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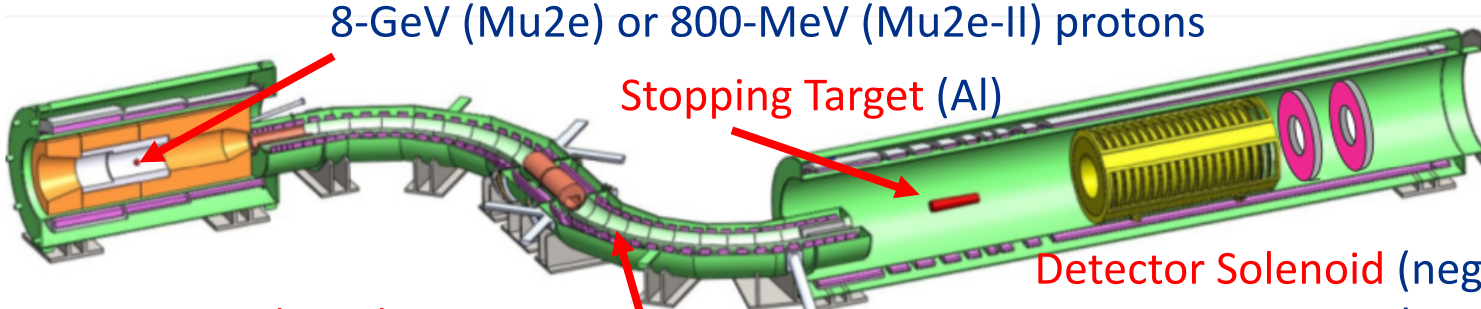
Pion-Production Target for Mu2e-II: Simulation Design and Prototype

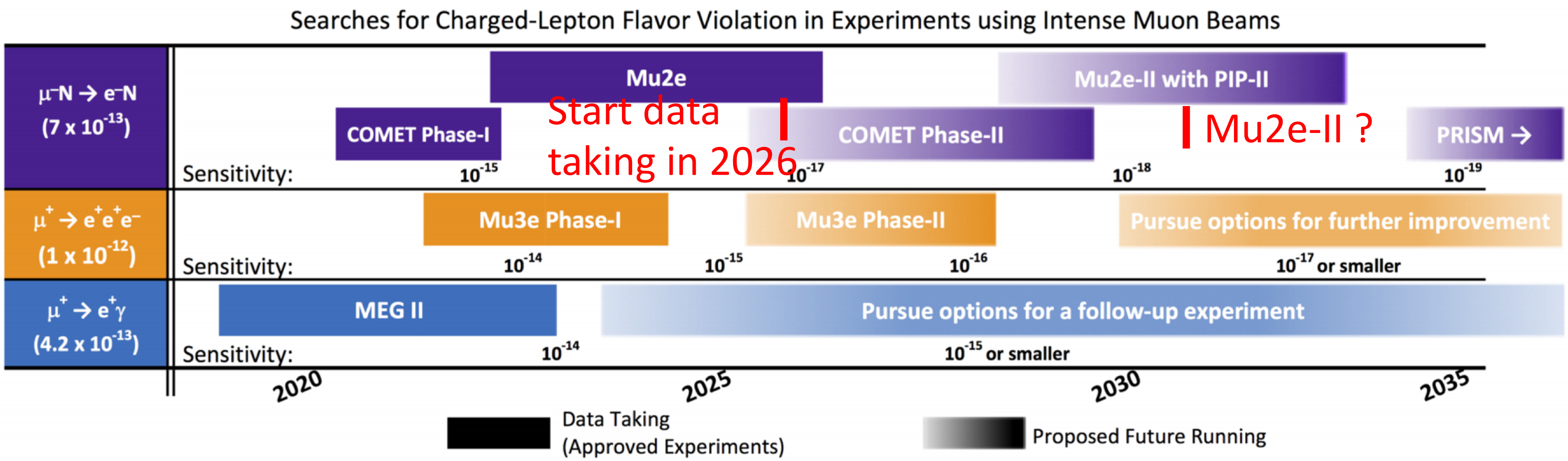
International Conference on High-Energy Physics (ICHEP 2022), July 7, 2022, Bologna, Italy

