PRECISE STUDIES ON He-PROCESSING AND HPR FOR RECOVERY FROM FIELD EMISSION BY USING X-RAY MAPPING SYSTEM

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Abstract

We usually met the degradation of superconducting RF cavity on the cryomodule test and beam operation even if the performance of this cavity is good on the vertical test (V.T). Field emission is the most severe problem for this degradation after reassembly work from vertical test. Not only high pressure rinsing (HPR) but also He-processing, which is more suitable method without the reassembly work for recovery, is recommended and tried to recover this degradation. However, we did not investigate the details of how field emission sources were processed and removed after HPR and He-processing. We deeply investigated the processing procedure during He-processing and how many field emission sources removed after HPR by using rotating X-ray mapping system in V.T [1].

INTORODUCTION

The ERL project in Japan was started with an aim to realize 3 GeV class ERLs. Especially, more than 100mA beam current will be expected for the ERL operation. For this aim, nine-cell SC cavities, named as "KEK-ERL model-2 cavity"[2], used for the main linac cryomomoule and were developed to achieve a stable accelerating gradient of 15 - 20 MV/m under the beam of 100 mA. High Q-value of more than 1×10^{10} is also required to realize energy recovery condition with high gradient of 15 - 20 MV/m. In order to know the cavity performance of KEK-ERL model-2, we carried out the vertical tests and achieved 25MV/m gradient in vertical test and satisfied our requirements of more than 1×10^{10} of Q_0 with 15 MV/m as shown in the right figure of Fig. 1 [3]. After vertical test, these two cavities of KEK-ERL model-2 were assembled into Compact ERL(cERL) [4] main linac cryomodule and its cryomodule was placed inside cERL radiation shield at fall of 2012. High power test of cryomodule was carried out at December of 2012. The degradation of Q-values of two cavities were observed from 10 MV/m as shown in the left figure of Fig. 1. We also observed heavy radiations from 9-10 MV/m [5, 6]. We assumed that the field emission sources like small particles inside these cavities were created during string assembly and resulted in the Q-values degradation. Furthermore, degradation was proceeded during beam operation from 2013 [7]. At present, reason why field emission became worse is not clear. It is important to overcome these degradations during string assembly and beam operation.

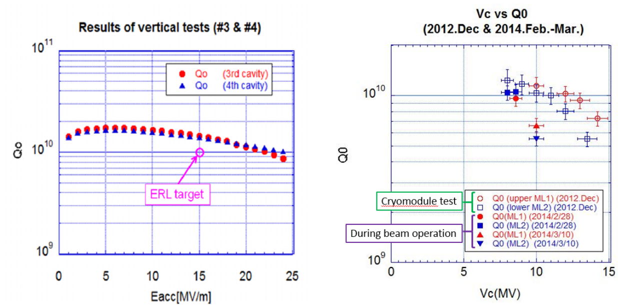

Figure 1: (Left) The results of vertical tests of KEK-ERLmodel-2 cavities. Horizontal and vertical axis shows accelerating field (Eacc) and Unloaded Q-values (Q_0). (Right) Performance degradation due to full-assembly (open circles and squares), and during beam operation (solid circles, squares and triangles).

This degradation of Q-value come from field emission was also appreared in KEKB [8] an CEBAF accelerator in Jlab [9]. So it is crucially important to suppress field emission all over the world [10]. There are some approaches to suppress the field emission. One is the high power pulse processing (HPP) and the other is the He processing. Both approaches can give the recovery from field emission after the cryomodule assembly and during beam operation. HPP is the normally used processing method after cryomoudule assembly and during the beam operation. By applying the higher peak voltage with about 1 ms pulse length compared with the nominal operating voltage, this peak power of higher voltage would burn the field emission source and recover from the degradation. We also applied the HPP to our cryomodule in Compact ERL (cERL) and could suppress the degradation during long term beam operation [7]. He processing is thought as more powerful processing method. By feeding the He gas with $10^{-2} \sim 10^{-4}$ Pa into the cavity in cryomodule with a higher RF voltage, He ion with high energy probably would attack the field emission source and crush it. Actually, this He processing worked in CEBAF cryomodule and recently C100 cryomodule performances of CEBAF, part of which suffered from field emission, were recovered from 9.3 MV/m to 13.1 MV/m in average [11]. HPP is expected that more powerful recovery method compared with pulse processing. However, we did not know the mechanism of He processing in detail. Especially we did not know that how field emission source would be processed while He processing applied.

