High-Power Targetry for Muon Production

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NuFact 2024

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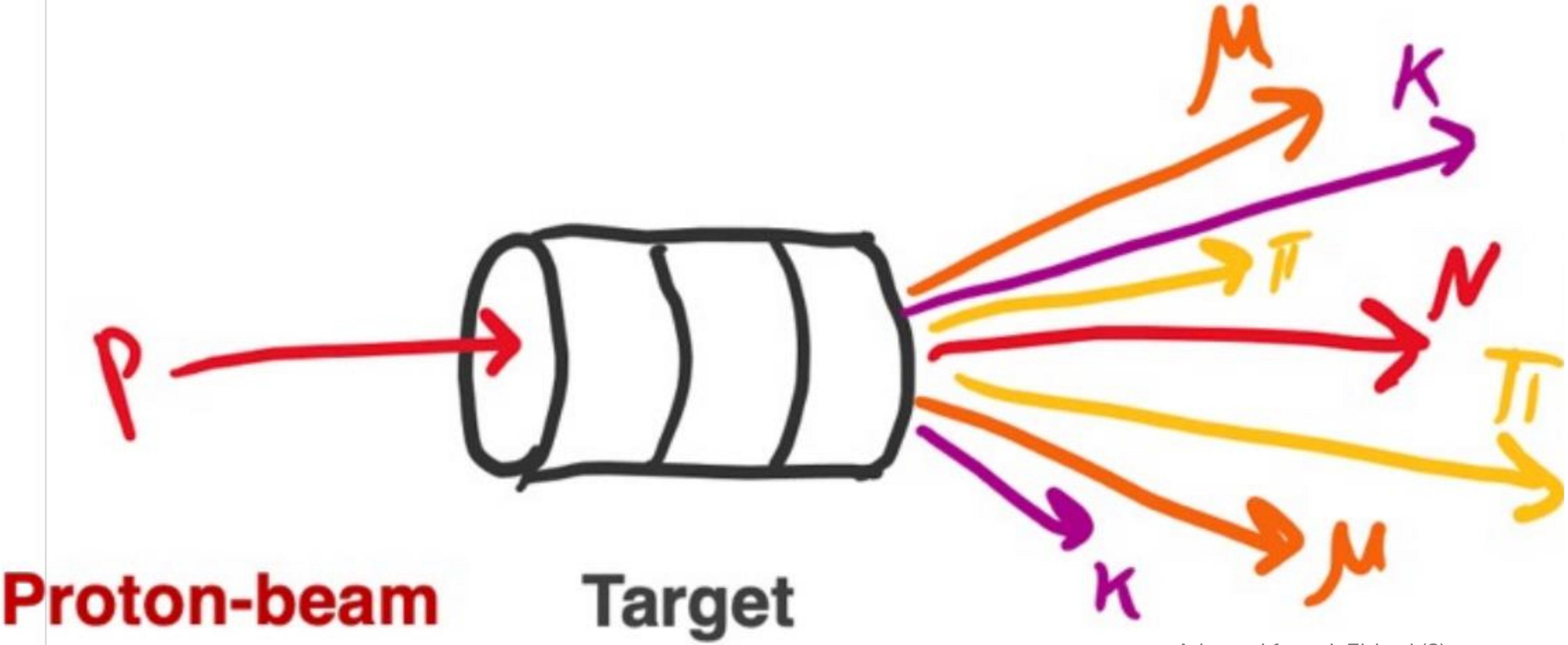
FERMILAB-SLIDES-24-0252-AD

Outline

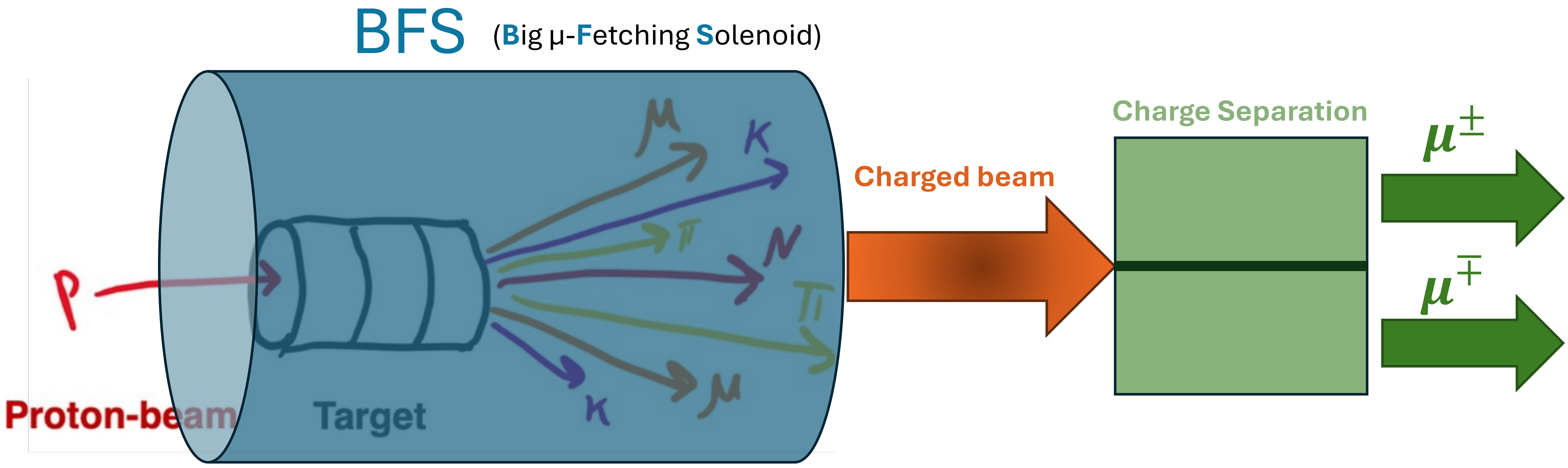
- Muon production target constraints & wish list
- Expectation vs Reality
- Target material considerations (radiation damage)
- (very briefly) Takeaways and future timelines

How we make muons



Adapted from J. Eldred (?)

How we make a **muon beam**



Muon production target wish list

Maximize production

Long-lived (in a beam)

Compact

Muon production target wish list

Maximize production

Long-lived (in a beam)

PICK TWO

(state-of-the-art)

Compact

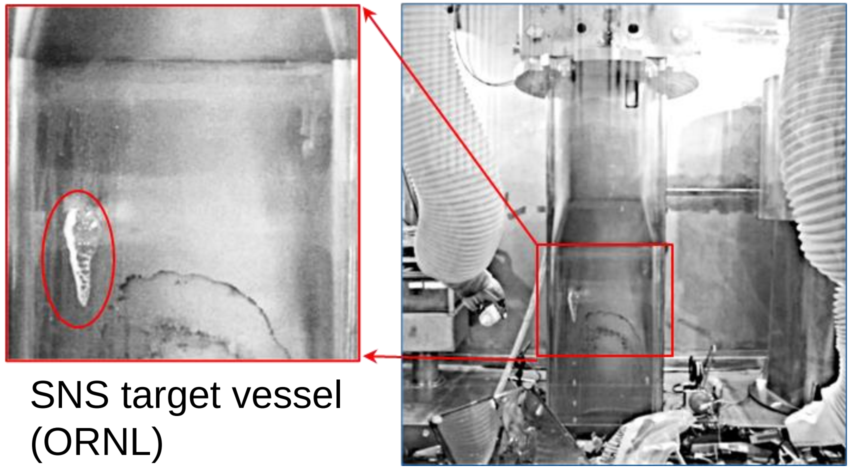
Early target failures: limited beam power

