High-Power Targetry for Muon Production in HEP

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Muon4Future 2025

2025-05-27

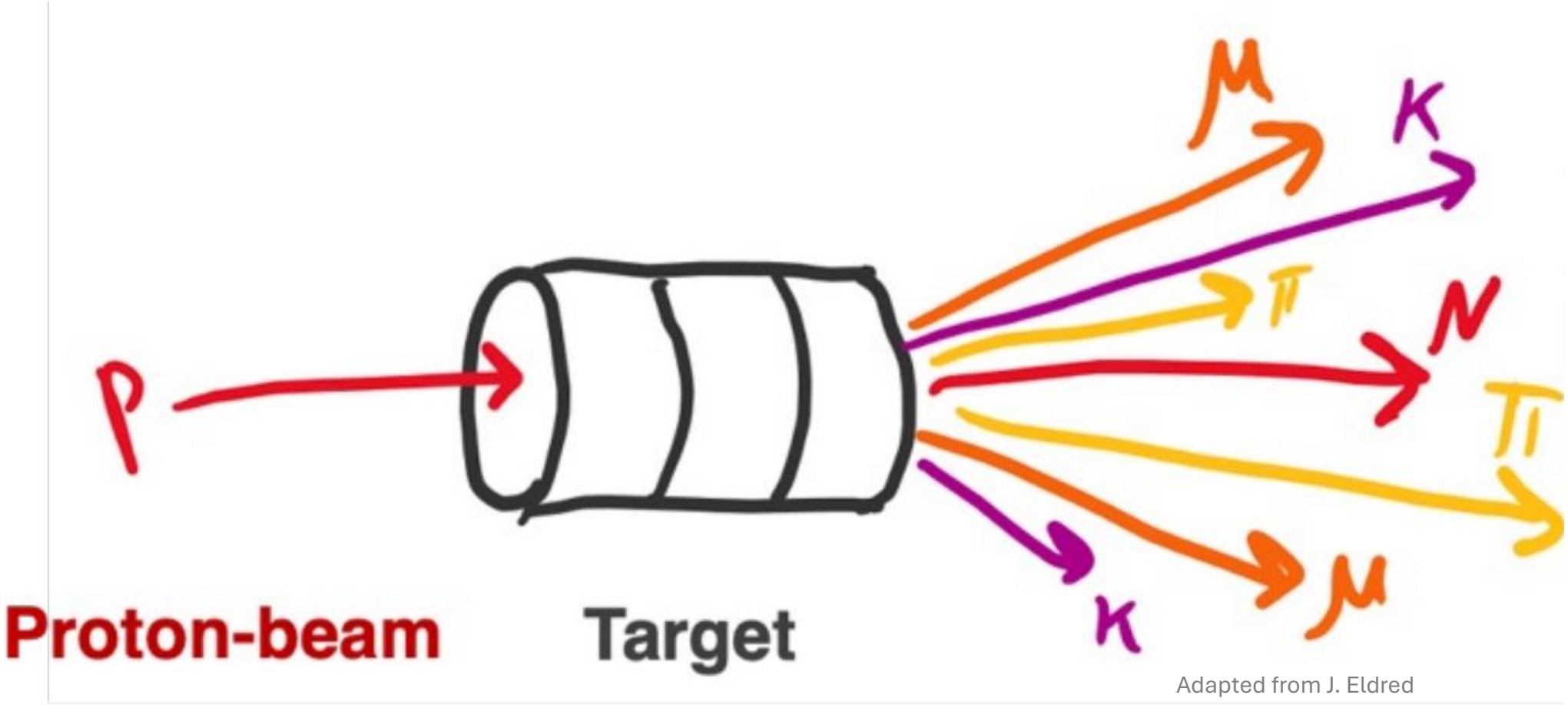
Glossary

- dpa: Displacements Per Atom. A calculable proxy for radiation damage
- PIE: Post Irradiation Examination. Studying physical properties of material exposed to high levels of irradiation.
- Beam power (W): Beam energy * number of particles / second
- SNS: Spallation Neutron Source at Oak Ridge National Lab (ORNL)
- NUMI: Neutrinos at Main Injector. Beamline at FNAL that provides 120 GeV @ > 1 MW.
- MINOS: Main Injector Neutrino Oscillation experiment utilizing neutrinos produced at NUMI

Outline

- Muon production target constraints & wish list
- Expectation vs Reality
- Target considerations (radiation damage)
- (very briefly) Takeaways and future timelines

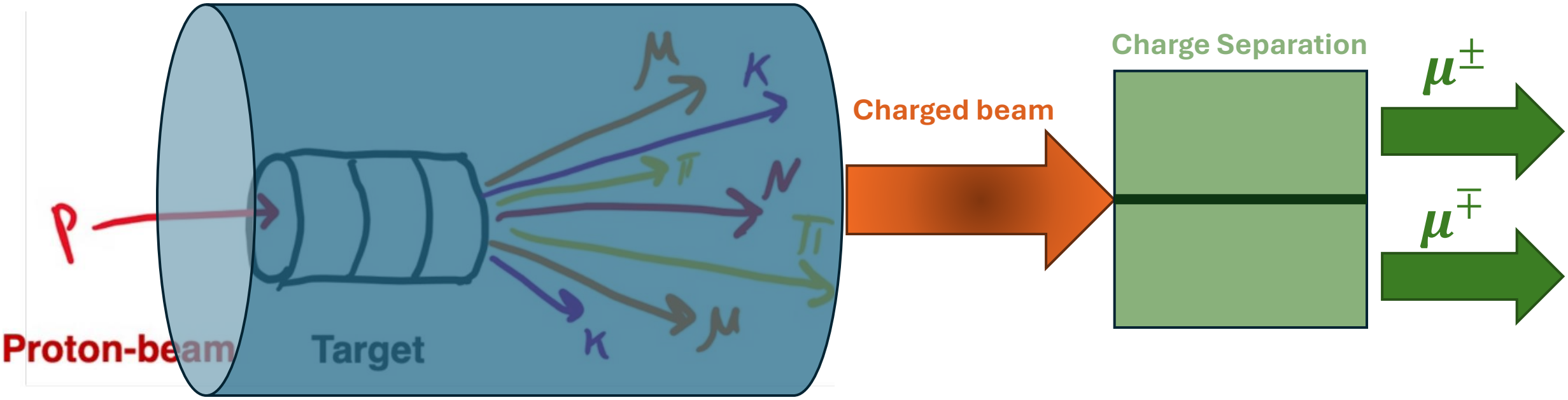
How we make muons (all you have to do…)



Adapted from J. Eldred

How we make a **muon beam**

High-Field Solenoid (many-T)



*NB: Currently favored method, not the only way…

Muon production target wish list

Maximize production

Long-lived (in a beam)

Compact

High power targetry reality

Early target failures: limited beam power

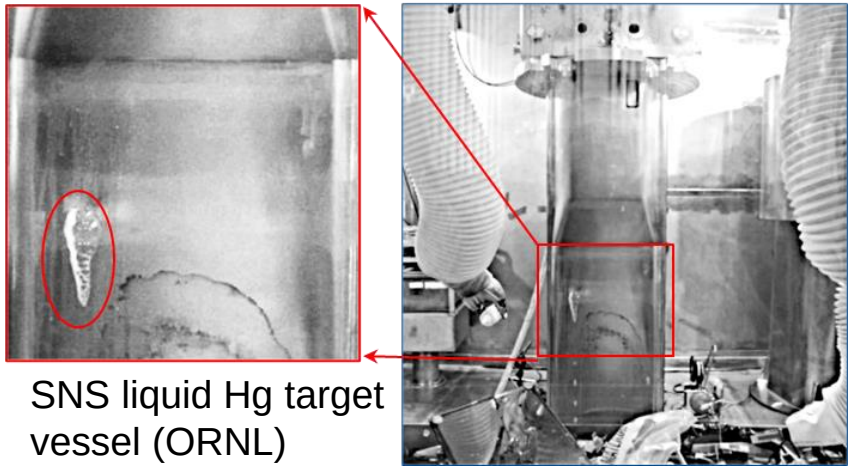
Figs adapted from F. Pellemoine

Maximize production

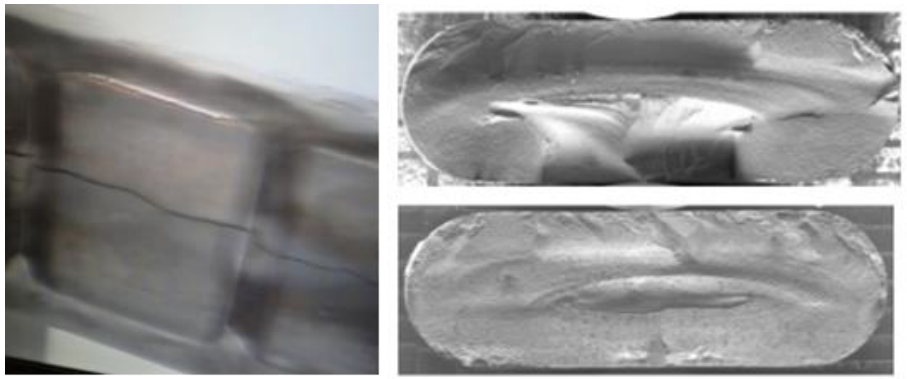
Long-lived (in a beam)

~~**Compact**~~

HUGE targets!
(will be worse for muon targets In smaller volumes)

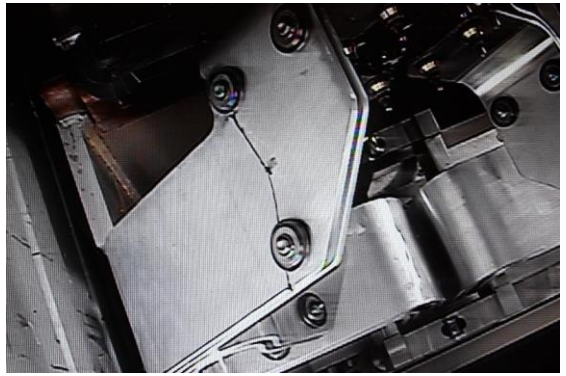


SNS liquid Hg target vessel (ORNL)



MINOS NT-02 target failure: radiation-induced swelling (FNAL)

MINOS NT-01 target containment water leak (FNAL)



Horn stripline fatigue failure (FNAL)

SNS (Oak Ridge)

Oak Ridge officials are puzzled by failure of targets at Spallation Neutron Source FREE

31 December 2014

Current users of the eight-year-old facility are mostly unaffected by the reduction in beam power. But officials expect to lose 10% of operating time this fiscal year.
David Kramer

