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Production Target Studies at the M4 Diagnostic Absorber

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High power production targetry is becoming essential to the future of HEP, but our current physics simulations are lacking validation in the lower energy ranges that many proposed secondary beam experiments will use. We propose a study of target materials at the M4 diagnostic absorber to monitor target temperatures during irradiation by an 8 GeV proton beam and provide some experimental validation for our simulations at lower energies as well as potentially perform post-irradiation examination of samples to understand changes to material properties.

Fundamental research in high power production targetry is becoming increasingly necessary to the field of high energy physics (HEP) as we propose a growing number of secondary beam experiments which will far surpass the limits of what prior targets have been able to withstand. Simulation is generally our first step in ensuring the viability of a target, but many of the proposed secondary beam experiments (including Mu2e, Mu2e-II, the Advanced Muon Facility, and a potential muon collider) will require high Z production targets to endure lower energy beams, from 8 GeV down to 800 MeV, an energy range that we don't currently have any experimental validation for. As a result, we are looking to better understand material behavior during irradiation at these lower energies to improve our capacity to develop durable and efficacious targets.

I. THE FERMILAB M4 BEAMLINE

One potential opportunity for examining material behavior is at the diagnostic absorber along the 8 GeV M4 beamline at the Fermilab muon campus. A schematic of the Fermilab accelerator complex is shown in Fig. 1. Protons are first accelerated by the Linac up to about 400 MeV, and then further accelerated in the Booster up to 8 GeV. From there, most experiments at Fermilab receive protons from the Main Injector, which accelerates the 8 GeV protons from the Booster up to 120 GeV. Muon campus experiments, however, receive protons from the Recycler, which does not further increase the energy of Booster protons. Every 1.4 seconds, two Booster batches of about 4×1012 protons each enter the Recycler in 21 53 MHz bunches. The Recycler RF system then rebunches the two Booster batches into 8 2.5 MHz spills such that each spill has about 1×1012 protons. Each spill is then injected into the Delivery Ring, where it is resonantly extracted over the course of 43.1 ms and sent to the muon campus experiments. This repeats seven more times for the rest of the spills with 5 ms between each spill, so all 8 spills are extracted over about 380 ms total, and the entire process repeats every 1.4 seconds, yielding an average beam power of approximately 8 kW.

The M4 beamline, shown in green in Fig. 2, delivers protons from the delivery ring to Mu2e. There is also a diagnostic absorber (labeled M4DA in blue in Fig. 2) along the M4 beamline before Mu2e, which is a small beam absorber which can take up to 170 W of the Mu2e beam for commissioning purposes. Therefore, we can deliver one spill from the delivery ring to the diagnostic absorber every 6 main injector cycles, resulting in an average beam power of about 150 W.

There is a small available space (the space in the wall shown on the right side of Fig. 3) in front of the M4 diagnostic absorber in which we can place material samples to observe behavior under irradiation by 8 GeV protons. The only material property we can observe directly in situ is temperature, which we typically simulate by feeding an energy deposition simulation from FLUKA into a finite element analysis software like Ansys. Therefore, if we are able to measure the actual temperatures of the samples while in the beam, we can possibly provide validation for both Ansys and FLUKA at lower energies. However, we first want to ensure via simulation that the temperature of the samples will change significantly enough to be detected by the monitoring system. We also have interest in examining the samples after irradiation to understand changes to material properties which cannot be observed during irradiation, so we want to use simulation predict how radioactive the samples will be after irradiation to understand if it will be possible to further handle and study them.

II. DOSE CALCULATIONS

FLUKA simulations of tungsten and Inconel 718 cylinders with a 1 mm radius and a length of 5 cm were used to estimate dose after 1 week of running at about 200 W of 8 GeV beam and 1 hour, 1 day, and 1 week of cooldown time. The projections along the y-axis of dose in pSv/s within 5 cm of the target after a week of cooldown are shown in Fig. 4. The maximum dose at the surface of the tungsten cylinder is about 1.9×10^8 pSv/s, or 68.4 Rem/hr, and the maximum dose at 5 cm from the surface is about 1.1×10^7 pSv/s, or 3.96 Rem/hr. The maximum dose at the surface of the Inconel cylinder is about 1.1×10^8 pSv/s, or 39.6 Rem/hr, and the maximum dose at 5 cm from the surface is about 6.3×10^6 pSv/s, or 2.27 Rem/hr.

