IMPLICATIONS OF INCREASED BEAM CURRENT FOR THE DIAMOND STORAGE RING RF SYSTEM

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Abstract

Diamond Light Source presently operates for users with 300 mA beam current and initial tests have begun to upgrade this current towards an ultimate goal of 500 mA. The implications of such a beam current increase for the storage ring RF system will be significant, including the installation of a third superconducting cavity and a possible modification of the coupling parameters of the existing cavities. An overview of the planned enhancements of the RF system is presented, including an update of the procurement of a new CESR-design cavity and options for installation and operation of this cavity and supporting infrastructure.

OPERATIONAL HISTORY OF DIAMOND LIGHT SOURCE

Diamond is a 3 GeV third-generation light source. The SR RF straight is designed to accept up to 3 superconducting 500 MHz cavities similar to those used on CESR [1]. Currently two cavities are installed each connected to an IOT based 300 kW amplifier [2] and a LLRF system. The cavities are supplied with Liquid Helium from a Liquid Helium Refrigerator also considered part of the SR RF System. Any one of the three high-power RF amplifiers can also be configured to feed a fully shielded cavity conditioning area known as the RF Test Facility.

User operation began in January 2007 in decay mode, with 125 mA storage ring current. Top-up operation was introduced in October 2008 and beam current has been gradually increased to the present 300 mA. Over this period, the number of operational beamlines has increased from an initial 7 in 2007 to 22 in 2013. The storage ring tunnel shielding is designed to accommodate 500 mA current, and a full radiation survey has been carried out with every increase in beam current and installation of additional beamline in order to verify radiation safety.

Beam current history, shown in Fig. 1, is intimately linked to the availability of the RF cavities. The second of the two initially installed cavities was brought into operation shortly after the beginning of user operations and allowed the beam current to be increased to 250 mA by the end of 2009. Withdrawal of one cavity from service at beginning of 2010 following an incident during a scheduled cavity warm-up [3] temporarily reduced beam current to 150 mA, although the installation of a replacement cavity that year allowed 250 mA beam to be recovered by the end of 2012 and 300 mA to be delivered to users in mid-2012. The second original cavity was replaced in a single shutdown in late 2012, after which a period of 250 mA operation was necessary before returning to 300 mA beam current in early 2013. It is planned to increase user beam current to 350 mA in October 2013.

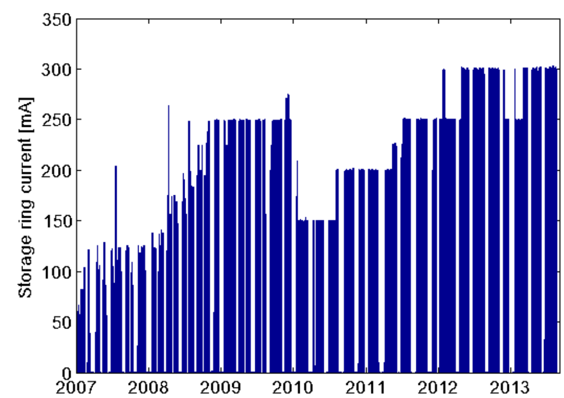

Figure 1: Diamond beam current history. The general envelope shows beam delivered to users, with gaps indicating shutdowns and occasional spikes of test beam in preparation for the next step up.

The storage ring RF system acts directly on the beam and contains no redundancy in its design and so beam trips on Diamond have always been dominated by this system, as can be seen in Fig. 2. In order to address the RF reliability issue, in mid-2010 titanium sublimation pumps were installed in the RF straight and ion pumps were upgraded and a programme of full and partial cavity warm-ups was instigated [4]: the reduction in the rate of fault accumulation through 2010/2011 is clear in the figure.

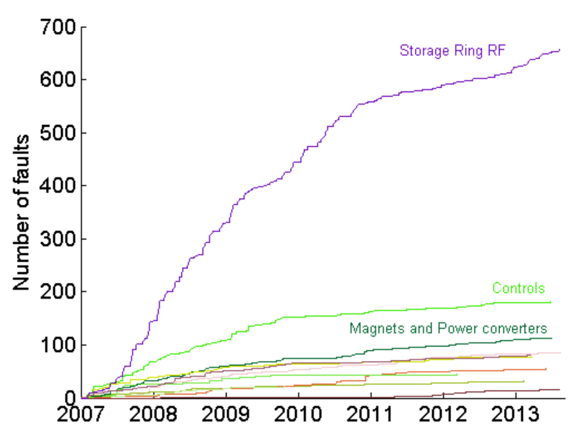

Figure 2: Accumulated faults sorted by technical group. The top three contributing groups are indicated.

