ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB097

DEGRADATION AND RECOVERY OF CAVITY PERFORMANCES IN COMPACT-ERL INJECTOR CRYOMODULE

E. Kako†, T. Konomi, T. Miura, H. Sakai and K. Umemori
KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki, Japan
SOKENDAI, The Graduate University for Advanced Studies, Hayama, Kanagawa, Japan

Abstract

After cryomodule assembly and first cool-down tests in 2012, the cERL injector cryomodule has been stably operated with beam for five years. However, gradual increases of x-ray radiation levels due to field emission were observed during long term beam operation. High power pulsed RF conditioning as a cure method was applied in the cool-down period in 2016 and 2017, so that degraded cavity performances have almost recovered up to the previous levels. Performance recovery status in three 2-cell cavities is reported in this paper.

INTRODUCTION

In order to demonstrate an excellent performance for a future project in ERL (Energy Recovery Linac), beam commissioning in compact-ERL (cERL) at KEK has been steadily in progress [1]. The target values of a beam current and beam energy in the cERL are 10 mA and 35 MeV, respectively. Operational beam currents at a beam energy of 20 MeV have increased step by step, up to 10 μA in 2014, 100 μA in 2015 and 1.0 mA in 2016 [2]. Beam operation with high bunch charges of 60 pC was successfully performed in 2017 [3]. An injector cryomodule is required to accelerate CW electron beams of 10 mA from the beam energy of 500 keV to 5.0 MeV [4]. Assembly of the injector cryomodule was started in April, 2012, and the completed cryomodule was installed in the accelerator hall in July, 2012 [5]. After this, cool-down cycles of 11 times have been carried out for 6 years. Increase of x-ray radiation level has been gradually observed during long term beam operation. High power pulsed RF conditioning was applied in order to supress field emission and reduce the x-ray radiation level. Performance degradation and recovery in the cERL injector cryomodule are described in this paper.

INJECTOR CRYOMODULE

Schematic drawing of an inside structure in the cERL injector cryomodule is shown in Figure 1. Each cavity was driven by two input couplers to reduce the required RF power handling capacity and to balance transverse momentum kicks owing to input couplers. Each 2-cell cavity was dressed with a helium (He) jacket, which was made of titanium and maintained the temperature at 2 K. Magnetic shields were put inside the He jackets. For damping higher-order-modes (HOMs), an HOM coupler scheme was chosen. Five loop-type HOM couplers were attached on both beam pipes of each cavity [6]. As a frequency tuning system, a slide-jack tuner equipped with a pair of piezo elements was attached at thick titanium base-plates. An RF input coupler is the most critical component in high power applications of superconducting cavities. A coaxial coupler, equipped with a warm (room temperature) single disk-type ceramic RF window with cooling water channels was used for the CW input couplers. After assembly of the injector cryomodule, the completed cryomodule was installed in the beamline, as seen in Figure 2. The No.1 cavity is driven by a 30 kW klystron, and the No.2 and No.3 cavities are driven by a 300 kW klystron. Then, cool-down tests for low and high RF power measurements were successfully performed before starting the beam commissioning. It was demonstrated that each coupler can transmit RF power of 40 kW in CW [7].

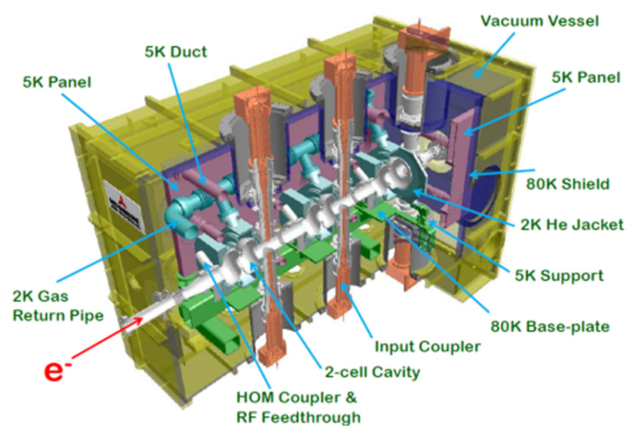

Figure 1: Injector cryomodule for cERL.


