ELECTRON BEAM HEATING EFFECTS IN SUPERCONDUCTING WIGGLERS AT DIAMOND LIGHT SOURCE

E. C. M. Rial and J. C. Schouten, Diamond Light Source, Oxfordshire, UK.

Abstract

We have investigated the effect of the electron beam on the heating of the copper beam tube (liner) which shields the coils and helium vessel in our two superconducting wigglers. We found that the heating is dominated by rf heating which increases with the square of the bunch charge while the direct synchrotron radiation heating is negligible. We present here the first result of a systematic study of this effect.

INTRODUCTION

Diamond Light Source (DLS) is currently operating with two multipole superconducting wigglers, one with 49 poles at 3.5T (I15) [1] and another with 45 poles at 4.2T (I12) [2]. The cryogenic arrangement is similar in both cases; each cryostat contains a liquid helium bath cooled by four cryocoolers. The design goal was to allow up to six months continuous operation in the storage ring between refilling the liquid helium bath. However, the helium boil-off is much higher than expected, necessitating much more frequent refills. As well as having a cost implication, this also currently poses a restriction on the operating beam current. It is important for us therefore to understand what the main drivers are of the beam heating in order to predict what the losses will be at higher current and also to guide us in finding possible solutions to the problem. It will also be of interest for the future application of superconducting undulators which need to run at much smaller vertical apertures where these effects may be stronger. In this report we present the results of measurements carried out under various beam conditions and their interpretation. We also briefly present our plans for dealing with the problem in the near and longer term.

OPERATING CONDITIONS

Prior to November 2008, Diamond had been operating in decay mode at beam currents of up to 250 mA, with just the I15 wiggler. At this stage the decaying beam did not overly stress the cryogenic system, and the rate of helium boil-off was tolerable. However after November 2008 Diamond began operating in 'top-up' mode, where the electron beam is topped up every 10 minutes to maintain the target current. Although successful in other aspects, this drastically increased helium use for the installed wiggler. Despite improvements to the cryostat in June 2009 the wiggler routinely exceeded its designed helium consumption of 0.05 litres/hour, boiling as much as 2.5 litres/hour at a beam current of 250 mA.

In March 2009 the second wiggler (I12) was installed, which had several improvements implemented in the design to reduce helium consumption. Nevertheless it still exceeded design specifications, boiling up to 1 litre/hour at 250 mA.

CRYOSTAT DESIGN

The operation of the two superconducting wigglers is fundamentally reliant on the $NbSn_3$ coils being held in a superconducting state at low temperatures. These low temperatures are maintained by keeping the magnet coils of each wiggler submerged in a bath of liquid helium. Thus any energy that enters the system will boil the helium in the bath, instead of causing the temperature of the magnet coils to rise.

The cryostat arrangement is illustrated in Figure 1 and consists of a helium vessel surrounded by two heat shields within an insulation vacuum, with a central beam tube which is thermally insulated from the helium vessel. There are four two-stage cryocoolers, two capable of cooling to 10 K and two capable of cooling to 4 K, which are connected to the cryostat at several places. The first stages of the two 4 K cold heads cool the high temperature superconductor leads as they enter the cryostat, and the second stages of these cold heads cool the helium vessel itself. The two heat shields are primarily cooled by the two 10 K cold heads, with the first stages cooling the outer 60 K heat shield, and the second stages cooling the inner 20 K heat shield.

The electron beam passes through a copper liner, which itself passes through a vacuum space that runs through the centre of the helium vessel. The liner is thermally connected to the inner heat shield at each end, but is isolated from the helium vessel by a small vacuum gap supported by PEEK (I15) or stainless steel (I12) spacers. In both cases the liner is made of high purity semi annealed copper with an elliptical aperture of 10 by 60 mm.

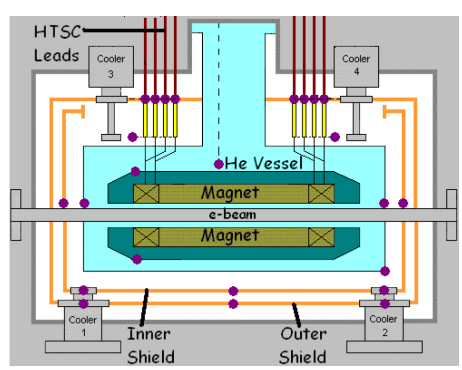

Figure 1: Illustration of Cryostat Structure.

