MEASUREMENT OF THE CAVITY PERFORMANCES OF COMPACT ERL MAIN LINAC CRYOMODULE DURING BEAM OPERATION

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Abstract

We developed ERL main linac cryomodule for Compact ERL (cERL) in KEK. The module consists of two 9-cell 1.3 GHz superconducting cavities, two 20 kW high power coupler, two mechanical tuner and three HOM dampers. After construction of cERL recirculation loop, beam operation was started in 2013 Dec. First electron beam of 20 MeV successfully passed the main linac cavities. After adjusting beam optics, energy recovery operation was achieved. Main linac cavity was enough stable for ERL beam operation with digital LLRF system and energy recovery was successfully done with CW 90 μA beam. However, field emission was a problem for long term operation. In this paper, we express the measurement of the cavity performances 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.

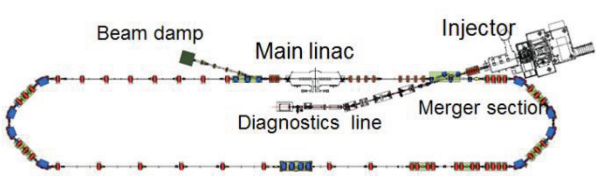

Figure 1: Conceptual layout of the cERL project.

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 35 MeV and 10 mA for the first stage of cERL, current operation is limited to 20 MeV and 10 μA. The beam energy was restricted because of severe field emission of main linac cavities. The beam current was limited due to safety reason. In this paper, we present performance of main linac cryomodule under the cERL beam operation.

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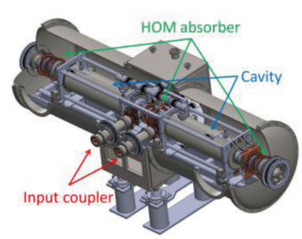
Table 1: Main Parameters for cERL Project

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

MAIN LINAC CRYOMODULE

The left of 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, 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.



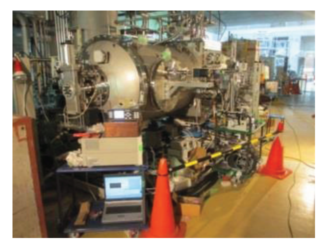


Figure 2: Schematic view of ERL main linac cryomodule (left) and the one placed inside the cERL radiation shielding room (right).

CERL BEAM OPERATION

Main Linac Cryomodule Performance

Main linac cryomodule was connected to He refrigerator system and cooled down to 2K. Figure 3 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.

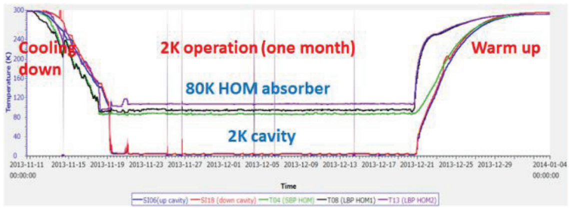


Figure 3: Example of cryogenic operation for the run at December of 2013. Temperatures of cavities are shown by red and blue lines.

At the second high power tests, one of main topics was preparation of the digital LLRF system [8]. 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 0.013 % R.M.S. for amplitude and 0.015 degree R.M.S. for phase were achieved. These values satisfied the requirement to the cERL operation. 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 [9,10]. At first, 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; 3 MeV at injector part and 8.6 + 8.6 MeV at main linac part.

cERL Beam Operation With Energy Recovery

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 4 shows example of beam profile at the first arc section. The right of Figure 4 shows beam position, i.e. 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. These procedures were applied to both cavities.

