HIGH POWER CW TESTS OF cERL MAIN-LINAC CRYOMODULE

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Abstract

A main linac cryomodule have been constructed for Compact ERL project. It contains two 9-cell cavities, mounted with HOM absorbers and input couplers. After cavity string assembly, they were installed into the vacuum vessel of the cryomodule. It was placed inside radiation shield of cERL and connected to a refrigerator system. The cryomodule was successfully cooled down to 2 K and low power and high power measurements were carried out.

COMPACT ERL PROJECT

Compact ERL (cERL)[1, 2] is a test facility, which is now being constructed on the ERL Test Facility in KEK. Its aim is to demonstrate technologies needed for future multi GeV class ERL. One of critical issues for ERL is development of the superconducting cavities.

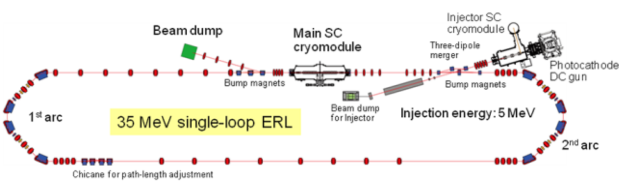

Figure 1: Conceptual layout of the cERL project.

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)

Conceptual layout of the cERL is shown in Figure 1 and its main parameters are shown in Table 1. At the first stage of cERL, minimum version of ERL will be constructed and electron beams of 10 mA will be accelerated up to 35 MeV. One main linac cryomodule with two 9-cell cavities have been constructed.

MAIN LINAC CRYOMODULE

Figure 2 shows a schematic view of the main linac cryomodule [3], which contains two 9-cell KEK ERL model-2 cavities [4] mounted with He jackets. Beampipe-type ferrite HOM absorbers [5] are connected at both sides of cavities, to strongly damp HOMs. The HOM absorbers are placed on 80K region. Coaxial input couplers [6] with double ceramic windows feed RF power to the cavities. Frequency tuners [7] control cavity resonant frequencies. Cooling pipes of 80K, 5 K and 2 K are extended throughout the cryomodule. The 80 K line was cooled by Nitrogen, and 5 K and 2 K lines were cooled by Helium. After filling with 4 K liquid He, insides of the He jackets were pumped down and the cavities were cooled down to 2 K. To keep the precise alignment, two cavities were supported by Ti frame with 5 K He line. And this 5 K frame was supported by the large girder (backbone) set at 300K. The magnetic shield was equipped to this 5K frame.

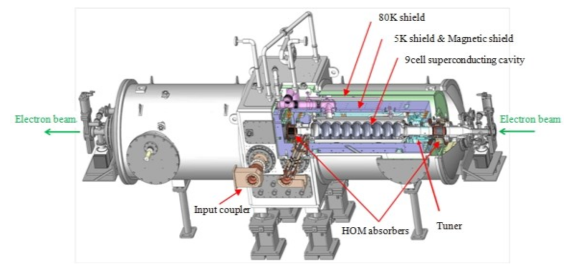

Figure 2: Schematic view of ERL main linac cryomodule.

Prior to the cryomodule assembly work, we have done the vertical tests of two cERL 9-cell cavities. The left figure of the Figure 3 shows the results of the vertical tests of two cERL 9cell KEK-ERL model-2 cavities [8]. These two cavities reached the 25 MV/m gradient and satisfied our requirements of cERL of $Q_0 = 1\text{x}10^{10}$ at 15 MV/m. High power test of input coupler was also applied under liquid Nitrogen cooling before the cryomodule test. The right figure of Figure 3 shows the result of high power test of input coupler for cERL main linac. Power reached the 25 kW and kept 20 kW with standing wave condition for 16 hours [6]. Cooling test and thermal cycle test of HOM absorber were done by using liquid Nitrogen [5]. After checking the performance of these important components like cavities, input coupler, HOM absorber and tuners, we started the assembly work of cERL cryomodule.

