

OPERATIONAL EXPERIENCE OF CW SRF INJECTOR AND MAIN LINAC CRYOMODULES AT THE COMPACT ERL

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Abstract

We developed ERL injector cryomodule and main linac for Compact ERL (cERL) project. The injector cryomodule includes three 2-cell L-band superconducting cavities. The main linac cryomodule includes two 9-cell L-band superconducting cavities. After construction of cERL injector and recirculation loop, beam operation was started with 20 MeV beam and after precise beam tuning, energy recovery operation was achieved with more than 80uA. Injector and main linac cavity were stable for ERL beam operation with Digital LLRF system. Field emission is the severe problem for main linac and heating of HOM coupler is the problem for injector. We mainly describe the cavity performances of two cERL cryomodules during long-term beam operation.

COMPACT ERL PROJECT

Compact ERL (cERL)[1, 2] is a test facility, which was 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.

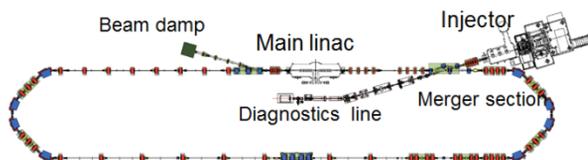


Figure 1: Conceptual layout of the cERL project.

Conceptual layout of the cERL is shown in Figure 1. The cERL main linac cryomodule was assembled and placed inside cERL radiation shield at fall of 2012. First high power test of cryomodule was carried out at December of 2012.

After commissioning of injector parts, recirculation ring was constructed during the summer and fall of 2013. Following the second high power test of main linac cryomodule, beam commissioning was started from December of 2013.

Its main parameters are shown in Table 1. Although the target beam parameters are 35MeV and 10mA for the first stage of cERL, current operation is limited to 20MeV and 10 μA. The beam energy was restricted because of severe field emission of main linac cavities [3]. The beam current was limited due to safety reason. In this paper, we present performance of injector and main linac cryomodule under the cERL beam operation.

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Table 1: Main Parameters for cERL Project

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

INJECTOR CRYOMODULE

The left figure 2 shows a schematic view of the injector cryomodule [4]. The injector cryomodule consists of three 2-cell cavities and each cavity is fed RF power by twin couplers. At the injector cryomodule, 100 mA of electron beam is planned to accelerated up to 10 MeV. Thus, total of 1MW RF power should be passed to the beam. 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. Design of HOM coupler was modified and also cooling ability was strengthened.

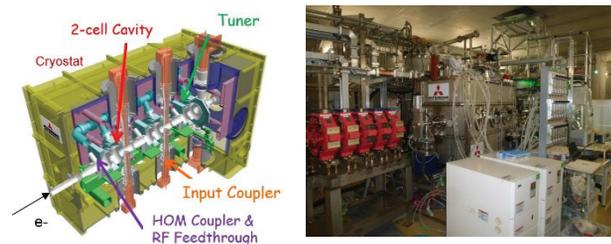


Figure 2: Schematic view of cERL injector cryomodule (left) and the one placed inside the cERL radiation shielding room (right).

MAIN LINAC CRYOMODULE

The left of Figure 3 shows a schematic view of the main linac cryomodule [3], which contains two 9-cell KEK ERL model-2 cavities [5] mounted with He jackets. Beampipe-type ferrite HOM absorbers [6] are connected at both sides of cavities, to strongly damp HOMs. The HOM absorbers are placed on 80K region. Coaxial input couplers [7] with double ceramic windows feed RF power to the cavities. Frequency tuners [8] control cavity resonant frequencies. Cooling pipes of 80K, 5K and 2K are extended throughout the cryomodule. The 80K line was cooled by Nitrogen, and 5K and 2K lines were cooled by Helium. After filling with

4K liquid He, insides of the He jackets were pumped down and the cavities were cooled down to 2K.

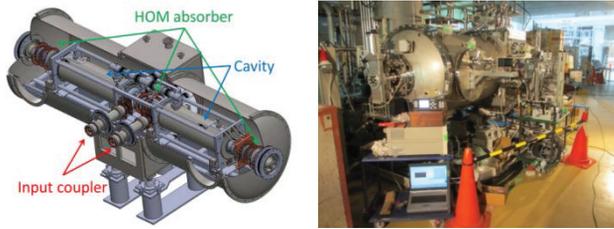


Figure 3: Schematic view of ERL main linac cryomodule (left) and the one placed inside the cERL radiation shielding room (right).

