The Fermilab Facility for Dark Matter Discovery (F2D2): A Conceptual PIP-II Beam Stop Facility for Dark Sector Physics

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NuFACT

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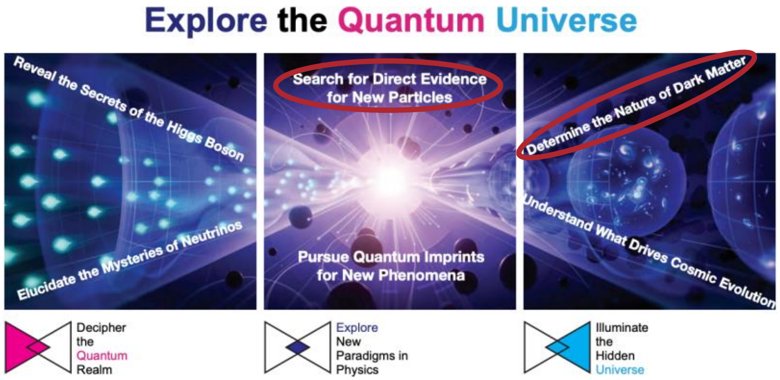
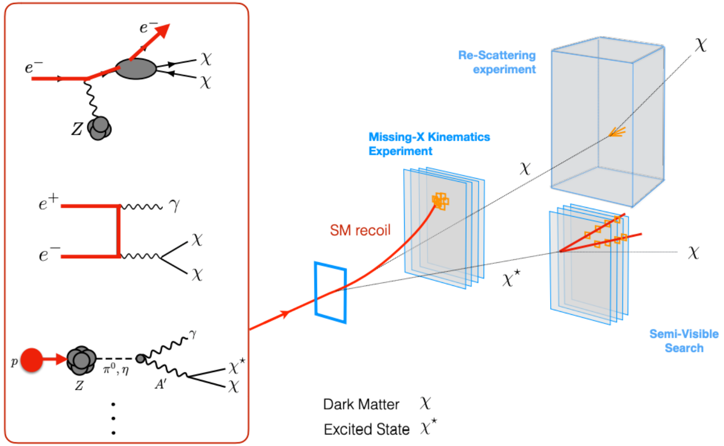
Overview

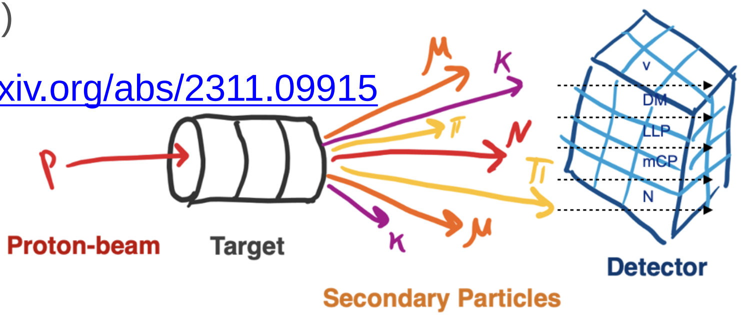
- Background
  - P5 – Dark sector searches
  - PIP-II – Use excess beam to do science
  - Beam dump experiments to find dark matter
- F2D2
  - Requirements, conceptual design, and facility layouts
- Technical Challenges
  - Thermals
  - Beam windows
  - Remote handling & vacuum sealing
- Future relevance – Targetry and Muon Collider

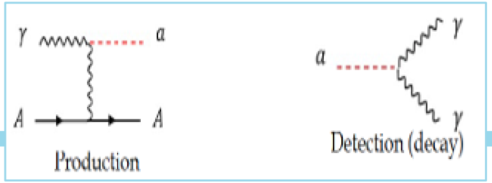
Dark Sector Searches with Beam Dumps

- Can you create dark matter in a target?
  - If so, amount of DM proportional to the number of protons on target
  - High current beam onto a target – more POT, more DM
  - Shield all known SM particles (the “target” is really a beam dump that absorbs the primary beam and any secondaries)
  - Place detectors in quiet zone after the beam dump, look for signal (see backup for links to some experiment concepts)
  - https://arxiv.org/abs/2311.09915









Figures from M. Toups, J. Yu

The PIP-II Superconducting Linac

- Excess beam available – LBNF/DUNE needs only 2% of nameplate capacity
  - CW acceleration – high power, high duty cycle (rated for 2 mA at 800 MeV, 1.6 MW)
  - With upgrades/extensions, 1 GeV at 2.5 mA (2.5 MW) possible near-term
  - PIP-II is a great tool – use it as a driver for smaller experiments
- Caveat – PIP-II (800 MeV+) is a completely different targetry design space than NuMI/LBNF (120 GeV)
  - Much higher energy deposition and radioactivation
  - High damage rates to most materials

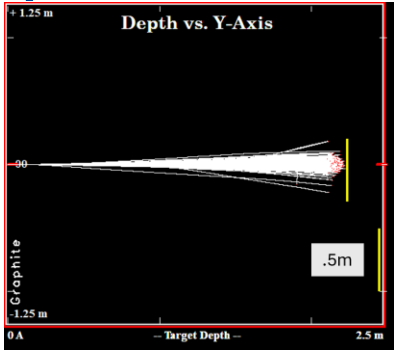
F2D2 Requirements

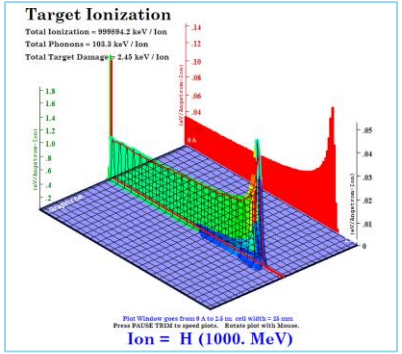
- Requirements
  - No (SM) particle flux out back of beam dump
  - Graphite absorbing elements to stop primary protons
  - Copper backstop (to attenuate pions, etc.), with surrounding steel and concrete shielding
  - Serviceable with replaceable components, plan for nominal 10-year facility life
  - Radiological considerations for access – (<20 mrem/hr (0.2 mSv/hr) maximum as a goal)
  - 40’ x 100’ hall footprint

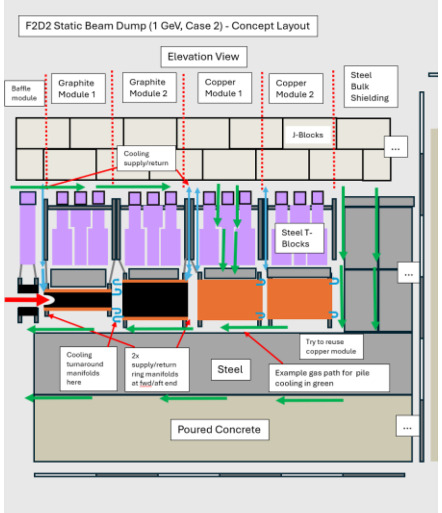
- Implementation
  - Graphite cores inside copper alloy cooling jacket
  - Diluted beam (σ = ~5cm) to reduce peak energy deposition (rastering/wobbling also possible)
  - NuMI/LBNF-style module construction to support core assemblies
  - Permanent, gas-cooled steel pile shielding with removable/serviceable core elements
  - All remote handling operations and staging/logistics must be inside coverage of facility crane
  - Work Cell – rad-shielded remote handling workspace

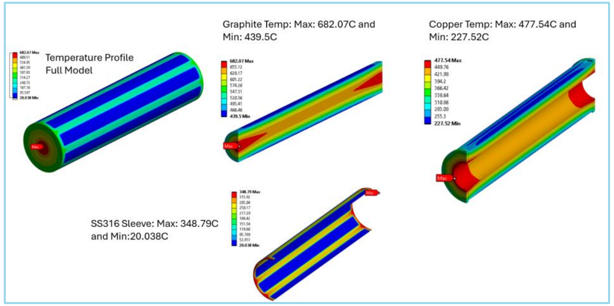
How to Design a Beam Dump (Abridged)

