

Summer Student Report: Influence of an impact angle and cooling on the temperature of the irradiated target

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Abstract - The effect of a particle beam's impact angle on the temperature in an irradiated target is still an open question. A Gaussian beam with a low impact angle within a target has a larger surface area than the same beam incident orthogonally, so greater heat transfer is expected for low impact angles. In this report, heat transfer due to orthogonal and glancing impact angles were compared. Two different loss scenarios were considered: a proton beam with 10^7 protons/bunch incident on a target for 5 seconds, and a proton beam with 10^5 protons/bunch incident for 1 second. The higher intensity beam at longer exposure demonstrated that although heat transfer is greater for low beam impact angles, higher intensities make cooling negligible. In the lower intensity simulation, however, cooling has more influence when the beam is incident at an angle than when the beam is incident orthogonally.

position and can lead to damage in the target. During the operation of a particle accelerator, beam losses can lead to beam interactions with accelerator equipment at small angles. In 2005, a 450 GeV particle beam struck the vacuum chamber of the TT40 transfer channel connecting in the Super Proton Synchrotron (SPS) at CERN at an extremely small angle (~ 10 mrad) and caused catastrophic damage¹. However, it has also been suggested² that the use of beam dumps with steeply-angled faces could potentially reduce the peak temperature in the beam dump, thus increasing performance and lifetime. In this study, the energy deposition and heat diffusion within a stainless steel target irradiated by a proton beam was investigated at both orthogonal and glancing angles of incidence. The effect of small angles of incidence was tested using a sample case of a 26 GeV proton beam. Both short- and long-duration beam exposures were studied. This report seeks to determine if the peak temperature in the irradiated target depends on the beam impact angle and exposure time.

1 Introduction

A proton beam interacting with matter is responsible for creating particle showers within the material. Both primary and secondary particles deposit energy in this material. Therefore, the irradiation of a target by a high-intensity and high-energy beam causes large energy de-

2 Mathematical Model

For simplicity, we assume that the beam has a circular Gaussian profile and travels a distance l along the target. The angled and orthogonal incidence cases are schematically shown below in Figure 1. The rate of heat transfer through

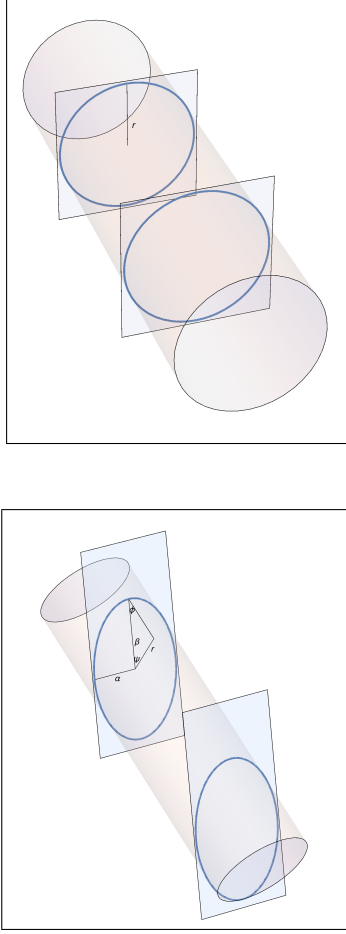


Figure 1: *Top: The orthogonal case, with circular cross section and beam radius r . Bottom: The non-orthogonal impact case, with elliptical cross section and cross-sectional area of $\pi\alpha\beta$, where α and β are the major and minor axes, respectively.*

this cylindrical surface is given by Fourier's Law

$$\frac{\partial Q}{\partial t} = -k \oint_S \nabla T \cdot d\vec{A} \quad (1)$$

where ∇T is the gradient of the temperature T , Q is thermal energy, S is the surface through which thermal energy flows, k is the thermal conductivity, and $d\vec{A}$ is the differential normal vector of a small area A . Thus, for a greater surface area, we should expect a greater magnitude of heat transfer. For a glancing impact case, the area of the elliptical beam cross-section is $A = \pi\alpha\beta$ where α and β are the semi-minor and -major axes, respectively. $\beta = \frac{r}{\sin \phi}$ and $\alpha = r$

if $\mathbf{n}$ is always coplanar with the cylindrical axis. Thus,

$$A = \frac{\pi r^2}{\sin \phi} \quad (2)$$

and the cross-sectional area of the beam is larger for glancing angles than that of a circular beam $\phi = \frac{\pi}{2}$ (the orthogonal case). The circumference, C , of the ellipse is given by the infinite series

$$C = \pi(\alpha + \beta) \sum_{n=0}^{\infty} \binom{0.5}{n} h^n$$

where

$$h = \frac{(\alpha - \beta)^2}{(\alpha + \beta)^2}$$

Let s and l be the horizontal and total distance the beam penetrates into the target, respectively. The area of the sides of the cylinder would then be sC , and the total surface area $\mathcal{S}$ of the cylinder would be

$$\mathcal{S} = \frac{2\pi r^2}{\sin \phi} + \pi s(\alpha + \beta) \sum_{n=0}^{\infty} \binom{0.5}{n} h^n. \quad (3)$$

