Considerations for a Mu2e-II Production Target

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(Dated: August 31, 2020)

The search for neutrinoless coherent muon to electron conversion at Fermilab in the Mu2e and proposed Mu2e-II experiments provide extremely sensitive searches for charged lepton flavor violation, up to six orders of magnitude greater than current exclusion bounds. Critical to this effort is a compact, high power-density pion production target, located within a high vacuum, high magnetic field region. We review the operating requirements and design criteria that are met in the Mu2e production target system, and then discuss some of the significant challenges involved in meeting the higher power requirements of Mu2e-II.

I. THE MU2E MEASUREMENT

The Mu2e experiment at Fermilab [1] will search for the charged lepton flavor violating neutrinoless coherent conversion of a negative muon into an electron in the field of a nucleus, with a four-order-of-magnitude sensitivity improvement over the current exclusion bounds. The proposed Mu2e-II experiment [2, 3] will improve the sensitivity to this channel by another one to two orders of magnitude. To achieve this goal at modest incremental investment, we plan to use the increased beam power available following the PIP-II accelerator complex improvements,[4] a new Mu2e-II beamline,[5] and to reuse the bulk of the Mu2e apparatus with targeted upgrades to address higher signal and background rates.

The figure of merit for conversion searches is $R_{\mu e}$, defined as the number of conversion candidate events normalized to the number of muon nuclear capture events:

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \to e^- + A(Z,N)}{\mu^- + A(Z,N) \to \nu_\mu + A(Z-1,N)} \ ,$$

where $A(Z,N)$ is the nuclear species with charge Z. The bulk of the experiment is designed to measure the numerator of this expression, identifying conversion candidate events in an extremely clean, low-background environment. The current exclusion bounds on the conversion process come from the SINDRUM-II experiment at PSI [6]

$$R_{\mu e} < 7 \times 10^{-13} (90\% \ \mathrm{CL}) \ .$$

Mu2e will either observe conversion, or push this exclusion bound down by an additional four orders of magnitude, while Mu2e-II will aim for an additional one to two orders of magnitude. Clearly, such sensitive searches require the efficient production and observation of an enormous number of muons.

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II. MU2E PRODUCTION TARGET

Mu2e is a "stopped muon experiment": we bring negative muons to rest in a low-mass stopping target made of aluminum foils, and observe their interactions with a series of detectors designed to efficiently reject the vast bulk of the background, while maximizing sensitivity for signal events. The stopping target and detectors are mounted in vacuum inside the Detector Solenoid (DS). Muons are transported to the DS via an S-shaped Transport Solenoid (TS) designed to eliminate line-of-sight paths between the stopping and production targets. The production target itself is located within a high-field Production Solenoid (PS) connected to the upstream end of the TS. A 7.3 kW, 8 GeV (kinetic energy) pulsed proton beam is delivered off-axis into the PS, striking the target and producing secondaries. The spent beam exits through a vacuum window, travels through the PS hall, and is stopped by a large, air-cooled steel beam absorber.

Many complicated inputs constrained the design of the Mu2e production target. The goal is to stop the maximum number of muons per incident proton. To do this, the target must be supported stably on the magnetic axis of the PS, in an extremely high field region (~ 5 T). To minimize pion reabsorption, target support structures must be minimal. Due to the harsh radiation environment, a remote handling system is required to replace not only targets, but vacuum access windows on the PS. Cost and space considerations require passive cooling. The pulsed beam time structure results in large thermal and stress cycles.

Iteratively optimizing against these constraints led to a unique, state-of-the-art design which will operate near the limits of current technology, with a goal of one-year operating life before replacement. The target system is a "bicycle wheel" design, with a large diameter ring that supports the target structure via three pairs of spokes. The target structure is a 220 mm long four-finned structure, to increase heat dissipation into the vacuum of the PS. To reduce the impact of thermal and stress variations during the beam pulsing, the target is longitudinally segmented (except at the tips of the fins, which are continuous so as to hold the target together). The total length of solid material is 160 mm, with a cylindrical core of 3.15 mm radius. Fins are 1 mm thick and extend 13 mm above the target core. Since the target is radiatively cooled, it would be expected to operate at elevated temperature, requiring a refractory material; the target will be machined from a solid rod of 1% La_2O_3 doped tungsten. This material selection has interacted with many of the other design choices; tungsten at elevated temperatures in poor vacuums can suffer from catalyzed oxidative surface erosion, changing emissivity, and recrystallation effects that can exacerbate creep and deformation. During nominal running conditions, the target is expected to absorb and re-radiate 730 W, raising its (peak) temperature to around 1200 °C. This will be one of the highest power density targets in long-term operations at any accelerator facility. It is also firmly in an unexplored region of the radiation damage parameter space.

