High-power Targetry for Multi-MW Beams

Kevin Lynch, Senior Scientist, Target Systems Department, Fermilab

NuFact 2024, Argonne National Laboratory

2024 September 16-21

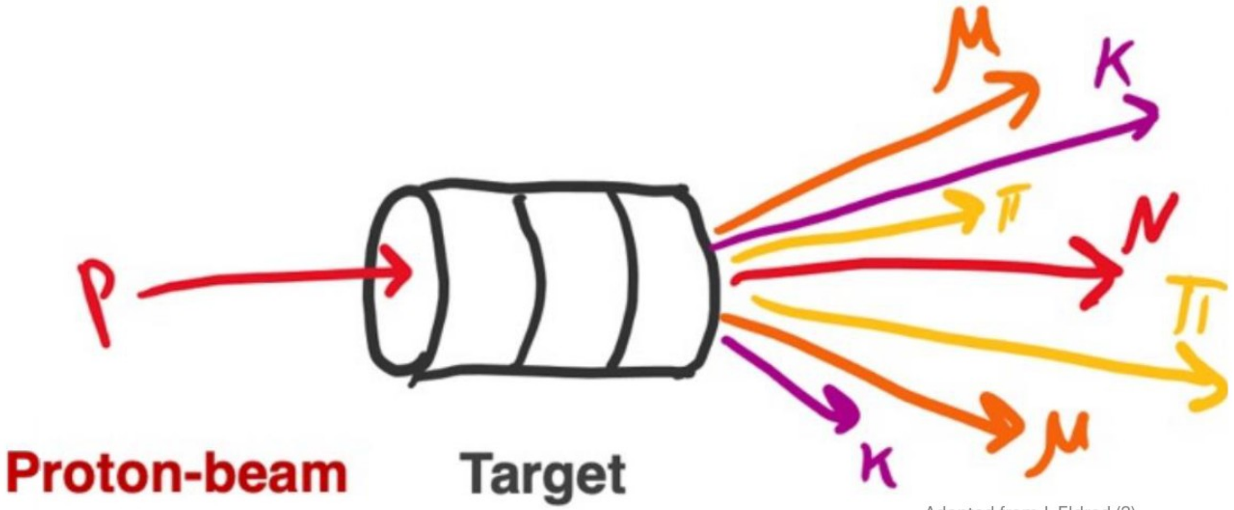
Thanks!

Let me start by thanking the organizers for their invitation to speak!

And thanks to all of you for staying even though I stand between you and dinner!

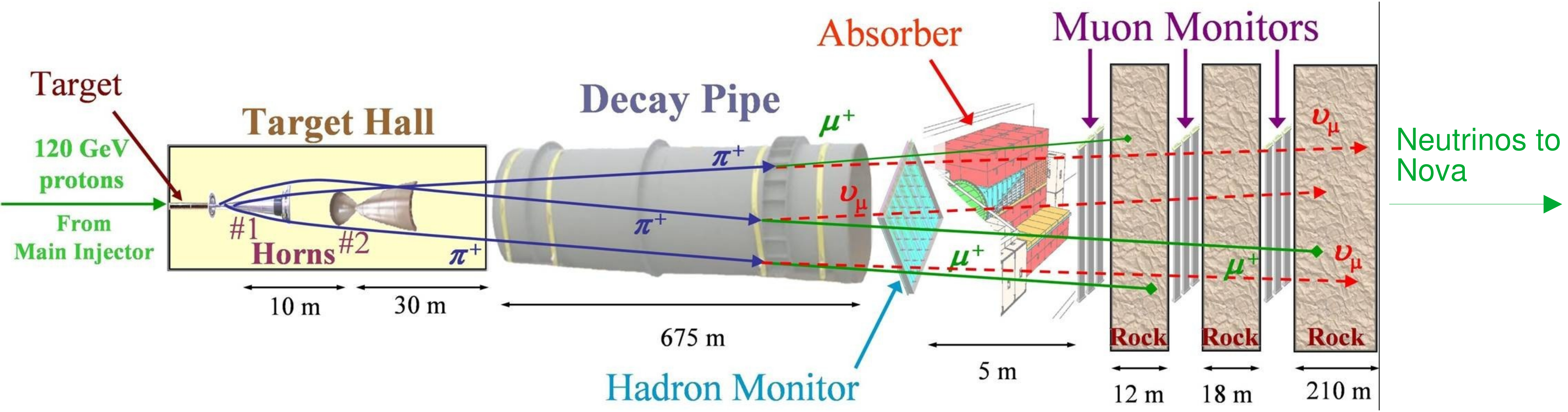
What’s a target?

- Targets are the fulcrum between the Accelerator Complex and Experiments
  - They convert the high-power primary beam (usually protons in HEP) into secondary beams of desirable properties
    - Pions, kaons, muons, neutrinos, neutrons, etc.



Adapted from J. Eldred (?)

But targets are always part of a much larger “targetry complex”



Fermilab NuMI target complex

But targets are always part of a much larger “targetry complex”

- The Target itself
- Heat and radiation protection devices
- Target containers
- Beam windows
- Cooling systems
- Spent-beam absorbers
- Electrical and mechanical support modules
- Colocated secondary beam focusing devices (horns)
- Remote handling systems
- Short and long-term radioactive storage facilities
- Beam and device health instrumentation