DOI: https://doi.org/10.1063/PT.5.1035

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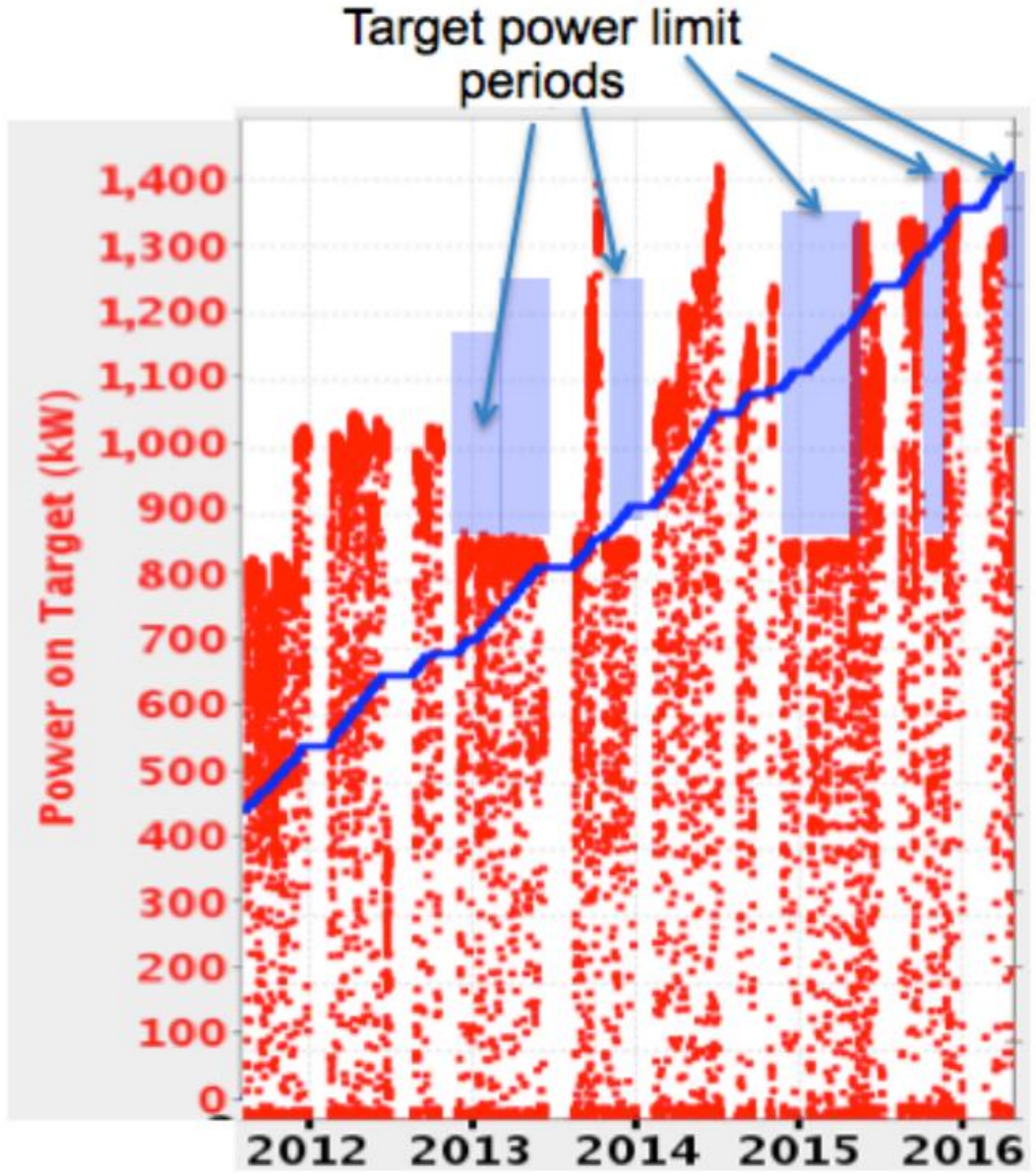


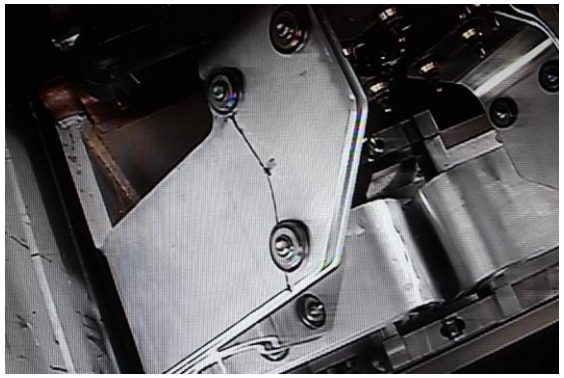
Figure 1: SNS Operational beam power, with periods limited by target concerns indicated in blue.
doi:10.18429/JACoW-IPAC2016-TUZB01

How do targets fail?

Thermal effects

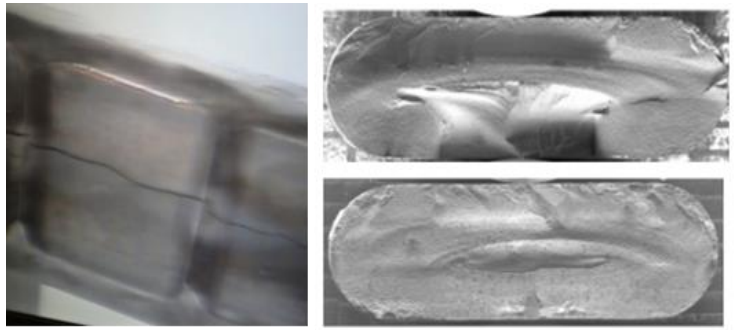
Small iridium rod at CERN HiRadMat

Cycle fatigue



Horn stripline fatigue failure (FNAL)

Radiation Damage



MINOS NT-02 target failure: radiation-induced swelling (FNAL)

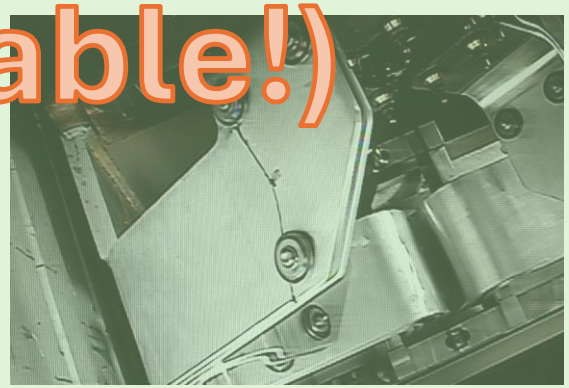
How do targets fail?

Thermal effects

Cycle fatigue

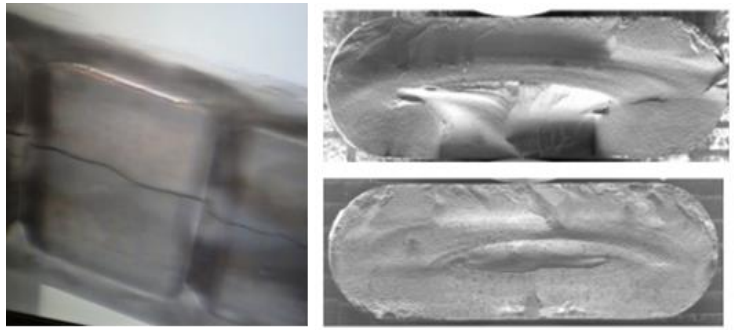
Challenging engineering (but solvable!)

Small iridium rod at CERN HiRadMat



Horn stripline fatigue failure (FNAL)

Radiation Damage



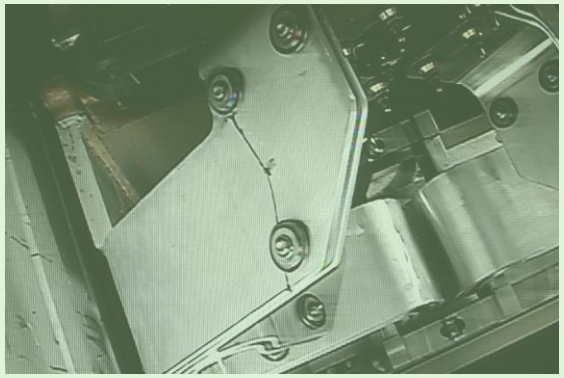
MINOS NT-02 target failure: radiation-induced swelling (FNAL)

How do targets fail?

Thermal effects

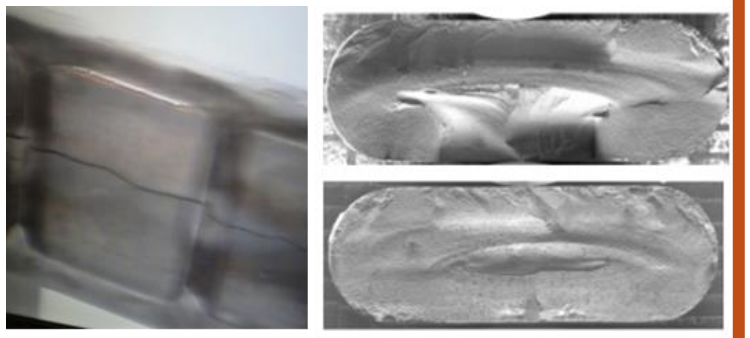
Small irridum rod at CERN HiRadMat

Cycle fatigue



Horn stripline fatigue failure (FNAL)

