Muon production at Mu2e

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Fermilab

International Muon Collider Collaboration: Demonstrator Workshop

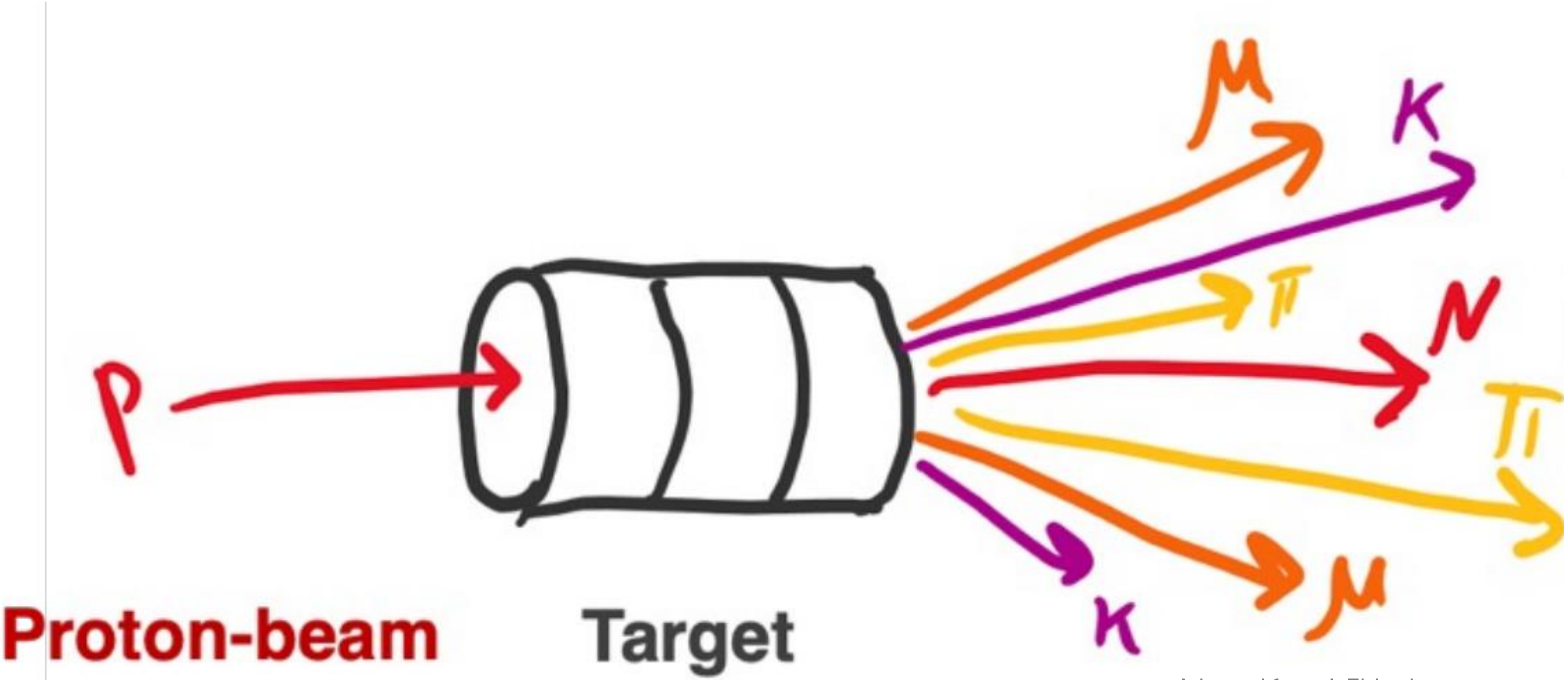
Thanks!

- Thank you to organizers for the talk invitation!
- Not a muon collider (or cooling) expert, but absolutely an enthusiast!
- Last Mu2e talk at MuCol workshop was 10 min, now 20 min!

Outline

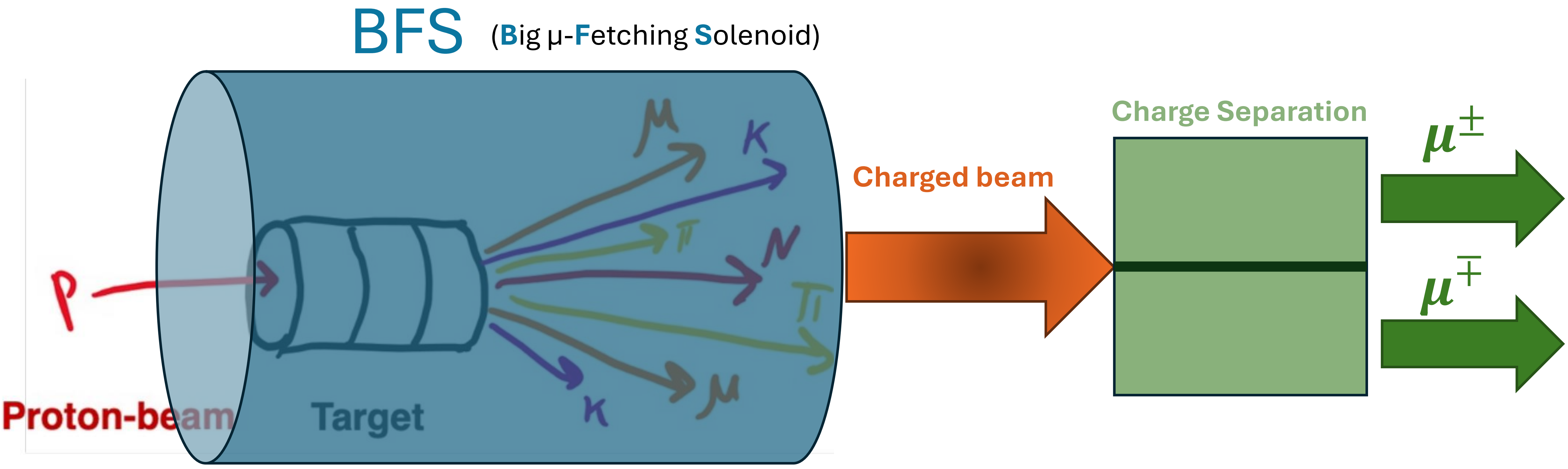
- Muon production basics
- Mu2e physics: Charged Lepton Flavor Violation
- Muon production at Mu2e
- Looking ahead to MuCol

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)

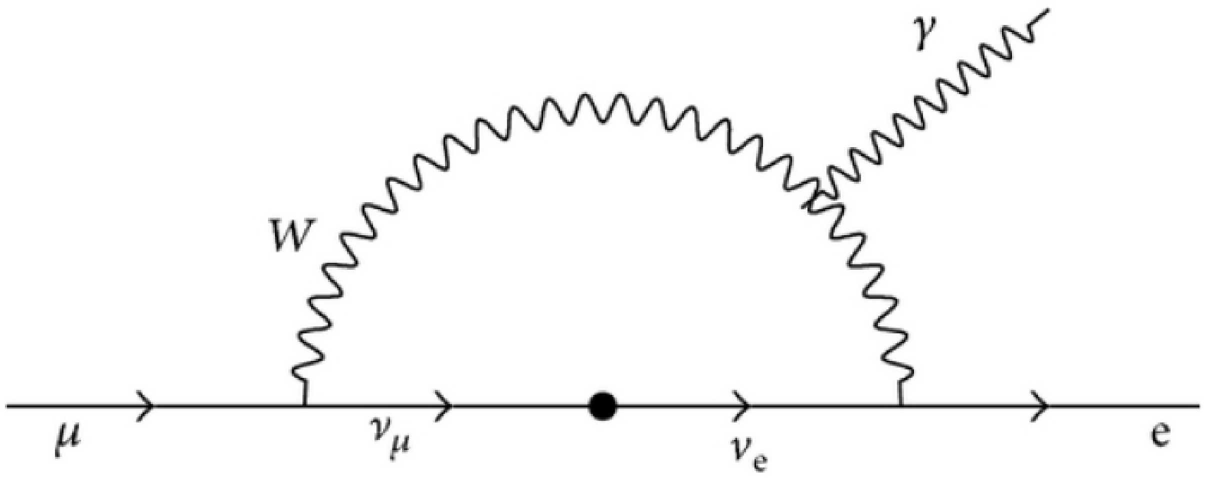
Compact

Charged Lepton Flavor Violation

Charged leptons are only fermions without observation of flavor violation

- Quarks mix (CKM)
- Neutrinos oscillate

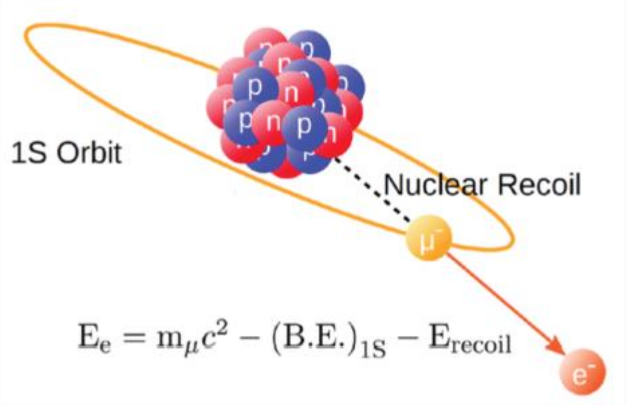
CLFV is required in νSM, but ludicrously suppressed



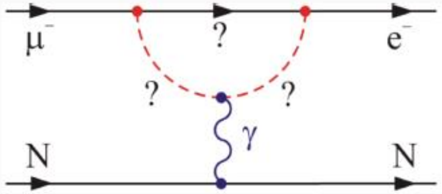
$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{k=2,3} U^*_{\mu k} U_{ek} \left(\frac{\Delta m^2_{1k}}{M^2_W}\right)^2 \right|^2 < 10^{-54}$$

