ELECTRON BEAM HEATING AND OPERATION OF THE CRYOGENIC UNDULATOR AND SUPERCONDUCTING WIGGLERS AT DIAMOND

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Abstract

Electron beam heating can be an important effect for the operation of a cryocooled permanent magnet undulator (CPMU), a superconducting undulator (SCU) or a superconducting wiggler (SCW) [1]. Diamond Light Source has two SCWs installed and one CPMU serving a total of three beamlines [2].

We have observed the effect of electron beam heating in all three devices. The effect of beam heating in the first SCW (SCW-1) was so severe that the device had to be modified several times because the resulting liquid helium consumption was very high. The effect of electron beam heating in the second SCW (SCW-2) was less but still led to a liquid helium consumption which was much larger than specified.

We report on the measurement of this beam heating effect in the wigglers, the changes which were made to both wigglers in order to reduce it and our operating experience since the changes.

The electron beam heating is also noticeable in the CPMU but is automatically compensated for by the heater control system.

ELECTRON BEAM HEATING

There are three main causes which can lead to electron beam heating: Synchrotron Radiation (SR) from the upstream dipole striking the inner beam tube or liner, Resistive Wall Effects (RWE) from the main beam current, and Electron Bombardment [1] from residual gas molecules being struck by the electrons. Previous work at Diamond has pointed towards the likelihood that RWE dominate the heating, as the heat load showed a quadratic relationship with bunch charge [3].

Resistive wall heating is described by Equation 1

$$\frac{P}{L} = \frac{n f_{rev} Q_b^2}{2\pi^2 r} \int \tilde{\lambda}^2(\omega) R_s(\omega) d\omega \qquad (1)$$

where P/L is the deposited power per length, n is the number of bunches, f_{rev} is the synchrotron revolution frequency, Q_b is the charge per bunch, r is half-gap of the electron transport liner, λ is the Fourier Transform of the bunch shape and R_s is the surface resistance in the anomalous skin effect regime [4], which in turn is related to the resistivity of the pipe material.

The deposited power varies with the square of the charge per bunch determined by both the number of bunches and the total beam current (Eq. 1). For a constant beam current and number of bunches it should also vary with a *-5/3* power relationship to the mean bunch length. This can be changed by varying the voltage of the RF cavities, as bunch length scales with the inverse square root of cavity voltage V_c. Hence P is proportional to $V_c^{5/6}$.

Of the three main causes of electron beam heating SR and Electron Bombardment are independent of the resistivity of the liner. However the RWE is proportional to the resistivity of the liner and hence depends strongly on the material and the temperature of the liner. Hence changes of the liner temperature and or electron beam parameters should affect the measured beam heating. We have measured the electron beam heating as a function of Q_b and V_c.

SUPERCONDUCTING WIGGLERS

Diamond has two superconducting wiggler devices built by the Budker Institute of Nuclear Physics (BINP). SCW-1 has been operating since January 2007 and SCW-2 has been operating since March 2009. The yoke and superconducting coils are located inside a conventional liquid helium bath which was specified to boil off no more than 0.05 litres of liquid helium per hour with a stored beam of 300mA.

In SCW-1 the helium consumption reached 3 ltr/h at 225mA and 660 bunches but this was mainly caused by a technical fault with the liner insulation. In SCW-2 which has an improved thermal insulation the effect of the beam heating on helium consumption was less at 0.5 ltr/h.

However it was also noted that the cryocoolers which cool the main current leads and the helium vessel were operating on both wigglers at around 3.6K while the helium vessel was at 4.2K. This indicated a weak thermal link between stage 2 of the cryocoolers and the helium vessel which prevented the extra cooling capacity being available for re-condensing the additional helium boil off.

Modifications to SCW-1

In March 2011 BINP installed a new liner in SCW-1 with a reduced height to improve the thermal isolation. They also improved the thermal cooling of the RF tapers which connect the liner to the outer room temperature flange by installing a thermal link to the 50K radiation shield as had been done for the SCW at ALBA [5]. This resulted in a better interception of the heat conducted from the room temperature end of the electron beam vessel.

Modifications to SCW-2

In order to make the best use of the excess cooling power of the cryocoolers true re-condensers were installed in SCW-2. These consist of gold plated copper cylinders extending into the top of the helium vessel and connected to stage 2 of the current lead cryocoolers. (These changes could not be made for SCW-1 as it would require a complete removal of the helium vessel.) This modification was based on the new design by BINP for ALBA [5].

In addition the same modification to the RF tapers as described for SCW-1 were made in SCW-2.