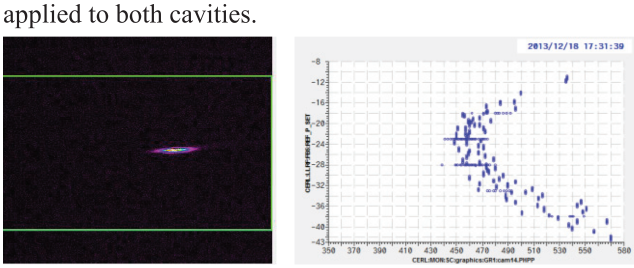


Figure 4: Beam profile observed by a screen monitor at the first arc section (left) and the RF phase scan to find acceleration phase (right).

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.

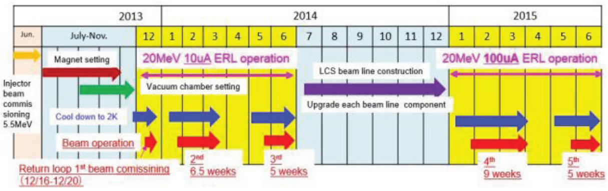


Figure 5: History of beam commissioning with energy recovery for 1.5 years.

We continue the beam operation to make the beam quality and beam current increase with energy recovery. Figure 5 shows the history of our cERL beam operation with energy recovery until now. We briefly summarize our beam operation history. After first beam commissioning at December of 2013, we did the energy recovery with 6.5 µA as shown in Figure 6. CW beam in 2nd and 3rd beam operation phase. In this phase, we learned the careful beam tuning without beam loss [11]. In the summer of 2014, we applied for a change of the maximum beam current (from 10 µA to 100 µA) to the authorities, and got approval in September. We started high current beam operation at 4th and 5th phase in 2015. During summer shutdown in 2014, we installed Laser Compton Scattering (LCS) beamline to demonstrate the future high-flux gamma-ray source [12] and advanced X-ray imaging technology [13]. By using this high beam current, we successfully obtain clear X-ray image come from LCS [14].

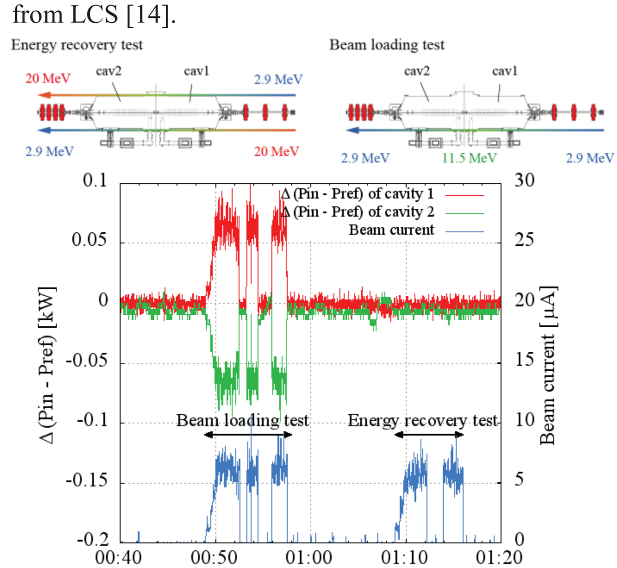


Figure 6: Energy recovery trial. Beam loading effect cannot be seen on "Energy recovery test". In the "Beam loading test", upper and lower cavity only accelerates and decelerates electron beams.

Figure 6 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

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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 [11]. Finally almost 100 % energy recovery was successfully done with CW 90 μA beam.

LONG TERM CAVITY PERFORMANCE

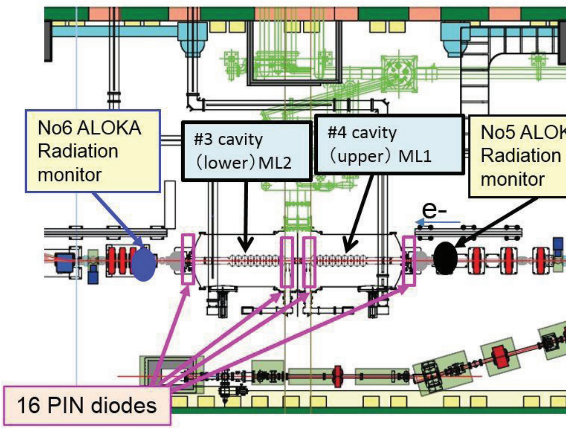

Figure 7: Setup of radiation monitors at cERL main linac cryomodule.