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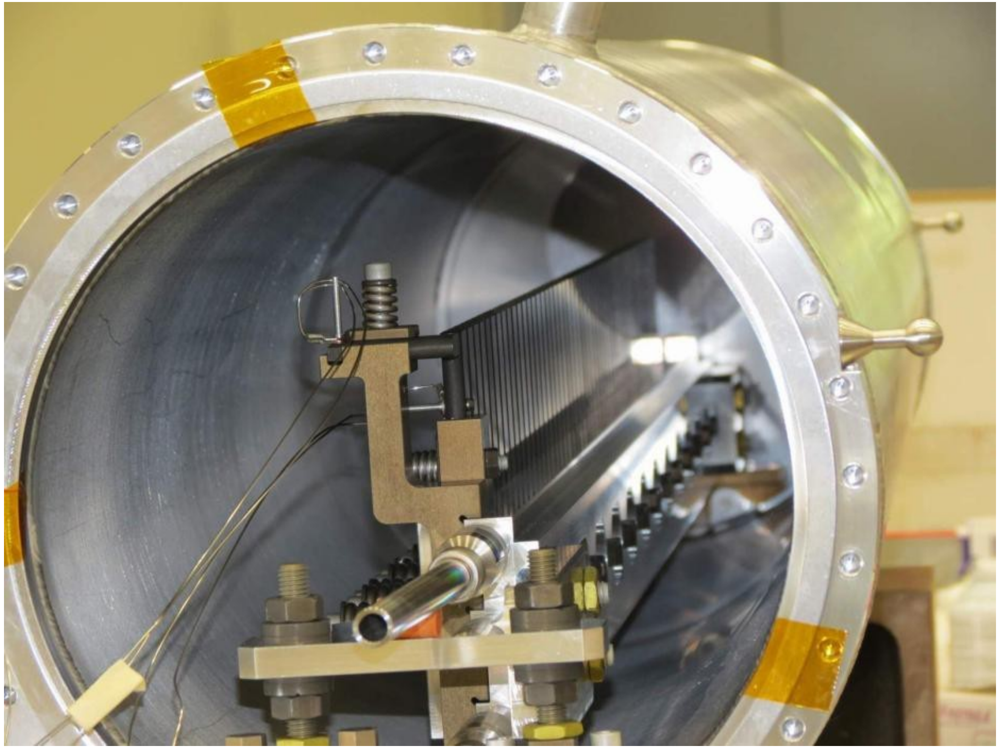
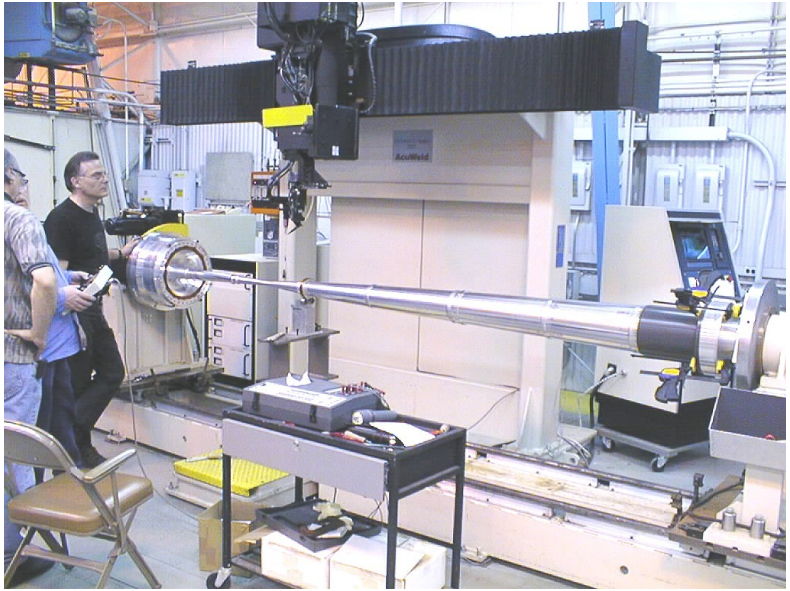
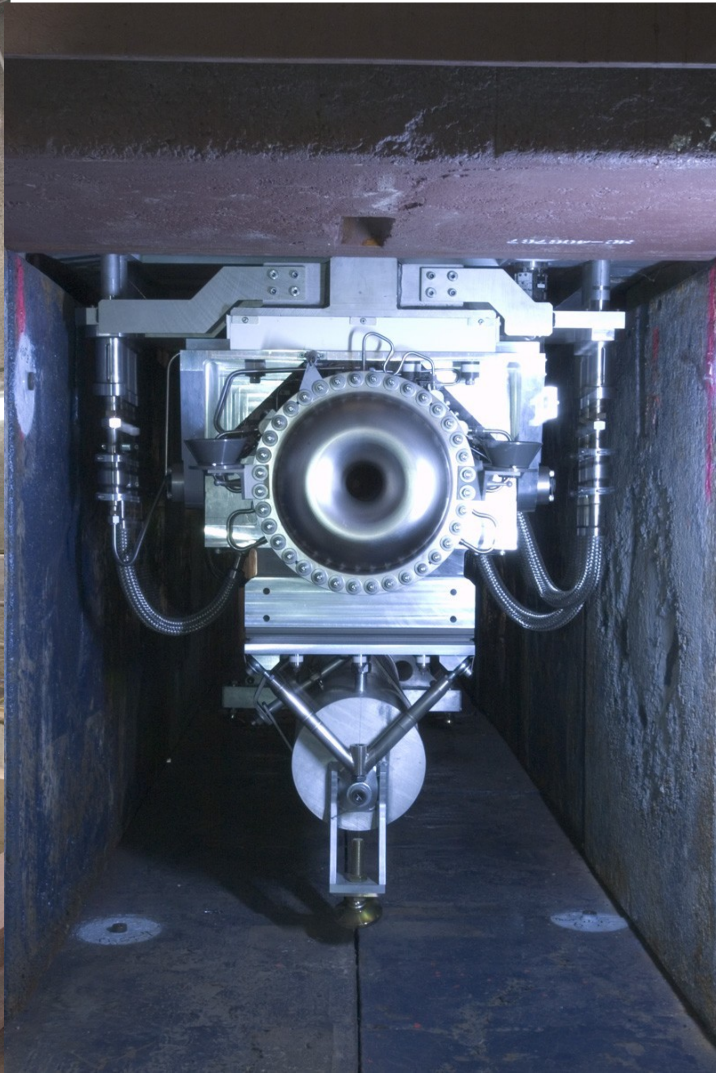
Targetry is an irreducibly multi-disciplinary topical area, requiring inputs from particle and nuclear physics, high energy density physics, radiation damage, materials science, mechanical, fluid, and thermal engineering, and fabrication and technical construction expertise

Device examples: a NuMI target



Device examples: NuMI Horns





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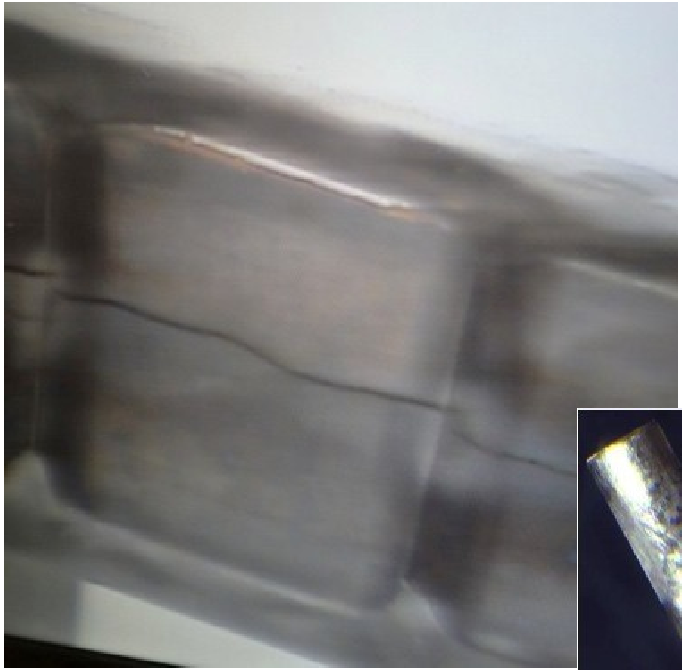
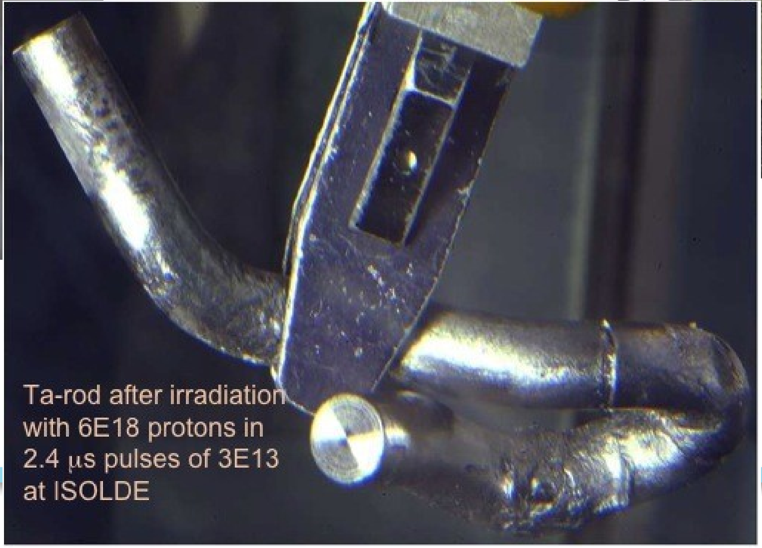
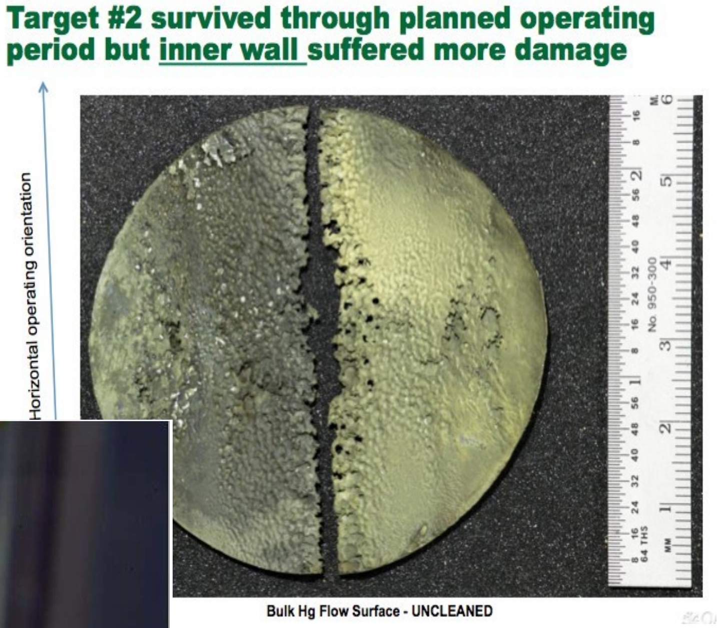
It can go wrong in a flash