CERL BEAM OPERATION

Injector Cryomodule Performance

After injector cryomodule was cooled down to 2K, we start the high power test in Feb. 2013. The RF conditioning of the three cavities was started in a pulsed operation and an accelerating gradient of 15 MV/m was successfully achieved.[9] By changing CW operation, We measured dynamic heat loads in three cavities. An estimated heat load in case of $E_{acc} = 8$ MV/m and $Q_0 = 1.5 \times 10^{10}$ is about 1 W at 2 K, However, the observed heat load was 10~15 W at 8 MV/m. This means one order lower Q_0 values. The reason for the large dynamic heat load was due to heat up at RF feedthroughs of HOM couplers. Improvement of an efficient cooling at the RF feedthroughs is an essential issue to reduce the heat load.

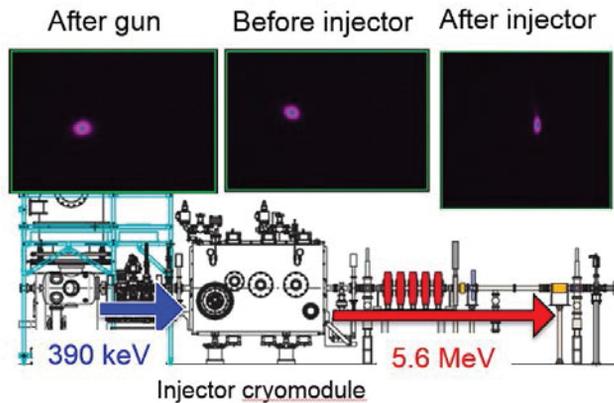


Figure 4: Measured beam profile of screen monitor before and after 5.6 MeV acceleration by injector cryomodule.

During the beam commissioning of injector part at February of 2013, 5.6MeV acceleration was achieved with 1 μ A beam by applying the almost 7 MV/m to three cavities of injector cryomodule as shown in Figure 4.

Main Linac Cryomodule Performance

Main linac cryomodule was connected to He refrigerator system and cooled down to 2K. Figure 5 shows typical example of cryogenic operation, at December of 2013. The cryomodule was cooled down with cooling rate of less than

3K/hour, in order to avoid thermal stress to the ferrite HOM absorbers.



Figure 5: Example of cryogenic operation for the run at December of 2013. Temperatures of cavities are shown by red and blue lines.

At the second high power tests, one of main topics was preparation of the digital LLRF system [10]. Cavity frequencies are controlled by the digital feedback system using the piezo tuners. Also RF amplitude and phase on the main linac cavities are stabilized by the digital feedback system. RF stability of 0.01 % R.M.S. for amplitude and 0.01 degree R.M.S. for phase were achieved. These values satisfied the requirement to the not only cERL operation but also multi-GeV ERL plan. Microphonics was also well suppressed.

Unfortunately, main linac cavity performance was not so good. Severe field emission was observed from low fields, for both cavities. Operation voltage was limited to 8.6 MV for each cavity, to avoid the problem caused by the heavy radiation. Therefore operation energy of cERL beam was limited to 20 MeV; 2.9 MeV at injector part and 8.6 + 8.6 MeV at main linac part.

cERL Beam Operation with Recirculation Loop

Beam commissioning of cERL recirculation ring started at December of 2013. At first, main linac cavities were detuned and the electron beam passed the cavities. After that, low field was applied to the upper cavity, and acceleration phase was searched. For this aim screen monitors were used. The left of Figure 6 shows example of beam profile at the first arc section. The right of Figure 6 shows beam position; energy, dependence on RF phase. On crest RF phase can be found from this scan and also acceleration voltage can be checked with the field strength of the bending magnets.

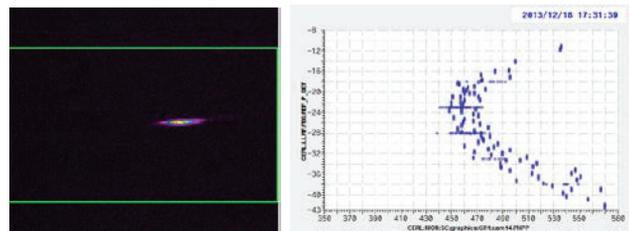


Figure 6: Beam profile observed by a screen monitor at the first arc section (left) and the RF phase scan to find acceleration phase (right).

