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COMMISSIONING OF THE HYBRID SUPERCONDUCTING / NORMAL CONDUCTING RF SYSTEM IN THE DIAMOND STORAGE RING

C. Christou, A. G. Day, P. Gu, P. Marten, S. A. Pande, D. Spink, A. Tropp
Diamond Light Source, Oxfordshire, UK

Abstract

Two 500 MHz HOM damped normal conducting cavities have been installed in the Diamond storage ring to ensure continuity of operation of Diamond in the event of a failure of one of the two existing superconducting cavities. The cavities were conditioned in Diamond's RF test facility and installed in the storage ring in 2017. Conditioning and operation use a new digital LLRF system. Test and commissioning results are presented, together with the current status of the hybrid RF system and options for further improvement in the near future.

BACKGROUND

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 (SC) CESR-B cavities [1], with two similar cavities available as spares. 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. There have been four cavity failures at Diamond to date: details are given in Table 1.

Table 1: Cavity Failures

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

After the failures in 2014 and 2015 Diamond was left with no spare cavities for several months. At present there is one spare available as repairs to cavity B are ongoing. To mitigate the risk of downtime arising from cavity failure, two normal-conducting (NC) EU HOM-damped cavities of the HZB design as installed at BESSY [2], and similar to those used at ALBA [3] have been installed.

As well as providing an easily maintained back-up to the SC cavities, the NC cavities improve ring reliability by allowing the SC cavity voltage and amplifier power to be reduced [4].

DESIGN AND ASSEMBLY

Two bare copper cavities, including tuner, coupler and pickups, were manufactured by Research Instruments to original drawings from HZB and delivered to Diamond in February and March 2017. The cavities were then incorporated into trolley modules including UHV tapers pumped by two 300 l/min ion pumps and fitted with vacuum instrumentation. A water manifold and distribution was also added, together with monitors and interlocks on the cooling circuits.

Both cavities were baked out and successfully vacuum tested in the first half of 2017 [5]. Figure 1 shows the bare cavity delivered by the manufacturer and the completed module after bake out and vacuum test.

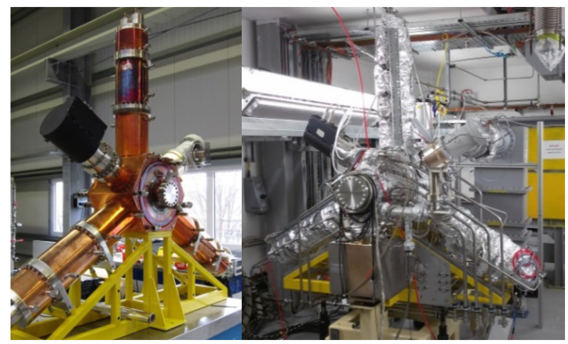

Figure 1: Cavity delivered by the manufacturer (left) and prepared for operation by DLS (right).

CAVITY CONDITIONING

Both cavities were conditioned beyond 60 kW in Diamond's RF test facility. Conditioning was carried out using a new digital low level RF (DLLRF) system based on that developed at ALBA [6] using the MicroTCA standard with a commercial advanced mezzanine card, Perseus 601X with Virtex6 FPGA from Nutaq, as the core processor of the control algorithm. Input and output interfaces use 16 Channel 14-bit ADCs and 8 channel 16-bit DACs [7]. The same DLLRF has been designed for use with the NC cavities in the storage ring, and offers advantages of flexibility and maintainability over the existing analogue LLRF systems used at Diamond.

Each cavity was conditioned within two weeks. Figure 2 shows the power delivered to the second cavity over this period. Both cavities had multipacting barriers at similar power levels, with frequent amplifier reflected power trips at 100 W, 11-13 kW, 19 kW, 25 kW, 35-39 kW, 50 kW and 60 kW for the case in the figure. After two weeks the cavity was able to run continuously at 20 kW, corresponding to a voltage in excess of the 300 kV planned for normal storage ring operation [4].

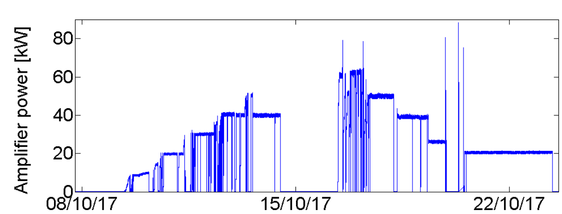

Figure 2: Cavity conditioning record.

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Each cavity is equipped with seven PT100 thermocouples bonded to the copper structure with Omegabond 200 epoxy, and 14 PT100 thermocouples poke welded to the cooling pipes. Temperature rose linearly with conditioning power in all cases, with four points exceeding 30°C at maximum power. The highest temperature was recorded on the cavity body at the base of the fundamental power coupler. Figure 3 shows power-temperature dependence of the hottest points.