Figs adapted from F. Pellemoine

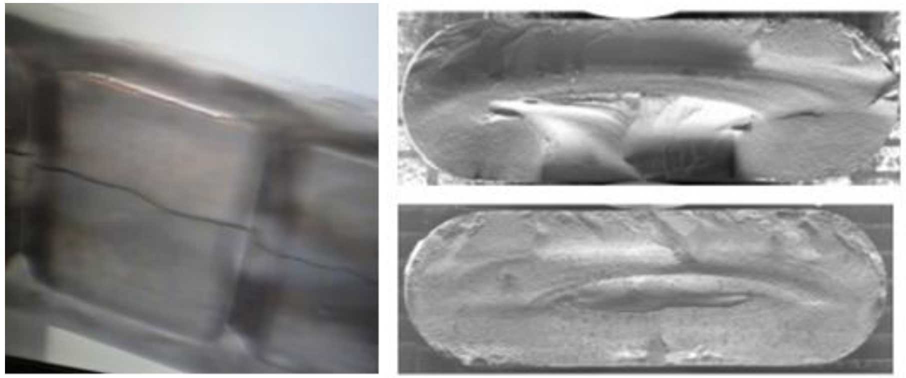
Maximize production | **Long-lived (in a beam)**

~~**Compact**~~

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

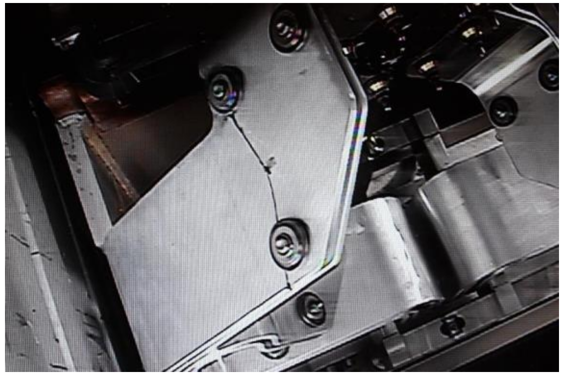


SNS target vessel (ORNL)



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

MINOS NT-01 target containment water leak (FNAL)



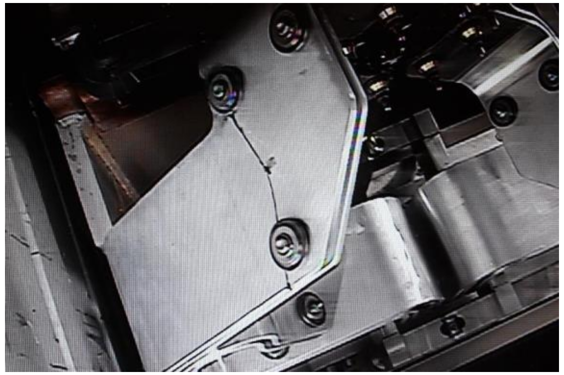
Horn stripline fatigue failure (FNAL)

How do targets fail?

Thermal effects

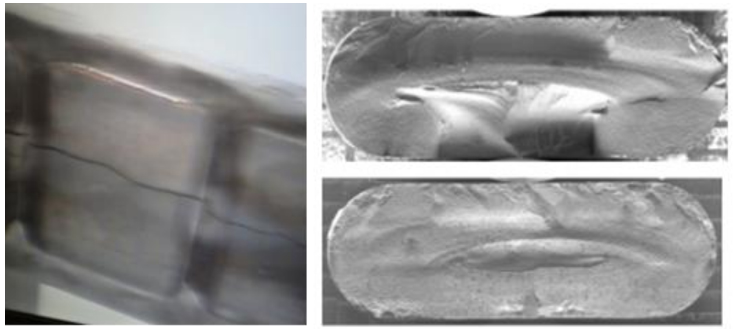
Small iridium rod at CERN HiRadMat

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

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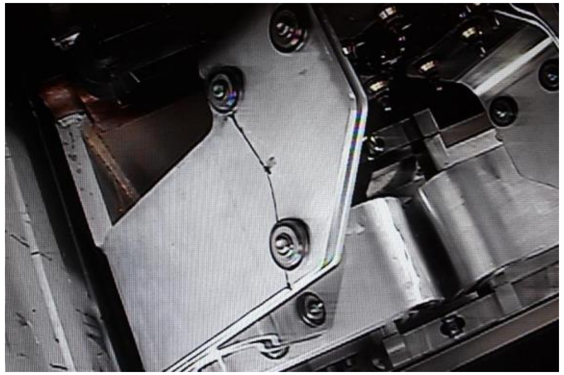
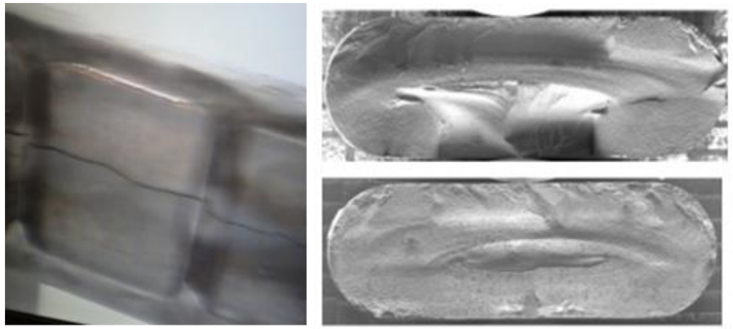


Horn stripline fatigue failure (FNAL)

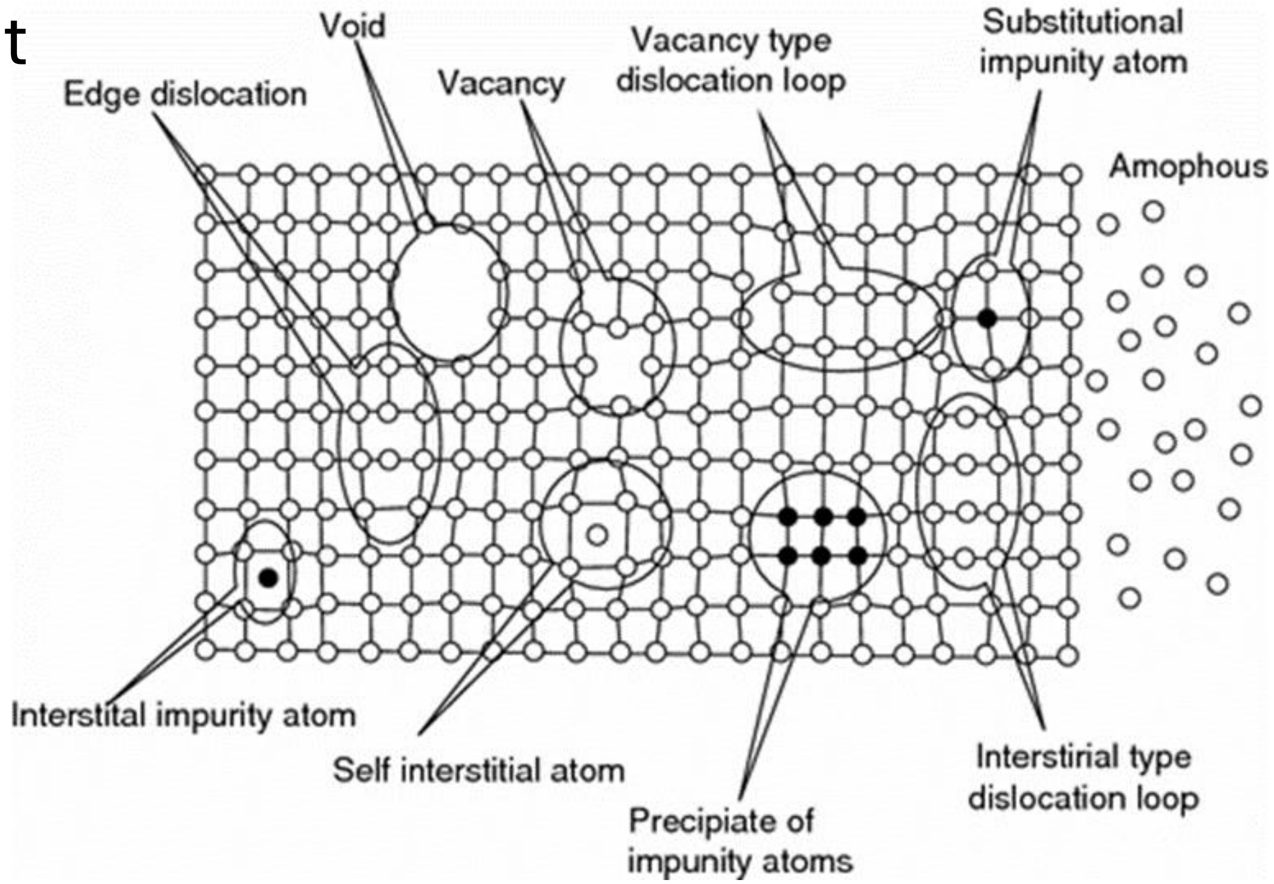


MINOS NT-02 target failure: radiation-induced swelling (FNAL)

Radiation Damage (Non-ionizing)

- Damage to atoms within the target
- Solids: summarized with units of **D**isplacements **P**er **A**tom (DPA)
  - DPA > 1~ is where effects are operationally noticeable
- Transmutation/Fragmentation
- Changes in
  - Thermal & physical properties
  - Creep & swelling
  - Fracture toughness (worsening)

Worse for smaller targets!



