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Pion-Production Target for Mu2e-II: Simulation Design and Prototype

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This paper discusses our recent advances in conceptual design R&D for a conveyor-type Mu2e-II target station based on energy deposition and radiation damage simulations. Our study involves Monte-Carlo codes as well as thermal and mechanical ANSYS analyses to estimate the stability of the system. The concurrent use of multiple simulation packages is intended to allow us to determine and minimize the systematic uncertainty of the simulations. Our simulations allowed us to rule out some designs (rotated and fixed granular targets) as less practical and supported our assessment of the new target station's required working parameters and constraints. The thermal and mechanical analyses we performed enabled us to determine the choice of cooling scheme and prospective materials for the conveyor's spherical elements. We will discuss the first prototype of the Mu2e-II target and mechanical tests performed at Fermilab that indicated the feasibility of the proposed design and its weaknesses, and we will suggest directions for further improvement.

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1. Introduction

The main goal of the Mu2e experiment at Fermilab is to search for indications of charged lepton flavor violation [1]. To achieve this goal, experimenters will be searching for the coherent neutrinoless conversion of a negative muon into an electron in the field of an Al nucleus by searching for 105-MeV electrons emitted in this process. This will allow Mu2e to probe effective new physics mass scales up to the 10^3–10^4 TeV range. One of the central elements of the Mu2e experimental facility is its target station, where negative pions are generated in interactions of the 8 GeV primary proton beam with a tungsten target, shaped similar to a rod, which will be capable of producing around $3.6 \cdot 10^{20}$ stopped negative muons in three years of running [2].

The Mu2e experiment is planned to be extended to a next-generation experiment, Mu2e-II, with a single event sensitivity improved by a factor of 10 or more. Mu2e-II will probe new physics mass scales up to 10^5 TeV by utilizing an 800-MeV 100-kW proton beam. This greater sensitivity is within reach by using the PIP-II accelerator upgrade, a 250-meter-long LINAC capable of accelerating a 2-mA proton beam to a kinetic energy of 800 MeV corresponding to 1.6 MW. The higher beam intensity would require a substantially more advanced target design. We are studying a novel conveyor target with tungsten or carbon spherical target elements moved through the beam path. The motion of the elements can be ensured either just mechanically or both mechanically and via He-gas flow.

Our study involves Monte-Carlo codes (MARS15 [3], G4beamline [4], and FLUKA [5]) and thermal and mechanical ANSYS analyses to estimate the suitability of the design.

1.1 Target design choice

We considered three options for designs of Mu2e-II targets. The first one is a rotating hollow cylindrical target either radiatively cooled or cooled with a flow of Helium through tubes distributed on the inner surface of the hollow cylinder (Figure 1, left). The second target option is a fixed granular one consisting of a lattice of static target balls with gaseous Helium as a possible option for a cooling medium (Figure 1, center). The third option is a conveyor-type target in which balls of a target material will be moving within the Heat and Radiation Shield (HRS) bore thus continuously delivering a new supply of target material into the beam and then removing the exposed target material from the beam for cooling (Figure 1, right).