Figure 2: Injector cryomodule installed in beam line.

† eiji.kako@kek.jp

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2017). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

18th International Conference on RF Superconductivity SRF2017, Lanzhou, China JACoW Publishing
ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB097

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2017). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

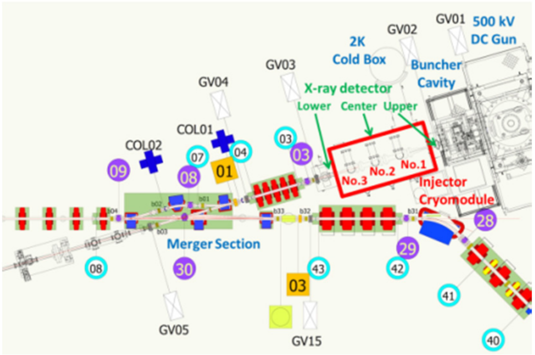

Figure 3: Schematic drawing of injector section.

An injector section, which includes an electron-gun with DC-500 kV, a bunching cavity and an injector cryomodule, was connected with a merger section, as shown in Figure 3. Three x-ray detectors to observe field emission phenomena along to three cavities were attached outside of the injector cryomodule.

LONG TERM BEAM OPERATION

History of cool-down cycles in the injector cryomodule is summarized in Figure 4. After low RF power tests in Sept. of 2012 and high RF power tests [7] in Feb. of 2013, beam commissioning of the injector section at 5 MeV was started in April, 2013. The operational accelerating gradients (Eacc) of three 2-cell cavities were 7.1, 7.5 and 7.1 MV/m in CW operation. Beam commissioning of re-circular ring with a main-Linac (ML) cryomodule including two 9-cell cavities was started in Dec. of 2013. The beam energy of 20 MeV in the re-circular ring was determined by relatively lower operating Eacc at 8.2 MV/m in two 9-cell cavities to avoid x-rays and dark currents due to heavy field emission [8]. In this case, the injection energy was lowered to 3.0 MeV, instead of 5.0 MeV. In the recent beam operation in 2017, high bunch charge of 60 pC in a burst mode operation was demonstrated.

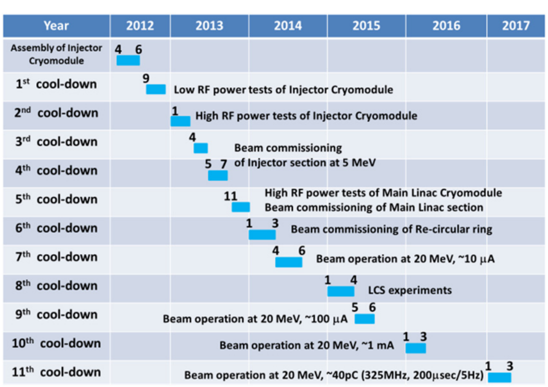

Figure 4: Cool-down cycles of injector cryomodule.

PERFORMANCE DEGRADATION

Observation of x-ray radiation levels by three detectors in three-cavity operation without beam is shown in Figure 5. The x-ray radiation level was initially around 1~5 μSv/h in 2013, and increased to 0.1~1 mSv/h in 2014.

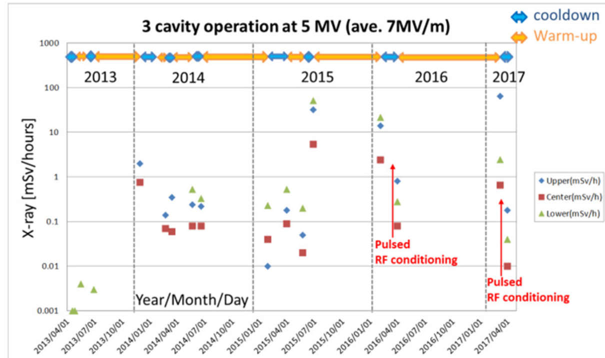

Figure 5: X-ray radiation levels observed three detectors in three-cavity operation at the total accelerating voltage of 5 MV from 2013 till 2017.