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Our aim is to deeply understand the mechanism of He processing by using X-ray rotating mapping system [1], which was originally developed the field emission pattern by using PIN-diode in vertical test. To survey the field emission pattern during He processing, we built the He processing system in our vertical test stand to see the field emission pattern by X-ray mapping system. Furthermore, we survey the effectiveness of High Pressure Rinsing by using this X-ray mapping system in V.T.

SETUP

Figure 2 shows the setup of vertical test. In order to study and retrace the field emission phenomena in cERL cryomodule, we use the #2 ERL-model-2 cavity, which has the same shape of the installed cavity in cryomodule.

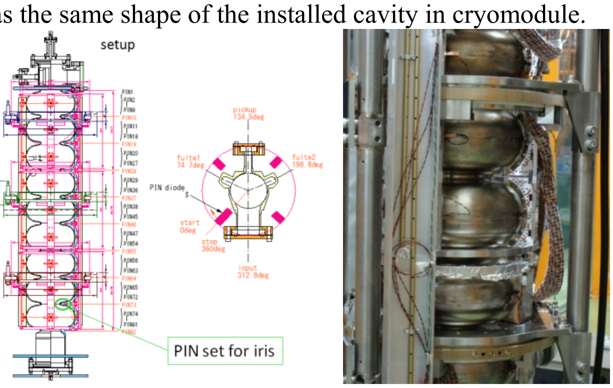

Figure 2: (Left) Layout of Si PIN diodes. (Right) X-ray Mapping system mounted on the cavity.

Table 1 shows our parameters of KEK-ERL model-2 9 cell cavity. The parameters in square parenthesiss shows the TESLA cavity. In order to realize the 100mA beam operation in ERL, we design our cavity so that the shunt impedance of HOMs was much suppressed to reduce HOM-BBU instability in design. Finally our cavity resulted that E_{peak}/E_{acc} of our cavity is 1.5 times higher than that of TESLA. Our cavity tends to increase the field emission due to the large E_{peak}/E_{acc}. This situation led us to develop the mapping system specialized to survey the field emission behaviour as shown in Fig. 2 [1].

Table 1: Parameters for KEK-ERL Model-2 Cavity

Frequency	1.3GHz	Coupling	3.8 %
Rsh/Q	897 Ω	Geom.Fac.	289 Ω
E_{peak}/E_{acc}	3.0[2.0]	H_{peak}/E_{acc}	42.5Oe/(MV/m)

The left figure of Fig. 2 show the detail of mapping system. Two types of sensor, one of which was the carbon resistor (Allen-Bradrey, 50Ω) and the other was the Si PIN photo diode (HAMAMATSU, S5821-02), were set to detect the heat spot and the X-ray radiation distribution due to emitted electron, respectively. The eight Si PIN diodes and seven carbon registers per cell and, in addition, one PIN diode per iris were arranged along the cavity as shown in Fig. 3. Totally, 82 PIN diodes were set at the same rotating angle. In addition, four carbon resistors per cell were set on the equator points at every 90 degrees in Fig. 3. Totally 93 carbon registers were set around the 9cell cavity. The generated current at the PIN diode was converted to voltage and amplified 10 times at operational amplifier. These data including sensors, power meters and rotating angle were taken by the real-time data acquisition system (YOKOGAWA, MX-100 & MW-100). Data were taken every 0.5 sec to reduce the AC noise coming from the amplifiers of diodes.

By using this obtained X-ray mapping profile, we could identify field emission source combined with the RF simulation [12, 13]. From previous experimental results in V.T, we considered to be able to survey the change of field emission property during He processing. We note that radiation monitor set on top flange of V.T stand is used to measure the radiation come from field emission.

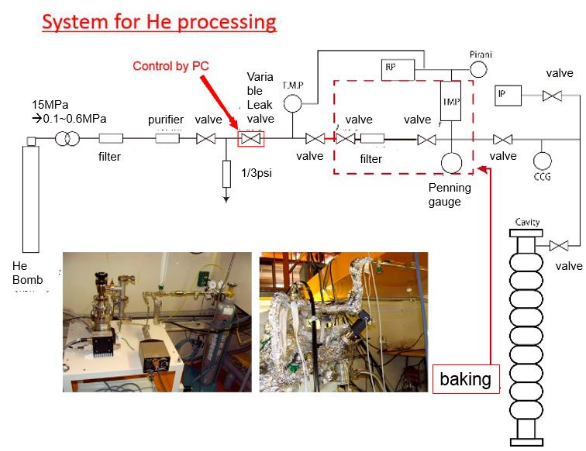

Figure 3: Setup of He line for He processing.

