keeping clean condition and so on, the cavity finally reached to 25 MV/m with condition of small field emissions. These results satisfy the specification for ERL main linac.

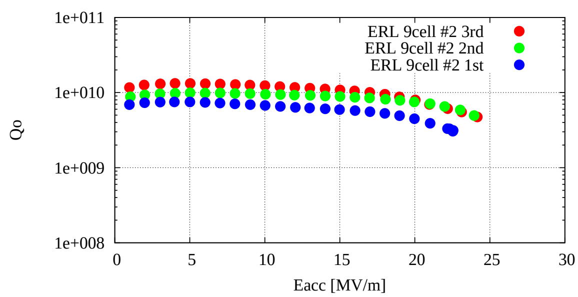

Figure 12: Vertical test results for prototype main linac 9-cell cavity #2.

Figure 12 shows vertical test results for cavity #2. For all measurements, field reached to more than 20 MV/m. For all cases, field limitations are quenches due to field emissions. It is mentioned that Q values are somewhat low for the plots of Figure 12. In these plots, the Q-E curves are for final state, i.e. taken at the end of vertical test. There are two reasons. One is that, SUS flanges were used for measurements. Another is that, degradation of Q values occurred during processing. It was observed that Q values were gradually dropped during processing at π-mode or pass-band modes, for both the 1st and 2nd vertical test.

After the 2nd vertical tests, the cavity was only warmed-up, without additional treatment, and the 3rd vertical test was carried out, in order to investigate the possible reason of this Q degradation. If it is caused by damages on niobium surface, it is expected that the Q values does not recover after warming-up. The results are shown in red dot in Figure 12. The Q values at lower field were recovered to initial value at the 2nd vertical test. The reason of Q degradation is considered to be trapping of magnetic field during processing. On the other hand, the Q values at higher field were same with final value of the 2nd vertical test. This is because field emitters do not change the situation after warming-up. Details of the vertical test results for the cavity #2 are described in [13].

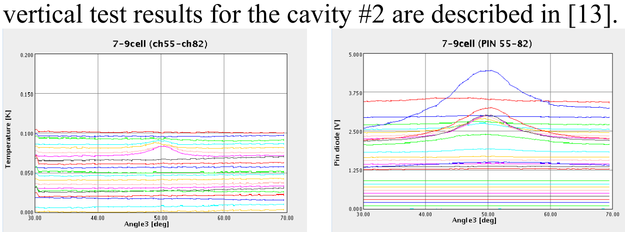

Figure 13: (left) Temperature mapping and (right) X-ray mapping for π-mode at 23 MV/m at the 3rd vertical test of cavity #2.

For the cavity diagnostics, the rotating type X-ray and temperature mapping system was developed. Details of system and some results are found in elsewhere [14]. At the 3rd vertical test, temperature mapping data was tried to be taken, in addition to the X-ray mapping data. This data had been difficult to be taken, because of relatively bad S/N ratio. By improving S/N ratio, clear data had been taken. The left and right of Figure 13 show one part of temperature and X-ray mapping from the 7th to 9th cell, for the field of 23 MV/m at the 3rd vertical test of cavity #2. Clear traces, caused by field emission, are found for both plots around 50 degrees at bottom of the 7th cell. After that, arrays of sensors were moved to around 50 degrees, where traces were found, then field was raised up. The X-ray signals gradually increased and a quench occurred at 25 MV/m. When the quench happened, big temperature rise of several K was observed. Details are also described in [13]. It is noted that the temperature and X-ray mapping data are strong tool to understand the phenomena of field emissions.

Input Coupler Development

Because of the energy recovery, no beam loading effect is considered for main linac cavities. The requirement for the input coupler is that cavity field should be kept stable, under detuning condition due to microphonics. Assuming maximum of 50 Hz detuning and external Q to be 2 x 10^7, maximum of 20 kW RF power is required to keep cavity field stable. This is the requirement for our input coupler. The input coupler has two windows, a warm and a cold window, to prevent dust contamination to the cavities. Variable coupling mechanism is realized by using bellows. Inside of inner conductor is cooled by nitrogen gas. The details of coupler design are found elsewhere [15].