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All you have to do is …

All you have to do is …

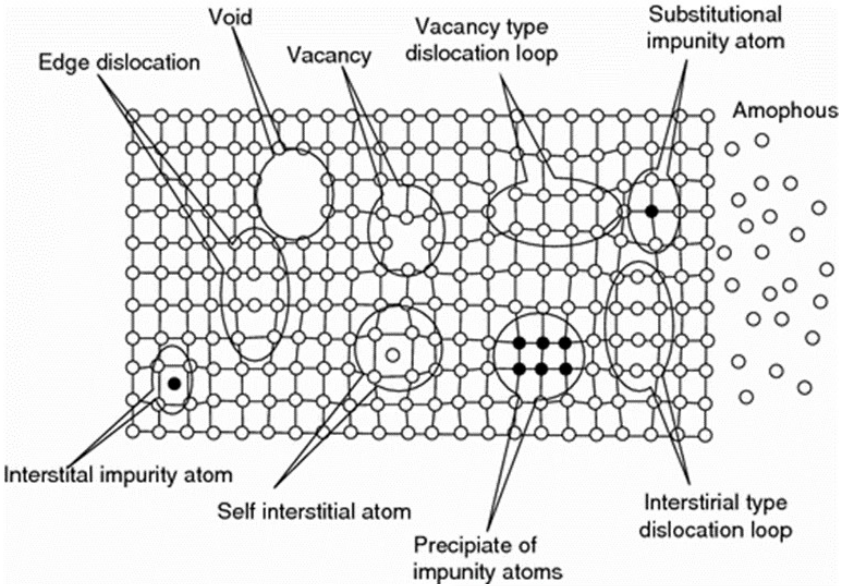
It turns out targetry is *really challenging* and the HEP community is not currently equipped to design, build, and operate facilities at the Multi-MW scale

Targets are hard because of the multi-disciplinary nature ... with next gen targets pushing well beyond the state-of-the-art

- Material behavior and evolution is poorly understood in the regimes of current and future interest
  - Impacts of radiation damage
  - Response to thermal shock at extreme energy densities
  - Highly non-linear thermomechanical behavior at high power density and large thermal gradients
- In addition there are understood – but extremely complex – technology challenges
  - Integrated systems design and simulation (complex multi-scale, multi-physics problems)
  - Radiation protection
  - Remote handling
  - High heat removal
  - Extremely high-cycle fatigue
  - Niche manufacturing technologies

Challenge: Radiation Damage

- Sustained irradiation disrupts the lattice structure of the material, leading to bulk performance degradation
  - Hardening and embrittlement
  - Creep and swelling
  - Loss of fracture toughness
  - Thermal/electrical conductivity reduction
  - Etc
- Essentially all bulk properties worsen under irradiation!
- Even worse, irradiation damage is not a state function
  - History matters! And we have no fundamental predictive models
- Post-Irradiation Examination (PIE) is critical to understand the impacts of irradiation so that we can predict what will happen in future designs
  - HEP facilities are woefully unprepared for this challenge



D.L. Porter and F. A. Garner, J. Nuclear Materials, **159**, p. 114 (1988)

R a D I A T E Collaboration

Radiation Damage In Accelerator Target Environments

RaDIATE collaboration created in 2012, with Fermilab as the leading institution

Objective:

- Harness existing expertise in nuclear materials and accelerator targets
- Generate new and useful materials data for application within the accelerator and fission/fusion communities

Activities include:

- Analysis of materials taken from existing beamline as well as new irradiations of candidate target materials at low and high energy beam facilities
- In-beam thermal shock experiments

Program manager: Dr. Frederique Pellemoine (FNAL)

Fermilab, Pacific Northwest National Laboratory, Argonne National Laboratory, Oak Ridge National Laboratory, European Spallation Source, University of Oxford, CERN, FRIB, Los Alamos National Laboratory, Brookhaven National Laboratory, Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, UKRI Science and Technology Facilities Council, J-PARC

Future Collaborators

CIMAP, CNRS, University of Birmingham, University of Bristol, TRIUMF, UK Atomic Energy Authority, Department of Engineering Physics University of Wisconsin-Madison

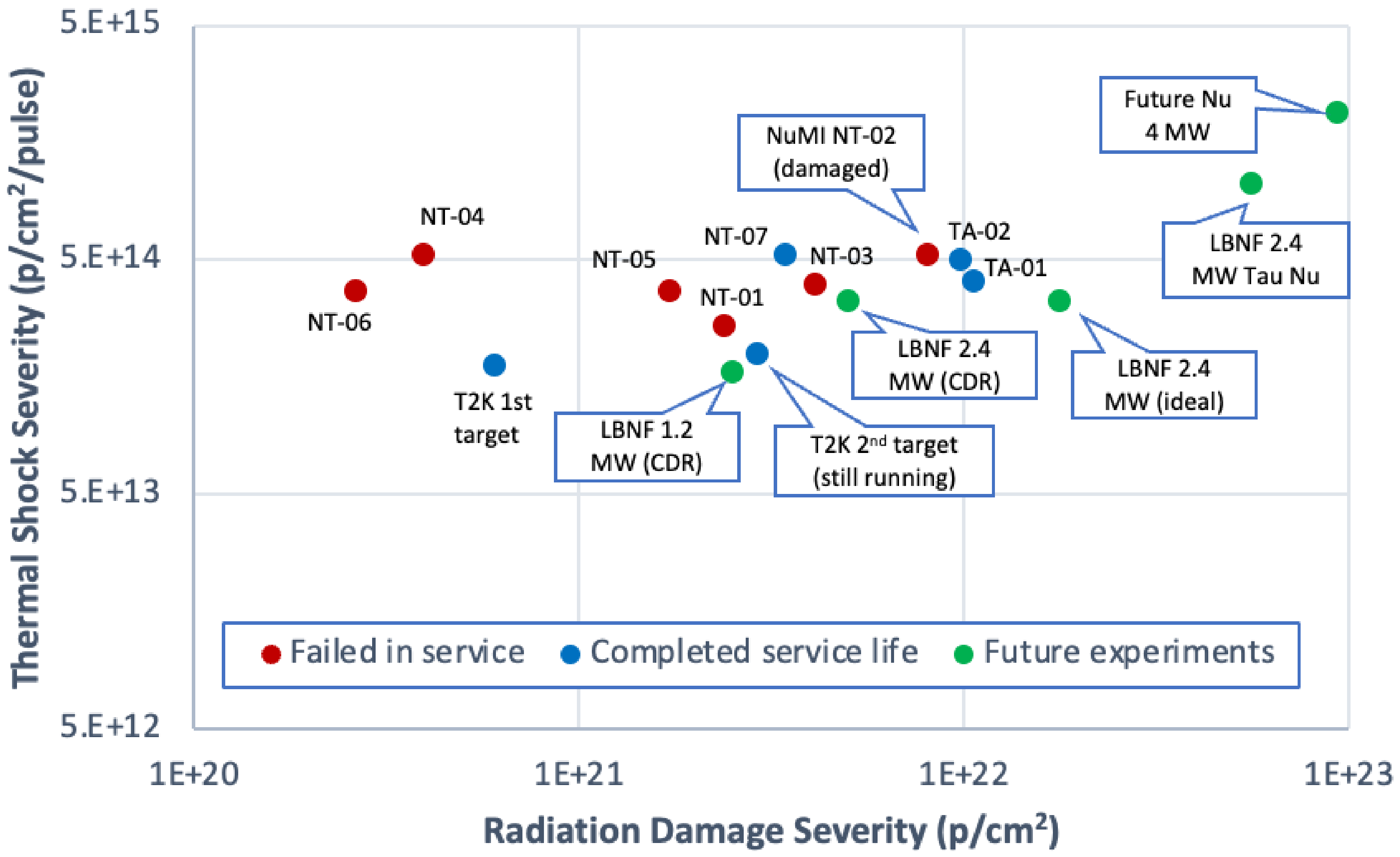
https://radiate.fnal.gov/

Challenge: Thermal Shock

- Pulsed beams impose sudden energy deposition, generating dynamic stress waves
  - Fast expansion of the material surrounded by cooler material generates localized compressive stresses
  - Stress waves move through the material at sonic velocity
  - Surface reflections can lead to either compressive or tensile stresses depending on surface constraints
  - Plastic deformation, cracking, and fatigue failure can result

Thermal shock effect in an Iridium rod exposed to a high-intensity beam pulse at CERN's HiRadMat facility

The combination of radiation damage and thermal shock dramatically multiplies the difficulties