ISBN 978-3-95450-143-4

As the beam current is increased towards 500 mA care must be taken to maintain this improvement in reliability, particularly in terms of identifying safe cavity voltages, IOT operating parameters and conditioning procedures.

POWER DEMANDS

Each Diamond cavity is equipped with a three-stub tuner in order to provide some flexibility in the coupling of the cavity to the amplifier: this method has been successfully used on CESR for some time [5] and is used on Diamond to minimise the total power requirement as the beam current is raised. Studies [6] show that the external Q of the cavities can be reduced well below $1x10^5$, allowing 500 mA beam current to be maintained with all operating insertion devices with three CESR cavities operating at a proven reliable voltage for Diamond. Fig. 3 shows a typical operating scenario, using three identical cavities with $Q_0 = 6.0x10^8$ and $Q_{ext} = 1.2x10^8$ operating at 1.4 MV to support beam currents up to 500 mA without exceeding the amplifier power limit of 300 kW.

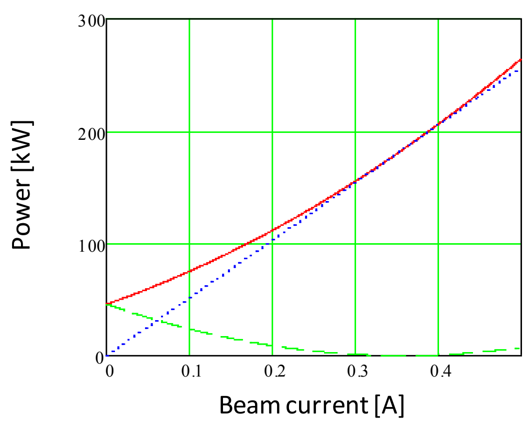

Figure 3: Total amplifier power (red), beam power (blue) and reflected power (green) for three identical CESR cavities in the Diamond storage ring.

In fact the Diamond cavities are not identical in their quality factors and reliable operating voltages, and so the exact operational configuration will differ somewhat from that shown in the figure. Nevertheless, it is clear that 500 mA operation requires the installation of a third cavity.

CRYOGENIC SYSTEM

Installation of a third cavity in the storage ring will increase the load on the helium plant. Recently, the second cavity to be removed from the storage ring has been under test in the Test Facility in order to establish its reliability as a spare. This trial involved a period of CW operation at 1.8 MV at the same time as a run of user beam with 300 mA beam current and two operational cavities. Under these conditions, the load on the Cold Box, based on the automatic attenuation of the turbine load maintaining a fixed level in the helium storage Dewar, was 82% of its capacity. Three major factors will change if a third cavity is placed in the storage ring:

- Beam heating in the storage ring will increase the cryogenic load on the third cavity compared to the load experienced in the Test Facility.
- Running the third cavity from the same storage ring valve box will mean that the Test Facility valve box and the two Multi-Channel Lines (MCLs) will not need to be used. This will decrease the heat load by approximately 50 W.
- The increase in beam current will also increase the dynamic heat load on each of the currently installed cavity modules.

The heat load on the RF helium plant when three cavities are running at 500 mA will need further investigation. It is highly likely that operation at this level will be close to the full 500 W capacity of the plant.

A further implication of three-cavity operation is the amount of gas storage space required when cooling down all three cavities within 24-36 hours. Currently, there is 105 m^3 of space, at 14.5 barA max. of which 3 barA must be left in the tanks. When cooling down two cavities, we find that 3.5-4 barA space is required in the buffers to accommodate the cool-down boil-off. Taking this into consideration, it leaves a usable volume of 1900 liquid litres equivalent. This is enough for three cavities, but does not leave a great deal of room for error.

PROCUREMENT OF A NEW RF CAVITY

The trial in the Test Facility has established that the more recently removed cavity is a viable system and so Diamond currently has two operating cavities and one spare. In order to maintain the spare for 500 mA operation, procurement of a fourth CESR cavity is underway. The cavity is being manufactured by RI Research Instruments GmbH, as were the first three, and contract completion is scheduled for early 2014. The final design uses the SSRF coupler tongue design and the CLS pump-out box to bring the external Q down from nearly $2.5x10^5$, for the installed cavities to $1.5x10^5$. This value may then be further reduced with the three-stub tuner.

Figure 4: Cavity 4 under test at Cornell University.