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

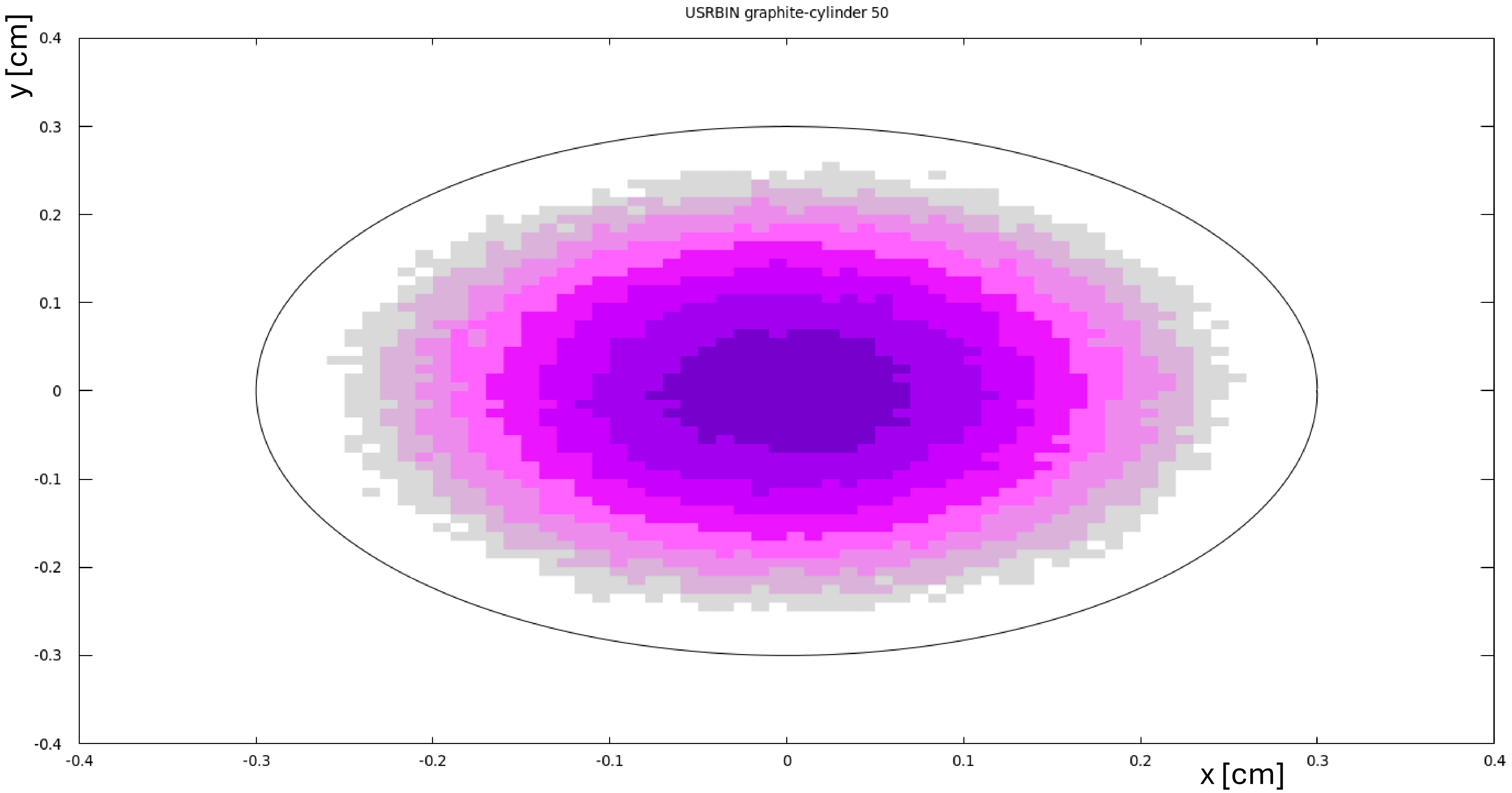
Simulate Radiation Damage (FLUKA)

