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OVERVIEW OF SUPERCONDUCTING RF CAVITY RELIABILITY AT DIAMOND LIGHT SOURCE

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Abstract

Diamond Light Source has been providing beam for users since January 2007. The electron beam in the storage ring is normally driven by two superconducting CESR-B cavities, with two similar cavities available as spares. Day-to-day reliability of the cavities, measured by storage ring MTBF, has improved enormously over the years. A full analysis of how this improvement has been achieved is given, with particular attention paid to cavity voltage and vacuum pressure management, and the scheduling and procedure of cavity conditioning. The benefits and risks of full and partial warm-ups of the cavities are discussed, and details and impacts of cavity failure and repair are presented.

CAVITY RELIABILITY

A schematic view of the CESR-B cavity used in the Diamond storage ring is shown in Fig. 1.The superconducting niobium cavity is powered through a waveguide coupler. The window is below the cavity, and the waveguide is maintainned at UHV by ion pumps on the pump-out box. Further ion pumps are located on the tapers upstream and downstream of the cavities.

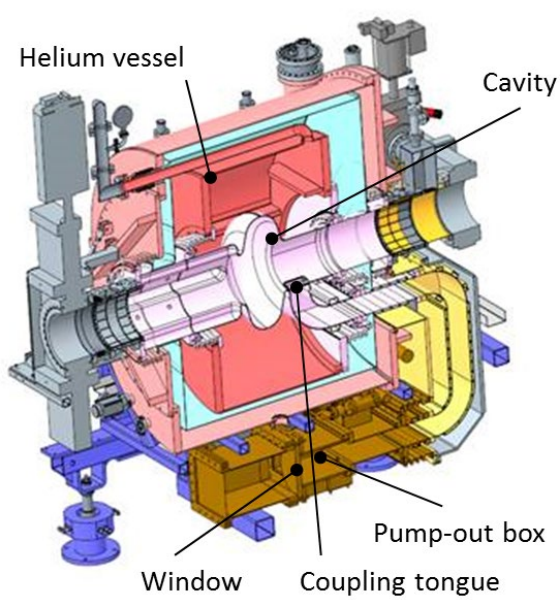

Figure 1: CESR-B cavity and cryostat.

The initial reliability of the RF cavities was poor, with frequent cavity trips leading to many beam loss events over the first four years [1], as illustrated in Fig. 2. Significant improvements in reliability have been achieved since 2011 by weekly cavity RF pulsed conditioning, regular warming-up of the cavities and by reducing cavity voltage [2].

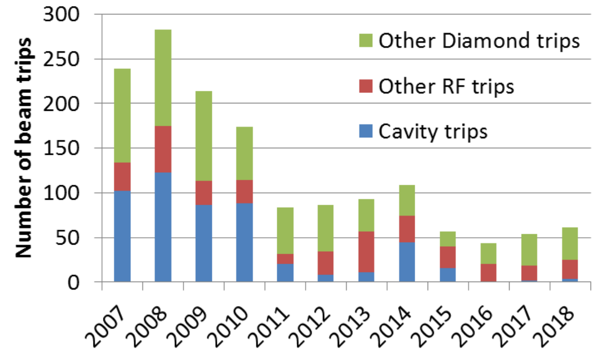

Figure 2: SR RF beam trips since 2007.

This preventative maintenance schedule has led to continual gains in RF MTBF, shown in Fig. 3, with the majority of RF faults in recent years occurring in the high power amplifiers.

Figure 3: 90-day rolling MTBF for SR RF.

There remains however a risk of prolonged downtime and reduced beam current resulting from a cavity failure. Failure of an operating cavity results in an extended loss of beam time as the failed module must be replaced with a spare. Furthermore, the repair can be slow and expensive.

DLS possesses four cavities, up to three of which can be installed in the RF straight at any one time. Figure 4 shows a timeline of the cavities in the three available positions, with each cavity represented by a different colour. In this paper the three available positions are indicated as 1, 2 and 3, and the four cavities are called A, B, C and D; coloured red, blue, green and purple respectively in Fig. 4. The current record in this figure also shows the gradual ramp-up of beam current following the installation of a new cavity in 2010 and to a lesser degree in 2015.

