DEVELOPMENTS OF HORIZONTAL HIGH PRESSURE RINSING FOR SUPERKEKB SRF CAVITIES

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Abstract

The Q factors of the eight superconducting accelerating cavities gradually degraded during the long-term operation of the KEKB accelerator. Since we will re-use those SRF cavities for the SuperKEKB, the performance degradation will be a serious problem. Several cavities degraded their performance significantly at high accelerating fields. The Q degradation is still acceptable for the 1.5 MV operations at SuperKEKB. However, further degradation will make the operation difficult. In order to recover the cavity performance, we developed horizontal high pressure water rinsing (HHPR). This method uses a horizontal high pressure water nozzle and inserts it directly into the cavity module. We applied this method to two degraded cavities and their degraded Q factors recovered above 1×10^9 at around 2 MV. In this paper we will present the HHPR method, high power test results after the HHPR and the residual gas analysis.

INTRODUCTION

An asymmetric energy electron-positron double-ring collider accelerator for B-factory, KEKB was shut down in 2010 and its upgrade machine, SuperKEKB [1] is now under construction. The luminosity will be increased up to 8×10^{35} cm^{-2}s^{-1}, 40 times the KEKB peak luminosity. The beam current of the high energy electron ring (HER) is 2.6 A with a beam size of 10×0.04 μm^2 and bunch length of 5 mm, while that of the low energy positron ring (LER) is 3.6 A with the bunch length 6 mm. The construction is almost completed and its commissioning will start in January 2016.

In the HER ring, eight SRF cavities [2] will be re-used for the electron beam acceleration. Expected beam-induced HOM power per cavity is more than 30 kW. This issue will be discussed elsewhere [3]. Another issue is cavity performance degradation during the KEKB operation. Q factors of several cavities degraded significantly at around 2 MV with intense X-rays after air exposure of the cavity at the coupler gasket adjustment or at the repair of indium sealed joints. Those degradations are mainly due to particle contamination. It is still acceptable for the SuperKEKB operation because the Q factors are still above 1×10^9 at 1.5MV. However, further degradation will make the operation difficult. Therefore performance recovery is desired.

The high pressure water rinsing (HPR) is effective to clean the cavity surface contaminated by micro-particles. To apply the HPR to degraded cavities, their cavity cells have to be dismounted from cryomodules. This procedure will make the risk of helium leakage at indium sealed joints. If we apply this method directly to the cavity in the cryomodule, we can save a lot of time and costs of re-assembly, and furthermore we can avoid the risk of leakage at the indium joints. Therefore we have developed a horizontal HPR (HHPR) [4] that can be applied to the cavity in a cryomodule. This method uses a horizontal insertion pipe with a water jet nozzle and an evacuation pipe for wasted water. We applied this method to two degraded cavity cryomodules. Their Q factors successfully recovered to 1×10^9 at 2 MV.

Since the cavity is not baked after the HHPR, H_2O contamination on the inner surface of the cavity might cause serious discharge. We studied a H_2O contamination effect not only during the high power test of the cavity but also in a coupler conditioning before cooldown. We also studied desorption gases during warm-up and at the baking of ion pumps to analyse H_2O contamination. The study showed that the H_2O contamination enhanced multipacting discharge in a coaxial structure of the coupler. However, a voltage bias conditioning effectively processed those multipacting levels.

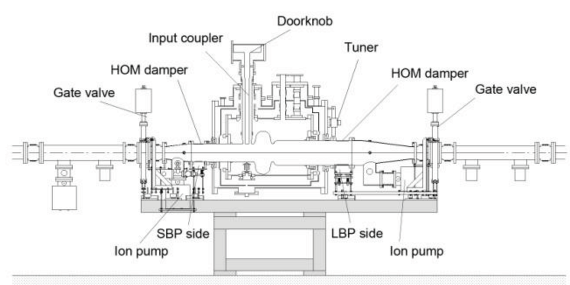

Figure 1: Cross-section of the SRF cavity module.