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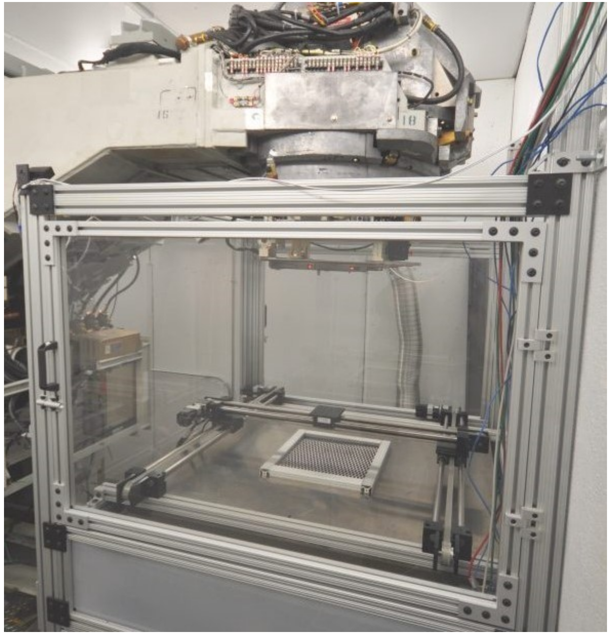
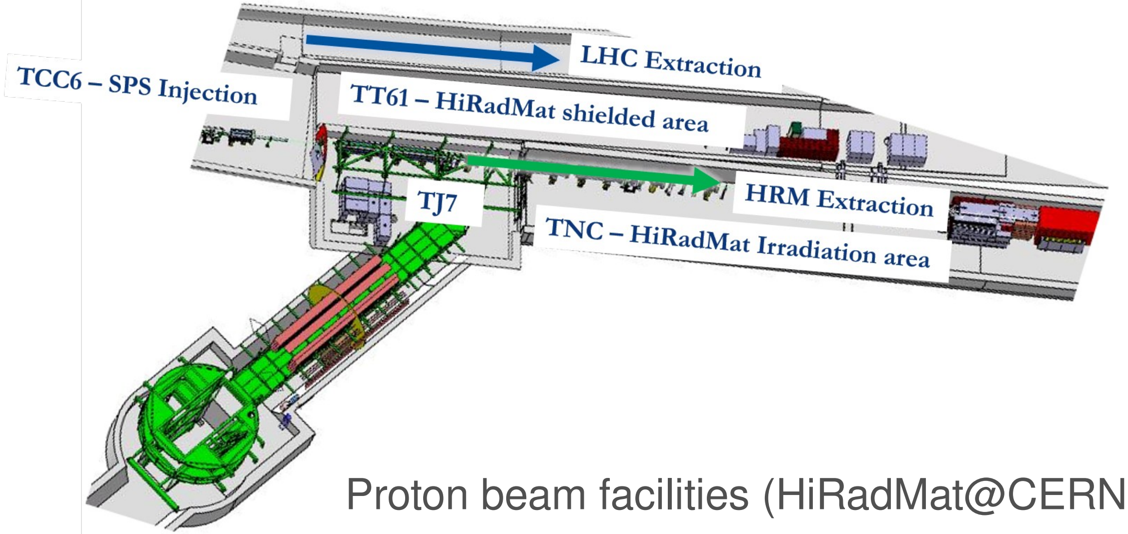
Challenge: Thermal shock

- There exist facilities for studying the dynamic thermal shock response/resistance for materials



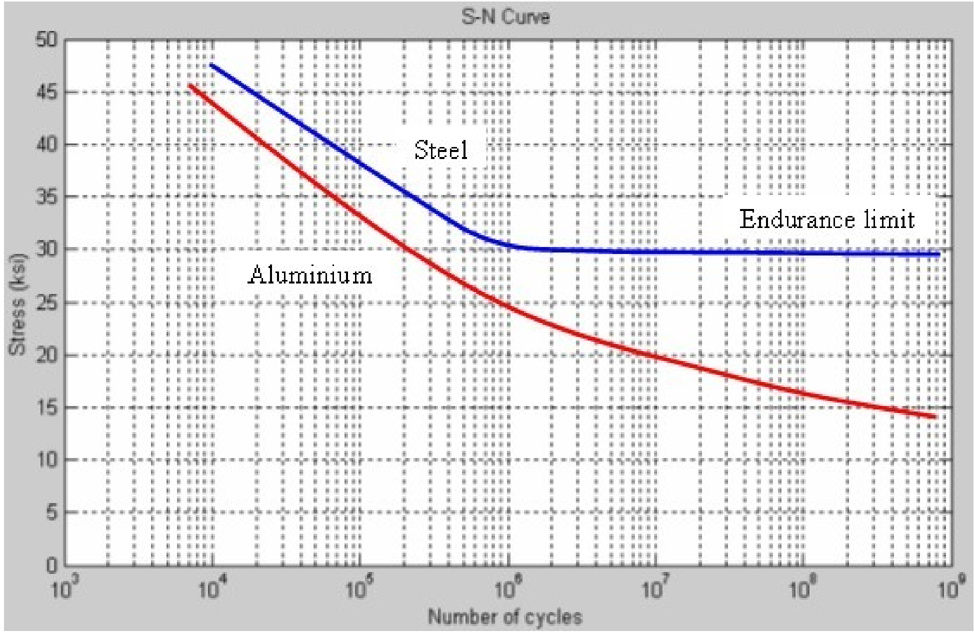
Electron beam facilities (A2D2@Fermilab)



Proton beam facilities (HiRadMat@CERN)

Challenge: High-cycle fatigue

- Fatigue failure is normally due to crack nucleation and slow growth over time, followed by sudden, catastrophic failure
- The probability of failure is generally logarithmic in the number of cycles and reduced by the loading stress
- Some materials have an endurance limit, while others don't
- As usual, it's unclear how the irradiation history impacts the fatigue behavior of any given material or device



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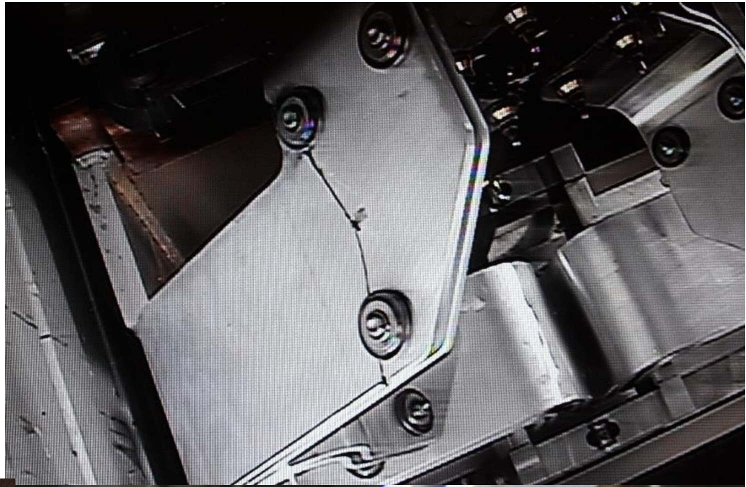
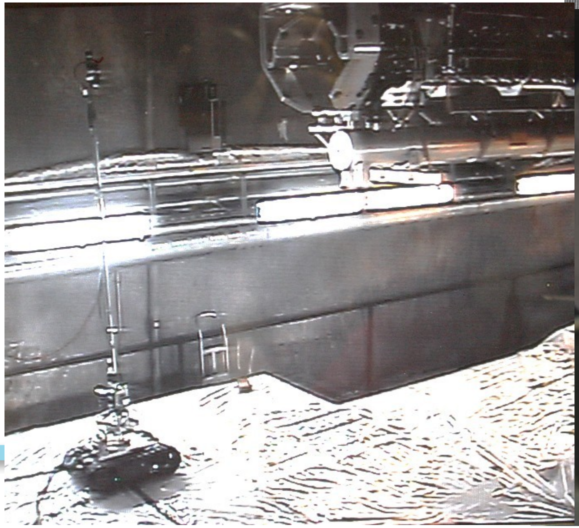
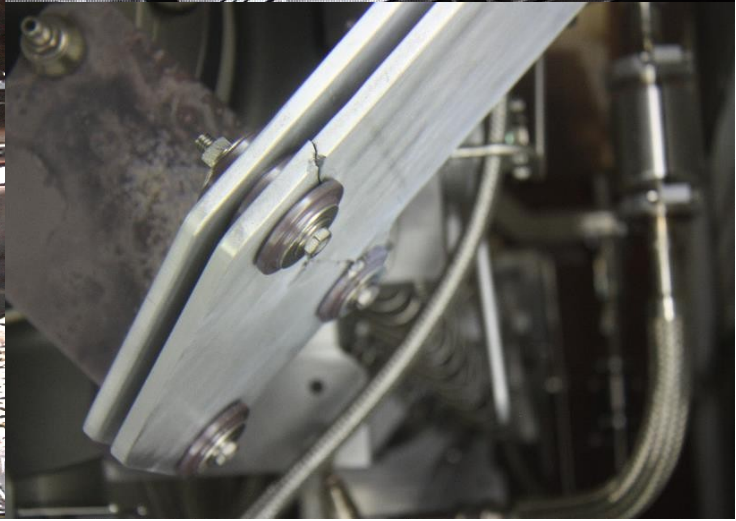
2016 NuMI Horn 1 failure