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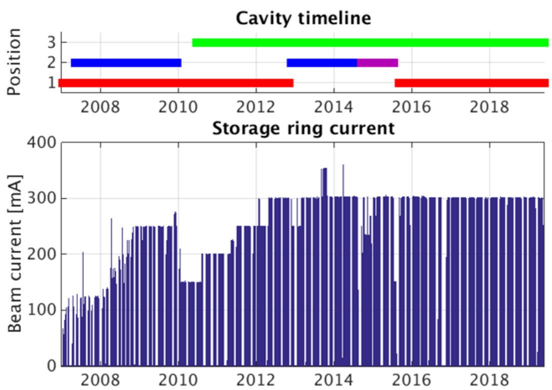

Figure 4: Storage ring current (below) and arrangement of cavities in RF straight (above).

There have been four cavity failures at Diamond: details are given in Table 1. Cavity failures to date have been leaks to critical volumes, either at metal seals or at the waveguide window.

Table 1: Cavity Failures

Cavity	Failure date	Detail
A	None	
B	2009, 2014	UHV leak
C	2006	Insulation vacuum leak
D	2015	Window failure

Warming the cavity up to room temperature imposes considerable mechanical stress on the cavity and increases the danger of leaks, particularly at the indium seals in the UHV assembly. RF pulsed conditioning is also not risk free as it involves the generation of high electric fields at the window. In order to lessen the risk of cavity failure it would be beneficial to minimise the number of cavity warm-ups and pulsed conditioning sessions, and so in recent years the frequency of these events has been gradually reduced. This paper discusses cavity reliability at Diamond, and summarises the recent investigation of the minimisation of warm-ups and RF conditioning.

CAVITY VACUUM TRIP DETAILS

There have been many operational issues identified for the superconducting cavity, including problems with flow meters, and tuner drive, "probe blips" and their interaction with the LLRF and various cryogenic issues [2]. The most frequent problem encountered in the early days and with the new cavity installed in 2014 was that of cavity "fast vacuum trips", in which an event in the cavity is recorded as a pressure burst measured on the UHV gauges. This problem was previously seen at Cornell and was identified as a high voltage arc [3]. At Diamond there are two different fault modes that display a spike in vacuum gauges: the first characterised by a pressure pulse at the pump-out box, and the second with multiple pressure bursts along the RF straight. Examples of both are shown in Fig. 5, with the locations of most intense gauge pulses indicated.

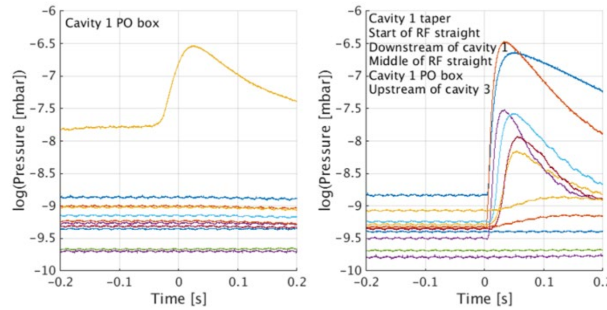

Figure 5: Cavity faults characterised by vacuum spikes at the pump-out box (left) and around the cavity (right). Gauges recording sharp gas pulses are listed in each figure.

The overwhelming majority of vacuum trips during user time are identified as cavity fast vacuum trips of the sort shown on the right side of Fig. 5. Further details of such a trip are shown in Fig. 6. The first indication of an event is a spike in an electron pickup below the coupling tongue, at which time the reflected power begins to rise. The pickup signal then falls, before rising to a much higher level. Reflected power continues to rise, eventually tripping the amplifier, and then the cavity field collapses in an irregular manner much more quickly than would be expected from the cavity filling time. The pressure pulse follows and the beam is lost. A possible explanation for such behaviour would be the formation of an arc in the vicinity of the coupler, initially generating a shower of free electrons before forming an intense attachment point on the wall and destroying the coupling of the cavity-amplifier system.

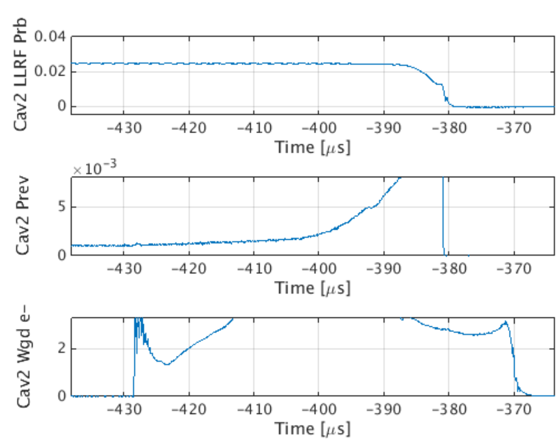

Figure 6: Cavity field (top), reflected power (middle) and waveguide pickup current (bottom).