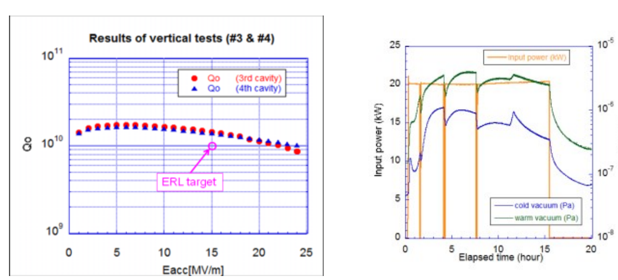

Figure 3: (Left) Results of vertical tests of two cERL 9-cell cavities. (Right) Result of high power test of input coupler for cERL.

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CRYOMODULE ASSEMBLY

Cavity string assembly was done at class-10 clean room, which was built on ERL development building of KEK. The left of Figure 4 shows the connection of the HOM absorber to the cavity. After this, the cold ceramic windows of input couplers were also mounted. These works were done as carefully as possible, to avoid dust contamination to the cavities. Figure 5 shows the cavity string after completion of string assembly works.

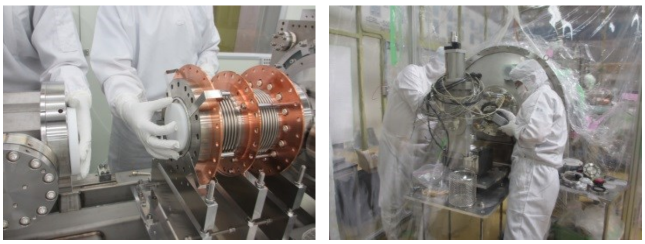

Figure 4: Connection of HOM absorber (left) and gate valve (right).

The next step, the cavity string went out of the clean room and was mounted on a cryomodule central tower. Frequency tuners of coarse mechanical tuners and fine piezo tuners were assembled on one side of the He jackets. After setting the cooling pipes, temperature sensors, magnetic shields, alignment targets and so on, they were covered with the vacuum vessel.

The warm ceramic windows of input couplers were jointed to the cold windows, and gate valves were connected to the both end of the beampipes, which is shown in the right of Figure 4. These works were performed inside a clean booth to avoid unwanted dust contaminations to the cavities.

Figure 5: After completion of cavity string assembly.

The assembled main linac cryomodule was moved into radiation shield of cERL accelerator, placed on beamline and connected to a refrigerator system, as shown in Figure 6.

The cavities located on upstream and downstream are called as #4 and #3cavities, respectively, according to the manufacturing number.

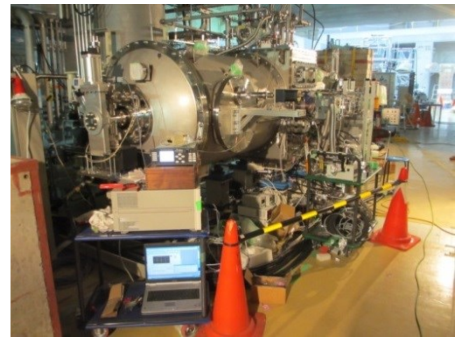

Figure 6: Main linac cryomodule placed inside radiation shield of cERL.

COOLING DOWN OF CRYOMODULE

Figure 7 shows cooling history of the main linac cryomodule, during first low power and high power measurements. Red and blue lines show cavity He jacket temperature, and green, black and purple lines show HOM absorber temperatures.

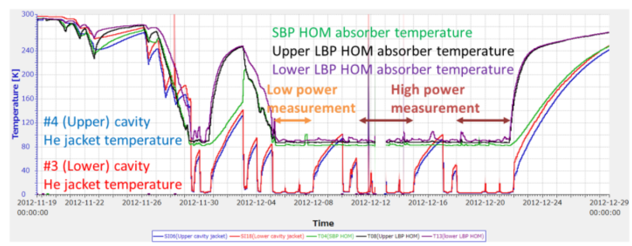

Figure 7: Cooling history of the cryomodule.