Radiation Damage

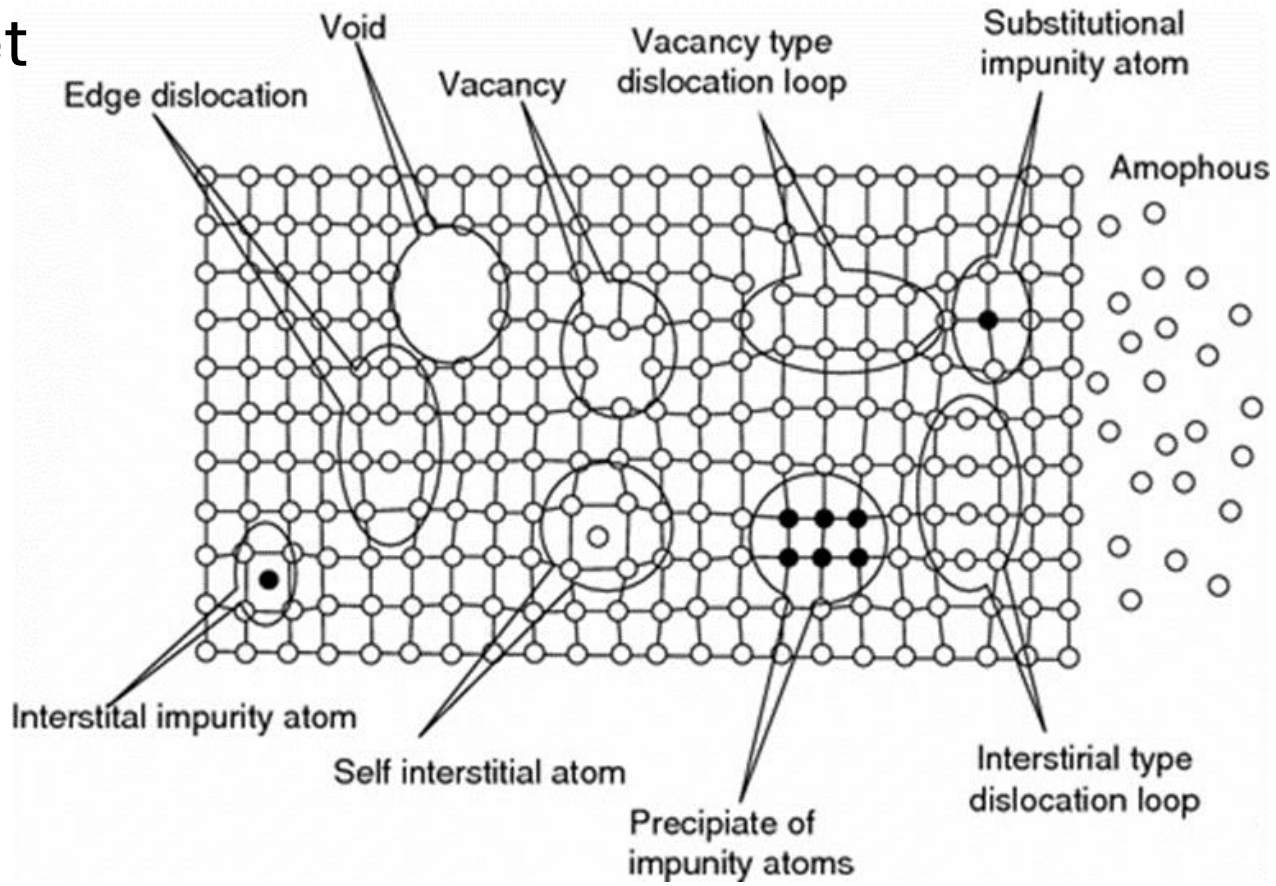


MINOS NT-02 target failure: radiation-induced swelling (FNAL)

Radiation Damage (Non-ionizing)

- Damage to atoms within the target
- Solids: summarized with units of **d**isplacements **p**er **a**tom (dpa)
  - dpa > 1: effects are operationally noticeable (general guideline)
- Fundamental material changes
  - Transmutation/Fragmentation
  - Thermal & physical properties
  - Creep & swelling
  - Fracture toughness (degrading)

Worse for smaller targets!



https://indico.stfc.ac.uk/event/961/contributions/6894/

Interpreting dpa (SNS)

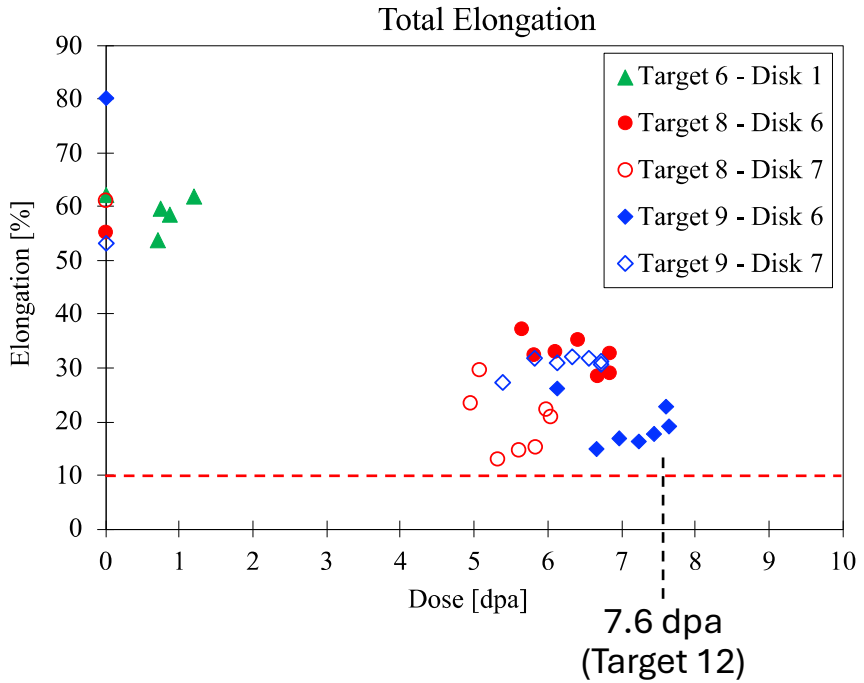
- Calculate dpa (MCNP) after beam exposure.
- Perform post irradiation examination (PIE) to **MEASURE** changes in physical properties and determine failure mechanisms.
- Self-assess failure modes and administrative limits of specific materials in specific environments as a function of delivered protons.

316L Administrative Limit

Vulnerability: Embrittlement through defect/He(?) production

Property Limit: 10 % total elongation

Dose Limit: 12 dpa (outer layer of shroud)



A case study for immediate next-generation muon-production experiment

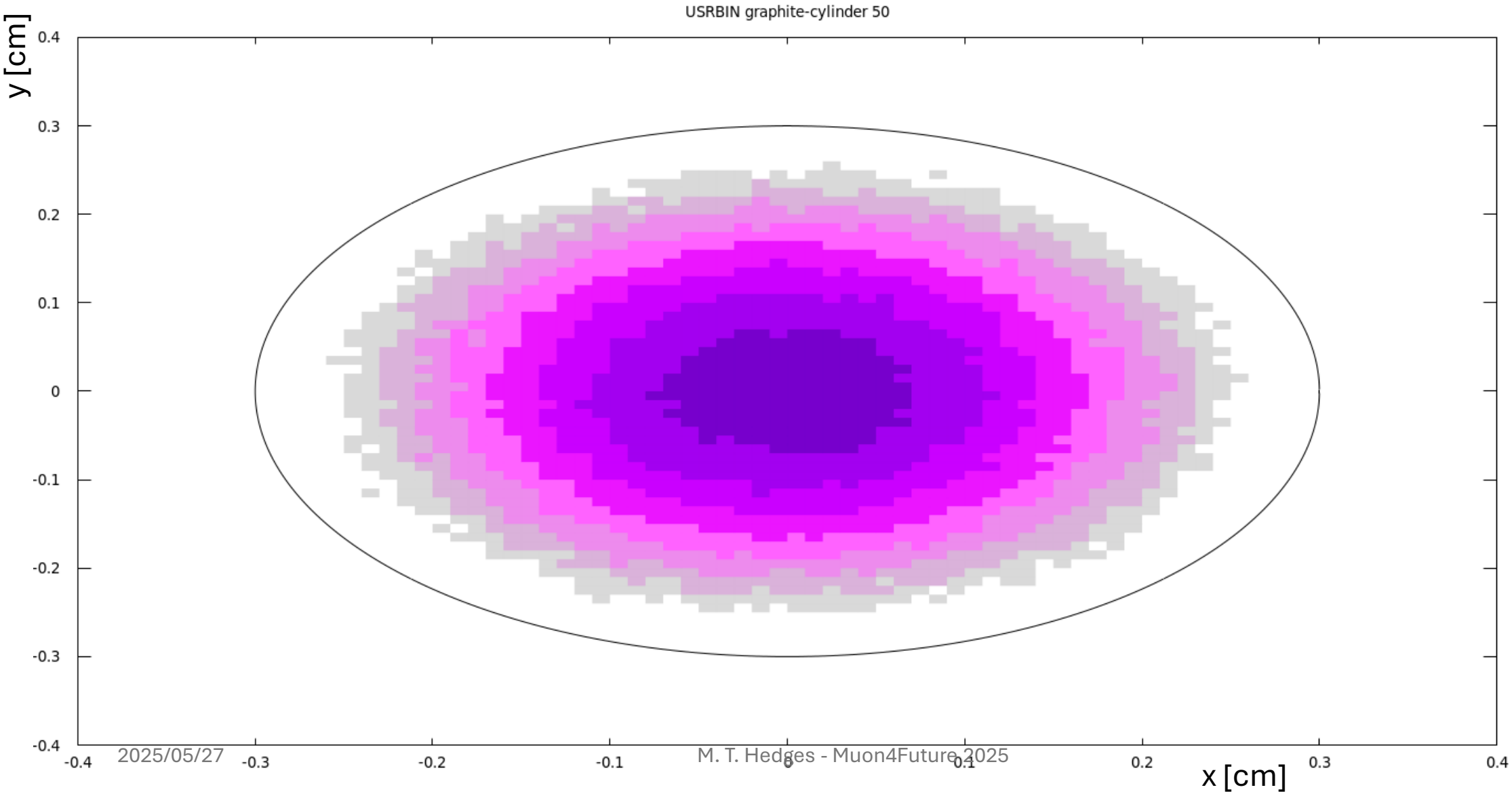
Simulate Radiation Damage (FLUKA)

- Mu2e proton beam:
  - 8 GeV (KE) protons, sigma = 1mm beam radius (gaussian beam)
  - 1.4e20 Protons on Target (POT) / year in nominal operation (8 kW beam)

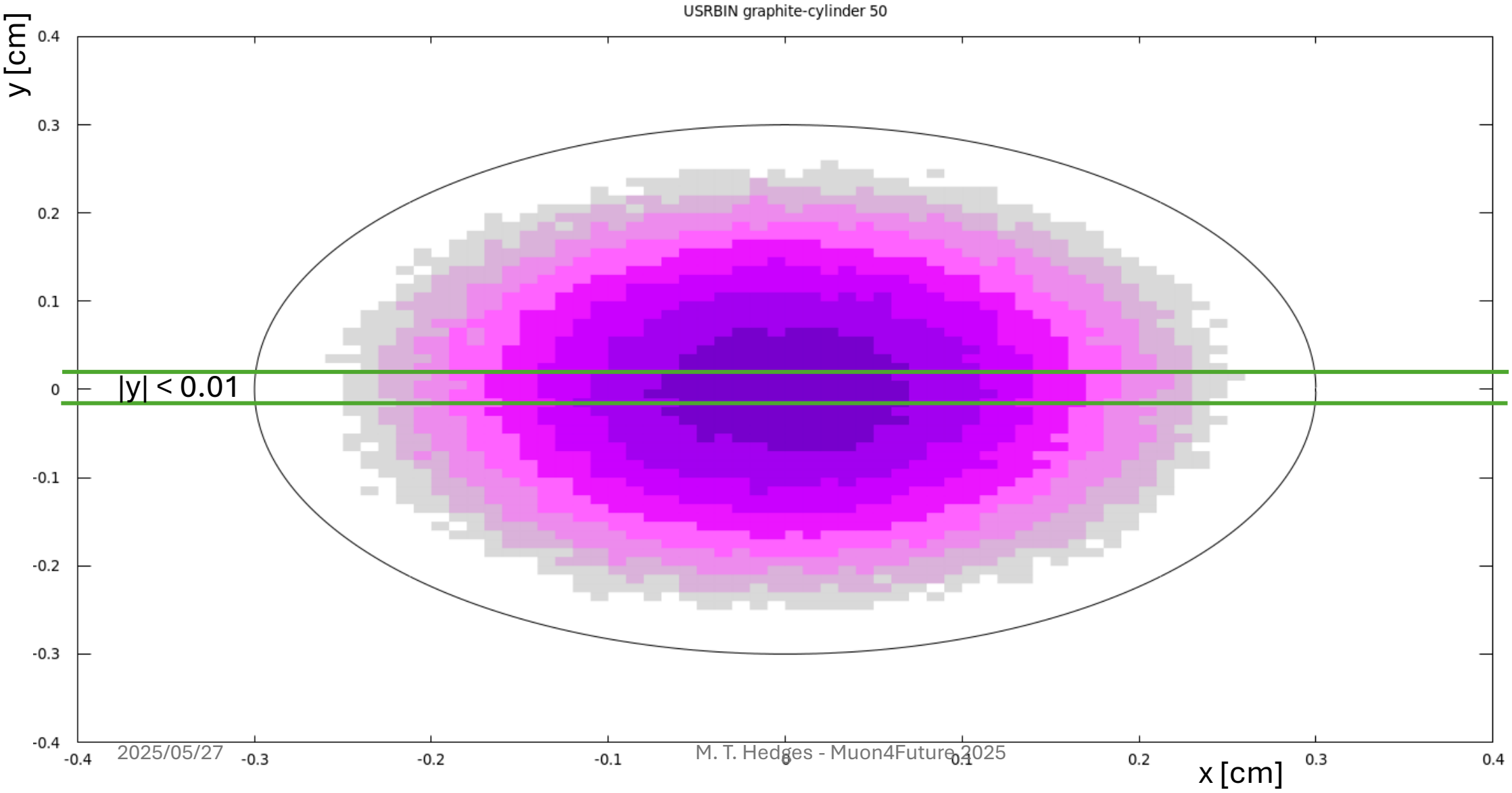
- Consider cylindrical target with radius = 3 mm, length = 220 mm
  - Sits inside a compact, high-field (~4.5 T) graded solenoid