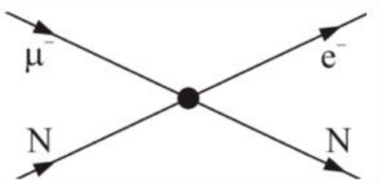
Any experimental observation would unambiguously indicate New Physics

CLFV: muon-to-electron conversion

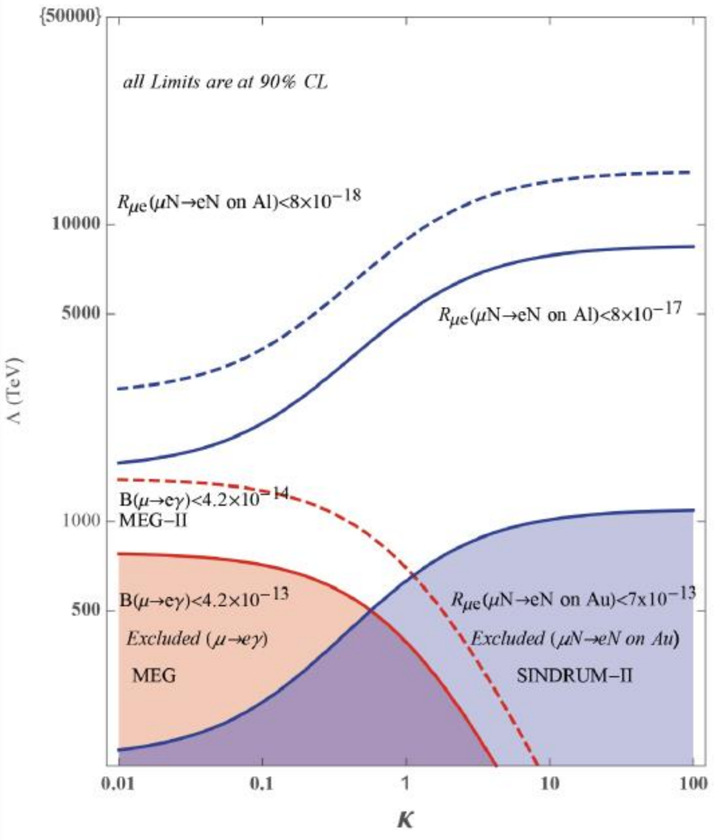


- Monoenergetic ~105 MeV/c conversion-electron (CE)
- Sensitive to Λ-scales $\mathcal{O}(10^3)$ TeV





Adapted from A. de Gouvea and P. Vogel,
Progress in Particle and Nuclear Physics 71, 75–92 (2013)



$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

Challenge 1: μ^- from FNAL Protons

High-level proton beam parameters

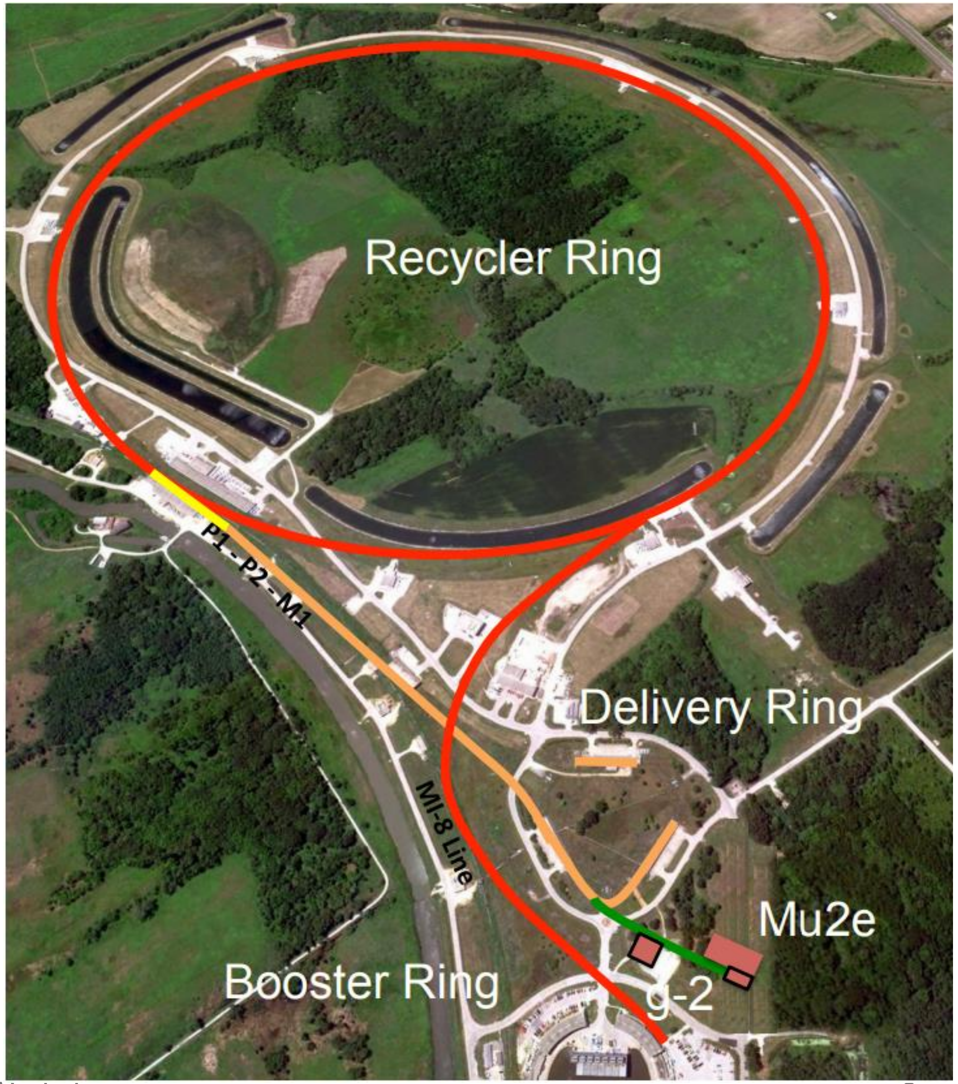
Linac: 400 MeV

Booster: 8 GeV

Recycler rebunches

Slow-extraction in Delivery Ring

Beam to Mu2e

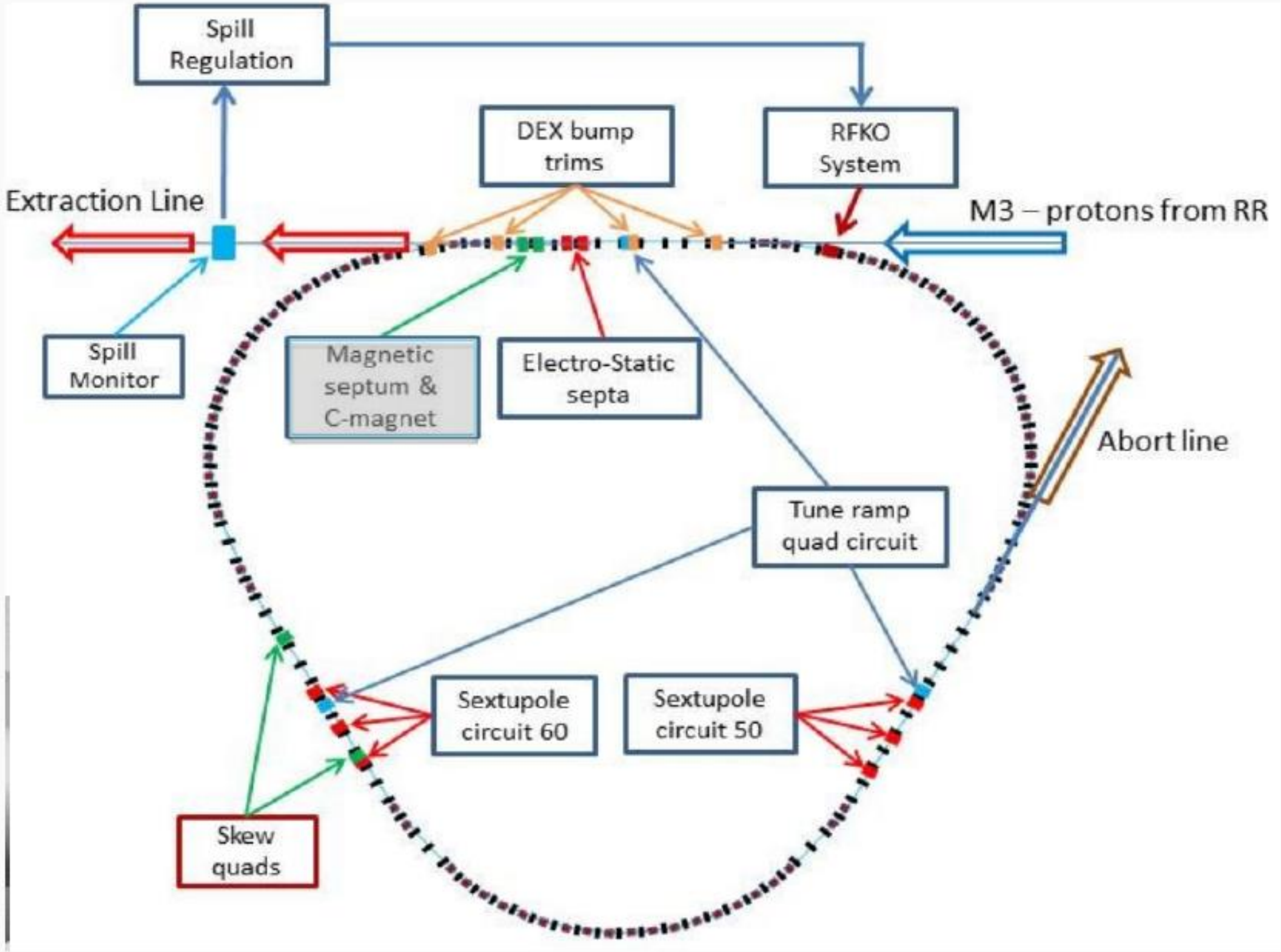


Resonant Extraction

Take-home: Inject instability, "scrape" off small piece of spill every revolution

