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# In How Long the ESS Beam Pulse Would Start Melting Steel/Copper Accelerating Components?

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A technical report on the

# IN HOW LONG THE ESS BEAM PULSE WOULD START MELTING STEEL/COPPER ACCELERATING COMPONENTS?

by

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### Abstract

In this report we calculated the amount of time in which the full ESS beam pulse would start melting steel or copper accelerator components. Calculations were done for energies 2.5 MeV - 80 MeV. The results are summarized in the conclusions part of the report.

## 1 Background

One of the functions of the ESS beam loss monitoring (BLM) system is to serve as a part of machine protection system (MPS) and generate a beam abort signal to prevent damage of accelerator components. In this report we calculated amount of time in which the full ESS beam would start melting steel and copper (we worked with stainless steel 304 grade). For lower beam energies the average energy transfer $\mathrm{d}E/\mathrm{d}x$ is larger and the energy transfer is even higher at the end of the proton range (Bragg peak, see below). Here we assumed that the beam deposits energy in steel/copper accelerator components instantaneously and estimated the MPS time response required to prevent start of melting the steel/copper for energies 2.5 MeV - 80 MeV (proton energy range in the ESS DTL). **Note that it usually takes several times less energy deposition (or several times shorter time) to start permanently damaging a material [1]. So one would have to rescale all the results in this report by a factor (usually less than 10) to get an MPS time response required to prevent permanently damaging steel/copper accelerator components.** Also note that it is most unlike to have a full beam loss upon an accelerator components during the normal operation of ESS. However, there is a higher risk during the commissioning phase when the repetition rate is low and steering is done manually.

## 2 Calculation Model

As already mentioned, we assume a full ESS beam hitting a steel or copper block perpendicularly (Figure 1). Figures 2 and 3 show the energy transfer/stopping power (MeV/mm) at the entrance (where protons hit the material) and range of protons in both of them as a function of proton energy [2].

When a proton beam pulse hits a block of steel or copper, it deposits energy in it and heats it up. The temperature growth can be calculated from the following equation:

$$cm\Delta T = E_{dep} \tag{1}$$

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[1] M.C. Ross et al., "Single Pulse Damage in Copper", Linac 2000 Proceedings, p. 47

[2] Calculated by SRIM/TRIM software

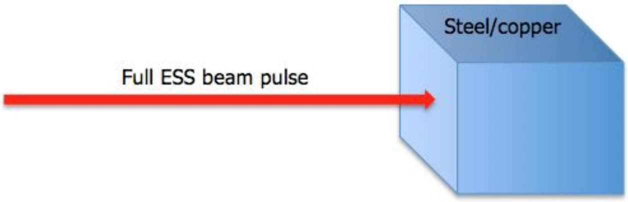

Fig. 1: Loss model - a full ESS beam hitting a steel/copper block perpendicularly.

where $c$ is the heat capacitance of the material, $m$ is the mass of the material hit by the beam, $\Delta T$ is the temperature rise and $E_{dep}$ is the energy deposited in the material by the beam.

If we assume that the beam shape is circular with a radius of $r$, then we could rewrite the equation above as:

$$\int_0^R c \cdot \rho \pi r^2 \Delta T \mathrm{d}x = \int_0^R \frac{\mathrm{d}E}{\mathrm{d}x} \cdot N \mathrm{d}x \tag{2}$$

where $\rho$ is a density of the material, $\mathrm{d}x$ is the infinitesimal longitudinal length, $R$ is the stopping range of protons in the material, $\mathrm{d}E/\mathrm{d}x$ is the stopping power of protons at the entrance (assuming it being constant) and $N$ is the number of protons ($\mathrm{d}E/\mathrm{d}x \cdot \mathrm{d}x$ would be energy deposited in the infinitesimal length $\mathrm{d}x$ of material by one proton).

