FIRST 18 MONTHS OPERATION OF THE DIAMOND STORAGE RING RF SYSTEM

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Abstract

Since the Diamond Light Source became operational in January 2007, the storage ring RF system has operated for 5000 hours in 2007 and is scheduled to operate for 5350 hrs in 2008. This paper presents some of the key challenges of the storage ring RF system including reliability, performance observations and future improvements.

INTRODUCTION

Diamond, a third generation 3 GeV synchrotron light source [1], commenced operation with users in January 2007. Since then the storage ring (SR) RF system has been operating to support users and for machine development. During the first year of operation the RF system was scheduled to support operation with beam for more than 5000 hrs. Since the start of operation, the RF power requirement has been steadily increasing to match the increase in losses as more beam lines become operational and as the beam current was steadily increased. Ultimately Diamond is intended to operate at 300 mA, with a possible upgrade to increase the beam current further.

The SR RF system [2] consists of 3 superconducting 500 MHz cavities similar to those used on CESR. Currently two cavities are installed each connected to an IOT based 300 kW amplifier [3] and a LLRF system. The cavities are supplied with Liquid Helium from a Liquid Helium Refrigerator also considered part of the SR RF System.

OPERATIONAL PERFORMANCE

During the first 12 months of operation, the RF Plant was scheduled to be available for user operation for just under 5000 hrs. During this time, the down time due to the RF systems was 60 hrs resulting in an availability of > 98%. Unfortunately following installation and commissioning one cavity developed a leak between the helium bath and the insulation vacuum and the cavity was subsequently removed from the Storage Ring for repair and later the spare cavity was installed. The early months of operation therefore were with cavity 1 only installed. Whilst the uptime of the RF system has been reasonable, since the start of operations the number of trips has been higher than expected with RF typically responsible for around 50% of beam trips. During early operation a number of beam trips were caused by early component failures and bad contacts but gradually the number of such trips has been significantly reduced. However, two categories of trips remain; these are cavity trips where the cavity field collapses rapidly, generally classified as ‘conditioning events’, and IOT trips indicating an internal arc in the gun end of the IOTs. The conditioning events are believed to be associated with multipactor events on the cavity equator and the trip signatures indicate a rapid loss of field, orders of magnitude faster that the typical decay time of high Q cavities. These events are by far the most frequent cause of beam dumps despite significant cavity pulse processing. The rate of trips can vary between no trips in 7 days to suddenly tripping every few hours without any particular change to operating conditions. Despite now having two cavities installed the majority of operation with users has been using Cavity 1 only. In 2007, the mean time between trips on RF System 1, including the RF distribution, MO and the Cryogenic refrigerator, was 38 hrs dominated by the high number of cavity vacuum trips. Without the cavity ‘conditioning’ trips the MTBF was 115 hrs. Taking into account all trips including dual cavity operation the total MTBF was 24 hrs for the year.

To date, operating with a single cavity has not been a limitation on the operation, as the SR beam current has not yet exceeded 200 mA during ‘User Mode’. However we will shortly increase the beam current and require both cavities in operation.

Tuner

It is essential that the cavity tuner operates smoothly with little backlash and large steps. Initially the tuner was found to stick and slip caused by bad mechanical linkage and alignment. This was observed on both cavities and during operation resulted in sudden phase jumps of 15-20 degrees corresponding to a tuner motion around 100 micron. During normal operation this was not a limiting factor as the LLRF compensated adequately, but it made conditioning more difficult and would ultimately limit performance when operating with a low phase stability margin. However, following careful realignment and adjustment the sticking and backlash problems have been eliminated.

A recent upgrade to EPICS 3.14 EPID record has enabled a proportional term only tuner control to be used. Previously it was difficult to correctly tune the tuner PID loop due to integrator wind-up observed with the use of a dead-band.

Cavity conditioning and reliability

Following installation of the cavities both have been found to suffer from the Q Virus (see for example [4]). This was also evident during the original commissioning. Typically the Q of the cavities is reduced by a factor of two when the cavities are cooled down slowly or if they are allowed to warm up to temperatures between 50 and

150 K. During normal operation the impact is not significant at present, as the liquid helium refrigerator has enough capacity to compensate for the higher dynamic losses. To avoid the Q virus, the cool-down procedure has been adjusted and the cavities are cooled down slowly to 200 K followed by a rapid cool-down in less than 90 minutes from 200 K to 4K.