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 Figure 7 [10]. Two ALOKA monitors were located both end of cryomodule, at almost beamline height, and used also to see radiation information.

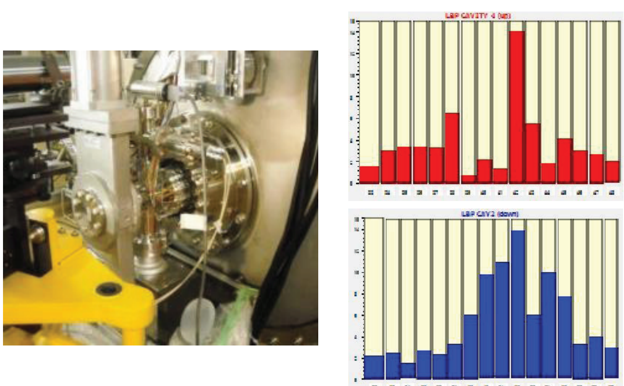

Figure 8: (Left) Si PIN diodes located around beam pipes and (right) example of radiation data taken by those Si PIN diodes.

Detail setup of Si PIN diodes was 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.

For the cERL operation, we selected acceleration voltage of 8.6 MV 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 in 2014.

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. Reason why field emission became worse is not clear, at present. We will continue more investigations and more dedicated analysis.

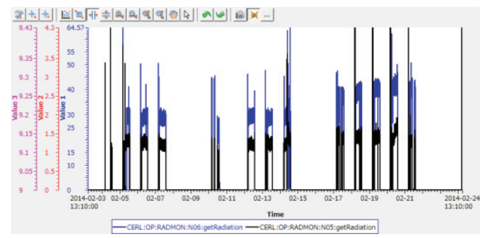

Figure 9: History of radiation status, monitored by ALOKA monitors, during cERL beam operation for three weeks at February of 2014. Radiation increased at February 14 in 2014. Spikes at the beginning of dairy operation are due to RF aging.

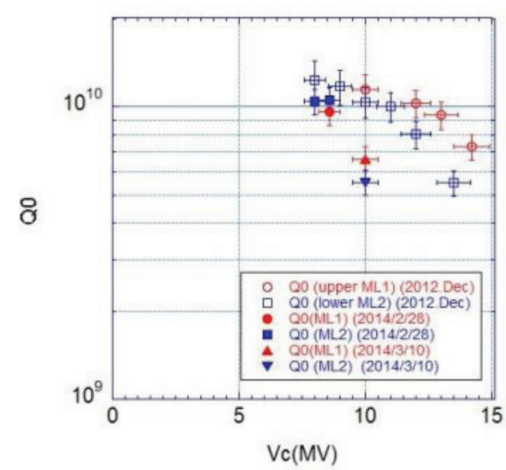

Figure 10: Q-values vs acceleration voltage. Red and blue points are for upper and lower cavities, respectively. Open circles (squares) show the measured data of high power test in 2012. Solid circles (squares) show the measured data during beam operation at 2nd phase in 2014. The Q-values were degraded during beam operation period.

As one trial to suppress field emissions, pulse processing method was applied. Several milliseconds of additional few MV pulses were added to nominal 8.6 MV 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.

