OPERATIONAL EXPERIENCE OF DIAMOND'S SUPERCONDUCTING CAVITIES

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Abstract

The Diamond Light Source has been operating with users since January 2007. From the start, the cavities suffered with a high number of trips, but recently significant improvements in reliability have been achieved. We report here operational data, initially with a single cavity, and later with two installed cavities. We describe our observations during cavity conditioning and present a variety of diagnostics which were installed to identify the origin of the trips.

INTRODUCTION

The Diamond Light Source is a 3 GeV synchrotron which started operation with users in 2007 [1,2]. Since the start of operation additional insertion devices have been installed and the beam current has been steadily increasing, whilst the Storage Ring RF systems have been adjusted to deliver more power and to make up for increasing energy loss per turn. The Diamond storage ring RF system [3,4] consists of two high power, 300 kW IOT based amplifiers each connected to a 500 MHz Cornell-type superconducting single cell cavity. A third system is available for testing and as a future upgrade.

OPERATIONAL OBSERVATIONS

Since the original start date of January 2007, the number of user hours has been increased from 3160 in 2007 to 4656 hrs in 2009 with further increases planned. Additionally, the RF systems must be available for machine development and start-up days; a total of 5700 hrs in 2009. The early operation was with a single superconducting cavity and a beam current of 125 mA, but since the middle of 2008, the second cavity was brought into routine operation. Early operation suffered from a variety of RF faults but the number of beam losses was strongly dominated by trips associated with the superconducting cavities. In 2007, operating only Cavity 1, the mean time between RF failures (MTBF) where a failure includes any trip resulting in a loss of beam, was just 20 hrs. During the first half of 2008 the MTBF dropped slightly to ~17 hrs, but meanwhile 2008 saw a steady increase in beam current and power demand. From the middle of 2008 Cavity 2 was brought into operation, and for the rest of 2008 the MTBF on System 1 immediately increased to 100 hrs, as the power demand was shared between Systems 1 and 2. System 1 includes the full RF chain associated with cavity 1. From then on, the total MTBF of the two systems together increased to 28 hrs, with the MTBF being dominated by trips associated with Cavity 2. During this period, the beam current was progressively increased to 250 mA and from the end of October 2008 Diamond started to operate in 'Top up' mode. We currently operate with a maximum loss per turn of 1.35 MeV subject to ID gaps and the field in the wigglers. The first run in 2009 was poor with the RF system reliability severely compromised by the high number of Cavity 2 trips, but from then on the situation started to improve. A shift in power balance between the two cavities, combined with extensive high power pulse conditioning with long pulses, started to improve the reliability of Cavity 2. Although the MTBF of the complete RF system is still dominated by Cavity 2 trips, the MTBF has improved significantly and since the start of May 2009 (Run 04) the MTBF of the complete RF systems of the last runs has increased to >80 hours including both complete RF systems and the cryogenic plant. This corresponds to an average MTBF of each system consistently approaching 200 hours.

ADDITIONAL CAVITY DIAGNOSTICS

Due to the high number of Cavity trips a variety of diagnostics have been installed in addition to the original GUI interlock screens. These include a Libera beam position processor configured to record rf amplitude and phase signals, a fast vacuum recorder and a National Instrument PXI data acquisition system.

The Libera beam position processor, which is also used for our beam position diagnostics [5], records fast measurements of the forward power, reflected power and cavity probe signals. This is triggered from the Machine Protection System (MPS) and combined with the beam position diagnostics gives a good view of the sequence of events associated with a beam trip. Figure 1 shows a plot of an RF trip. From this we can see that Cavity 2 tripped first. Of interest is that, in this example, the cavity field collapsed in very few turns immediately preceded by a rapid ramp in power as the LLRF compensates for the drop in field in the cavity. As each turn takes 1.87 µs, the resolution is adequate to see the sequence of events however is insufficient to observe very fast changes. The red vertical line at t=0, indicates the time of the MPS trigger. In this example, the RF tripped first and the MPS triggered about 250 turns later as the beam decays inwards and triggers the orbit interlock. Additionally, looking closer we observe that the forward power and reflected power increase rapidly as the field in Cavity 2 collapses. After the loss of field in Cavity 2, the circulating beam extracts more power from Cavity 1 causing the field in Cavity 1 to fall followed by a rapid increase in forward power on System 1 until System 1 also shuts down on an interlock. Immediately after both systems shutdown, the fields in both cavities drop until

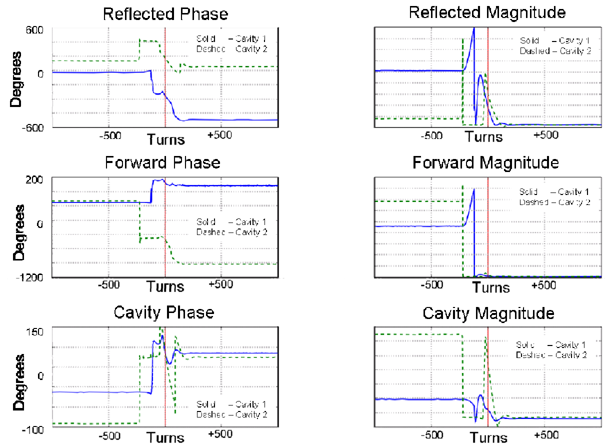

Figure 1: Plot from the RF post-mortem. This shows the magnitude and phase of the forward and reflected power and cavity field relative to the MPS trigger at t=0.

the circulating beam induces a lower field in both cavities until the beam is finally lost.

