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RF PLANS FOR THE DIAMOND-II UPGRADE

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Abstract

RF for the proposed Diamond-II upgrade will be based on normal-conducting EU HOM-damped cavities powered by high power solid state amplifiers and controlled by digital low level RF systems built on the microTCA platform. Design choices and experience from Diamond are discussed. The storage ring will also include a third harmonic cavity, and the different options for this device are reviewed. RF design of the booster is presented, and details are given of an upgraded linac and gun design intended to increase the charge for top-up.

BACKGROUND

Diamond-II is a proposed in-place upgrade to Diamond Light Source. The upgraded storage ring (SR) increases both the photon beam brightness and the number of insertion devices in the ring. A 3.5 GeV modified 6BA 24-cell lattice is foreseen with 18 standard straights, 6 long straights and 24 new mid-section straights [1].

To reduce the cost of Diamond-II, it is planned to reuse components from Diamond as far as possible, and so the Diamond 500 MHz RF frequency will be maintained, allowing much of the existing infrastructure to be reused. The precise Diamond-II frequency of 499.511 MHz arises from the SR circumference chosen to maintain the source points of the existing beamlines with a suitable harmonic number $h = 934$. This change from the present Diamond frequency of 499.68 MHz imposes constraints on the design of cavities and accelerating structures.

SR voltage is determined from the Touschek lifetime and RF aperture calculated for the Diamond-II lattice and new complement of insertion devices. Optimal voltage for Diamond-II is around 2.7 MV [1], a slight increase on the Diamond value of 2.5 MV. SR power to the beam is approximately 460 kW [1], again a marginal increase from the present Diamond requirement of 440 kW.

CAVITY CHOICE AND LOCATION

The Diamond SR is currently operating routinely with two superconducting (SC) CESR-B cavities, with two normal-conducting (NC) EU HOM-damped cavities in reserve and for special operating conditions for reduced bunch length [2]. The CESR-B cryostat assemblies are each over 2.5 m in length and are in a dedicated long RF straight. In comparison, the HOM-damped cavities, shown in Fig. 1 measure 50 cm from flange to flange and each shares a straight with an insertion device. There is insufficient space in Diamond-II for all required SC cavity cryostats whereas HOM-damped cavities can be installed in pairs in mid-section straights, as shown in Fig. 2, leaving the present RF straight free to be used for an insertion device for a new beamline.

Figure 1: EU HOM-damped cavity.

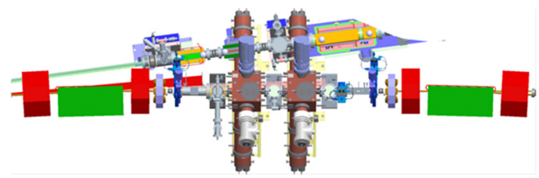

Figure 2: Two cavities in a mid-section straight.

The change in operating frequency would also be a problem for the SC cavities, as they have a much higher quality factor and smaller tuning range than the HOM-damped cavities. For these reasons, and for the simpler operation, maintenance and repairability of the NC cavities it has been decided to base the Diamond-II RF system on the EU HOM-damped cavities.

Multiple HOM-damped cavities must be used to reach the voltage and power target for the SR. Over time the lower running costs balance the higher capital costs of a larger number of cavities as the cavity wall losses are lower at the lower voltage, as shown in Fig. 3. Eight cavities is appropriate, giving an economical total cost and allowing operation at a conservative voltage of 338 kV, enabling some redundancy should one of the cavities or amplifiers fail.

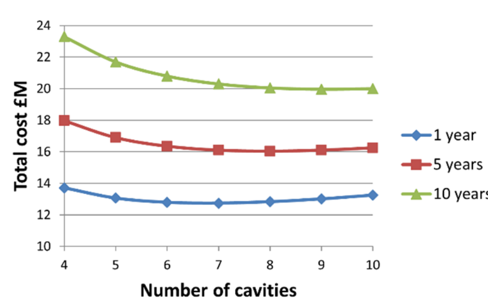

Figure 3: Cost of multiple HOM-damped cavities.

SOLID STATE AMPLIFIERS

A high-power 500 MHz amplifier may be constructed using klystron, IOT or LDMOS transistor technology. Klystrons have the advantage of high gain, whereas IOTs are more efficient and operate at lower voltages. Solid

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state amplifiers offer advantages over vacuum tubes in their extreme modularity and high redundancy, and are easier to work with, as they operate at tens of volts rather than the tens of kilovolts or more required for vacuum tubes. The absence of a high voltage power supply and PWM switching circuit removes the risk of high voltage breakdown and results in a cleaner spectrum.

Several recent light sources have been designed to operate with solid state amplifiers [3, 4], and several others have been upgraded to replace tubes with transistors [5, 6]. All report positive results. Diamond has recently installed two solid state amplifiers [7] operating at 80 kW and 60 kW consisting of 64 and 48 output power modules combined in a single cavity combiner, allowing a compact arrangement of modules, controls and power supplies in a single rack, shown in Fig. 4.