Figure 3 shows the He processing system in V.T stand. We care to keep flowing the clean He gas to the cavity by applying the 0.01μm filter in front of the He bomb. We use the electro polished pipe to our He line and baked up to 200 C^{o} for 24 hours before vertical test. He pressure was measured by penning gauge, which could read 10^{-4} Pa from up to 1 Pa, and Cold cathode gauge, which usually used to measure the cavity pressure. Variable leak valve was used to control the He gas flow precisely by remote.

RESULTS OF VERTICAL TESTS

We tried the vertical test by using #2 KEK-ERL model-2 cavity. Table 2 shows the history of our vertical test of #2 cavity. 11 times vertical tests were done. This cavity was fabricated as the prototype of cERL cryomodule cavity. Before the cryomodule assembly of cERL, we tried the three times vertical test to demonstrate our requirements by using this cavity and finally we satisfied our requirements of Q_0 > $1\text{x}10^{10}$@15MV/m. We also achieved more than 25MV/m accelerating field by using this cavity. This resulted in the construction of cERL main linac cryomodule [10]. After cERL cryomodule test, we kept this #2 cavity in vacuum in V.T stand. However, by observing the cavity degradation after cryomodule assembly and during beam operation on cERL cryomodule, we started to use this #2 cavity to study the degradation mechanism come from field emission in string assembly and during beam operation. We mainly show the result of 7th, 8th and 10th V.T, which studied He processing by using new He line system and X-ray mapping system. We also show the HPR study results in 11th V.T.

Table 2: History of Vertical Tests and Surface Treatments

	Surface treatment etc	Aim of VT
1st test	EP(100 μm), Annealing, EP2(20 μm), HPR, Baking	Performance check
2nd test	EP(20 μm), HPR, Baking	Performance check
3rd test	Warm-up	Check Q-value after warm-up
4th test	HPR (assembly input and bottom flanges)	HPR study
5th test	Keep with vacuum condition	Check reproducibility (same with 4th)
6th test	Ar purge (No flange assembly)	Check Ar purge procedure
7th test	(Warm up)	System check of He processing (0)
8th test	(Warm up)	Study on He processing (1)
9th test	Flange disassembly and assembly	Check dust contamination from re-assembly procedure
10th test	(Warm up)	Study on He processing (2)
11th test	HPR (assembly all flanges)	HPR study

7th and 8th Vertical Test Results

In 7th V.T we first use this He line and tried the He processing in 2K condition.

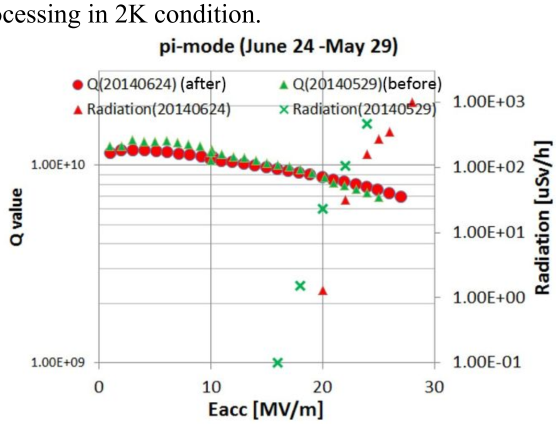

Figure 4: Q0 vs Eacc plot before and after He-processing. Green(Red) plots shows the Q-E results before(after) He processing on left vertical axis. Right vertical axis shows the radiation by Aloka.

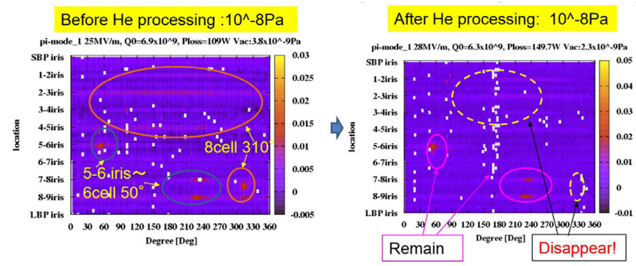

Figure 5: x-ray mapping profile before and after He processing. One emitter was disappeared on 8cell 310°.