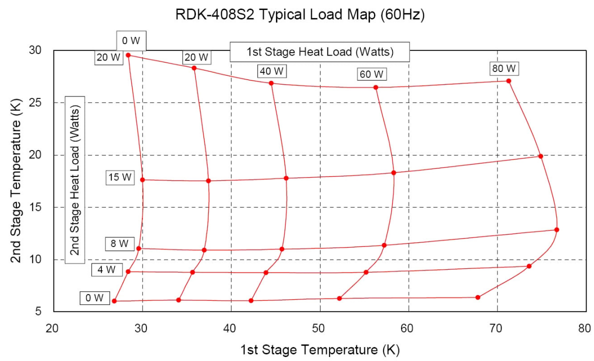

Figure 2: Typical Heat Load Map.

MEASURED HEAT LOADS

There are temperature sensors at or near each stage of each cold head, as well as at other locations, and the readings from these sensors are archived by the control system. The rate of helium boil-off is also recorded. The temperatures are translated into heat loads using the relevant heat load maps provided by suppliers, such as the one in Figure 2. Because we are mostly concerned about the heat loads on the liner, the power associated with the helium boil-off is summed with the heat loads of the second stages of the cryocoolers which cool the inner shield. Higher boil-off and differing field demands do affect the outer shield temperature, but any contribution to heat load proved not to be significant.

The data shown in this report was taken between September 2009 and May 2010, at beam currents between 70 mA and 275 mA, with the two typical bunch trains of 686 and 900 bunches (see Figure 3).

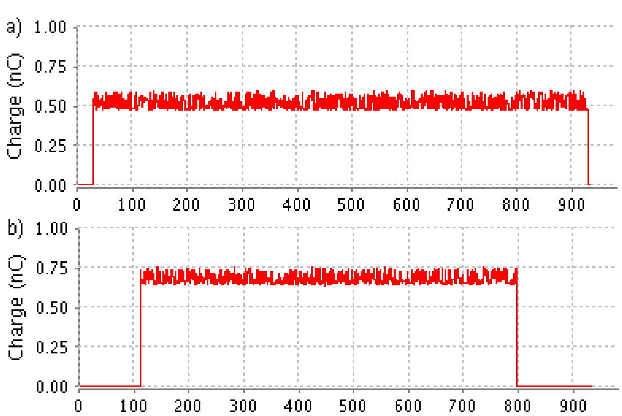

Figure 3: Two different filling patterns typically used at Diamond, a) 900 bunch train, b) 686 bunch train, shown for 250 mA total beam current.

Each point represents one data set, where a data set is collected for periods of continuous stored beam. The first two hours of each period is discarded as the cryostat is far from equilibrium during this time.

Interpreting the Results

The aim of this report is to establish the relationship between the heating seen by the wiggler cryostats (H) and the electron beam conditions.

Each of the N_b bunches in the ring (assumed here of equal charge Q_b), can cause heating of the liner through two independent mechanisms. The first mechanism is due to the impact of synchrotron radiation, resulting for example from misalignment of components or reflection, which increases linearly with bunch charge. The second mechanism is RF heating, which is proportional to the square of the bunch charge. We have therefore:

$$\mathrm{H} = aN_bQ_b + bN_bQ_b^2 \tag{1}$$

In order to observe how the heating varies with bunch charge, with varying number of bunches, we have charted the heating per bunch as a function of bunch charge:

$$\frac{\mathrm{H}}{N_b} = aQ_b + bQ_b^2 \tag{2}$$

Results for I12 and I15 Cryostats

Figure 4 plots the heating per bunch as seen by the I12 cryostat for both 686 and 900 long bunch trains.

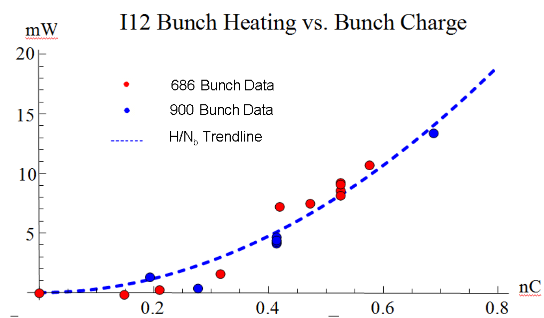

Figure 4: Heat Load vs. Bunch Charge for I12.