The Mu2e experiment and its upgrade Mu2e-II

- The Mu2e experiment at Fermilab: search for indications of charged lepton flavor violation. The coherent neutrinoless conversion of a negative muon into an electron in the field of a nucleus by measuring 105-MeV electrons emitted from an Al target.
- To probe effective new physics mass scales up to the 10^3–10^4 TeV range.
- Negative pions will be generated in interactions of the 8-kW 8 GeV primary proton beam with a tungsten target ($3.6 \cdot 10^{20}$ stopped negative muons in three years of running).
- Mu2e-II, with a single event sensitivity improved by a factor of 10 or more (mass scales up to 10^5 TeV) by utilizing an 800-MeV 100-kW proton beam.
- Using the PIP-II accelerator upgrade, a 250-meter-long LINAC, 2-mA proton beam to 800 MeV @ 1.6 MW (the power not used by Mu2e-II will be directed to other experiments).



The Mu2e and Mu2e-II schedule



- From A.Baldini et al., European Strategy for Particle Physics on behalf of the COMET, MEG, Mu2e and Mu3e collaborations, 2020.

Scope of LDRD (Laboratory-Driven R&D)

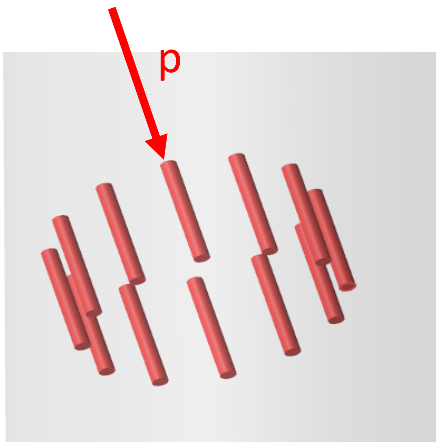
- There is no Mu2e upgrade target concept close to satisfying the new requirements (for a 100-kW 800-MeV proton beam). (A 50-kW target prototype was designed for MECO and PRISM at Irvine CA: MECO Production Target Development", J.L.Popp, AIP V.721, p.321, 2003.) (High energy density, DPA)
- We are developing a conceptual design using the MARS15, FLUKA, and G4beamline Monte-Carlo codes, and Mathematica
- We are considering the most favorable aspects of the granular, "conveyor", and rotating cylindrical targets.
- We are simulating the overall target pion production performance and durability at beam induced pulsed energy deposition spikes, thermal stress, radiation damage, muon stopping rates, residual activation and radiation loads.
- **The project is aimed at the** design of the prototype **of the Mu2e-II pion-production target for the** 100-kW 800-MeV **proton beam and its mechanical tests.**

Deliverables:

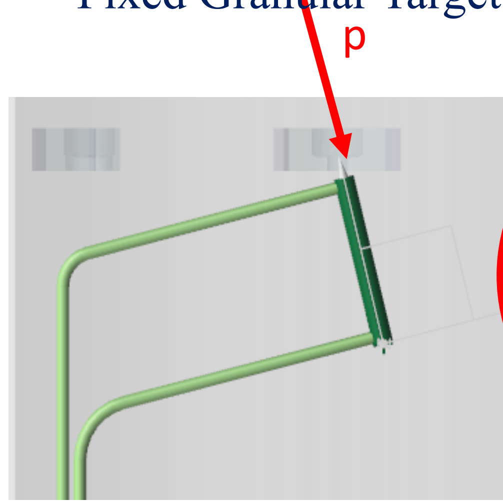
- Mid-2020 – Mid-2021: the plausible design for the Mu2e-II target.
- **Mid-2021 – Mid-2022: designed, built, and tested. Conclusions regarding feasibility to be drawn. First prototype version built and tested.**