- How does DPA look for different target materials?
  - Assume full year of running (1 replacement / yr)
  - Plot x vs z heatmap of DPA / proton in central slice of y to capture peak DPA in beam center
  - NB: These are preliminary, exploratory plots: over-interpret at your own risk!

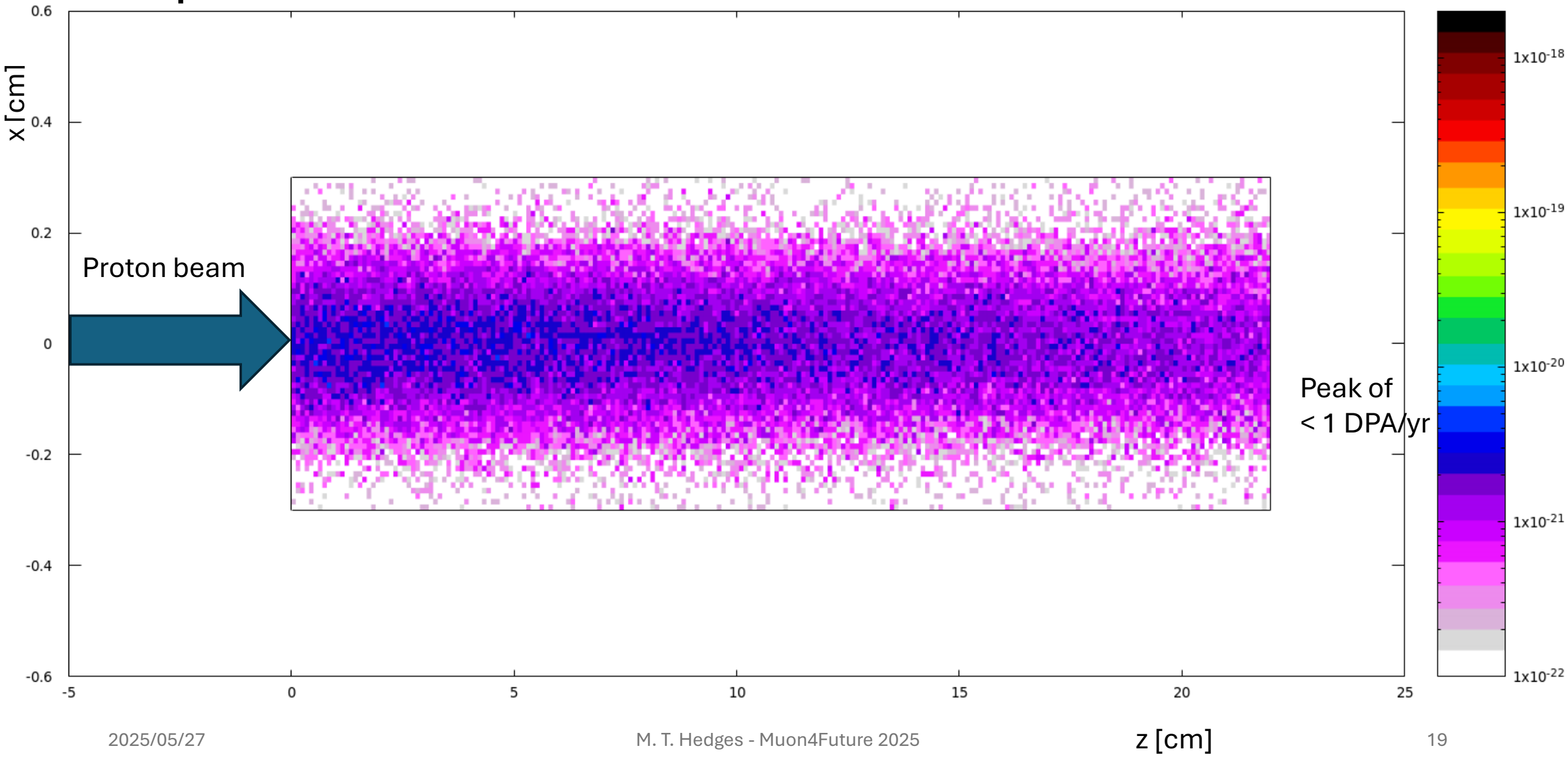
Slicing to find peak DPA



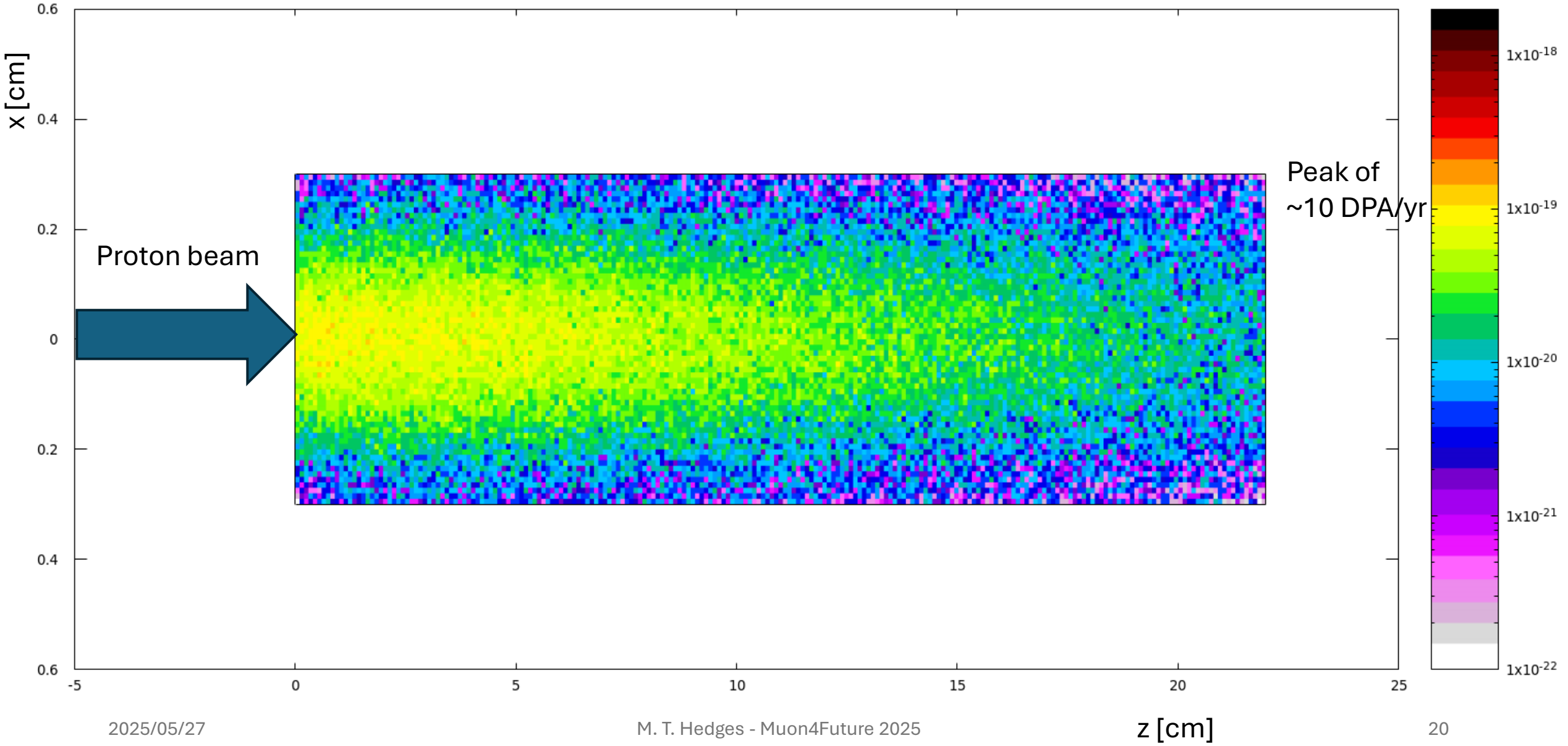