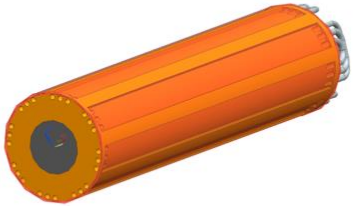
- Length/diameter of graphite to stop diluted primary beam
  - Confirm with SRIM/TRIM, MARS
- Estimate energy deposition (heat) from MARS/FLUKA and beam parameters
  - Size cooling systems with design correlations, hand calcs
  - Confirm sizing with thermal finite-element calculations – temp limits by material?
- Calculate prompt and residual dose for given beam parameters (MARS)
  - Iterate to necessary shielding thickness
- Calculate radiation damage (dpa), estimate life (graphite annealing)



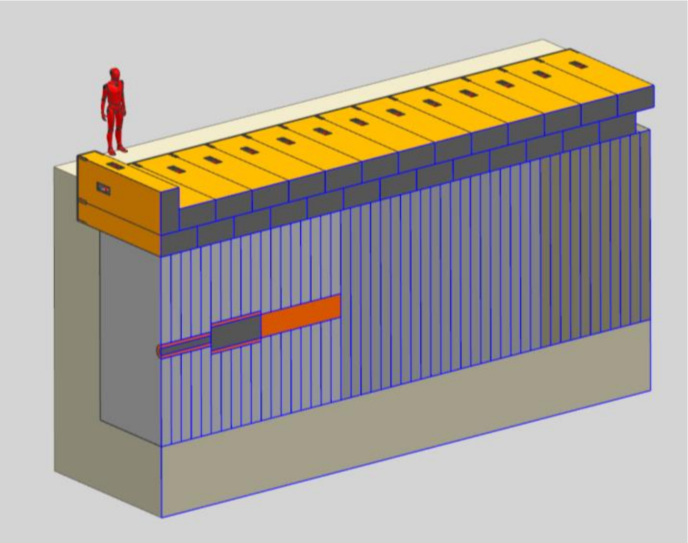


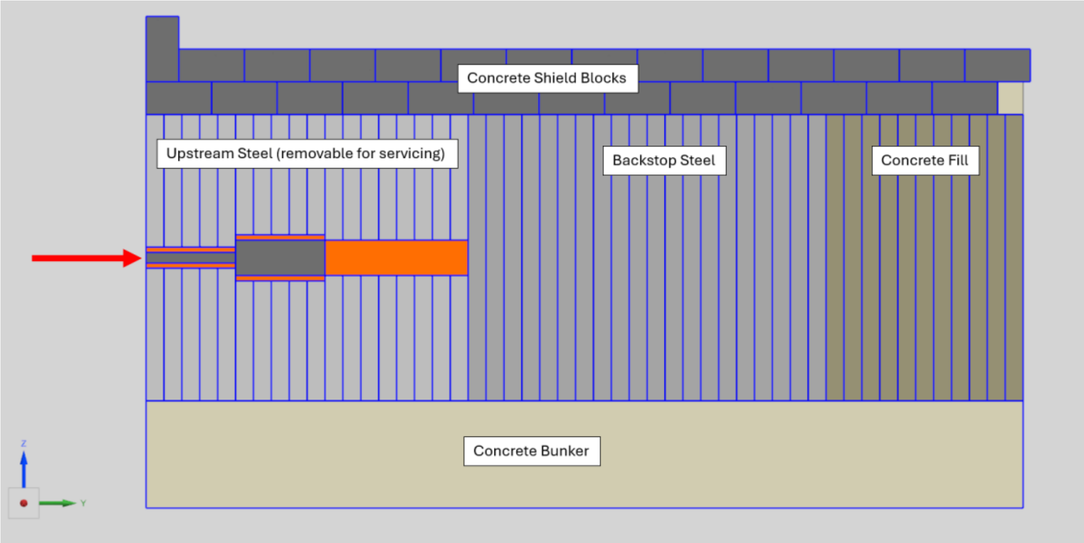






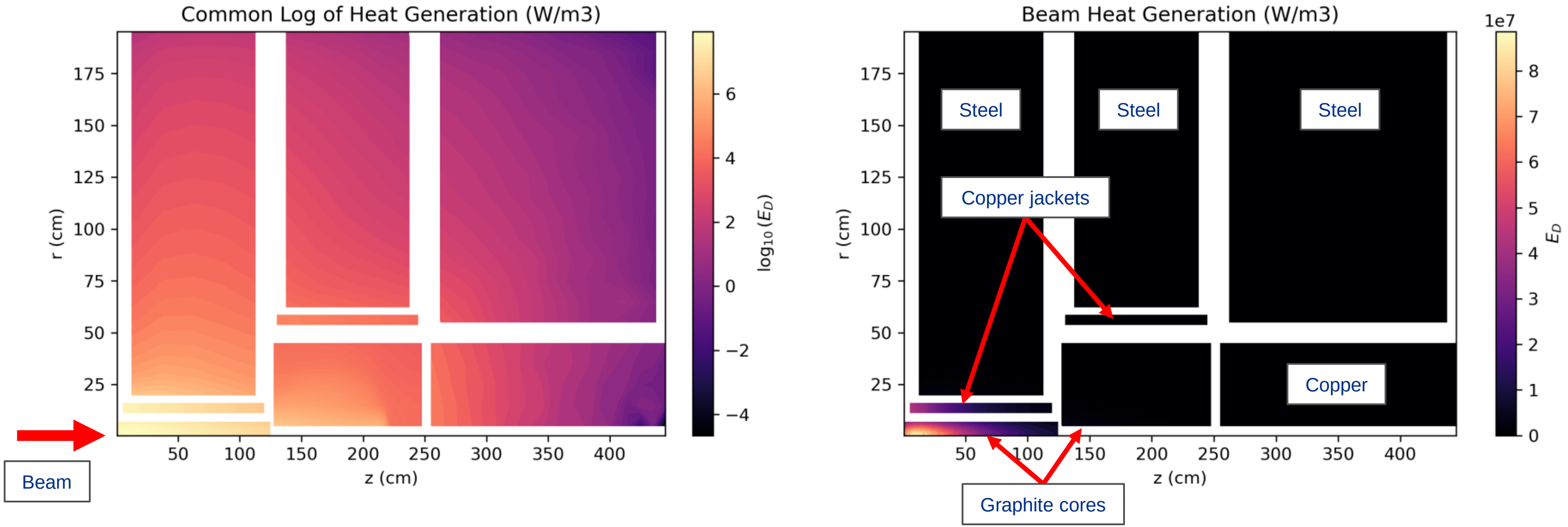
Beam Dump Pile





Conceptual layout of the beam dump.
This is a simplified model being fed into FLUKA to verify:
1) the transverse depth of steel required for radiation shielding and
2) the on-axis shielding required to minimize detector backgrounds.
For scale reference, the shielding layers are 0.25m thick.

F2D2 EDEP Map

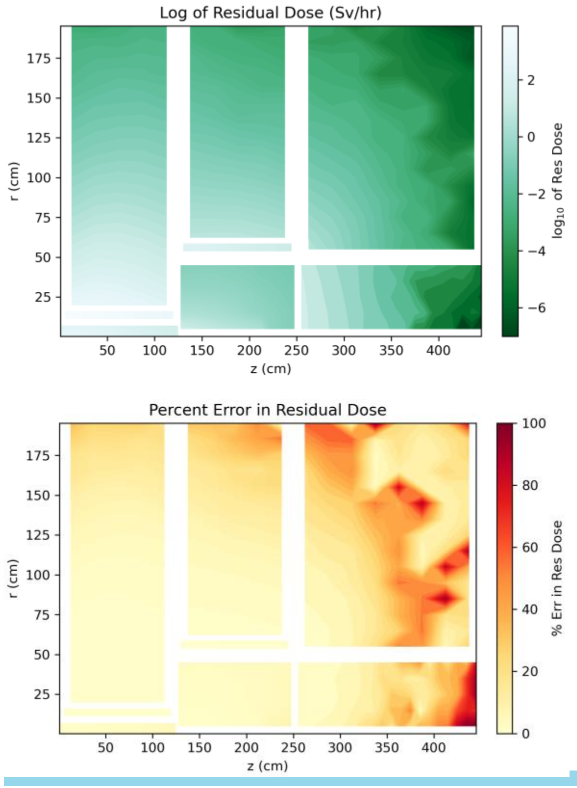


Peak energy deposition ~90 MW/m^3, z=~20 cm into the graphite
Note the sharp falloff in EDEP at about z=220 cm – that's the protons stopping