Mu2e target will see:

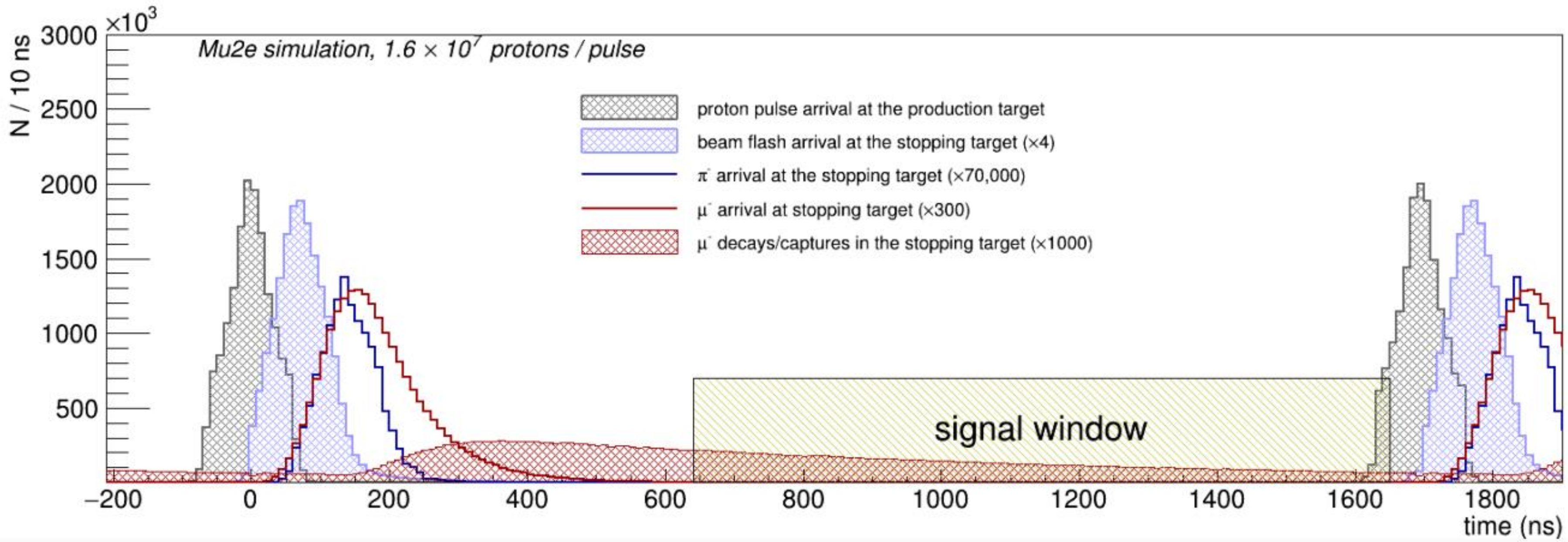
- $\sim 4 \times 10^7$ protons @ 8 GeV
- ~ 1 mm gaussian beam radius
- 250 ns pulses
- 1.7 μs pulse period
- At 2.5 MHz



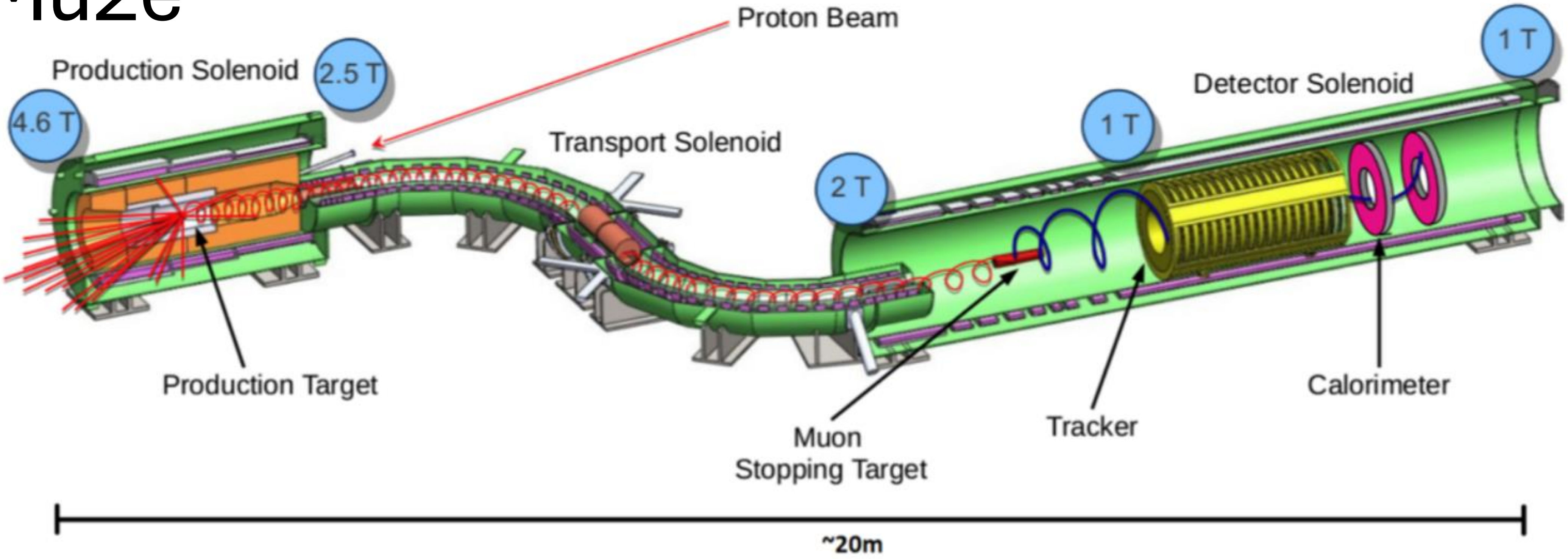
Challenge 2: Ideal Mu2e conditions

Mu2e needs:

- High yield of *stoppable* muons ⇒ low momentum μ^- beam
- Minimal beam-induced backgrounds (i.e. radiative pion capture)
- Low radiation environment



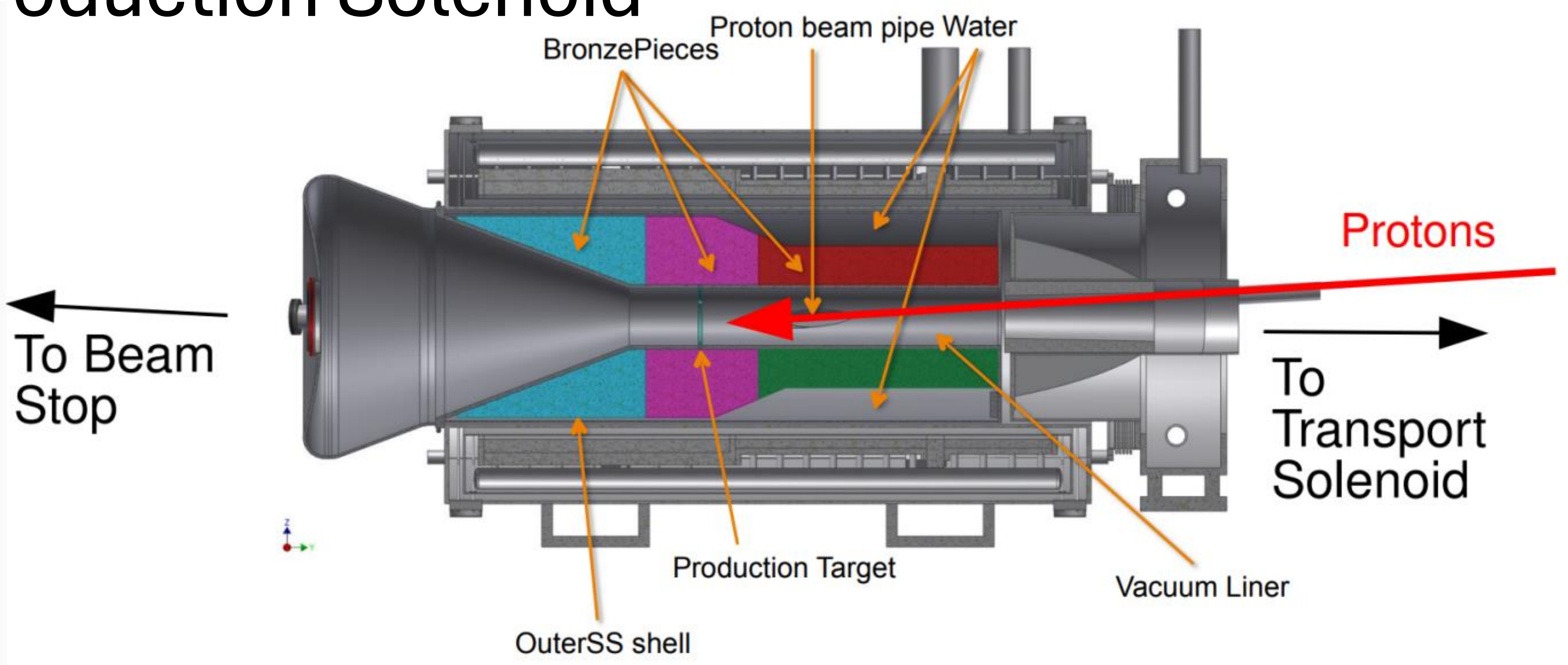
Mu2e



Discovery potential of $R_{\mu e} = \frac{\Gamma(\mu^- + N(Z,A) \to e^- + N(Z,A))}{\Gamma(\mu^- + N(Z,A) \to \nu_\mu + N(Z-1,A))} > 2 \times 10^{-16}$ (5σ)