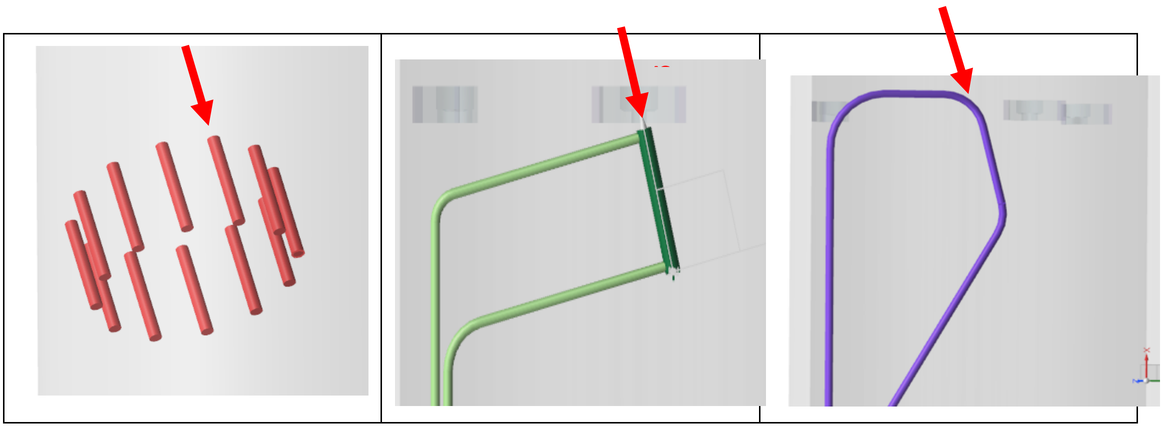

Figure 1. Three target design options. Left – rotating elements; Center – fixed granular with gas cooling; Right – "conveyor" target.

One of the aims of this optimization study was to develop the design that will be as much as possible compatible with the Mu2e baseline Heat and Radiation Shield (HRS); the Mu2e baseline HRS has the inner bore of 20 cm. Therefore, at the initial stage of consideration we ruled out the rotating element design because its implementation would require a more significant space in the HRS inner bore(see Figure 1, left). Also, the extensive presence of target hardware in the bore would complicate its cooling and become a nuisance to the muon flow from the target to Transport Solenoid (TS). The rotating element target would, nevertheless, have such an advantage that the alternate placement of several target rods in the beam in the course of their rotation would allow to distribute the heat load as well as radiation damage. Hence, we have postponed the consideration on this target option until it can be ensured that the requirement of compatibility with the current HRS dimensions can be relieved.

The fixed granular target option (Figure 1, center) requires smaller space in the HRS bore, however, its cooling cannot be performed efficiently because in the course of the experimental run all energy is deposited at the same location without a possibility to remove or replace the target online with the beam. MARS15 simulations have shown that its peak radiation damage will be higher than 300 DPA/yr. This would require a very frequent replacement of the target (almost every month of operation). Therefore, the fixed granular target option was also ruled out on the aforementioned grounds.

The conveyor target (Figure 1, right), in which spherical target elements are moved inside the channel, supplied to the beam interaction point and then removed out of the HRS bore, appears to be the most optimal among considered options. Its downside seems to be its relative technical complexity that requires construction of a prototype for mechanical and thermal tests. However, in simulation studies it outperforms the other options. First, conveyor target would occupy a relatively small space in the HRS bore because only its beam interaction section, inlet and outlet channels have to be located in inside; other units such as storage of target elements, drive mechanism, and cooling gas equipment all can be placed outside HRS. Second, helium gas could be used for both cooling and moving elements inside conveyor (in addition to the mechanical drive). Thirdly, because of both circulation of target elements in the channel and a possibility to replace damaged elements outside HRS without stopping the experiment, radiation damage accumulated in the target can be distributed among a large number of elements and impacts on operation minimized.

Due to the aforementioned considerations, we assumed the conveyor target for the baseline version of the Mu2e-II production target.

1.2 Energy deposition simulations in a W conveyor target

MARS15 and FLUKA simulations of radiation quantities were performed using the models shown in Figure 2. The optimal interaction zone length (the straight section in the target) was found in optimization studies to be ~9 spherical elements (for W or WC). The G4beamline code was used in the interaction length optimization. For other prospective target materials the optimal interaction length can be longer if the densities of the materials are lower than for W. For example, for a SiC target the length should be ~19 spherical elements. This model assumes the radii of the spherical elements to be 0.5 cm. Simulations were also made for 0.63-cm and 0.75-cm radii.