Prioritizing the designs under consideration for prototyping

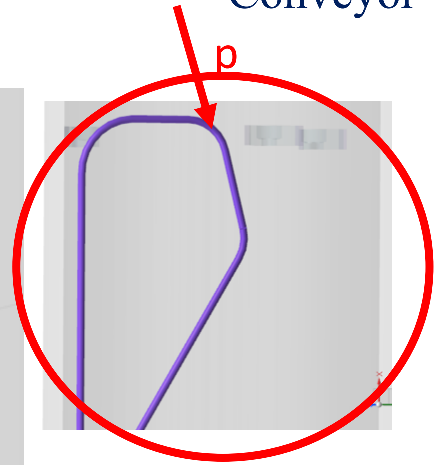
Rotating Elements



Fixed Granular Target



Conveyor



Pros: small space required; two-phase ammonia could be used for both cooling and moving elements inside conveyor; radiation damage can be distributed; Cons: technical complexity (prototyping needed)

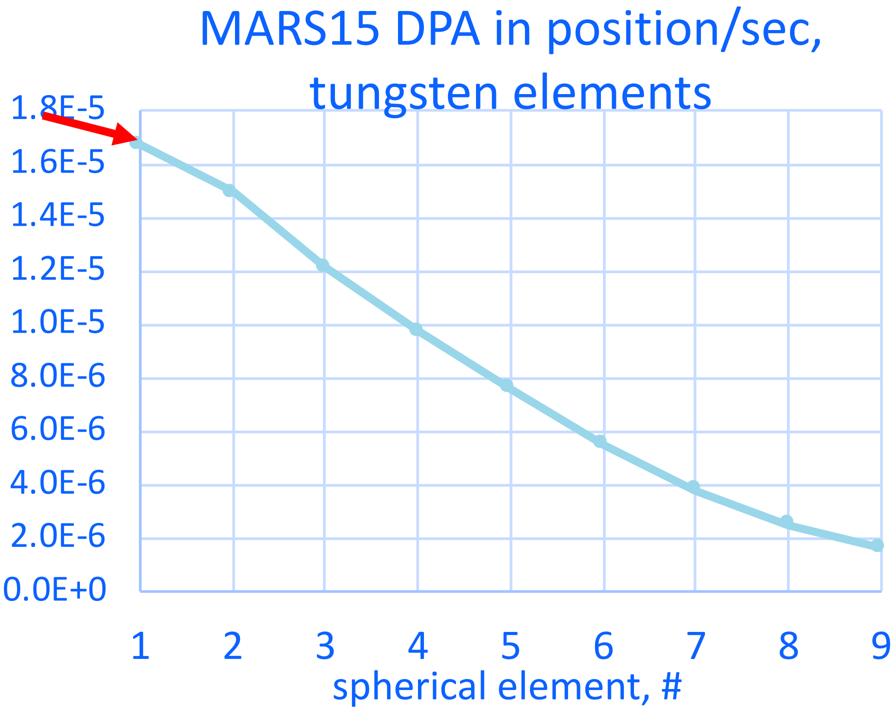
Pros: radiation damage can be distributed over many rods
Cons: its hardware would require a significant space inside the bore (complicates cooling and muon flow)