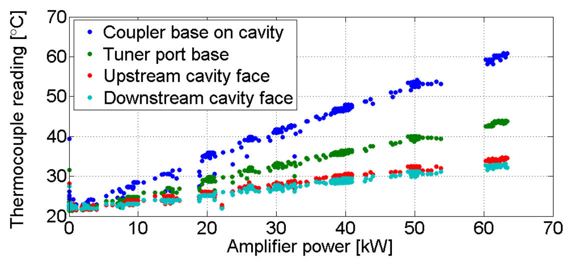

Figure 3: Temperatures recorded during conditioning.

Optical arc detectors are not used; arc protection is provided by a fast vacuum interlock to the amplifier.

Short term stability of the cavities with the DLLRF is characterised by the phase noise plot shown in Fig. 4. Phase noise of the closed loop between 10 kW and 60 kW, measured at a diagnostic point in the DLLRF front end, is similar to that of the oscillator used to drive the system with the addition of some noise in the 1 kHz to 10 kHz range. Spurs are visible at harmonics of mains frequency in both oscillator and DLLRF measurements.

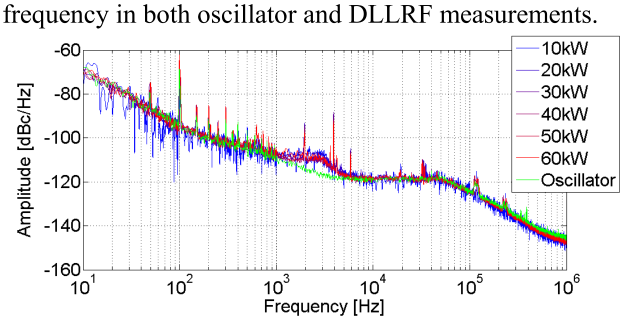

Figure 4: Phase noise at cavity pick-up.

INSTALLATION IN THE STORAGE RING

The two cavities were installed in the storage ring in August and November 2017 in straights adjacent to the existing RF straight. Figure 5 shows a cavity installed upstream of the RF straight, immediately before an insertion device. CST Microwave Studio simulations of the arrangement indicate that the primary BPM at the start of the straight is not affected by leakage of RF from the cavities; detailed experimental verification is ongoing.

The cavities are linked to the amplifiers by 9 3/16 inch coaxial transmission line. The first, complete, line uses the pre-existing 300 kW isolator and tunnel penetration and runs entirely within the storage ring tunnel. The second line is being assembled at the time of writing, and uses a new 150 kW isolator and enters the tunnel through a personnel labyrinth near the cavity. Power is limited to 120 kW by the 6 1/8 inch tee to the input coupler.

Figure 5: Cavity installed in storage ring.

The limited length between the insertion device and the BPM assembly meant that the cavities had to be vented on installation, and so a further bake was carried out in the ring after the UHV connection was made.

There is significant beam loading of the cavities at 300 mA storage ring operation, and so the cavities are overcoupled in the absence of beam. RF parameters of the installed cavities are given in Table 2

Table 2: Cavity Parameters Measured with VNA

Cavity	Coupling	Q_0
N1	5.17	33,000
N2	5.25	33,000

TESTS WITH BEAM

Since installation, the storage ring has operated for the majority of user beam at 300 mA with the cavities detuned by 400 kHz; less than the storage ring rotation frequency of 534 kHz but far enough from resonance to minimise the effect on the beam. The effect of the cavity detune can be seen in Fig. 6, in which the cavity frequency was scanned across the RF frequency.

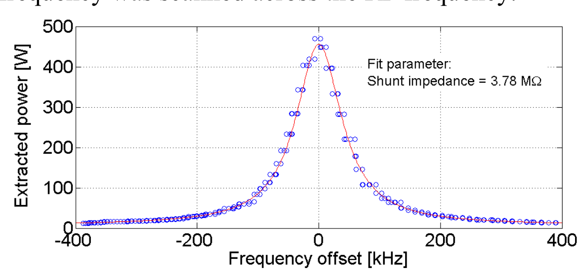

Figure 6: Cavity detuning with a 20 mA beam.

Power extracted from a parasitic cavity in the ring, P_b, at a current I is given by

$$P_b = 2I^2 R_s \frac{\beta}{(\beta+1)^2} \cos^2(\psi)$$

where β is the cavity coupling and the cavity detuning angle, ψ, for a frequency detune of δf relative to the RF frequency, f is given by

$$\psi = \arctan\left(2Q_L \frac{\delta f}{f}\right).$$

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A best fit of the free parameters to the power measurement in Fig. 6 gives the shunt impedance of the cavity, around 3.75 MΩ in both cases, with quality factor and coupling of the fit within 10% of the values measured directly with a VNA and given in Table 2.

Figure 7 shows the higher order modes in the cavity to 1.8 GHz, measured with a VNA. The spectrum is consistent with that measured at BESSY [8] with the exception that the problematic high-impedance mode observed near 680 MHz at BESSY and Alba [9, 10] has been eliminated by the removal of the HOM damper-to-cavity flange. Spectrum analyser measurement of reverse power gives a similar spectrum. To date, the cavities have been transparent to the beam, and there has been no requirement to operate the LMBF system [11] to suppress longitudinal multibunch instabilities.