First we confirmed that the feeding He gas did not cause the degradation of cavity performance. After this confirmation, we start the He processing. Figure 4 shows the results of Q-E curve before and after He processing in 7th and 8th vertical test, respectively. When we fed He gas into the cavity up to 10^{-4} Pa and increase the accelerating field to more than 24 MV/m, we observed the reduction of radiation. After this change, cavity pressure did not reduced to less than 10^{-5} Pa and we did not measure the true cavity performance after He processing. Therefore, we warmed up again and retried the vertical test with low pressure of about 10^{-8} Pa at 8th vertical test. The red circles of Fig. 4 shows the Q-E plot of 8th vertical test as the results after He processing. By applying the He process, we increase the radiation onset come from field emission. Figure 5 shows the x-ray mapping profile around 25 MV/m before and after He processing in 7th V.T. we observed the sharp radiation peak on 8cell 310° and broad profile around 1-4cell. By field emission simulation, field emission source was assumed to be on the iris of 8cell 130° broad and created this sharp and broad peak [13, 14]. After He processing, this 8cell 310° sharp peak and 1-4 cell broad peak was disappeared. On the other hand, 5-6 cell 50° sharp radiation peak, which connected the 7-8 cell broad radiation profile of 230°, did not change before and after He processing. From these results, One field emission source was processed by He processing.

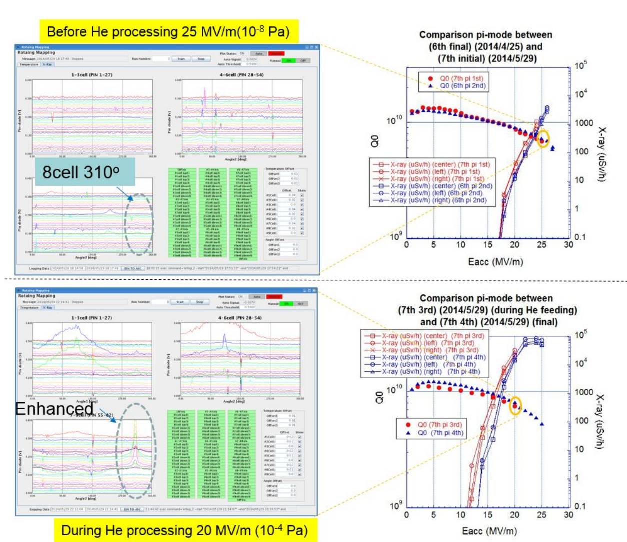

Figure 6: Top (bottom) figures show the Q-E curve with xray mapping profile before (during) He processing.

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We show the measurement results during He processing in detail in 7th vertical test. Top figures of Fig. 6 show the results of Q-E curve (right) and X-ray mapping profile on 25 MV/m (left) before He processing. On the other hand, bottom figures of Fig. 6 show the results of Q-E curve (right) and X-ray mapping profile on 20 MV/m (left) during He processing. We kept the He pressure around 10^{-4} Pa and increase the RF power to the cavity as already explained above and we observed the decreasing of the radiation onset during He processing. When we kept this condition, we observed the enhance of this radiation trace on 8cell 310^o as shown in the bottom figure of Fig. 6 compared with the x-ray profile before He processing as shown in top figure of Fig. 6. We noted that 1-4 broad radiation profile also enhanced during He processing. After feeding RF power higher under keeping cavity pressure around 10^{-4} Pa, suddenly radiation decreased and radiation peak of 8cell 310^o was disappeared as the results. We considered that the enhancement factor of β_{FN} was increased locally around 8cell 130^o by adding He gas and accelerated the processing on the local field emission site.

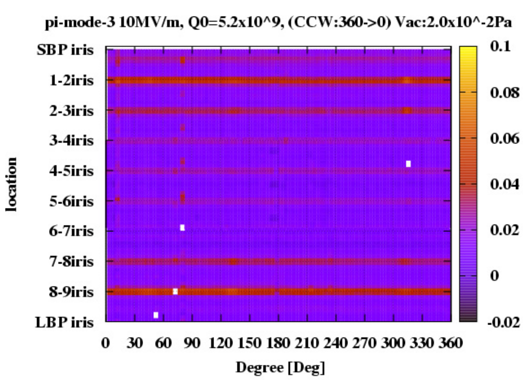

Figure 7: X-ray mapping profile of $2x10^{-2}$ Pa pressure at 10MV/m.

We shows the another results during He processing. Figure 7 shows the results of x-ray mapping profile when the He pressure in cavity increased up to more than 10^{-2} Pa in 8th vertical test. In this bad pressure, the radiation around all cavity surfaces was suddenly appeared when we fed the cavity voltage around 10 MV/m. radiation monitored on top flange was saturated and Q-value decreased in this situation, even if accelerating field is low like 10 MV/m. we considered that this bad pressure with RF voltage made plasma state inside the cavity and many radiation suddenly irradiated to all direction. We also tried the processing on this condition (named as all surface mode). Unfortunately, we did keep this condition for a long time due to the radiation interlock. We totally tried 50 min processing on all surface mode and measure the x-ray profile again. However, under all surface mode, x-ray profile did not change. We found that this all surface mode under He processing did not give the strong processing.

