BEAM DUMP AND COLLIMATION DESIGN STUDIES FOR NLS: THERMAL AND STRUCTURAL BEHAVIOUR

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Abstract

The proposed UK New Light Source project will need beam dump to absorb a bunch charge of 200 pC with the repetition rates starting from 1 kHz initially up to 1 MHz in the upgrade. We are exploring an option of a solid dump with a graphite core to absorb the beam power up to 450 kW for the upgrade option as this is the most challenging design. Since the beam dump design will also affect the building layout, the choice of its design should be made at an early stage. Based on the feasibility studies of a solid dump, a decision not to go for more complex water dump can be taken. The post linac collimation section should protect the undulators from irradiation due to beam halo particles. This paper shows results and conclusions from simulations of the impact of the NLS beam on different solid beam dump solutions and the effect of the beam halo on the collimators.

INTRODUCTION

The 2.25 GeV energy electron beam of the UK New Light Source (NLS) [1] needs to be dumped at several locations and each beam dump has to absorb a power of ~450 W when operating at the baseline bunch repetition rate of 1 kHz and ~450 kW when upgraded to 1 MHz.

For the upgrade option with 1 MHz repetition rate, it has been proposed to transport beams to a single 450 kW beam dump. A solid dump similar to the XFEL [2] is considered for NLS to absorb the beam power of 450 kW. The beam power is entirely contained in solid materials in such a dump, minimising the problems associated with radioactive water handling in case of water dump. In order to design a solid dump, careful choices on the dump material, beam size and its sweeping have to be made to keep the temperatures and stresses within the acceptance limits.

A collimation system is necessary in NLS to deal with the beam halo which will be generated due to dark current in the injector and in the accelerating modules, scattering from residual gas particles, off-energy beam tails caused by CSR in the bunch compressors and beam spreader. If not collimated, this beam halo can demagnetise the undulator magnet, cause Bremsstrahlung co-axial with the photon beam lines and can activate the components of the facility.

MATERIAL CHOICE, BEAM RADIUS AND SWEEPING REQUIREMENTS

Heat extraction capabilities of the power deposited by the beam are the principal constraint in the dump design. We adopt a geometrical solution based on a cylindrical absorber. We assumed in the calculations a cooling system which keeps the external surface of the cylinder at 40 °C. A material of low Z, with low power dissipation characteristics per unit length, together with high radial thermal conductivity will help reduce the equilibrium temperature (temperature in the steady state) inside the dump. To achieve high radial thermal conductivity we need to reduce the radial distance towards the cooled surface.

These constraints lead to a dump design of a low density core covered by a higher density shell with low thermal resistance and therefore, the materials we are interested in are graphite for the dump core and copper for the outer shell. The characteristics of graphite and copper used in the design presented here are shown in Table 1.

Table 1: Physical characteristics of graphite and copper used for dump design simulations

	Graphite	Copper
Density [g/cm^3]	1.71	8.96
Critical energy E_C[MeV]	84.25	20.17
Radiation Length X_0[cm]	25.1	1.44
Molière radius R_M[cm]	7	1.6
Melting Temp T_{melt}[°C]	3800	1083
Operating Temp T_{op}[°C]	500-600	<200
Static stress limit [MPa]	100-250 compression >40 tension	$\sigma_{0.2}\approx$150-400 (plast. limit)
Cyclic stress limit [MPa]	60 compression 30 tension	60-100

The beam size at the entrance of the beam dump has to be large enough in order to reduce the deposited energy density and not to damage the graphite. The limit of energy density for the graphite to avoid reaching the ultimate tensile strength limit is of 248 J/g [2]. However, this is a very conservative limit and excursions beyond it could be acceptable. For the energy that 100,000 bunches would deposit we are above tolerable tensile limit for beam sizes smaller than 2 mm. Therefore, we cannot continuously direct the beam to a fixed position in the dump core and we will require sweeping the beam to different positions inside the dump. In this study we have selected a radial beam size of 2 mm as a starting point, which should be perfectly achievable in the beam line that transports the beam towards the dump and this beam size keeps us below the tensile limit for slightly less than

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100,000 bunches. The simulations shown in the following sections indicate that by sweeping the beam in twelve different sweep spots both stress and temperature within graphite core remain below acceptable levels.

To deal with increase in the power density per length by a factor of 1.75 compared to XFEL, radius of sweep circle is roughly scaled from 5 cm (XFEL) to ~9 cm [3]. This radius will be equivalent as to having a bigger beam size and therefore thermal effects will also relax as heat will flow towards the centre of the core as well as towards the outer copper shell which will allow a rapid cool down of the dump.