We would like to calculate how many protons will heat up the material up to a melting temperature $T_{melt}$. If the material is at a an initial temperature $T_i$ in the beginning, we can find for $N$:

$$N = \frac{c\rho\pi r^2 (T_{melt} - T_i)}{\mathrm{d}E/\mathrm{d}x} \tag{3}$$

We plotted the number of protons it takes to start melting steel/copper as a function of proton energy (for 1, 2, 3 and 4 mm beam radius - Figure 4). $T_i \approx 25\ ^0\mathrm{C}$; $c_{\mathrm{steel}} = 0.5\ \mathrm{J/g^0C}$, $\rho_{\mathrm{steel}} = 8.03\ \mathrm{g/cm^3}$, $T_{melt,\mathrm{steel}} = 1370\ ^0\mathrm{C}$; $c_{\mathrm{copper}} = 0.385\ \mathrm{J/g^0C}$, $\rho_{\mathrm{copper}} = 8.94\ \mathrm{g/cm^3}$, $T_{melt,\mathrm{copper}} = 1085\ ^0\mathrm{C}$. Notice that $N \sim r^2$, that is twice larger (radius) beam will take 4 times as many protons to have a same effect as a given size beam.

At ESS, the proton beam is pulsed and there is $8.94 \cdot 10^{14}$ protons in 2.86 ms long pulse (or rate $= 3.126 \cdot 10^{17}$ protons/sec within a pulse). The amount of time in which the beam starts melting steel/copper accelerator components is N/rate (see Figure 5).

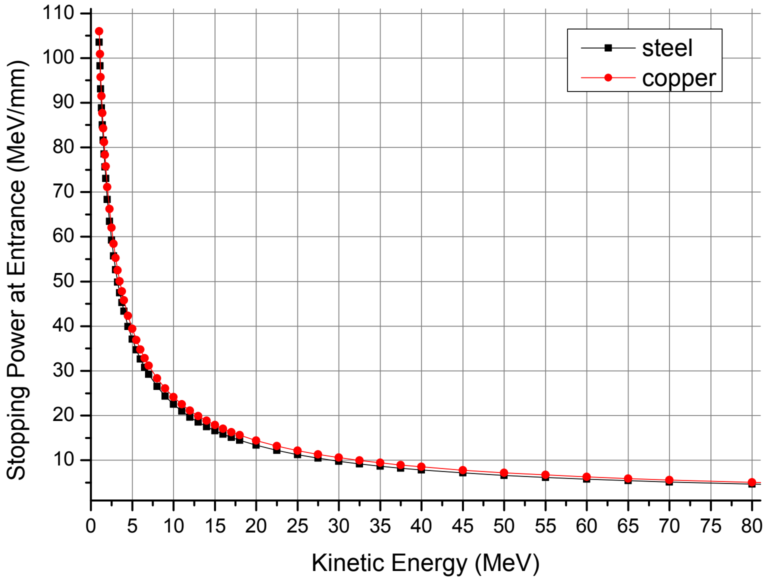

Fig. 2: Stopping power of protons at the entrance of steel and copper, as a function of proton energy.

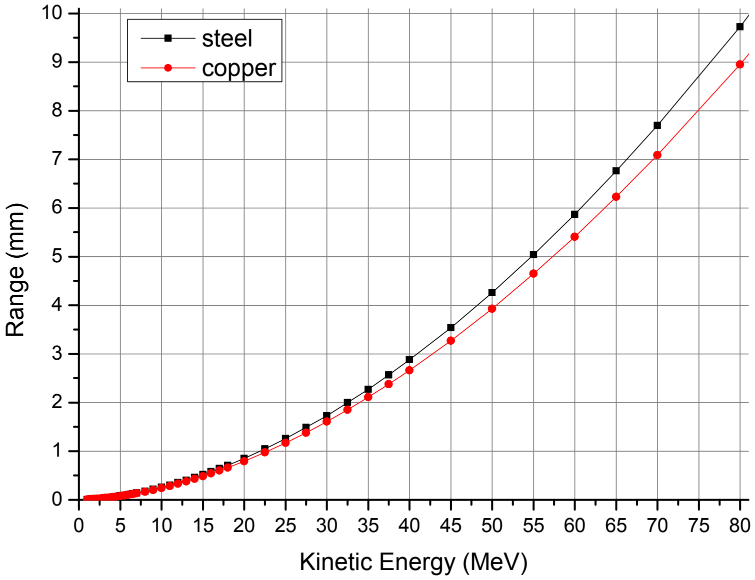

Fig. 3: Ranges of protons in steel and copper, as a function of proton energy.