- $R_{\mu e} < 8 \times 10^{-17}$ (90% CL)
- $\mathcal{O}(10^4)$ improvement of previous result (SINDRUM-II)

Production Solenoid



Compact, high-Z pion-production target in high B-field with backwards extraction

Production Target

LaO_2-doped Tungsten, core EDMed from single rod

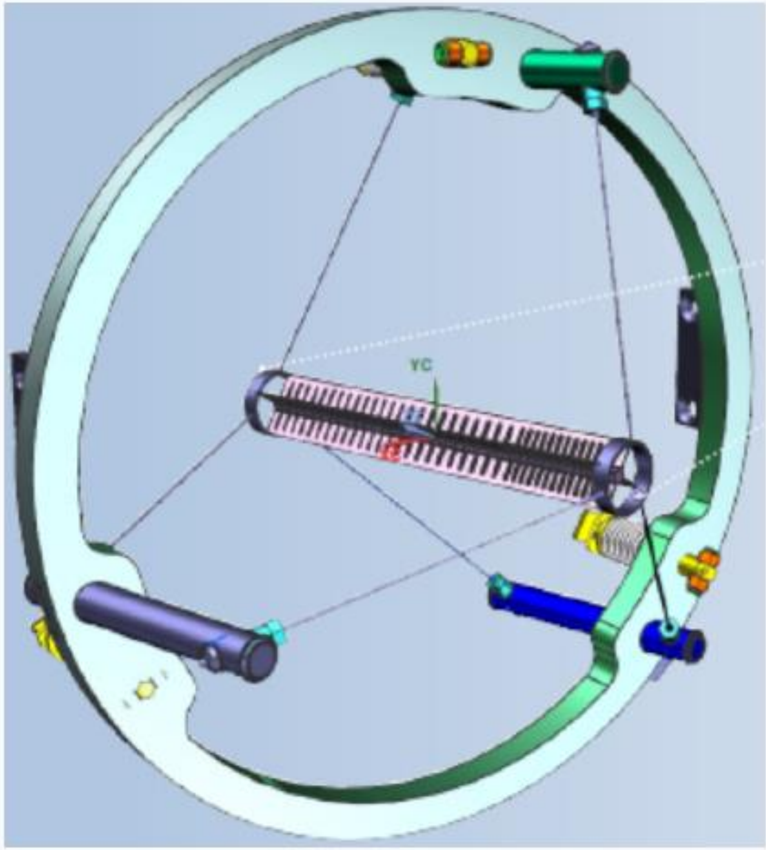
Longitudinally segmented cylinder
⇒ stress management

Longitudinal fins
⇒ thermal and structural management

1mm tungsten spokes

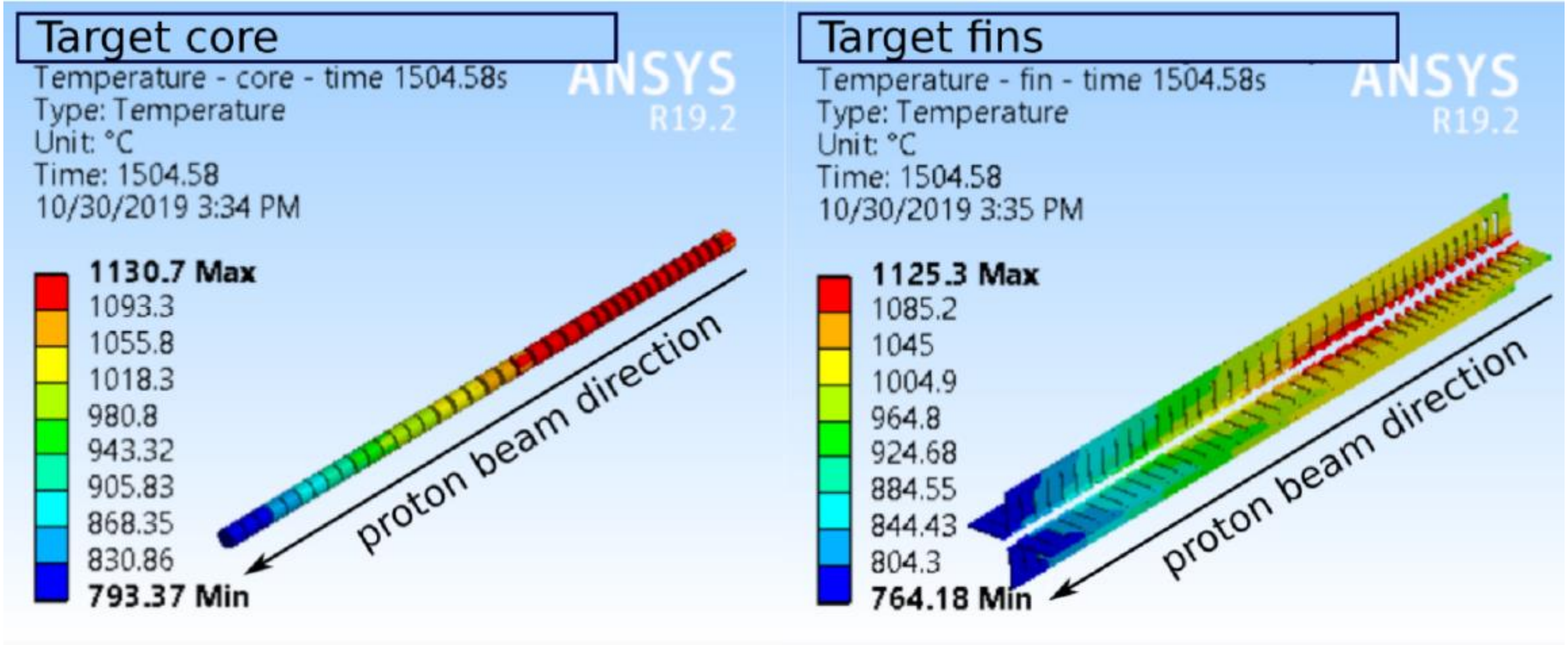
~700 W power absorbtion ⇒ ~1500 K

- Radiatively cooled



Expect target lifetime of ~1 year: ⇒ replace during summer shutdowns


Simulation Driven Design



Segmentation helps mitigate thermal shock problems
Fins and LaO help mitigate creep and temp problems

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

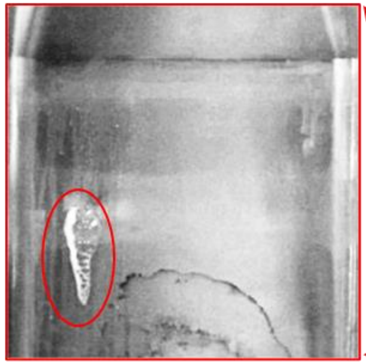
Early target failures: limited beam power

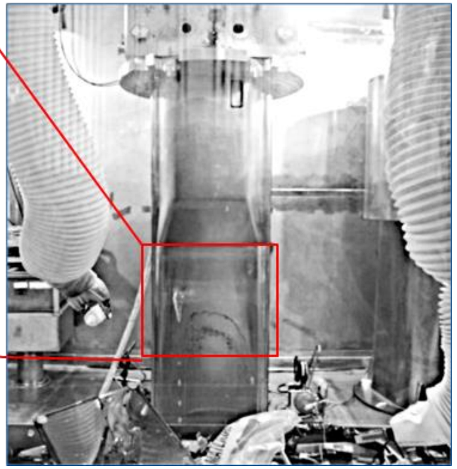
Figs adapted from F. Pellemoine

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

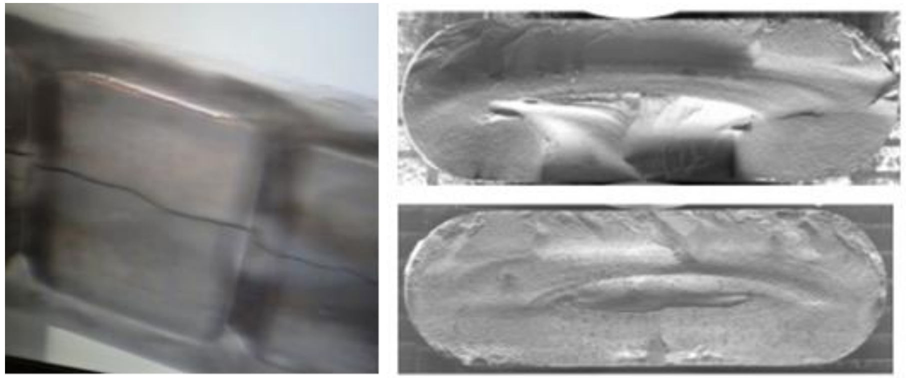
~~**Compact**~~

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



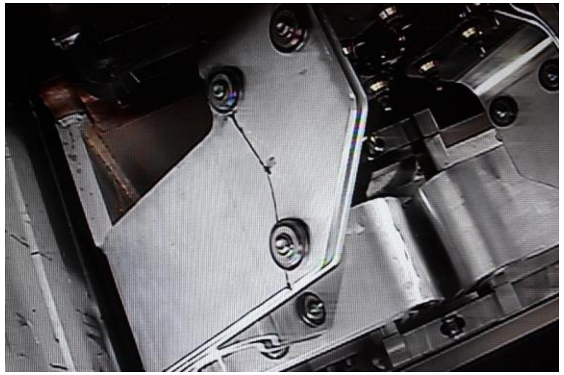


SNS target vessel (ORNL)



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

MINOS NT-01 target containment water leak (FNAL)



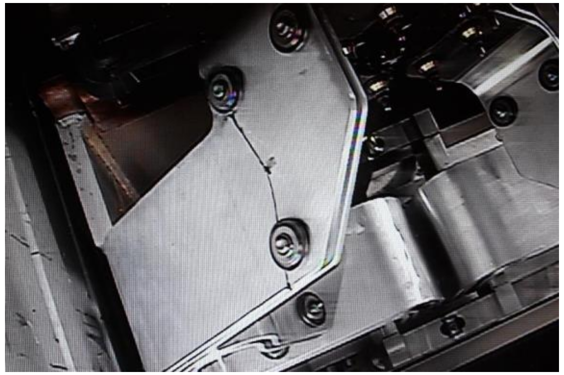
Horn stripline fatigue failure (FNAL)

How do targets fail?