Optimisation of Dump Radial Dimensions

The radial extension of an electromagnetic shower is characterised by the Molière radius (R_M) and can be calculated by the following expression [2]:

$$R_M \approx \frac{21.2 MeV}{E_c} X_0 \qquad (1)$$

Where E_C is the critical energy and X_0 is the radiation length of the material. And the radius needed to absorb 99% of the energy deposited radially by the electromagnetic showers is five times R_M.

In our initial design we are using a sweep radius of 9 cm adding a thickness of 5 cm of graphite after that, which corresponds to 0.72 R_M. Therefore the thickness of the copper shell needs to be 4.3 R_M which corresponds to 7 cm thus giving a total radius of 21 cm (14 cm of graphite plus 7 cm of copper).

Optimisation of Dump Length

The length of material that is needed to avoid a leakage of beam energy bigger than 1% can be expressed as:

$$L_{99\%} = \left(1.52 \cdot \ln\left(\frac{E_0}{MeV}\right) - 4.1 \cdot \ln\left(\frac{E_c}{MeV}\right) + 17.6\right) X_0 \qquad (2)$$

E_0 is the primary particle initial energy (2.25 GeV in our case). For the graphite and electrons of 2.25 GeV, $L_{99\%}$ corresponds to a total length of 280 cm. In order to reduce this length we can use copper as a backstopper (which has an $L_{99\%}$ at 2.25 GeV of 17 cm) downstream of the graphite. We chose a combination of 200 cm of graphite and 10 cm of copper for our studies.

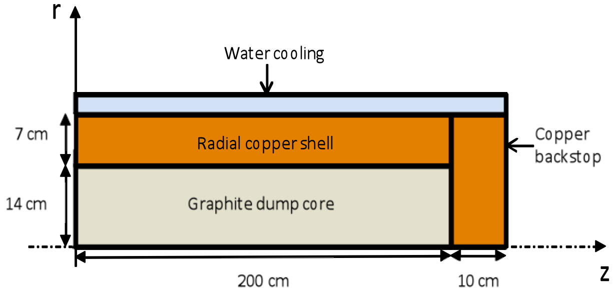

Figure 1: Schematic cylindrical layout of the proposed dump solution.

This configuration, shown in Fig. 1, absorbs 99.4% of the primary beam energy and is the one used in the ANSYS [4] calculations. The increment of temperature in the copper backstop after 1 second of operation at 1MHz is below 10K in this case, therefore safe for the graphite-copper junction [2].

STEADY STATE AND TRANSIENT RESULTS FOR THE BEAM DUMP

The FLUKA [5] outputs of energy density deposition were converted into a power density using a beam frequency of 1 MHz and introduced as heat generation into the ANSYS model at the beam sweep positions in the dump for a certain time. The external surface of the copper shell was forced to remain at 40 °C simulating water cooling. Fig. 2 shows the temperatures achieved by a steady state model of dump configuration showed in Fig. 1. The maximum temperature reached inside the graphite body is ~430 °C (where the electromagnetic shower generated from the beam is maximum), and just below 150 °C in the impacting open surface of the graphite. These temperatures are well below 500 °C which sets the operational limit for graphite in open air; this temperature can be even higher if the dump window is kept under vacuum.

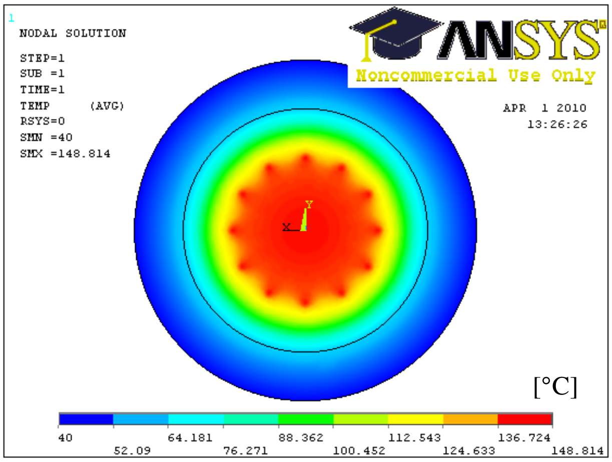

Figure 2: Temperatures at the entrance of the beam dump.

A transient study was also performed to assess a proper sweeping frequency according to the stresses obtained. The results of the stress calculations in the graphite core and copper shell can be compared with the mechanical stress limits of the material by means of a certain failure criterion expressed by the equivalent stress value σ_{eq}, which can be defined as:

$$\sigma_{eq} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \qquad (3)$$

At a given position σ_1, σ_2 and σ_3, the first, second and third components of stress, which are the stress components in the three main directions of the given coordinate system, which in our case is Cartesian.

In this report, results using a sweeping frequency of 10 Hz that means staying in the same spot for 100 ms (100,000 bunches) are shown. This frequency sets the highest limit of consecutive bunches hitting the same spot in graphite and therefore it can be used as a reference.