All cavities suffer from vacuum trips if the voltage is increased beyond a safe limit, which differs for each of the four Diamond cavities and is in the range of 0.8 MV to 1.4 MV. The fact that similar cavities can have greatly different safe operating voltages suggests that the limitation arises in the manufacturing and assembly of the devices. Safe operating levels have been established by reducing cavity voltage until the vacuum trips vanish, as

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shown in Fig. 7 for cavity A in the first years of Diamond operation.

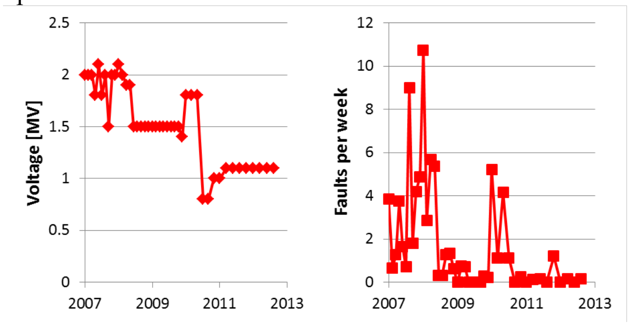

Figure 7: Cavity voltage (left) and trip rate (right) during the first operating period of cavity A.

WARM-UPS AND CONDITIONING

The ability to maintain a high electric field in a cavity depends on several parameters, including the surface finish of the walls, the UHV vacuum level and also the accumulation of adsorbed gas on the walls [4]. Gas can be cleared from the walls by warming the cavity up to room temperature and pumping away released gas. This risky process has been carried out many times for the Diamond cavities, but there is no strong evidence to justify this procedure. Figure 8 shows that for the sixteen shutdowns in which the cavities were fully warmed up, the reliability in the subsequent run, measured by the number of trips per week, was on average no better than the trip rate in the preceding run. Similarly, for the forty shutdowns in which the cavity was not warmed up, the reliability was no worse. Benefits of a full warm-up in a shutdown do not carry through the next run and so full warm-ups have been discontinued; the cavities are kept cold as far as possible, only warming up to room temperature for essential maintenance of the cryogenic plant.

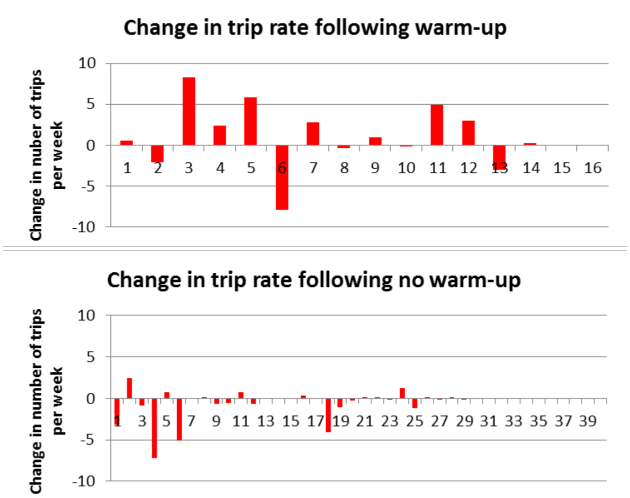

Figure 8: Change in weekly trip rates from run to run with warm-up in the intervening shutdown (above) and without warm-up in the intervening shutdown (below).

Warming the cavities up to approximately 50 K in a partial warm-up places less stress on the structure but can still be used to release light gases from the cavity walls. Figure 9 shows partial pressures of gases measured during a partial warm up: hydrogen and helium are released below 30 K and heavier gases above this temperature. The RGA recording helium partial pressure automatically rescales around 10^{-8} mbar and so the initial spike in helium pressure is in fact greater than shown in the figure.

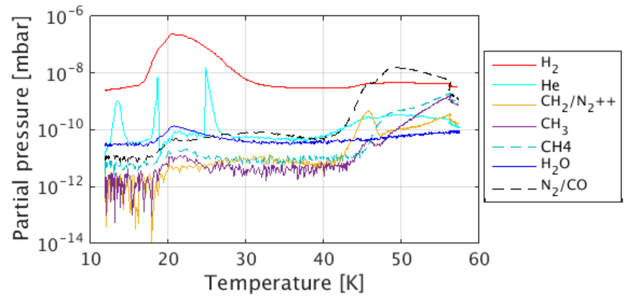

Figure 9: Partial pressures of common gases during partial warm-up beyond 50 K.