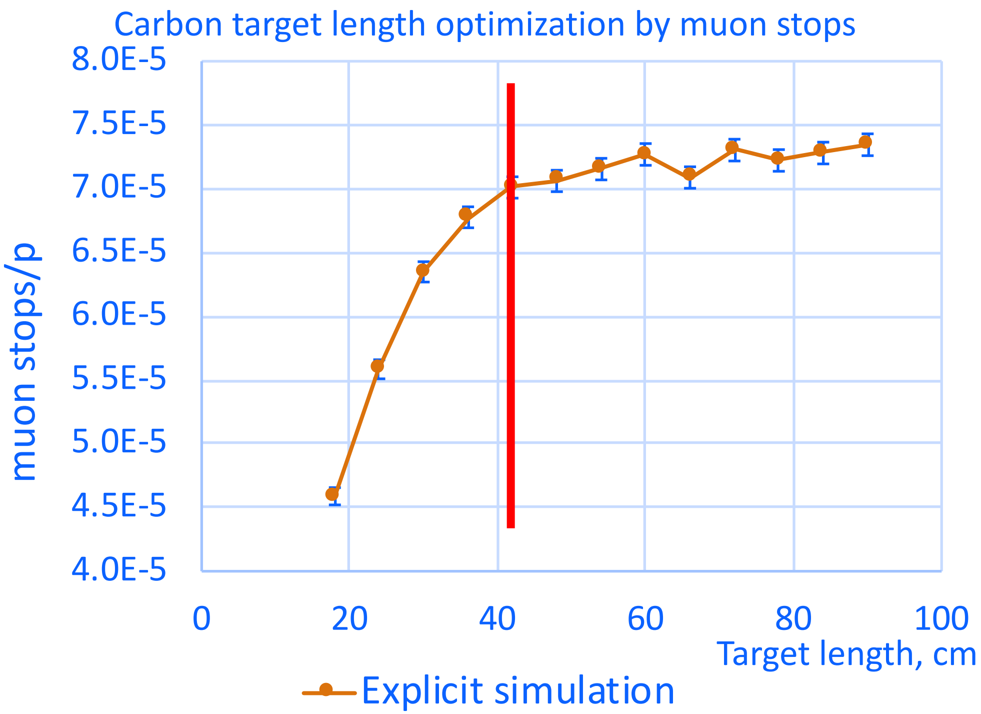
Pros: small space required
Cons: peak DPA (MARS15) >300/yr; gas cooling cannot be performed efficiently

Target to be placed in the inner bore of Heat and Radiation Shield

- Constraint: compatibility with the current HRS design (inner bore R=20-25) cm)

Interaction zone length and DPA





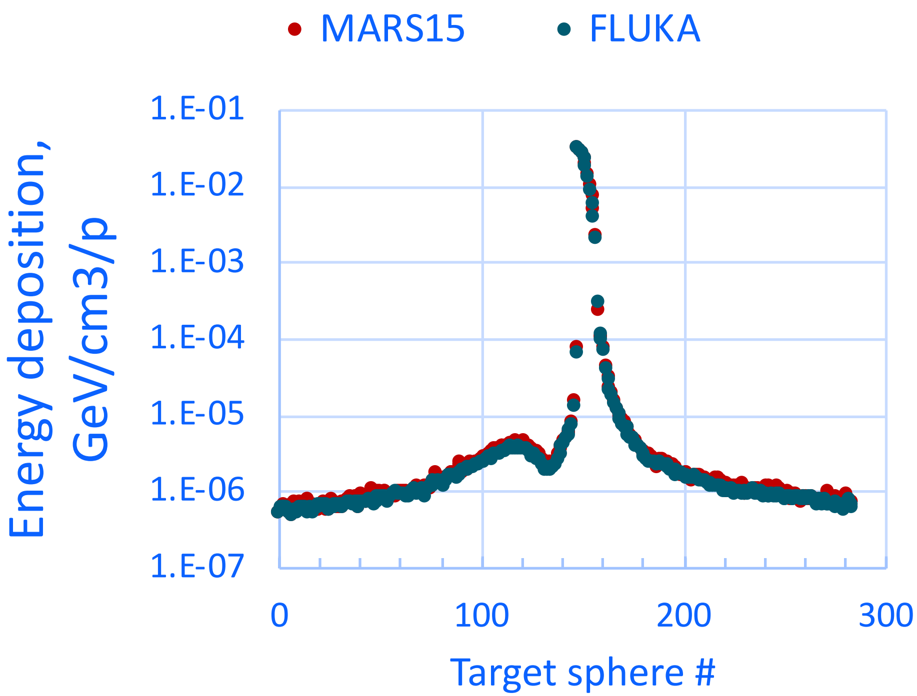
min balls required (DPA) = 150/yr

DPA limit assumed <= 10 (ESS, Habainy 2018)