Slicing to find peak DPA



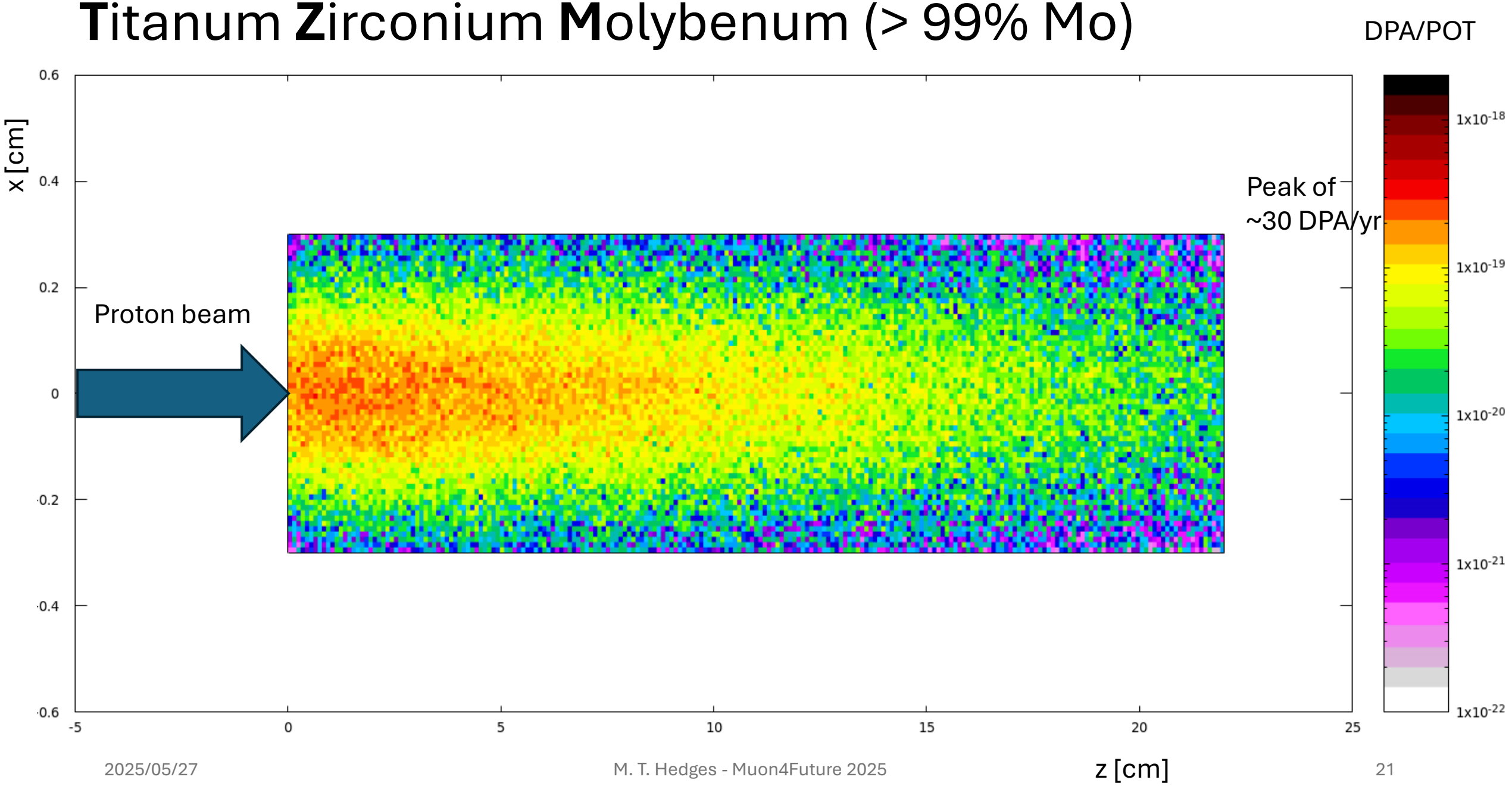
Graphite


DPA/POT
1x10-18
1x10-19
1x10-20
1x10-21
1x10-22
x [cm]
z [cm]
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-5
0
5
10
15
20
25
Proton beam
Peak of
< 1 DPA/yr

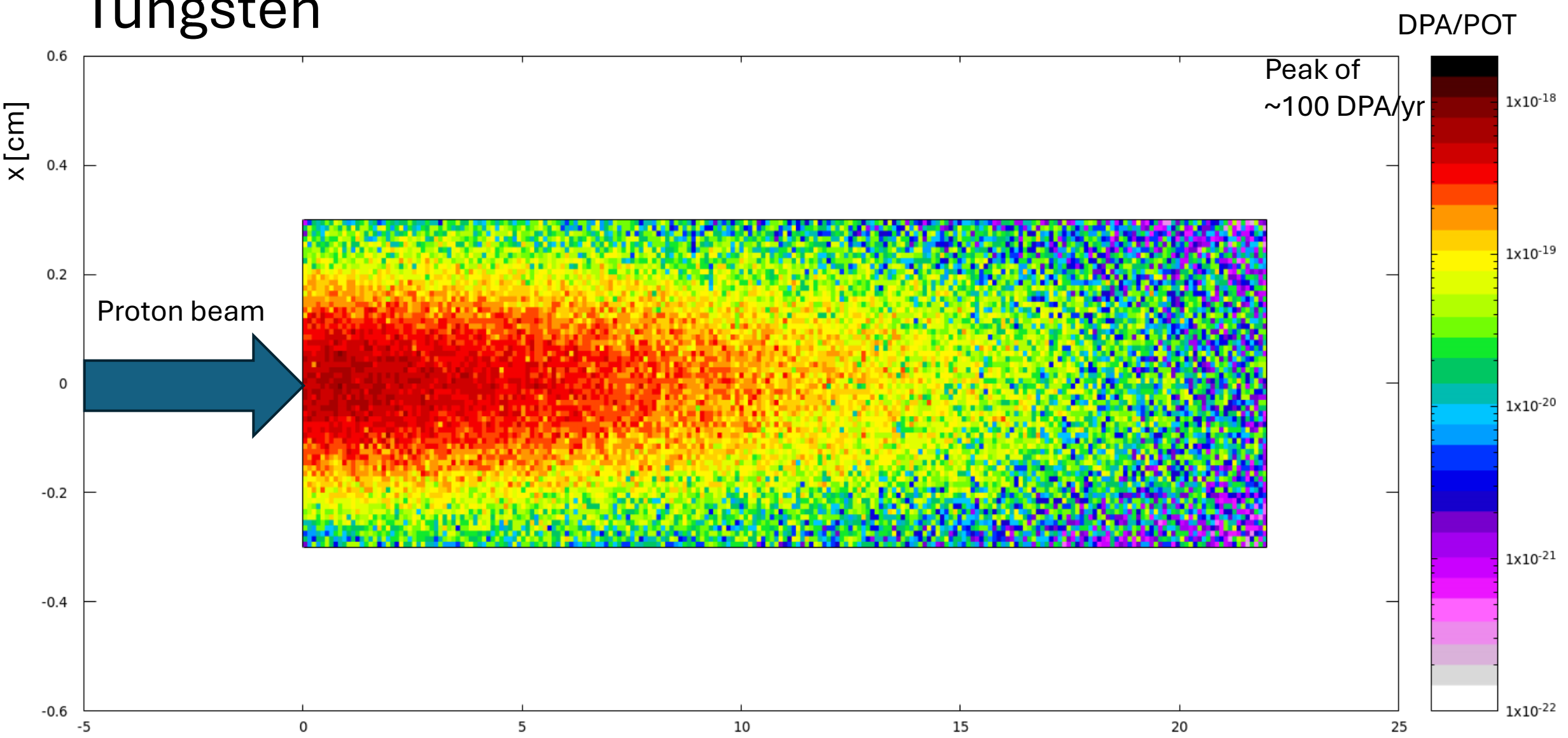
Inconel (Ni alloy)



Titanum **Z**irconium **M**olybenum (> 99% Mo)