- 700kW horn failed after 3 years in service
- 27M beam pulse cycles
- Likely a fatigue failure accelerated by vibrations/ringing
  - These things are LOUD when they pulse

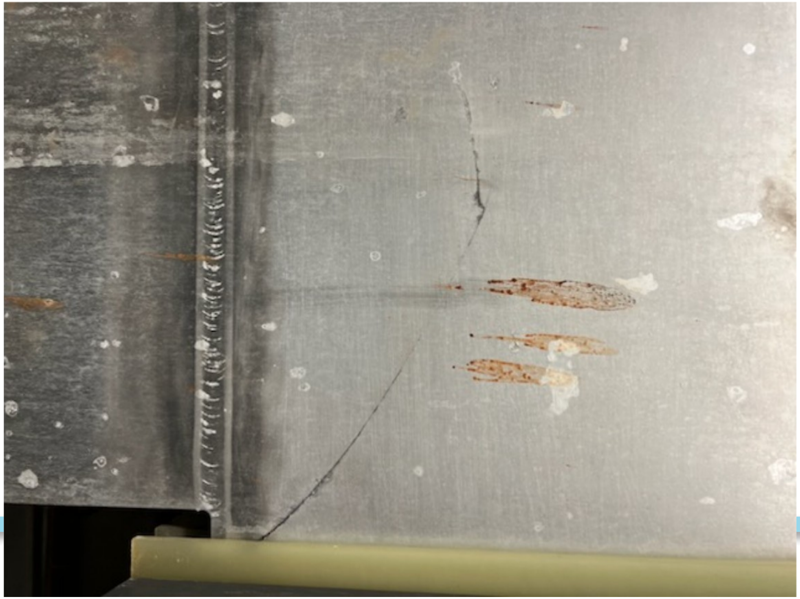


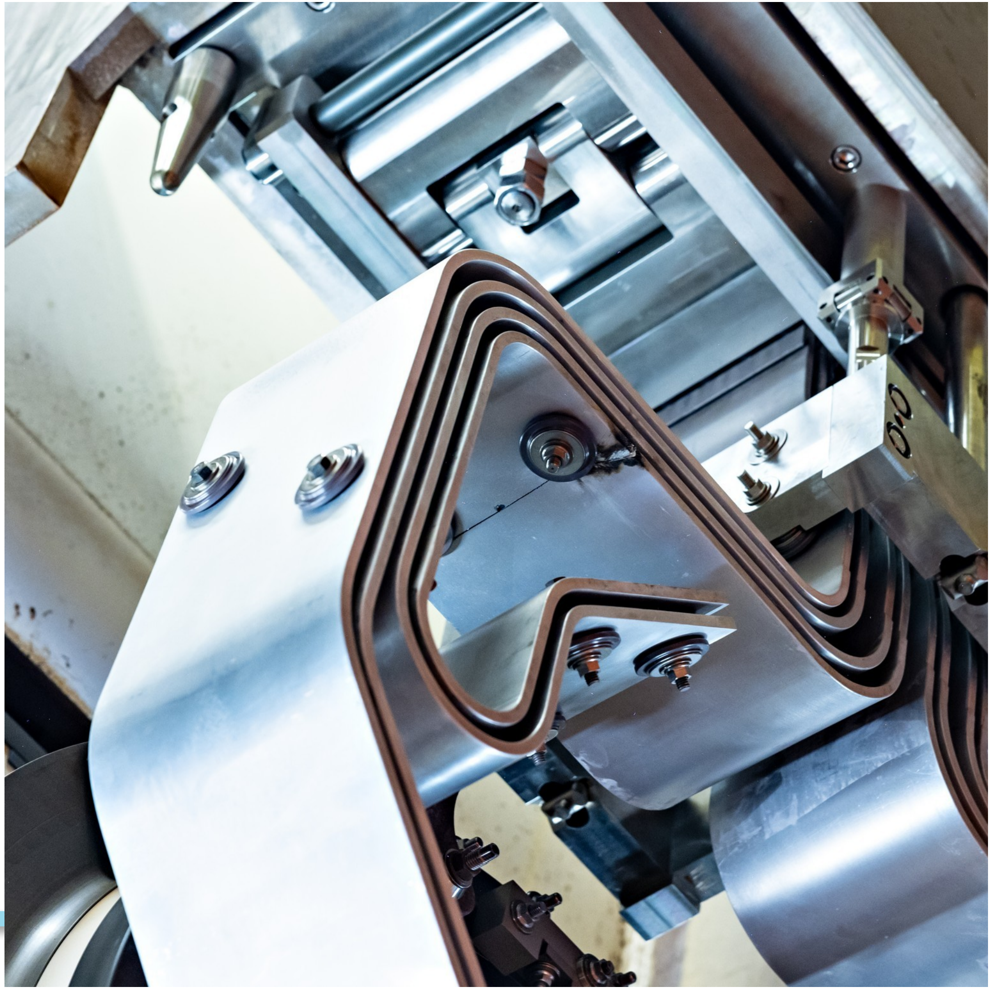




2022 NuMI Horn 2 failure

- Simultaneous bus and horn failure
  - Bus original to facility: high cycle fatigue
  - Horn failed at 24M beam pulses





Challenge: Radiation protection

- Extensive shielding required to reduce prompt doses outside target enclosures
  - Severely radioactivated shielding and components
- Airborne radiation with lifetime of hours must be contained within the facility
  - Complicates facility design
  - Complicates facility maintenance
    - Cooldown times of hours
- Radiolysis produces corrosives
  - Ozone and nitric acid eat lots of materials

- Long-lived isotopes create operational and environmental release hazards
  - ^{7}Be
    - Produced from proton interactions with atmospheric N and O
    - Persistent surface contamination
  - ^{3}H
    - Long lived environmental hazard
    - Migrates through shielding from point of production for decades
    - Regulatory emission limits easily exceeded in high-power operation without significant mitigation efforts
- Cooldown requirements dramatically increase the program impacts of operational failures

Challenge: Radiation protection

- Target component manipulations remain “hot jobs” for years after operation
  - 50mSv/yr is occupational dose limit for FNAL rad workers

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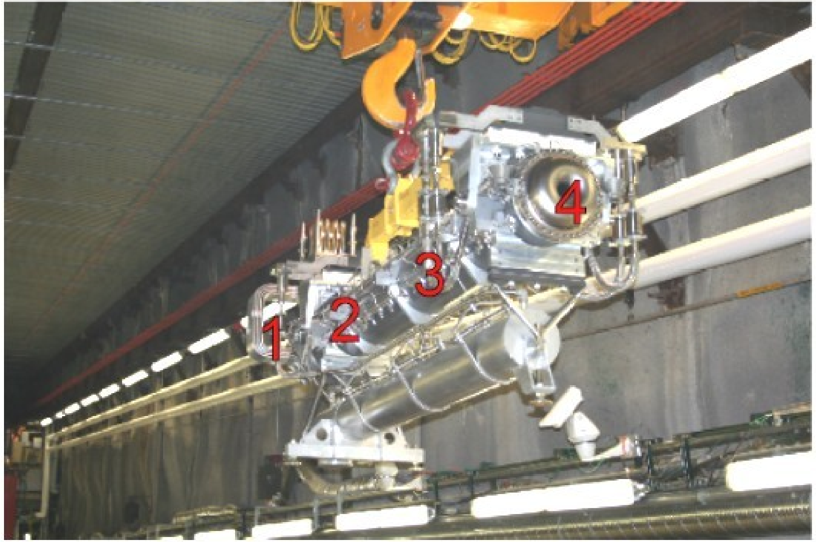
ACCELERATOR DIVISION

