SIMULATION OF THE BEAM DUMP FOR A HIGH INTENSITY ELECTRON GUN

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Abstract

The CLIC Drive Beam is a high-intensity pulsed electron beam. A test facility for the Drive Beam electron gun will soon be commissioned at CERN. In this contribution we outline the design of a beam dump / Faraday cup capable of resisting the beam's thermal load.

The test facility will operate initially up to 140 keV. At such low energies, the electrons are absorbed very close to the surface of the dump, leading to a large energy deposition density in this thin layer. In order not to damage the dump, the beam must be spread over a large surface. For this reason, a small-angled cone has been chosen. Simulations using geant4 have been performed to estimate the distribution of energy deposition in the dump. The heat transport both within the electron pulse and between pulses has been modelled using finite element methods to check the resistance of the dump at high repetition rates. In addition, the possibility of using a moveable dump to measure the beam profile and emittance is discussed.

INTRODUCTION

The Compact Linear Collider (CLIC) will use a novel two-beam acceleration scheme to collide electrons and positrons at up to 3TeV [1]. Energy is extracted from a very intense, lower energy Drive Beam (DB) using specially designed RF structures, and transferred to the less intense, high energy colliding beams.

In order to prove the feasibility of generating such an intense electron beam, a new test stand will be installed at CERN during 2015. Only the electron gun is to be tested, so the beam will remain unbunched and at low energy. Some relevant parameters are shown in table 1.

Table 1: Relevant Parameters for the CLIC Drive Beam Test Stand

Beam Energy	100 – 140 keV
Beam Current	4.2 A
Pulse Length	150 µs
Pulse Population	4×10^{15} e$^-$
Pulse Energy	88 J
Repetition Frequency	1 - 50 Hz
Beam Emittance	12 mm mrad
Beam size at dump	σ=2.5mm

The high beam current means that stopping the beam is not trivial. Low energy electron beams are stopped very quickly in almost all materials, so the density of energy deposition close to the surface is extremely high. Thus, a beam dump must be designed to safely absorb the beam by distributing the heat load over as large a surface as possible.

In addition, the test stand aims to demonstrate the stability of the electron gun. Both the current flatness during a pulse and the charge variation between pulses should be below 0.1%. Thus, the beam current must be measured with a resolution at least at this level.

BEAM DUMP DESIGN

The depth profiles for energy deposition by the electron gun beam in various materials are shown in figure 1, assuming that the beam is incident normal to the surface. Since the energy is deposited in a very thin layer, the energy deposition density, and therefore the temperature rise, will be very large. The integrated peak energy deposition during the pulse is shown in figure 2 for the most promising materials. It can be seen that for the nominal current, no material can survive the full pulse. Thus, the beam must be incident at a shallow angle in order to dilute the beam.

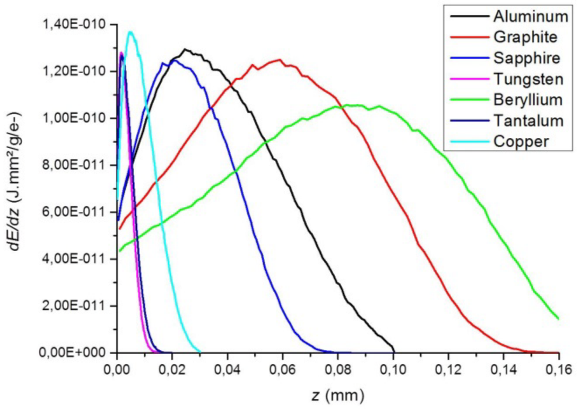

Figure 1: Energy deposition profiles for a 140 keV electron beam incident normal to the surface, for various materials, normalised to the material density.

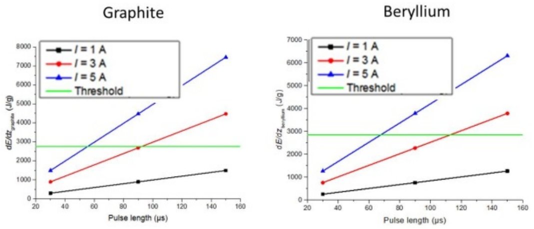

Figure 2: Integrated energy deposition during the pulse.

It can be seen that Beryllium had the best performance. However, its toxicity considerably increases the difficulty and cost of manufacture. Graphite performs almost as well and has a considerable advantage in terms of safety. Graphite is therefore retained as the material for the beam dump. The physical properties of amorphous graphite are shown in table 2.

