

MANAGEMENT FOR THE LONG-TERM RELIABILITY OF THE DIAMOND SUPERCONDUCTING RF CAVITIES

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Abstract

Diamond started operation with users in January 2007 and the Diamond storage ring superconducting RF (SRF) cavities were initially the largest single contributor to unplanned beam trips. Extensive effort has been dedicated to understand and improve the long-term stability of the SRF cavities. Our experience shows that the long-term stability of superconducting RF cavities relies heavily on the surface conditions. Gases accumulate on the cold surfaces with time due to its huge cryo-pumping capacity. We believe the accumulated gases are the cause of fast vacuum trips during operation. In Diamond, we have developed a systematic approach to control the long-term stability of the SRF cavities. We will discuss here our approach and also present the future work that should be completed.

INTRODUCTION

The Diamond storage ring (SR) RF system [1] consists of two 500 MHz Cornell-type superconducting single cell cavities powered by two high power, 300 kW IOT based amplifiers. A third amplifier is available for high power test of IOTs, RF windows and SRF cavities. Tripping of the RF system is the biggest single contributor to Diamond beam dumps. Cavity trips used to constitute 75% of all RF trips. The long-term reliability of the cavities is of vital importance to the RF system and Diamond as a whole.

A lot of effort, including improving our data acquisition system, numerical modelling and detailed fault analysis, was dedicated to understanding the mechanism behind the trips. The most frequent cavity trip was identified as the fast vacuum trip, which used to constitute 80% of all cavity trips. It took us a long time to develop a set of systematic measures to control this kind of trip. As a result, the long-term reliability of the cavities improved significantly. In 2012, there were 13 cavity trips in total compared to the 85 trips in 2009. Cavity trips now constituted around one third of all RF trips. This was achieved at the same time with the increase of beam current from 250mA to 300mA in top-up mode.

CAVITY TRIPS

In Diamond, the cavity trips are classified according to their signatures [2]. They are mainly classified into fast cavity vacuum trips, trips on the RF window, cavity quench, cavity arc and other trips.

Fast vacuum trips can be traced to the early

commissioning of CESR SRF cavities at Cornell. They have also been observed in many other labs. The trip rate is found to increase with time and eventually they limit the maximum cavity voltage when the cavity is left untreated. We can identify three signatures of this kind of trip.

- The cavity field collapses within several microseconds.
- There is always a spike on the e- pickup before the trip.
- In the vacuum post-mortem, it can be observed that there are vacuum spikes on every gauge around the cavity which tripped. Gas can travel to and beyond the other cavity. Gas can't travel through the cold waveguide bend into the waveguide of the other cavity.

This can be clearly seen in the vacuum post-mortem and RF post-mortem plot in Figure 1.

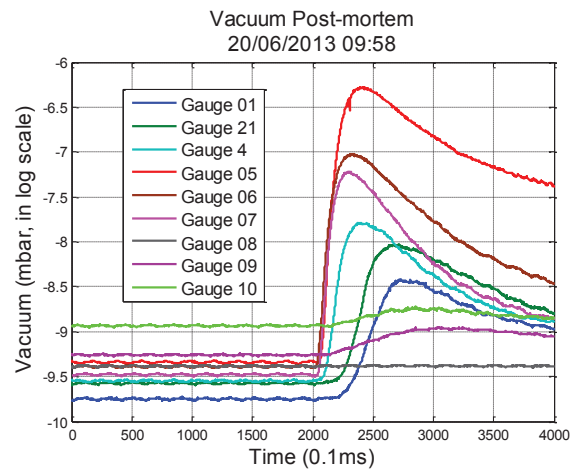


Figure 1: Vacuum post-mortem of fast vacuum trip.

A trip on the RF window only shows vacuum spikes on the pump-out box, as shown in Figure 2. The decay curve of the cavity field is consistent with a high Q cavity. This is possibly related to the multipacting band in the reduced-height waveguide from the RF window to the input coupler of the SRF cavity. Like the fast vacuum trips, the trip rate on RF window also increases with time when left untreated. The available power level will be limited by this kind of trip.

