THE FERMI@ELETTRA BEAM DUMP *

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Abstract

The electron beam dump is designed to accomodate a 1 nC, 1.8 GeV[1], 50 Hz repetition rate beam. Using GEANT simulations, materials are chosen to absorb the 99% of the beam energy and to limit the radio-isotope production. In addition, from the energy deposition distribution inside the dump, the thermal load is estimated. The necessary requirements, the design and the expected performance are presented and discussed.

INTRODUCTION

The fermi@elettra project [1] is a linac based FEL, currently being build at Sincrotrone Trieste. The electron beam specifications are given in table 1.

Table 1: FERMI@elettra Main Parameters

Parameter	FEL-1	FEL-2
Beam Energy	1.2 GeV	
Bunch charge	0.8 nC	1 nC
Norm. Emittance	0.8 - 1.2 μm.rad	1 - 2 μm.rad
Repetition Rate	10-50 Hz	50 Hz

Although the beam average power at present is modest (90 W) the electron beam dump is designed in consideration of future power upgrades up to a maximum of 10 kW. At this power range, an aluminum-graphite type of dump is suitable and it has to meet the following requirements :

- Compact solid beam dump, with reduced radioisotope production.
- No major maintenance interventions for many years.
- Absorption efficiency $>$ 99%.
- Graphite temperature $<$ 450°[2].
- Aluminum temperature $<$ 200°[2].

BEAM DUMP

Geant simulation were performed in order to specify the beam dump design. Geant is a toolkit for the simulation of the passage of particles through matter, and calculates the energy deposited in material [3].

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[1] Maximum electron energy accessible by the linac.

Design

The Fermi@elettra beam dump is sketched in figure 1. It is made of a graphite core cylinder (^{6}**C** , $\rho = 2.1$ g.cm^{-3}). Graphite practically does not produce radioisotope [4], so it is the first target the electrons encounter, but its absorption length is long ($\mathcal{L}_{\mathrm{C}} \simeq 20$ cm). Surrounding the core, the main body is made of aluminum (^{13}**Al** , $\rho = 2.7$ g.cm^{-3}). Aluminum is classified as "Relatively unsuceptible to activation" and has a shorter absorption length ($\mathcal{L}_{\mathrm{Al}} \simeq 9$ cm). To absorb the shower tail a copper (^{29}**Cu** , $\rho = 8.96$ g.cm^{-3}) downstream end is added. Copper is "Moderately suceptible to activation" but has a short absorption length ($\mathcal{L}_{\mathrm{Cu}} \simeq 1.5$ cm).

The graphite core cylinder is pushed 10 cm inwards the aluminum body in order to reduce backscattered exiting secondary particles.

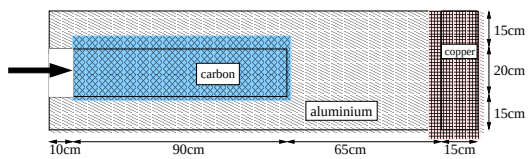

Figure 1: FERMI@elettra Beam Dump design.

Geant Simulation

Electrons are shot into the beam dump one by one. This is repeated a large number of times to insure statistical significance. The primary electron transversal positions and momentum directions are randomly taken from a gaussian distribution defined from the beam emittance and beta values at the beam dump position. The beam dump itself is defined as described in the previous section. Geant tracks the primary particle, the secondary particles are created at each interaction along propagation. It calculates the energy deposited at each of the track steps. Figure 2 shows an example of 1 electron shot into the beam dump.

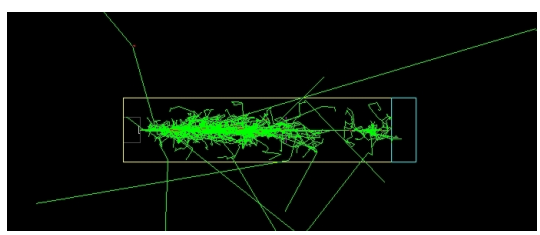

Figure 2: One eletron tracking in Geant. Each green line represents a particle from the shower.