These doses are likely too high to directly handle these samples after a week of running and a week of cooldown time, but a week at constant 200 W power is on the very high end of what we actually expect to subject samples to. They are low enough that it seems within of the realm of possibility to study samples which have been in the beam for less than a week, so our next steps will involve simulations with decreased beam

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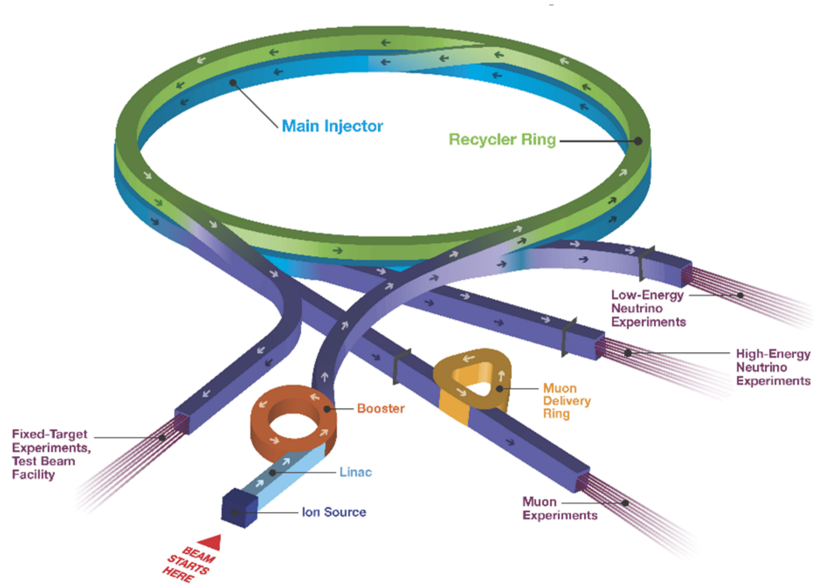

FIG. 1. A schematic of Fermilab's accelerator complex.[1]

FIG. 2. A schematic of Fermilab's muon campus beamline.[2]

FIG. 3. The M4 diagnostic absorber.[3]

time to decide where a reasonable limit of run time is for post irradiation examination, but these preliminary results leave us optimistic about the possibility of performing PIE.

III. TEMPERATURE ESTIMATES

Temperature estimates were done using energy depositions from FLUKA simulations of the same cylinders described for the dose calculations. The projections along the y-axis of energy deposition in the target in GeV/cc/primary are shown in Fig. 5.

The first set of temperature estimates were done using the Stefan-Boltzmann law:

$$\frac{P}{A} = \varepsilon\sigma T^4, \qquad (1)$$

where P is the power radiated by an object (which we are assuming here is equal to the power absorbed), A is the surface area of the object over which the power is radiated, ε is the emissivity of the material, σ is the Stefan-Boltzmann constant, and T is temperature of the object. The total power in each cylinder was determined by summing the energy deposition over the target volume and multiplying by the number of protons on target per second. This was then divided by the lateral surface area of the cylinder to get power per area, and then the Stefan-Boltzmann equation was solved for temperature. An emissivity of 0.3 was used for tungsten, and an emissivity of 0.8 was used for Inconel 718 (though Inconel 718 can be manufactured with varying emissivities from about 0.1 to 0.9).