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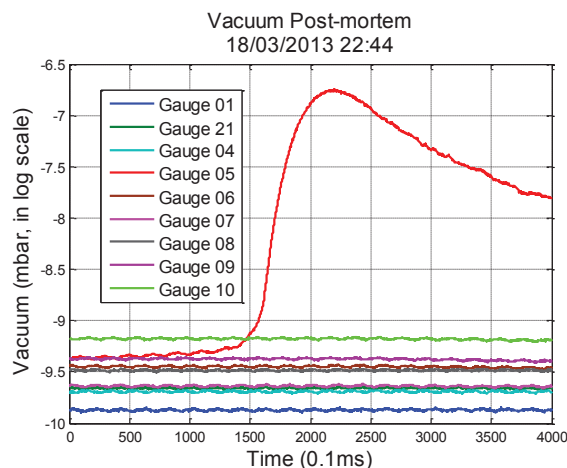


Figure 2: Vacuum post-mortem of trip on RF window

During the two kinds of trip mentioned above, no excessive helium gas flow or cavity temperature variation can be observed. These two kinds of trip show common characteristics, they increase in frequency with time if preventative action is not taken and vacuum events accompany both of them.

GAS EVOLUTION ON COLD SRF SURFACES

For electron storage rings, the dominating dynamic pressure is due to photon-induced desorption from intense synchrotron radiation. In an RF straight, HOM heating is the major source of outgassing, as the synchrotron radiation will not shine on any surface by design. In Diamond, it will usually take around 3 days of normal operation with beam for the vacuum along the RF straight to stabilize at a higher level. When the filling pattern or the beam current changes, the stable vacuum level will also change as HOM heating is proportional to the square of bunch charge.

The RF ceramic window has been considered as the major source of gas. It has long been known that strong RF fields can cause gas desorption. Vacuum pressure can be seen to increase with RF power in the waveguide. This is stable outgassing outside the multipacting bands. Peeled copper plating was also found during cavity 2 repair. This may be caused by excessive heating by multipacting electrons.

Originally the beam pipes in RF straight, including those inside the SRF module, were not baked before installation. Those unbaked components tend to generate heavier gas load.

The cold surface of a CESR SRF cavity is over 3 m² including Nb cavity, the cold helium gas cooled HEX, and LN₂ cooled RBT/FBT transition and waveguide elbow. The cold waveguide section alone has an estimated cryo-pumping speed of 600 l/s [3, 4]. The SRF cavities become very efficient cryo-pumps. The diameter of the beam pipes in the RF straight is 240 mm. The conductance to the SRF cavities is much larger than the conductance to the ion pumps. As a result, most of the

gases generated due to the beam and RF field will be condensed onto the cavity surfaces.

Many gas species, including He, H₂, H₂O, CO/N₂, CO₂ can be observed during warming-up of the SRF cavity. This is shown in Figure 3. H₂ has the highest peak. CO/N₂ is the second highest peak. Water comes as the third. The integrated data show these three gas species constitute the major part of the total outgas. Helium is also present. Its presence sometimes instigates worries about a possible leak from the helium can to cavity UHV.

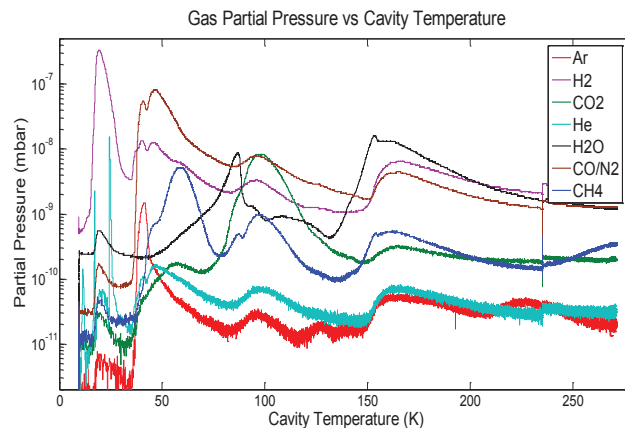


Figure 3: Gas Species found during a Warm-up.

THE ROOT CAUSE OF FAST VACUUM TRIP AND TRIP ON RF WINDOW

Field emission is present in CESR SRF cavities due to their large surface area. With the accumulation of gas on the SRF surfaces, processed field emission sites can be reactivated. From 1.7 MV onwards, outgassing spikes inside the cavities, accompanied by sharp radiation increase, are observed every week during CW (continuous wave) test. Sometimes the cavities will eventually trip on a sharp vacuum burst.