DATE 9/3/15	TIME: 1000	PURPOSE: replacement survey	RWP #



NUMI Horn #1

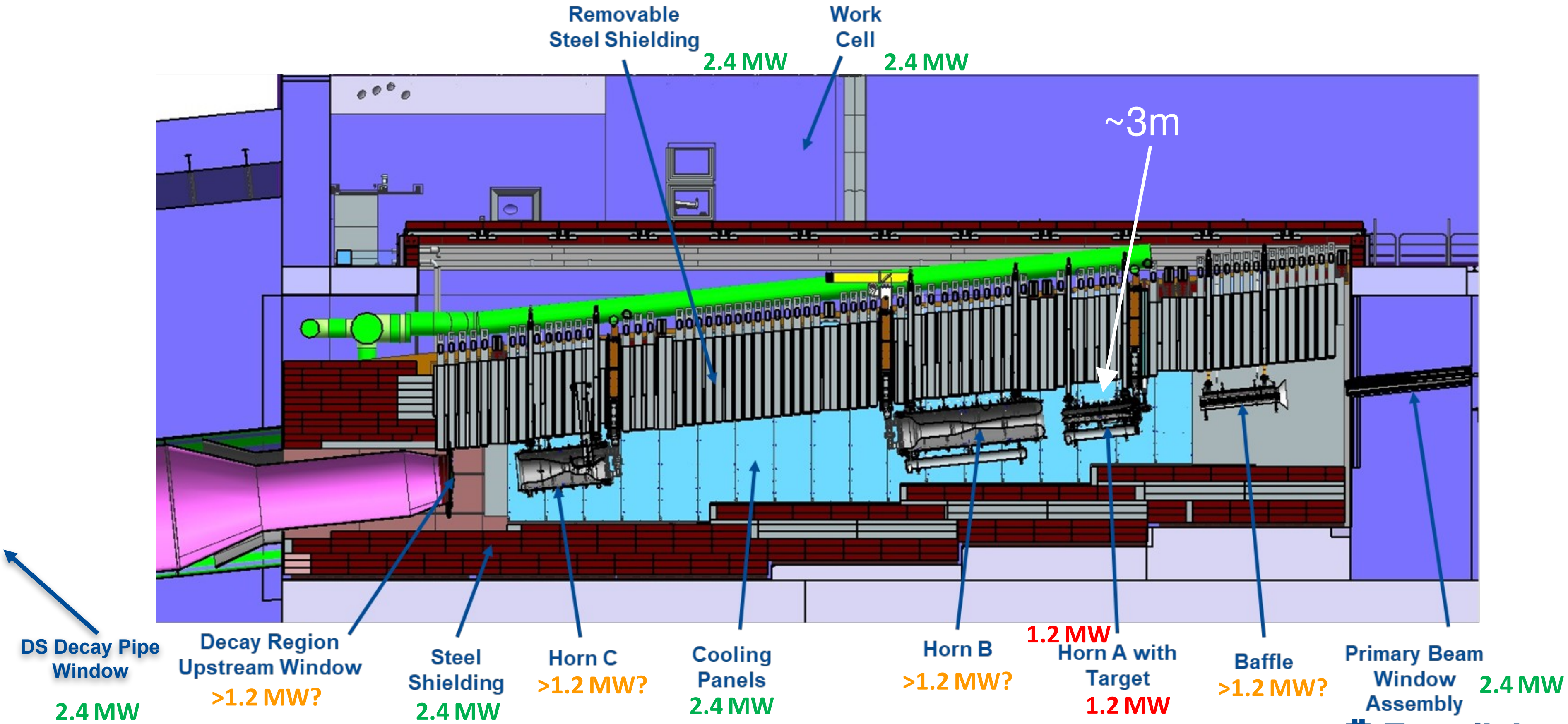
Point	Doserate @ 1 foot (mr/hour)	mSv/hr @ 30cm
1	50000	500
2	100000	1000
3	110000	1100
4	80000	800

Rates after 8 week cooldown at 700kW

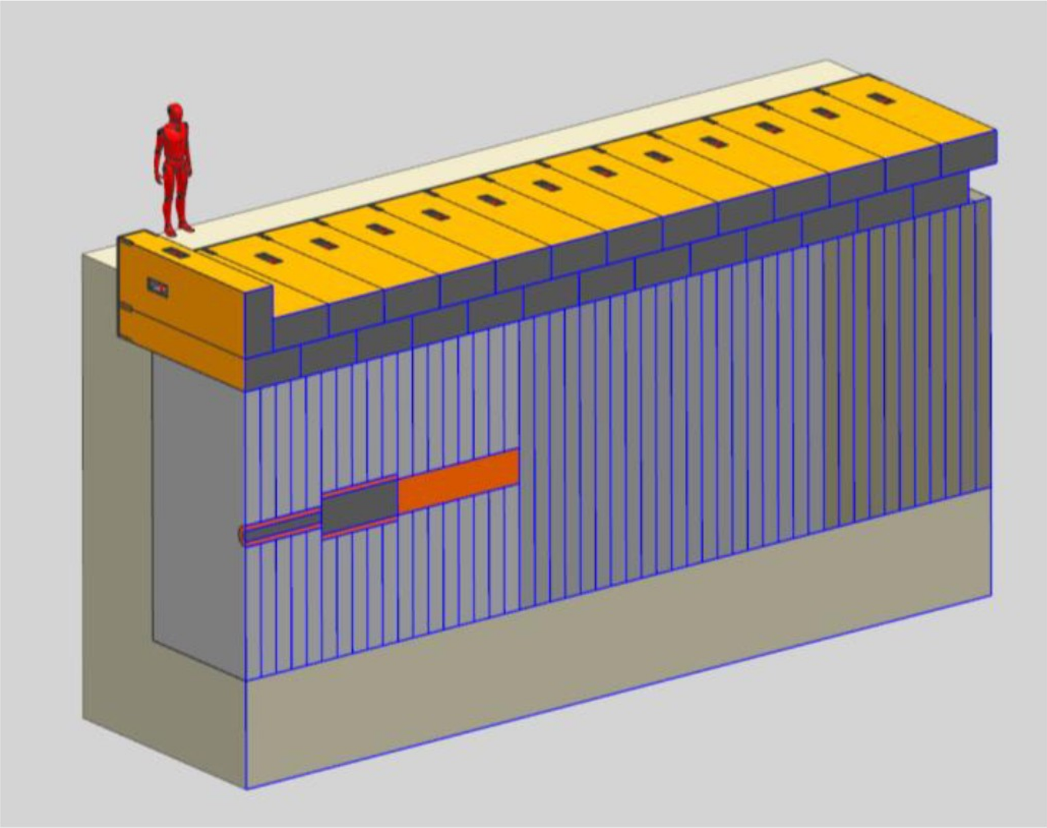
Our big ambitions amplify the practical difficulties of proposed facilities

- Beam power is the driving parameter behind many of the most difficult problems
  - Radiation and thermal shock damage
  - Facility scale and footprint
  - Component lifetime
- Spare component manufacturing is an expensive, labor intensive, time consuming process
  - Typical focusing horn is three years calendar time start-to-finish
  - This is not assembly line stuff, and requires significant engineering and technical skills
- Hotter components need to be stored more securely and for longer than we are used to
  - Radioactive waste stream management is expensive and paper-work intensive
- The lack of PIE capabilities leave large uncertainties on both the design side and in assigning root causes of component failures
  - We're redesigning the Mu2e target in the face of lifetime uncertainties driven by missing knowledge of radiation damage impacts in our operating regime