Particle Yield, Deposited Energy

Figure 3 shows the distribution of the ratio of the total deposited energy to the incoming electron energy. It shows the absorption efficiency distribution which is in average 99.1%.

There is less than 1% of the incoming electron which escape the beam dump. Most of the escaping particles are electrons or photons with an average energy ∼5 MeV. But most of the non absorped energy is carried away by the few (less than 1% in number of exiting particles) slow neutrons. For these neutrons, an external shield will be added accordingly.

The escaping energy propagates downstream behind the beam dump for 55%, backwards in front of it for 10% and on the sides for 35%

Figure 4 presents the energy deposition distribution profile. From this distribution, the temperature can be estimated.

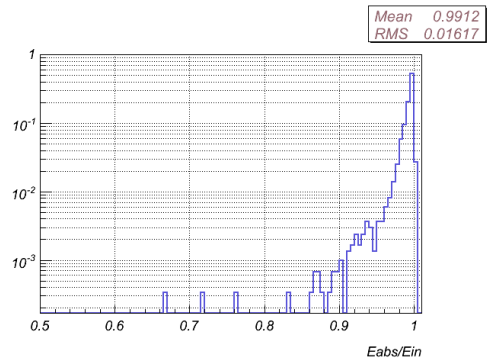

Figure 3: Distribution of the ratio between the deposited energy and the primary electron energy. Normalized to one electron

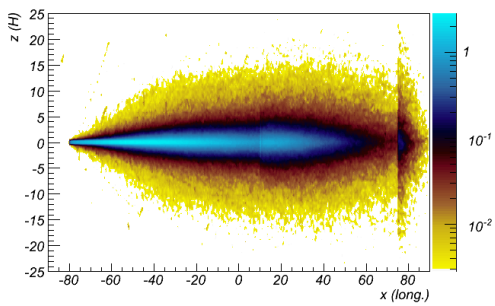

Figure 4: Distribution of the deposited energy in the beam dump, viewed from the top in MeV/cm^2. Normalized to one electron.

TEMPERATURE

The general distribution of the temperature $T(r, z, t)$ inside a cylindrical dump is obtained with the solution of the heat equation:

$$\frac{\partial}{\partial t}T(r,z,t) = \frac{\lambda}{\rho c}\nabla^2 T(r,z,t) + \frac{1}{\rho c}Q(r,z,t) \quad (1)$$

with ρ the mass density, λ the heat conductivity and c the specific heat. $Q(r, z, t)$ is the heat source which describes how much energy is deposited per unit of volume, where r is the radius and z is in the direction of the incoming electrons. We are looking for an estimate of the temperature which can be reached in the dump. One can divide the problem in two parts: instantaneous heating and average heating.

Instantaneous Heating

Instantaneous heating comes from the energy of a single bunch. The beam size (about 0.1 mm) is much larger than the characteristic thermal diffusion length :

$$L = \sqrt{\lambda t_b/\rho c} \sim 9\,\text{nm} \quad (2)$$

Assuming the instantaneous rise of temperature is directly proportional to the deposited energy we have:

$$\Delta T_{\text{inst}} = \frac{E(r,z)N_b}{\rho c} \quad (3)$$

where $E(r, z)$ is the deposited energy per unit of volume from one electron bunch and N_b is the number of electron per bunch. This process can damage the surface of the dump if the energy deposited is ≥ 100 J.cm^{-2}. In our case, the deposited energy per surface unit is much less.