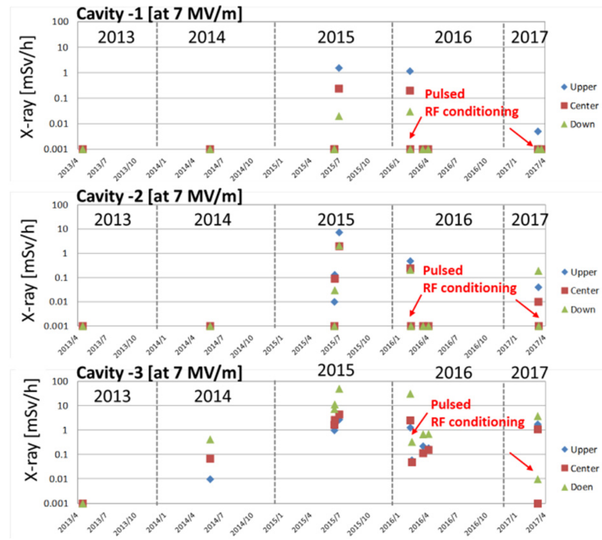

Figure 6: Observation of x-ray radiation levels in an individual operation of three cavities at 7 MV/m from 2013 till 2017.

Remarkable increase of the x-ray radiation above 10 mSv/h suddenly occurred in the middle of 2015. Changes of x-ray radiation levels at 7.0 MV/m in each individual cavity operation are shown in Figure 6. The radiation levels in all three cavities were lower than 1 μSv/h in the initial state in 2013. However, the radiation levels around the No.3 cavity close to the merger section increased to 0.5 mSv/h after one-year operation. In 2015, increase of the x-ray radiation level reached to 100 mSv/h in No.3 cavity, 10 mSv/h in No.2 cavity and 1 mSv/h in No.1 cavity. As seen this figure, degradation of cavity performance firstly initiated in the No.3 cavity, and the contamination area seems to have gradually extended toward the No.2 cavity and No.1 cavity. Pulsed RF conditioning was applied to supress field emission in the beginning of the beam operation in 2016, as seen in Figure 5 and 6. As the consequence of this effect, the x-ray radiation levels of three cavities were remarkably decreased. However, in the next cool-down period of 2017, increase of the x-ray radiation level was observed again. Therefore, the second pulsed RF conditioning was

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB097

repeated similarly in the beginning of the beam operation in 2017.

UNEXPECTED DISCHAGE PHENOMENA

Causes of the sudden increase of x-ray radiation level in 2015 could not be initially understood. However, the reason was clearly confirmed in the careful beam operation in 2016 and 2017. Two types of unexpected discharge phenomena were observed in the injector section. One is a discharge phenomenon at a Faraday-cup due to charge-up by field emitted electrons from the injector cryomodule, as shown in Figure 7. Many bursts of vacuum pressure at a vacuum gauge close to a buncher cavity were observed during the beam operation in June of 2016. The x-ray radiation level also gradually increased due to contaminated particles produced by this discharge. The insulator of the Faraday-cup was connected with an earth potential to avoid a charging up phenomena. The other potential components like laser mirrors made of grasses were also replaced by metal materials to prevent their charging-up.

Another is a very complicated phenomenon, as shown in Figure 8. Sudden increase of x-ray signals only at the lower-side x-ay monitor (red line) was observed due to accidental discharge phenomena. Field emitted electrons from three cavities hit the photocathode, and then, secondary electrons extracted by applied DC voltage of 400 kV and furtherly accelerated by injector cavities. Finally, high energy electrons collided with a screen monitor and radiate x-rays. It was found that operation at accelerating voltage without field emission was a key point to avoid this phenomenon.