Thermal effects

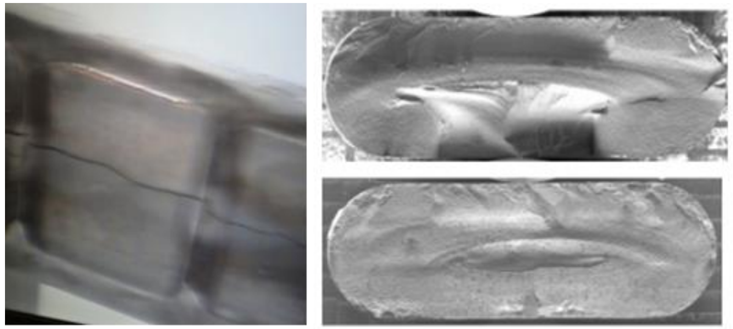
Small iridium rod at CERN HiRadMat

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

Radiation Damage

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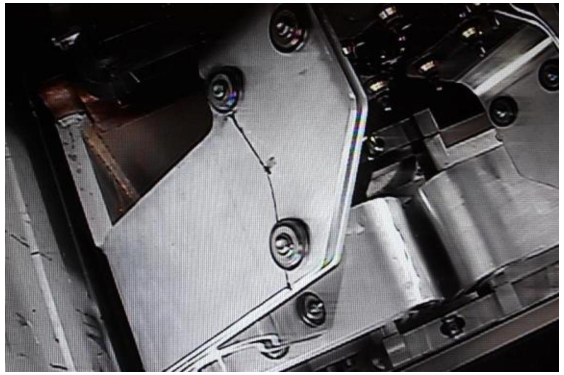

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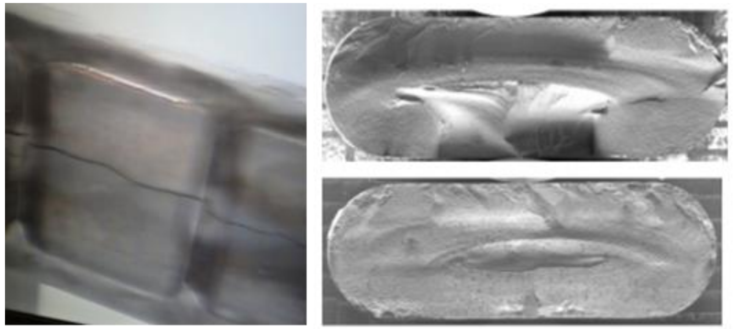
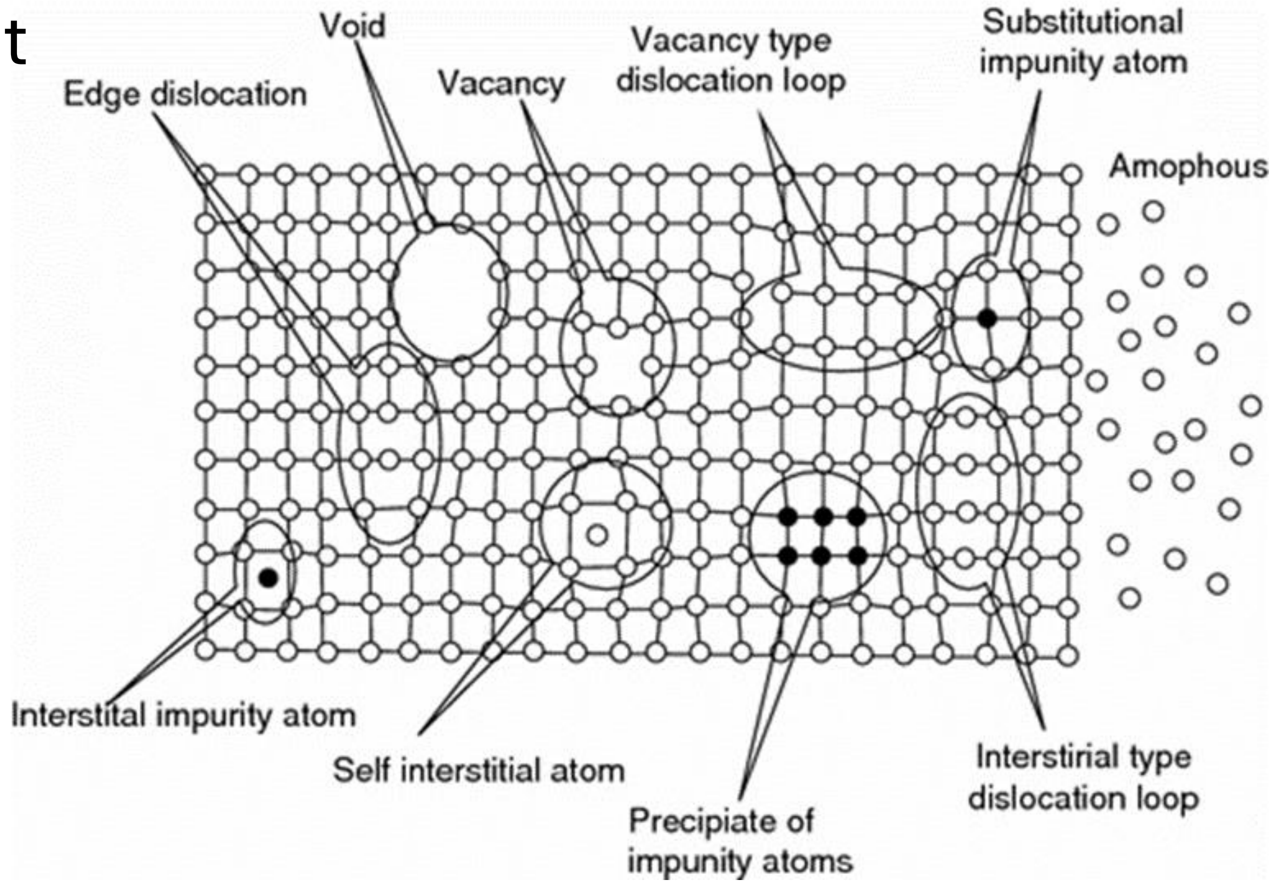


MINOS NT-02 target failure: radiation-induced swelling (FNAL)

Radiation Damage (Non-ionizing)

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



Worse for smaller targets!

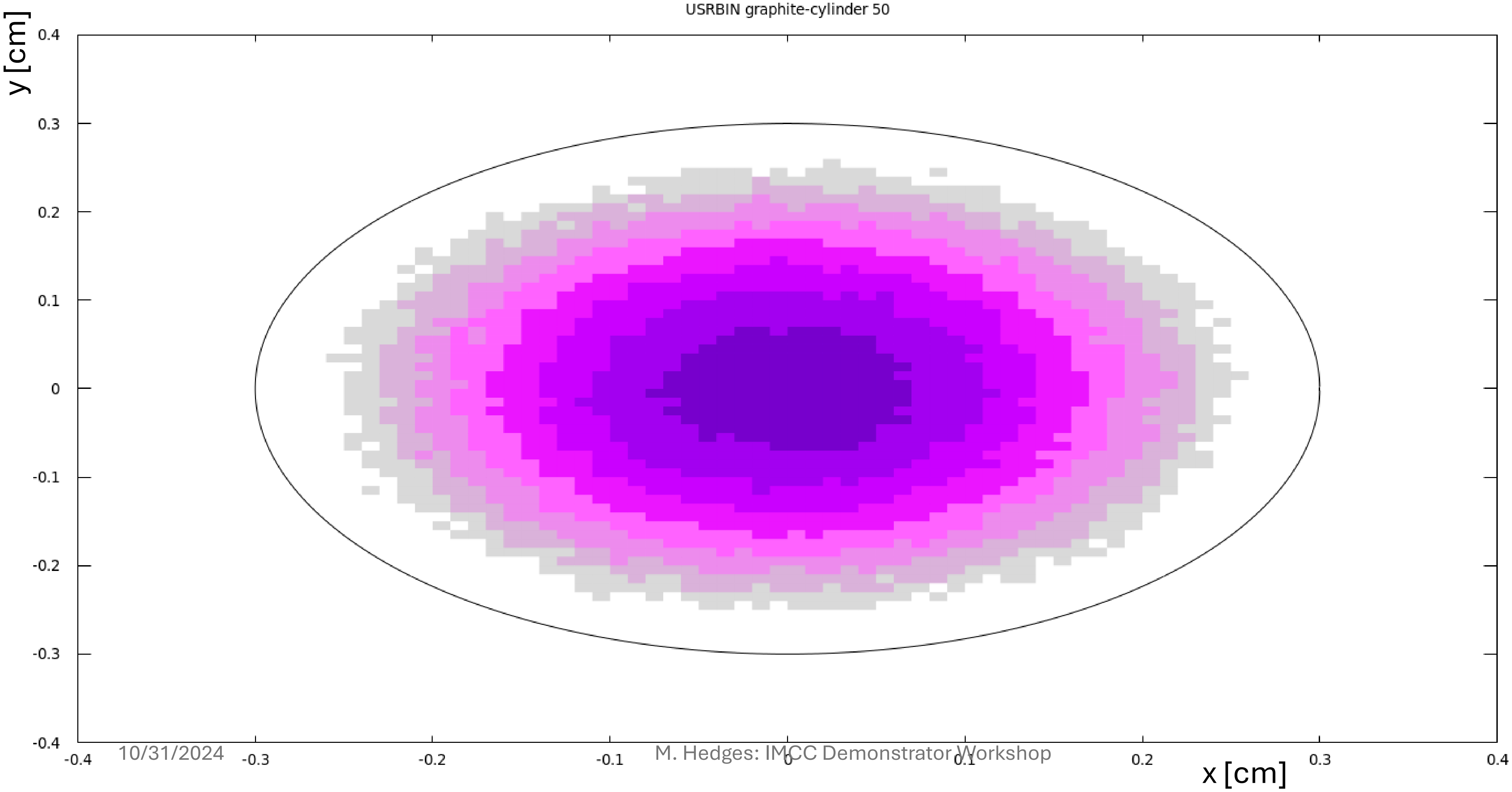
Simulate Radiation Damage (FLUKA)