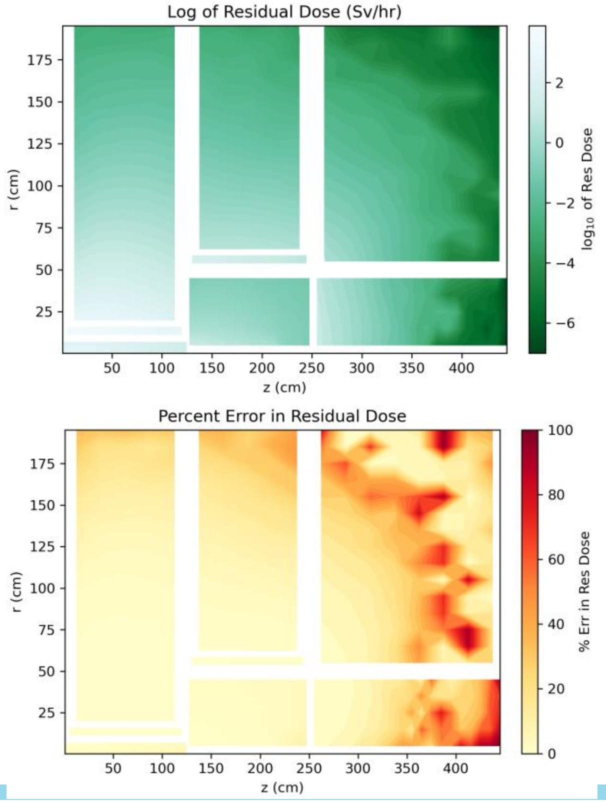
F2D2 Radiation Map – 100d irradiation

*More on this later…

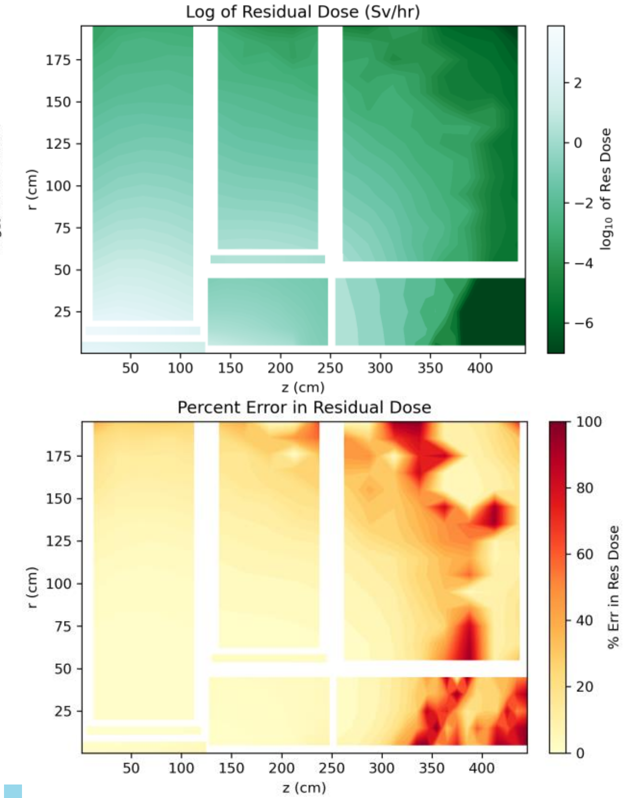
Four Hours Cooling



One Day

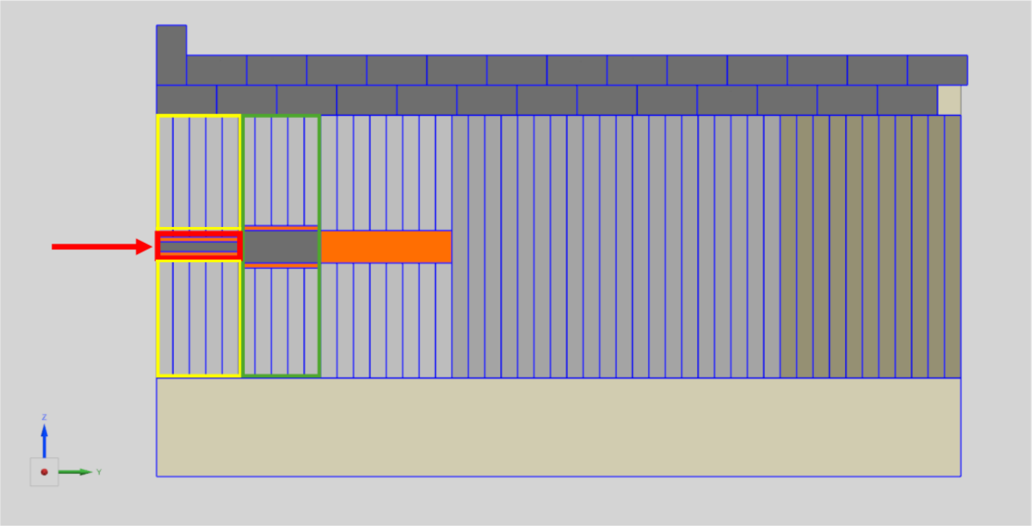


One Week



Thermal Management – Core Cooling

- Beam dump absorbs all beam energy
  - 2.5 MW absorbed, minus neutrinos, etc.
  - Stop muons and neutrons
- Phase-change cooling for core (see comparisons in backup)
  - Forced-gas (helium) not sufficient
  - Non-boiling forced water convection is better (need margin)
  - Boiling heat transfer retains safety margin : Hypervapotrons, swirl tubes, screw tubes, etc.
    - Need R&D effort



EDEP Totals by Component	Calculated EDEP (Watts)	EDEP Power (kW)
Graphite Core 1	604079	604
Copper Jacket 1	1100751	1100
Steel Shield 1	375667	376
Graphite Core 2	81129	81
Copper Jacket 2	8923	9
Steel Shield 2	12384	12.3
Copper Slug	3323	3.3
Steel Shield 3	1638	1.6
Grand Total	2187895	2188

Thermal Management – Pile Cooling

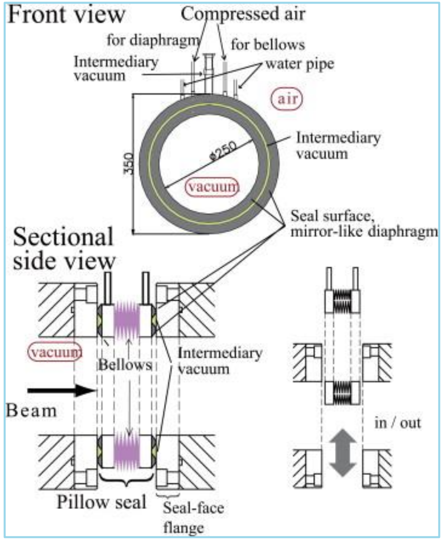
- Inert gas cooling for bulk steel shielding
  - Can't expose graphite cores to oxygen – fire hazard, and limit temp to avoid sublimation
    - Can't enclose graphite in a canister like NuMI – more actively-cooled windows that are already a design challenge
  - Nitrogen? – heritage for LBNF TSP and LHC beam dumps, very cheap
    - Risk of creating cyanides that attack structure (comments from CERN)
  - Helium? – effective but very (very!) expensive, availability may get worse
  - Argon? – cheaper than helium, chemically inert, but radioactivates to 41-Ar
- Argon appears to be a viable option – allow 41-Ar to decay before accesses/venting
  - Aim to minimize number of windows around beam dump environment
  - Cheap enough to make work, even if the pile is vented without recovering argon for accesses
  - Scale estimates from nitrogen handlers for LBNF Target Shield Pile