This analysis raised the question of what effective beam power to assume the target will experience. We use the average power (200 W for the purpose of these simulations) as an operational limit for the diagnostic absorber, which assumes 1×10^{12} protons on target in about 7 seconds. However, 1×10^{12} protons are delivered to the target within 43 ms, which comes out to nearly 30 kW if we disregard the downtime. Taking these two extremes, the temperature estimates for tungsten come out to 483°C (200 W) and 2430°C (30 kW), and the temperature estimates for Inconel 718 come out to 198°C (200 W) and 1409°C (30 kW), These are drastically different enough at the extremes (and neither are particularly close to the temperatures we expect based on prior work) that we can't make any particularly useful predictions about the actual temperatures from them, and we don't have a straightforward way to approximate how quickly the power radiates from the sample, so this approach is likely not of much value for this purpose. These estimations, as I mentioned previously, assume that the power absorbed is equal to the power radiated, so we would not expect them to be especially accurate anyway, but because we have no way to assume an accurate power in the first place, we are unable to make even a vague estimate this way.

The second set of temperature estimates were done using the specific heat equation

$$Q = mc\Delta T, \qquad (2)$$

where Q is heat transferred to an object, m is the mass of the object, c is the specific heat of the material, and ΔT is the change in temperature of the object. The average heat absorbed per gram (Q/m) was determined by averaging the energy deposited over the target volume, multiplying by the number of protons per spill (1×10^{12}), and dividing by the material density (19.3 g/cc for tungsten and 8.2 g/cc for Inconel 718). The temperature changes were then calculated using the specific heats of the materials, yielding a change of about 9°C per spill in Inconel 718 and about 30°C per spill in tungsten, both of which should be detectable by a monitoring system. Because the beam power was not involved at all in this calculation, that layer of ambiguity was removed from these estimates. We did make the assumption that the heat capacities are constant, but changes to the heat capacities here are likely negligible since the targets are solid and thus the heating process is effectively isochoric. Furthermore, preliminary Ansys temperature calculations, shown in Fig. 6, are generally in agreement with these rough calculations, which provides additional validation that these estimates are reasonable.

IV. CONCLUSIONS

High power production targetry is becoming essential to the future of HEP, but our current physics simulations are lacking validation in the lower energy ranges that many proposed secondary beam experiments will use. We propose a study of target materials at the M4 diagnostic absorber to monitor target temperatures during irradiation by an 8 GeV proton beam and provide some experimental validation for our simulations at lower energies. We estimate that there will be about a 9°C temperature increase per spill in Inconel 718 and about a 30°C increase per spill in tungsten, both of which should be significant enough for a temperature monitoring system to detect.

Additionally, we are interested in post-irradiation examination of material samples to better understand changes to material properties and aid in our ability to extend target lifetimes, which will require an understanding of how radioactive we expect the samples to get. After a week of constant 8 GeV beam at 200 W, the expected doses would likely be too high to directly handle the samples, but they are low enough that a shorter period of beam time may result in low enough doses for handling. Our next steps will include repeating simulations with shorter beam times to determine a reasonable limit.

[1] Fermilab. *Fermilab's Accelerator Complex*. https://www.fnal.gov/pub/science/particle-accelerators/accelerator-complex.html.
[2] D. Stratakis, B. Drendel, J. P. Morgan, M. J. Syphers, N. S. Froemming, Phys. Rev. Accel. Beams **22**, 011001 (2019).
[3] J. Wang, Mu2e-doc-53035 (2025).