- 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 (at Mu2e)?
  - 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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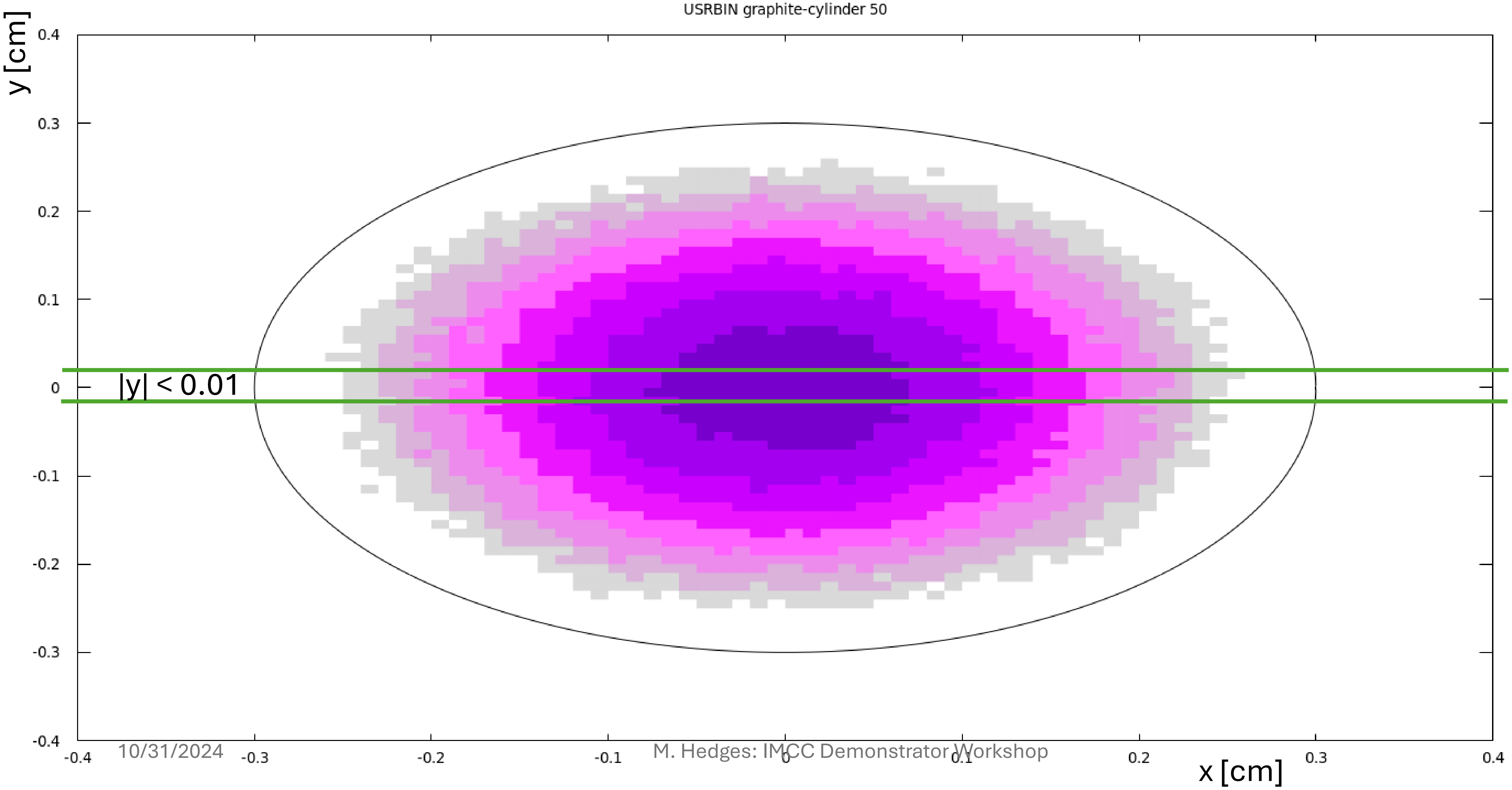
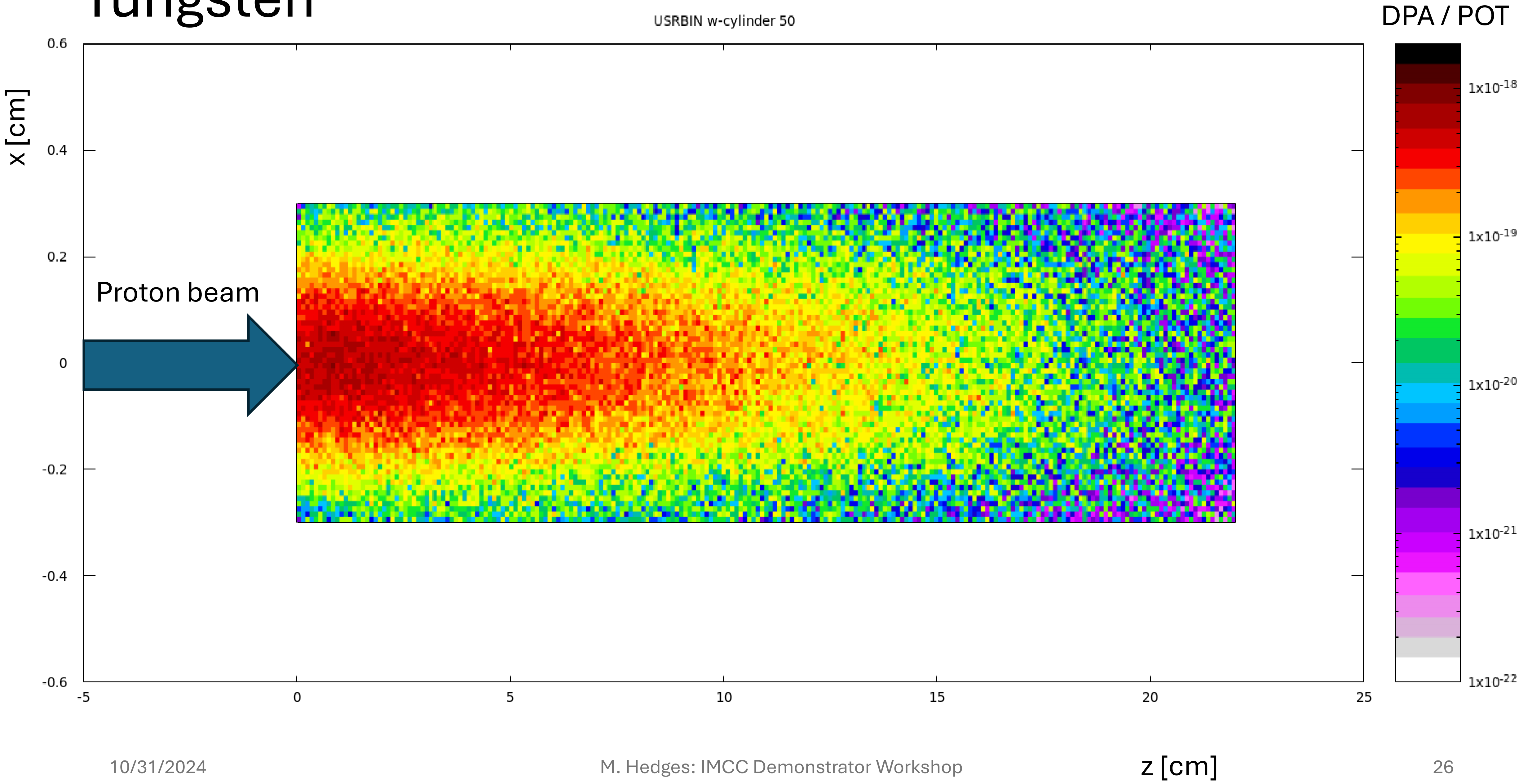
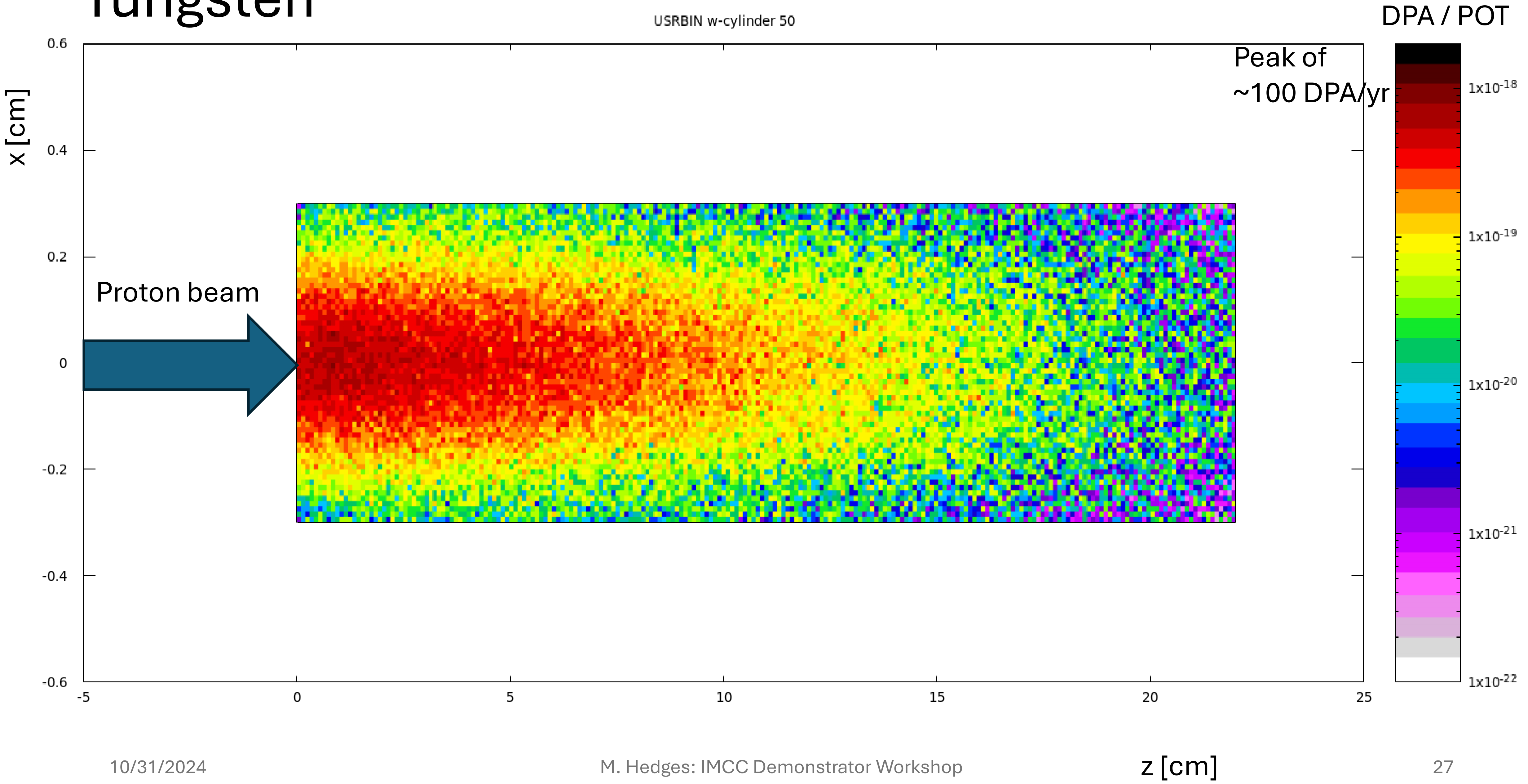