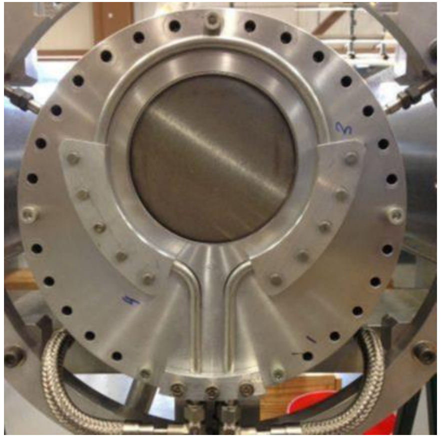
Beam Windows and Vacuum Sealing

- Low energy = high power deposition
- Actively-cooled, double-wall beam windows to isolate beamline vacuum from target station environment
  - Edge cooling insufficient (NuMI window at right)
  - High damage rates – needs separate replacement for target primary beam window, target vessel window
- Pillow vacuum seals
  - Inflatable metal bellows presses against a flat flange - allows remote disconnection & reconnection of a vacuum volume
  - Example seal at right from BigRIPS at RIKEN, Japan: https://doi.org/10.1016/j.nimb.2013.08.056

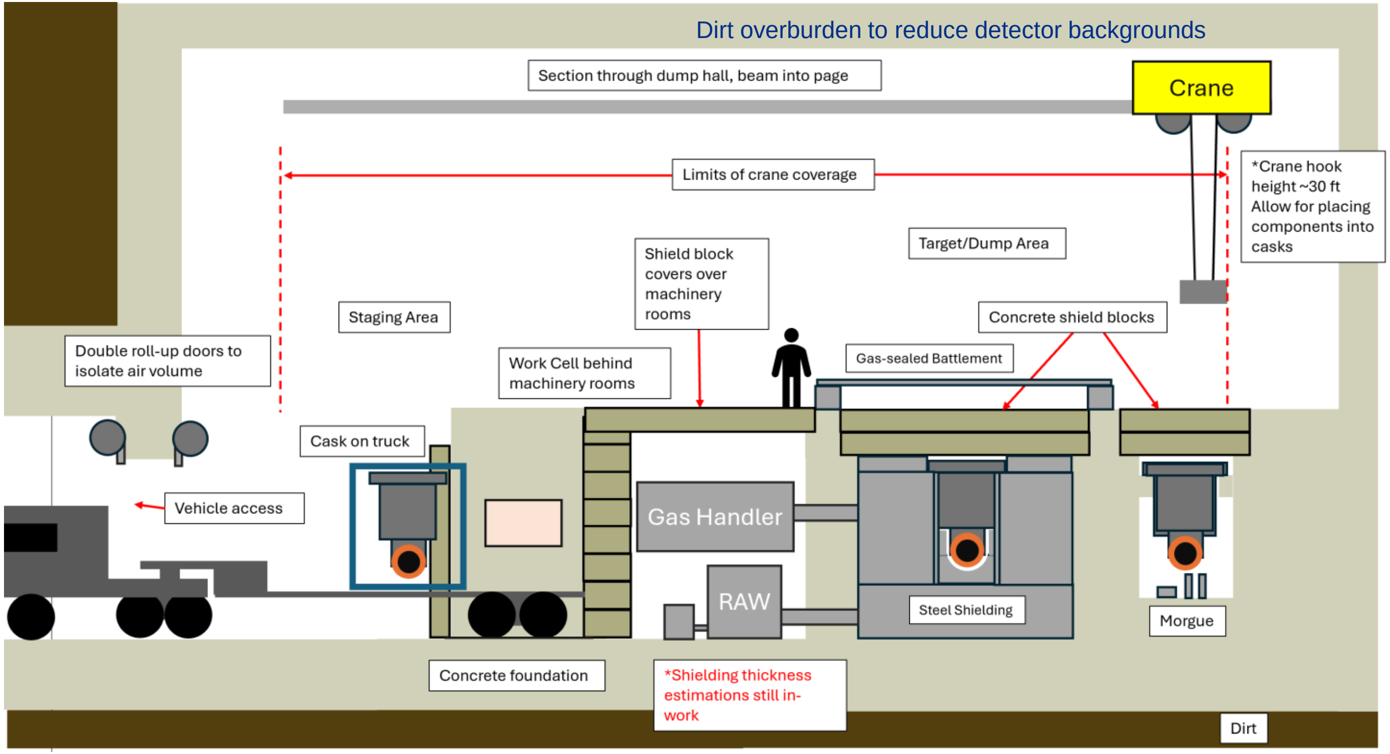
*At 2.5 MW of beam current

Window Material	Stopping Power @ 1GeV (SRIM)	Power deposited (per mm thickness)
Be	.33 MeV/mm	1.65 kW/mm
Al	.47 MeV/mm	2.34 kW/mm
Ti	.72 MeV/mm	3.6 kW/mm
W	2.36 MeV/mm	11.8 kW/mm