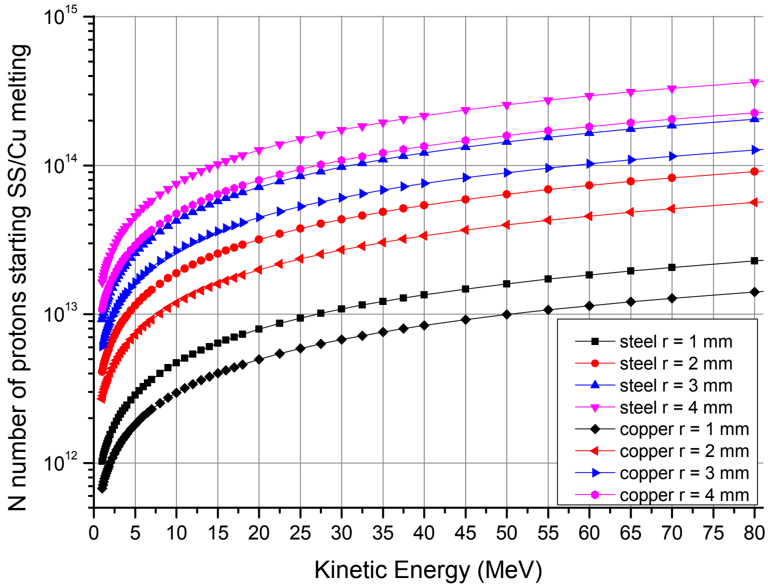

Fig. 4: Number of protons which would start melting steel/copper.

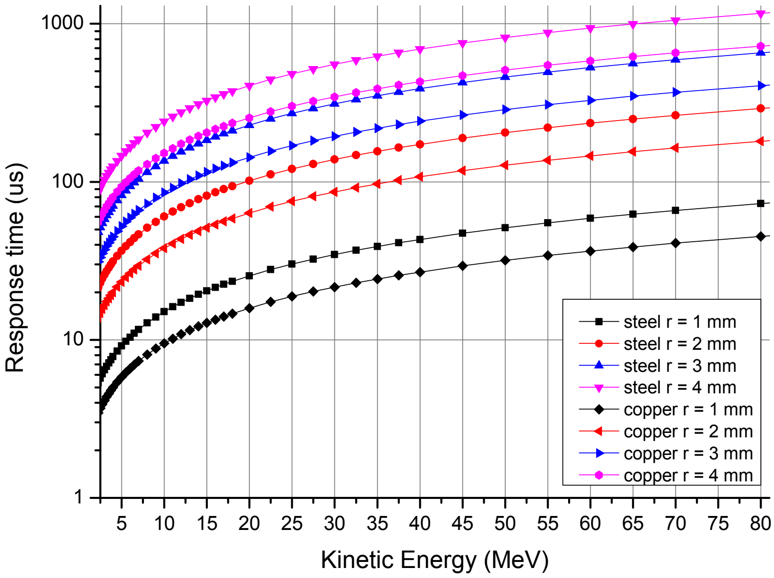

Fig. 5: Time in which a full ESS beam would start melting steel/copper.

# 3 Bragg Ratio

As mentioned in the beginning, the energy transfer is maximum at the end of the range (the so called Bragg peak appears at the end of the range). In order to take this into account we calculated the ratio of the stopping power at the Bragg peak versus the stopping power at the entrance (Bragg ratio). The ratios are given in the Table 1. They are calculated from the Bragg peaks generated by the SRIM/TRIM software. An example of such a Bragg peak in copper is shown in Figure 6, for 10 MeV proton. As we see the Bragg ratio in this case is $\sim 4.4$.

