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LONG-TERM OPERATION EXPERIENCE WITH BEAMS IN COMPACT ERL CRYOMODULES

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Abstract

Compact ERL (cERL) was constructed at KEK as a prototype for 3 GeV ERL light source. It consists of two types of SRF cavities. Three injector 2-cell SRF cavities and two main linac 9-cell SRF cavities. The beam operation started at 2013 with a few hundred nA. Beam current increased step by step and currently reached to 1mA (CW). Energy recovery has successfully achieved. Performance of the SRF cavities through long term beam operation has been investigated. cERL has suffered from heavy field emissions in operation. Field emissions of the main linac cavity started just after module assembly work, and during beam operation, performances of both the main linac and the injector SRF cavities sometimes degraded. One reason of degradation was discharges occurred at beamline components due to charge-up of electrons. Pulse aging technique helped to recover SRF performances. With the beam induced HOMs, the beam position and the beam timing studies were started. In this presentation, details of SRF beam operation, degradation, applied recovery methods are described.

INTRODUCTION

Now a day many SRF based accelerators are operated, constructed and designed [1-3]. Stable beam operation is essential for these facilities, however, sometimes degradations occur for SRF cryomodules [4]. Recovery method from degradation is also important [5,6].

Operation of cERL started at 2013. We had four years operation experiences since then. Beam current is updated to 1 mA (CW). Change of cavity performance during beam operation is summarized below.

COMPACT ERL

Compact ERL

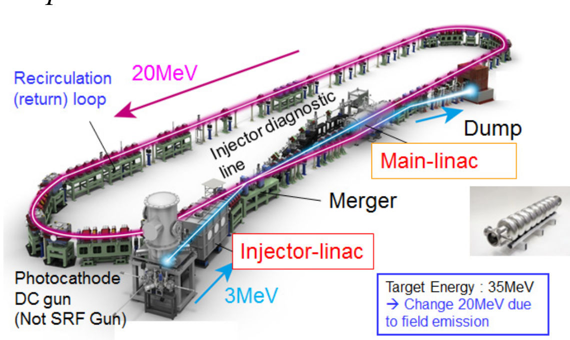

Figure 1: Schematic view of cERL.

Table 1: Design Parameter of the cERL

Nominal beam energy	35 MeV → 20 MeV
Nominal injection energy	5 MeV → 2.9 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)

Figure 1 shows schematic view of cERL [7,8] and Table 1 shows design parameters. High charge and low emittance electron beam from 500 kV DC photocathode gun come to the injector cavities and accelerated to 3 ~ 5 MeV. Beam pass through merger section accelerated to 20 MeV at the main linac cavity and then after circulation it is decelerated and dumped. Because of severe field emission occurred at the main linac cavities, beam energy is limited to 20 MeV.

Injector Cryomodule

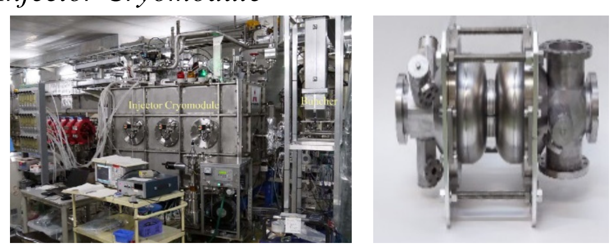

Figure 2: (left) Injector cryomodule and (right) injector 2-cell SRF cavity.

Left and right of Figure 2 shows the injector cryomodule [9] and the 2-cell SRF cavities [10]. Two input coupler ports and five HOM couplers are mounted on one cavity.