Average Heating

Average heating assumes the energy deposition is not pulsed in time. The equilibrium temperature is obtain from the stationnary case:

$$\frac{\partial}{\partial t}T(r,z,t) = 0 \quad (4)$$

with $Q(r, z) = N_b\,\nu_b\,E(r, z)$ where ν_b is the repetition rate. Assuming only radial flow on obtain :

$$\Delta T_{\text{eq}}(r,z) = \frac{N_b\,\nu_b}{\lambda}\int_0^R \frac{ds}{s}\int_0^s E(u,z)u\,du \quad (5)$$

which is integrated numerically using the energy deposition distribution from Geant simulation.

Figure 5 shows the two contributions of the temperature rise at the dump center ($r = 0$) along the beam dump axis. The presented case is for a 10 nC bunch charge and 10 Hz repetition rate, 2 μm.rad emittance and $\beta_{x,y}$ = 20 m [5]. It assumes a perfect heat flow on the sides of the beam dump, in contact with the ambient air or a cooling system. As in equations 3 and 5 the temperature is directly proportional to the bunch charge, it is straight forward to scale the temperature in figure 5 for other values of bunch charge.

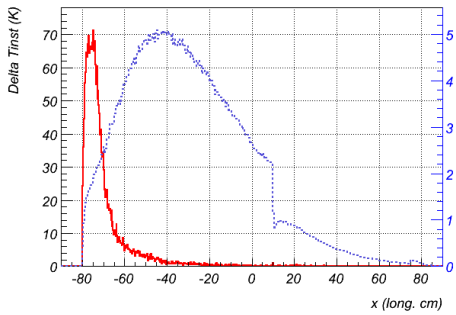

Figure 5: Temperature variation at the dump center ($r = 0$). The two contributions are shown : $\Delta T_{\rm inst}$ in plain red line with the left hand side axis, $\Delta T_{\rm eq}$ in dotted blue line with the left hand side axis.

In case of a smaller emittance the beam spot size is smaller and has an influence on the temperature rise. The instantaneous temperature goes with the inverse square of the beam size. Modifying the emittance from 2 μm.rad to 0.8 μm.rad, implies a factor $\sigma^2/\sigma'^2 = \epsilon/\epsilon' = 2/0.8 = 2.5$ on the maximum instantaneous temperature rise. Even in these conditions, the maximum temperature stays below the critical ones.

CONCLUSION

The presented beam dump for the FERMI@elettra project meets the requirements in terms of energy absorption, reduced radioisotope production, and temperature rise. Figure 6 shows the design of the dump that is currently in the construction phase. Table 2 sums up the maximum temperature rise in the graphite core expected in the present normal running conditions. Based on the above results no cooling system is needed for the time being. Moreover, it has a high stopping power as the probability for a primary electron to exit the beam dump of the order of 10^{-11}, with a number of electron per bunch of 1 nC of about 10^{11}.

Table 2: Maximum Temperature Rise from the Instantaneous and Average Heating in the Graphite. (in °C.)

Freq.	$\epsilon = 2$		$\epsilon = 0.8$	
f	$\Delta T_{\rm inst}^{\rm max}$	$\Delta T_{\rm eq}^{\rm max}$	$\Delta T_{\rm inst}^{\rm max}$	$\Delta T_{\rm eq}^{\rm max}$
10 Hz	10	0.5	25	0.5
50 Hz	10	2.5	25	2.5

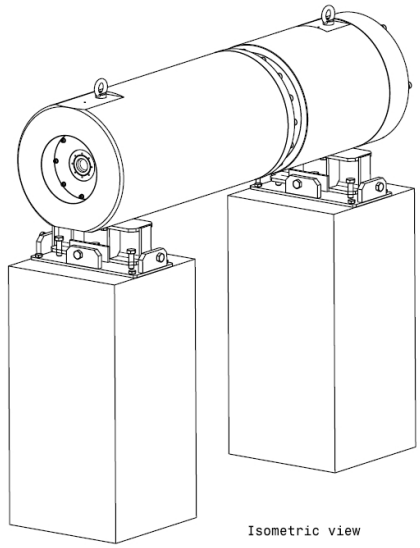

Figure 6: Beam Dump design.

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