Table 2: Physical Properties of Amorphous Graphite (at 300K where applicable) [2]

Density	1.8 g / cm^3
Specific Heat Capacity	0.76 J / g K
Thermal Conductivity	100 W / m K
Thermal Expansion Coefficient	4.0 x10^{-6} / K
Sublimation Temperature	3900 K

The high specific heat capacity, which also rises with temperature, means that graphite can accept 7.9 kJ / g before reaching its sublimation point. In reality, however, the stress caused by the sudden thermal expansion would destroy the graphite at a much lower temperature. Thermo-mechanical stress due to sudden heating ΔT is given by

$$Stress = E \, \alpha \, \Delta T \, f(v)$$

where E is the Young's modulus, α the coefficient of thermal expansion, and v Poisson's ratio. The nature of $f(v)$ depends on whether the problem is considered in 1, 2 or 3 dimensions.

During heating some parts of the graphite feel compressive stress and other regions feel tensile stress. The graphite to be used in the dump construction has a strength of 120 MPa (compressive) and 40 MPa (tensile). However it is estimated that the repeated stress cycles will reduce the dump lifetime if the maximum stress exceeds 32 MPa [3]. This equates to a maximum single-shot temperature rise of $\Delta T \approx 1100$ K.

Despite the favourable properties shown above, the intensity of the beam is sufficiently high to destroy the graphite if it hits the surface at right angles. If the beam is incident at an angle θ to the surface, the area over which the beam is spread is increased by a factor of $1/\sin\theta$. In order to maximise this area, a small-angled cone has been chosen for the beam dump. The baseline design is shown in figure 3. A graphite cone of 12 mm thickness is mounted in a copper block. The copper is provided with water cooling in order to take away the excess heat. The cone has an open diameter of 50 mm and a length of 500mm, giving a half-angle of 2.86°.

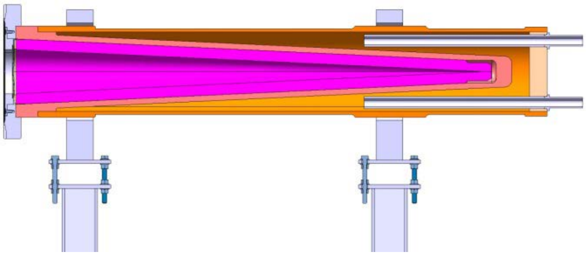

Figure 3: Design of the proposed beam dump. The inner cone is graphite, while the outer block is made of copper.

ENERGY DEPOSITION SIMULATIONS

The range of 140 keV electrons in graphite is given by the ESTAR database as 180 μm [4], calculated according to the Continuous Slowing Down Approximation (CSDA). However, this range is measured along the trajectory of the electron. Since the electron transport in this regime is dominated by multiple scattering, the penetration depth is in fact considerably smaller than the CSDA range.

Furthermore, if the electron hits the surface with a small angle, it has a large probability of being scattered out of the material as shown in figure 4. In the case of a conical dump, this does not mean that it escapes the dump but that it is re-incident in another location. The mean penetration depth is decreased, since the electron has a lower energy on its second hit. Since electrons are only being 'swapped' between different locations inside the cone, there is no spreading out effect due to backscattering, unless the beam is incident off-axis.

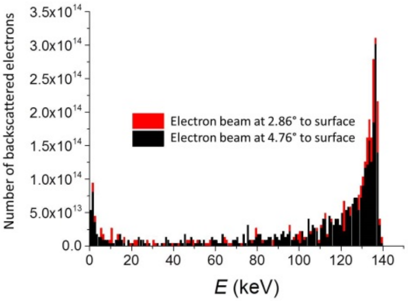

Figure 4: Energy spectrum of electrons exiting the graphite after scattering. A pulse of 4x10^{15} electrons incident at a small angle on a graphite surface was simulated.

In order to calculate the energy deposition profile, simulations have been carried out using the Geant4 code [5]. The simulations were carried out using either a gaussian or uniform circular beam, incident on-axis to a graphite cone of variable opening angle. The backscattered electrons are also tracked, so that the derived energy deposition profile includes the effect of re-incident electrons. For each event, the energy deposition is scored, its distance from the surface of the cone is calculated, and it is added to a histogram. The Geant4 step length is limited to a maximum of 1 μm in order to increase the accuracy of the profile. It can be seen from figure 5 that the effective range of the electrons strongly reduces at small angles. This is mostly due to the effect of backscattered electrons.