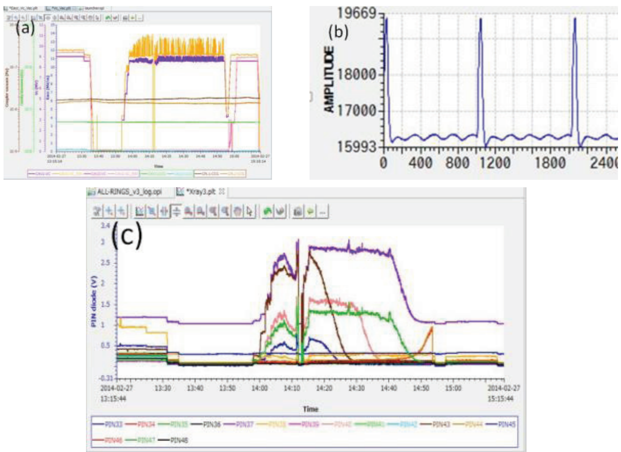

Figure 11: (a) RF field during pulse processing and (b) its magnification. (c) Decrease of radiation signal, observed by Si PIN diodes, during pulse processing.

During the beam operation at 3rd phase in 2014, we met 18 trips of both cavities. Most of the trips stemmed from the high gain of LLRF system, which could perform the good RF stability. For example, when the outer disturbances like cable noise and small unexpected mechanical vibration were appeared, the input RF power suddenly rise up and hit the upper limit of power level. Furthermore, we applied the high charge pulse mode to study the low emittance beam generation. Thanks to the beam loading effect with high charge, we also hit the upper limit due to the high gain at 3rd phase. This resulted in the RF trip many times. During summer shutdown, we optimized the gain of LLRF system to be robust from the outer disturbance and keep the high RF stability. And we started the beam operation for 9.5 weeks at 4th phase in 2015.

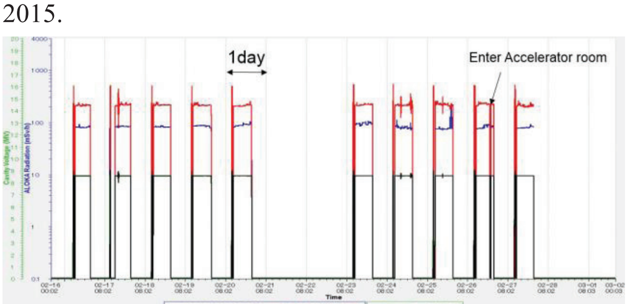

Figure 12: 2 weeks cavity voltages with radiation. Green (black) line shows the upper (lower) cavity voltage. Blue (red) line shows the measured radiation by upper (lower) ALOKA monitor. Spikes at the beginning of dairy operation are due to RF aging. Once we enter the accelerator room to check beam monitor.

Figure 12 shows the cavity voltages and radiation history for 2 weeks in 4th phase. By optimizing the gain of LLRF, we did not meet the RF trip of both cavities as shown in Figure 12. No trip was observed for 1.5 months at both cavities. We also note that the measured radiation kept same level within this 4th phase operation in spite of no pulse processing. From these stable operation results for 9.5 weeks, we tried to increase operational voltage at next operation phase in order to search whether we could keep the higher voltage stable for long term beam operation.