Tab. 1: Bragg ratio for steel and copper.

| Proton energy (MeV) | Bragg ratio for copper | Bragg ratio for steel |
|---|---|---|
| 2.5 | 2.7 | 3.2 |
| 5.0 | 3.6 | 4.2 |
| 7.5 | 4.0 | 4.3 |
| 10.0 | 4.4 | 4.6 |
| 12.5 | 4.7 | 4.7 |
| 15.0 | 4.8 | 4.7 |
| 17.5 | 5 | 4.9 |
| 20.0 | 5 | 5 |
| 25.0 | 5 | 5 |
| 30.0 | 5 | 5 |
| 35.0 | 5 | 5 |
| 40.0 | 5 | 5 |
| 45.0 | 5 | 5 |
| 50.0 | 5 | 5 |
| 60.0 | 5 | 5 |
| 70.0 | 5 | 5 |
| 80.0 | 5 | 5 |

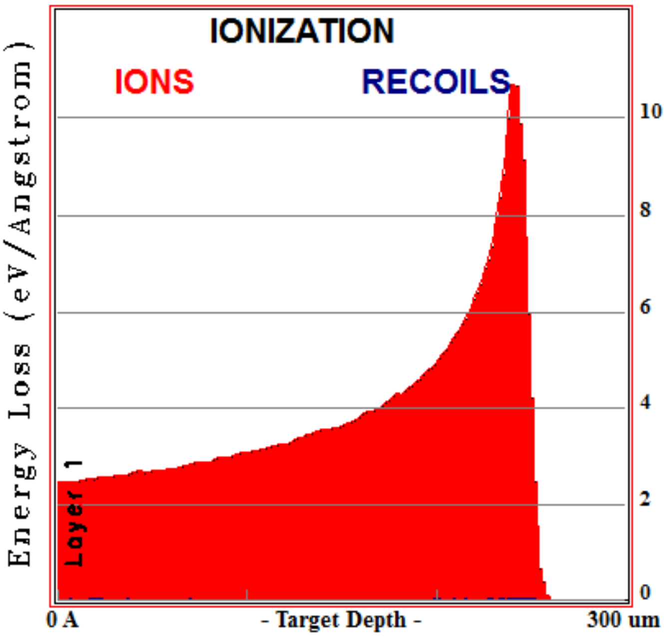

Fig. 6: Bragg peak of 10 MeV protons in copper.

## 4 Conclusions

Figure 5 will look like Figure 7 when we correct for the Bragg ratio factor.

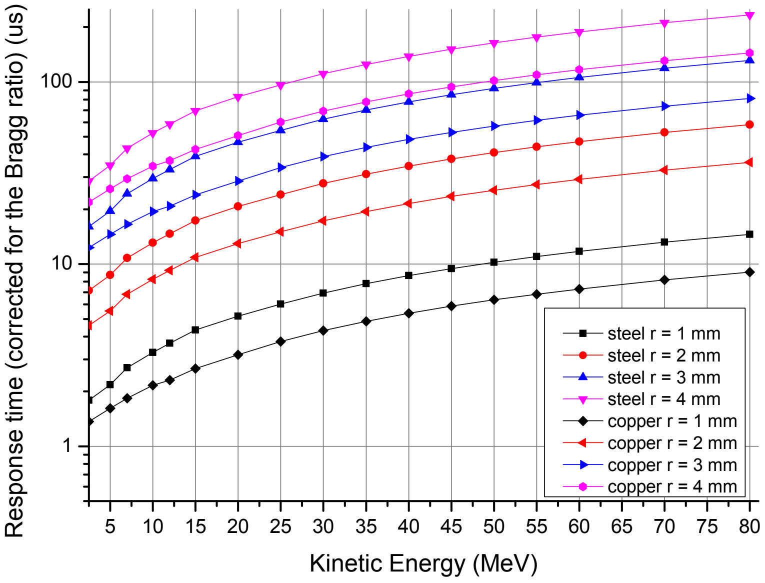

Fig. 7: Time in which a full ESS beam would start melting steel/copper (corrected for the Bragg ratio).

Thus the amount of time in which the full ESS beam would start melting steel/copper can be 1.5 $\mu$s - 25 $\mu$s for the beam radius of 1 mm - 4 mm. This time increases sharply as the energy increases (see Figure 7).