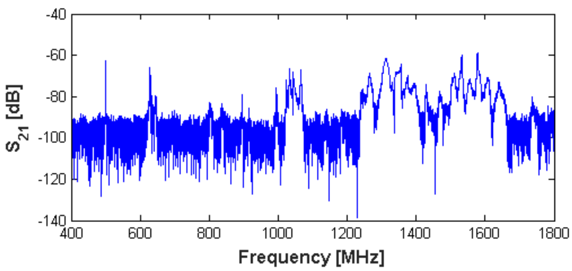

Figure 7: Higher order mode measurement.

The two new cavities are powered by a previously redundant amplifier, and studies are continuing to demonstrate the resilience of the beam to failure of this amplifier. Figure 8 shows the effect of turning off the amplifier during high power operation with 150 mA beam: power lost from the NC cavity is made up by an increase in the SC cavity powers, and power is extracted from the beam consistent with the expressions for detune and induced power above. There is some disturbance on the horizontal beam position and power levels in the remaining cavities.

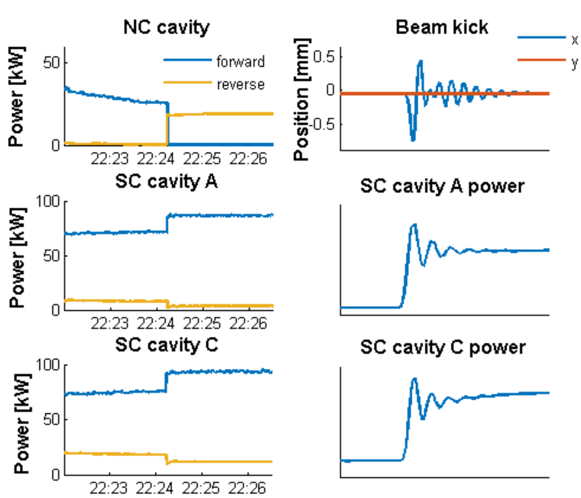

Figure 8: Response to the loss of NC cavity power.

OPERATION WITH USER BEAM

Until the installation of the first NC cavity, operation of the Diamond storage ring in low alpha mode [12] involved running the two SC cavities at voltages far above their reliable operating thresholds [5]; as a result, reliability in this mode was poor. Introduction of the first of the two NC cavities allowed the voltage on the SC cavities to be reduced, resulting in a more reliable beam, as can be seen in Table 3, showing the number of faults in three 48-hour periods of low alpha for users since the present cavity configuration was adopted in 2015.

Table 3: Cavity Faults in THz/IR Low Alpha Mode

Run	Cavities	Cavity faults
2015 run 4	2 SC	6
2016 run 1	2 SC	7
2018 run 1	2 SC + 1 NC	0

The 48 hour low alpha run of the NC cavity at 400 kV was the first extended period of user beam with the NC cavity and the DLLRF system. Stability of the cavity voltage is shown in Figure 9. The NC cavity voltage is stable over the 30 hours of monitoring, with no steps or drifts in long-term levels. Similar stability is evident for cavity phase.

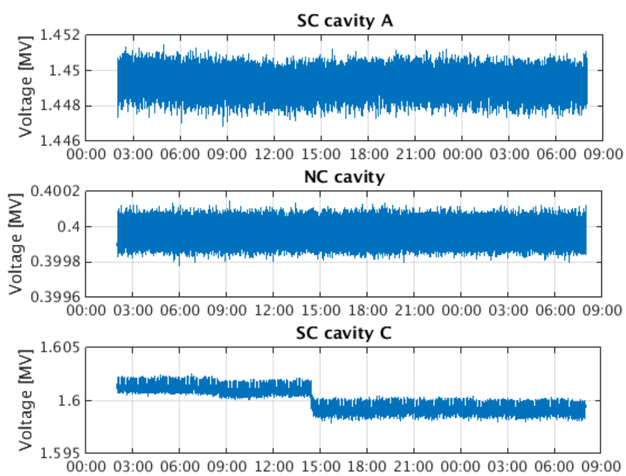

Figure 9: Long-term stability of cavity voltages.

PLANNED UPGRADES

The two NC cavities installed in the ring in 2017 ensure continuity of operation in the event of the failure of one SC cavity. Installation of a third NC cavity would support sufficient beam current for users in the event of a failure of both SC cavities or loss of the helium plant, and so procurement of a third NC cavity has begun. Protection of individual IOTs in the amplifier with 50 kV MOSFET switches rather than by switching of the common high voltage power supply is also under test.

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SUMMARY

Two normal conducting cavities have been successfully installed in the Diamond storage ring. Measurements of cavity quality factors, shunt impedances and higher order mode content have met expectations, and the cavities have been incorporated into user beam operation, initially parked off resonance with no adverse effects noted on the beam, and then with the first cavity powered up during low alpha operation for users, reducing the demand on superconducting cavity voltage and delivering a consequent reliability improvement.

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