Following each cavity cool-down and prior to the start of each new run, the cavities are pulse conditioned. This has two effects; it reduces the cavity losses and improves the maximum voltage before the onset of the Q drop. Initially, this was carried out manually by adjusting the RF to the resonant freuquency of the cavity. To keep the cavities on resonance using the LLRF tuner control, we now use pulses which maintain a low field in the cavities during the 'OFF' period. This enables a phase measurement to be carried out even for short pulses and the cavity resonance is maintained. This allows pulse conditioning to take place over extended periods, and furthermore, the cavities can be detuned by fixed amounts, to shift the standing wave in the waveguide.

Diamond initially started operations with 125 mA of beam current and the beam current during operations has been slowly increasing. To ensure that the cavities were capable of supporting the increasing power, significant time was spent conditioning up each window and waveguide. Two hard multipactor bands were observed for both cavities. The first at 125 kW at 1.7 - 1.8 MV and later a second band at 175 mA. Increasing or decreasing the voltage allowed more power to be transmitted to the beam, however conditioning to overcome the multipactor was preferable. Conditioning with beam turned out to be slow as the edge of multipactor was extremely sharp and a small incremental increase in power, < 500 W, resulted in very fast vacuum spikes causing a trip on vacuum interlocks associated with the window and the waveguide. Various methods of conditioning were developed including operation with a voltage ripple on top of the main voltage, sweeping to move the phase of the standing wave, but ultimately the most successful conditioning was by slow increments in current often as low as 0.2 mA. The current is injected at a voltage above the multipactor region and subsequently the voltage is slowly reduced though the multipactor band. This process was slow but once the window and waveguide had been thoroughly conditioned, the modules maintain their condition even after a complete warm-up. Once outside the two strong multipactor bands conditioning was significantly faster. Each installed module has now been operated at power levels above 260 kW to the beam and so far there are no indications that the limit has been reached.

CAVITY PERFORMANCE

LN2 Supply Pressure Fluctuations

The cavities are each supplied with a continuous flow of LN2 to cool the thermal radiation shields and the waveguide thermal transitions to reduce the static load on the LHe consumption. The LN2 is supplied at a nominal 2.0 bar but the pressure varies between 1.5 bar and 3.5 bar. This introduces two effects; firstly the temperature of the LN2 varies by several degrees and secondly gas pockets in the LN2 pipe work within the cavity cryostat change is size effectively causing the thermal distribution to vary. Both effects combine to result in a temperature variation of the beam-pipe. It is the associated thermal expansion which causes the resonant frequency of the cavity to change. This can be seen in Figure 1, which shows a correlation between LN2 pressure variation and change in cavity frequency. Whilst this is non-ideal, operationally it does not cause any difficulties as the changes are relatively small, slow and are easily compensated for by the constant retuning of the cavities to maintain a constant resonant frequency. Initial measurements with the LN2 pressure maintained at a constant pressure, stable to 150 mbar peak-to-peak, reduced the frequency variations due to the LN2 pressure from 700 Hz to 50 Hz. Even at the improved pressure stability the LN2 pressure variations correlate to changes if frequency, but is no longer the dominant effect. Tests are currently underway to trial a local modification to the LN2 supply which will reduce further the pressure variation on the LN2 supply.

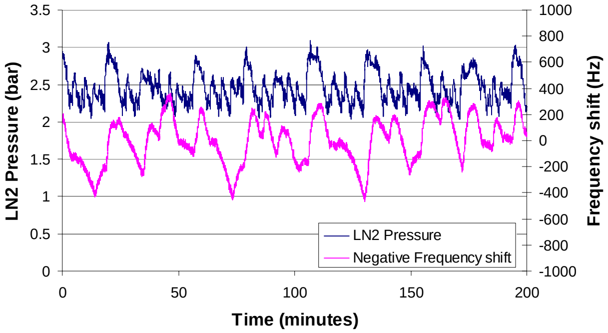

Figure 1: LN2 pressure variations and changes in resonant frequency of the cavities.

LLRF

The LLRF loop gain reduces as beam is injected causing the closed-loop error to increase and the cavity voltage to drop. A slow acting software loop has been implemented to monitor the voltage during injection and beam decay and to apply an appropriate correction to keep cavity voltage constant.

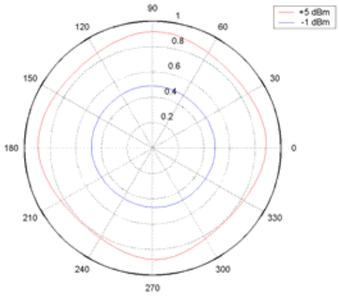

Figure 2: IQ demodulator vector plot, showing the imbalance of the demodulator at higher input levels. 1 and 5 dBm correspond to 35 kW and 135 kW respectively.