LBNF Target Systems: target hall beam intercepting devices

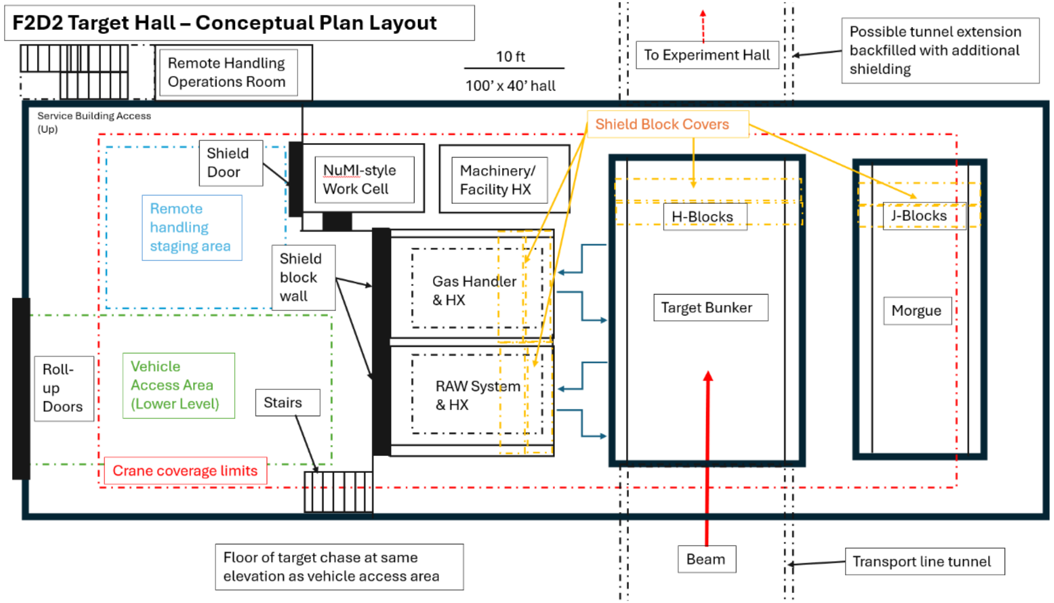


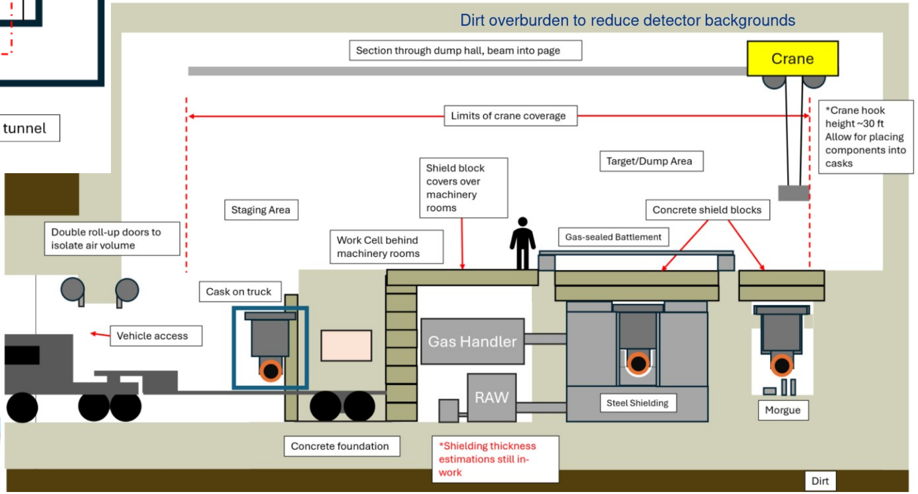
F2D2 – Proposed Fermilab Facility for Dark Sector Discovery; up to 2.5MW, 1(ish)GeV beam



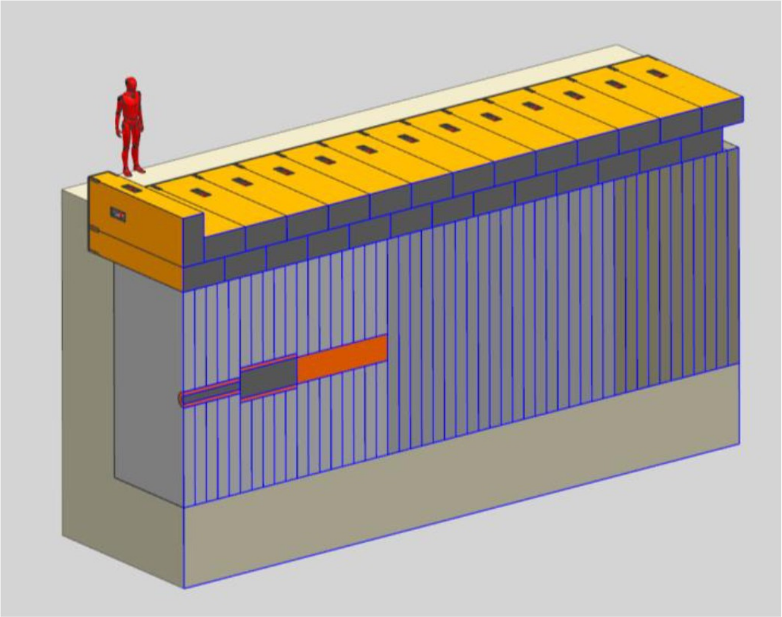
F2D2 – Proposed Fermilab Facility for Dark Sector Discovery; up to 2.5MW, 1(ish)GeV beam

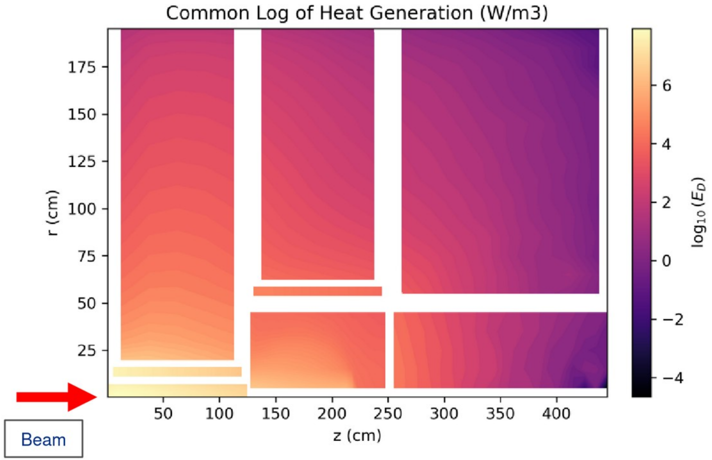
See J. Williams talk



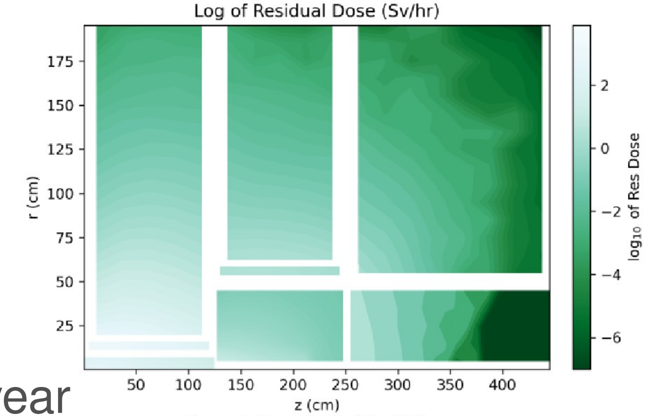


F2D2 – indicative of thermal and radiological challenges of Multi-MW facilities





One Week



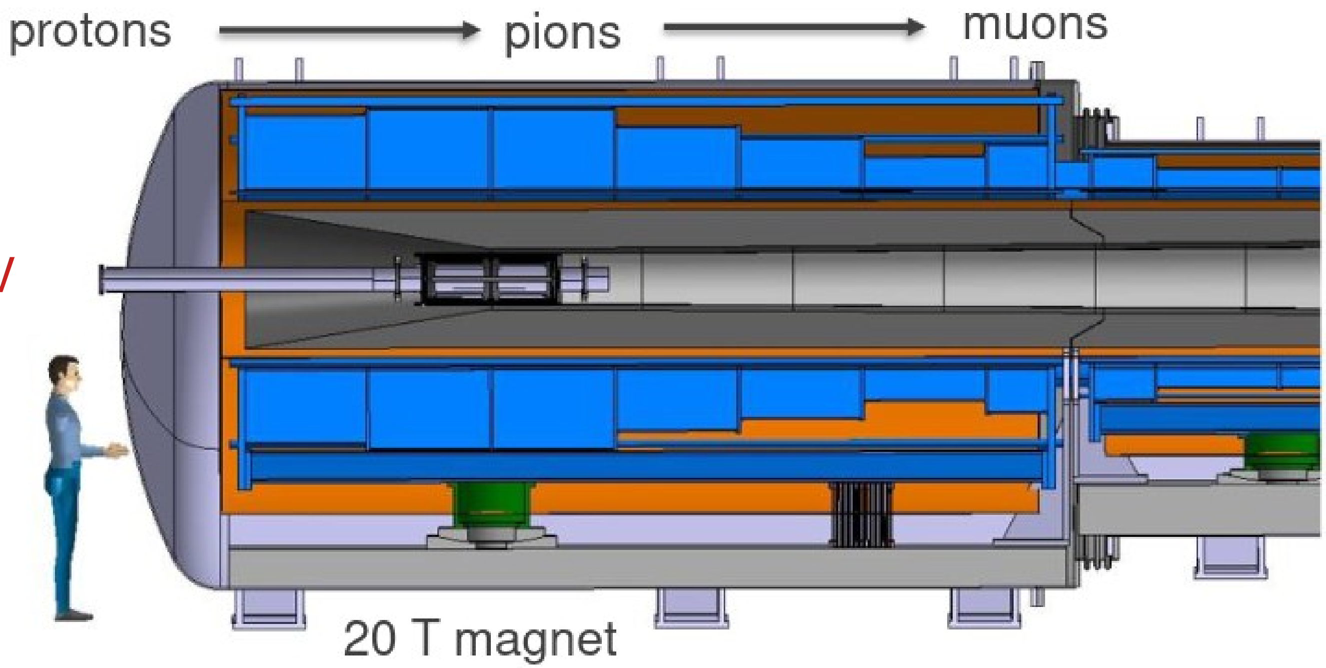
100 days ~ 1/3 year

Muon Collider

See D. Stratakis' talk

- A high power target buried inside a high field superconducting solenoid … what could possibly go wrong?

