Cause and Effect of a Melted Target

Chris Booth – 22nd January 2009

This note attempts to address two questions:

- If the target was heated by repeatedly intercepting the proton beam at injection, how much beam loss would have to be caused to heat the target to melting point?
- If the target tip is maintained at melting point, what temperature would the stop and the magnets reach? (Could these have been damaged as a result overheating?)

Energy deposited by 70 MeV protons

From the Particle Data Group publications, it is clear that the $\frac{\mathrm{d}E}{\mathrm{d}x}$ curves for aluminium ($Z = 13$), iron ($Z = 26$) and tin ($Z = 50$) are all very similar in shape. It is therefore assumed that energy deposition in titanium (Z = 22) can be calculated by using the curve for iron and renormalizing by the tabulated values of $\left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\mathrm{min}}$. At 70 MeV (kinetic energy), protons have $\beta\gamma \sim 0.4$, and $\frac{\mathrm{d}E}{\mathrm{d}x} \sim 6.56\ \mathrm{MeV/(g\ cm^{-2})} \sim 30\ \mathrm{MeV/cm}$. Assuming $\frac{\mathrm{d}E}{\mathrm{d}x} \propto \frac{1}{\beta^2}$, which should not be a bad approximation below 70 MeV, treating the target as many thin slices gives the energy loss in traversing 10 mm of titanium as 41 MeV. (As a cross check, the same method determines the range to be 12.3 mm, compared with a PDG value of 14.5 mm. The figure of 41 MeV is therefore probably a slight overestimate.)

Power required to melt the target

An estimate of the beam heating required to melt the target can be obtained by considering an isolated 5 mm high section of target blade, and equating heat in to radiated heat out. Assuming a radiative emissivity of 30% (a guess!), the power required to reach the melting point of 1941 K or 1668°C is 26.5 W. This is equivalent (using the previous result) to the energy deposited by 4×10^{12} 70 MeV protons per second. However, recent running was not at 1 Hz, but at 50/128 Hz (or less). This implies intercepting 1.0×10^{13} low energy protons per pulse, or 40% on the injected current. This presumably could not have occurred in a sustained manner, without ISIS either tripping or inhibiting injection.

What is more, the above figure is definitely a lower limit. The target is not an isolated 5 mm section, so heat would be conducted up from the exposed section to adjacent parts of the target and then the shaft, and part of the heat would be radiated away from these sections. The thermal model used for previous calculations was re-run, with the energy deposition increased to 26.5 W (instead of 1.9 W in normal running). With the same assumed radiative emissivity, the temperature of the target tip was found to reach 1610 K, 330 K below melting point. For the tip to reach melting point, the input power has to be 47 W. This corresponds to 7.2×10^{12} 70 MeV protons per second or 1.8×10^{13} protons per actuation at 50/128 Hz (73% of the injected beam).

Effect on stop and magnets

Despite the above findings, the thermal model was used to determine the effect on the stop (292 mm from the tip) and magnets (349 mm from the tip) of maintaining the target at melting point for a prolonged period. Because of the low thermal conductivity of titanium, together with the large distances involved, these components only attain temperatures of 10° and 8° above ambient. What is more, it takes a large fraction of an hour for even these temperatures to be reached. Thermal damage to these components due to beam heating therefore appears to be ruled out.

Conclusions

It appears that the target could not have been melted as a result of prolonged exposure to protons at injection over many actuations. The only way this could have occurred was if the target interrupted basically the whole beam for several pulses, with either the ISIS trip not functioning or the machine being reset several times in close succession.

Even with the target tip held at the melting point of titanium for an hour or more, there is insufficient conduction up the shaft to cause damage to the magnets or to explain loosening of the stop due to thermal expansion.