Precise and dedicated beam tuning had been carried out and electron beam could successfully circulate the ring and reached to the beam dump. For the ERL, adjustment of recirculation loop length is important for energy recovery.

Deceleration phase of main cavities were investigated from the position of the screen monitor and the field strength of bending magnet at the beam dump section, while changing the length of recirculation loop by adjusting chicane or arc sections.

Figure 7 shows trials of energy recovery experiment. In the “Beam loading test”, electron beam of 6.5 μA CW was accelerated by the upper cavity and then decelerated by the lower one. The beam loading effect can be seen in the figure as the variation of difference between input and reflection power. It is noted that the sign of this variation is opposite between two cavities. On the other hand, in the “Energy recovery test”, no variation can be seen within measurement precision. This means energy recovery is successfully performed. Finally, in 2015 energy recovery was done by more than 80 μA CW beam.

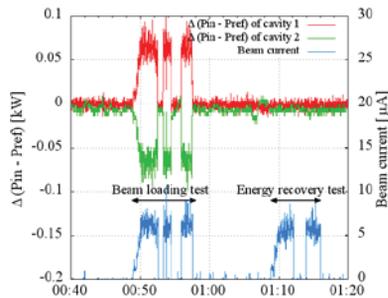


Figure 7: Energy recovery trial. Beam loading effect cannot be seen on “Energy recovery test”. In the Beam loading test, upper and lower cavity only accelerates and decelerates electron beams.

LONG TERM CAVITY PERFORMANCE

For the superconducting cavities, especially for CW accelerators, field emission is one of big issue against stable operation. In order to monitor real time radiation status, Si PIN diodes and ALOKA radiation monitors were used. As shown in the left of Figure 8, Sixteen sensors were set like a ring, around the beampipe at each side of each cavity. Total 64 sensors were used for monitoring. The right of Figure 8 shows typical radiation distribution measured by Si PIN diodes. They are sensitive to angle information of field emissions. Monitoring this distribution, we can get some information about emitter locations. Two ALOKA monitors were located both end of cryomodule, at almost beamline height, and used also to see radiation information.

For the cERL operation, we selected acceleration voltage of 8.6MV for each cavity. This is higher than radiation on-set for both cavities. Thus, our cavities have been operated with field emissions. Even during beam operation, sometimes increases of radiation were observed. Increases of signals were seen both of Si PIN diodes and ALOKA monitors. One radiation history taken by ALOKA monitors is shown in Figure 9. Increase of radiation is observed at February 14.

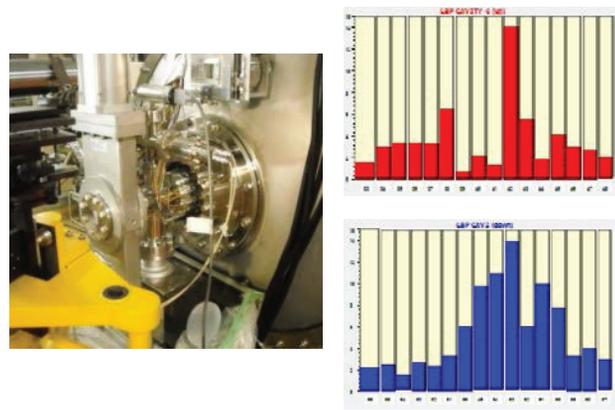


Figure 8: (Left) Si PIN diodes located around beam pipes and (right) example of radiation data taken by those Si PIN diodes.

Q-values of cavities were several times measured. Results are shown in Figure 10. Although radiation existed and Q-values were low from the first high power test at 2012, after some period of beam operation, Q-values became further worse. Finally, we kept same performance within error-bars after degradation from May 2014 to Mar. 2015. At present, Reason why field emission became worse and stopped is not clear. We will continue measuring the cavity performances.

