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Beam Loss Monitor Performance Requirements

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ABSTRACT

Performance requirements for the Beam Loss Monitor/Fast Shut Down System are established based on estimated worst case beam loss accidents.

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Beam Loss Monitor Performance Requirements

The function of the Beam Loss Monitors (BLMs) is to sense levels of beam loss which may cause physical damage to the accelerator. The damage mechanism is a localized melt through of the accelerator vacuum wall. The BLMs transmit signals to the Fast Shut Down (FSD) system indicating the presence of potentially harmful beam loss levels. The FSD system then acts to shut beam off at the localized beam loss site within a time sufficiently short to prevent damage. There are two performance requirements which must be specified: (1) the threshold level of beam loss which the BLMs must respond to; and (2) the time within which the FSD system must shut off beam at the loss site.

In an earlier TN (TN-92-046), I demonstrated that a small diameter, full current CW beam, incident normally on a thin vacuum wall, would melt a hole through a vacuum wall in a relatively short time, of order 100 μsec. In the worst case situation of a very tiny beam spot, the calculated melt through times are nearly independent of the material of the vacuum wall. This calculation has been applied to establish the time response requirement for the BLM/FSD system - item (2) above.

We can use the same consideration discussed in TN-92-046 to establish a meaningful threshold level for BLM response. We do so by estimating an absolute worst case time for beam to melt through a thin wall. We calculate this time as $t_{min} = \Delta T_m C_p A_{beam} / I_{beam}(dE/dx)$, where ΔT_m is the melting temperature minus the ambient temperature (assumed to be 35 C) and C_p is the specific heat of the material struck by beam, A_{beam} and I_{beam} are the transverse area and average current of the beam, and dE/dx is the electron energy loss. For our worst case, we take a uniform 100 μ diameter beam spot, a CW current of 200 μA, and a dE/dx of 2 MeV-cm^2/gm. We consider only two materials - stainless steel and niobium. For these two cases, we find:

Stainless steel: ΔT_m = 1392 C, C_p = 0.50 J/gm-^{o}C, yields t_{min} = 137 μsec

Niobium: ΔT_m = 2435 C, C_p = 0.268 J/gm-^{o}C, yields t_{min} = 128 μsec

These minimum melt through times are fairly conservative estimates, for several reasons. First, the value of dE/dx used overestimates the actual energy deposited in the material; second, the specific heat increases as the temperature rises, which increases t_{min}; and third, the deposited energy in the above estimate is only sufficient to raise the material to its melting temperature, and does not include the latent heat of fusion necessary to actually melt the material.

The minimum melt through times above correspond to delivering an integrated beam current of at least 25600 μA-μsec. It is not unreasonable to allow 10% of this integrated beam current to be the threshold for a BLM trip. In TN-92-046, we established a maximum allowed time of 50 μsec between a BLM trip signal and beam shut off at the site of the beam loss. This time explicitly includes 21 μsec to account for the maximum possible beam stored in the accelerator. This 50 μsec corresponds to 10000 μA-μsec of beam loss. If we add to this a suggested 2500 μA-μsec BLM trip threshold, we come to 12500 μA-μsec, less than 50% of the minimum time integrated beam current to melt through in a worst case beam loss accident. It is recognized that in practice it is very difficult to set a BLM threshold precisely. However, even a factor of five error in setting the suggested threshold would not bring the integrated beam current to the level necessary for a melt through in the worst case.

The worst case minimum melt through times above were calculated by assuming that all of the dE/dx energy loss is deposited in the local volume hit by beam, and that no mechanisms to remove heat act during the short time available. It is worth examining these assumptions a bit, to determine how conservative our BLM trip threshold and FSD time response specification really is. In particular, since by far the worst possible melt through accident in the accelerator would be in the niobium within a cryomodule, this case should be examined in more detail.

In TN-92-046, it was shown that radiative cooling is not significant until temperatures well above the melting temperature are reached. However, thermal diffusion is a significant heat removal mechanism in niobium, even at room temperature, for conditions not very different from the worst case conditions above. To see this, one can define a characteristic time for thermal diffusion τ, equal to the area of the beam divided by the thermal diffusivity of the material struck by beam. If the energy per unit volume delivered to the material during time τ is less than the energy per unit volume necessary to melt the material, thermal diffusion will keep the material from melting through locally. Of course in that case, the energy delivered to the material in question is still producing heat, and cannot be tolerated indefinitely.

The characteristic time τ is:

$$\tau = (A_{beam})C_p\rho/\kappa$$

where C_p is the material specific heat, and κ is the thermal conductivity. The rate at which energy is deposited in a thin plate is:

$$P = (dE/dx)(I_{beam})\rho t$$

where t is the plate thickness. Since tA_{beam} is the volume in which the energy is deposited, the energy deposited per unit volume during time τ is:

$$P\tau/V = (dE/dx)(I_{beam})\rho^2C_p/\kappa$$

The energy per unit volume required to bring the material to its melting point is reasonably estimated as $T_mC_p\rho$. By requiring that the energy deposited per unit volume during time τ is less than the energy per unit volume necessary to melt the material, we obtain:

$$(dE/dx)(I_{beam})\rho/T_m\kappa < 1$$

For niobium, using $dE/dx = 2$ MeV-cm^2/gm, $\rho = 8.5$ gm/cm^3, $T_m = 2470$ C, and $\kappa = 0.55$ J/sec-cm-C, we find I_{beam} less than 80 μA. This estimate indicates that even at room temperature, beam currents below about 80 μA would not melt through niobium. In the case where the niobium is at liquid helium temperature, the thermal conductivity of even our poorest quality niobium is greatly increased, and in this case even a full current beam would act to heat the entire niobium structure and evaporate the helium, rather than melt through the niobium locally. For stainless steel, the above estimate gives I_{beam} less than 15 μA.

The discussion above is based on the idea that a beam melt through accident would occur when the beam passes through a single thin plate, and thus that the effects of electromagnetic shower multiplication do not need to be considered. One can imagine a beam loss incident in one of the linacs where a particular mis-steering of the beam could direct it through multiple niobium walls. In the worst of such cases, shower multiplication could significantly increase the local dE/dx losses. However, in these cases, the niobium, and hence the radiation length, is distributed over a reasonable longitudinal distance. Estimates based on various real geometries within our cryomodules, and approximations to shower development theory, indicate that in these cases the spot size grows faster than the number of electrons present, even at shower maximum, and thus the time to melt room temperature niobium through actually increases as the shower develops. Again, if the niobium were at liquid helium temperature, the loss would heat bulk niobium and evaporate helium, rather than melt through. I conclude that it is highly unlikely that any beam loss accident could quickly melt through the niobium if it were at liquid helium temperature, and that even at room temperature, the 2500 μA-μsec BLM trip threshold, coupled with a 50 μsec FSD propagation time to beam shutoff at the loss site, offers fully adequate protection.

In summary, I believe that the proper requirements for the BLM/FSD system are that (1) the BLMs produce a trip signal following a time integrated beam loss of 2500 μA-μsec, and that (2) the FSD system shut off beam at the site of the localized beam loss no longer than 50 μsec after receipt of a BLM trip signal.

It should be noted that there is one presently identified situation where the above BLM/FSD specifications will not protect accelerator elements. This is the case of RF power loss to the RF separators. Such an accident could damage the extraction septa in a time short compared to 50 μsec, and indeed in a time short compared even to the 21 μsec of maximum possible stored beam. This situation must be dealt with separately.

Discussions with John O'Meara, Walter Tuzel, and Larry Doolittle have been very helpful in my thinking about these specifications. Of course, any errors are mine alone.