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Time Response Requirement for the BLM/FSD System

The temporal response requirement for beam shutoff in the event of beam loss in the accelerator is determined by the worst-case time for beam to burn through the accelerator vacuum wall. This worst-case condition occurs when the highest possible beam current density strikes a thin wall at normal incidence. Such a circumstance might occur if beam were to strike the thin wall of a stainless steel bellows convolution, for example. In this circumstance, electron *dE/dx* is the energy deposition mechanism, without any shower multiplication. Grazing incidence situations are more complicated, due to factors such as increased electron path length, shower multiplication, electrons scattering out, and a larger projected beam area. Peter Kloeppel has calculated, using EGS, several such cases, with the conclusion that normal incidence is indeed the worst case. In what follows, I will estimate a minimum beam burn through time for the normal incidence case, and from this number, infer a response time requirement for the BLM/FSD system.

The logic in calculating this estimated burn through time is as follows. We first calculate the power deposited in the material under the worst case conditions. We then demonstrate that radiation cannot cool this power level at any temperature close to the material melting point. We then calculate the time to reach the material melting point given the power deposition, and show that this time is very short. This short time essentially precludes any significant conductive cooling. Hence, the material melts.

I take the worst case beam to be 200 μA CW, with a uniformly filled beam spot of 100 μ diameter. For my example, I use stainless steel with a density ρ of 7.9 gm/cm^3 and a thickness t of a typical bellows wall, 0.006" = 0.015 cm. It is worth noting that the time to melt through a thin plate of any particular material does not depend on the density or thickness of the material. I use *dE/dx* for minimum ionizing particles equal to 1.67 MeV/(gm/cm^2). Thus, in this example, the power deposited in the thin stainless steel bellows wall is:

$$P = (dE/dx)\rho t I = 40.2 \text{ W}.$$

Note that this power is deposited initially in an area of 0.785×10^{-4} cm^2, giving an instantaneous power deposition over half a MW/cm^2!! Even a 1 mm diameter beam spot gives over 5 kW/cm^2, which is well outside the realm of tolerable, for stainless steel or any other material.

To estimate the temperature which would be reached were radiation the only heat loss mechanism, I assume we have a 1 mm diameter emitting area, ten times larger in diameter than the minimum beam spot size, which in fact allows for significant radial thermal conduction over the time scales of interest. I take an emissivity of 0.4, and assume we are radiating equally from two surfaces to a 0 K cold surface. This conservative set of conditions gives a temperature of 5760 K to dissipate 40 Watts, very substantially above the melting point of stainless steel, 1700 K (1427 C).

To calculate the instantaneous rate of temperature rise, I use a specific heat for stainless steel of 0.50 j/gm-K. For 40 W deposited in a 100 μ diameter spot, this gives an instantaneous rate of rise *dT/dt* of 8.6×10^6 K/sec. This rate of rise would bring stainless steel to its melting temperature in 166 μsec. The actual time to melt through will be different for a variety or reasons. For example, the actual beam spot is not likely to be uniformly populated, but has some profile, leading to a greater power deposition in the center of the beam spot. There is atmospheric pressure on the outside of the heated material, which will force a hole to appear before the actual melting temperature is reached. As the heated area is small, and since stainless steel retains much of its strength to quite high temperatures, this effect will not be large. Even though the thermal conductivity of stainless if small, there will be some radial conduction. The specific heat changes somewhat as the temperature is increased, but this is not a large effect. The instantaneous rate of temperature rise calculated above is by far the dominant consideration. Even at the melting temperature, radiation provides only a fraction of a watt of cooling, and so does essentially nothing to damp the rapid temperature rise.

The characteristic time for radial diffusion is given by:

$$\tau = r^2 / 4\alpha.$$

Thus, the characteristic time to double the radius of the heated area in stainless steel approaches 500 µsec, much longer than the calculated time to reach the melting temperature, justifying the statement that radial conduction does little to alleviate the problem.

It is amusing to note that the instantaneous rate of rise of temperature in a thin plate does not depend on either the density or thickness of the material, but only on the beam current density. In particular:

$$dT / dt = (dE / dx) I / C_p \text{ A}.$$

Thus, for example, copper, with its lower melting temperature and lower specific heat, would reach its melting temperature more quickly than stainless steel – a calculated time of 98 µsec, which is again a time too short for conduction to offer much relief. Niobium has a much higher melting temperature than stainless, but only about half the specific heat, leading to a much higher value for the instantaneous rate of temperature rise, but a very comparable estimate for the burn through time.

The basic conclusion from the above estimate is that the instantaneous rate of temperature rise in thin metal plates struck by a 200 µA CW beam of 100 µ diameter is so high that it will bring that material to its melting point in a time on the order of 100 µsec. The time scale is so short that radial heat conduction does not offer much relief. Radiative cooling of these high power levels is not significant until temperatures well above the melting point are reached. Given that the basic time scale of concern is 100 µsec, we should require that the BLM/FSD system respond in a time safely less than this number. A response time of 50 µsec is a realistic and conservative design goal, and will provide some margin for uncertainties such as non-uniform beam profiles, burn through temperatures somewhat lower than the melting temperature, and the possibility that the beam spot might be smaller than 100 µ in diameter. The lower limit for the response time is given by the fact that in principle, beam could persist for 20 µsec after a beam loss was detected.