$\mathcal{S}$ is always greater in the glancing angle case for $\phi < \pi/2$ than in the orthogonal case for $\phi = \pi/2$. Thus, we should expect a greater heat transfer in the glancing angle case for a cylindrical beam.

Although the heat transfer is greater for a particle beam incident at an angle, the energy deposition should be independent of the angle of incidence. When a beam with circular cross-section travels a distance l into a target, then the volume where the energy is deposited is $V = \pi r^2 l$. For the glancing angle, the cylindrical volume only depends on the horizontal distance $s = l \sin \phi$. Thus, the glancing angle volume is

$$V = A \times l \sin \phi = \frac{\pi r^2}{\sin \phi} \times l \sin \phi = \pi r^2 l$$

which is the same volume as the beam with circular cross-section and orthogonal incidence. Because the volume of both cylinders are the same, then we should expect that for both glancing angles and orthogonal impact, the energy deposition within the target should be the same.

3 Simulation Methods

The interaction of a beam with a target at an angle can be simulated in two different ways: (1) by rotating the position of the beam and keeping the target fixed, or (2) by rotating the target and keeping the beam position and direction fixed. Because the volumes whose energy is deposited are the same in both angled and orthogonal beams, maximum energy deposition between different angles of incidence should be the same. Rotating the position of the beam while keeping the target orientation fixed led to different energy deposition curves (see Figure 2). The discrepancy appears due to the differences in the volume of the mesh, as seen by the beam. However, by rotating the target and fixing the position and direction of the proton beam, the maximum energy deposition for different angles of incidence were constant (see Figure 3), which is expected given the mathematical model outlined above. The latter method was chosen to calculate the energy deposition in an irradiated target. We tilted the target in FLUKA with respect to the beam and aligned the beam axis along the z axis. Thus, for both orthogonal and glancing simulations, the beam struck the histogram bins orthogonally, and the volumes of the bins were equal in this approach. Figure 3 depicts this scheme and shows the energy deposition curves.

The simulations were performed by two separate software platforms. Energy deposition was calculated with FLUKA, a Monte Carlo simulation software for calculating beam and matter interactions. For this study, a Gaussian beam with 26 GeV protons $\sigma_x = \sigma_y = 1\text{mm}$ was used. The target was stainless steel, which is a compound comprised of 72.76% Fe, 17.9% Cr, 86.8% Ni, 0.42% Ti, 1.05% Mg, 0.46% Mo, 0.1% V, 0.48% S. Energy deposition was calculated for both orthogonal beam impact ($\theta = \pi/2$) and $\theta = 10$ mrad beam impact, where θ is the angle of incidence depicted in Figure 3.

After the energy deposition was calculated, heat transfer was calculated with ANSYS, a multiphysics finite element simulation software. The energy deposition (in units of GeV/cc/pp) was

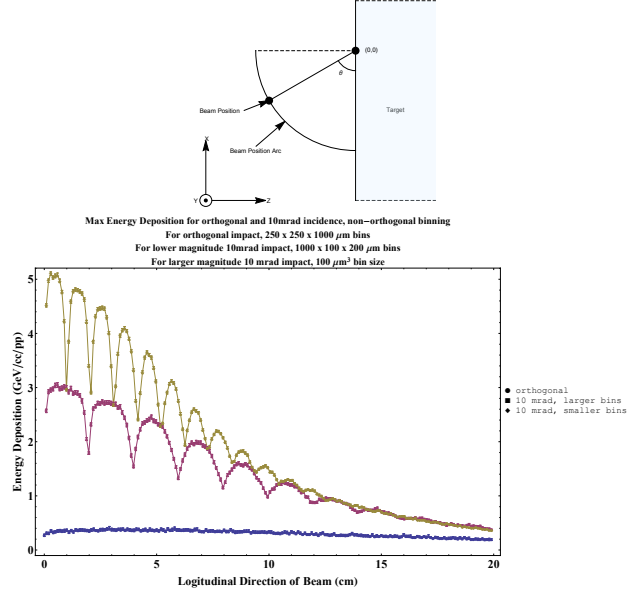


Figure 2: *Top: Rotated beam position model, where the beam would rotate about a fixed target. Bottom: Energy deposition curves between different beam angles demonstrate a computational artifact*

