ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-THPO008

LONG-TERM OPERATION WITH BEAM AND CAVITY PERFORMANCE DEGRADATION IN COMPACT-ERL MAIN LINAC IN KEK

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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. 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 [1]. Beam current increased step by step and currently reached to 1 mA (CW) [2]. Energy recovery has successfully achieved. However, field emission was one of the problems for long term operation [3]. Therefore, the performance of the SRF cavities through long term beam operation has been investigated. In this paper, details of SRF beam operation, degradation, applied recovery methods are described.

INTRODUCTION FOR COMPACT ERL

Compact ERL Accelerator

Compact ERL (cERL) [1] is a test facility, which was constructed on the ERL Test Facility in KEK. Its aim was to demonstrate technologies needed for future multi GeV class ERL light source [4]. Recently, the future light source project in KEK was shifted to the high-performance ring accelerator. KEK directorates kept the importance of the R&D for industrial application based on ERL technologies like EUV-lithography [5] and so on. R&D of cERL was shifted to the industrial application from 2017.

cERL consists of 500 kV DC photocathode gun, which made high charge and low emittance electron beam, the injector cavities, the main linac cavity, which made energy recovery, recirculation loop and the beam dump. Detailed design beam parameters are shown in Table 1.

Table 1: Design Parameters of the cERL

Nominal beam energy	35 MeV
Nominal injection energy	5 MeV
Beam current	10 mA (initial goal)
	100 mA (final goal)
Normalized emittance	0.1 – 1 mm-mrad
Bunch length	1-3 ps (usual)
(bunch compressed)	100 fs (short bunch)

Main Linac Cryomodule

The left of Fig. 1 shows a schematic view of the main linac cryomodule [3], which contains two 9-cell KEK ERL model-2 cavities [6] mounted with He jackets. In order to achieve strong HOM damping for high-current ERL, iris diameter is increased to 80 mm. Epeak/Eacc becomes high and to be 3.0. Beampipe-type ferrite HOM absorbers [7] are connected at both sides of cavities, to strongly damp HOMs. The HOM absorbers are placed on 80 K region. Coaxial input couplers [8] with double ceramic windows feed RF power to the cavities. Frequency tuners [9] 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. 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 [10].

Unfortunately, main linac cavity performance was not so good. Severe field emission was observed from low fields, for both cavities [3]. 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.

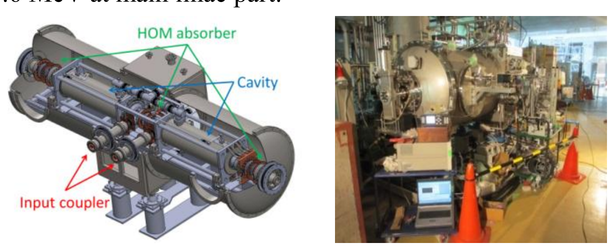

Figure 1: Schematic view of ERL main linac cryomodule (left) and the one placed inside the cERL radiation shielding room (right).

Beam Operation History until 2016

We briefly summarize our beam operation history. After first beam commissioning at December of 2013, we did the energy recovery with 6.5 μA. CW beam in 2nd and 3rd beam operation phase. In this phase, we learned the careful beam tuning without beam loss [11]. We started 100 μA 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 and advanced X-ray imaging technology [12]. By using this high beam current, we successfully obtain clear narrow-band X-ray image come from LCS [13]. During summer shutdown in 2015, we upgraded the DC Gun and added the radiation shield to be operated for 1 mA energy recovery condition. In 2016, we started the 6th phase beam operation for 7 weeks. Finally, energy recovery has successfully achieved with about 1 mA (CW) beam [2].

Q-values of cavities were several times measured until 2016. Results are shown in Fig. 2. Main linac 1 (ML1) and Main linac 2 (ML2) represent the KEK-ERL model-2

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29th Linear Accelerator Conf. LINAC2018, Beijing, China JACoW Publishing
ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-THPO008

cavity set in main linac cryomodule on the upstream side and downstream side, respectively. 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. However, we kept cavity performance after degradation from May 2014 to Mar. 2015. The unexpected vacuum burst or discharge event sometimes occurred during beam operation. The cavity performance was kept by using pulse processing method [14]. In 2016, cavity performance of ML1 became worse more. Until 2016, the reason why cavity performances became worse was not clear. Therefore, we continued measuring the cavity performances in 2017 and 2018.

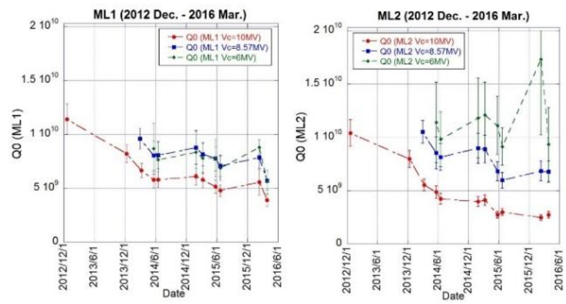

Figure 2: Measurement of the Q-values of 6, 8.57 and 10 MV cavity voltage during long-term beam operation from 2012 to 2016 including high power test of Main linac 1(left) and 2 (right).