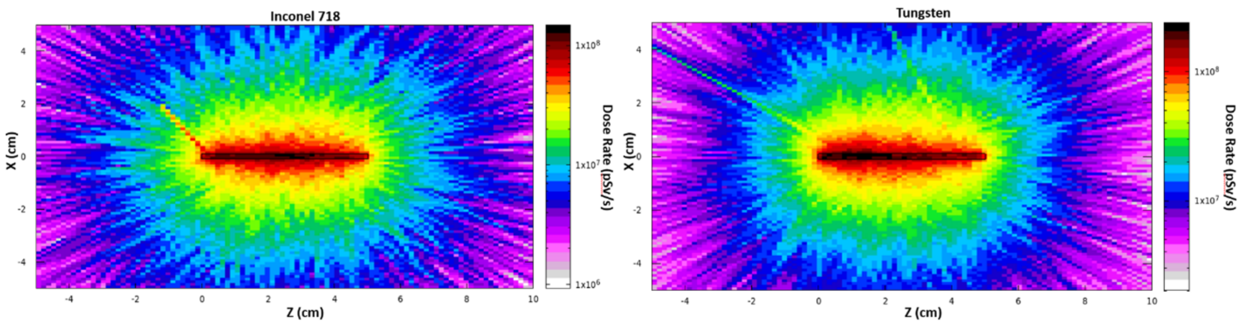

FIG. 4. FLUKA calculations of dose rates in pSv/s projected along the y-axis within 5 cm of Inconel 718 and tungsten cylinders (1 mm radius, 5 cm length) after 1 week of 8 GeV beam at 200 W and 1 week of cooldown.

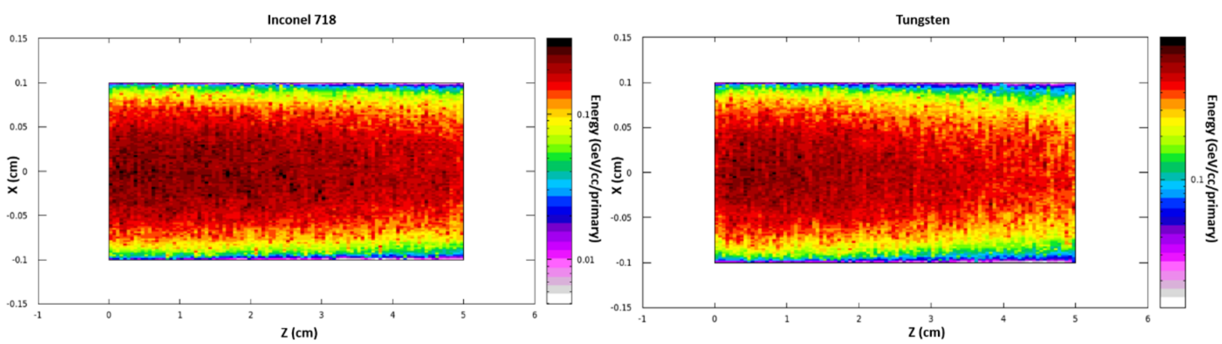

FIG. 5. FLUKA calculations of energy depositions in GeV/cc/primary in Inconel 718 and tungsten cylinders (1 mm radius, 5 cm length) from the 8 GeV beam.

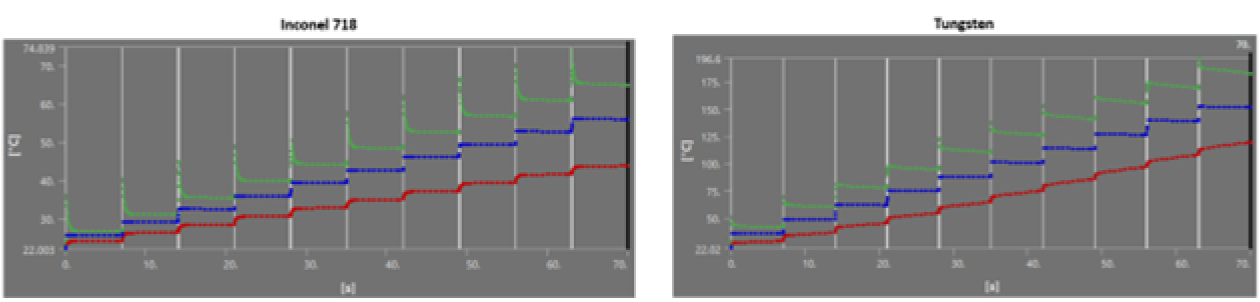

FIG. 6. Preliminary Ansys temperature calculations over 10 spills from room temperature courtesy of Kateryna Havryshchuk.