Figure 4: High power solid state amplifier schematic.

Redundancy, spectral purity, ease of operation and security of supply as IOT broadcast transmitters are replaced by solid state devices has led to the selection of 500 MHz solid state amplifiers for Diamond-II.

The power limit of Diamond's HOM-damped cavities is 120 kW and so in summer 2021 a 120 kW amplifier [6] will be installed in the SR with a third HOM-damped cavity. This installation will be a model for Diamond-II RF, where the cavities and amplifiers will operate below 80 kW when critically coupled with beam, as shown in Fig. 5. This is well within specification and has sufficient overhead to operate with 7 cavities in the event of a fault on one RF station.

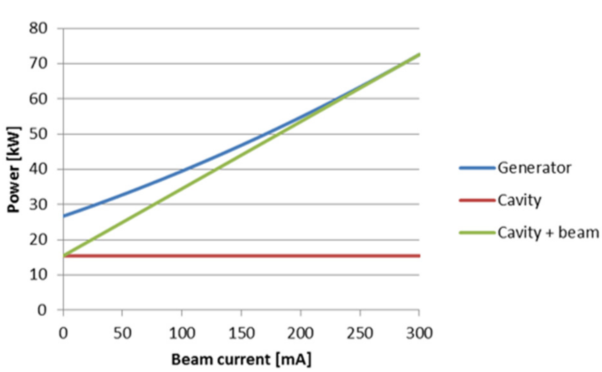

Figure 5: RF powers with 8 HOM-damped cavities.

HIGHER HARMONIC CAVITY

Cavities at the n^{th} harmonic of the RF frequency are necessary in Diamond-II to lengthen bunches in order to minimise SR component heating, alleviate collective instabilities and maximise beam lifetime [8]. The optimal flat potential case, may be achieved if the first and second derivatives of the RF waveform are zero, with the relative voltage and phase of the higher harmonic cavity, k_{fp} and φ_{hfp} given below [9, 10], with V_{rf} and U the RF voltage and single turn loss respectively,

$$k_{fp} = \sqrt{\frac{1}{n^2} - \frac{1}{n^2-1}\left(\frac{U}{e_0 V_{rf}}\right)^2},$$

$$\tan(n\varphi_{hfp}) = -\frac{\frac{nU}{e_0 V_{rf}}}{\sqrt{(n^2-1)^2 - \left(n^2 \frac{U}{e_0 V_{rf}}\right)^2}}.$$

In a passive harmonic cavity [11-14] the field is generated by the beam. The load of a SC cavity is almost completely reactive and so the phase of the induced field is largely independent of beam current, allowing the harmonic cavity to be used at a wide range of beam currents. With a NC harmonic cavity [15, 16] the induced phase is current dependent, and so the harmonic cavity operation is only optimal at one beam current. In order to operate over a wide range of currents the NC cavity can be actively driven by an external amplifier [17].

Shunt impedance of a SC harmonic cavity is higher than that of a NC cavity and so a single SC device can be sufficient whereas multiple NC devices may be needed to generate the same voltage. The CEA/SLS/Elettra "Super-3HC" third harmonic cavity [12] is a potential harmonic cavity for Diamond-II and is available from industry. Bunch lengthening at two different beam currents is shown in Fig. 6.

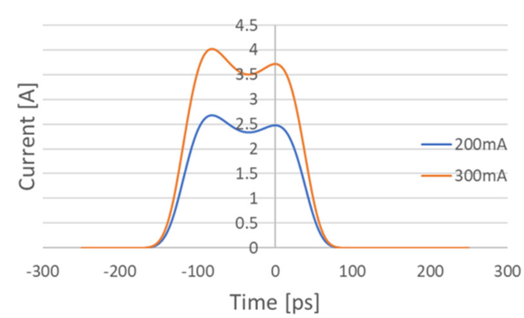

Figure 6: Bunch profiles for a Super-3HC cavity detune of 57 kHz at 300 mA and 38 kHz at 200 mA.

Both SC and NC harmonic cavities add Robinson instability terms to the SR, but the effect for a SC device is lower. The effect can be damped by a detune of the fundamental cavity [18]. Beam loading is less for a SC cavity than a NC cavity [19], but is still considerable, particularly for a long SR fill pattern with a single gap. The effect can be reduced by breaking the fill up into

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shorter trains with multiple gaps in the ring, as can be seen by the plot of calculated bunch lengths in Fig. 7.

Effective operation over a broad range of beam currents, reduced Robinson instability, lower sensitivity to beam loading and the existence of the legacy Diamond cryogenic plant are advantages of a SC harmonic cavity. In contrast, NC harmonic cavities are cheaper to install and easier to maintain and are able to operate optimally across a large range of SR conditions when used in active mode with suitable RF amplifiers.