Main Linac Cryomodule

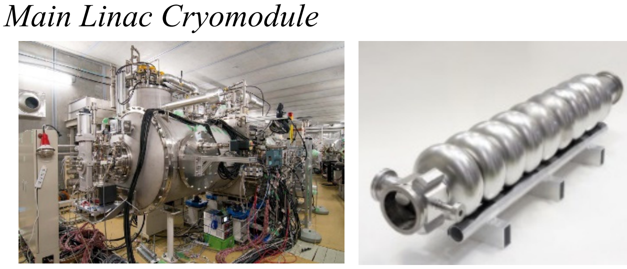

Figure 3: (left) Main linac cryomodule and (right) main linac 9-cell SRF cavity.

Left and right of Figure 3 shows the main linac cryomodule [11] and the 9-cell SRF cavities [12]. 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.

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BEAM OPERATION

Beam Current Upgrade

Table 2: History of cERL Beam Operation

Period	Energy [MeV]	Current [μA]	Comment
2013/4-7	5	0.3	Commissioning of injector section
2013/11-12	5	0.3	Commissioning of main linac section
2014/1-3	20	0.3	Commissioning of re-circular ring
2014/4-6	20	10	Operation with 10 μA
2015/1-4	20	10	Laser Compton Scattering experiment
2015/5-6	20	100	Operation with 100 μA
2016/1-3	20	1000	Operation with 1000 μA
2017/1-3	20	40 pC/ bunch	Pulse operation for beam optimization

Table 2 shows history of beam operation. Beam operation started from a few hundred nA. Then step by step, beam current was increased. For all of these periods, beam current was not limited by the accelerator components, but limited from radiation safety requirement. To reduce the radiation level, total beam loss should be suppressed and controlled.

Beam commissioning strategy is as below.

1. Beam commissioning start from pulse mode. After adjustment of beam orbit, operation move to higher repetition or CW mode.
2. Sophisticated beam tuning, such as beam based optics matching is carried out.
3. Using collimators, position and amount of beam loss is well controlled. The collimators have important role to control beam loss.
4. Interlock system, such as loss monitor and radiation monitor, is essential to minimize accidental beam loss.

Sometimes beam loss may cause unexpected vacuum burst or discharge and they may cause degradation of SRF cavity performances. Control of beam loss is important not only for the radiation safety, but also to protect accelerator components.

Typical SRF Cryomodule Performance

Typical one day operations of the injector and the main linac cryomodules are shown in top and bottom of Figure 4, respectively. Accelerating voltage or gradient, vacuum pressure of the cavities and He loss are shown.

Piezo tuners work well for both systems and digital RF systems work fine. RF stability of amplitude and phase are obtained to be less than 0.01 % and 0.01 degree for both the injector and main linac cavities. These values satisfy cERL requirements.

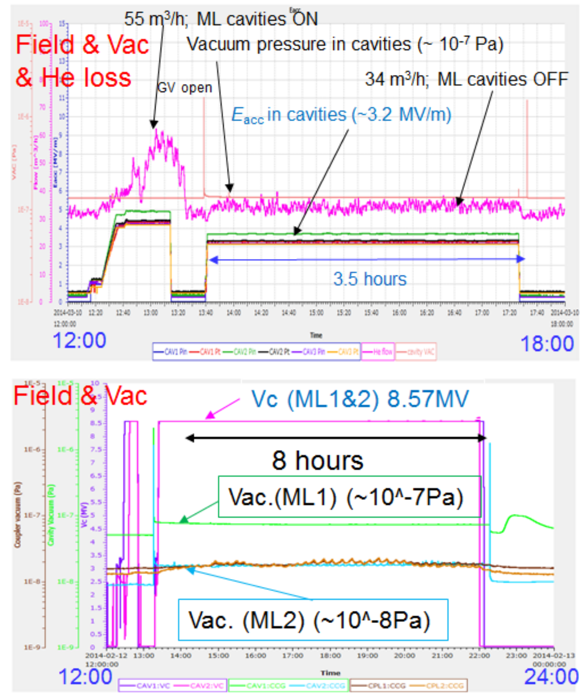

Figure 4: (top) Typical operation pattern of injector cryomodule. (bottom) Typical operation pattern of main linac cryomodule.