converted to a power load (in units of W m^{-3}) and applied to a three dimensional mesh within a 304 stainless steel target where heat diffusion was calculated both with and without cooling. Cooling was applied via convective heat transfer onto the outside of the target in ANSYS from liquid Helium-II held at 2 K with convective heat transfer coefficient $h = 250 \text{ W m}^{-2} \text{ K}^{-1}$, calculated from the Film-Boiling II (FB-II) model³. Two types of beam losses were simulated: 10^7 protons/bunch lost over 5 seconds and 10^5 protons/bunch lost over 1 second. In each case, proton bunches were separated by 25 ns.

4 Results and Discussion

In Figure 4, the peak temperature simulated inside the target during beam exposure is plotted vs time for the two different bunch intensities for various time scales. In the top graph, the peak temperature was simulated over for 5 seconds of impact of a 26 GeV proton beam with 25 ns bunch spacing and 10^7 protons per bunch for or-

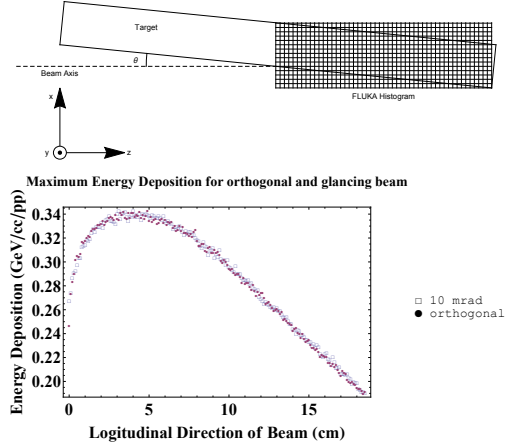


Figure 3: *Top: Model with fixed beam position and direction and variable target orientation. Bottom: Maximum energy deposition of 26 GeV protons in stainless steel target both orthogonal and glancing beam impact angles.*

thogonal ($\pi/2$) and 10 mrad impact angles. The simulation was performed both with and without cooling. Although the peak temperature in the 10 mrad case seems to be greater than the peak temperature in the orthogonal case, this is most likely an interpolation error between ANSYS and FLUKA and not a physical effect of the beam exposure. The peak temperature curves in the 10^7 proton/bunch case for short times (< 1 second) are practically identical, and cooling and angle of incidence have no or negligible effect.

However, in the simulation with 10^7 protons/bunch, one small effect to note is that the difference between the peak temperatures of the glancing angle simulations with and without cooling is greater than the difference between the two orthogonal simulations. This would indicate that the original hypothesis, that heat transfer is greater for beams incident at an angle, is correct. The change in temperature after 5 seconds for the glancing case is $\Delta T_g = 8.056$ K, while $\Delta T_o = 5.1567$ K.

Although heat transfer increased in the glancing case, the model demonstrates that at 10^7 protons/bunch, the irradiation of the target overpowers the effect of cooling. That is, if the beam intensity is too great, cooling will have little to no effect, even if the geometry of the

beam within the target might theoretically increase heat transfer. However, if the beam intensity is decreased, then the peak temperature in the target will be more susceptible to cooling. In the bottom of Figure 4, the two curves where cooling is not present in the simulation are, again, identical. This is to be expected, as the previous simulation demonstrates that an angle of incidence does not effect the peak temperature. The two curves subjected to cooling, however, demonstrate a much greater response to the presence of cooling. The glancing angle simulation begins to decrease in temperature at $\sim .45$ s, while the orthogonal simulation temperature has a maximum at $\sim .75$ s.

Thus, peak temperature susceptibility to cooling is dependent on both the impact angle and beam intensity. Above a certain threshold, the beam is too intense for the cooling used in this report and its presence will have a negligible effect. However, for lower intensities, the bottom plot in Figure 4 demonstrates that even on short time scales the peak temperature within the target decreases more quickly when the beam is incident at an angle.

5 Conclusions

Simulations were performed to model the temperature dependence in an irradiated target on the angle of incidence of the impacting projectile. We focused our attention on a 26 GeV proton beam incident on a stainless steel target both orthogonally and at an angle of 10 mrad (measured wrt. the target face). From a simple geometric argument, we showed that heat transfer should improve with a glancing angle of incidence, and thus any target impacted by a glancing beam would be more susceptible to cooling. The energy deposition data was calculated in FLUKA for both orthogonal and glancing angles of incidence.