III. CONSIDERATIONS FOR A MU2E-II PRODUCTION TARGET

In Mu2e, the strongest constraint on our search sensitivity is available beam power: the primary background to our signal search is cosmic ray induced signal fakes. Cosmic ray backgrounds scale with total run time; skirting those background limits requires increasing the number of stopped muons we observe per unit of run time. An evolution of the Mu2e experiment - Mu2e-II - has been proposed for the PIP-II era at Fermilab. In most respects, it is expected that much of the costly experimental apparatus (solenoids, civil construction, etc) can be reused, with modest, targeted investments in other areas (beam delivery, detectors, computing, etc), to improve the sensitivity by an additional one to two orders of magnitude. Mu2e-II will have significant physics value whether or not Mu2e sees a signal: in the absence of a signal, additional parameter space is opened to improve the search, while an observation can be followed up with a variety of other stopping target materials which access process matrix elements with different sensitivities, potentially elucidating the details of the underlying physics.

Mu2e-II is envisioned to directly utilize 100 kW of the 800 MeV beam from the PIP-II linac, with a production target system constrained by many of the issues that drove the Mu2e target development. The lower beam energy leads to significantly increased fractional power deposition in the target - about 20-25% for Mu2e-II compared to 10% for Mu2e. Radiation damage is expected to increase significantly as well, and essentially nothing is known of the radiation tolerance of materials in this regime. It is clear that the Mu2e target concept - a radiation cooled, refractory metal target - will not meet the ambitious goals of Mu2e-II. The Mu2e-II production target will need - at the very least - active cooling and serious consideration of mitigating the radiation damage issues.

In order to begin addressing these issues, we submitted a Laboratory Directed Research and Development (LDRD) proposal to Fermilab [7] which was funded for Fiscal 2020-2021. The scope of work includes the development of target station conceptual designs to address the major challenges of high muon production with minimal thermal, stress, and radiation damage characteristics. Parameters will be predicted with mature simulation models of the Mu2e apparatus in MARS15 and G4Beamline, with thermal and stress calculations performed in ANSYS. We will also rely on results from sensitivity studies in the Mu2e Geant4-based offline simulation framework, to ensure consistency of our results with Mu2e standards regarding muon stopping rate calculations. We will choose at least one of the most promising designs for mechanical prototyping and component level thermal testing.

In our proposal, we discussed three potential target concepts for further development. We started with the observation that static, monolithic targets are the most effected by thermal and stress cycling, as well as accumulation of radiation damage byproducts. We are exploring various designs that mitigate those risks in various ways. First, we are exploring rotating systems - either a "cassette" of cylindrical targets, or a single larger diameter hollow cylinder - cooled with helium gas. This would have the dual benefits of mechanical simplicity and prior implementation experience. In the constrained volume available in Mu2e-II, however, pion reabsorption in the non-active target material may significantly impact the availability of muons. Second, we are exploring granular target materials, again with Helium gas cooling. Such a system would have excellent thermal properties as the cooling gas flow would be naturally distributed throughout the target volume. However, it would be difficult to reliably renew the material during operation to mitigate the radiation damage problem, and a larger volume of material would be required to provide the same production mass as a solid target. Our third choice is a "conveyor" type target, where helium-cooled macroscopic spherical target balls are moved through a piping system, presenting a number of balls to the beam path at one time. This system would allow nearly continuous reintroduction of fresh, undamaged material to the system, at the expense of a potentially complicated mechanical system for reliably keeping the balls in motion.

Along with developing a physical design is the critical choice of target and support system materials. While Mu2e used refractory materials for thermal reasons, it is certainly not clear that such a choice makes the most sense for Mu2e-II. At the significantly lower beam energy, beam scattering in high density materials will be significantly larger, suggesting that we consider lower-Z materials. Of course, to maintain muon production with lower-Z materials requires a longer target. The multi-Tesla field of the PS will result in significant steering of the proton beam trajectory. This will likely require a slender target that is physically curved to match the proton beam trajectory. There is significant experience with high-power graphite target systems, and reactor environments use exotic materials such as AlBeMet and MoGRCF; SiC may also be worth considering. Additional R&D on the radiation damage in these materials under extreme conditions could prove decisive in our choices for Mu2e-II.

IV. CONCLUSION

A decade long effort involving tens of person-years was required to develop the Mu2e production target concept, and additional testing work remains before procurement of production targets can commence. A similar amount of effort will be required to develop a next generation target for the Mu2e-II project. While some R&D work has already begun, much effort remains to identify and develop a concept likely to meet the host of significant challenges. We would welcome additional input and collaborators in this effort.

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