Energy Recovery

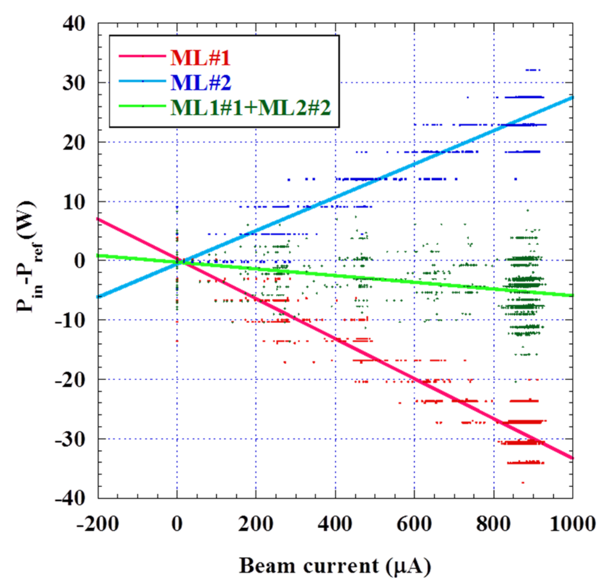

Figure 5: Successful of energy recovery. Effect of beam loading is shown by "Pin – Pref", for each main linac cavity at 0 ~ 900 μ m operation. Details are described in literature.

Efficiency of energy recovery was estimated from difference of "Pin – Pref". Once acceleration gradient of both main linac cavities were fixed, offset of "Pin – Pref" was adjusted to zero. Difference of "Pin – Pref" shows beam loading, since wall loss and calibration errors were corrected to zero. Figure 5 shows beam current dependence

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of beam loading. Since lower (higher) energy of beam was accelerated and higher (lower) energy of beam was decelerated, at the ML #1 (#2), opposite slopes can be seen both cavities. The ML#1 located upper-stream. As total, 4 W of power were obtained from beam at 900 μA operation. Considering feeding RF power for beam acceleration is 17.1 MV x 900 μA = 15.4 kW. Efficiency of energy recovery is 100 % + 0.03 %. Most perfectly energy recovery was realized.

LONG-TERM OPERATION OF INJECTOR CRYOMODULE [13]

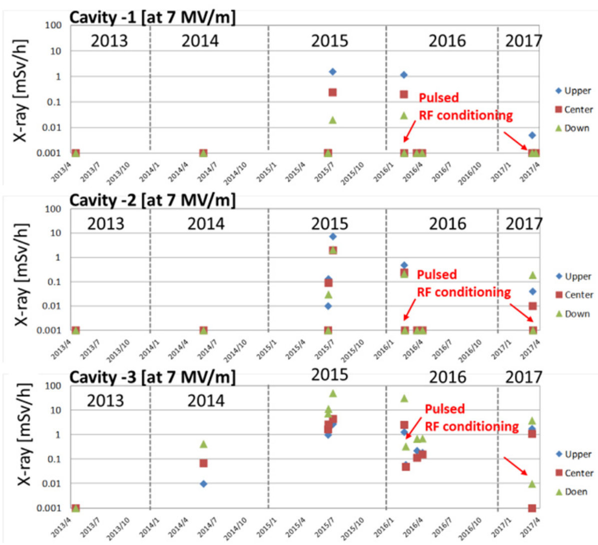

Figure 6: Long-term status of radiation for three injector cavities. From upper stream the cavity-1, 2 and 3 were located.

Figure 6 shows long-term status of radiations for three injector cavities. Some degradation occurred at 2014 for the cavity-3. Suddenly X-ray raise up at the operation of 2015. Details of this phenomenon are explained in the next sub-section. After that, several times pulse processing were applied and radiation were reduced.