The cavity vertical cold test was carried out at Cornell University in July 2013. Fig. 4 is a picture of the niobium cavity being transferred to the test Dewar. Q_0 was measured as a function of accelerating field and the results, shown in Fig. 5 established that the quality factor of the cavity comfortably exceeds the specification of $Q_0 > 1x10^9$ at $V_{acc} < 6.67$ MV/m and $Q_0 > 5x10^8$ at $V_{acc} < 9.33$ MV/m.

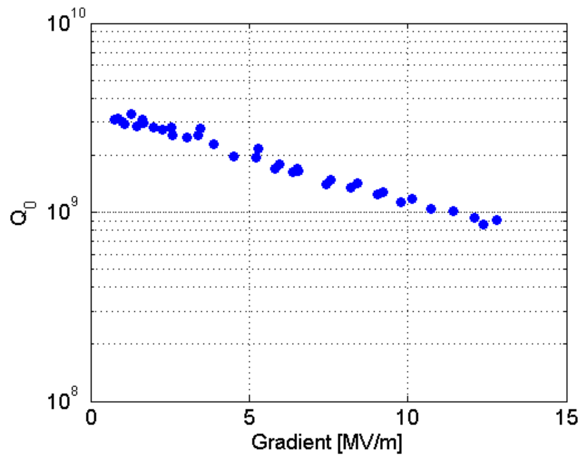

Figure 5: Q_0 as a function of accelerating voltage measured during the vertical test.

The high-power conditioning and test of the window for the fourth cavity was carried out at the Diamond RF Test Facility in March and April 2013, together with that of a second window intended for another RI project. Both windows were shown to withstand 300 kW CW travelling wave power for extended periods and were also placed in the maximum of a standing wave field for 160 kW CW amplifier operation and pulsed power levels in excess of 200 kW without any degradation of performance.

Following the successful vertical test, the cavity and window have been shipped to RI and are currently being integrated into the cryostat.

SITING OF THE NEW CAVITY

The new cryostat is designed to fit into the RF straight together with the other two operational cavities, although other possible locations are also being investigated. The RF straight is constructed with large bore beam pipes and large, relatively slow gate valves and so the entire RF system may be at risk of catastrophic failure in the event of a leak at some point in the RF straight. The only example we have on Diamond of a comparable vacuum event occurred in the injection straight in July 2009, when the septum vessel developed a leak during beam injection. A slow pressure record is presented in Fig. 6, and the peak pressures measured immediately after the event are shown in Fig. 7. In this case, the loss of vacuum extended across the whole of the injection straight and, to a lesser extent, into the neighbouring cells. There would therefore be some advantage to placing the new cavity distant from the RF straight.

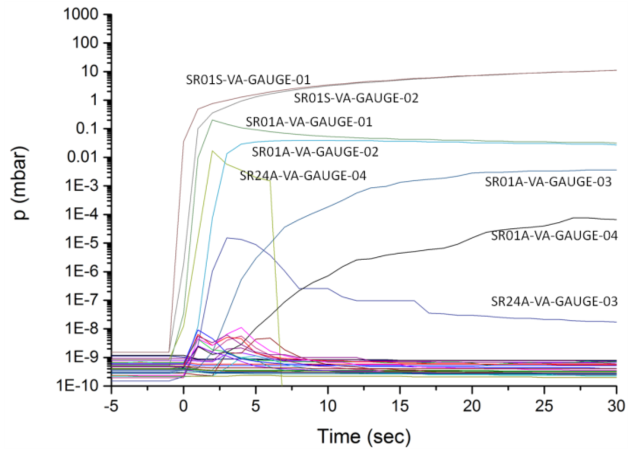

Figure 6: Pressures recorded in the vicinity of the injection straight following the vacuum event in July 2009.

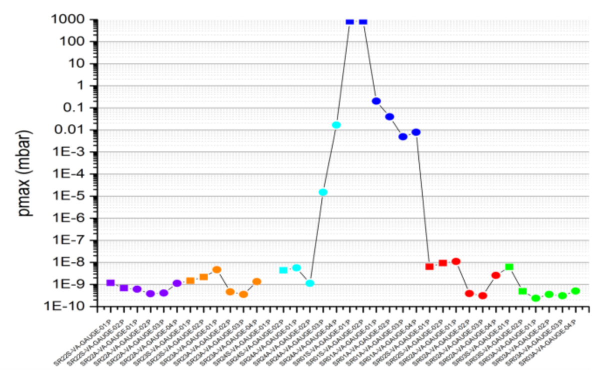

Figure 7: Peak pressures recorded after the July 2009 event. Colours denote different cells, with gauges in the straights (round markers) and arcs (square markers).