Next, the energy deposition data was imported into ANSYS in order to calculate the heat transfer within the target. We compared the results for two beam loss scenarios: for 10^7 protons/bunch over 5 seconds of exposure, and 10^5 protons/bunch over one second of exposure. Both simulation scenarios used a 25 ns bunch spacing. In the former case, resulting peak temperatures were similar for the orthogonal and glancing case after 1 second of beam exposure. The peak temperature in the simulations both with and without cooling fell along the same curve. After 5 seconds of exposure, the peak temperatures still fell along very similar curves, but cooling had a more substantial effect on the glancing angle case than on the orthogonal case. With 10^5 protons, the glancing angle case demonstrated a larger susceptibility to cooling. Heat transfer within the irradiated target during beam exposure does increase when irradiation occurs at a glancing angle when below a threshold beam intensity. If there are too many protons/bunch, then the peak temperature in the material will not change, as the energy deposited in the material is too great for cooling to be effective.

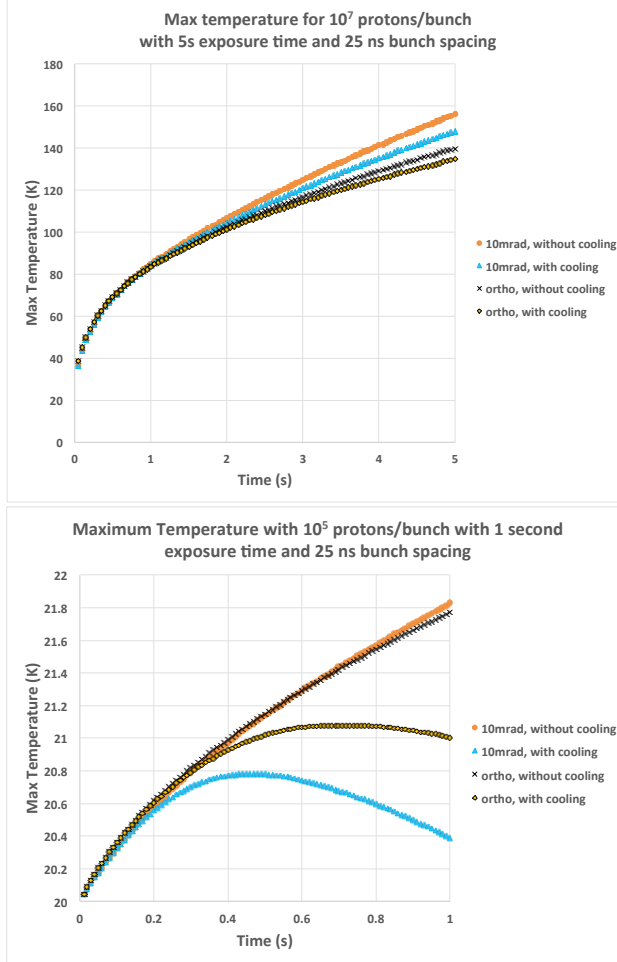


Figure 4: *Peak temperature inside a cooled and not cooled stainless steel target initially at 20 K vs. time of exposure to a 26 GeV proton beam with 25 ns bunch spacing for orthogonal and 10 mrad beam angle of incidence. Top: over 5 second of exposure to the beam with 10^7 proton per bunch Bottom: over 1 second of exposure to the beam with 10^5 proton per bunch*

Outlook

A few open questions remain. The exact nature of the FLUKA artifact depicted in Figure 2 is

still unknown. Why does the peak energy deposition increase when the proton beam is incident at a glancing angle? Similarly, more work is required to clarify the difference between the peak temperature in the orthogonal and glancing angle case for a 10^7 protons/bunch for long exposure times. Is this increasing difference due to FLUKA-ANSYS interpolation errors, or is this a physical effect? In this report, the target temperature was initially at 20 K, while the temperature of the Helium-II was 2 K. Another open question is how the irradiated target responds to cooling when the target's initial temperature is close to 2 K. Would it be more susceptible to cooling for higher beam intensities?

Additionally, one of the original goals of this project was to create a model that mimicked the geometry of the beam screen in the LHC. Seeing as low impact angle beam losses often affect this particular component, understanding glancing angle impact in the beam screen is an important research question. This project was only able to discuss temperature dependence on irradiation impact angle from a purely physical point of view. To attack this problem from an engineering standpoint will require much more work to adapt the simulation results to physical systems and hardware.

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Notes

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