Degradation due to Unexpected Discharge (1)

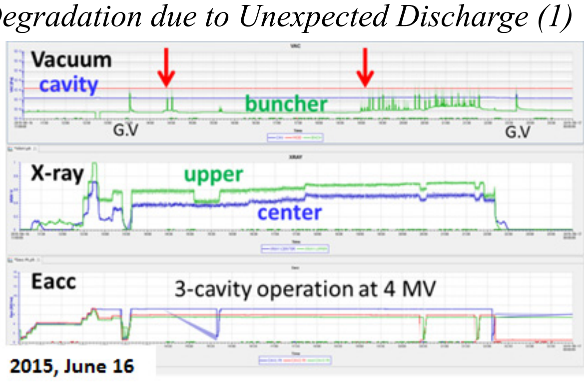

Figure 7: Unexpected discharge events. Vacuum on the buncher cavity were very spiky and radiation level of the injector cavities were drastically increased.

Figure 7 shows unexpected discharge events. During beam operation, vacuum level observed at the buncher cavity section, just upper-stream of injector cryomodule, was very spiky. At the same time, radiation on injector cavities were drastically increased. It is noted that radiation of Figure 7 is shown by logarithmic scale.

During this operation, low current beam was captured at a faraday cup, which was located on just up-stream of the injector cavities.

What we found later was the faraday cup was isolated from beampipe and field emitted electrons from injector cavities were charged up. Then frequent discharges happen and cavity performances were largely degraded.

During shutdown period, the faraday cup was shielded to beampipe and the problem disappeared.

Isolated components surrounding SRF sections are very dangerous. This situation should be avoided.

Degradation due to Unexpected Discharge (2)

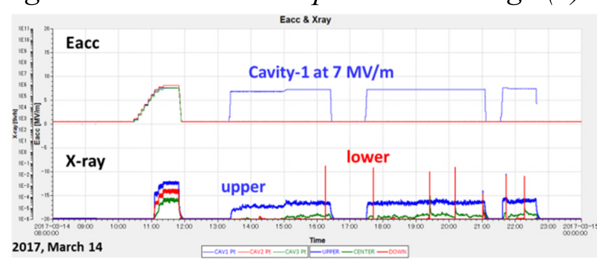

Figure 8: Unexpected discharge events. The vacuum of the injector cavity show spikes and radiation level is also unstable.

Another unexpected discharge events (in Fig.8) happen at operation of 2017. This time the cavity vacuum shows large spikes and some increase of radiation can be seen.

This time what happened was like followings. Field emitted electron ran inside cavities backwards and hit photocathode of the gun. Secondary electrons were extracted by DC voltage and again accelerated by injector cavities. Finally, electrons collided with the down-stream screen monitor. The screen monitor was charged up and showed vacuum spikes due to discharge.

Both of case (1) and (2), the reason of discharge is combination of field emission from the cavities and charge up at surrounding components.

Recovery by Pulse Processing

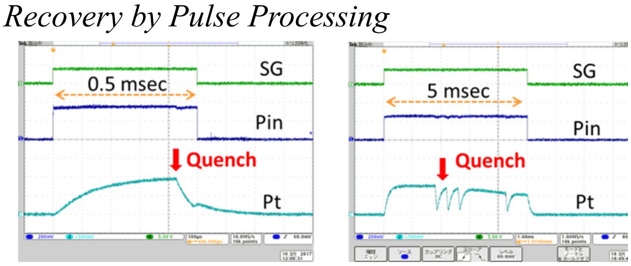

Figure 9: (left) and (right) shows signals of Pin, Pt and signal generator for 0.5 msec and 5.0 msec pulse processing.

Figure 9 shows signal of Pin, Pt and signal generator for (left) 0.5 msec and (right) 5.0 msec pulse processing.

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Because of low Qext of the input couplers and high power klystron fed RF power into cavities, pulse operation from zero field could be realized. Pulse processing from 8 to 17 MV/m were applied to cavities at 2017/March.

Pulse processing started from 0.5 msec pulse, then move to 5.0 msec pulse and finally go to CW. Right of Figure 9 show some processing during 5.0 msec pulse.