MAIN LINAC CAVITY PERFORMANCES DUTING THE LATEST TWO YEARS

Beam Operation from 2017 to 2018

Table 2 shows our beam time during the latest 2 years. R&D of cERL was shifted to the industrial application from 2017. Unfortunately, we did not obtain the sufficient beam time for R&D as shown in Table 2. However, during these short beam operation time, we could many important and interesting R&D for not only industrial application but also the basic beam study for short bunch and high charge beam operation [15-17].

Table 2: cERL Beam Operation from 2017 to 2018

Period (operation time)	Energy [MeV]	Current [mA]	Comment
2017/3 7th phase (3 weeks)	(20→) 17.5	60 pC/ bunch	Degradation of cavity performance. Pulse operation for beam optimization.
2018/3 8th phase (2 weeks)	17.5	60 pC/ bunch	Pulse operation for THz radiation experiment
2018/6 9th phase (4 weeks)	17.5	60 pC/ bunch &1 mA (CW)	Pulse operation for beam optimization & THz radiation experiment & CW beam operation

ML1 Cavity Performance and Processing

We met the severe cavity degradation of ML1 during 7th phase in 2017. Figure 3 shows the time trend of the performance degradation during cavity processing on 8th.Mar.2017 before beam operation. Frist we applied CW field to the ML1 cavity for processing. When the field reached to the 5 MV, the field in the cavity suddenly fell down and cavity vacuum in the ML1 cavity increased. After that, cavity voltage did not increase more than 1 MV.

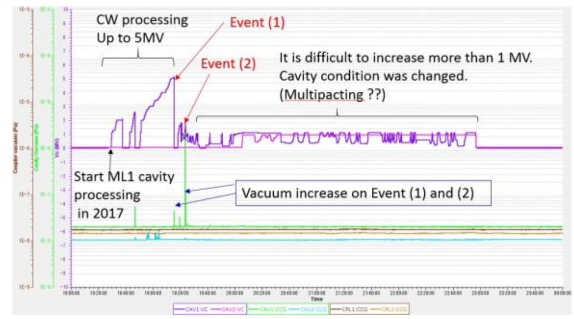

Figure 3: ML1 cavity processing trend on 8th.Mar.2017 before beam operation. Purple (pink) line shows the cavity voltage in ML1 (ML2). Green (line blue) line shows the vacuum inside the cavity of ML1 (ML2). Green (light blue) line shows the vacuum inside the cavity of ML1 (ML2). Brown (Gold) line shows the vacuum in warm side of the input coupler of ML1 (ML2).

Figure 4 show the expanded views of the figure around event (1) and (2) denoted in Fig. 3. The left figure of Fig. 4 shows 2 min. time trend including the first RF down event (event (1)) when the cavity field fell down at first. As the cavity field fell down, ML1 cavity vacuum increased. After event (1), we observed the large vacuum increasing even though the cavity voltage is lower than 5 MV. The right figure of Fig. 4 shows 2 min. time trend including the RF changing event (event (2) after the cavity fell down event (event (1)). The vacuum kept higher pressure than usual for more than 20 sec. after event (2) was occurred at 2 MV cavity field. Discharge event with long time occurred in the ML1 cavity at this time and the cavity condition would be changed drastically. Finally, we did not increase the cavity field after these events; the severe multipacting was observed after these events.

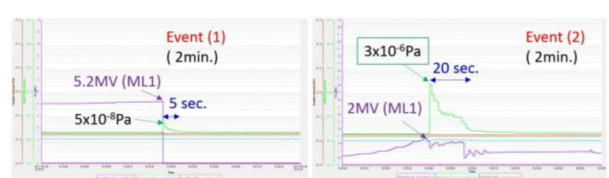

Figure 4: The left (right) figure shows the expanded view around event (1) and (2) denoted in Fig. 3, respectively.

After long processing at a few MV level, we finally processed the cavity again and increased the cavity field up to 6.5 MV. Figure 5 shows the trend of processing after event (1), (2). As the field reached the 6.5 MV field, suddenly field was fell down and we did not increase the cavity field more, even though the field could increase up

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to 11 MV before these events were occurred in 2016. We note that we add the pulse processing as shown in Ref. [14] on 7th, 8th and 9th phase to increase the cavity field. Total processing time was about 10 hours. However, we could increase up to only 6.9 MV for ML1 cavity after long term pulse processing. The reason of the limitation of cavity field was not field emission but thermal break down. Some particulates would be made during event (1) or (2) and resulted in the heating the cavity at the lower field.