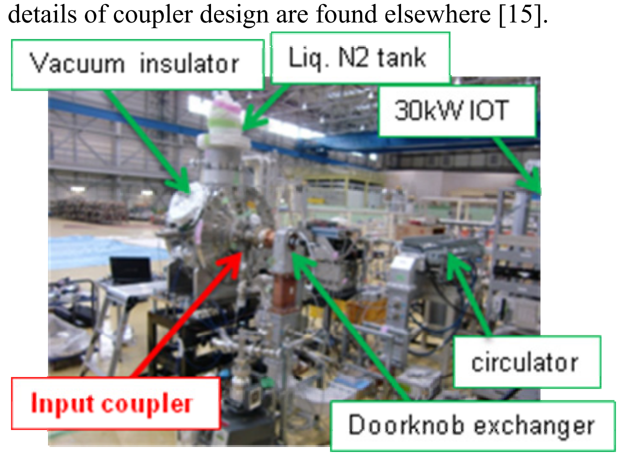

Figure 14: Setup for high power test for input coupler, under 80K temperature

A prototype input coupler was fabricated, to check its performance. High power test stand was constructed at ERL Test Facility in KEK. Setup is shown in Figure 14. In order to simulate the condition inside cryomodule, the input coupler was installed into vacuum chamber and the cold window was cooled by liquid nitrogen. RF power was fed by a 30 kW IOT and pass through the coupler, then reflected by an end plate. The coupler was processed with the condition of standing wave.

At initial trial of high power test, field was smoothly increased and reached to 20 kW. At 20 kW, however, suddenly a discharge happened accompanied by an arc and vacuum interlocks. After that, input power was limited to 10 kW and normal processing procedure did not help to increase the input power. A pulse processing method was applied and the situation was gradually improved. After eight hours pulse processing, RF power reached to 25 kW. Then, RF power had been kept to be 20 kW. Figure 15 shows that RF power had been successfully kept during 16 hours. During this test, the input coupler was enough stable, except that the arc sensor worked three times by noise. Measured temperature rise was adequate. Details of high power test are described in [16].

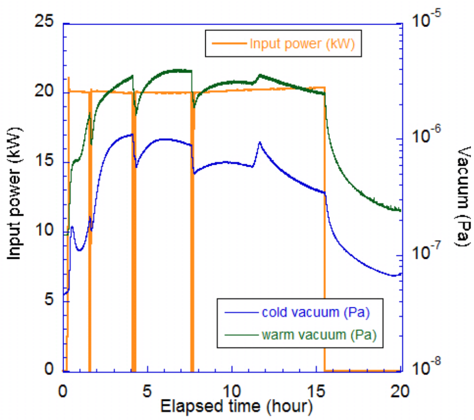

Figure 15: Results of high power test. RF power had been kept to be 20 kW.

After high power test with cooling condition, a thermal cycle test was followed. After ten times of thermal cycle, between room temperature to 80K, no leaks were observed and no cracks were found on the ceramic windows. From these high power test and thermal cycle tests, it is realized that the input coupler satisfied the specification of ERL main linac.

Beampipe HOM Absorber

Beampipe HOM absorber is applied for efficient HOM damping. The HOM absorber will be installed into a cryomodule, and located under 80 K condition. After investigating the RF characteristics at low temperature, one ferrite was selected as the material for HOM absorption [17].

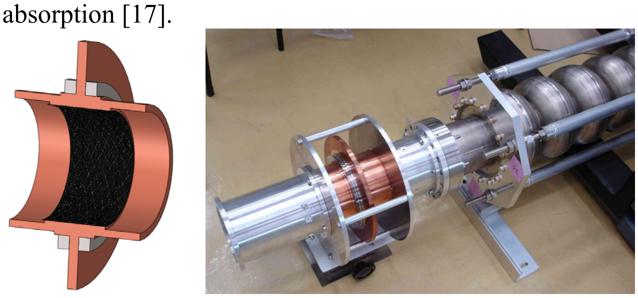

Figure 16: (left) Schematic view of the HOM absorber model with HIP ferrite. (right) The HOM absorber model mounted on the cavity #2 for HOM measurement.

Two kinds of prototypes were fabricated. One type is shown in Figure 16, it is called as the HOM absorber model with HIP ferrite. HIPped ferrite is attached on the inner surface of copper base. This model has used to HOM absorption measurements and thermal cycle tests [18]. Another type is called as the HOM absorber model without HIP ferrite. It has almost final structure, including the Comb-type RF bridge at inside and the bellow at the outside of the HOM absorber, but no ferrite was attached. This model has used to investigate thermal property.