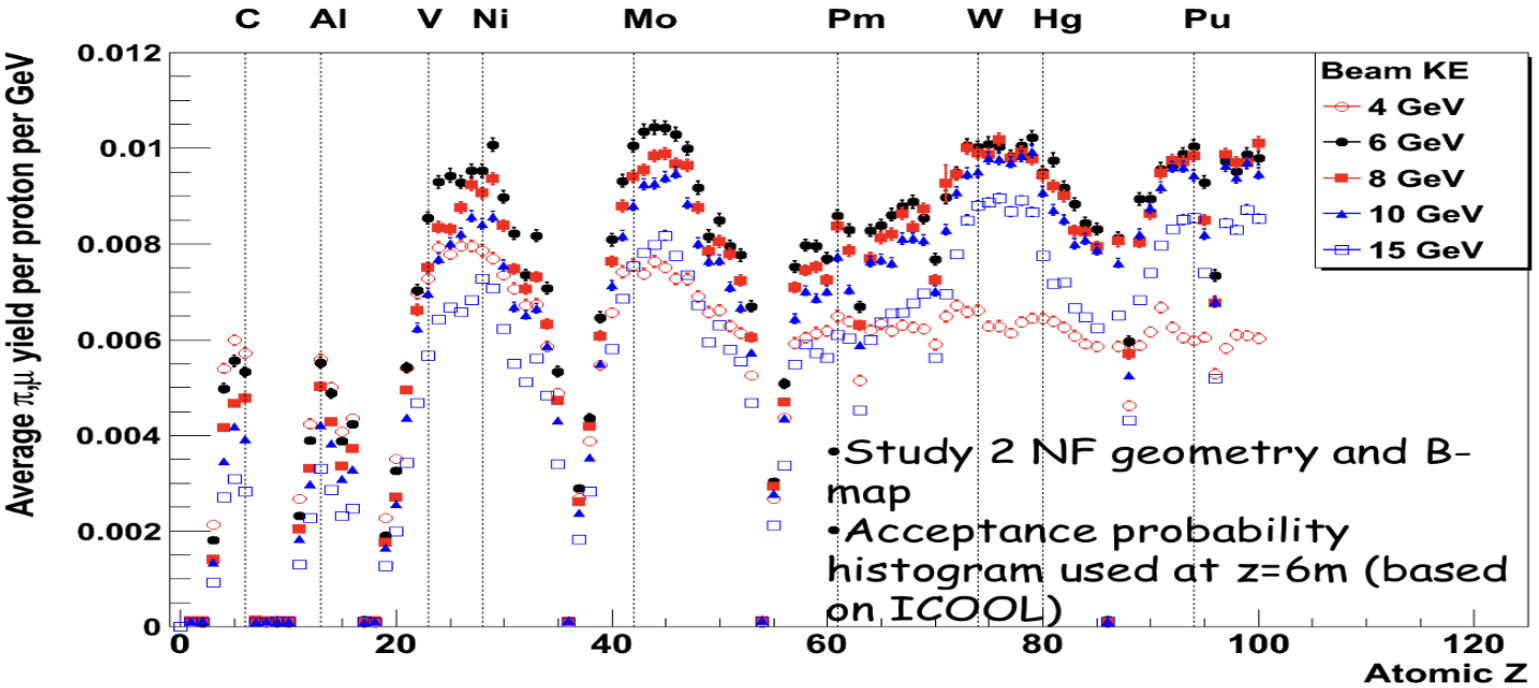


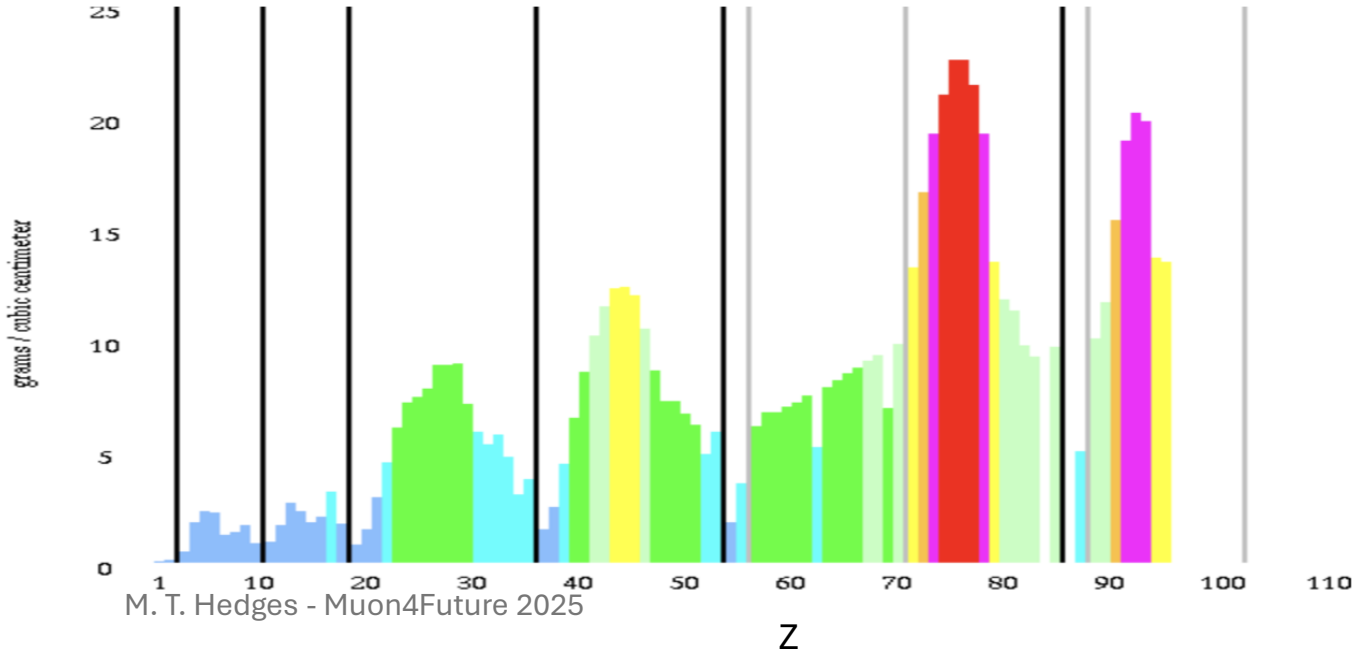
Tungsten


DPA/POT
Peak of
~100 DPA/yr
Proton beam
x [cm]
z [cm]
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-5
0
5
10
15
20
25
1x10-18
1x10-19
1x10-20
1x10-21
1x10-22

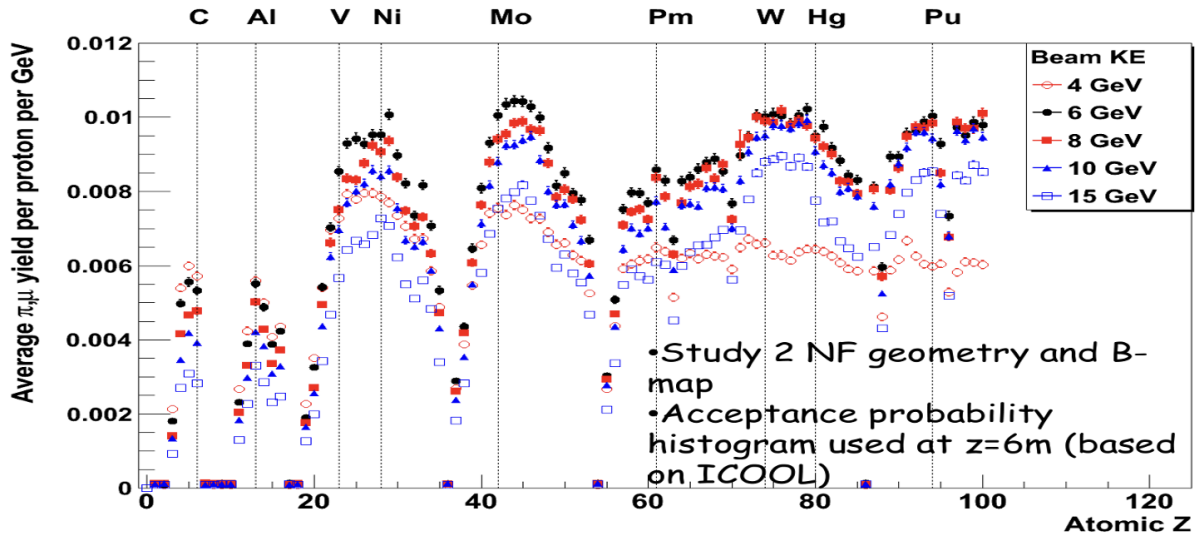
BUT THE MUON YIELDS!?!?!?!

Source: IMCC meeting, talk on fluidized tungsten targets (2023) https://indico.cern.ch/event/1250075/contributions/5348859/attachments/2670245/4628813/IMCC_fluidized-tungsten-target_v1.pdf

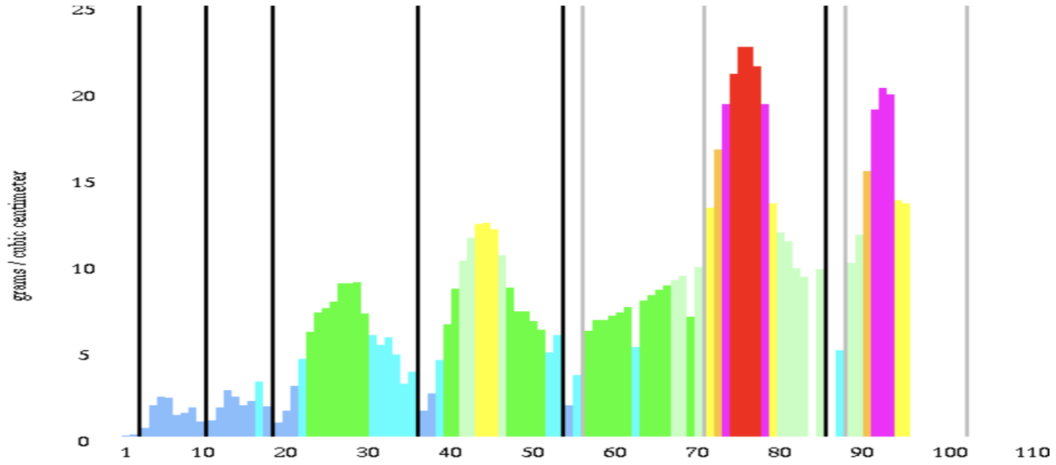




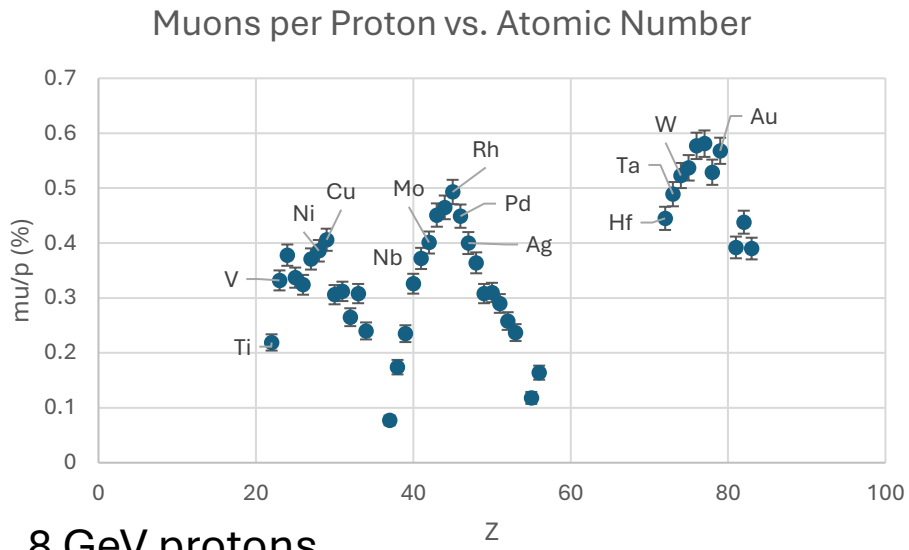
G4Beamline yield validation



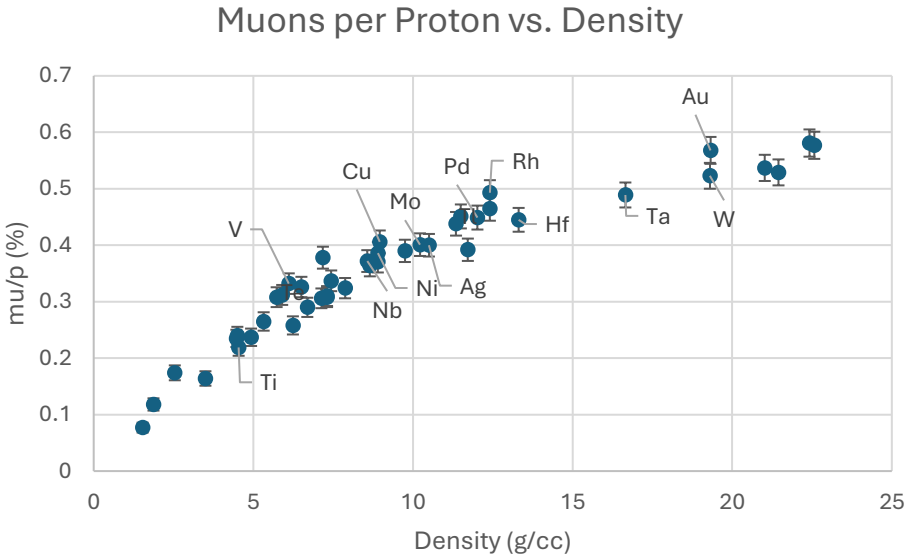
- Study 2 NF geometry and B-map
- Acceptance probability histogram used at z=6m (based on ICOOL)



Source: Madeleine Bloomer, Emory University
FNAL Undergraduate Summer Intern (2024)