Each set of points appears to follow a similar relationship, and so a curve has been fitted to the combined data set. The parameters of this curve, *a* and *b*, have been assumed to be greater than zero, and are shown in Table 1.

Figure 5 plots the heating per bunch as seen by the I15 cryostat for both 686 and 900 long bunch trains.

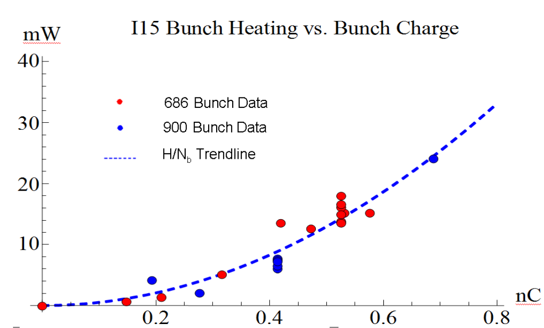

Figure 5: Bunch Heating vs. Bunch Charge for I15.

Again, although the data set for each fill pattern is plotted separately, the curve has been fitted to the combined data set. The parameters of *a* and *b* for this curve are also shown in Table 1.

Table 1: Deduced parameters for Equation 2 from fitted curves in Figures 4 and 5

Wiggler	a (mW/nC)	b (mW/nC^2)
I12	1.15×10^{-6}	29.66
I15	2.71×10^{-6}	51.82

Conclusions

Figures 4 and 5 clearly show that the extra heat load on the cryostats by the electron beam are related to the charge of each bunch in the bunch train. The coefficients of the fit shown in Table 1 also clearly indicate that the relationship of heating to bunch charge is predominantly quadratic for both the I12 and the I15 cryostats. This points to RF heating being the major contributory factor to the beam heating effects seen. We do not have enough data to see the effect of the change in electrical resistivity of the copper due to the increased temperature.

I15 sees approximately 60% more heat than I12, There are two possible explanations for this difference in heating. Firstly it should be noted that the length of the narrow gap region of I15 is slightly (11%) longer than I12, which both increases the heat load on the liner and the heat conduction path to the points of contact with the cryocooler, resulting in a correspondingly higher temperature in the liner. Secondly the liner in I15 (our first wiggler) has been repaired a few times in order to improve the thermal insulation. This has most probably changed the RRR value of the copper by work hardening resulting in a higher resistivity at low temperatures.

The fits shown in Figures 4 and 5 are quite reasonable, and so it is possible to extrapolate with some confidence the total power that will be seen at higher currents, specifically the target current of 300 mA for Diamond. These predictions are shown in Table 2, although they make no prediction of how much of the load will be borne by the cryocoolers, and how much by the helium bath.

Table 2: Predicted heat loads on the Diamond Wigglers for a stored beam of 300mA

Wiggler	N_b	Q_b (nC)	H/N_b (mW)	H (W)
I12	686	0.827	20.3	13.9
I12	900	0.630	11.8	10.6
I15	686	0.827	35.4	24.3
I15	900	0.630	20.6	18.5

Thus the heat load on the copper liner of the I15 wiggler is predicted to be up to 24.3 Watts (13 Watts per meter) at 300 mA, for a 686 bunch train.

REMEDIAL EFFORTS

Interim Solution

At beam currents of higher than 250 mA it is not currently possible to maintain enough helium in the I15 cryostat to enable the magnet to be used for a full six day user run. As entries into the tunnel storage ring vault are undesirable during user runs, a system has been installed to allow us to remotely control the transfer of extra helium into the cryostat. With this system in place disruption to the storage ring has been minimised, and enough helium has been maintained inside the cryostat to enable the I15 wiggler to be operated as required.

Future Plans

Although we have an interim solution for filling wigglers for consumption rates of up to 3.6 litres per hour, such a solution is clearly not ideal in the long-term, not least because of the significant cost involved. Two possibilities are therefore being examined: either installing some form of helium recovery system or making significant modifications to the wigglers themselves such that they can cope with the higher heat load.

REFERENCES

[1] S. Khrushchev et al, "3.5 Tesla 49-pole Superconducting Wiggler for DLS", Proceedings of RuPAC, 2006, Novosibirsk, p. 398.

[2] Technical Report 4.2 Tesla Superconducting Multipole Wiggler I12 Beamline of DLS, Mezentsev et al, 2009