- 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

- 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



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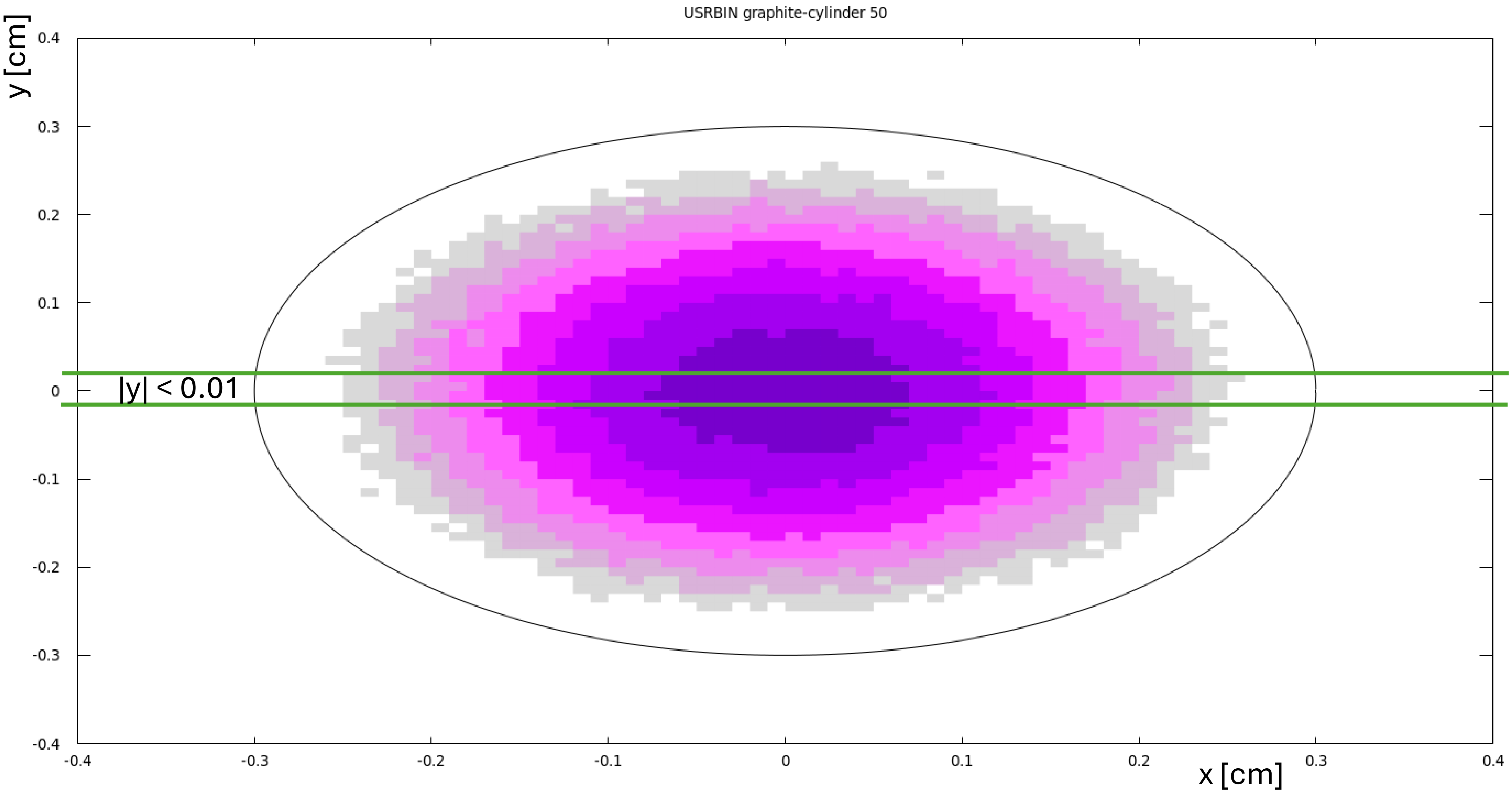
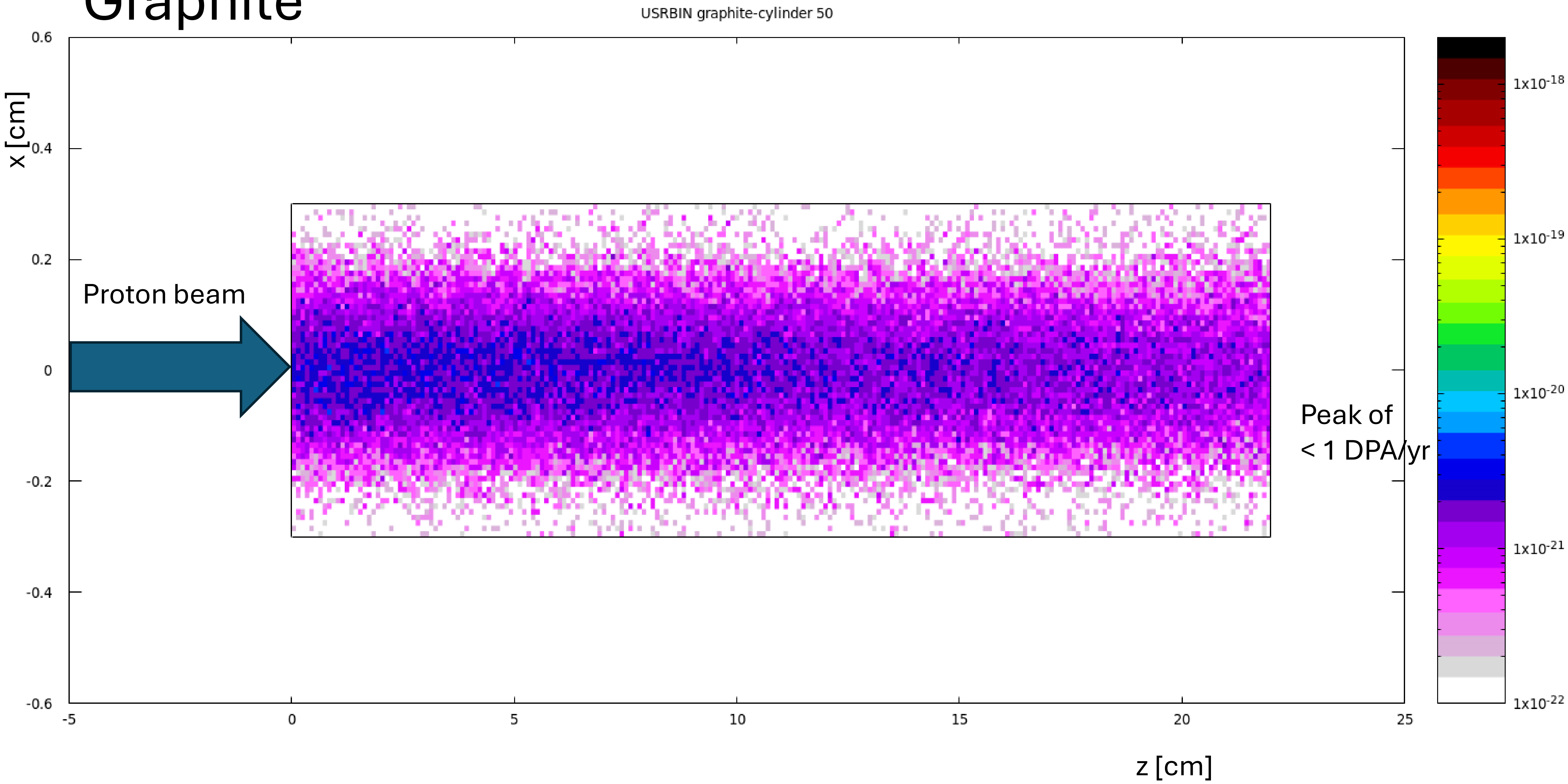
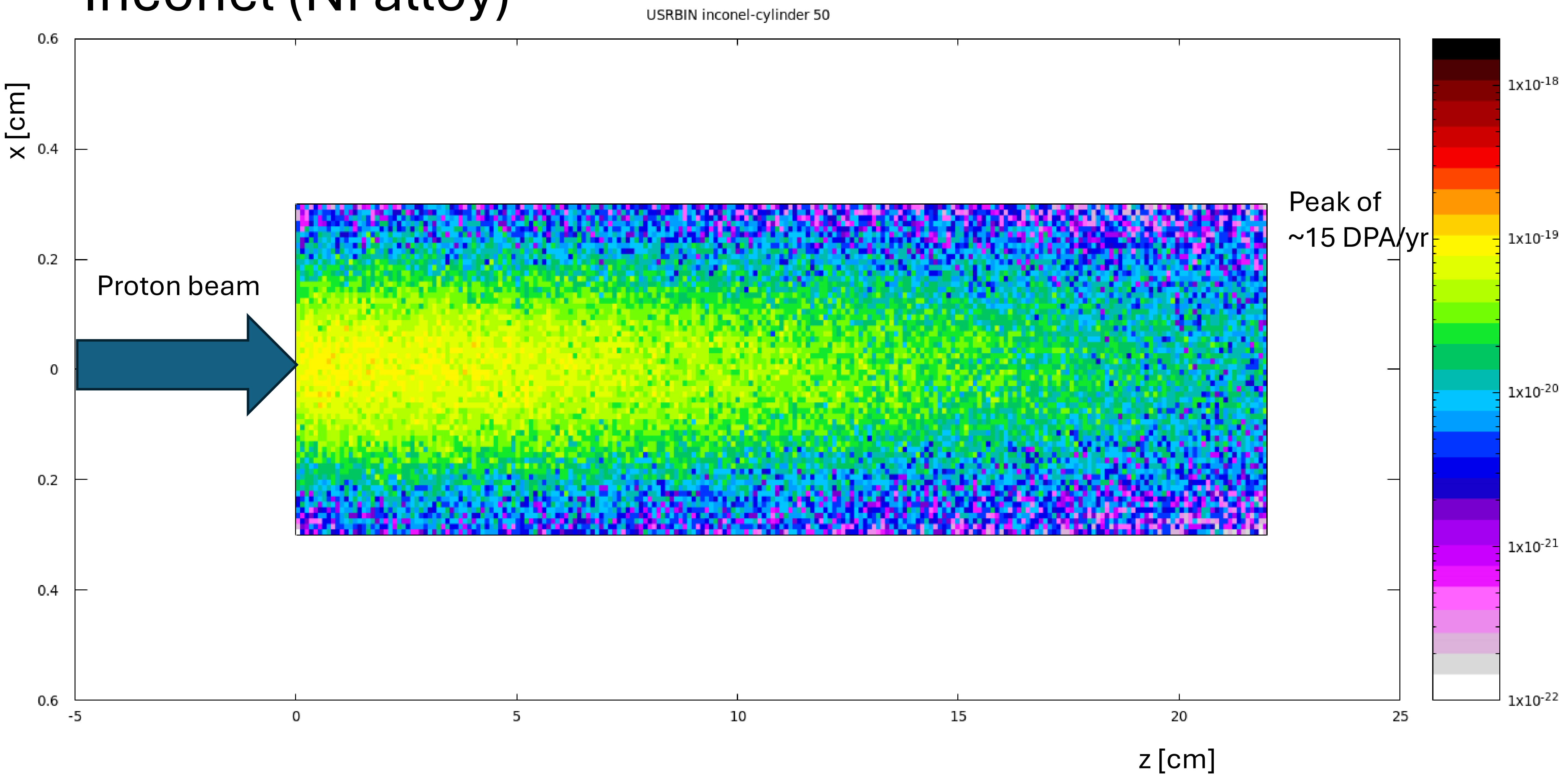