HIGH POWER PULSED CONDITIONING

One of potential methods to cure degraded cavity performances is a pulsed RF conditioning with high power. RF parameters for pulsed conditioning are summarized in Table 1. Two klystrons of 30 kW and 300 kW can supply enough RF power to the cavities. The RF conditioning was carried out by three steps: 1. short pulsed operation (duty 0.25%), 2. long pulsed operation (duty 2.5%) and 3. continuous work (CW) operation. The typical pulsed waveforms are shown in Figure 9. Observed x-ray and Eacc during RF conditioning are shown in Figure 10. Here, quench detection by a lower Q_L calculated from a decay time of Eacc in every RF pulse was applied, and it worked very well, effectively to reduce a consumption of Liq. He. Figure 11 shows the pulsed waveforms of a quench event, which the Q_L interlock system worked. The signal of Pt shows the abnormal state due to local heating of cavity surface. The achieved Eacc was pushed by repeated quench events and the observed radiation level was gradually decreased. The source of field emission might be destroyed by a collision of emitted electros with higher energy.

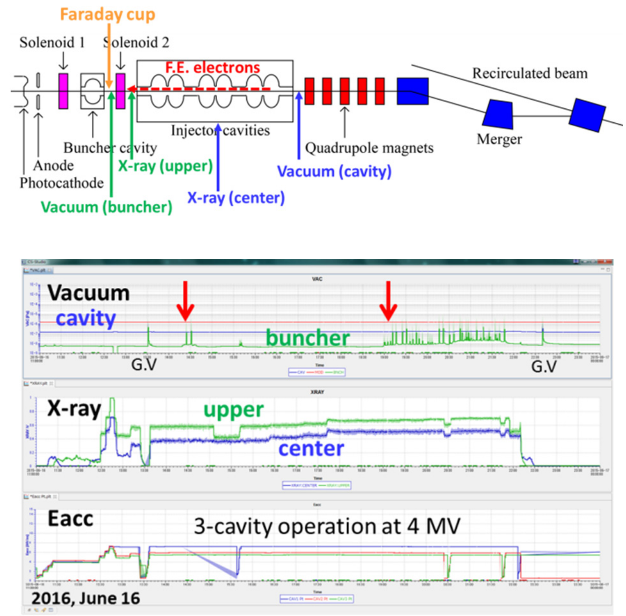

Figure 7: Schematic drawing of the injector section: Field emitted electrons induced a charge-up of a Faraday cup, and vacuum deterioration was observed due to accidental discharge phenomena.

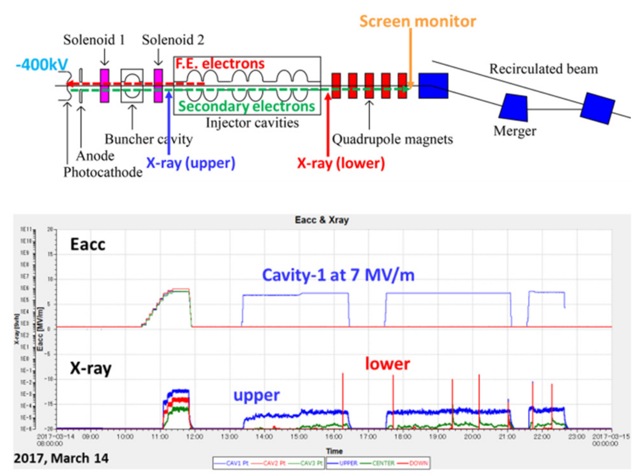

Figure 8: Sudden increase of x-ray signals (red) due to accidental discharge phenomena. Field emitted electrons attacked a photocathode. Then, secondary electrons extracted by DC voltage and accelerated by three cavities. Finally, high energy electrons collided with a screen monitor.