Tungsten

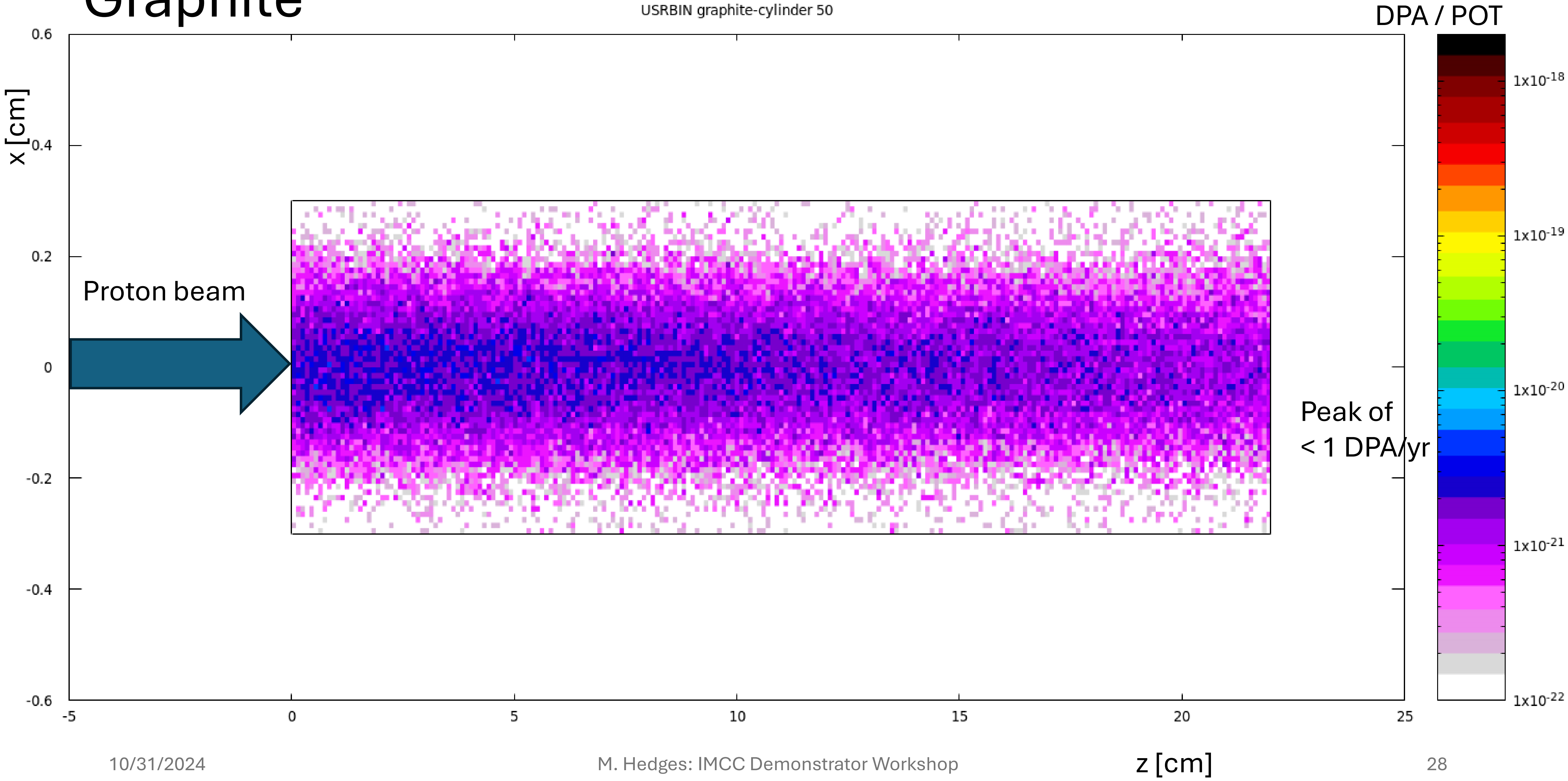


USRBIN w-cylinder 50
DPA / POT
x [cm]
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-5
0
5
10
15
20
25
Proton beam
1x10-18
1x10-19
1x10-20
1x10-21
1x10-22
z [cm]

Tungsten


USRBIN w-cylinder 50
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

Graphite



USRBIN graphite-cylinder 50
DPA / POT
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
Proton beam
Peak of
< 1 DPA/yr

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

- Cooling is a major challenge, *but production is too*
  - Don't be surprised if production also needs a "demonstrator"
  - Very few places where this can be carried out… (exp. with PIE in hot-cell)

All you have to do is …

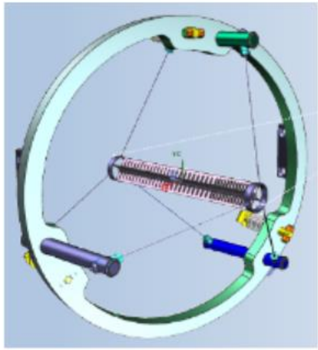
Kevin Lynch (FNAL TSD Dept. Head): NuFact 2024

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

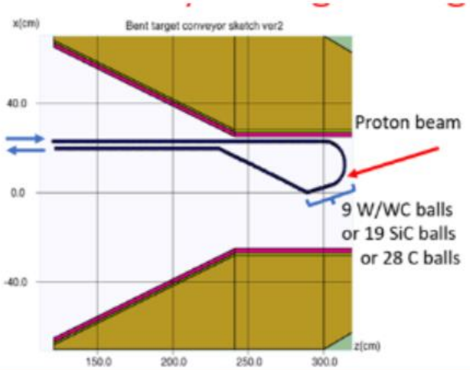
Thanks, and Happy Halloween!

Backup

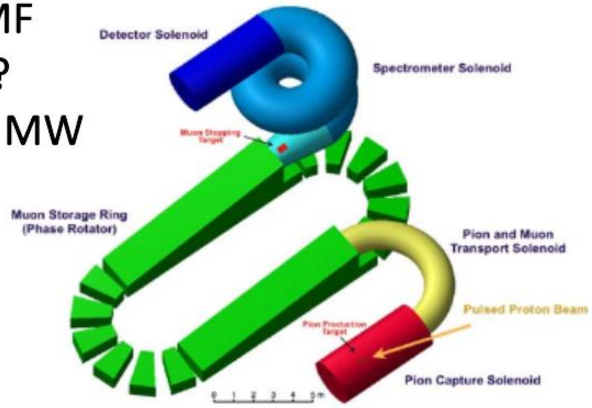
Mu2e
Tungsten, 6.3 mm x 220 mm
8 kW beam in 4.5 T



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



AMF
???
~1 MW

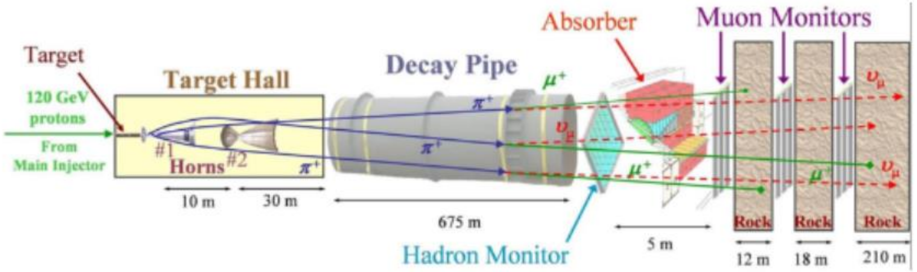


Compact, high-power targets and accompanying beam-intercept devices inside extraction solenoid