KEKB SRF CAVITY

Eight SRF cavities were installed in the KEKB tunnel to accelerate the electron beam together with ARES normal conducting cavities. A schematic diagram of the KEKB SRF cavity is shown in Figure 1. The cavity is a 509 MHz single cell cavity optimized for KEKB. Ferrite HOM dampers attached on both beam pipes heavily damp HOM modes to suppress the beam instability. A coaxial type power input coupler [5] attached on the beam pipe feeds RF powers to the beam. The external Q factor of coupling was first set at 7×10^4 then adjusted to 5×10^4 as the beam current was increased. Each cavity provided the cavity voltage of 1.2~1.5 MV and the beam power of 350~400 kW.

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Those SRF cavities had been stably operated for KEKB for more than 10 years. Those RF parameters are summarized in Table 1. The SRF cavities will be used for SuperKEKB to accelerate the beam current of 2.6 A at the cavity voltage of 1.5 MV. Each cavity has to deliver the RF power of 400 kW to the beam. Those RF parameters are listed in the same table.

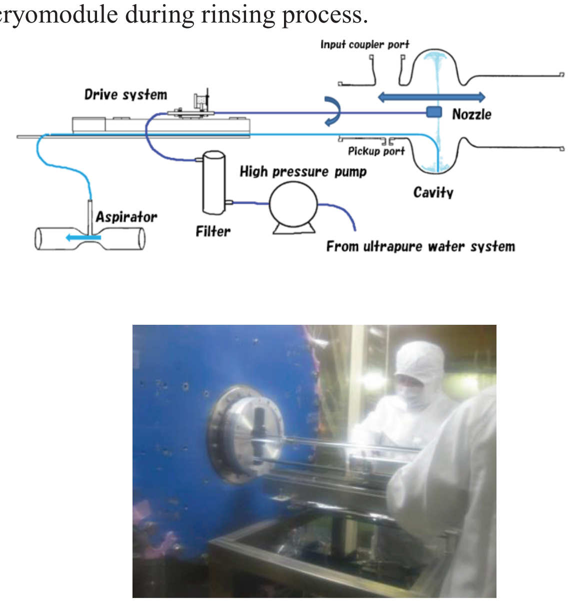
Table 1: SCC Parameters

Parameters	**KEKB (operation)**	**SuperKEKB (design)**
Number of cavities	8	8
Beam current [A]	1.4	2.6
Bunch length [mm]	6	5
RF voltage [MV/cavity]	1.2~1.5	1.5
Beam power [kW/cavity]	350~400	400
HOM power [kW/cavity]	16	37

HORIZONTAL HPR

The degraded cavity module is set at an assembly area with a clean booth. The inner conductor of the input coupler and both large and small tapered beam pipes with HOM dampers are dismounted from the cryomodule together with a vacuum pumping unit. A HHPR apparatus is set at the small beam pipe side while a blank flange is set on the large beam pipe.

Special care has to be given to the coupler inner conductor. The H_2O contamination on the coupler surface after the HHPR might enhance multipacting discharge. Furthermore, water drops on the ceramic RF window might cause a crack on the ceramic. Therefore, we decided to take out the inner conductor from the cryomodule during rinsing process.



(a)

(b)

Figure 2: HHPR apparatus. (a) Schematic diagram of the apparatus, (b) Picture of the apparatus during the HHPR.

Apparatus

Schematic diagram of our HHPR system is shown in Figure 2(a) and a picture of the apparatus is shown in Figure 2(b). A pure water system supplied ultra-pure water (18.2 MΩ) through an outlet filter of 0.2 μm. A high pressure reciprocating plunger pump pressurizes ultra-pure water to 7 MPa. The pressurized water is led through a final filter of 0.5 μm to a water jet nozzle which has six holes that are equally spaced with the same diameter of 0.54 mm. The nozzle is made of stainless steel that was hardened by martensitic transformation. We keep the nozzle in a dry condition after HHPR to prevent rust. A stainless steel pipe supports the nozzle horizontally and inserts it into the cavity. A drive system rotates the nozzle 60 degrees and moves it along the center of the cavity. An aspirator pump evacuates wasted water through another stainless pipe.