In addition to the Libera Beam position electronics units, we have implemented a fast vacuum recorder which records the output from the gauge controllers (Figure 2). Although the signal is delayed by the electronics, the vacuum data is synchronised and the delays for each channel are expected to be very similar. From the vacuum data and consideration of gas transport delays, the approximate location of the point of gas production can be estimated. Additionally, we see that generally gas cannot get through a cold bend. This is clear as there is no increase measured by the window on Cavity 1 for a trip on Cavity 2, as this would require the gas to make it through the cold waveguide bend despite having no direct line of sight.

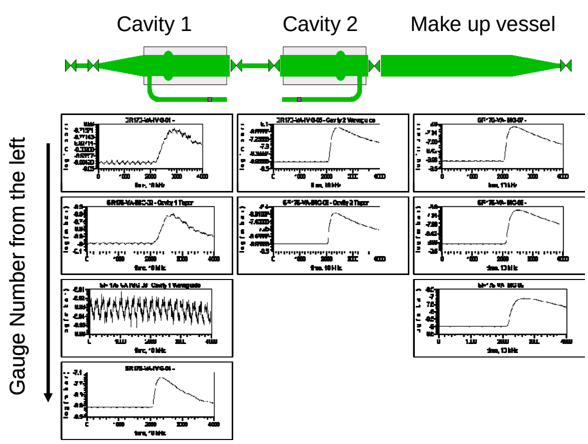

Figure 2: Vacuum signals following an RF trip.

Figure 2 shows the synchronised vacuum signals following a trip on cavity 2. The earliest vacuum signal is on Gauge 6 which is closest to the coupler on cavity 2. The remaining signals follow subject to delays corresponding to the delay in time of flight of the propagating gas. Gauge 03 is the window on Cavity 1. Note the signal is very small and the ripple is electronic noise. The vertical scale for each plot is logarithmic and is scaled for each gauge. The horizontal time axis is the same for each plot.

Since gas originating from the beam pipe cannot get to the window and gas from the window region cannot get to the beam pipe, different types of trips can be distinguished. For example, during early beam conditioning of the RF window the system could trip due to multipactor (MP) on the RF window. This would occur as the beam current was ramped to a new high level but gas is only produced for a limited voltage range. Outside that range, either above or below, no activity was observed. For such instances, there was no signal on the gauges on the beam pipe (Figure 3). Such trips have now been eliminated following extensive conditioning with beam. Typically, however, for our most frequent trips on the cavities, gas is observed both on the beam pipe and on the gauges near the window of the cavity in question. This indicates that the site of the gas production either moves during the breakdown event or an initial event can trigger a secondary event.

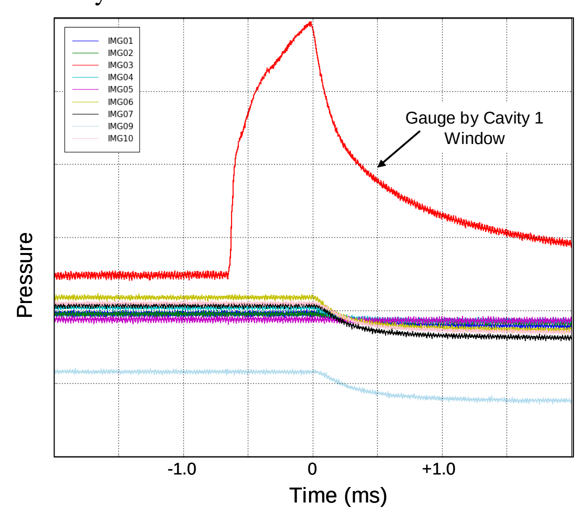

Figure 3: Plot of vacuum data during a beam conditioning trip. Here the only signal is on the window of Cavity 1 as the gas cannot propagate through the cold waveguide bend.

Initially, further analysis was made using oscilloscopes, but it soon became clear that using standard 4-channel oscilloscopes the number of channels became a limiting factor and so a fast data acquisition was installed. This system is based on the National Instruments PXI platform and is equipped with three 8-channel, 60 MHz oscilloscope cards with a common trigger, which enables us to record data for many more signals simultaneously and synchronised. In addition to the 60 MHz cards, the data acquisition unit can trigger and download the data from an external oscilloscope for direct comparison with the 60 MHz channels. This enables the full 500 MHz waveform to be resolved. Furthermore, slow signals such as temperature signals are recorded via a FPGA controlled acquisition card. This system as a whole enables a vast variety of signals to be recorded and synchronised for further analysis. Plots from selected channels of the data acquisition are shown in Figure 4.