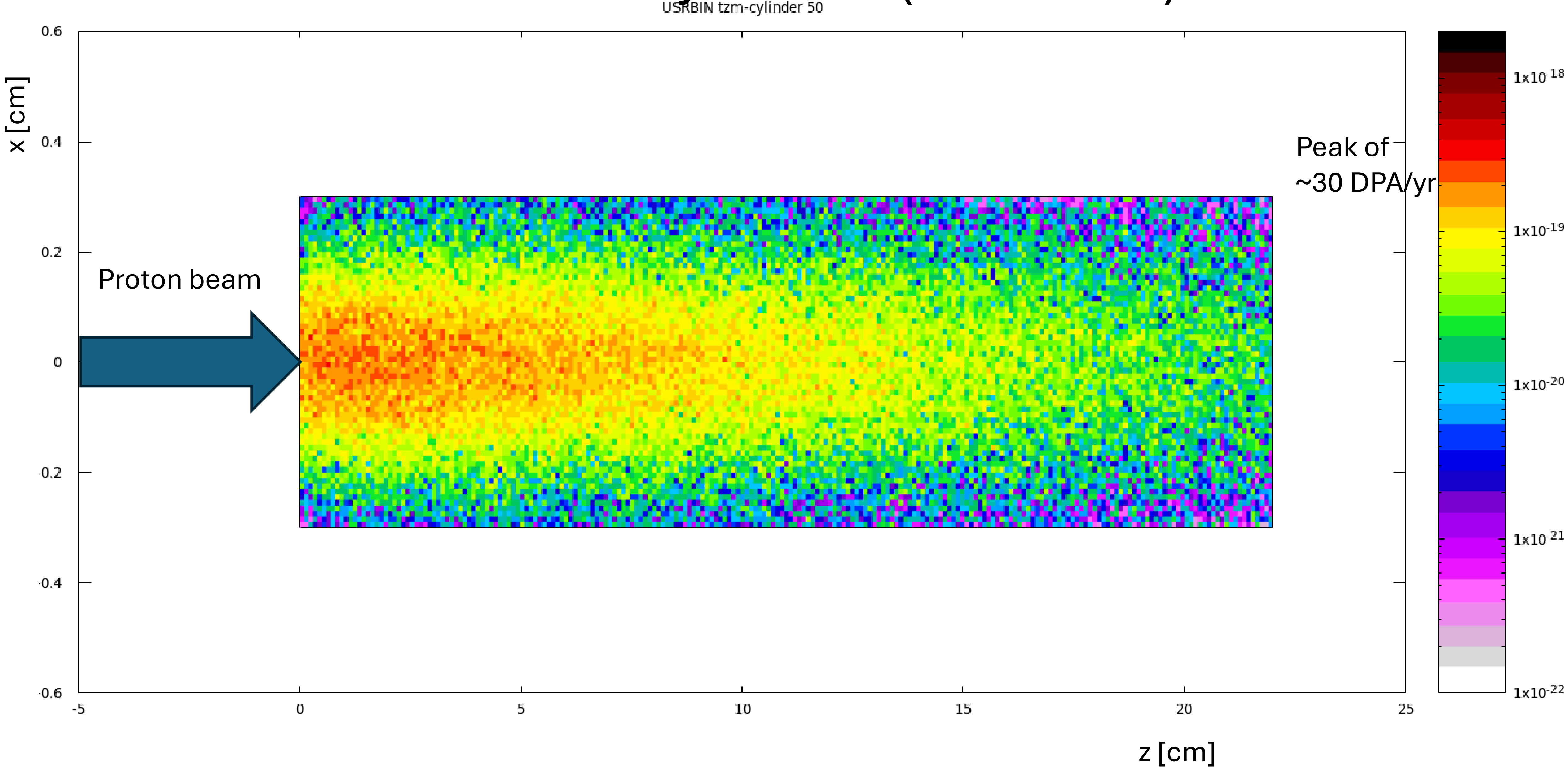
Graphite


USRBIN graphite-cylinder 50
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
x [cm]
-5
0
5
10
15
20
25
z [cm]
Proton beam
Peak of
< 1 DPA/yr
1x10-18
1x10-19
1x10-20
1x10-21
1x10-22

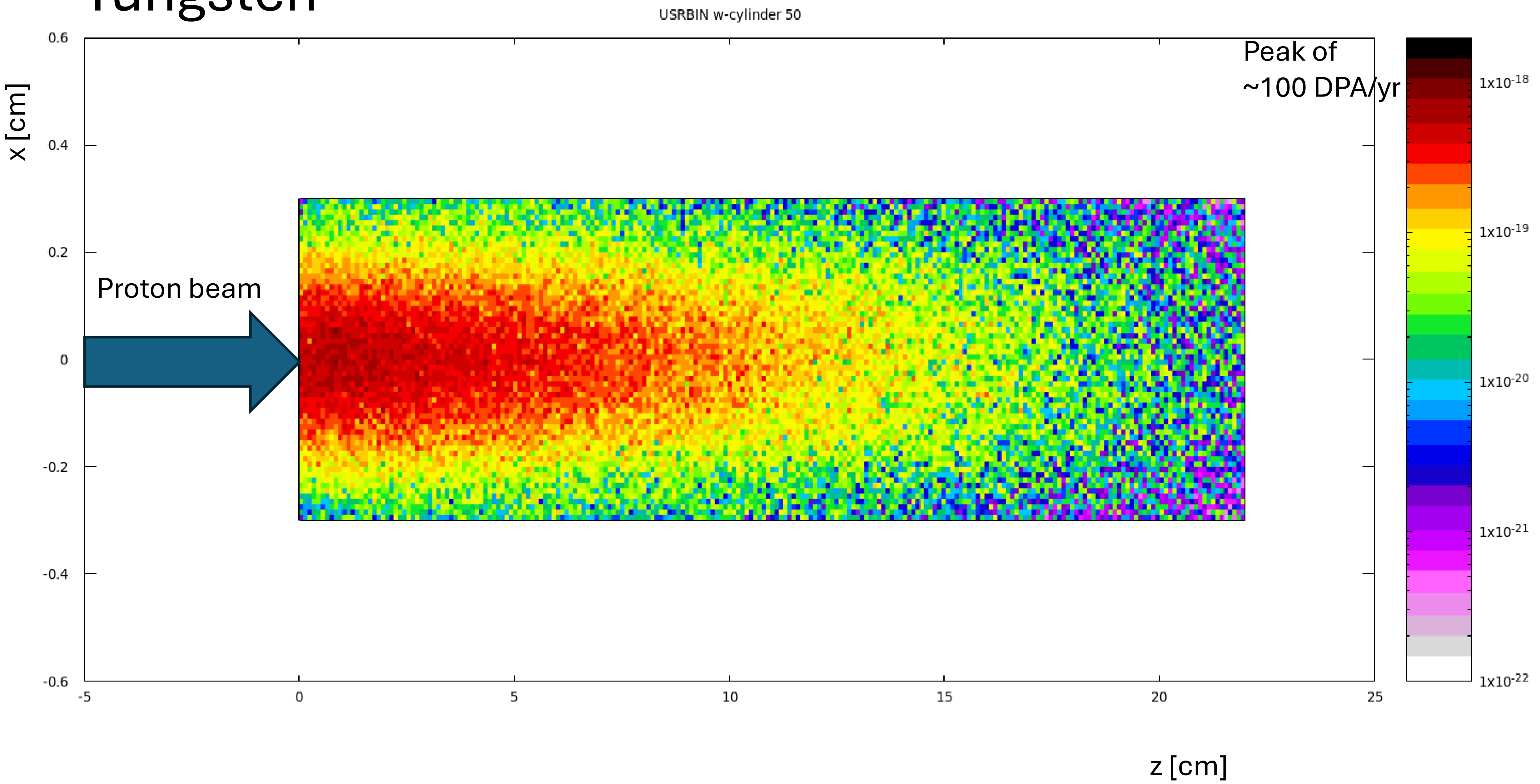
Inconel (Ni alloy)