8 GeV protons



G4Beamline yield validation

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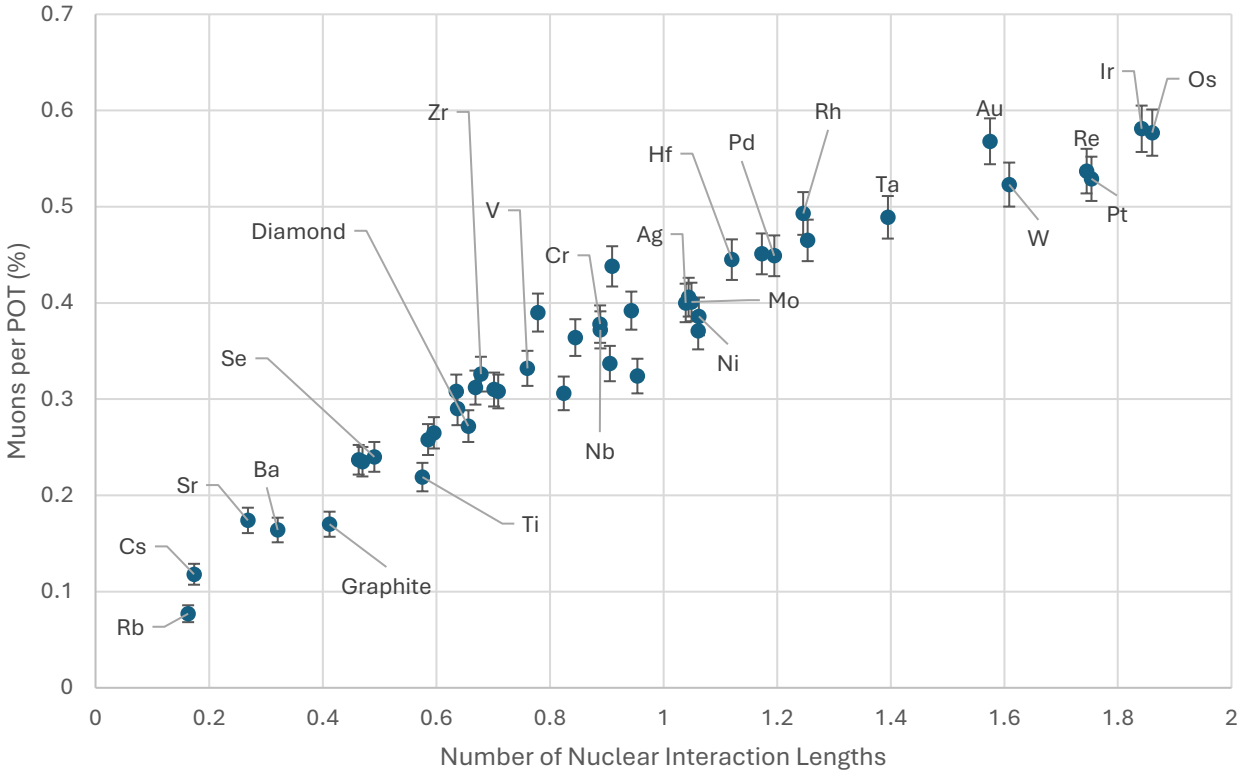
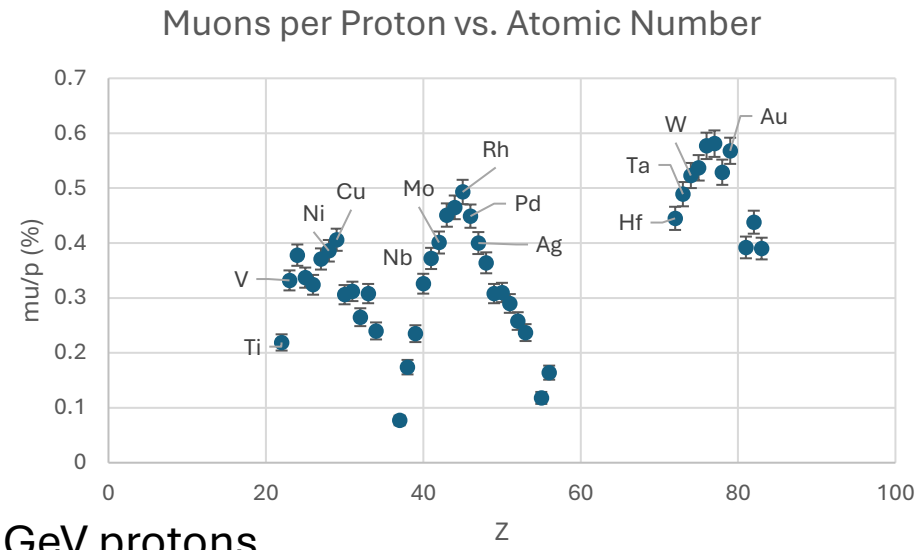
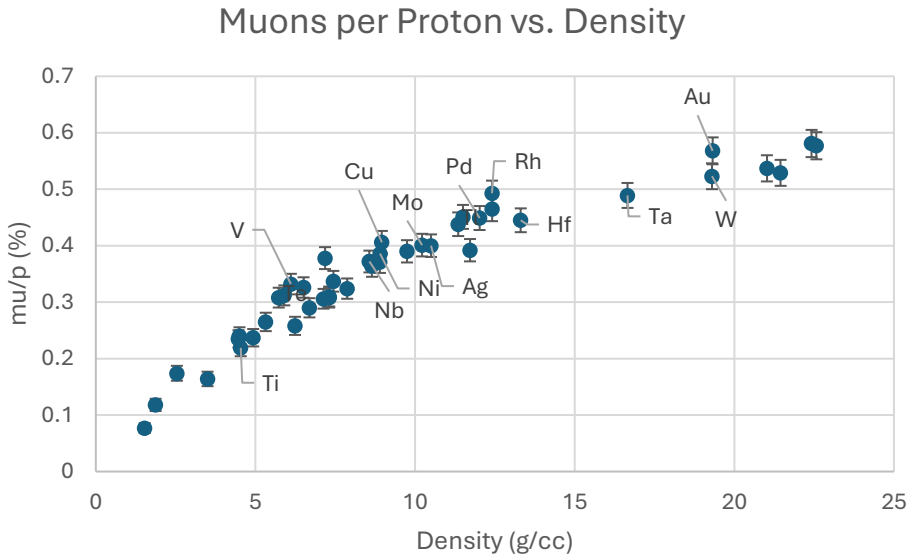


https://pdg.lbl.gov/2024/AtomicNuclearProperties/



8 GeV protons



Takeaways

- Increasing target density worsens radiation damage faster than muon production increases.

- Comparing targets across varying beam conditions is highly non-trivial.
  - 1 MW != 1 MW, 1 dpa != 1 dpa (across beams, materials, target designs, etc)
  - Focused studies on favored production scenarios are crucial

- Very few studies on ***highly irradiated*** (beyond 5-10 dpa) materials for beam-intercept devices (targets, windows, etc).

Takeaways

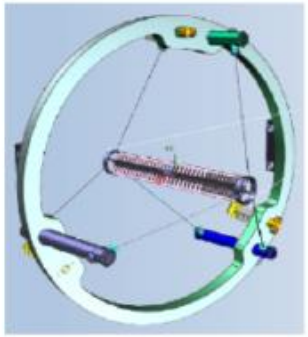
- Mu2e: 1e20 POT per year at 8 GeV (~8 kW) will already bring radiation damage concerns for almost any compact target
  - We are considering different designs to address this
  - Mu2e will probably be the last attempt of a solid, fixed, radiatively cooled target (high-Z or otherwise) for muon production
- The MW era of high-power targetry will raise major challenges in radiation damage and radiological effects
  - 1 MW beam != 1 MW-yr of operation if target failures persist
- Many challenges in muon beams, ***and production is a big one***
  - We will need to address this as global community to enable future facilities, ***highly synergistic across everything related to muon beams***

All you have to do is …

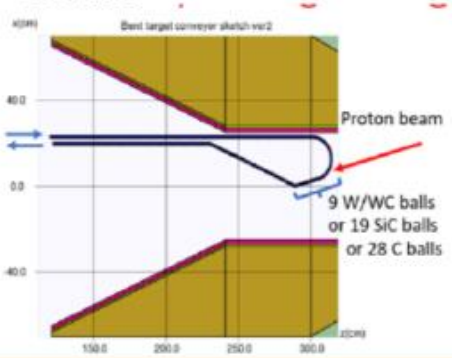
It turns out targetry is *really challenging* and the HEP community is not currently equipped to design, build, and operate facilities at the Multi-MW scale

A very bright (busy…?) future for target systems at FNAL

Mu2e
Tungsten, 6.3 mm x 220 mm
8 kW beam in 4.5 T

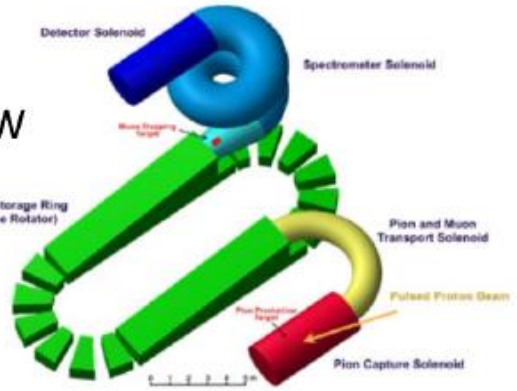


Mu2e-II
R = 1 cm W/WC spheres
100 kW



8 GeV

AMF
???
~1 MW



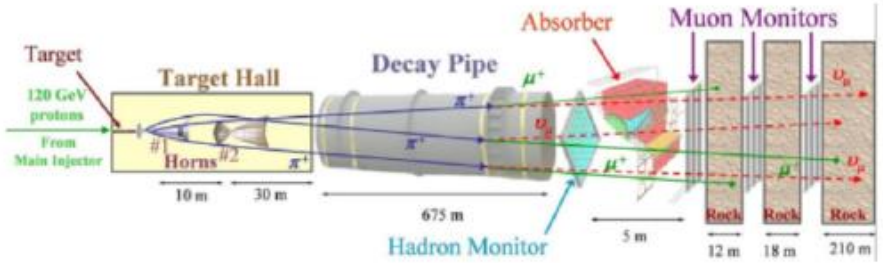
Compact, high-power targets and accompanying beam-intercept devices inside extraction solenoid

Muon collider
??????????????????????
Multi-MW in 20 T!!!