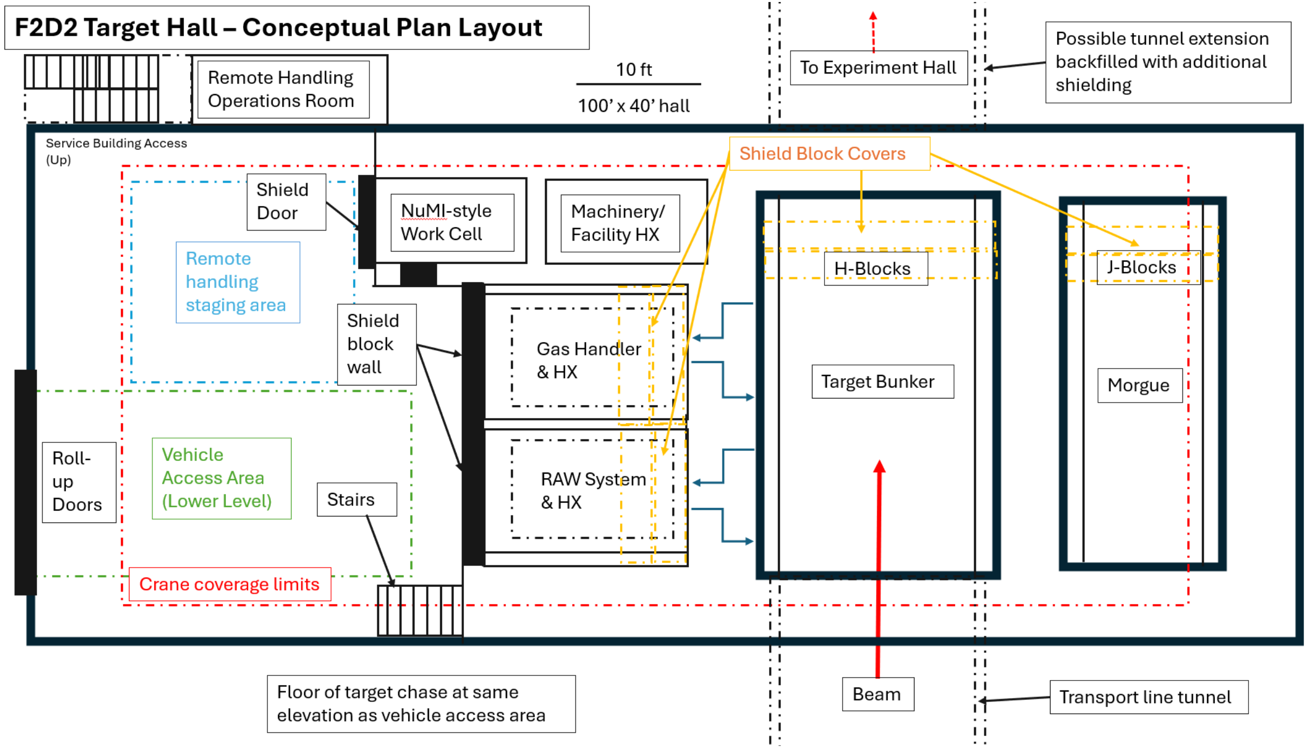


Facility layout concepts



Section of beam dump hall with direct vehicle access

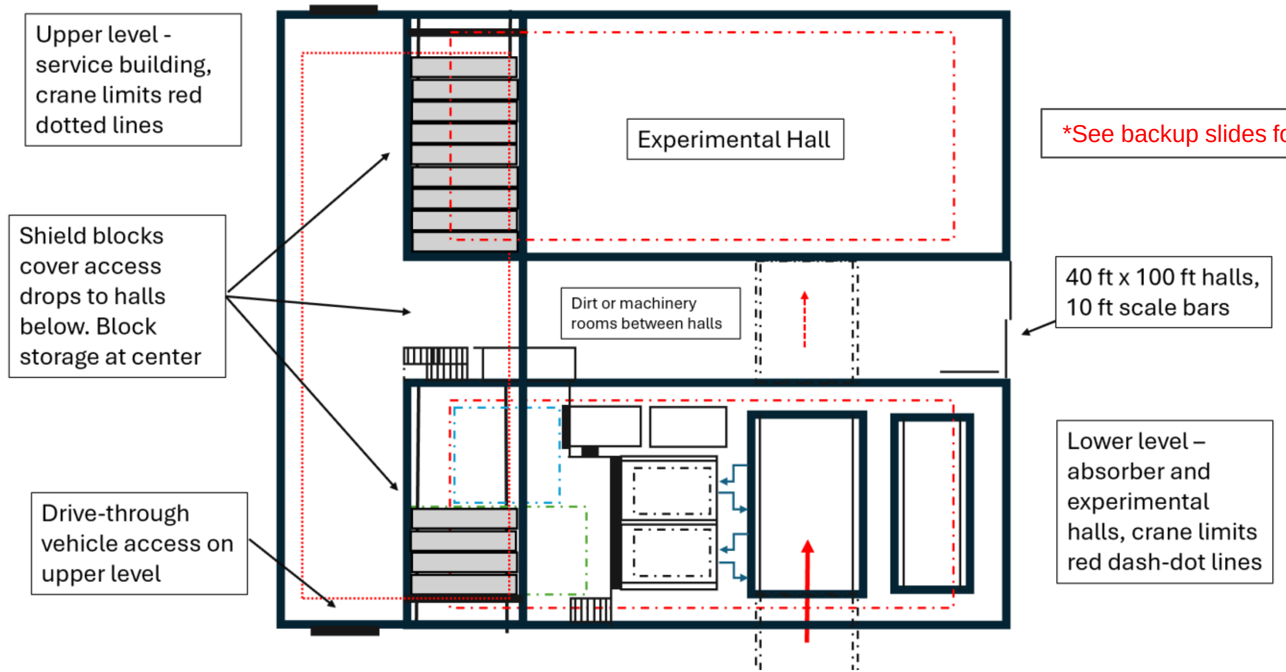
Facility layout concepts



Plan view of same beam dump hall layout

Facility layout concepts

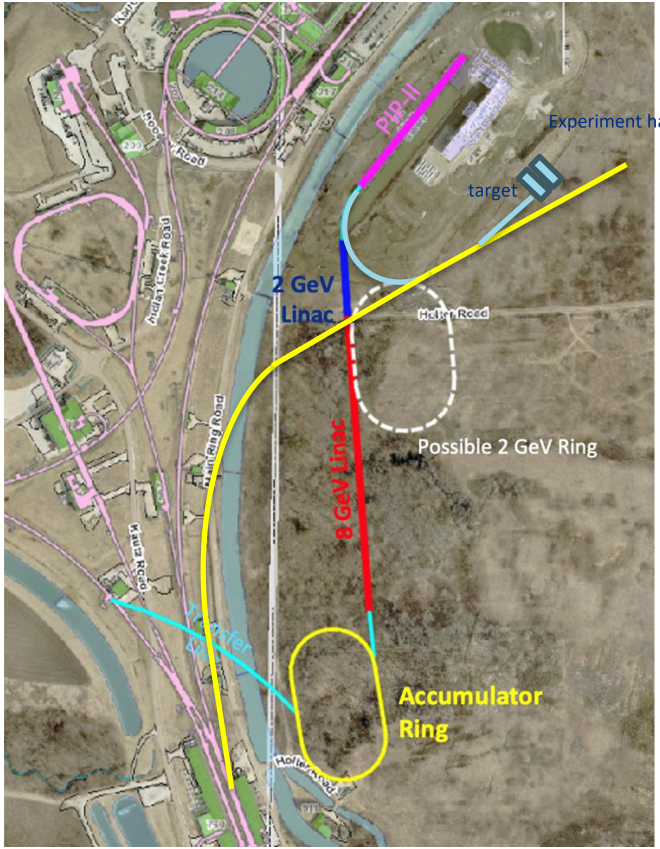
F2D2 Service Building Concept with Absorber and Experimental Halls – Plan View



*See backup slides for experiments

Integrated F2D2 facility plan layout with upstairs vehicle access and crane hatches to access experiment and beam dump halls

F2D2 Site Layout – Integrated with Future Fixed Target Campus



F2D2 – Science Experiments Plus Engineering Testbed

- F2D2 is a compelling engineering project beyond P5 science goals
  - The F2D2 beam stop exists largely independent of the downstream experiment hall
    - Use as a high-power targetry test and irradiation facility after experiments
    - Present lack of this capability at Fermilab – **This is a facility we can use!**
      - We have limited hot cell/PIE capabilities – visual examination only at C0
- F2D2 is currently envisioned as a small facility – 40' x 100' target hall
  - High-activity remote handling is expensive and bulky – can we keep it small?
  - Need R&D on specific cooling items (windows, phase-change cooling, etc.)
- **Not only does F2D2 contribute to P5 science goals, F2D2 is a design testbed and technology test area for Muon Collider facilities!**
- Next report to leadership at end of calendar year

Looking forward to 2045…

- ***<u>All of these problems will need to be solved for the Muon Collider</u>***
  - **Thermals & Radiation**
  - **Remote handling & waste stream management**
  - **Conventional facilities**
- The μ-Collider needs a beam dump for a high-power low-GeV-energy beam – just like F2D2
  - Work so far shows that a solid beam dump (vs. a pool of liquid mercury) might be feasible thermally
    - Still need to evaluate thermal stresses, tritium, CW vs. pulsed beam, etc. Long way to go.
- The μ-Collider target station will be harder than F2D2, probably even more radioactive
  - Need to think about remote handling and final disposition for kSv/hr waste now
  - SNS has PIE capability on-site to diagnose target issues – we need hot cells and hot labs

Thank you for your attention!

F2D2 Task Force Members

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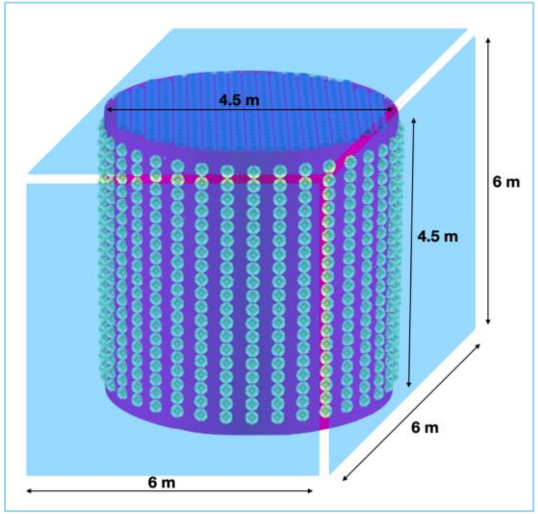
Collaborations / Partnerships / Members [19.5pt Bold]