Rinsing Condition

The rinsing condition was determined from a study using our test cavity [4]. The rinsing area is cell and both iris regions only. Its span is 450 mm. The driving speed of the nozzle is 1 mm/s and the rotation speed is 6 degree/s. Total rinsing time is 15 minutes. Rinsing parameters are summarized in Table 2.

Table 2: HHPR Parameters

Water pressure	7 MPa
Nozzle	Martensitic stainless steel, ϕ0.54 mm in dia., 6 holes
Driving speed	1 mm/sec.
Rotation speed	6 degrees/sec.
Rinsing time	15 min.

Post HHPR Process

After the HHPR, cavity is evacuated for a few days by an oil-free scroll pump (pumping speed: 210 L/min) to dry up a lot of water drops inside the cavity and the outer conductor of the coupler. Final vacuum pressure is 1.2 kPa. After the evacuation the nitrogen gas is introduced into the cavity for re-assembling the coupler and end beam pipes. Turbo-molecular pump evacuates the re-assembled cavity to 2×10^{-4} Pa. Finally ion pumps evacuate it below 10^{-7} Pa. The cavity is moved from the assembly area to a high power test stand. We apply no baking after HHPR.

HIGH POWER TEST

The First High-Pressure-Rinsed Cavity

We applied the HHPR to our degraded cavity. This cavity leaked at indium sealed joints and significantly degraded after the repair of joints. The Q factors became 8×10^{8} with intense X-rays even at the cavity voltage of

1.3 MV. Particle contamination was suspected for this degradation.

The cavity was cooled down to 4.4 K and high-power tested at the test stand. Only four RF trips occurred before the cavity voltage reached 2 MV. No serious multipacting levels or quenches were observed. X-ray radiation was greatly improved at 1.3 MV. Maximum cavity voltage of 2.08 MV was achieved. The voltage was limited not by the cavity performance but by the radiation levels allowed at the test stand. We measured unloaded Q factors at several cavity voltages by a liquid helium evaporation method in a Helium vessel. Those Q factors are plotted in Figure 3(a) along with the degraded Q factors and Q factors before degradation. The Q factors successfully recovered near 1×10^9 at 2 MV.

This cavity was installed in the accelerator ring and replaced with another degraded cavity.

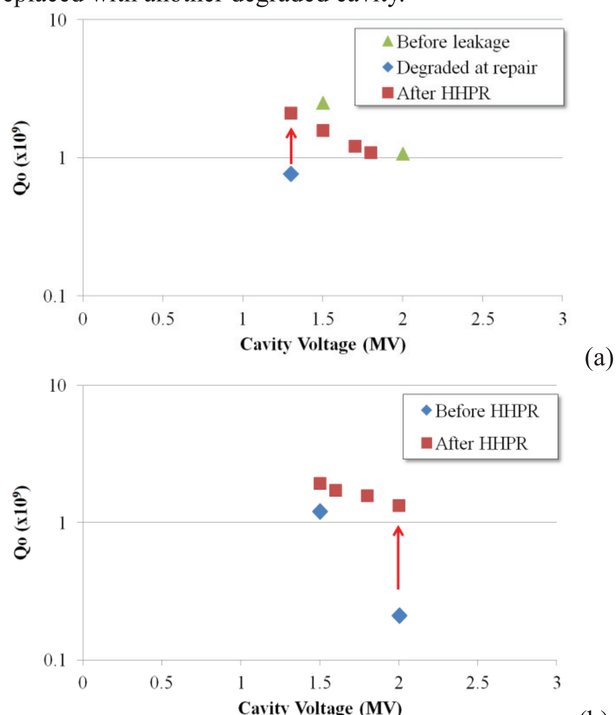


Figure 3: Qo factors before and after HHPR. (a) The first HHPR cavity, (b) The second HHPR cavity.

The Second High-Pressure-Rinsed Cavity

The second cavity degraded when a small amount of air was introduced into the cavity by the miss operation of a vacuum valve. The Q factors significantly degraded with intense X-rays around 2 MV. Particle contamination is a cause of degradation.