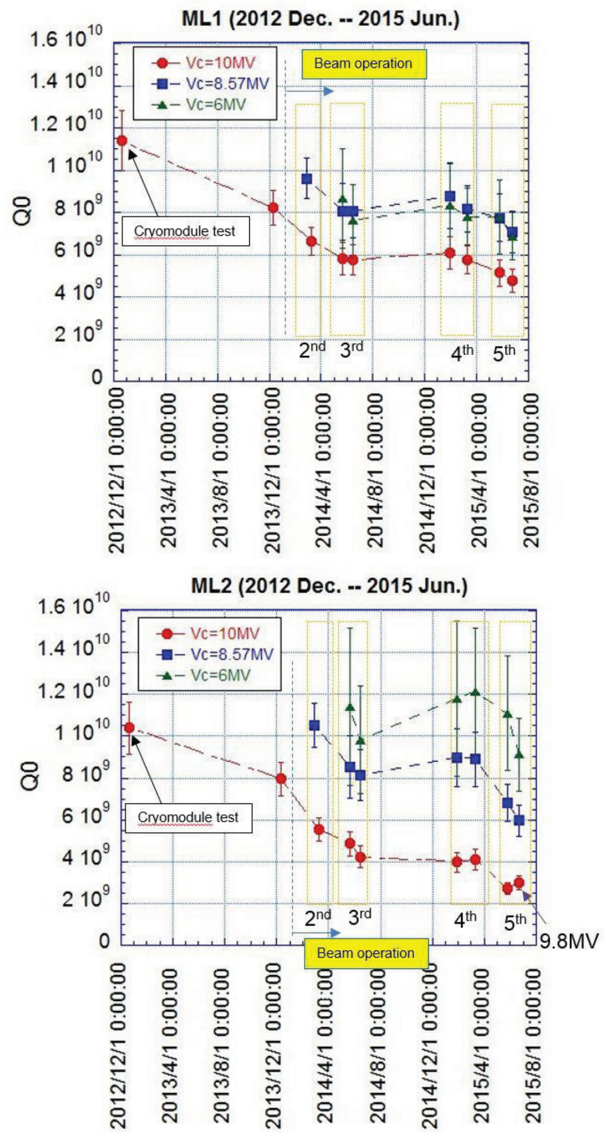

Figure 13: Measurement of the cavity performances of 6, 8.57 and 10 MV cavity voltage during long-term beam operation including cryomodule test of ML1 upper cavity (top) and ML2 lower cavity (bottom). Red, blue and green points are for 10MV, 8.57MV and 6MV, respectively except for the final red circle of 9.8 MV. Dotted boxes show the beam operation phases.

At the 5th phase, upper cavity operated at 10 MV to experience beam operation with higher field. On the other hand, lower cavity operated at 7.2 MV to keep 20 MeV

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beam energy of recirculation loop. In this phase, we tried several beam studies. Therefore, we operated 10 MV at upper cavity for 13 days in total. During high field operation of 10 MV at the upper cavity, only one RF trip which stem from the cavity itself (arc sensor of cold window) was observed. In this case, we only kept 7.0 MV to the upper cavity for more than 1 week before this trip. We noted that we applied higher voltage than operational voltage before the operation every day. However, during the 7.0 MV operation of the upper cavity, we did not apply the higher voltage than 7.5 MV. We thought that we did not have enough processing time to keep higher voltage of 10 MV after long term low voltage operation.

The Figure 13 shows the summary of Q-value measurements at 10, 8.6 and 6 MV of both cavities of this cryomodule from Dec.2012 to Jun.2015. After beam operation, the degradation was observed as already discussed above. However, after this degradation, we kept the same performance within error bars at the end of 4th phase. After the more degradation between the 4th and 5th phase, we kept the same performance within error-bars even if we applied the 10 MV operation. We noted that during 4th and 5th phase in 2015 we did not apply the pulse processing. Therefore, we met the slow degradation. Next, we will try the pulse processing before the beam operation.

DISCUSSION

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; (1) apply more sophisticated pulse processing, (2) apply He processing, (3) 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. To investigate this processing effect, we studied the above processing effect in V.T stand in parallel with beam operation. We obtained that these processing and HPR works well. Details are described in [15].

SUMMARY

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. After beam tuning, energy recovery operation was successfully performed. RF stability of cavities were enough good for cERL beam operation. Field emission is one big issue for CW operation of ERL cavities. Even during beam operation, increases of radiation were sometimes observed for 1.5 years. Pulse processing method was efficient to suppress field emissions. And finally we managed not to make the cavity performance drastically worse and keep the beam operation by using cryomodule within our cryogenic capacity. We noted that even if we applied 10 MV to our cavity, we could stably operate with only one trip in 5th phase. Large field emission had no correlation with the RF trip of the cavity in our cryomodule. In future, we'd like to apply He processing to make the cavity field gradient higher.

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