Fig. 3 shows a quadratic fit done to each peak of each cycle and the time and value when that stress stops increasing. The compressive stress value at equilibrium is just below 3 MPa and it is achieved after ~13 seconds.

A compressive stress value of 3 MPa is well below the cyclic stress limit of the graphite. However, the peak of stress, tensile stress, happens in the graphite/copper union and a quadratic fit done to the stress values in that union shows that the stress plateau is reached after ~33 seconds at a value of 27 MPa which is below the cyclic stress limit for copper and just under the cyclic stress limit in tension for graphite.

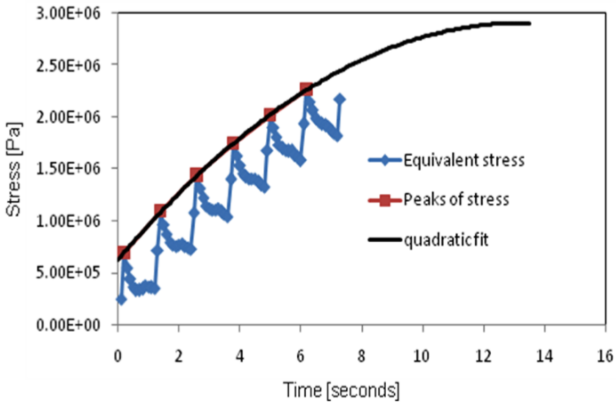

Figure 3: Equivalent stress in the initial sweep spot position in the graphite core and a quadratic fit done to its peaks of stress.

The cyclic stress behaviour showed in these calculations is mainly due to the low sweeping frequency chosen, which corresponds to the maximum time the beam can stay in a fixed position in graphite for the selected beam size of 2 mm. If we were to increase this frequency and instead of stopping in each sweep position 100 ms we would stop 20 or 10 ms the stress behaviour would approximate more to a quasi-static regime rather than a cyclic one. Therefore increasing the sweeping frequency could help maintain the beam dump avoiding stress fatigue scenarios and using the static stress limit as reference instead which is higher than the cyclic one. Nevertheless, the stress shown in these studies are within the safe operation limits and make us think that the beam dump would survive with this configuration and this kind of sweeping/beam size strategy.

COLLIMATOR DESIGN

The betatron collimators will need adjustable gap in two transverse planes, whereas energy collimators will have jaws in the horizontal plane. A copper block of 10 radiation length should be enough to absorb the beam halo particles. In order to minimise wakefields arising due to a step change of beam radius from 20mm to the required gaps in the collimators of ~2 mm, a tapered design will be required for these collimators. For our calculations, we consider that the halo contains 10^{-3} of the beam particles. A steady state study of the thermal behaviour of the upper jaw was done to determine the need of cooling of the system. We did not use a tapered geometry for these calculations. Even if the jaws will not need to be cooled by water they will need to release the heat to a heat sink: a bigger radiative surface, with or without fins, that will help get rid of the excess heat. This surface will then release the heat to the ambient air. Fig. 4 shows a model of collimator being heated by the halo and connected to two copper fins cooled by a convection value equivalent to natural convection (10 W/m^2). The temperature reached by the collimator core is below the maximum copper operating temperature. The other option is to build a forced convection system that will ensure a cool down temperature.

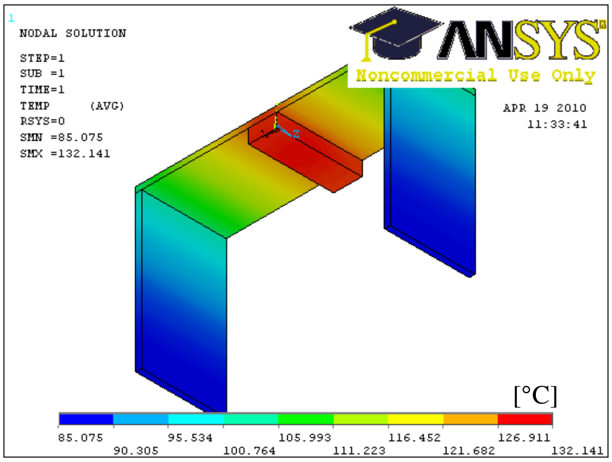

Figure 4: Temperatures at a copper collimator model and at its heat sink fins, in °C.

CONCLUSIONS

These simulations indicate that it is possible to use the solid dump based on graphite for the high repetition rate of 1 MHz for the NLS. A beam dump design (size, materials and configuration) together with a beam sweeping strategy were chosen and their suitability was proven. A future study on tritium production due to the cooling water should be addressed.

A heat sink and natural convection are enough to avoid high temperatures in the collimator.

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