Multipacting bands are present in the reduced height waveguide. Absorption of gas can enhance secondary electron yield by a factor of 2 or higher [5]. So processed multipacting bands can reappear. Cavity 2 and cavity 3 all experienced recurrence of multipacting at around 120 kW after a period of operation. Outgassing points were found when the cavities were tuned off resonance.

As the gas can't reach vacuum gauges up and down stream of the cavity, trips on the RF window are most likely caused by the re-activation of multipacting bands in the thermal transition area before the niobium waveguide bend. In the fast vacuum trips, electron activity was seen on the pickup in the waveguide just under the coupler tongue. This suggests multipacting in this area. The released ions and electrons must travel very fast to trigger an avalanche of the accumulated gas on the cavity surface, thus generate enough electrons and ions to dissipate the stored energy in the cavity in several microseconds.

The above analysis leads to our belief that changing of the surface property due to the condensed gas is the root

cause of those two kinds of trips. The evolution of gas on the cold cavity surface has the dominant impact on the long-term reliability of SRF cavities.

This problem was attacked in a systematic way by improving vacuum pumping to reduce the gas accumulation rate, regular warm-up and partial warm-up in order to get rid of the accumulated gas and high power pulse conditioning to remove gas from sensitive places and reduce the secondary electron yield of the surface.

VACUUM CONFIGURATION IMPROVEMENT

The RF straight used to rely on conventional ion pumps. Their pumping speed for CO/N₂ and water remains high, but the pumping speed of hydrogen decreases rapidly when the pressure reaches 10⁻⁸ mbar. More efficient pumps for hydrogen need to be installed to compete with the cryo-pumping of the SRF cavities. TSP (Titanium sublimation pumps) and NEG (Non-evaporable getters) are both excellent pumps for hydrogen and they are widely used in accelerators. TSP depends on the evaporated titanium surface to capture hydrogen. Its pumping speed is defined by the surface area. Its capacity can be renewed after titanium is sublimed on the pumping surface. The pumping surface can be regenerated in a short time. This makes it very convenient to be accommodated into the time slot of MD (machine development) time. The NEG pump has even higher pumping speed and capacity, but its regeneration takes a much longer time. Both TSP and NEG are also very good at pumping CO/N₂ and water.

The SRF modules came with a TSP cartridge installed, but there was no isolation valve between the ion pump with TSP cartridge and the cavity UHV. Those TSP pumps were never fired because of the danger of contamination of the cavities. In June 2010, ion pumps with TSP cartridge were installed during cavity 3 installation. They can be isolated from the cavity UHV by closing the gate valves on the cavities. From 2011, TSPs were fired regularly during MD time. Two ion pumps with NEG cartridge were installed on cavity 2 pump out box during repair. Cavity 2 was installed in November 2011 to replace the damaged cavity 1. We took this opportunity to upgrade the vacuum pumping in the RF straight. Figure 4(a) shows the vacuum configuration before this upgrade. Figure 4(b) shows the new vacuum configuration. After the upgrade, we have a combined pumping system consisting of ion pumps, TSP and NEG pumps. The cavity 1 makeup piece and two intermediate sections were also baked before installation. Table 1 shows the improvement of vacuum after we started firing TSP pumps in 2011 and the upgrade in November 2011. Note that cavity 1 and cavity 3 were installed before November 2011. Cavity 2 and cavity 3 have been in service since November 2011. The high readings of gauge 10 is due to the excessive heating of the BPM buttons in the spool piece.

TSPs are fired every week in MD time. The NEG pumps are re-generated during every shutdown.

WARM-UP AND PARTIAL WARM-UP

The cavities are fully warmed up to room temperature every shut down. The RF windows are baked to 120 °C and held for 3 days. The cavities are also partially warmed up to 50 K in every run. The partial warm up frequency depends on the deposition rate of the gas. This depends on the out gassing rate, which in turn depends on the beam current, the filling pattern and the RF power level. Some signatures can be observed during the conditioning of the cavities. In the early days of the commissioning of the cavities, urgent partial warm-up sometimes maybe needed. The cavities need to be conditioned afterwards as the gas distribution is changed totally after the thermal cycle. Some gas will lodge on sensitive areas.