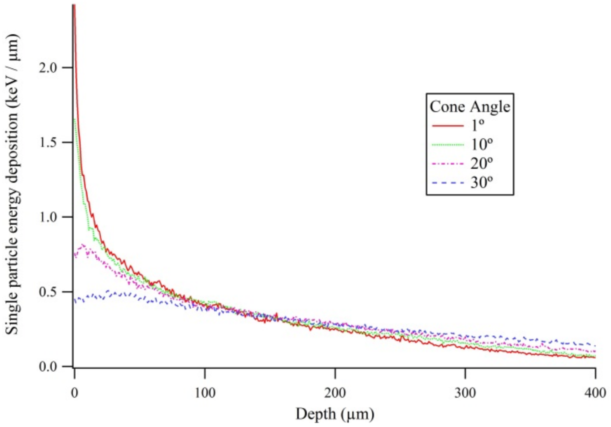

Figure 5: Energy deposition profiles for a beam of 140 keV electrons hitting a graphite cone of various angles.

The energy deposition profile is then normalised to the expected beam flux. The beam at the dump is expected to be Gaussian with a diameter (±2σ) of 10 mm. This equates to a charge density in the center of the beam of 1.5 mC / cm^2, integrating over one pulse. However, the conical surface dilutes the charge density by a factor of $1/\sin\theta$. In the baseline dump design the cone half-angle of 2.86° gives an effective charge density of 75 µC / cm^2. The dependence of the effective range on the cone angle acts in opposition to the dilution effect, giving an unexpected relationship for the peak energy deposition, as shown in figure 6. It can be seen that the worst case is for a cone of 10-20°.

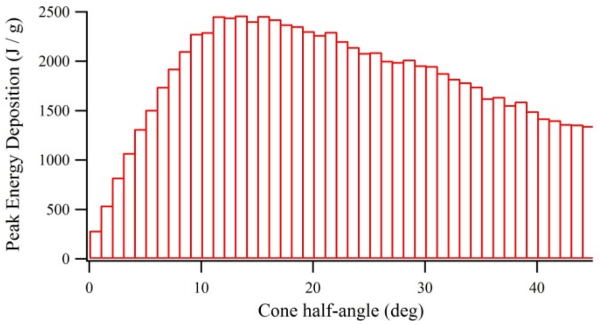

Figure 6: Peak energy deposition versus cone angle, taking account the beam parameters and the dilution effect of the angled surface.

THERMAL SIMULATIONS

The diameter of the beam is much larger than the depth over which the energy is deposited. Thus, it is possible to treat the heat transport problem as 1-dimensional, under the conservative assumption that the diffusion of heat parallel to the surface is negligible compared to that normal to the surface.

We used a simple finite element method to estimate the temperature profile of the graphite. In each time step,

1) If the beam is on, heat is deposited according to the profile computed above using geant4.

2) Heat is radiated from the first (surface) bin.

3) Heat is transported from each bin to its two neighbours according to the temperature difference between them.

The size of the bins and the timestep were chosen to be sufficiently small that the results are independent of small changes in these values. The specific heat capacity of graphite is strongly dependent on temperature (figure 7), and the temperature calculation must take this into account.

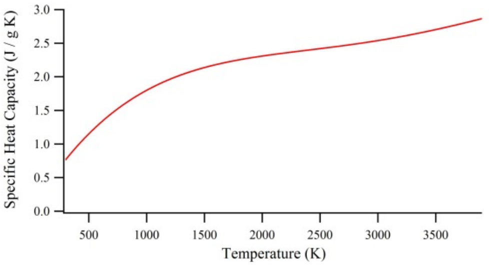

Figure 7: Specific heat capacity of graphite.

First, we look at the heat transport within the 150 µs of the beam pulse. The thermal diffusion length μ of a material is given by

$$\mu(t) = 2\sqrt{kt/C\rho} \approx 200\mu m$$

where k is the thermal conductivity, C the specific heat capacity and ρ the density [6]. Since the beam energy is deposited in a layer comparable in thickness to the diffusion length, we can predict that the heat transport will be significant even in this short time period, and will reduce the peak temperature reached. This is confirmed by the simulation as shown in figure 8.

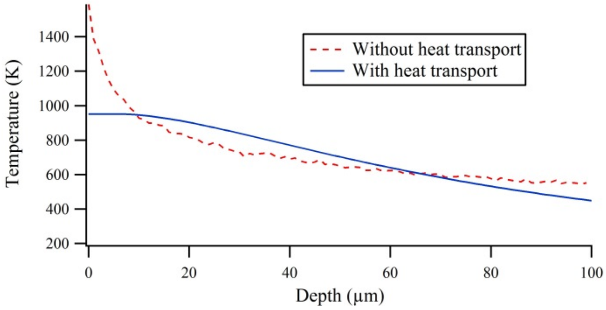

Figure 8: Temperature profile of the graphite at the end of a single beam pulse, with and without simulation of the heat transport.

