Survivability of a Target for an Intense Proton Beam

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1 Problem

The primary target at a multi-GeV proton accelerator is a copper cylinder of cross-sectional area 1 cm^2 and volume 1 cm^3. The proton pulse is shorter than the time it takes for a sound wave to travel 1 cm in copper.

An intense, repetitive proton beam can lead to damage and destruction of the copper target in at least three ways:

1. The target could explode due to the energy deposition by a single pulse of protons.
2. The target could melt due to the cumulative energy deposition over many pulses.
3. The target could 'turn to dust' (lose its mechanical strength) due to radiation damage over many pulses.

a) Estimate the minimum energy deposition in Joules per gram of copper such that the target would explode from a single pulse.

b) Estimate how many protons such a pulse would contain.

c) Suppose the number of protons per pulse is reduced to 1/10 that of part b). If the target is cooled only by radiation, estimate the maximum number of pulses per second the target could sustain without melting.

d) Suppose the target is cooled sufficiently that it does not melt under the conditions of part b). How many pulses would it take for the target to suffer radiation damage that significantly alters the mechanical properties (state of annealing, say) of the copper?

2 Solution

a) An explosion is due to the shock wave set up by a pulse of energy deposition. The energy must be sufficient to break the bonds between the copper atoms. This can be estimated in various ways. For example, the boiling point of copper is about 2400C (or just guess 1000C, say), which is 10 times room temperature $\Rightarrow$ 1/4 eV to break a bond (or just guess about 1 eV per atom...)

   Copper has atomic number 63.5, so one gram of copper contains about 10^{22} atoms. So it takes about 2.5×10^{21} eV/gram to explode the copper.

   One Joule is $1/(1.6 \times 10^{-19}) \approx 6 \times 10^{18}$ eV. Hence, it takes about 400 Joule/gram of energy deposition to explode the copper. [The inheirited wisdom from those who do this for a living is 500-1000 J/g.]

b) How many protons? A useful fact is that a multi-GeV proton deposits about 1 MeV per (gram/cm^2 of material it passes through – if it does not interact with the nucleus. The target is only about 1 cm thick, compared to a nuclear interaction length of 20 cm, so we ignore nuclear interactions. Since we need 2.5×10^{21} eV/gram to explode, we need about 2.5×10^{15} protons in the pulse.

   What if we can't remember the useful fact? Well, we might guess that a proton transfers about 1 eV to each atom it passes through. The cross section of an atom is about $(1\ \text{Å})^2 \approx 1 \times 10^{-16}$ cm^2. A gram contains 10^{22} atoms, so there are about 10^6 collisions/(gram/cm^2, leading to 1 MeV of energy deposition.

c) Each pulse now deposits 40 J/gm into the copper target.

   Copper has density 9 gm/cm^3, so the target has 9 gm.

   The total energy deposited is 360 Joules/pulse.

   The melting point of copper is about 1000° C, *i.e.*, 1300K.

   If the target is just below the melting point after a pulse hits, it must radiate away 360 Joules before the next pulse arrives.

   The cooling of the target follows Stefan's law: rate $= \epsilon\sigma A T^4$.

   $\epsilon =$ emissivity of copper ≈ 0.1.

   $\sigma =$ Stefan's constant $\approx 6 \times 10^{-5}$ Gaussian units.

   $A =$ total area.

   Cross section area $= \pi d^2/4 = 1$ cm^2 and $V = 1$ cm$^3 \Rightarrow L = 1$ cm, $d = 2/\sqrt{\pi}$ and area of side $= 2\pi d = 4\sqrt{\pi} \approx 7$ cm$^2, \Rightarrow A \approx 9$ cm^2.

   $T \approx 1.3 \times 10^3,\ T^4 \approx 3 \times 10^{12}$.

   rate $\approx 0.1 \times 6 \times 10^{-5} \times 9 \times 3 \times 10^{12} \approx 1.6 \times 10^8$ erg/sec.

   1 Joule $= 10^7$ erg, so rate ≈ 16 Joules/sec.

   So it would take about $360/16 = 23$ sec for the target to cool enough that it could take another pulse.

   Pulse rate $= 1/23 = 0.04$/sec.

d) Radiation damage? This is more open ended. One could argue that breaking of the atomic bonds between neighboring atoms is radiation damage. If so, every atom will have experienced one such damage incident after 10 pulses, according to the statement of the problem.

   I gather that greater mechanical disruption is caused when an electron is ionized from an atom – even though the ion/electron will soon recombine. A practical rule of thumb is one electron ionized in a typical material for every 30 eV deposited by a particle beam. Most of the energy goes into vibrational excitations that do not ionize the atoms, and cause less damage.

An estimate of 1-30 eV cost per damaged atom would be a reasonable answer. This corresponds to 40-1200 pulses to accumulate significant radiation damage under the stated conditions.

An unstressed copper target would probably not “turn to dust”. However, targets of brittle materials like tungsten notoriously do turn into powder under large radiation doses.