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



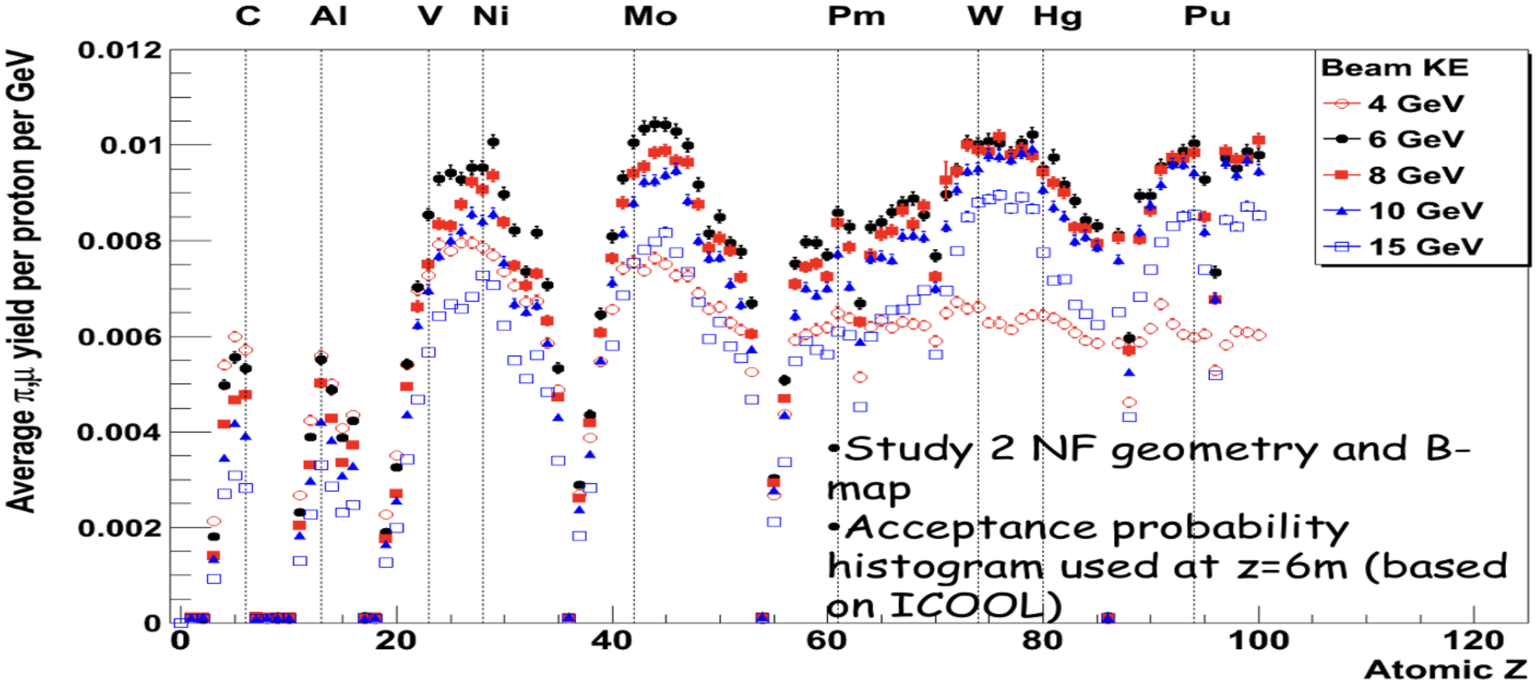
Tungsten

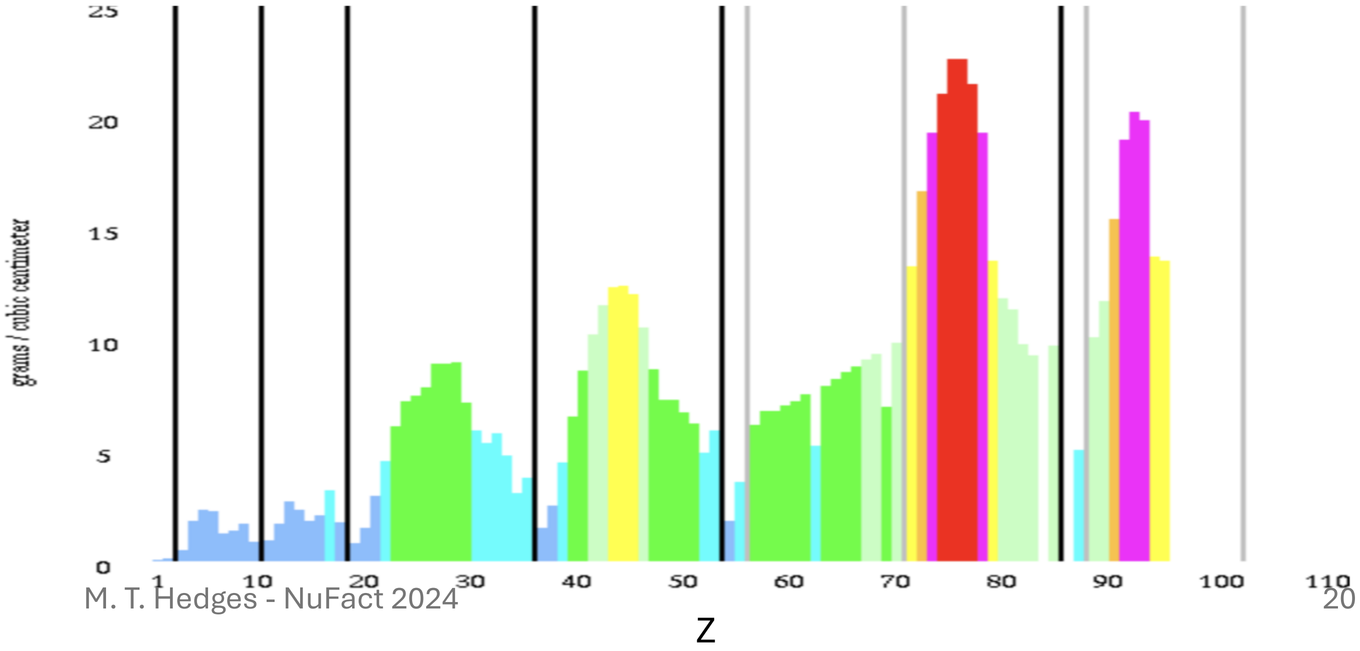


USRBIN w-cylinder 50
Peak of
~100 DPA/yr
Proton beam
x [cm]
z [cm]
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-5
0
5
10
15
20
25
1x10-18
1x10-19
1x10-20
1x10-21
1x10-22

BUT THE MUON YIELDS!!!!

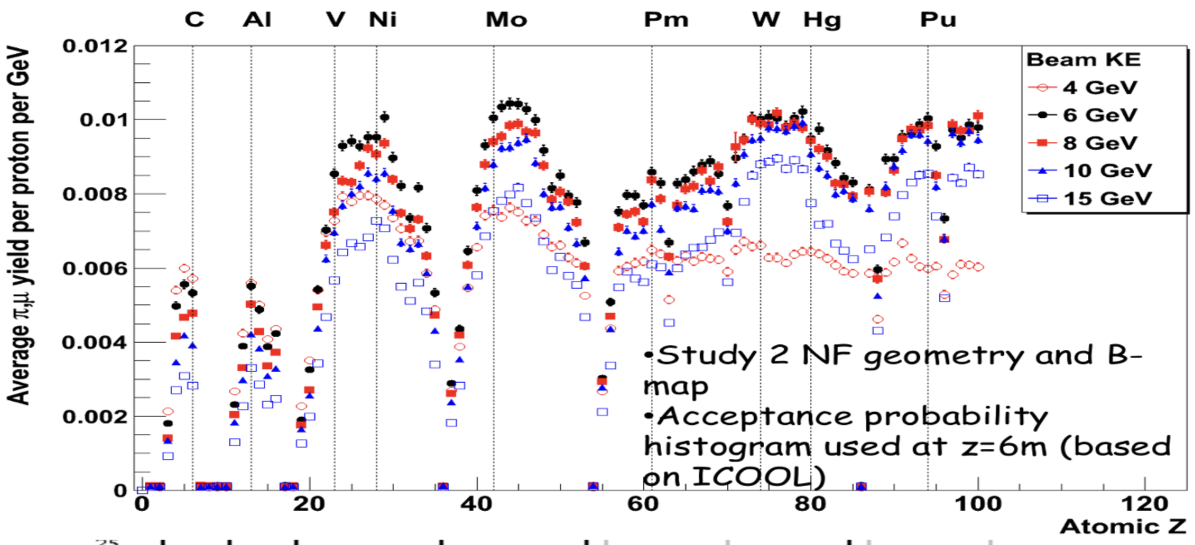
Source: IMCC meeting, talk on fluidized tungsten targets (2023) https://indico.cern.ch/event/1250075/contributions/5348859/attachments/2670245/4628813/IMCC_fluidized-tungsten-target_v1.pdf