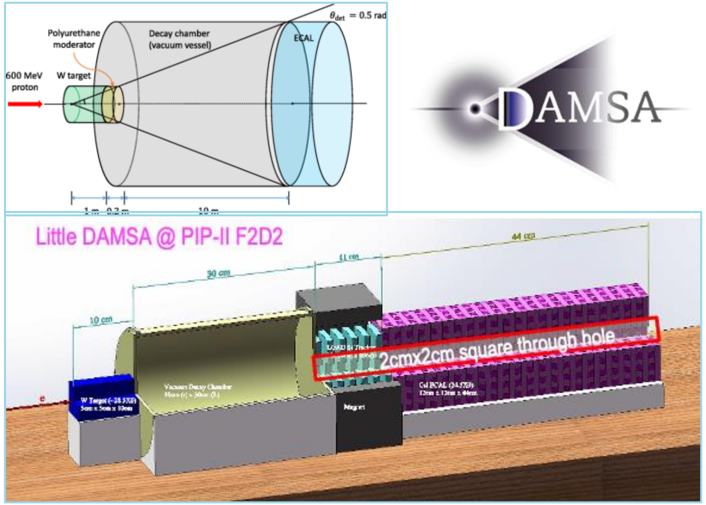
Backup

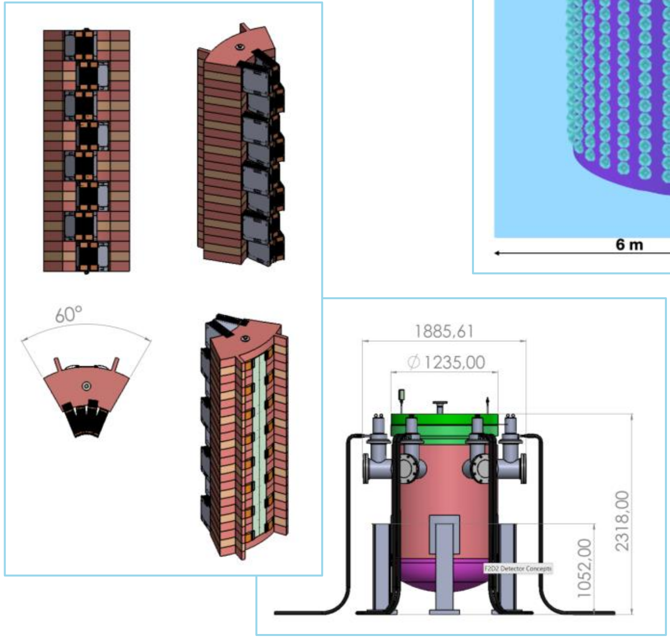
F2D2 Detector Concepts

- DAMSA: Very short baseline beam dump experiment
- OSCURA: Skipper CCD, low threshold
- PIP2-BD: 100t LAr Scintillator
- And other opportunities



PIP2-BD



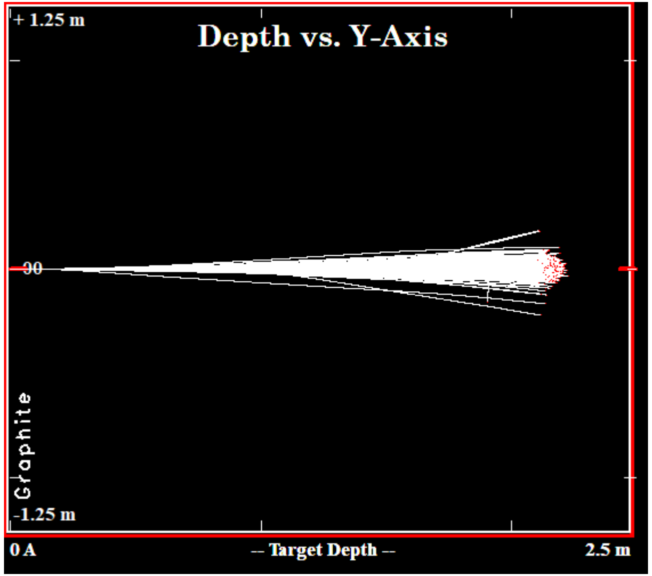


OSCURA

DAMSA

Fermilab

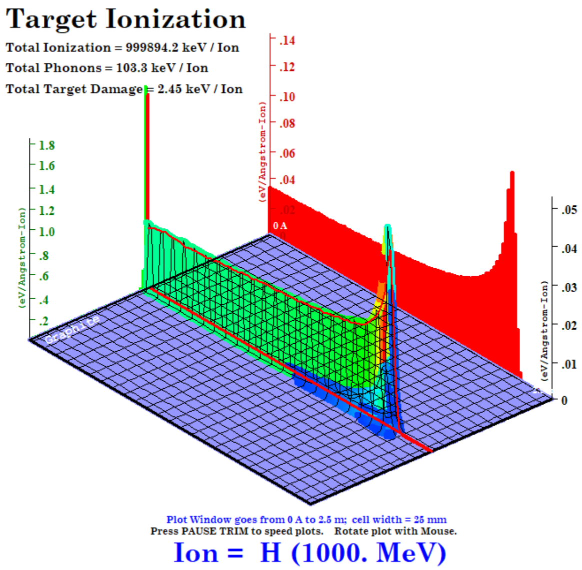
SRIM/TRIM Studies



1 GeV protons into 1.7 g/cc graphite

TRIM output of particle traces

*note this is a zero-thickness input beam, not a diluted beam



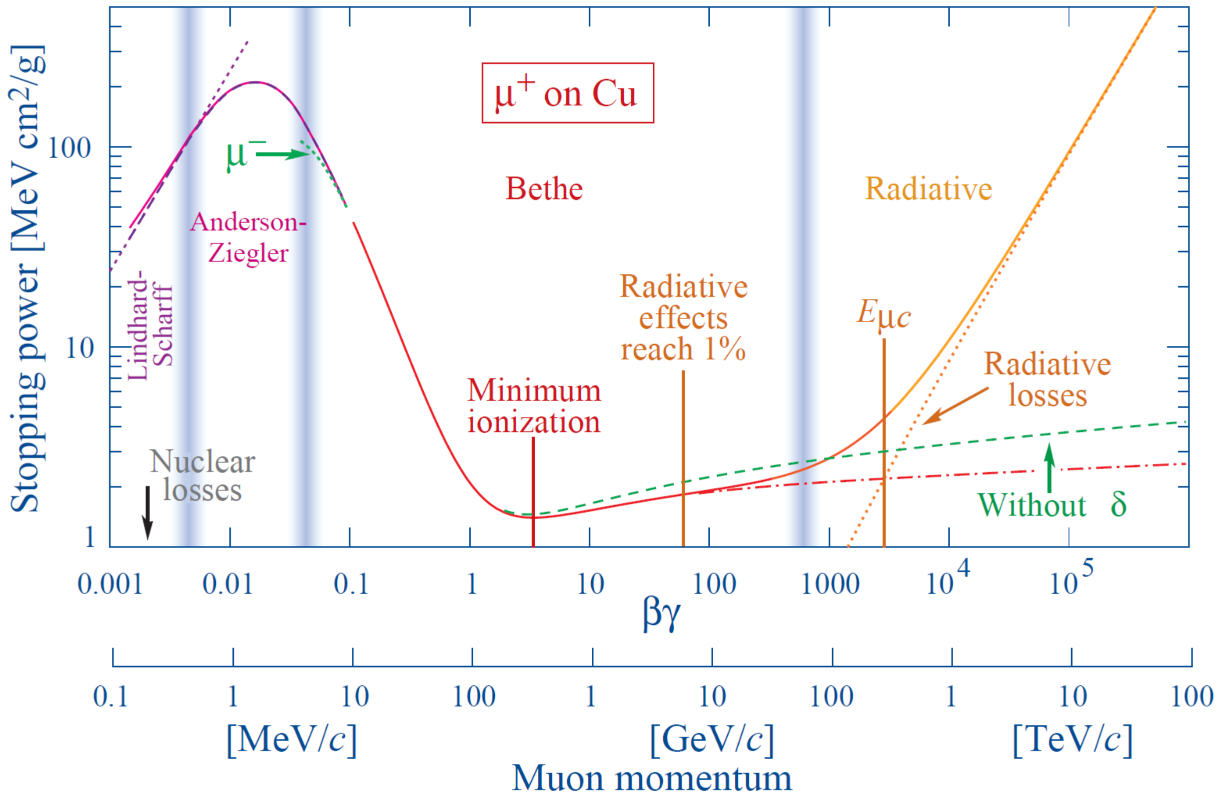
Plot of ionization energy deposited in target per primary proton

Most energy deposition is from electronic (ionization) interactions, not nuclear interactions.