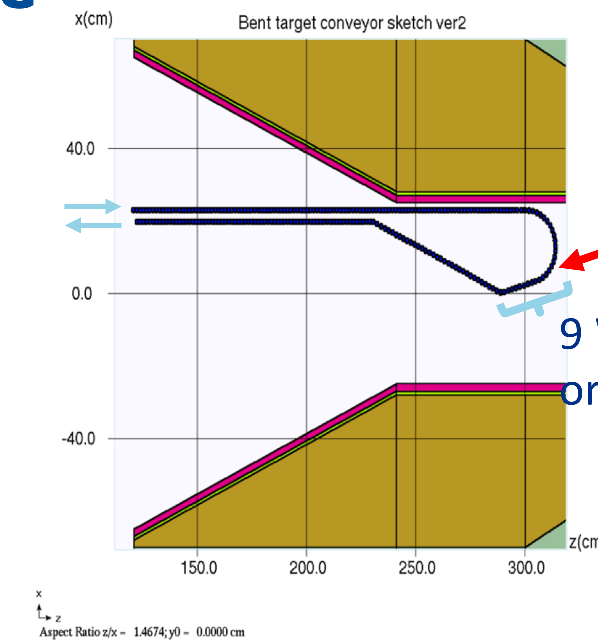
Based on muon stopping rate studies with MARS15 and G4beamline the optimal target lengths were determined to be: 28 balls (C target), 9 balls (W and WC targets), 19 balls (SiC); MoGRCF was studied, too. Agreement between transmission and explicit allows saving computation time.