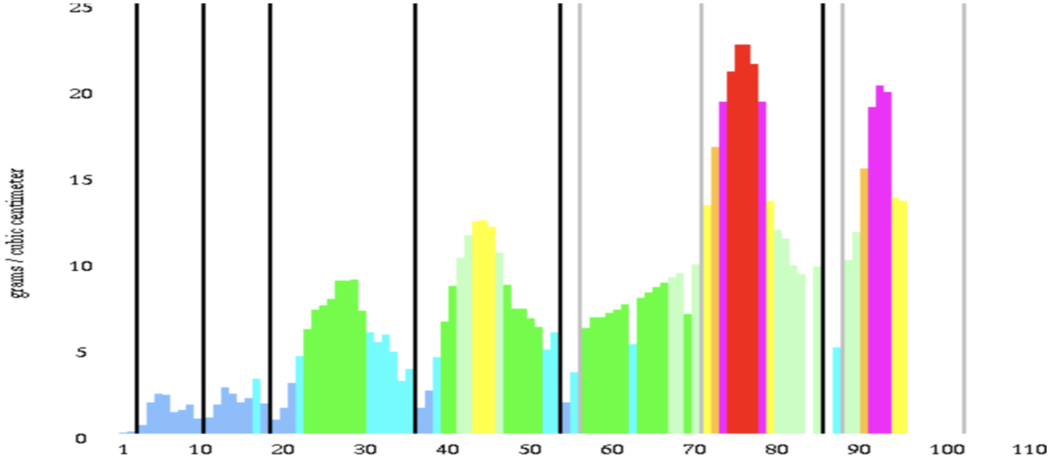


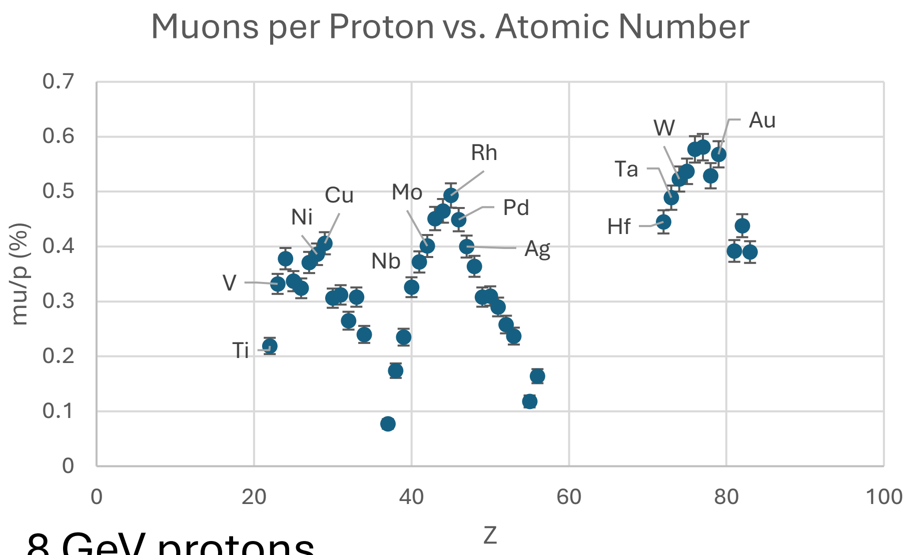


G4Beamline yield validation

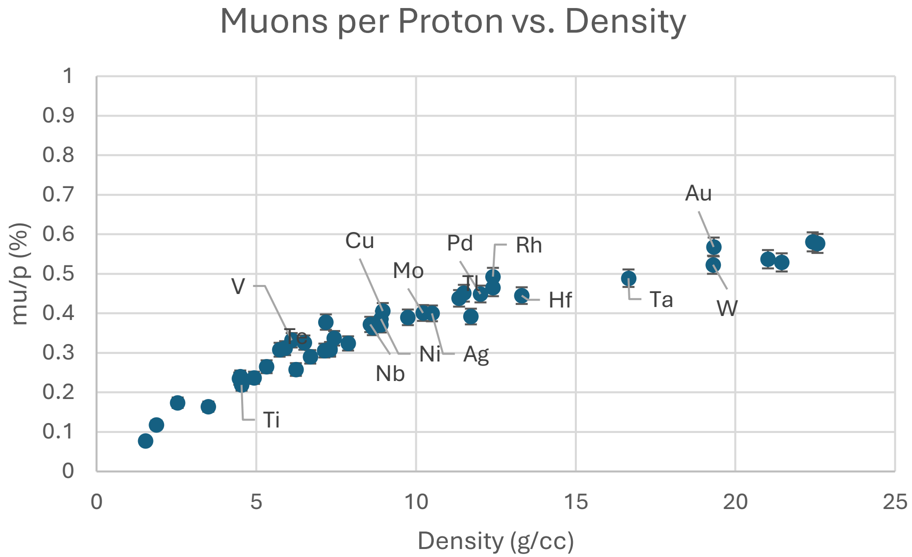
Source: Madeleine Bloomer, Emory University
FNAL Undergraduate Summer Intern (2024)