The spike near where the protons stop is the Bragg peak

Fermilab

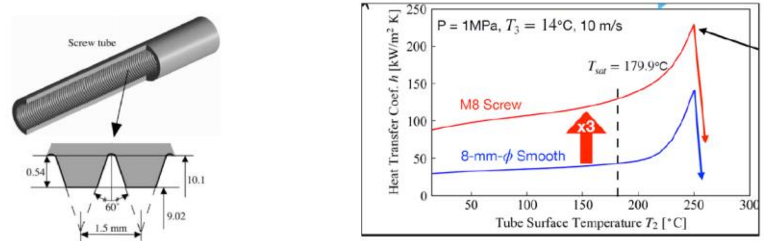
Stopping Power



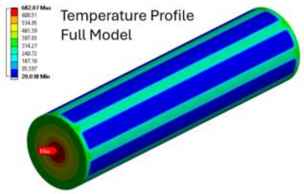
From Particle Data Group, "Passage of Particles Through Matter" https://pdg.lbl.gov/2021/reviews/rpp2020-rev-passage-particles-matter.pdf

Parametric Thermal Study – Core Cooling

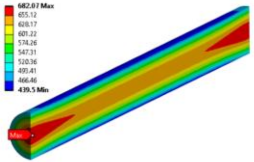
Component	h = 7000 W/m^2*K		h = 20000 W/m^2*K		h=30000 W/m^2*K	
	Tmax (C)	Tmin (C)	Tmax (C)	Tmin (C)	Tmax (C)	Tmin (C)
Graphite Core	682.44	438.84	524.19	293.53	494.16	266.34
Copper Block	477.36	224.05	317.43	91.618	286.86	66.651
SS Sleeve	347.19	20.035	185.06	20.003	153.35	20.002



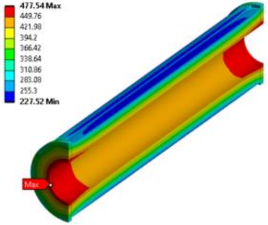
Source:https://indico2.riken.jp/event/3102/contributions/21952/ , J. Boscary et al., Fusion Eng. Des. 43, 147 (1998) , K. Masaki et al., Fusion Eng. Des. 61, 171 (2002).



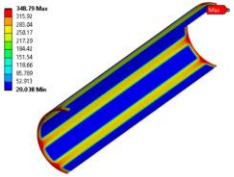
Graphite Temp: Max: 682.07C and Min: 439.5C



Copper Temp: Max: 477.54C and Min: 227.52C



SS316 Sleeve: Max: 348.79C and Min:20.038C



Theory - Fins and Channels

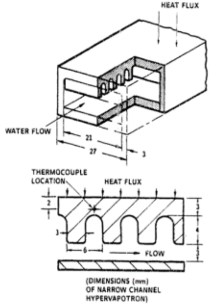


Fig. 1. Hypervapotron geometry. Dimensions are in millimeters (typical fin height = 3–6 mm, thickness = 3 mm, pitch = 6 mm).

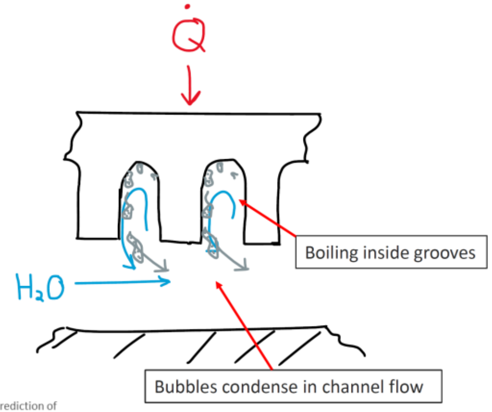
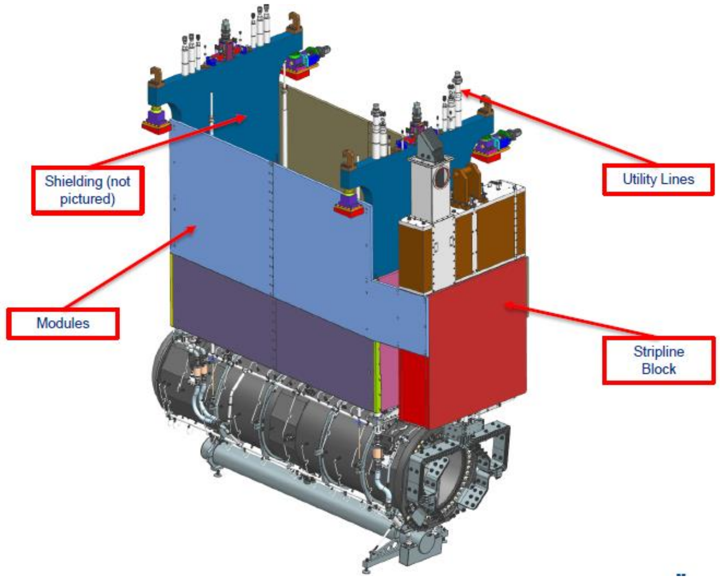
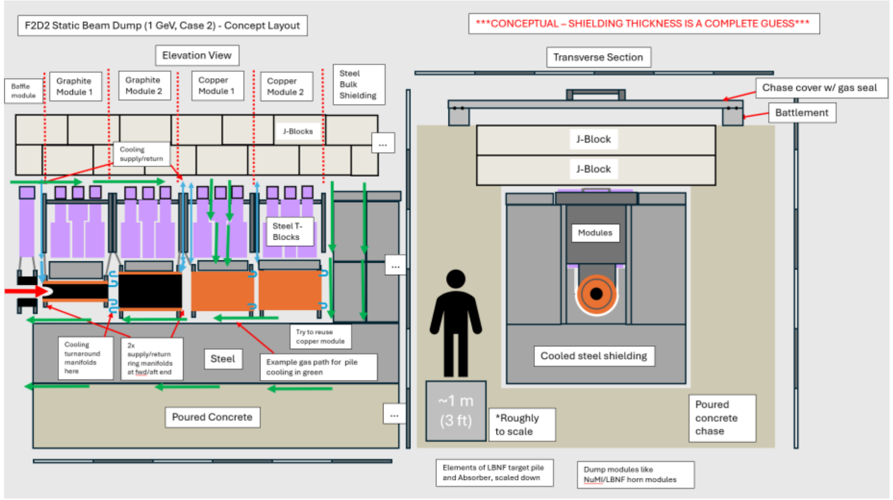


Image source: C.B. Baxi, H. Falter. "A Model for Analytical Performance Prediction of Hypervapotron," General Atomics Project 3467, 1992

Modules





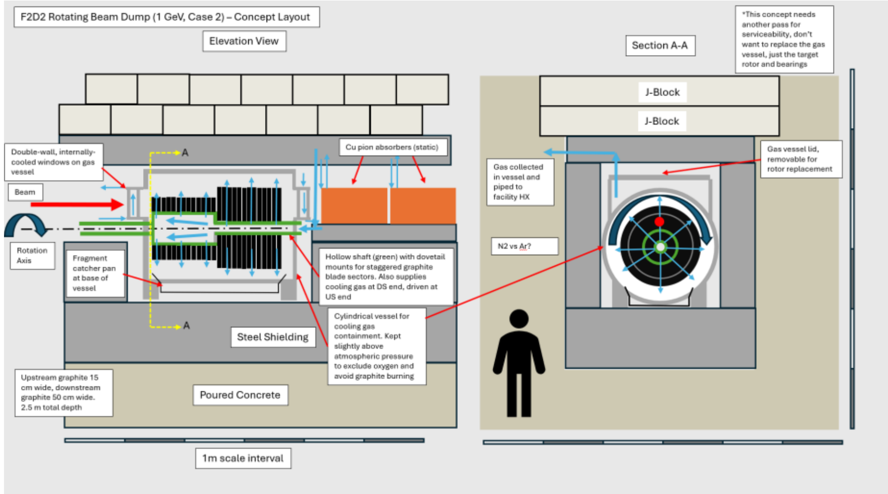
LBNF Horn B Module

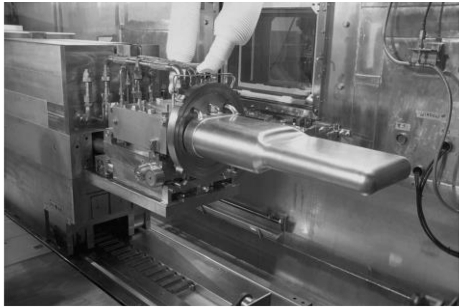
The module is a removable, reusable steel carrier frame that suspends the focusing horn in the LBNF target chase. It supplies gas, water, and electrical power to components underneath steel shielding blocks (not shown)