Figure 10 shows comparison between before and after the pulse processing. Order of two, radiation signals decreased after the processing.

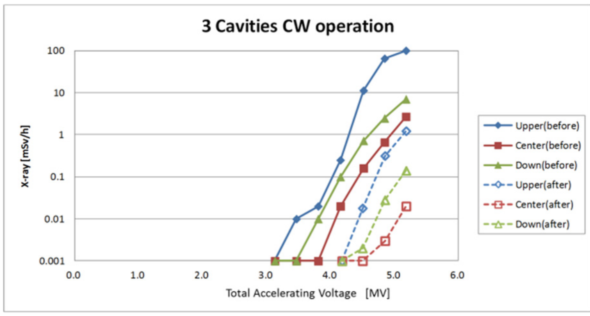

Figure 10: Comparison of radiation before and after the pulse processing for three cavities. Order of two, radiation level was decreased.

LONG-TERM OPERATION OF MAIN LINAC CRYOMODULE

Degradation during Beam Operation

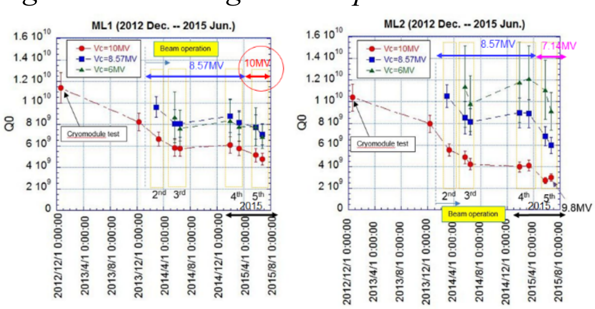

Figure 11: History of Q-values for the main linac cavities. (left) and (right) for ML #1 and ML #2 cavities, respectively.

Figure 11 shows history of Q-values for main linac cavities. Left is for ML#1 and right is for ML#2 respectively. Both figures show tendency that Q-values were decreased gradually. Not only 10 MV, but also Q-values of 8.6 MV also show degradation.

Cavity performance just after module assembly were drastically degraded. Both cavities can reach 25 MV/m at vertical test with small field emission. After cryomodule assembly, we performed high-power cryomodule test. During power rise, suddenly radiation occurred and on-sets of radiation for both cavities changed to around 8 MV/m. However, still Q-value at 10 MV/m are not so bad at that time. It is clearly seen during beam operation, degradation of Q-values occurred.

Reason for degradation is unknown. It might from dusts or gases from surrounding components. But it might also come from field emissions itself exist in the mail linac cavities.

Recovery by Pulse Processing

Sometimes pulse processing were applied to the main linac cavities. Figure 11 shows signals from Pt, Pin, Pref and an arc sensor. Arc sensor signals are also sensitive to X-rays from field emitted electrons.

In the case of the main linac cavities, additional pulse signals were added to CW base. For example, Figure 12 shows the example of the pulse processing of 8.6 MV (CW) + 2.3 MV (10 Hz x 4 msec) = (max) 10.9 MV. This procedure was applied because of high Qext of input coupler and relatively low power of solid state amplifiers.

Figure 13 shows comparison before and after the pulse processing for main linac cavities. It showed one or two orders of suppression of radiation signals.

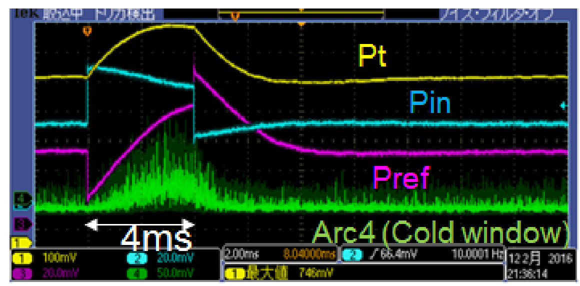

Figure 12: Signals for Pt, Pin, Pref and arc sensor during pulse processing.