Operating under different conditions, the LLRF voltage and power measurements were found to vary. These variations, Figure 2, have been traced to variations in demodulator amplitude with the phase of the RF, due to their non-ideal behaviour. This results in an uncertainty on the measured cavity voltage and amplifier power levels. Investigations are currently underway, to correct for this with a multiple phase angle entry look-up table.

ROBINSON STABILITY

Diamond was originally designed to operate with two cavities, a beam current of 300 mA and total accelerating voltage of ~ 3.3 MV subject to the IDs installed, however the optimum Q_{ext} varies with specific operating conditions. To minimise reflected power at 300 mA, the optimum Q_{ext} for each module is 1.6 x 10^5 but the two modules have Q_{ext} values, which were fixed during construction, of 2.3 and 2.4 x 10^5. This causes the reflected power to be non-zero and the beam is theoretically Robinson unstable. Figure 3 shows the theoretical Robinson Threshold current, I_{Th} for stability [5] compared with the stored open loop current. The actual stored current is consistently lower that the theoretical value due to large voltage and phase variations effectively reducing the stability margin for currents below I_{Th}. Diamond however has a relatively low Synchrotron oscillation frequency between 1.5 and 3 kHz depending on the over voltage, which in combination with the fast LLRF system, means that even at that frequency, sufficient gain remains in the control loop to enhance the phase stability allowing currents significantly above I_{Th} to be stored at the expense of increased reflected power.

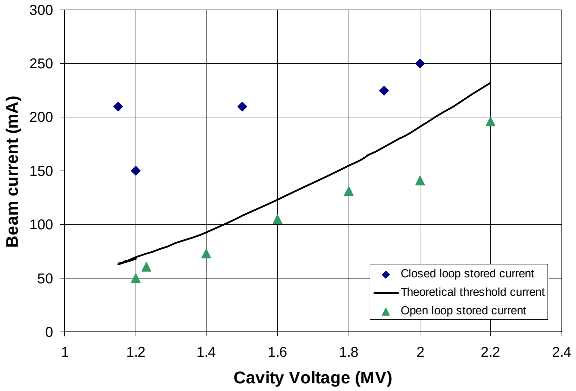

Figure 3: Theoretical Robinson Stability threshold current compared with open and closed loop stored current. The measured closed loop currents do not represent the maximum current possible.

To improve the match, a 3-stub tuner is installed between the high power circulator and each cavity. This method is successfully in use on CESR [6]. Using the 3-stub tuner the Q_{ext} has recently been modified from 2.3 x 10^5 to 1.7 x 10^5 close to the optimum Q_{ext} for 300 mA dual cavity operation, see Figure. 4. The reason for the non zero power at 140 mA is due to the cavity being slightly off resonance.

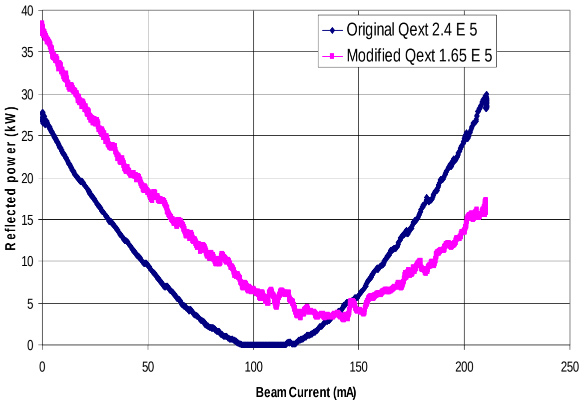

Figure 4: Measured shift in the optimum operating current with the use of the 3-stub tuner operating with a single cavity at 1.5 MV and 1.0 MV loss per turn. This corresponds to optimum Q_{ext} for dual cavity operation at 300 mA.

SUMMARY

Diamond has now been operating with users for nearly 18 months, during which a number of changes have been made to improve the reliability of the SR RF systems and the liquid helium refrigerator. Many causes of trips have been investigated and eliminated, however the RF systems continue to have a number of trips associated with both conditioning events in the superconducting cavities and IOTs trips. The MTBF is generally improving and it is expected that together with improved fault diagnostics and the completion of the RF Test facility currently under construction, a cure for the remaining trips can be achieved.

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