Following cooling strategy was required; (1) the HOM absorbers should be cooled down slowly, to avoid cracking on ferrite absorbers. Slope of 3 K/hour was required. This rate was used for cooling test of the HOM absorbers. (2) Large temperature difference was avoided among each cooling lines. Typically it was required to be less than 50K.

As shown in Figure 7, the cryomodule was successfully cooled down and the cavity temperatures reached to 2 K. During measurements, 80 K line was continuously operated, while 5 K and 2 K lines were not operated during midnight and weekend.

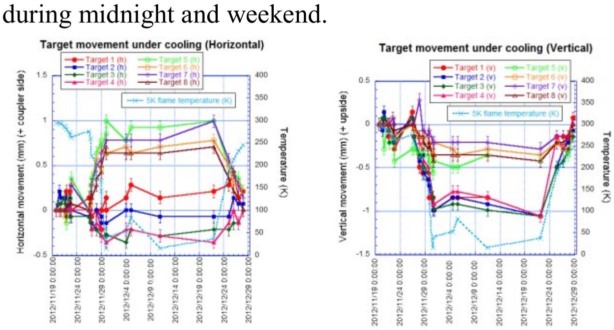

Figure 8: (Left) Horizontal displacements of alignment targets set in cryomodule. (Right) Vertical displacements of alignment targets set in cryomodule.

During cooling down procedure, cavity displacements were monitored using the optical and laser targets, set inside the cryomodule. Figure 8 shows the measurements results of displacements of alignment targets set on 5 K frame. The left (right) figure of figure 8 shows the displacements of target from #1 to #4 set on the top (side) of 5 K frame near the both ends of two cavities. These displacements were measured by alignment telescope via the view ports during the cool down. From these measurements, the displacements of cavity center, from room temperature to 2 K, were estimated to be less than 0.4 mm. These measurements agree well with the position monitor by using white light interferometer [9]. And this value is within our alignment tolerance.

LOW POWER MEASUREMENTS

After cooling down to 2 K, performances of each component were firstly checked. Components such as the frequency tuner, HOM absorber and input coupler are shown in Figure 9.

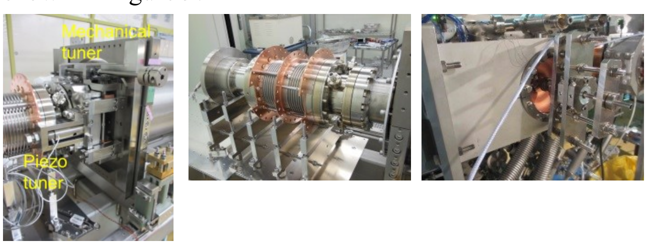

Figure 9: (left) Frequency tuner, (center) HOM absorber and (right) input coupler.

Figure 10 shows performances of frequency tuners; (left) coarse mechanical tuners and (right) fine piezo tuners. Movements of mechanical tuners were smooth enough and their strokes were as expected. The left of Figure 8 shows that the cavities can be successfully tuned to 1.3 GHz by mechanical tuners. Performances of piezo tuners were also fine. Their movements were smooth and precise enough. Reproducibility did not show any problems.

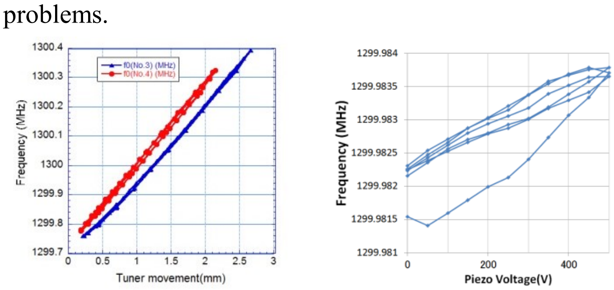

Figure 10: Performances of the mechanical tuners (left) and piezo tuners (right).

For the HOM measurements, one fundamental pickup antenna and three HOM antennas were used for each cavity. The HOM ports were located just side of the HOM absorbers.