8 GeV protons



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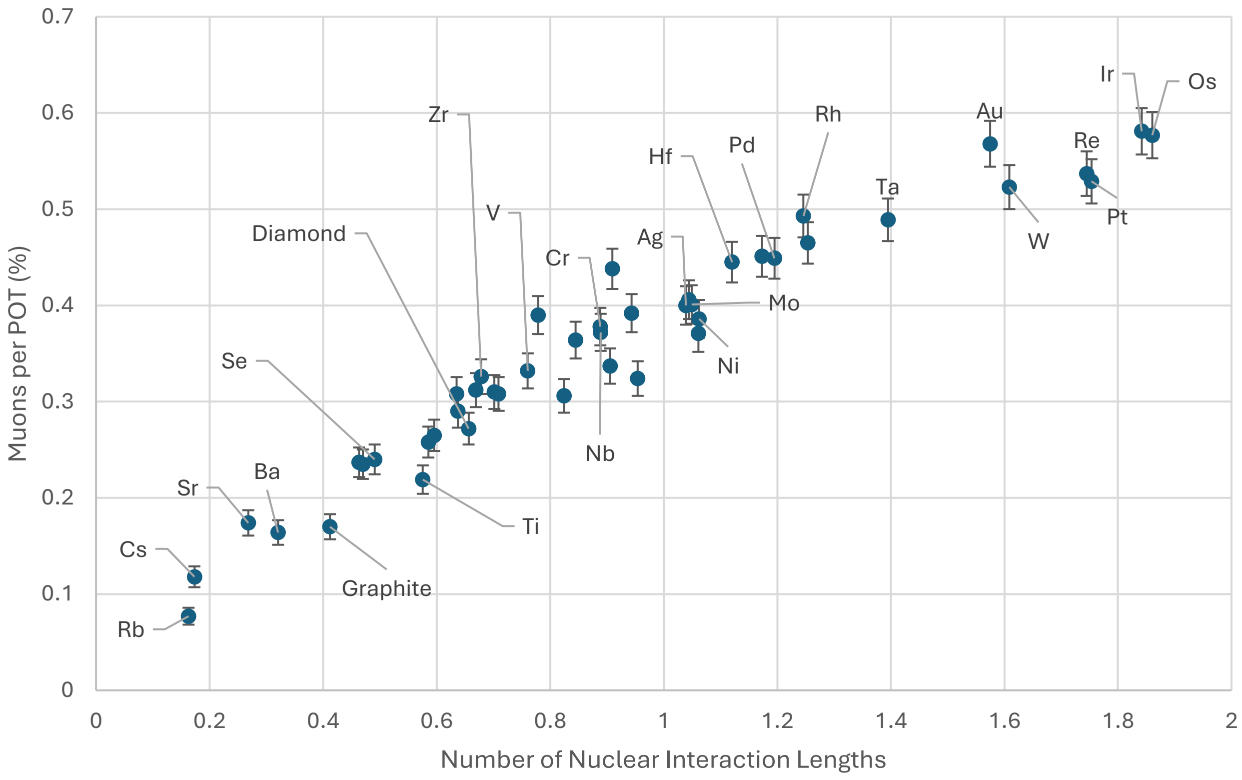
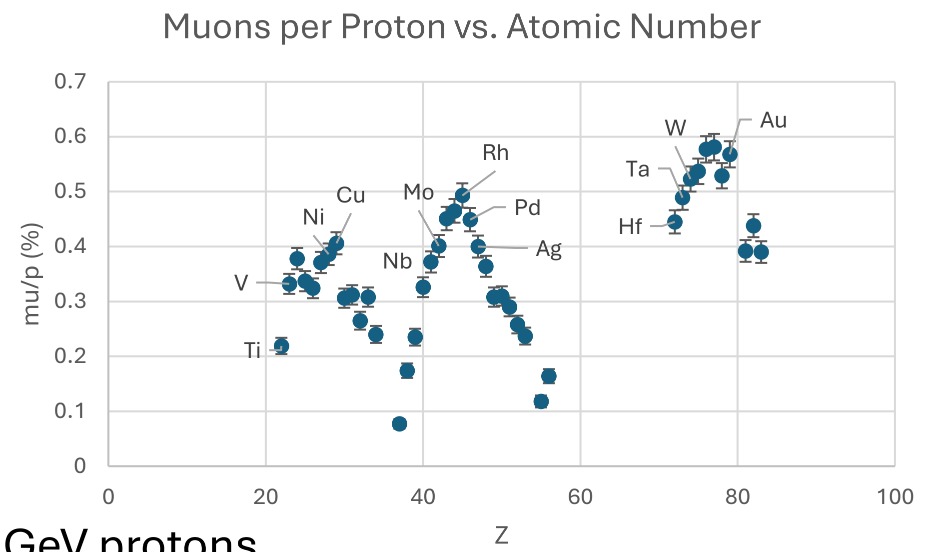
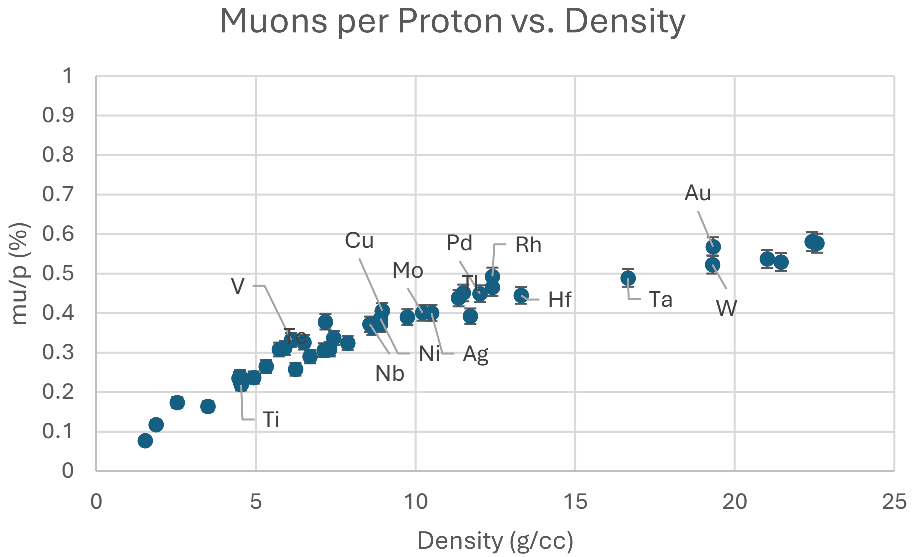




8 GeV protons



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

Takeaways

- Increasing target density worsens peak radiation damage faster than muon production increases
- Good news! Lower density targets also absorb less energy, and (usually) run less hot
- Fewer beam studies done with mid-density targets (e.g. TZM)
- Fun fact: Inconel was the material for FNAL antiproton source!

Wouldn't Inconel (Ni) melt? FNAL Pbar note 683

- Pbar group expected a small beam would cause a "molten channel" to form in the target and decrease antiproton yield

While the Nickel target was in use, the proton beam intensity at times reached 5.0E12 protons per pulse with a RMS beam size of σ_{xy} = 0.15, 0.16. The beam models, as represented by figure 1, would estimate a peak energy deposition of 1,500 joules/gram. This should be above the melting point of nickel and should have led to antiproton yield reduction towards the end of the beam pulse. This would be consistent with the lack of yield improvement at the smallest spot sizes, previously mentioned. Unfortunately, beam measurements have not shown this effect.

https://lss.fnal.gov/archive_notes/pbarnote/fermilab-pbar-note-683.pdf

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Can we utilize this further with two-phase (molten core) targets??

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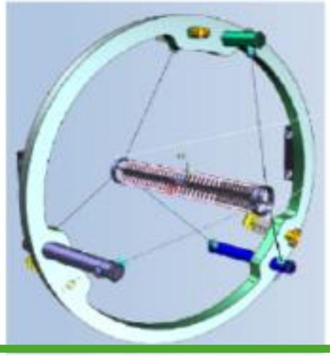
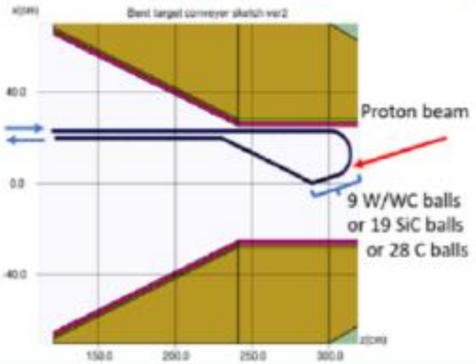
Mu2e
Tungsten, 6.3 mm x 220 mm
8 kW beam in 4.5 T

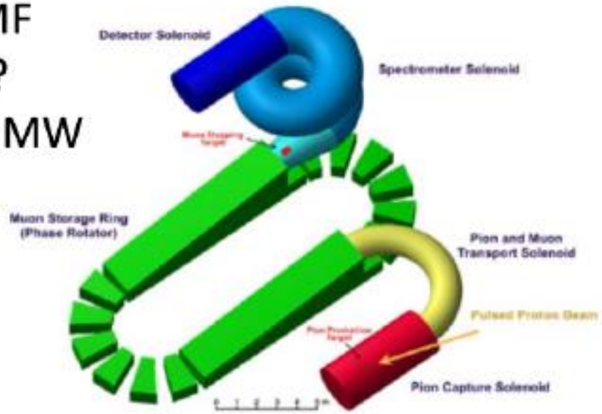


First demonstrator!

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



AMF
???
~1 MW

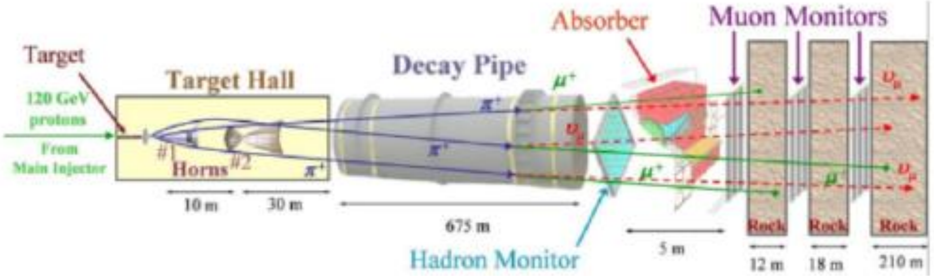


Compact, high-power targets and accompanying beam-intercept devices inside extraction solenoid

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

Short → Near → Long

NuMI



LBNF