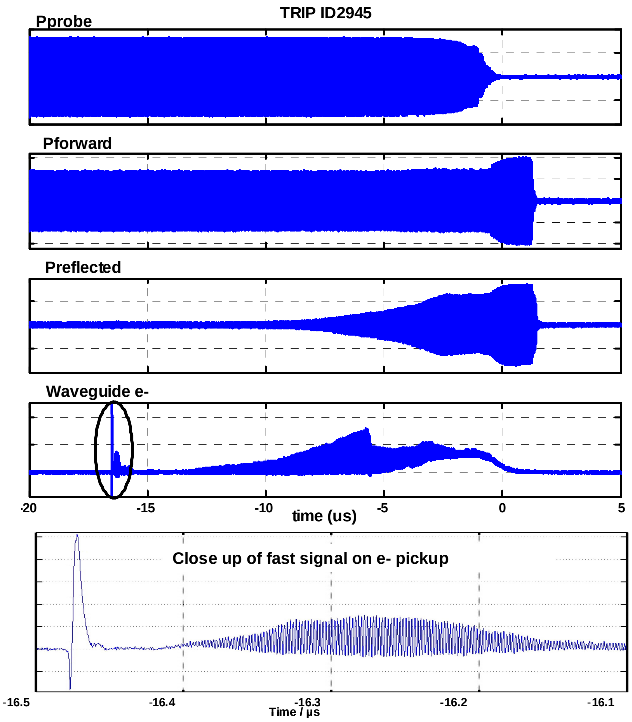

Figure 4: Plot of signals measured immediately before and after a cavity trip. The top 4 plots show 25 µs worth of data and the bottom plot shows a close up of the region circled on the waveguide e- pickup.

During Run 1 in 2009, Cavity 2 was tripping regularly, approximately 10 hrs after each injection. The number of trips suggested that the time between trips was not random. Previously this had not been so clear, in part due to operation in decay mode and partly due to the relatively high number of other machine trips. The waveguide for each cavity is fitted with solenoid coils which can be energised to 'bias' the waveguide and reduce the risk of MP. Unfortunately, no settings have yet been found which show any reduction in the frequency of the trips. As a further attempt to find a more reliable operating point, the power balance between the two cavities was changed to bring Cavity 1 below ~120 kW and Cavity 2 above 170 kW. Following the shift in power, the frequency of the trips dropped immediately and we now generally operate the cavities with the view to avoid a forward power between 130 – 165 kW.

PULSE CONDITIONING

Since installation, we have continued to condition the cavities during shutdowns with pulses up to 100 kW and of length 1-10 ms. Although the cavities appeared to be conditioned i.e. the cavities were no longer producing gas, operation with beam continued to be problematic. The peak power during the pulse conditioning was subsequently increased carefully by slowly increasing the peak power followed by a slow increase in pulse duration. At the same time the cavity was tuned in and out of resonance to 'sweep' the standing wave in the waveguide. At that point we found significant gas being released and particularly for a certain range of detune angles which correspond to a particular standing wave pattern in the waveguide. Pulse conditioning is now carried out with pulses up to 250 kW and up to 75 ms long. Figure 5 shows a typical pulse conditioning plot which releases gas as the cavity is being detuned. With this process, it is possible to condition the surfaces such that no significant out-gassing is observed during the pulses at that particular operating point, however, we often see repeat periods of higher pressure despite no obvious changes to the system. Additionally to date we always see significant gas following operation with beam, although the time for it to condition out during pulse conditioning during shutdowns is getting shorter.

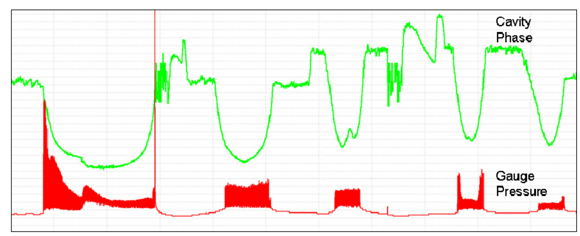

Figure 5: Plot of gauge pressure in the waveguide/window as the phase of the cavity is changed.

Diamond continues to carry out regular pulse conditioning of the cavities to continue to improve the reliability of the cavities and the RF system as a whole. It is clear that we are dealing with a dynamic situation. In addition, we are investigating possibilities of identifying the onset of MP with the view of breaking the MP condition before the cavity breaks down. It is hoped that this will help to reduce further the number of cavity trips during operation.

CONCLUSION

Diamond is operating routinely for users with two superconducting cavities in operation. Despite a high number of trips during initial operation, the MTBF of the cavities and the RF systems has improved markedly. A variety of diagnostics have been installed and a number of different modes of trips have been identified.

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