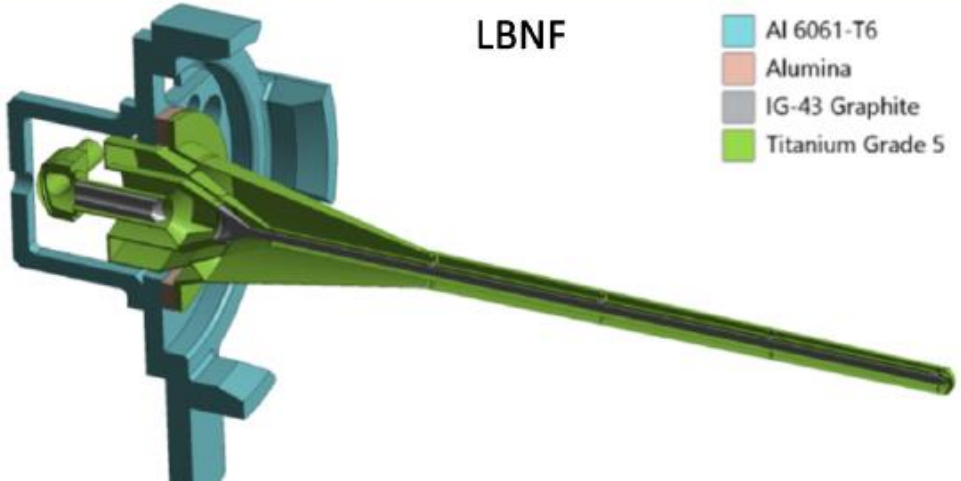
Short → Near → Long

NuMI

120 GeV

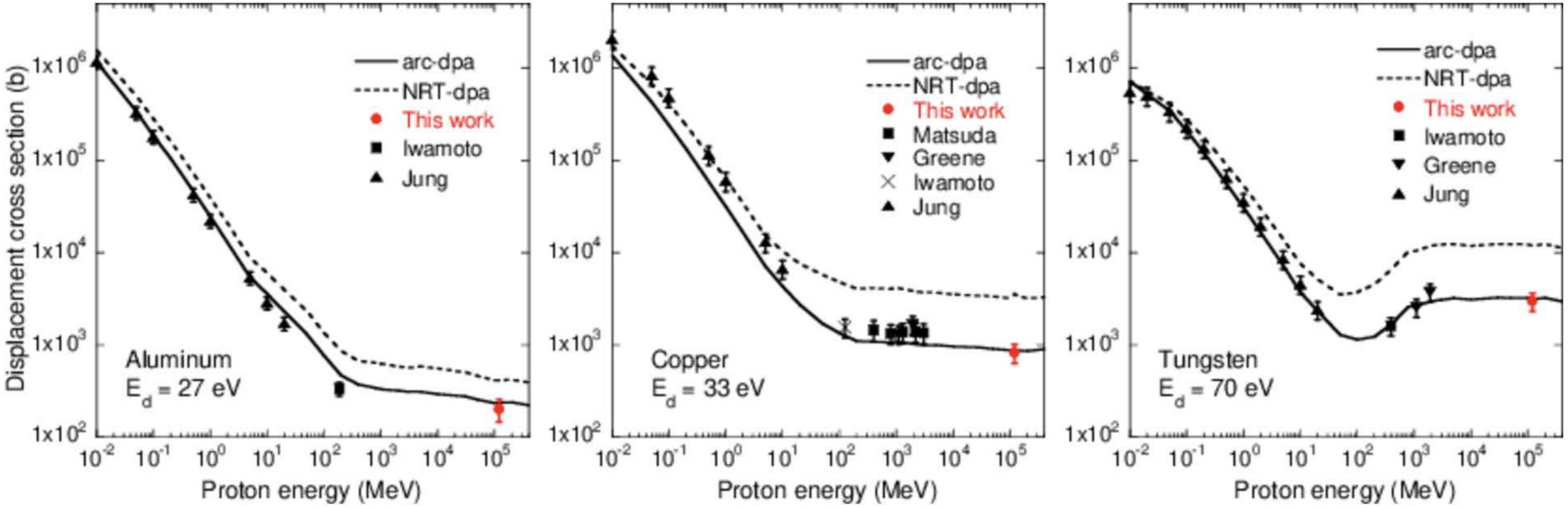


LBNF



Backup

1 MW != 1 MW for radiation damage



7th High Power Targetry Workshop

Jun 4 – 8, 2018
US/Eastern timezone

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Thermal diffusivity of proton and spallation neutron irradiated tungsten

Jun 5, 2018, 11:30 AM
20m
1200 FRIB Bldg

Oral | 3-Post Irradiation Ex... | Session 3-Post Irradiati...

https://indico.fnal.gov/event/15204/contributions/30225/

Speaker

Jemila Habainy (European Spallation...

Description

Thermal properties of pure tungsten, irradiated in the Swiss neutron spallation source at the Paul Scherrer Institut, have been studied in the temperature range 25-500 °C. Disk-shaped specimens were prepared from a tungsten sheet which was irradiated with approximately 550 MeV protons. The specimens tested in this work received total damages of maximum 3.9 and 5.8 dpa at average irradiation temperatures of 115 and 140 °C, respectively. The thermal diffusivity of the irradiated tungsten was measured using the conventional flash method. For both specimens, the results show a significant decrease in thermal diffusivity after irradiation; attaining a value of around 35 mm^2/s throughout the test temperature range. Relative to unirradiated tungsten, the irradiated samples show thermal diffusivity values which are 28-51% lower, depending on temperature. Annealing of the irradiated specimen at 1000 °C for 1 h resulted in a slight recovery of thermal diffusivity. In addition, thermal conductivity values were calculated from the observed thermal diffusivity data. The effect of decreasing thermal conductivity on the of dynamic thermal stress in the target of the European Spallation Source has also been studied.

Primary author

Jemila Habainy (European Spallation...

Co-authors

Prof. Srinivasan Iyengar (Div. of Materials En...
Dr Yong Dai (Paul Scherrer Institut)
Dr Yong Joong Lee (ESS)

Summary

Studies of thermal and mechanical properties of irradiated tungsten:

Thermal diffusivity – decreased by 28-51% lower, depending on temperature. Annealing of 3.9 dpa W, at 1000 °C for 1 h, resulted in a slight recovery of thermal diffusivity.

Fatigue – lowest runout at 135 MPa. Rolled tungsten has higher fatigue limit but shows more scatter.

Hardness – increased by almost 75 % at 3.5 dpa

Ductility – tungsten shows zero ductility at ESS relevant temp., already at 1.3 dpa

Oxidation – even 5 ppm impurity in He will oxidize tungsten

SNS Results for Inconel and Aluminum

https://indico.stfc.ac.uk/event/961/overview

16th International Workshop on Spallation Materials Technology (IWSMT16)

October 28, 2024 to November 1, 2024
The Cosener's house
Europe/London timezone

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Contact
IWSMT-2024@stfc.ac.uk

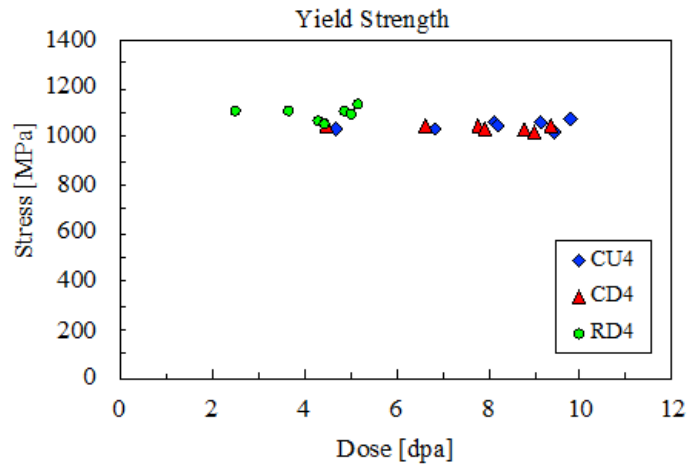
IWSMT16 will be held at the Cosener's house, Abingdon, UK and will include a tour of ISIS at STFC's Rutherford Appleton Lab, Didcot, UK and the new Materials Research Facility at UKAEA's Culham Laboratory

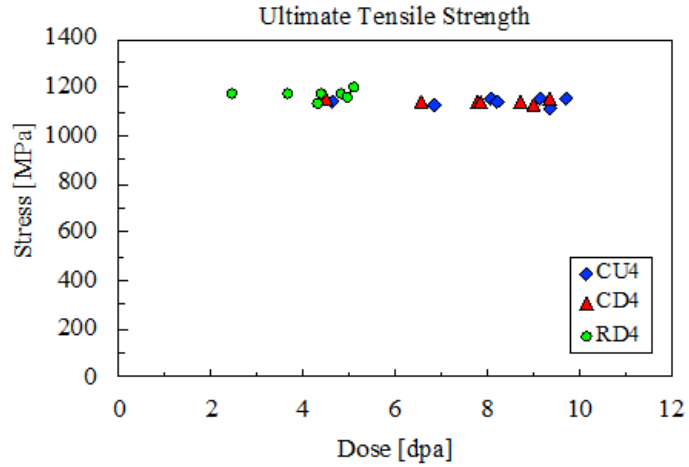
Workshop themes:

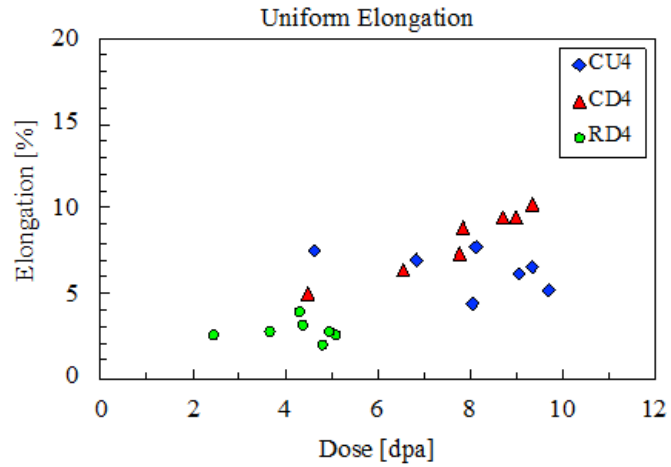
1. Facility overview, updates and developments. Operational experience of targets, beam windows, cooling and ancillary systems.
2. Spallation neutron/muon source component, systems & materials related technology and innovation.
3. Application of new materials data and/or safety codes, computational modelling/analysis.
4. Liquid/solid and particle beam interactions and associated studies: pressure waves, cavitation, erosion, corrosion etc and mitigation techniques.
5. Results from Post-Irradiation Examination of target and structural materials, innovative experimental techniques in study of irradiated materials.
6. Fundamental studies on the effects of radiation damage in materials. Innovative radiation damage resistant materials technology.
7. Collaborations, opportunities and future plans e.g. for materials irradiations & PIE

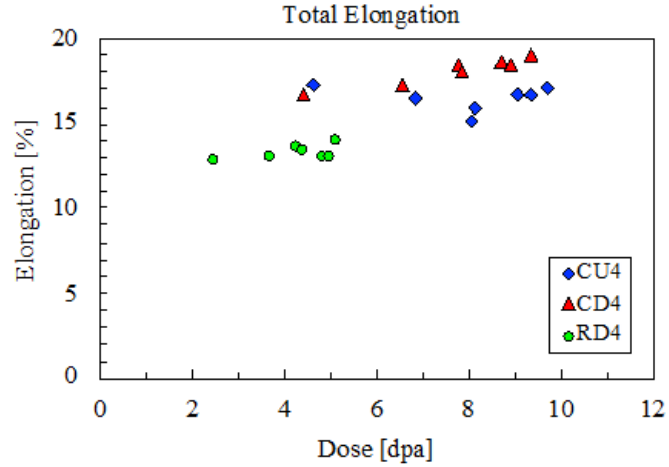
Inconel 718 from PBW-4 displayed radiation-enhanced ductility

- Yield strength and ultimate tensile strength values were remarkable consistent
  - ΔYS = 112 MPa
  - Δ UTS = 83 MPa
- Uniform and total elongation values <u>increased</u> with increasing dose
- An increase with ductility is not typical and has not been reported in the literature for irradiated Inconel 718
- **What radiation-induced change caused this behavior?**
  - 483-1833 appm He
  - 1881-7211 appm H









D.A. McClintock et al., *Observations of radiation-enhanced ductility in irradiated Inconel 718: Tensile properties, deformation behavior, and microstructure*, Acta Materialia 231 (2022) 117889.