Secondly, we look at the temperature evolution over several pulses. We simulate the most demanding case of operation at 50 Hz. It is necessary to make several assumptions about the transfer of heat from the graphite into the copper block. We assume that the water cooling system will be able to maintain the temperature rise in the copper block to a maximum of 50 K. At 50Hz the average power deposited by the beam is over 5 kW, so the design of the cooling system is not trivial, but it will not be discussed in this paper. With this condition, and taking a conservative value for the thermal conductivity across the graphite/copper boundary, we can see from figure 9 that the maximum temperature stabilises after a few shots.

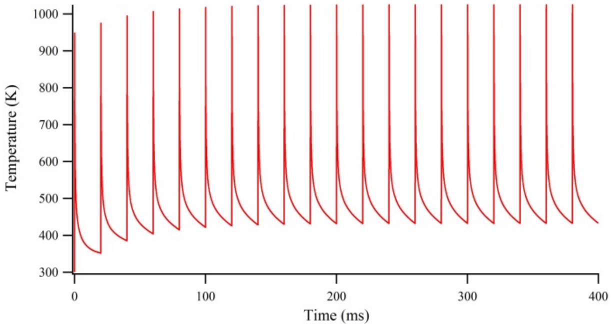

Figure 9: Peak temperature in the beam dump when exposed to the electron beam at 50Hz.

CURRENT MEASUREMENT

In order to measure the beam current, three options have been considered, and a final decision is yet to be reached.

1. Isolate the Whole Dump

In order to use the beam dump as a Faraday Cup, it must be electrically isolated. The three main points of contact are the beam pipe, the mechanical supports, and the cooling water circuit. The latter in particular is difficult from an engineering point of view. In addition, due to the considerable size of the dump, care must be taken to extract the current in such a way as to preserve the signal integrity.

2. Isolate the Graphite Plates Only

An alternative solution is to electrically isolate the graphite plates from the copper cooling block. Naturally, a good thermal contact is still required, so the insulating material must have a high thermal conductivity as well as a large electrical resistance. Shapal [7] fulfils these requirements as well as being relatively easy to machine. Its thermal properties being similar to those of graphite (see table 3) it should be possible replace the 12mm thick graphite cone with two 6mm thick nesting cones, the first of graphite and the second of Shapal, without affecting the thermal performance of the dump.

Table 3: Thermal Properties of Shapal [7]

Thermal Conductivity	90 W / m K
Thermal Expansion Coefficient	5.1 x10^{-6} / K
Maximum Temperature	2200 K

However, it is difficult to assure a good thermal contact between two large surfaces in vacuum. A large pressure must be exerted in order to maximise the thermal conduction between the two materials. By adding a layer of Shapal, we create two interfaces, graphite-Shapal and Shapal-copper, thus increasing the risk of a poor thermal contact.

3. Beam Current Transformer

Given the technical difficulties of isolating the dump, it may be more practical to separate the functions of beam dump and current measurement. In this case the dump would be preceded by a beam current transformer which would measure the current entering the dump, and the dump itself would not have to be electrically isolated.

CONCLUSION

A test stand for the electron gun of the CLIC Drive Beam will be installed at CERN. This paper presents the design of the beam dump for this high-intensity beam. No material can withstand the beam at normal incidence. Instead, a conical dump is proposed. We have shown that the dump can withstand the beam energy deposition even at the highest repetition rate of 50Hz.

ACKNOWLEDGEMENTS

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REFERENCES

[1] M. Aicheler et al., "A Multi-TeV linear collider based on CLIC technology: CLIC Conceptual Design Report", Geneva, 2012.
[2] Data Sheet, Ringsdorff Specialty Graphite, www.sglgroup.com (Accessed 26/08/2014).
[3] F. Carra, A. Dallocchio, "LINAC4 3MeV Test Stand : Thermo-Mechanical Fatigue Analysis of the SLIT", Geneva, 2010.
[4] ESTAR database, NIST, physics.nist.gov/PhysRefData/Star/Text/ESTAR.html (Accessed 25/08/2014).
[5] S. Agostinelli et al., "Geant4 - a simulation toolkit", Nucl. Instrum. Meth. A 506 (2003) 250–303.
[6] E. Marín, "Characteristic dimensions for heat transfer", Lat. Am. J. Phys. Educ. 4 (2010).
[7] http://www.shapal.info/physicalproperties/, (Accessed 26/08/2014).