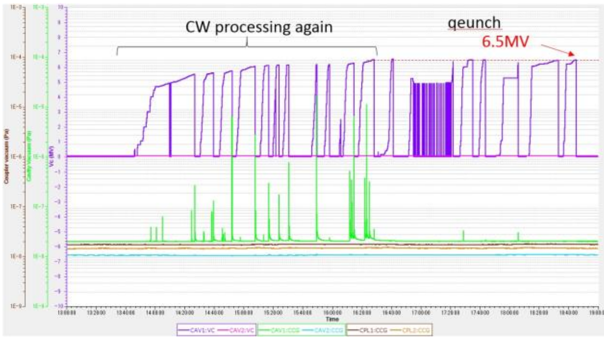

Figure 5: ML1 cavity processing trend again on 10th.Mar.2017 after field decreasing event as shown in Fig. 4.

ML2 Cavity Performance and Processing

Fortunately, event (1) and (2) did not decrease the ML2 cavity performance. However, ML2 cavity met severe field emission. At 8th phase beam operation on Mar.2018. Q-value of ML2 gradually decreased after the beam operation in 7th phase. We applied the pulse processing at 9th phase before beam operation.

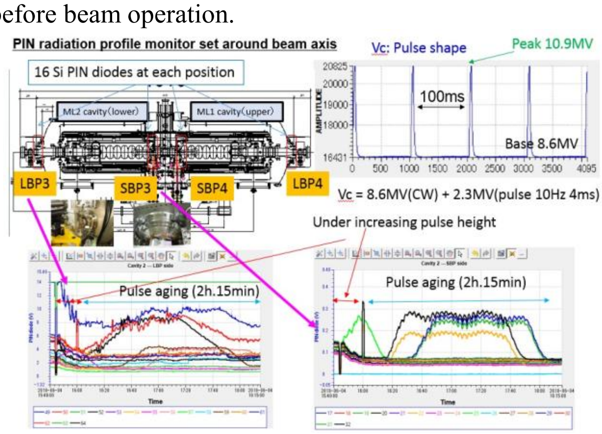

Figure 6: Pulse processing condition for ML2 cavity at 9th phase. Lower figures shows the trend of the PIN diode signals set on the both ends of ML2 cavity under the pulse processing as shown in the upper left figure of this figure.

Figure 6 shows the condition of the pulse processing. We applied the 8.6 MV for the base field and added the pulse peak field up to 10.9 MV to carry out the high power peak processing for this cavity. This pulse repetition is 10 Hz as shown in the right upper figure in Fig. 6. During pulse processing, we saw the PIN diode signals beside the ML2 cavity. After 2 hours pulse processing, all PIN diode signals drastically decreased and we finished the pulse processing.

Measurement of Q-value of Both Cavities

We did not measure the Q-values in 2017 due to the lack of time. After each pulse processing of two cavities, we twice measured the Q-values of both cavities in 2018.

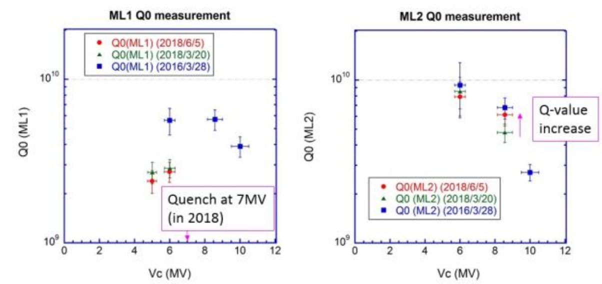

Figure 7: Q-value measurement results of ML1(left) and ML2(right). Horizontal (vertical) axes show the cavity voltage (Vc) and unloaded-Q values of both cavities.

Figure 7 shows the results of the Q-value measurements in 2016 and 2018. After the unexpected event shown in Fig. 3 for ML1, we could not obtain the higher Q-values in 2018 than that in 2016, which already had the lower cavity performance than before. Furthermore, cavity voltage was limited up to 6.9 MV in both 8th and 9th phase beam operation in 2018 even though we tried pulse processing for 10 hours. Pulse processing was not effective for the ML1 cavity after these unexpected events. On the other hand, after the pulse processing for ML2 as shown in Fig. 6, we could recover the ML2 cavity performance. Q-values at 8.6 MV in Jun.2018 increased after the pulse processing and come back to the same value as that in 2016. Field emission was severe problem in ML2. However, cavity performance was recovered by using pulse processing method until now. By keeping this cavity voltages to 6 MV of ML1 and 8.6 MV of ML2, we could start beam operation in Mar. and June. 2018 and could keep 1 mA beam operation again with energy recovery condition.

SUMMARY AND FUTURE PROSPECT

During the latest 2 years operation, cavity performance was degraded. Especially, ML1 cavity was drastically degraded by the unexpected burst event. After this event, we could not recover the cavity performance to the previous values in spite of many pulse processing. For ML2 cavity, we could keep the cavity performance under the severe field emission. Pulse processing worked well to keep the cavity performance for ML2. During the burst event, we observed the long vacuum increasing event. At this event, discharge would occur and some components like HOM absorber, ceramic of the input coupler and/or the other vacuum components near ML1 cavity would break and make some particulates in the ML1 cavity. We plan to increase the beam current up to 10 mA. However, we would like to open the cavity to identify the degradation source by directly seeing the inside of the cavities.

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