Table 1: RF conditioning parameters; Measured loaded Q value (Q_L), Filling time of Eacc (τ-filling), Required RF power for achieving Eacc = 15 MV/m and 20 MV/m.

	No.1 cavity	No.2 cavity	No.3 cavity
Q_L	1.2×10^6	5.3×10^5	5.4×10^5
τ -filling	0.15 msec	0.07 msec	0.07 msec
15 MV/m	12 kW	27 kW	27 kW
20 MV/m	21 kW	47 kW	47 kW

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2017). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB097

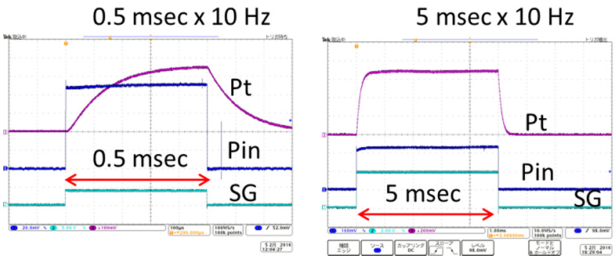

Figure 9: Pulsed waveforms for RF conditioning; input RF power (Pin), transmitted power (Pt) and pulsed signal from a signal generator (SG).

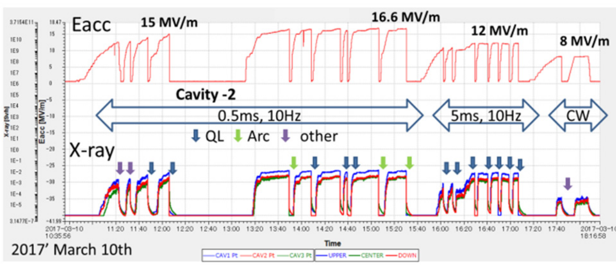

Figure 10: Time evolutions of accelerating gradients, Eacc, (top) and x-ray radiation levels (bottom) during high power pulsed RF conditioning for 8 hours.

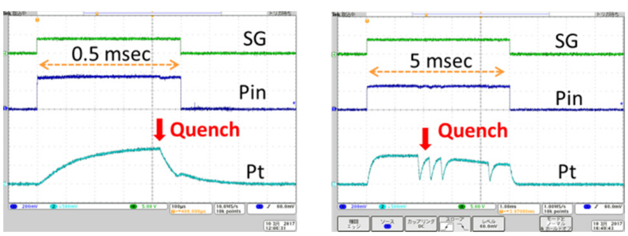

Figure 11: Pulsed waveforms of a quench event during RF conditioning.

RECOVERY OF CAVITY PERFORMANCE

Cavity performances were checked in the beginning of the 10th cool-down in 2016. However, any changes of x-ray radiation levels did not observed in comparison with the previous cool-down period in 2015, as shown in Figure 5. The x-ray radiation levels in each cavity dramatically decreased by high power pulsed RF conditioning in the first trial in 2016 and the second in 2017. Figure 12 shows the observation of x-ray radiation levels in CW operation, before and after high power pulsed RF conditioning in an individual cavity in 2017. Especially, onset level of x-ray in the No.1 and No.2 cavities successfully improved from 6 MV/m to > 8 MV/m by suppression of field emission activities. The x-ray radiation level at 7 MV/m in the No.3 cavity also remarkably lowered from ~10 mSv/h to less than 0.1 mSv/h. As the results of pulsed RF conditioning, a stable beam operation at 4 MeV with less than 1 μSv/h, as seen in Figure 13, become to be possible in the injector section. On the other hand, the reason for increase of the x-ray level during warm-up period from 2016 to 2017 was not clearly understood.