We found two pattern processings about He processing. One pattern of He processing gave the enhancement of β_{FN} of local field emission source by keeping He pressure around 10^{-4} Pa and feeding the RF power higher. We named this pattern as "Enhance mode". On the other hand, another pattern of He processing irradiated the radiation to all direction by keeping He pressure around 10^{-2} Pa and feeding the RF power, which named as "All surface mode". We found that only "Enhance mode" of He processing resulted in processing the emitter.

10th and 11th Vertical Test Results

Before 10th V.T, we retraced the string assembly work of cERL main linac cryomodule in class 10 clean room in order to search which part of reassembly work from vertical test to crymodule would affect the cavity degradation. After retracing reassembly work, we tried 9th V.T and found that the onset of radiation reduced from 18 MV/m to 10 MV/m. We realized that our reassembly work about the exchange of flanges was poor and bad to keep cavity performance from V.T to cryomoudule. To recover this bad performance cavity in 9th V.T, we tried He processing again in 10th V.T to eliminate the field emission sources.

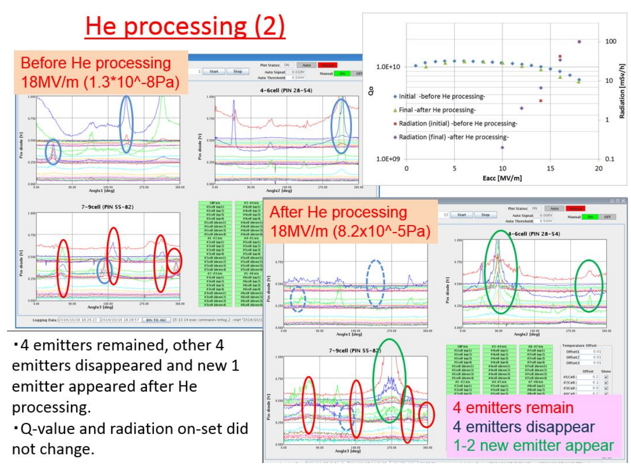

Figure 8: x-ray mapping profile before and after He processing on 10th vertical test.

Figure 8 shows the results of 10th V.T before and after He processing. There are 8 field emission sources before He processing. By applying "Enhance mode" of He processing, 4 emitters were disappeared after He processing. Unfortunately, one emitter of sharp peak on 5cell 90^o was created during He processing. As the results, onset of radiation did not change after He processing. However, we found that many emitters were removed by He processing.

Finally, we tried the HPR after He processing. Figure 9 shows the results of 10th V.T before He processing and 11th V.T after HPR. After HPR, radiation onset improve from 10 MV/m to 14MV/m. Furthermore, no x-ray profile by x-ray mapping was observed after HPR on 18 MV/m. We concluded that we drastically improved the cavity performance if we applied HPR to degradation cavity.

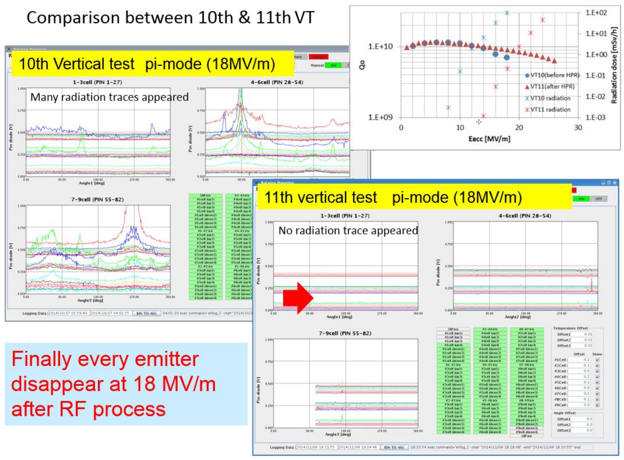

Figure 9: x-ray mapping profile before and after HPR on 11th vertical test.

SUMMARY

In order to study the degradation mechanism come from field emission in string assembly and during beam operation we measured the cavity performance in V.T by using KEK-ERL model-2 #2 cavity. Especially, we mainly studied the effect of He processing and HPR by using new He line system and X-ray mapping system in V.T stand. From three times V.T results of He processing, we found that we could remove the many field emission sources under not "All surface mode" but "Enhance mode" of He processing by using x-ray mapping system. Finally, we realized that HPR would drastically recover the cavity performance.

Next we will try He processing in cryomodule. Before the cryomodule test, now we plan to do power test by only using input coupler adding He gas to check whether ceramic window will not break by adding He gas to coupler.

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