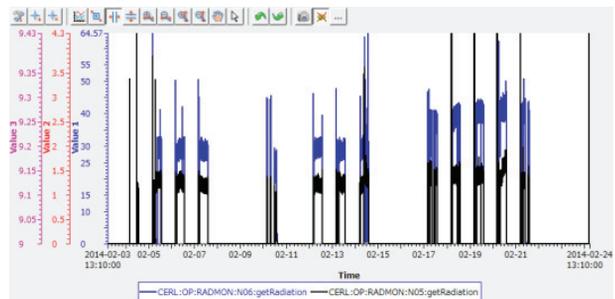


Figure 9: History of radiation status, monitored by ALOKA monitors, during cERL beam operation for three weeks at February of 2014. Radiation increased at February 14. Spikes at the beginning of dairy operation are due to RF aging.

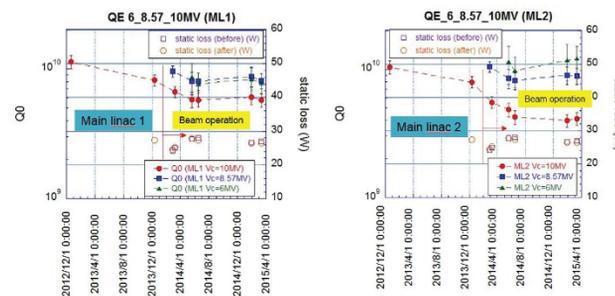


Figure 10: Measurement of the cavity performances of 6, 8.57 and 10 MV cavity voltage during long-term beam operation including high power test of Main linac 1(left) and 2 (right).

As one trial to suppress field emissions, pulse processing method was applied. Several milliseconds of additional few MV pulses were added to nominal 8.6MV CW RF field. Figure 11 shows the trial of pulse processing to the upper cavity. Figure 11 (a) shows RF field applied on the cavity and (b) shows its pulse structure. Figure 11 (c) shows variations of radiation signals monitored by Si diodes during processing. Time period of Figure (a) and (c) are same. It can be seen that several radiation signals became smaller during processing. Radiation becomes about half. Thus, Pulse processing method is considered to be effective to suppress field emissions.

At moment, field emission limits main linac cavity performance. To recover the design acceleration field of 15 MV, it is essential to eliminate it. Our ideas of countermeasure against field emission are as following; (a) apply more sophisticated pulse processing, (b) apply He processing, (c) disassemble the cryomodule, apply HPR to the cavities and reassemble it.

It is noted that suppression of field emission is of course essential for CW operation of superconducting cavities, but also recovery method from heavy field emission is important. If an effective recovery method is realized, possibly without disassembling the cryomodule, it is desirable.

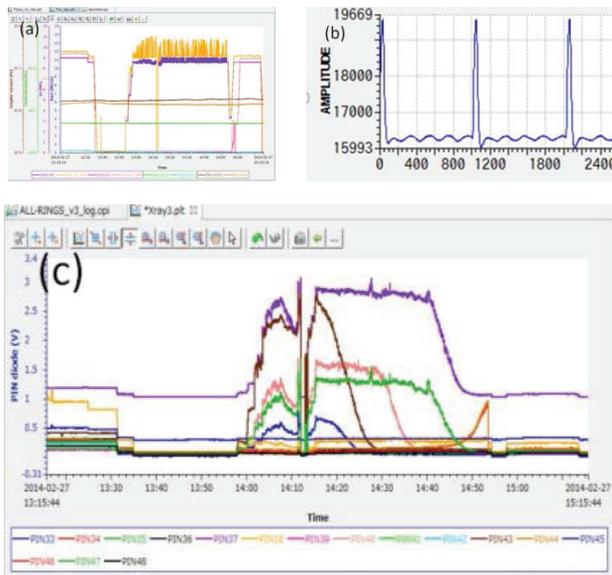


Figure 11: (a) RF field during pulse processing and (b) its magnification. (c) Decrease of radiation signal, observed by Si PIN diodes, during pulse processing.

SUMMARY AND FUTURE PLAN

The compact ERL in KEK was constructed and beam commissioning has been carried out for recirculation loop. Operation voltage of main linac cavities was restricted to 8.6 MV per cavity. So beam energy was limited up to 20 MeV. After beam tuning, energy recovery operation was successfully performed. RF stability of cavities were enough good for cERL beam operation. Field emission of main linac cavity is one of big issues for CW operation of

ERL cavities. During beam operation, increases of radiation were sometimes observed. Pulse processing method was efficient to suppress field emissions.

We continue to see the cavity performance during the CW beam operation up to more than 10 mA. And we plan to make the new cryomodule with for 9-cell cavities to overcome field emission problem with higher gradient and prepare the mass production.

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