We applied the HHPR to this cavity with the same procedure as the first HHPR. After the HHPR, the high power test was conducted. Only one RF trip occurred before the voltage reached 2 MV. The maximum voltage achieved was 2.15 MV which was limited by the radiation level at the test stand. Q factors measured at this high power test are plotted in Figure 3(b) along with the degraded ones. Q factor at 2 MV drastically recovered above 1×10^9.

EFFECT OF H_2O CONTAMINATION

Baking cavities and couplers are necessary to suppress outgas and make the cavity operation stable. Our cavities are usually baked at 120 ^{0}C around its cell area after pure water rinsing at the electro-polishing. The coupler inner and outer conductors are also baked at around 100 ^{0}C before the installation to the cavity module. However, it is impossible to bake the cavity or coupler in the cryomodule after the HHPR. Although we have confirmed that the cavity performance does not change without baking from our study using a test cavity (Ref. 4), the effect of unbaked coupler to the cavity performance was not clear. We studied how H_2O contamination affects the coupler and cavity performance. We also studied desorption of the H_2O gas during the warm-up and at the ion pump baking.

Coupler Conditioning at Room Temperature

CW Conditioning Since our coupler has a coaxial structure, suppression of multipacting discharge is one of key issues for cavity operation. The coupler was conditioned before cooldown with fully reflected RF powers up to 300 kW. Multipacting levels are processed with increasing RF powers. Several interlocks cut the RF power before multipacting causes fatal damages on the coupler surface or its ceramic RF window. Interlocks were given by a metal covered ionization vacuum pressure gauge (MG), an electron probe to detect electrons near the ceramic and Pin-diode light sensors to detect arcing at the ceramic RF window and the door knob transition. The MG has an iridium alloy filament applicable near 1 Pa. Several thermo-couple temperature sensors were attached on the inner/outer conductor, the exterior of the ceramic window and a door knob transition.

Pulse Conditioning Input RF power is modulated in a short period of time with power increase of ~10% from its background RF power. Its time duration is 400-1000 μs and repetition rate is 50-100 Hz. Multipacting discharge begins and grows in this short period of power increase, but ends before the vacuum burst occurs. This short period multipacting improves surface conditions of the coupler.

Bias Conditioning The inner conductor of the cavity is electrically isolated from the outer conductor. Inner conductor is charged with DC bias voltage from the external power source. This voltage biasing effectively controls multipacting intensity and discharging site along the coupler [6]. It enables the conditioning to be safer and more effective than the usual DC conditioning. Electric voltage from 0 to +/- 2000 V was charged to the inner conductor during the bias conditioning.

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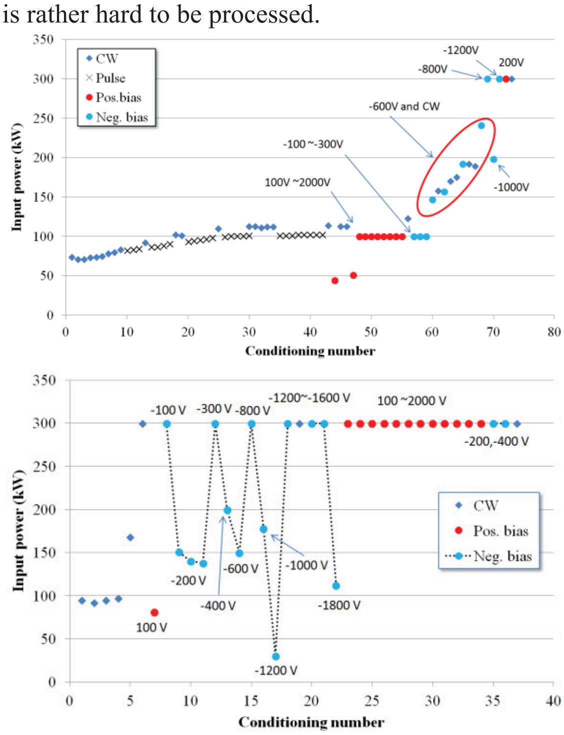
Coupler Conditioning after Horizontal HPR