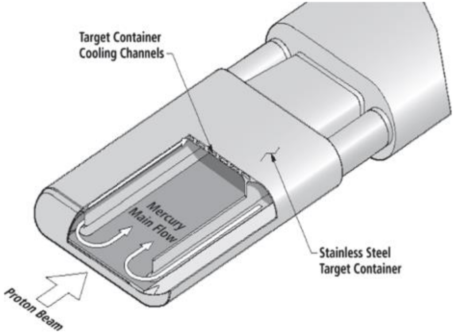
Conceptual layout of F2D2

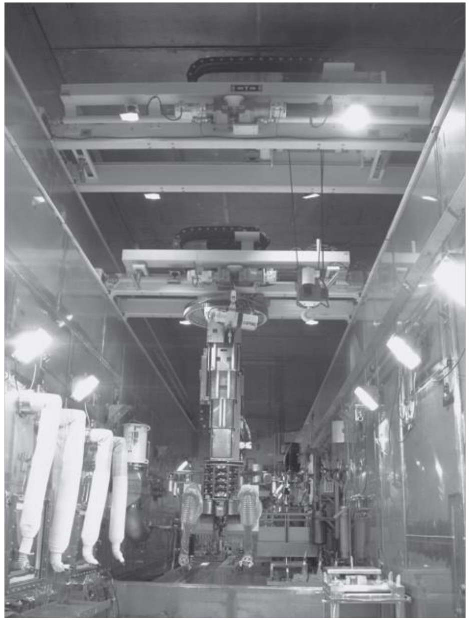
Study of a similar module system to suspend dump cores underneath radiation shielding. The current design iteration has approximately 1 m more steel shielding in all transverse directions and fits under H-size concrete blocks, instead of J-size.

Rotating vs. Flowing targets









Rotating dump concept for F2D2

Spread out energy deposition, distribute activation

Significantly more complex, but probably needs less-frequent replacement

ORNL SNS Mercury Target and Service Bay

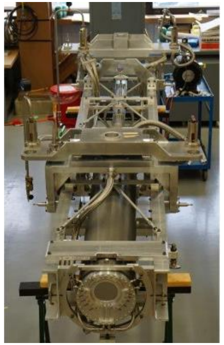
Remote handling is central to SNS.

The target station building is massive, ~100m x 60m

J.R. Haines et al. / Nuclear Instruments and Methods in Physics Research A 764 (2014) 94–115

Fermilab Targetry: Past, Present, and Future

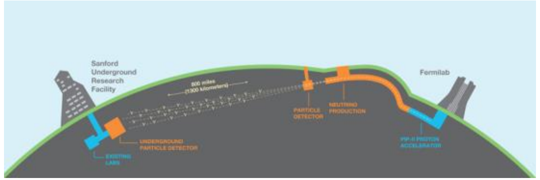
TeV pbar source - kWs



NuMI - <1 MW

Muon g-2 (pbar target) - kWs

LBNF – 1.2-2.4 MW beam



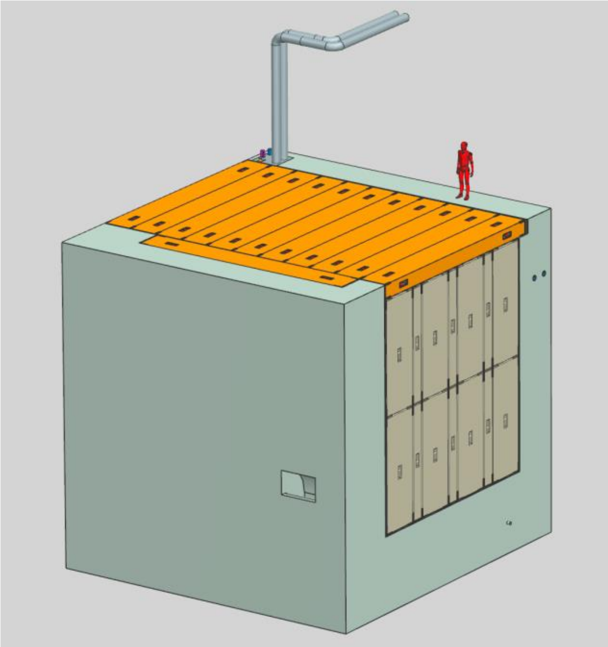
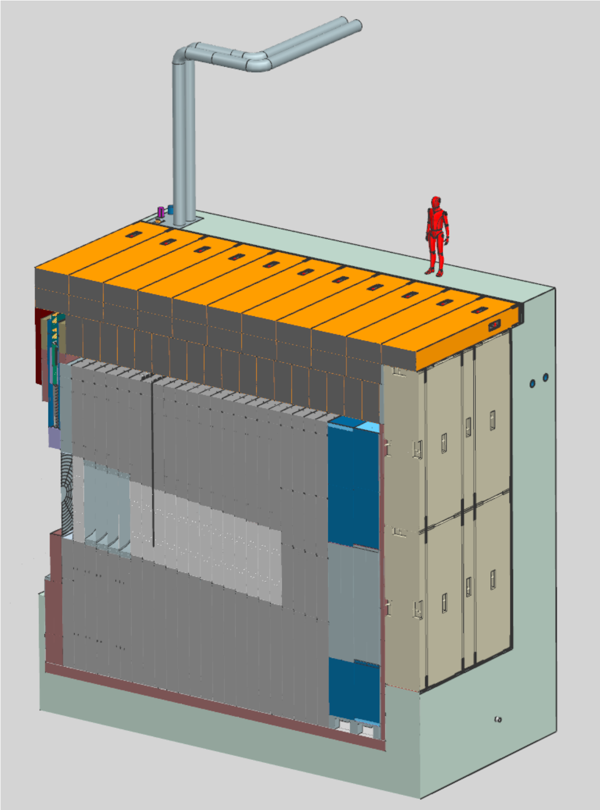
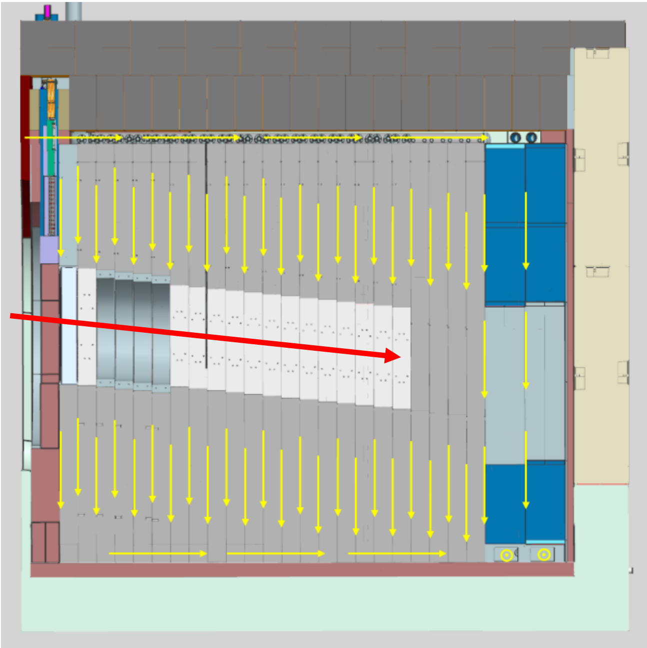
Mu2e – 8 kW beam

μColl– 5-10 MW beam?

1980 1990 2000 2010 2020 2030 2040

2024 – 1 MW NuMI!

LBNF Hadron Absorber – 2.4 MW Beam Absorber

LBNF Absorber Radiation Studies – from MARS group

- High-energy muons and neutrons are very penetrating – see muon plume to right of LBNF Absorber below
  - Need more detailed Monte Carlo simulations to ensure F2D2 backstop attenuates muons and neutrons