Improved Performance

After these modifications the helium consumption in both wigglers fell to zero. The temperature of the helium and the magnet in both Wigglers dropped from 4.2K to respectively 3.5K in SCW-2 and 4.0K in SCW-1 with corresponding pressures of 0.53bar and 0.72 bar down from 1 bar. Also the temperatures of the inner radiation shield and the copper liner dropped significantly: from 16.4K to 9.1K in SCW-1 and from 10.5K to 9.1K in SCW-2.

Effect on Electron Beam Heating

The beam heating in the wigglers is calculated by using the temperature rise in the liner and the heat shields to deduce the extra cooling power of the cryocoolers plus the additional liquid helium boil off.

The power removed from the outer 60K heat shield by stage 1 of the cryocoolers is influenced far more by the current in the current leads than by any beam heating effects. Hence only the effect on stage 2 of the cryocoolers is taken into account. The figure below shows heat load in SCW-2 against the sum of the squares of the bunch charges to remove the effect of the bunch filling pattern. There is still some scatter to the results which is largely due to effects of varied bunch length.

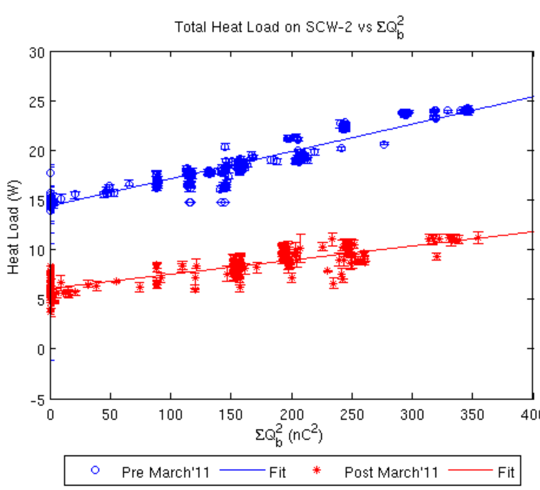

Figure 1: Total Heat Loads 10 K cryocoolers in SCW-2 before and after refurbishment

As can be seen from Figure 1, the beam heat load is much reduced. The same has been seen in SCW-1. The drastic reduction in both SCW-1 and SCW-2 has led to the conclusion that it is the common modification of the taper cooling on the 60K screen that has driven the improvement.

Measurements have also been taken to determine the relationship between bunch length (RF cavity voltage) and heat load, the results of which are shown in Figure 2. As can be seen, there is evidence of the expected relationship for SCW-1.

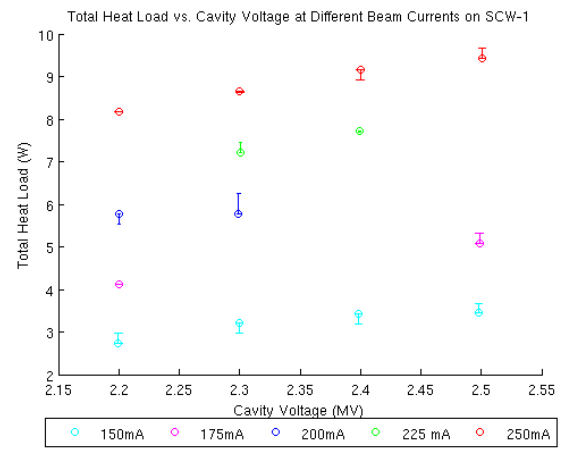

Figure 2: Heat Load Variation on SCW-1 against Cavity Voltage.

Table 1 shows predictions of the ideal situation vs actual measurements before and after the Wiggler refurbishments for a typical 686 bunch fill at 250mA, bunch length of 15ps. Given the uncertainties in the measurements the agreement between the actual and the predicted is very good for SCW-2 although less so for SCW-1. At present there is no explanation for the difference between SCW1 and SCW2

Table 1: Predicted Heat Loads From Beam Heating Only for SCW-1 and 2 Using Eq. 1 vs. Measured

In Watt	Predicted	Actual before	Actual after
SCW-1: 10mm liner	3.62	15.7	
SCW-1: 9mm liner	4.03		11.77
SCW-2: 10mm liner	3.27	8.98	4.54

Additional Operational Changes

Because both wigglers do not boil off any helium the temperature of the helium vessel will fall below 4.2K with a corresponding pressure below atmospheric. The helium system with its safety pressure relief valves, helium siphon entry and multiple KF couplings is not sufficiently leak tight to allow long periods of operation at negative pressure without the risk of air being drawn in. Hence we have fitted an additional pressure controller which uses the built-in heater to keep the helium vessel at 1040mbar. The amount of heat required equals the spare cooling capacity of the cryocoolers and will automatically adjust itself to any beam heating. By monitoring the heater output as function of beam current we have another measure of the beam heating.