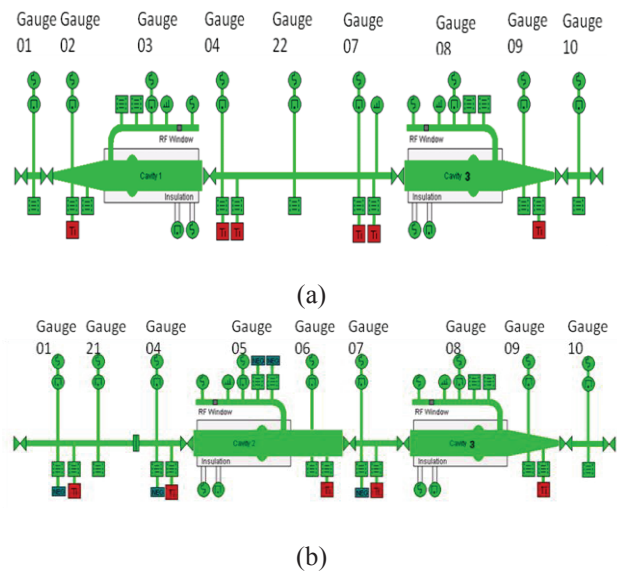


Figure 4: Vacuum Upgrade (a) before (b) after.

CAVITY CONDITIONING

During cavity conditioning, the cavities are tested to 2.1 MV CW first. This is used as a benchmark to check the cavity condition. Outgassing peaks, radiation level and Venturi differential pressure can be checked and compared with earlier data. For example, cavity 3 recently developed trips on the Venturi differential pressure interlock. This was traced to insufficient liquid nitrogen cooling on the FBT and RBT side.

High power pulsed conditioning is conducted every week during MD time. The cavities are conditioned using a 2.5 MV peak cavity voltage, 10% duty cycle (10 ms/100 ms) pulse.

Pulse conditioning with the cavity off resonance is also done every week. For the heavily over coupled cavity with coupling factor β , the impedance of the cavity appears to the waveguide as $\frac{Z_c}{n^2} = \beta Z_0$, which is much larger than the waveguide impedance. When the detune

angle is scanned, the standing wave pattern will shift accordingly. In this way, the waveguide is checked to find sensitive points. After an outgassing point is found, the detune angle is kept there until the outgassing stops or the level is very close to the normal level.

Table 1: Improvement of Vacuum after Upgrade
(Unit: mbar)

Gauge No.	Before TSP Firing	After TSP Firing	After NEG Installation
1	9×10^{-10}	7.1×10^{-10}	2×10^{-10}
2	1.0×10^{-9}	5.8×10^{-10}	N. A.
21	N. A.	N. A.	2.6×10^{-10}
3	1.2×10^{-9}	6.9×10^{-10}	N. A.
4	1.0×10^{-9}	3.5×10^{-10}	2.2×10^{-10}
22	1.1×10^{-9}	6.3×10^{-10}	N. A.
5	N. A.	N. A.	4.8×10^{-10}
6	N. A.	N. A.	4.2×10^{-10}
7	9.8×10^{-10}	3.6×10^{-10}	3.3×10^{-10}
8	9.1×10^{-10}	6×10^{-10}	4.7×10^{-10}
9	1.1×10^{-9}	6.6×10^{-10}	5.8×10^{-10}
10	1.2×10^{-9}	9.1×10^{-10}	1.5×10^{-9}

FUTURE WORK

Warm-up and partial warm-up needs to be planned carefully. It is desirable to minimize the number of thermal cycles as it is not known how many cycles the SRF modules can endure. This requires the knowledge of exact signature signals to predict when the cavities will need a partial warm-up or full warm up. We have done some work but no definite result has been reached.

The vacuum level on the pump out box tends to fluctuate much more than other vacuum readings. This can be traced to the fluctuation of the temperature of the LN2 cooled waveguide section. This means that the temperature profile along the waveguide keeps changing. It may possibly trigger vacuum events. Further experiments will be carried out to stabilize it.

All the cavities still suffer from probe blips. As a result we can only operate the LLRF with relatively small gain.

SUMMARY

We have developed a set of measures to control the long term reliability of the SRF cavities. This results in a big improvement in cavity MTBF. The cavity trips are now under effective control.

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