Figure 11 shows measured HOM frequencies and their loaded Q-values of #3 cavity. Generally speaking, measured HOM characteristics agree with calculated ones, while detailed analysis are on-going. The ferrite of the HOM absorber seems to work well at 80K.

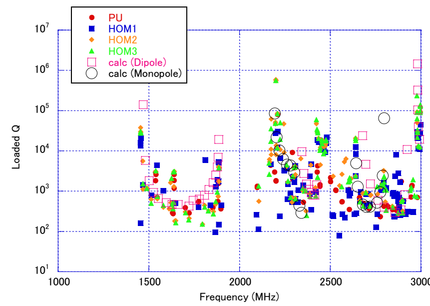

Figure 11: Measured HOM characteristics for #3 cavity, compared with calculated ones. PU means fundamental pickup antenna and HOM1, HOM2 and HOM3 mean HOM probes.

The input couplers were designed to adjust coupling by changing length of inner conductor, in a range of $Q_{ext} = (1 – 4) \times 10^7$. Their movements were checked and found that $Q_{ext} = 8.7 \times 10^6 – 3.3 \times 10^7$ for downstream coupler and $Q_{ext} = (1.5 -5.3) \times 10^7$ for upstream coupler. Before the high power test of cryomodule, we fed the power to input coupler up to 25 kW to processing the coupler.

Performances of all components for the main linac cryomodule were confirmed to be fine.

HIGH POWER MEASUREMENTS

The left figure of Figure 12 shows the setup of the high power test of cERL main-linac cryomodule. High power measurements were performed using a 30 kW IOT. Cavity frequencies were tuned to close to 1.3 GHz. For these tests, cavity resonant frequencies were followed by changing the frequency of a signal generator. To investigate field emissions, radiation monitors were placed on both sides of the cryomodule near the axis of the cavities.

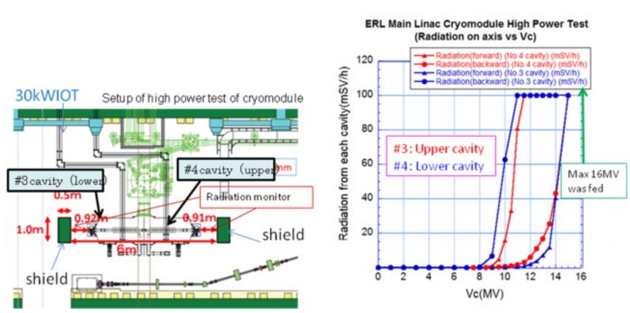

Figure 12: (Left) setup of the high power test of cERL main-linac cryomodule. (Right) Measured accelerating voltage (Vc) and radiation doses for both cavities.

The right figure of Figure 12 shows the results from high power measurements. Accelerating voltage, Vc, reached to 16 MV for both cavities. They, however, suffered from heavy field emissions. Unfortunately, field emissions were observed from around 8 MV for both

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cavities. Relation between Vc and Eacc is indicated as Vc [MV] = 1.038 x Eacc [MV/m].

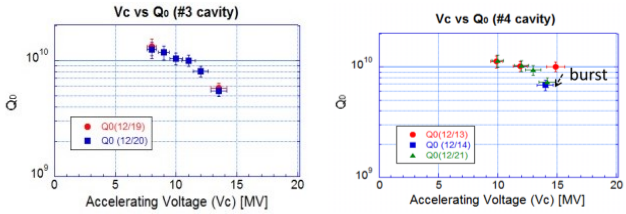

Figure 13: Measured Qo values for #3 cavity (left) and #4 cavity (right).

Figure 13 shows measured cavity unloaded Q-values (Qo) for both cavities. The Q values were estimated from amount of liquid He consumption. For these measurements, static losses were estimated to be around 11 W and subtracted from total losses to lead dynamic losses. Degraded Q-values at higher voltage, Vc > 10 MV, were caused by field emissions. We note that Q-value is higher than $1x10^{10}$ at 15 MV before the unexpected burst event in #4 cavity. But after burst the Q-value decreased and radiation drastically increased.