The beneficial short-term effect of a partial warm-up is shown in Fig. 10, recorded during operation with cavity D in 2015. At this time, partial warm-ups were carried out weekly. Each partial warm-up regenerates the cryopumping surfaces of the cavities and is evident in the figure as a sharp drop in pressures of both cavities. As the vacuum degrades over the week, the cavity vacuum trip events return and a partial warm-up is required again. The cycle of multiple trips and warm-ups was eventually broken in the last week of February by reducing the operating voltage from 1.0 MV to 0.8 MV, at which level the trips do not occur over the week. Tests later that year tests showed that the cavity did not trip even when a partial warm-up was skipped.

It is not clear from Fig. 10 whether the benefit of a partial warm-up arises from the clearance of material from the walls or from the improved vacuum conditions within the cavity.

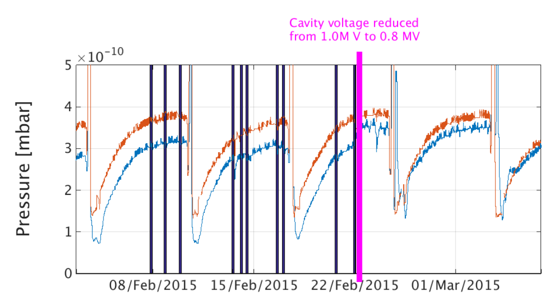

Figure 10: Pressures in cavity taper (red) and pump-out box (blue) before and after voltage reduction. Cavity trip events are shown in black.

The cavities have routinely been pulse conditioned with a train of high power RF pulses with a 10% duty cycle. In this procedure, the standing wave can be swept along the length of the waveguide by detuning the cavity. A calculation of the standing wave in the cavity and along the waveguide is shown in Fig. 11, together with a calculation of fields at the window for different detune

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angles [5]. The lower plot shows that the field at the window is strongly asymmetric about the zero detune.

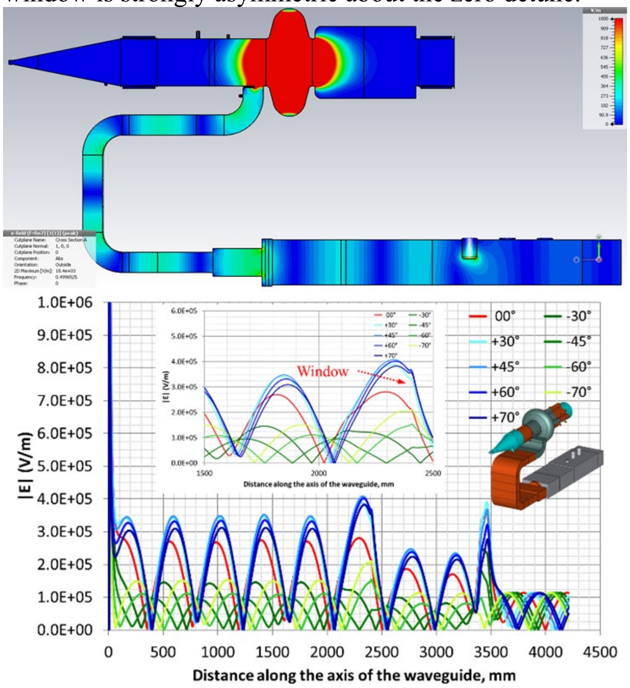

Figure 11: Standing wave during cavity conditioning (above) and calculated field in waveguide and window for detuned cavity (below).

The strong field at the window causes outgassing, and so the pressure measured at the pump-out box can be used as a gauge of field strength there. Pressures recorded for the present two operating cavities are given in Fig. 12, showing a strong asymmetry with phase in both. The cavities in positions 1 and 3 are operated at different coupling values and with different three-stub tuner positions because of their different operating voltages and so the peaks lie on different sides of the zero detune point.