MARS15/Fluka DPA consistency analysis is ongoing

Energy deposition for a W target

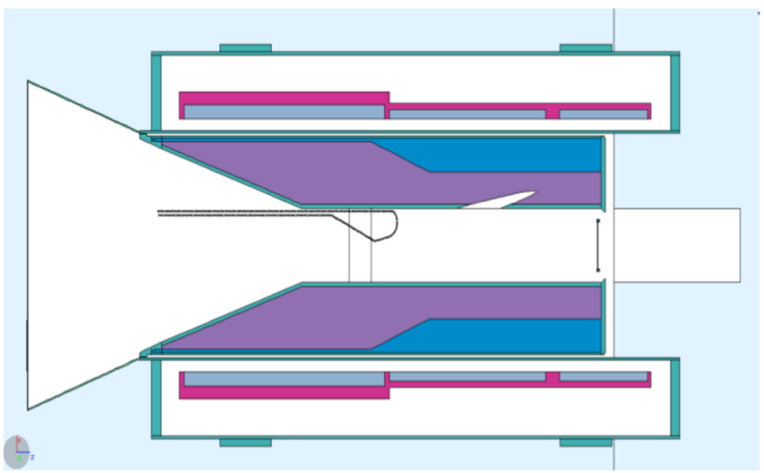


MARS15 model



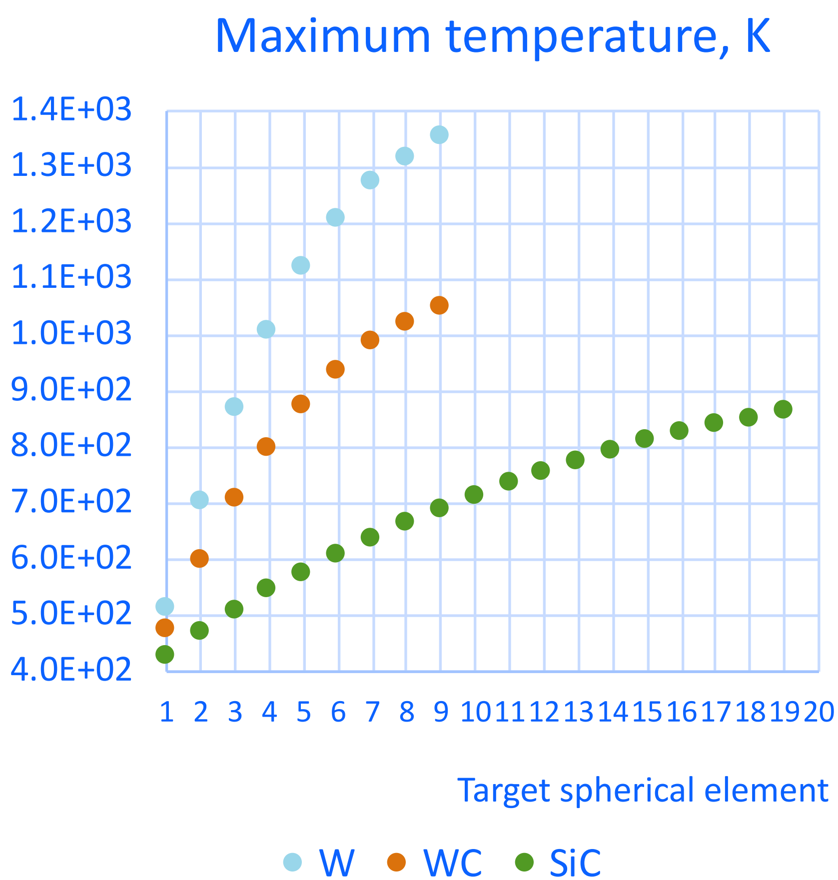
9 W/WC balls or 19 SiC balls

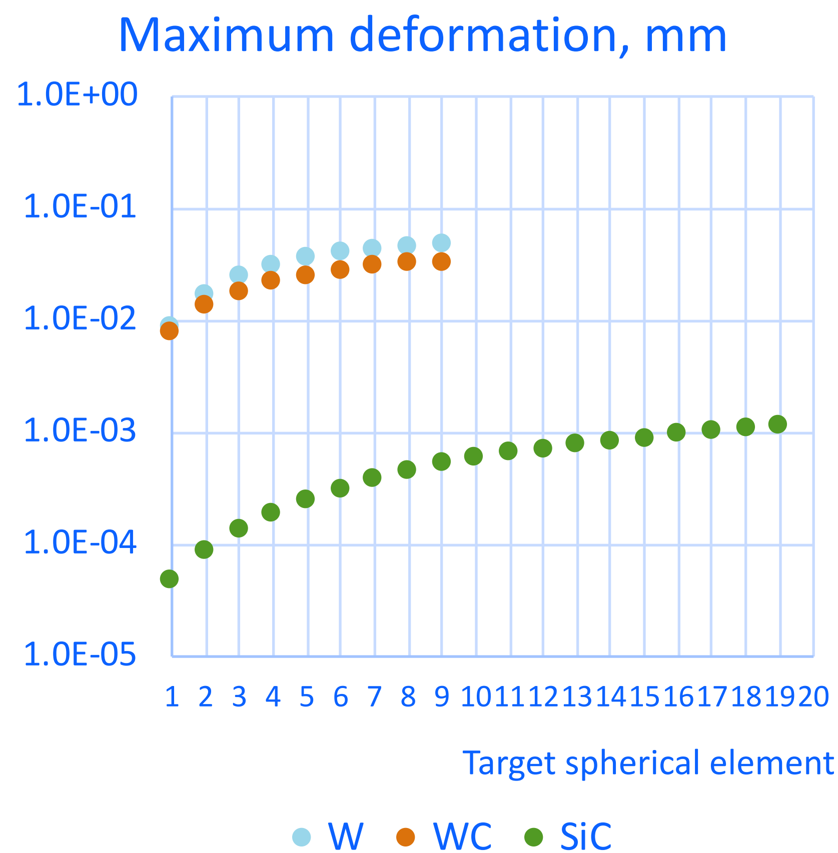
FLUKA model



- MARS15/FLUKA data agreement is better than 20% for energy deposition.
- Total E_{dep} = 31.8 kW; peak DPA (Nordlund) = 330 DPA/yr (assuming a fixed ball in beam, no tubing);
- Motion speed of spherical elements in conveyor is 10 cm/sec,
- (1.35 sec for an element to pass the beam). More spherical elements are required by thermal analysis