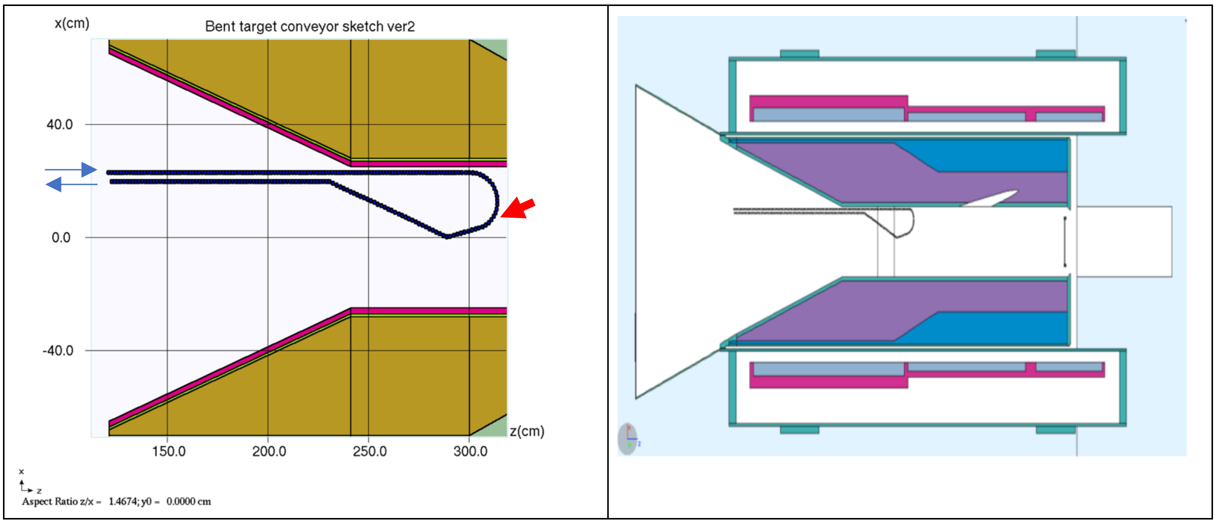

Figure 2. Simulation models of the W conveyor target. Left: MARS15. Right: FLUKA. Red arrow shows the proton beam direction. The blue arrows show the circulation flow direction.

Total simulated energy heat load in the target was found to be 31.8 kW. The nominal velocity of the spherical elements in the conveyor is expected to be ~10 cm/s (i.e. it should take an element about 1.35 s to pass the beam). Figure 3 shows that the agreement between MARS15 and FLUKA is better than ~20% in worst cases, and overall is about 5%.