CRYOCOOLED UNDULATOR

In June of 2010, Diamond Light Source (DLS) installed a CPMU manufactured by Danfysik [6]. It is a hybrid design with a 17.7mm period and a K of 1.7. The active length is about 2m, and the magnets are Vacodym 776 TP NdFeB from VacuumSchmelze. The optimum operating temperature was established to be 147K.

The magnet girders of the CPMU are cooled by a standard liquid nitrogen cryocooler system as used on many beam monochromators. In order to keep the magnets at the operating temperature of 147K the magnet girders are fitted with strip heaters. The temperature of the magnet girders is maintained by a standard Eurotherm controller.

Magnetic Performance

The CPMU has been operating since August 2010. Figure 3 shows the comparison with the spare undulator which the beam line was previously using[2].

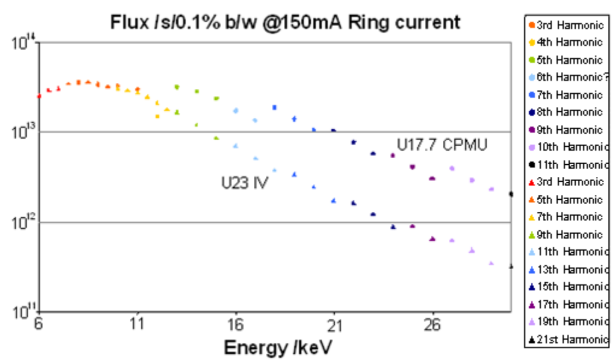

Figure 3: Comparison of CPMU17.7 and IVU23.

Operational Experience

The most significant risk associated with the CPMU is the loss of cryogenic cooling. The device is unbaked and the vacuum is maintained in part by the cryo-pumping of the cold surfaces. When the cooling fails and the temperature starts to rise the vacuum in the CPMU will deteriorate over a number of hours due to thermal desorption and the safety interlocks will shut off the stored to prevent excessive Gas Bremsstrahlung.

In order to deal with a major fault we have installed two additional valves in the high pressure cryolines between the CPMU and the cryocooler. This allows the cryocooler to be replaced while the CPMU is still warming up slowly.

Electron Beam Heating in the CPMU

A fixed heat load (Q_{tot}) is required to maintain the temperature of the CPMU magnets over and above the temperature that would be achieved through cooling alone. Assuming that all environmental heat sources are constant, the only varying heat sources are the beam heaters (Q_{htr}), and electron beam heating (Q_{ebh}). As such we have a direct measure of the electron beam heating through the relation

$$Q_{tot} = Q_{htr} + Q_{ebh} \qquad (2)$$

If the electron beam heating is dominated by RWE then Q_{ebh} should fall as g^{-1} where g is the gap, and the output from the strip heaters should rise to compensate for this reduction.

We have measured this at varying gaps with two different fill patterns at 250mA. As can be seen from the data in Figure 4 the electron beam heating is much stronger for 686 bunches than with 900 bunches. This is expected as, according to Equation 1, the heating should vary with Q_b^2, the charge per bunch squared. However we have insufficient data to show that $Q_{ebh} \sim (g^{-1})$.

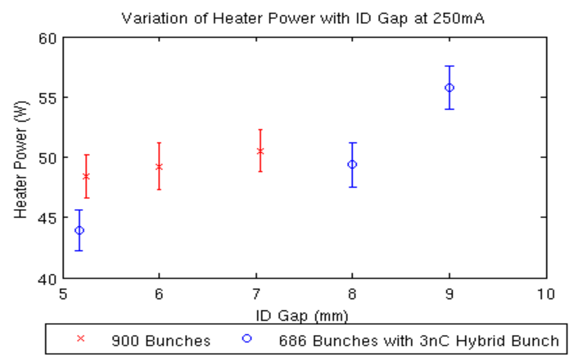

Figure 4: Heat load on CPMU with ID Gap.

We plan to make a more detailed study varying current, ID gap and the shape of the bunch train.

CONCLUSION

The large reduction in the beam effects in both superconducting wigglers after a reduction of the liner operating temperature show that the electron beam heating is dominated by RWE.

We can also study the electron beam heating by measuring the CPMU heater output as function of gap. Preliminary measurements also show that the beam heating is dominated by RWE.

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