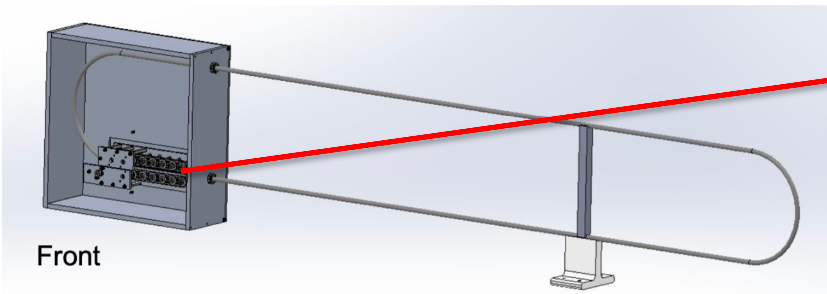
Conservative thermal and mechanical ANSYS analyses: conveyor

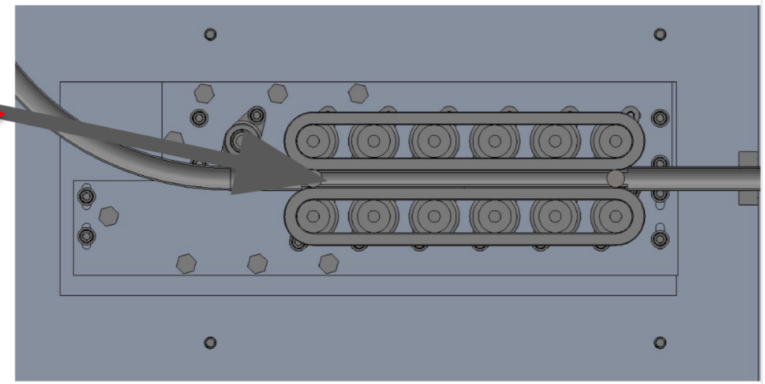




Melting points:
3422 C for W; 2870 C for WC; 2730 C for SiC

Current prototype design



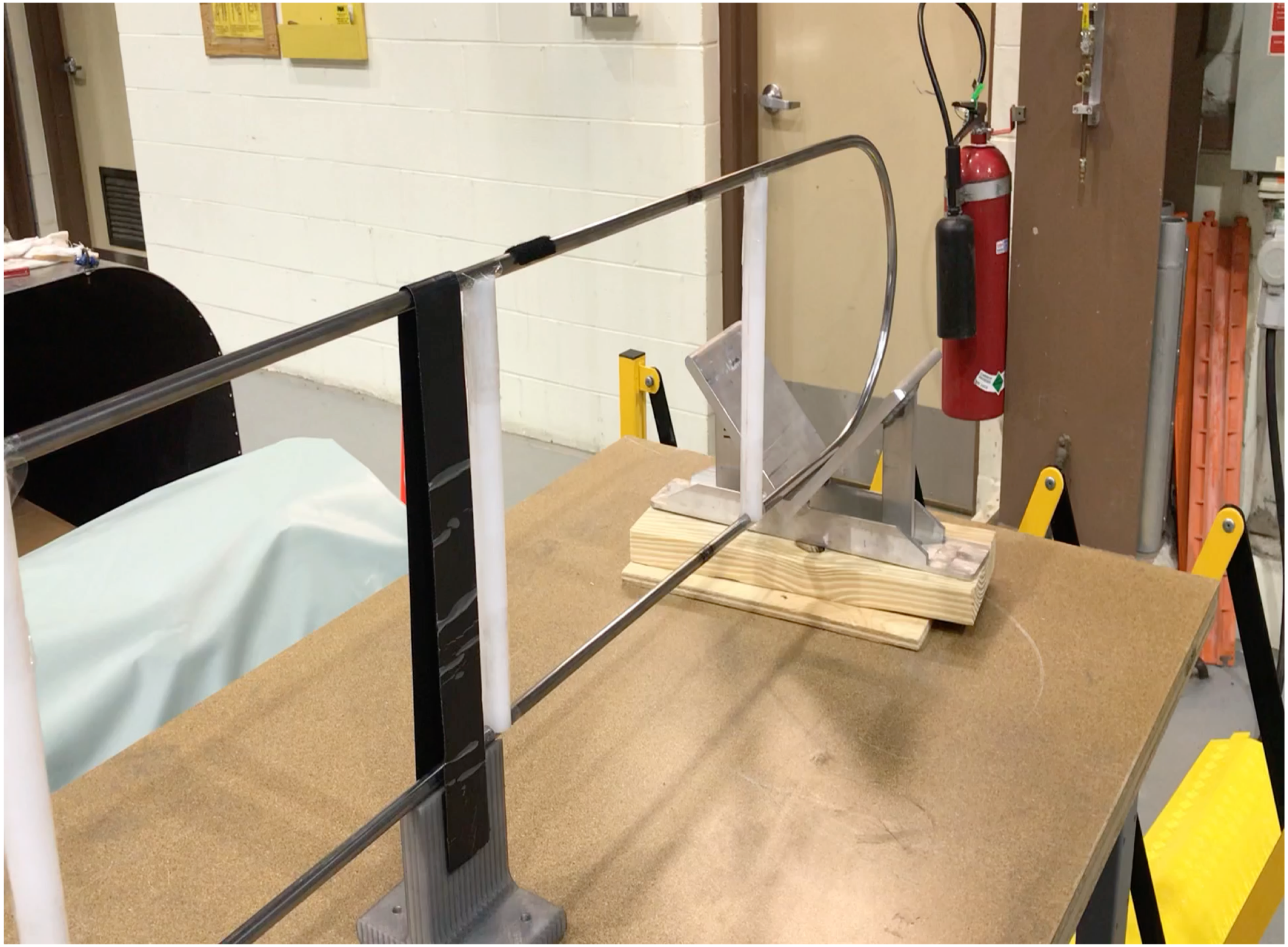


The engineering was done by Euclid

Current design:

- circulates Steel balls R=0.5 cm
- U-turn R=15 cm; L = 245 cm.
- Racetrack shape (no beam straight section)
- Tubing slightly larger than the balls (tolerance)
- Variable velocity
- Sealable design (for future vacuum to avoid oxidation in air)
- Track actuated from two sides in gearbox
- Track is gripped in drivetrain

Mechanical tests at Fermilab



In Fermilab's MI-8 Mezzanine: test at 12.3 cm/s

Takeaways and future plans

- Our simulations allowed us to rule out some designs (rotated and fixed granular targets) as less practical.
- The thermal and mechanical analyses enabled us to determine the possible choice of cooling scheme and prospective materials.
- The first prototype of the Mu2e-II target has been build and its mechanical tests performed at Fermilab. They indicated the feasibility of the proposed design.
- We have determined the directions for prototype's further improvement (sprocket mechanism, He-gas cooling, realistic shape).

	Tungsten/WC	Lower-density bent (Carbon)
Rotated	Requires large hardware device inside HRS	Too large to fit in HRS
Fixed granular	DPA is too high	DPA is high; lower pion production
Conveyor	Thermal and mechanical analyses are ongoing; currently looks feasible	Lower pion production; thermal analysis is ongoing; currently looks feasible