The exact positioning of a new cavity, if placed away from the RF straight, will depend on the space available in other parts of the ring, and the ability of the cryogenic system to supply helium to a cryostat that may be located some hundred metres distant from the current RF straight.

There are two possible approaches to the cryogenic issue: one to use the existing valve box and build a multi-channel line to the new location with manual shut-off valves, and a second option to build a new valve box close to the new location with a supply from the existing helium ‘fridge.

The first option looks the more viable. The implications are that of increased heat load, the cost of line and the controllability of the system with the valve box being more remote that it is currently. It is felt that the extra heat load will be about 30 W.

The second option would mean the modification of the manifold and MCL that feed the current valve box. It would also mean the production of a new valve box and a slightly simpler MCL than in the first option. The advantage would be the possible better control of the cryogen feeds into the cryostat.

If the test facility is to remain operational at the same time as three cavities then a fourth high-power amplifier

ISBN 978-3-95450-143-4

will be necessary. A study of the options available is ongoing, and encompasses both IOT-driven amplifier options and also solid state amplifiers similar to those installed at other light sources [7, 8]. The modular nature of solid state amplifiers is reported to result in a much greater reliability than IOT-based systems, although a fourth IOT-based amplifier would be preferable in terms of spares and support.

OTHER RF SYSTEMS

The requirement for 500 mA storage ring current affects other RF systems at Diamond. In particular the requirement for minimised Mean Time To Recover (MTTR) following a beam loss and reduction in the duration of the disturbance to the beam during top-up demands high electron emission from the linac in multibunch and single bunch mode respectively. The linac gun cathode, an Eimac YU-171 dispenser cathode, was exchanged in September 2013 for the first time since linac commissioning in 2005 and the increase in bunch charge is evident and shown in Fig. 8, suggesting that the original cathode was beginning to show signs of BaO depletion. No detrimental effects have been observed on temperature or pressure in the storage ring cavity or waveguide with the rapid increase in amplifier power during the swift storage ring fill since the new linac gun cathode was installed.

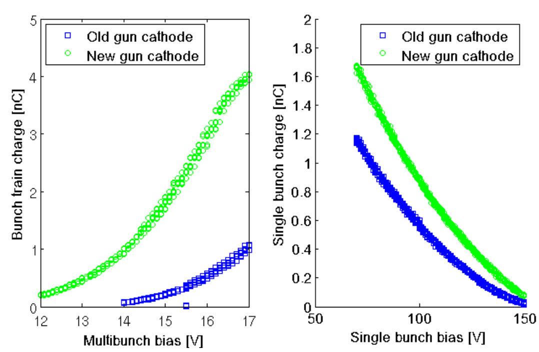

Figure 8: Bunch charges from old, partially depleted linac gun cathode and new cathode installed in September 2013.

The booster RF system, consisting of a five-cell copper cavity driven by a single IOT, is affected indirectly in a small way by the increase in storage ring current to 500 mA. The requirement for MTTR and top-up minimisation demands maximum efficiency of beam transfer from the linac through the booster into the storage ring. Investigations of beam capture at the booster injection energy of 100 MeV [9] show that beam transfer efficiency is increased slightly when the minimum cavity voltage on injection is dropped below the normal value available from the present LLRF system. Work is therefore underway to increase the dynamic range of the booster RF amplitude loop.

Increased Touschek scattering at 500 mA operation will reduce the lifetime of the beam in the storage ring. This effect may be offset by the addition of a higher harmonic cavity system to increase the electron bunch length. Several variants of this approach are available, including both superconducting and normal conducting systems, and active or passively powered devices [10, 11]. High current operation at Diamond would benefit from the installation of a higher harmonic cavity, and so the study has begun of the requirement, advantages, location and support of such a device.

SUMMARY

Investigations of how to bring about an increase in beam current at Diamond Light Source from the 300 mA currently offered to users towards an ultimate target of 500 mA have begun. The enhanced current affects all technical groups, particularly through increased beam heating, but is primarily of interest to the RF group because of its requirement for a third operational cavity and the necessity of lower external Q values to ensure a good match to the amplifier at higher beam currents. Progress towards the increased current target has been described and plans for possible changes to the RF and cryogenic system have been outlined. The need for the maintenance of high reliability at the increased beam current has been stressed.

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ISBN 978-3-95450-143-4