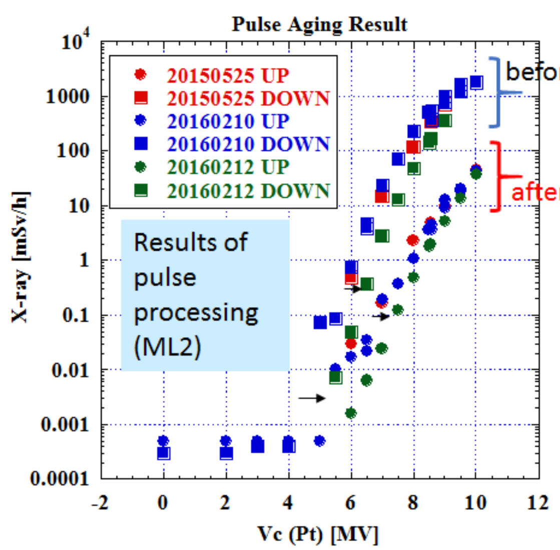

Figure 13: Comparison of radiation signals before and after pulse processing. One or two orders of reduction of radiation can be seen.

Interlock Status of Main Linac during Operation

Figure 14 shows interlock states for main linac cavities. At 2014, most of RF trip come from miss-operation of beam and cavities, sometimes due to bad LLRF parameters. After that, operation parameters were well adjusted and RF trips reduces. During 2015, RF trips were a few times per month. At June of 2015 and March of 2016 shows rather

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large number of RF trips. During these periods, rather attractive operations were performed. Cavity voltage was raised to 10 MV/m and also high-current beam operations were carried out.

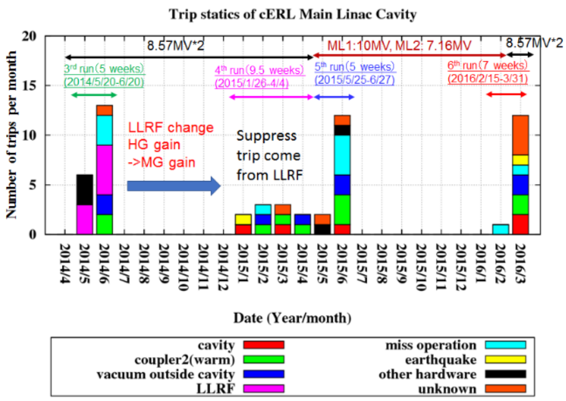

Figure 14: Trip status of Interlock for main linac cryomodule.

EXPERIMENTS UNSING HOM SIGNAL FROM INJECTOR CAVITIES

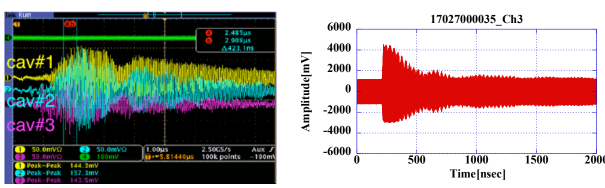

Figure 15: (left) Example of dipole mode HOM signals for study of the cavity alignment. (right)

HOM signal excited from the injector cavities were used for studies. Left of figure 15 shows example of dipole mode HOM signals [14]. These signals were used for study of the injector cavity alignment. Results indicate that horizontal alignment were not well.

Right of Figure 15 shows example of monopole mode HOM signal. This signal is used for beam timing study. Details of study will be done in the future.

SUMMARY

Beam commissioning of cERL started at 2013. Since then, we experienced four years of beam operation. Beam current of cERL was increased step by step and reached to 1 mA (CW). Amount of beam loss is controlled during beam commissioning. Both of injector linac and main linac have suffered from degradation by field emission. Pulse processing is helpful to keep cavity performance. Sometimes combination of field emission and surrounding components made discharge and led to degradation.

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