In the CW conditioning of the first HHPR cavity, we observed many vacuum pressure bursts which come from multipacting discharge for input RF powers below 100 kW. We tried the pulse conditioning but the coupler was not effectively processed. Figure 4(a) shows a conditioning history in which input RF powers at the vacuum bursts are plotted in the order of conditioning number. No vacuum burst occurred when the RF power reached 300 kW. After several bursts in the pulse conditioning, we tried the bias conditioning and could increase RF power at the negative bias voltage of -600 V. We tried the CW conditioning several times after the bias conditioning at -600 V. We finally reached 300 kW at the bias voltage of -800 V. We omitted conditioning lower than -1400 V because we reached 300 kW in the CW mode. As our multipacting simulation for the bias condition shows, negative voltage conditioning causes multipacting at the outer conductor surface. The negative voltage of -600 to -800 V seems suitable for conditioning of the outer conductor after HHPR. Non-bias and low voltage positive bias conditioning has two-side multipacting levels between inner and outer conductors below the RF power of 100 kW. This type of multipacting is rather hard to be processed.



(a)

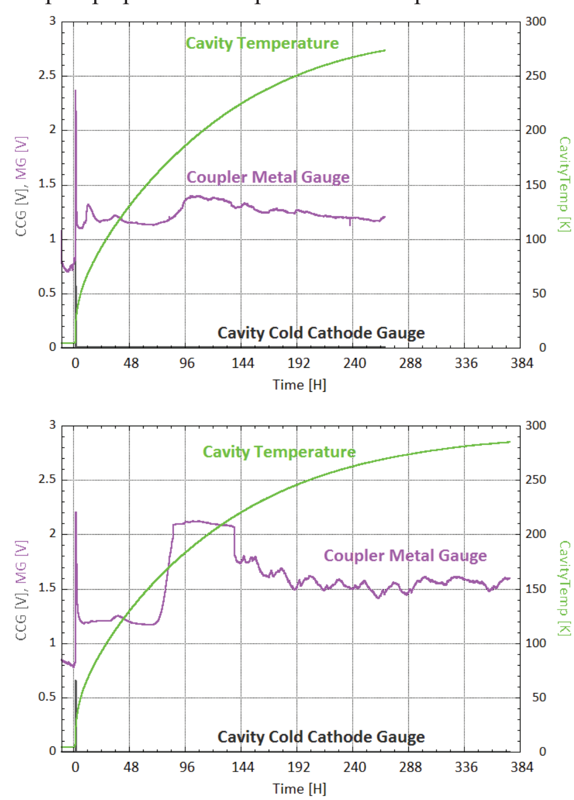
(b)

Figure 4: Coupler conditioning history. Input RF powers at the vacuum bursts are plotted in the order of conditioning number. No vacuum burst occurred when the RF power reached 300 kW. (a) The first HHPR cavity, (b) The second HHPR cavity.

We also observed vacuum pressure bursts at the coupler conditioning of the second HHPR cavity. We tried the bias conditioning with negative voltages soon after several vacuum bursts. The coupler was processed with negative biasing from -100 to -1800 V. Vacuum bursts occurred at several negative biasing points but once processed up to 300 kW, the coupler was quickly processed with positive bias voltages from 100 to 2000 V (Fig. 4(b)). We tried the negative bias conditioning at -200 and -400 V again and reached 300 kW without vacuum bursts. The negative voltage bias conditioning was effective for H_2O contaminated coupler surface.

Desorption Gas Analysis

Outgas of the cavity is one of the major issues because condensed gasses on the cavity surface trigger high voltage breakdown and therefore make the cavity operation unstable. We studied desorption gases during warm-up after the high power tests and at the baking of ion pumps prior to its operation for SuperKEKB.



(a)

(b)

Figure 5: Vacuum pressure during warm-up. (a) The first HHPR cavity, (b) The second HHPR cavity.