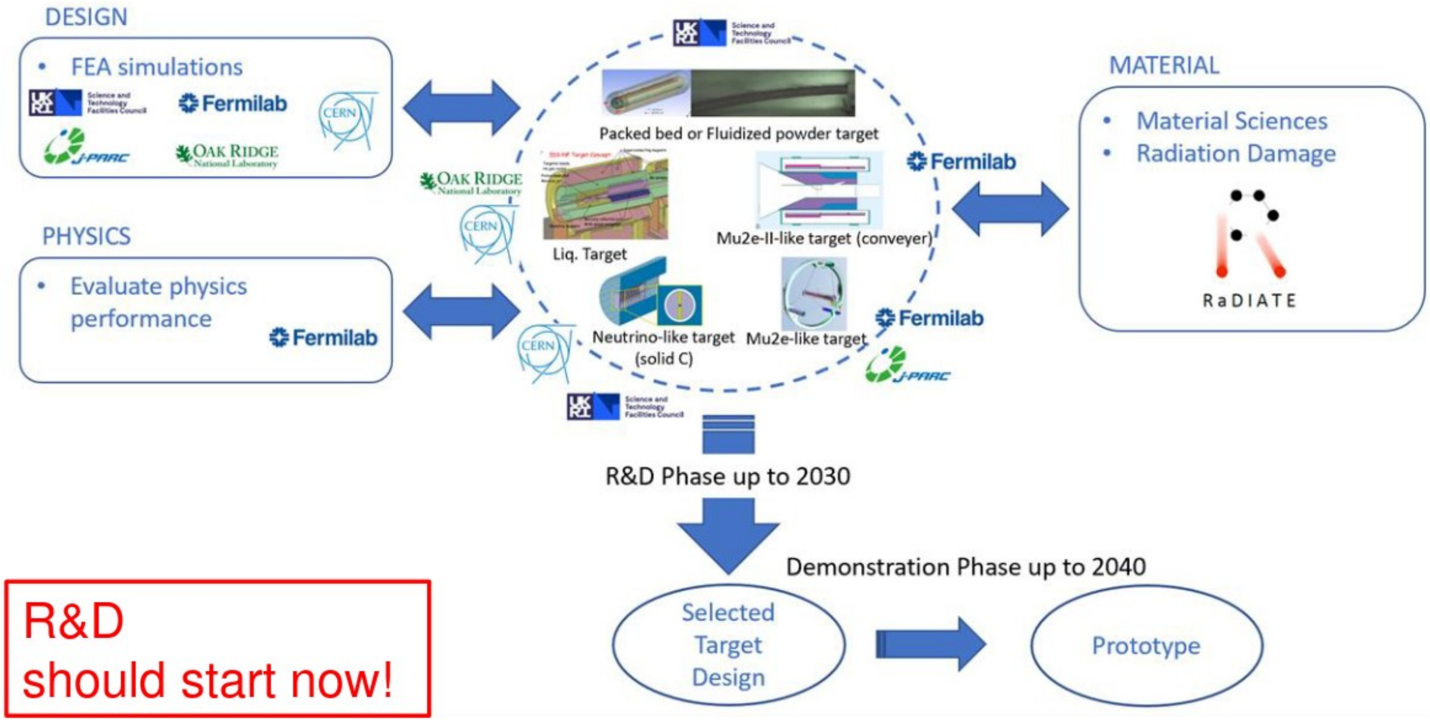
2-4 MW @ 5-20 GeV



Muon Collider

See D. Stratakis' talk

- We really have no idea how to build and operate a muon collider target complex
- R&D needs are included in the (soon to be released?) GARD HPT Roadmap



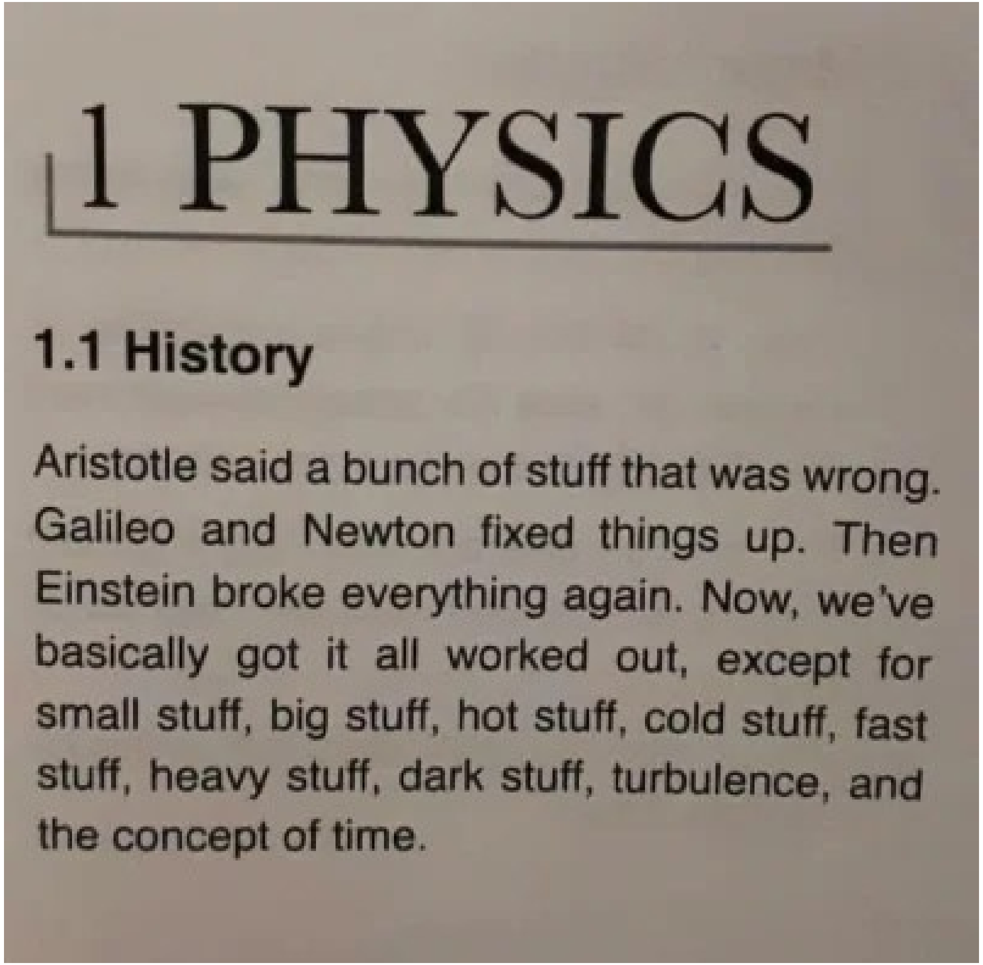
In summary …

- High power targetry is hard
  - Radiation damage and thermal shock
  - Radiological issues
- Next generation facilities will require advances well beyond the current state of the art across a broad range of topics
- Significant R&D is absolutely necessary to meet these challenges
  - And we need that work to start *now* if we hope to make intelligent decisions on the appropriate timescales

Special thanks to the many colleagues who have taught me what little I know about target systems

- Bob Zwaska
- Nikolai Mokhov
- Frederique Pellemoine
- Kavin Ammigan
- Chris Densham
- Steve Werkema
- Dave Pushka
- Kris Anderson
- Michael Hedges
- Alajos Makovec
- Jonathan Williams
- Diktys Stratakis

Thanks!



1 PHYSICS

1.1 History

Aristotle said a bunch of stuff that was wrong. Galileo and Newton fixed things up. Then Einstein broke everything again. Now, we've basically got it all worked out, except for small stuff, big stuff, hot stuff, cold stuff, fast stuff, heavy stuff, dark stuff, turbulence, and the concept of time.

Science: Abridged Beyond the Point of Usefulness Zach Weinersmith