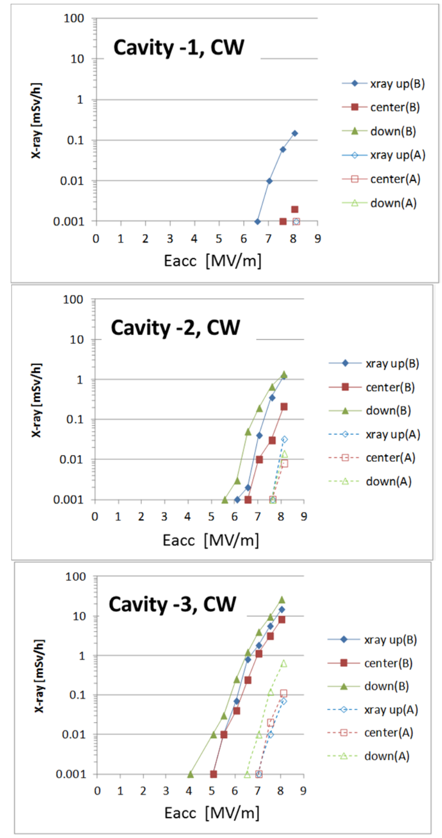

Figure 12: Observation of x-ray radiation levels in CW operation, before (solid line) and after (broken line) high power pulsed RF conditioning in an individual cavity; No.1 cavity (top), No.2 cavity (middle) and No.3 cavity (bottom).

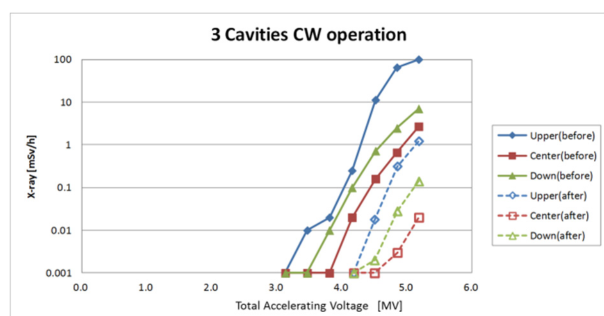

Figure 13: X-ray radiation levels observed three detectors in CW operation of three cavities simultaneously, before (solid lines) and after (broken lines) pulsed RF conditioning.

SUMMARY

Observation of x-ray radiation levels around the injector cryomodule showed gradual increases during long term beam operation. Cavity performances in the injector cryomodule were seriously degraded due to heavy field emission during beam operation at 5 MeV injection. The degraded cavity performances were successfully recovered by high power pulsed RF conditioning with duty cycles of 0.25% and 2.5%.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2017). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB097

REFERENCES

[1] S. Sakanaka *et al*., "Recent Progress and Operational Status of the Compact ERL at KEK", Proc. of IPAC2015, Richmond, VA, USA (2015) 1359-1362.

[2] T. Obina *et al*., "Recent Developments and Operational Status of the Compact ERL at KEK", Proc. of IPAC2016, Busan, Korea (2016) 1835-1838.

[3] T. Miyajima *et al*., "60 pC Bunch Charge Operation of the Compact ERL at KEK", Proc. of IPAC2017, Copenhagen, Denmark (2017) 890-893.

[4] S. Noguchi *et al*., "Present Status of Superconducting Cavity System for cERL Injector Linac at KEK", Proc. of IPAC10, Kyoto, Japan (2010) 2944-2946.

[5] E. Kako *et al*., "Construction of Injector Cryomodule for cERL at KEK", Proc. of IPAC2012, New Orleans, Louisiana, USA (2012) 2239-2241.

[6] K. Watanabe *et al*., "Development of the Superconducting RF 2-cell Cavity for cERL Injector at KEK", NIM-A, 714 (2013) 67-82.

[7] E. Kako *et al*., "High Power Tests of Injector Cryomodule for cERL", Proc. of IPAC2013, Shanghai, China (2013) 2340-2342.

[8] K. Umemori *et al*., "Operation Status of Compact ERL Main Linac Cryomodule", Proc. of IPAC2014, Dresden, Germany (2014) 2537-2539.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2017). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.