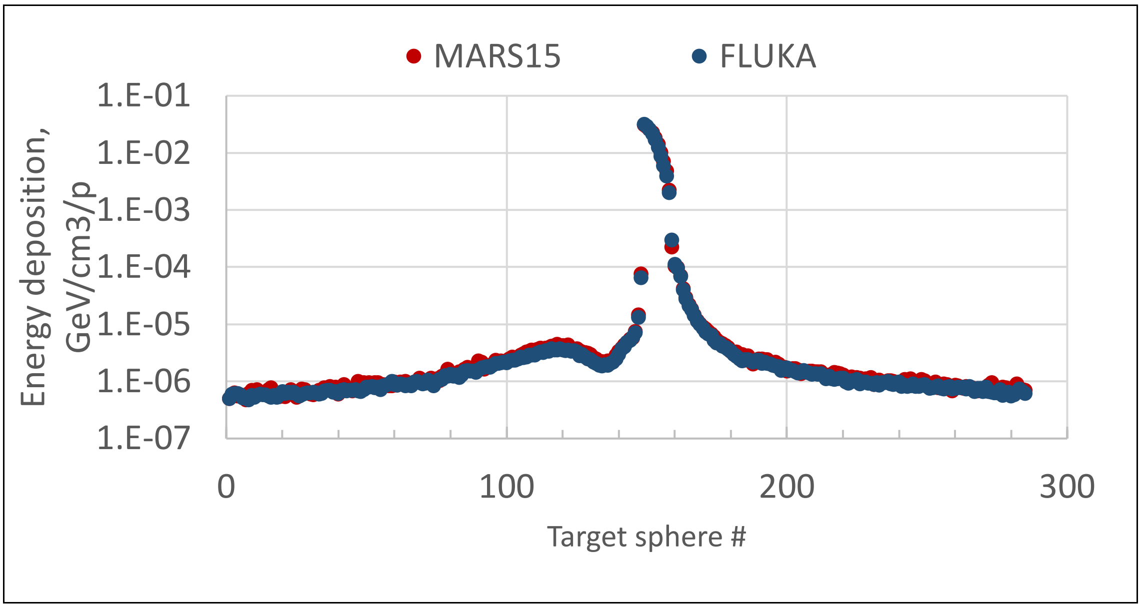

Figure 3. Energy deposition simulated with MARS15 and FLUKA.

1.4 ANSYS analysis

The results of the ANSYS analysis are shown in Figure 4. The maximum temperature for the W target after one cycle of irradiation (before cooling as cooling is not included in the model) is below 1400 K (melting point for W is 3422 C). Assuming the cooling will be efficient enough, this indicates that the target has a sufficient safety margin for the maximum temperature. The cooling scheme is under consideration, and two possible candidates for the target model are two-phase ammonia cooling and He gas cooling. Additional prototype development and tests will be necessary to make a choice of the optimal cooling scheme. Maximum deformation (Figure 4, right) for a W target is predicted to be at the level ~0.07 mm, which is less than the expected tolerance for the piping radius.

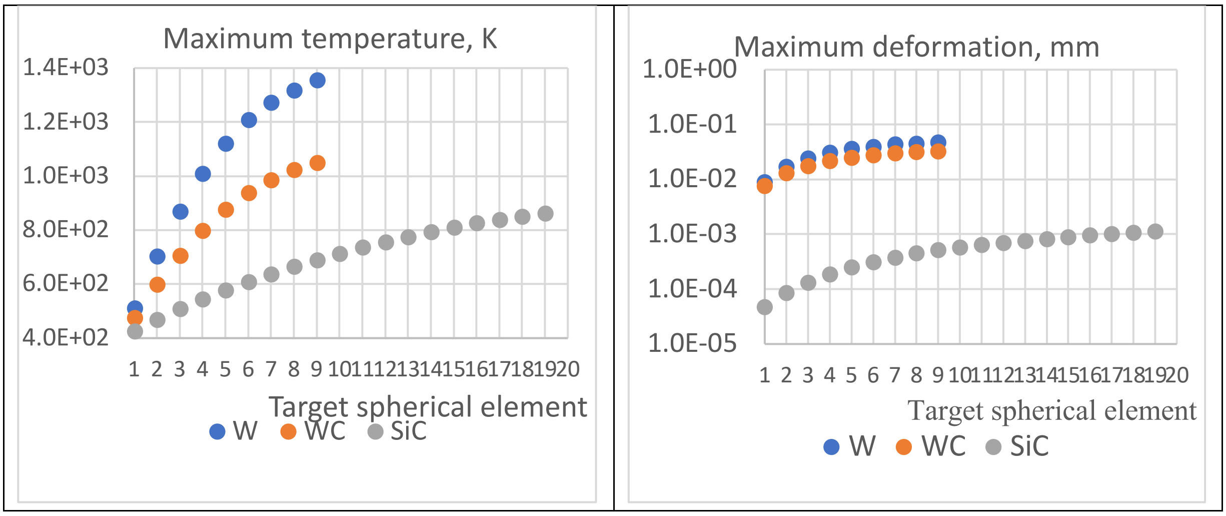

Figure 4. ANSYS analysis of the conveyor target. Left: maximum temperature in one cycle. Right: maximum mechanical deformation in one cycle.