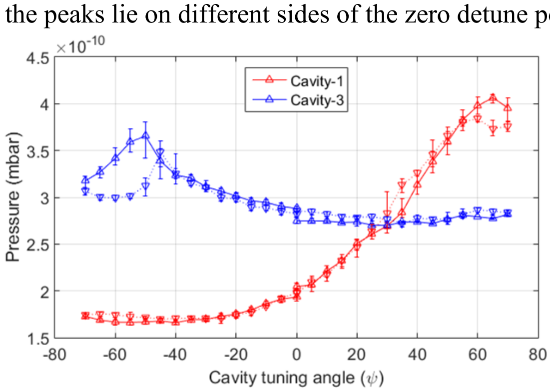

Figure 12: Pump-out box pressure with cavity detune.

The conditioning procedure has been standardised and the amount of material released can be calculated by integrating the measured pressure during conditioning with respect to time. The integral of pressure for every conditioning session of cavity D is given in Fig. 13. From March 2015 onwards the smooth outgas of Fig. 12 was overwhelmed by spikes recorded at the pump-out box gauge caused by events at the window. The extra material generated during conditioning from March onwards was not evident as a change in base UHV pressure during operation and had no effect on the rate of vacuum trips, which had been reduced to zero by the voltage reduction in February. Instead, it appears that the activity arose from degradation of the window assembly itself, eventually leading to failure of the window seal, as shown in the photograph in Fig. 13.

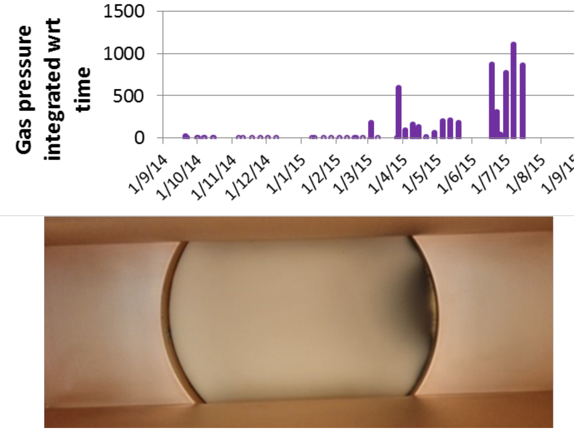

Figure 13: Gas evolved during pulsed conditioning prior to window failure (above) and failed window (below).

REDUCTION IN FREQUENCY OF WARM-UPS AND CONDITIONING

As warming up and conditioning cavities may carry risk, these interventions have been gradually reduced in recent years. Figure 14 shows all warm-ups since the installation of cavity D in 2014, with the integral of pressure with respect to time plotted for each warm-up representing the amount of gas released. The upper plot over time (for cavity C) shows the increasing time between warm-ups, and shows that full warm-ups release more gas than partial warm-ups. Results for the three cavities below show that there is gradual accumulation of material over short periods (seen in the centre plot), but beyond 20 to 30 days there is little, if any, correlation between warm-up frequency and evolved gas. Most importantly, the vacuum trips that had been eliminated by reduction of operating voltage did not return, even when the period between warm-ups reached a year.

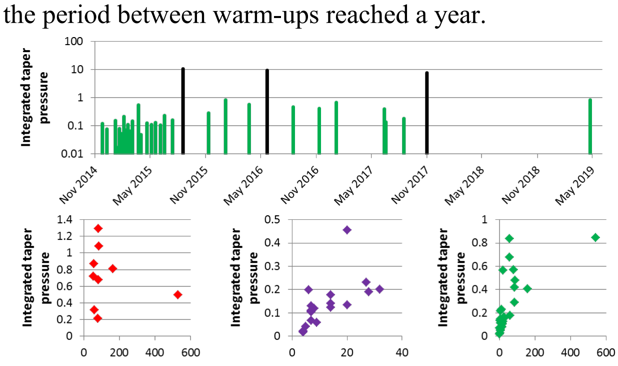

Figure 14: Full (black) and partial (green) warmups since 2014 (above) and gas evolved in cavities A (red), D (purple) and C (green) (below).

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A similar test for reduction of conditioning frequency has been carried out from the beginning of 2018 to date. In the plots given in Fig. 15 it can be seen that the UHV pressures in the two cavities reach an equilibrium level after approximately a week. This is also evident in Fig. 10. The state of the cavities can also be judged by the dose rate measurement from a radiation monitor placed downstream of the cavities, data from which is shown in the lower plot of Fig. 15. The dose rate increases over the week, and whereas the cavity UHV is helped by one day a week of generally low-current machine development operation the dose rate continues to rise until the conditioning is carried out again. The increase in dose rate from the radiation monitor decreases with time, and appears to be approaching an equilibrium value after several weeks, similar to the accumulated gas timescale of Fig. 14.