The cavity has two types of vacuum gauge. One is a cold cathode gauge (CCG) attached on the cavity's beam pipe and the other is the MG attached at the coupler near the ceramic RF window. Figure 5(a) shows vacuum pressures during the warm-up of the first HHPR cavity. The vacuum pressures increased at several cavity temperatures. Desorption gases are identified by their boiling temperatures. The MG detected H_2, CO, CO_2, and H_2O gases. The H_2 gas has the largest peak pressure of the order of 10^{-6} Pa while the other gases have one order of magnitude smaller one. The CCG detected H_2 gas only and other gases are below its detection limit. The H_2O gas did not significantly condense on the cavity surface.

On the other hand, as shown in Figure 5(b), a broad peak of the H_2O gas was observed by the MG during the warm-up of the second HHPR cavity. This peak is supposed to come from trapped H_2O on the coupler surface since the CCG does not show a significant pressure increase. The trapped H_2O did not cause serious multipacting discharge in the coupler. Warm-up and further evacuation will remove this trapped gas.

We analyzed outgas at baking of ion pumps of the first HHPR cavity in the accelerator ring prior to its operation for SuperKEKB. The ion pumps were baked with 200 W heaters and outgas was analyzed with a quadrupole mass spectrometer (QMS). Outgas increased as the temperature rises and soon began to decrease at 100 ^{0}C although the temperature is still rising. We detected H_2, He, CO, CO_2, H_2O and CH_4 gases as shown in Figure 6. The helium gas was introduced at the helium leakage from the helium vessel. Desorption of the H_2O gas is not large compared to the hydrogen gas.

Despite the cavity was treated with high pressure water jet and a lot of water drops remained in the cavity, oil-free pumping can remove H_2O sufficiently from the cavity surface.

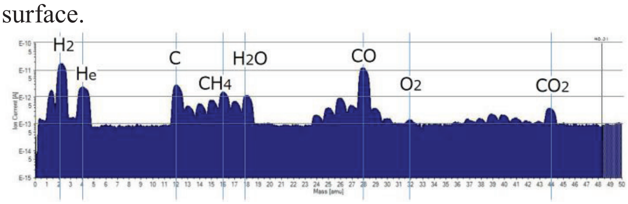


Figure 6: QMS analysis of desorption gases at ion pump baking.

FUTURE DEVELOPMENTS

We have established the performance recovery of degraded cavities due to particle contamination by the HHPR. To apply this method, we have to move the degraded cavity to our assembly area. Moving the cavity out of the tunnel takes a few days since we have to open the massive radiation concrete shields. Prompt performance recovery will be expected if we apply the HHPR to a degraded cavity in the tunnel. This method will greatly contribute for shortening the required time for recovery. Furthermore, the risk of vacuum leakage and particle contamination will be avoided if we can conduct the HHPR with the coaxial coupler, because we do not need to open the coupler port for installing the inner conductor. For those improvements, we need:

- Clean environment for assembling end beam pipes.
- Ultra-pure water system in the tunnel.
- R&D for HPR on the coupler inner conductor.

The H_2O contamination on the coupler surface is not severe because we could process multipacting by the bias conditioning. To achieve the horizontal HPR with the coupler, we need to confirm that the HPR has no effect on its performance. We are planning to conduct high power tests for a wet coupler without baking at our coupler test stand. R&D continues for further developments on the HHPR.

SUMMARY

We have established horizontal HPR that can be applied directly to the cavity in a cryomodule for performance recovery. This method save a lot of time and costs, and avoid the risk of leakage at indium sealed joints. Two degraded cavities have recovered and their Q factors became around 1×10^9 at 2 MV. No significant multipacting levels or quenches were observed. A coaxial coupler structure seems sensitive for H_2O contamination but can be effectively conditioned with a voltage bias conditioning. Desorption of H_2O gas during warm-up and at baking of ion pumps was measured. It was not significant compared to the Hydrogen gas. The second HHPR cavity has a broad peak of H_2O desorption from the coupler surface. It has no serious effect on its performance. We are planning to apply the HHPR to degraded cavities in the tunnel. This method will greatly reduce the required time and costs.

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