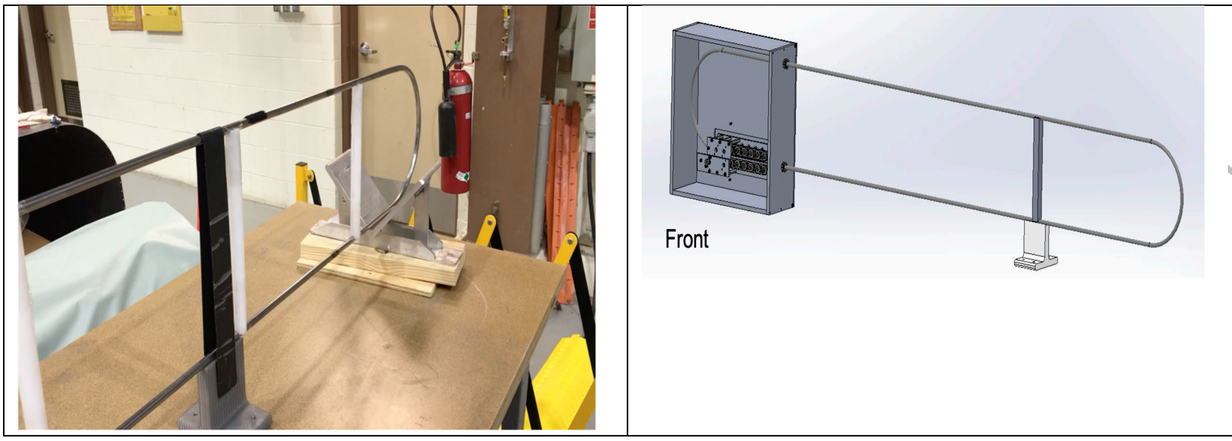

Figure 5. The first prototype of the conveyor target. Left: at Fermilab (MI-8 mezzanine). Right: a CAD model used in the fabrication.

1.5 The conveyor target prototype

The prototype (see Figure 5) of the target circulation system with the parameters optimized in the course of our simulation studies was designed by Euclid Techlabs, LLC. The model circulated stainless steel spheres (R=0.5 cm). The piping did not include the strait beam interaction section and has a U-turn (R=15 cm) and a racetrack shape; the length is 245 cm. Tubing has a slightly larger radius than that of the spheres (tolerance) to allow an unobstructed motion. The device also was fabricated to have a sealable design to enable a future upgrade to a vacuum to avoid oxidation of the target elements in air.

The electric engine was calibrated at Fermilab to determine the velocities of the spheres in the piping. We tested the prototype mechanically at the following velocities: 8 cm/s, 12 cm/s, and 16 cm/s. During several-hour tests at each velocity, the prototype exhibited a stable operation in all the three regimes. A caveat of such design that was found is that after a few hours of operation the traveling belt began to crumble. This observation indicated that during extended operation of the conveyor target, especially in a high-radiation environment, a traveling belt will not be a feasible design element. Another disadvantage of the traveling belt is that during the tests we found that not all rollers in the gearbox were engaged: some of them slipped and did not turn. However, in general, the conveyor design, despite the simplifications in the prototype, was found to be feasible.

1.6 Summary

We have performed simulation studies of three designs of the pion-production target for the Mu2e-II upgrade, namely, rotating rod, fixed granular, and conveyor target. We found that the former two designs at this stage of considerations can be ruled out (the rotating rod one because of loss of the muon yield in the constrained space of the HRS inner bore; the fixed granular one because of a large peak DPA, which would require its frequent replacement). Based on the simulation we made a decision to proceed with the conveyor design because there were no showstoppers found. Also, our simulations showed that total heat load and DPA in the conveyor design will be acceptable if we take into account the possibility to cool the spherical elements between cycles of irradiation or replace then once they acquire significant amount of radiation defects. We designed and mechanically tested a first prototype. Our tests supported our conclusions regarding the feasibility of the conveyor design.

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