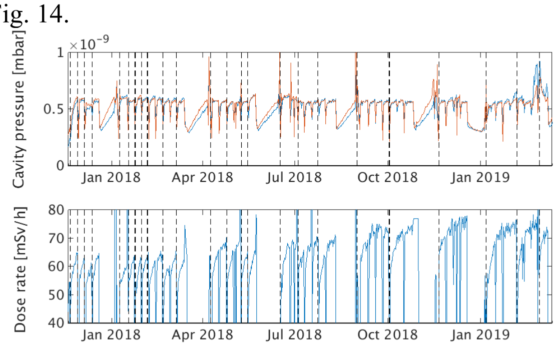

Figure 15: Pressures in two cavities (above) and radiation monitor reading (below). Conditioning periods are indicated by dotted lines.

Cavity vacuum trips did not return, even with three week intervals between conditioning. It is not clear whether pulsed RF conditioning can be eliminated entirely, as the test had to be curtailed in early 2019 following an amplifier fault. This fault resulted in the RF system running in an unexpected configuration, leading to a loss of control of vacuum pressure along the RF straight. The pressure rose to three times its normal level and vacuum trips in both pump-out box and at the cavity returned, as shown in Fig. 16.

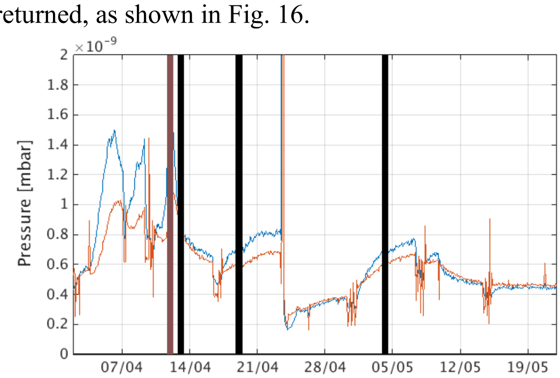

Figure 16: Cavity pressures in 2019 run 2 in cavity A in position 1 (blue) and cavity C in position 2 (red) with vacuum events in pump-out box (brown) and cavity (black) indicated.

Multiple conditioning sessions and a partial warm-up on the 23rd of April were not able to stop the trips, and reliable operation only returned when the UHV level returned to normal.

One unexpected effect of a year without a warm-up of any sort is illustrated in Fig. 17. The top plot shows the beam current over the two runs so far this year and the bottom plot shows the pressure in the insulation vacuum of one cavity. Insulation vacuum pressure was seen to rise to a high level over the run, and then recover in the shutdown. This behaviour was cleared by the partial warm-up of the 23rd of April.

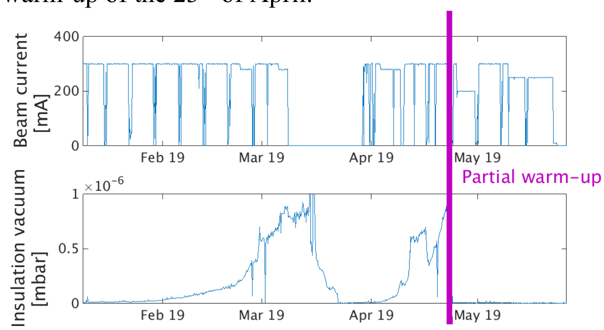

Figure 17: Beam current (above) showing user runs in 2019 and cavity insulation vacuum (below). The partial warmup is indicated.

CONCLUSIONS

Diamond's superconducting storage ring cavities experience the vacuum arcs reported since the early days of the CESR-B cavities at Cornell, but the frequency of these arcs can be controlled, and largely eliminated, by reducing the cavity voltage sufficiently, as long as the cavity UHV pressure is maintained at a good level. Warm-ups of the cavity to room temperature carry considerable risk and provide no apparent long-term benefit, and so can be eliminated completely without reduction in operational reliability. Partial warm-ups to 50 K are less hazardous to the cavity and provide a significant short-term improvement in reliability. Once the cavity fast vacuum trips were under control an elapsed time of one year between partial warm-ups did not result in the return of the trips, although a partial warm-up was then needed to recover the cryostat insulation vacuum. Weekly pulsed RF conditioning is not required to maintain fault-free operation, but no firm conclusion can yet be drawn regarding the maximum period between conditioning sessions. The study is continuing.

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