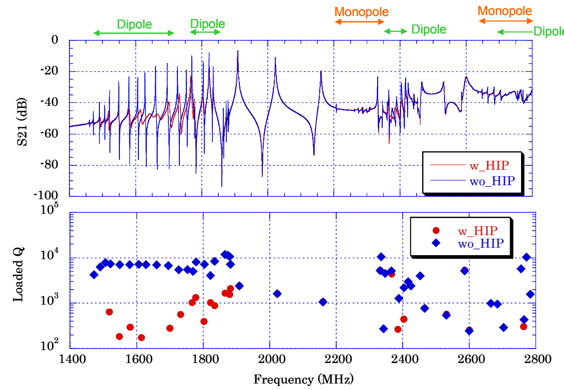

Figure 17: (top) HOM spectrum and (bottom) loaded Q values for with (red) and without (blue) HOM absorber model with HIP ferrite.

The right of Figure 16 shows setup for HOM measurement. The HOM absorber model with HIP ferrite was mounted on the LBP part of the prototype cavity #2. HOM characteristics were measured with and without the HOM absorber model with HIP ferrite, at room temperature. The results of measurements are shown in Figure 17. The Q values of both monopole and dipole modes were sufficiently damped.

Using two HOM absorber model with HIP ferrite, thermal cycle tests have been performed between room temperature and 80 K. Surface of HIP ferrite was carefully observed with a closeup CCD camera. It is noted that, even before thermal cycle tests, some linear cracks were observed on the ferrite surface. After five thermal cycles, some more linear cracks were observed for the ferrite surface of one prototype. It, however, seemed to be safe for the operation. For another prototype, the thermal cycle was applied two times. After that, it was found that small piece of ferrite was chipped off. Reasons and details are under investigation.

Thermal property of the HOM absorber was studied, using the HOM absorber model without HIP ferrite [18, 19]. The HOM absorber model was installed into the adiabatic vacuum chamber, which is the same one used for the input coupler tests, and cooled down to liquid nitrogen temperature. Thermal resistance of bellows was measured and found to be no problem. Cooling ability against HOM absorption power was also checked by supplying power to heaters, which was attached inner surface of the model. Obtained temperature distribution was used for detailed design of main linac cryomodule.

Cryomodule

For the initial stage of cERL, one cryomodule with two 9-cell cavities will be constructed. Its design is shown in the top of Figure 18. Slide-Jack and piezo tuners are used for frequency tuning. As shown in bottom of Figure 18, two 9-cell cavities were already fabricated. Two input couplers, three HOM absorbers and two Slide-Jack tuners are under fabrication. The cavities are under surface treatment. Vertical test will be performed at autumn. Also, coupler aging will be carried out this winter. A module assembly will be planned around spring, after He jackets will be mounted on cavities.

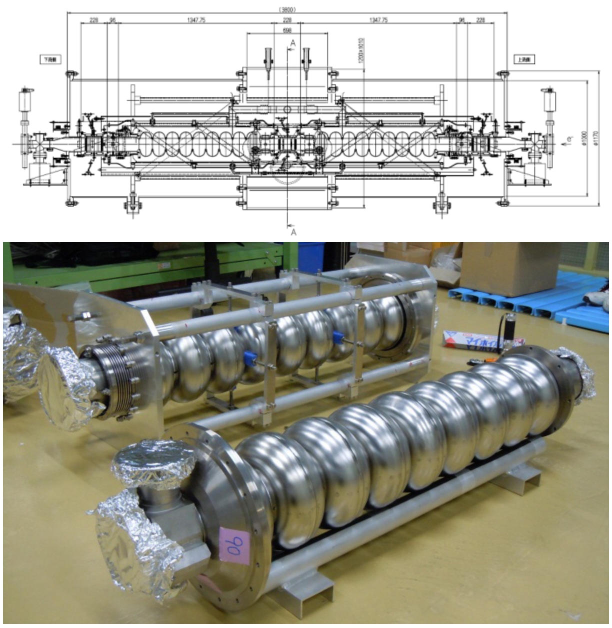

Figure 18: (top) Design of the cERL main linac cryomodule. (bottom) 9-cell cavities, which will be installed into the cERL cryomodule.

SUMMARY

cERL is under construction at the ERL Test Facility in KEK. For the injector parts, performance of 2-cell cavity was checked by vertical tests, with improved cooling for HOM couplers. High power test of input couplers were also carried out. Further cooling is desirable for the future high current operation. But it is enough for the first stage of cERL operation. For the main linac part, the 9-cell cavities reached to 20 MV/m. RF power of 20kW was successfully feed to the input coupler. Several tests were performed for the HOM coupler and results were used for cryomodule design. Both for the injector and main linac parts, components were already fabricated or under fabrication. Both cryomodules will be assembled next year. Then after cooling tests and high power tests, cERL beam operation will start.

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