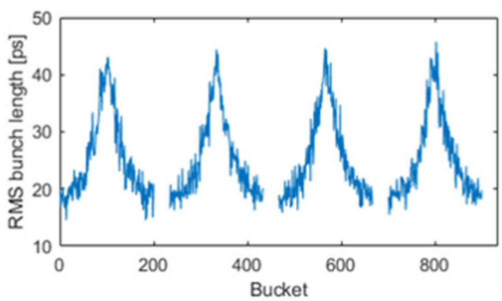

Figure 7: Bunch lengths with an SC harmonic cavity.

DIGITAL LLRF

Diamond has recently installed a digital LLRF system developed in collaboration with Alba based on Virtex6 FPGA on a microTCA 4 platform, fast ADCs and DACs [20]. A schematic is shown in Fig. 8. The DLLRF ensures polar or IQ amplitude and phase regulation, tunes the cavity and provides additional functionality such as restart, conditioning and postmortem logging. The system has been running in Diamond since 2017 and a version configured for a solid state amplifier is suitable for use in Diamond-II.

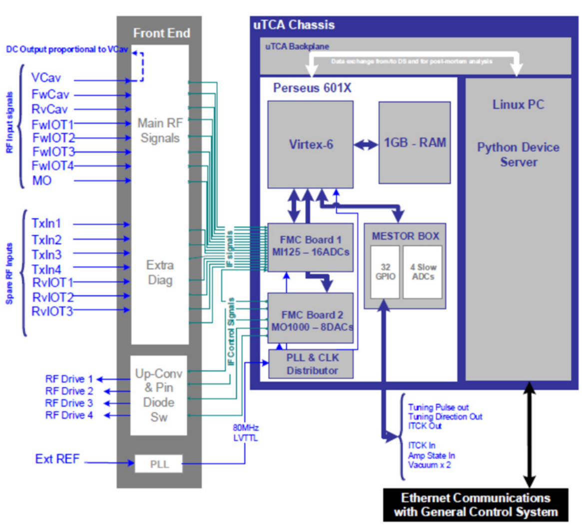

Figure 8: Schematic of Diamond digital LLRF.

INJECTOR RF

Efficient injection into the Diamond-II SR will require upgrades to the injector complex, including a new 3.5 GeV low-emittance booster synchrotron [21]. Peak booster RF voltage of 2.0 MV is generated by two Petra 5-cell cavities and two EU HOM-damped cavities to ensure redundancy of cavities and amplifiers. The booster RF stations will use solid state amplifiers and the same digital LLRF as in the SR, configured to control the appropriate cavity.

In order to reduce the number of top-up shots and associated disturbance to user beam, work is ongoing to increase the charge transmitted through the linac and booster each shot. Charge generated at the gun can be increased by using a larger thermionic cathode than the one used at the moment. A new gun has been designed using EGUN [22] and CST Microwave Studio [23]. Figure 9 shows the electrode geometry needed to accommodate the larger cathode. It is planned to operate the gun around 150 kV at 7 A.

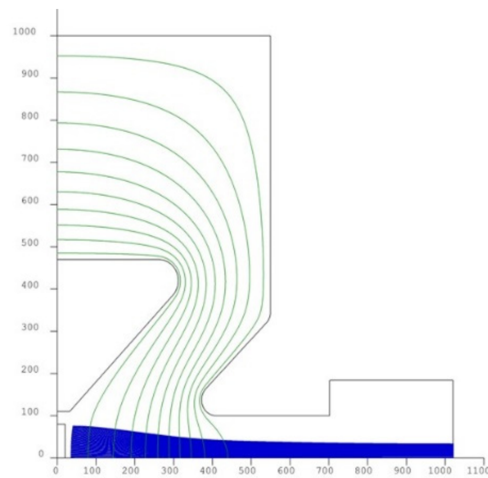

Figure 9: EGUN model of new gun, unit = 0.1 mm.

Injection efficiency from linac into booster is energy dependent [24] and so it is planned to increase the energy of the linac from 100 MeV to 150 MeV. The increased energy will reduce geometrical emittance of the linac beam, lower the scattering from residual gas on injection and reduce the dynamic range of all booster components.

The present linac structures can be made to operate at the Diamond-II frequency by heating them to 64 °C. It is also possible to continue to operate the linac at the old frequency. In this option linac and booster/SR frequencies are generated in a two-channel arbitrary waveform generator with samples of different frequency in each buffer. Triggering the two buffers with a common clock ensures synchronisation of injection into the booster. A third alternative is the option of replacing the accelerating structures with new ones designed to operate at the new frequency.

SUMMARY

RF plans for Diamond-II are advanced. The system will use NC cavities and solid state amplifiers regulated by a digital LLRF operating on a microTCA platform. Booster RF will be generated in multiple cavities and linac charge and energy will be upgraded. Options are considered for linac operation with a change in SR frequency.

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