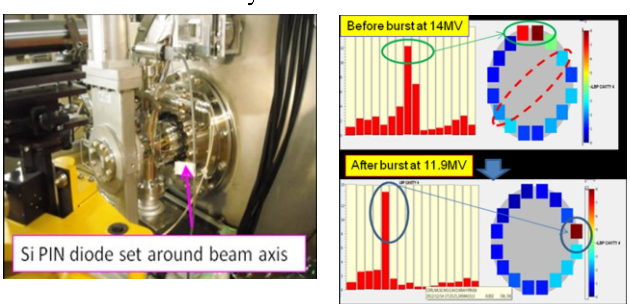

Figure 14: (Left) Setup of the 16 Si PIN diode profile monitor. (Right) the measurement results of 16 Si PIN diode profile monitor set downstream of cryomodule before and after burst events during #4 cavity high power test. Red dot line shows the radiation pattern shown in vertical test.

To investigate the field emission change in detail, we set the 16 Si PIN diodes profile monitor around beam axis at the end of cryomodule as shown in the left figure of Figure 14 because the electron produced by field emission will be accelerated along the axis [10,11]. The right figures of Figure 14 shows the measurement results of the profile monitor set downstream of cryomodule while keeping the 14.5 MV of #4 cavity. We note that the profile was drastically changed before and after burst events and the gradient decreased. Unknown field emission source would be created at the burst events.

We note that both cavities had shown good performances at vertical tests as mentioned above [8]. Field emission on-sets had been 14 MV/m and 22 MV/m, and unloaded Q-values had been also fine, $Q_o > 1 \times 10^{10}$ at 20 MV/m at vertical tests. From these facts, field emissions observed at cryomodule high power tests were most likely induced during module assembly works.

Finally we could keep the field level 13.5 MV at #3 cavity and 14.2 MV at #4 cavity for more than one hour.

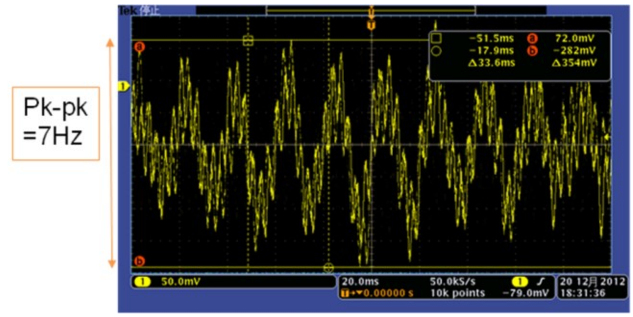

Figure 15: Measurement results of microphinics of #3.

During the high power test, we measured the microphonics under $Q_L(=1.5x10^7)$ of #3 cavity. Figure 15 show the measurements results of michrophonics by detecting the phase ($\Delta\phi$) between input power of cavity and output power from cavity via pick up port without feedback loop. Measured amplitude of Δf (pk-pk) is 7 Hz, which is much smaller than the expected michrophinics of 50 Hz. This means that tuner feedback is sufficiently applicable.

SUMMARY AND FUTURE PLAN

The main linac cryomodule have been constructed for cERL project. Cavity string assembly was carefully done in the clean room. It was installed into vacuum vessel of the cryomodule, placed on the beamline of cERL and connected to the refrigerator system. The cryomodule was successfully cooled down to 2 K. Performances of components, such as the input couplers, frequency tuners and HOM absorbers, were confirmed. High power measurements were also carried out. Accelerating voltage of 16 MV was achieved for both cavities. Suppression of field emissions is one of challenging issues near future.

In 2013, injector beam line was constructed and beam commissioning of injector parts was started [2]. Other beam lines of cERL like round loop will be constructed of this summer and autumn in 2013. After that, first energy recovery beam is expected to pass though the cavities.

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