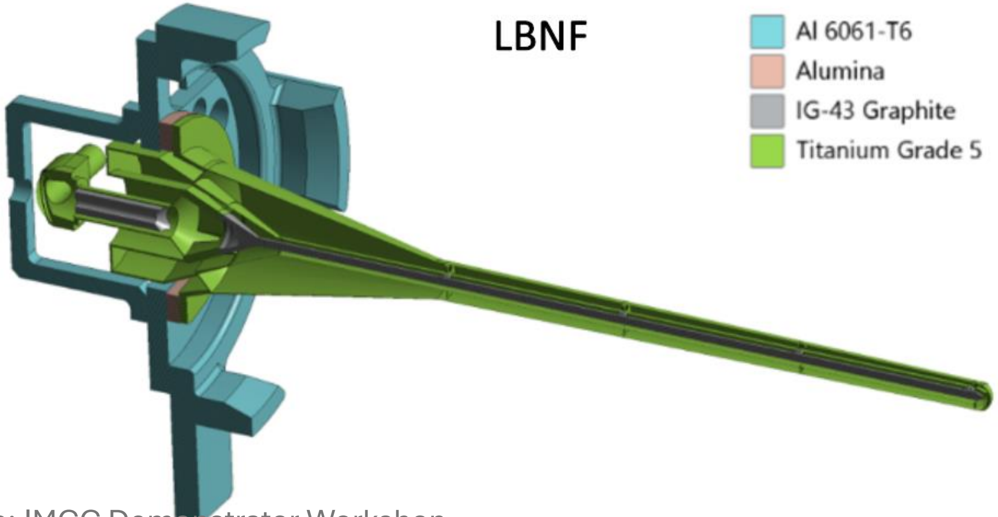
Muon collider
?????????????????????
Multi-MW in 20 T!!!

Short → Near → Long

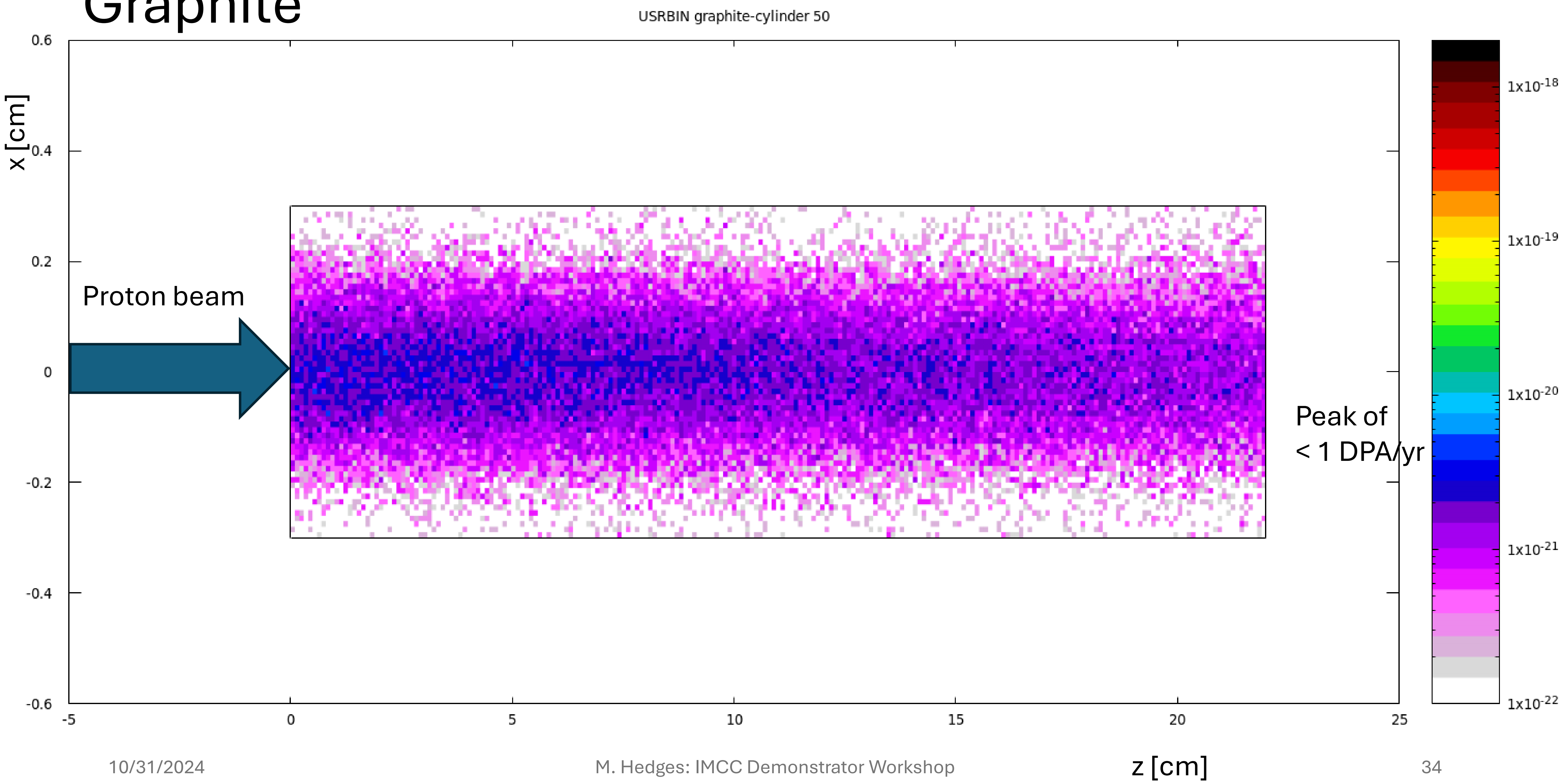
NuMI



LBNF



Graphite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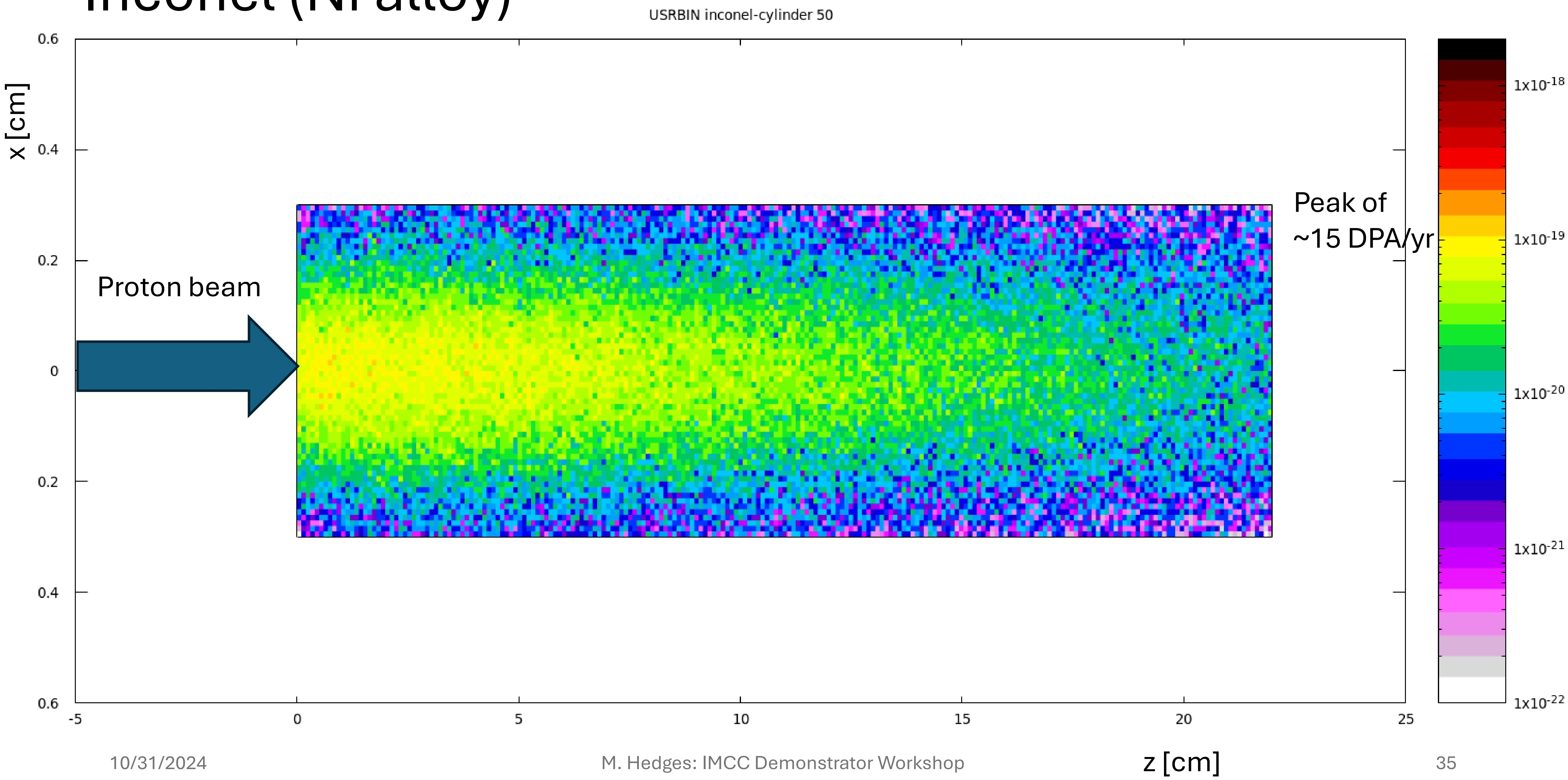
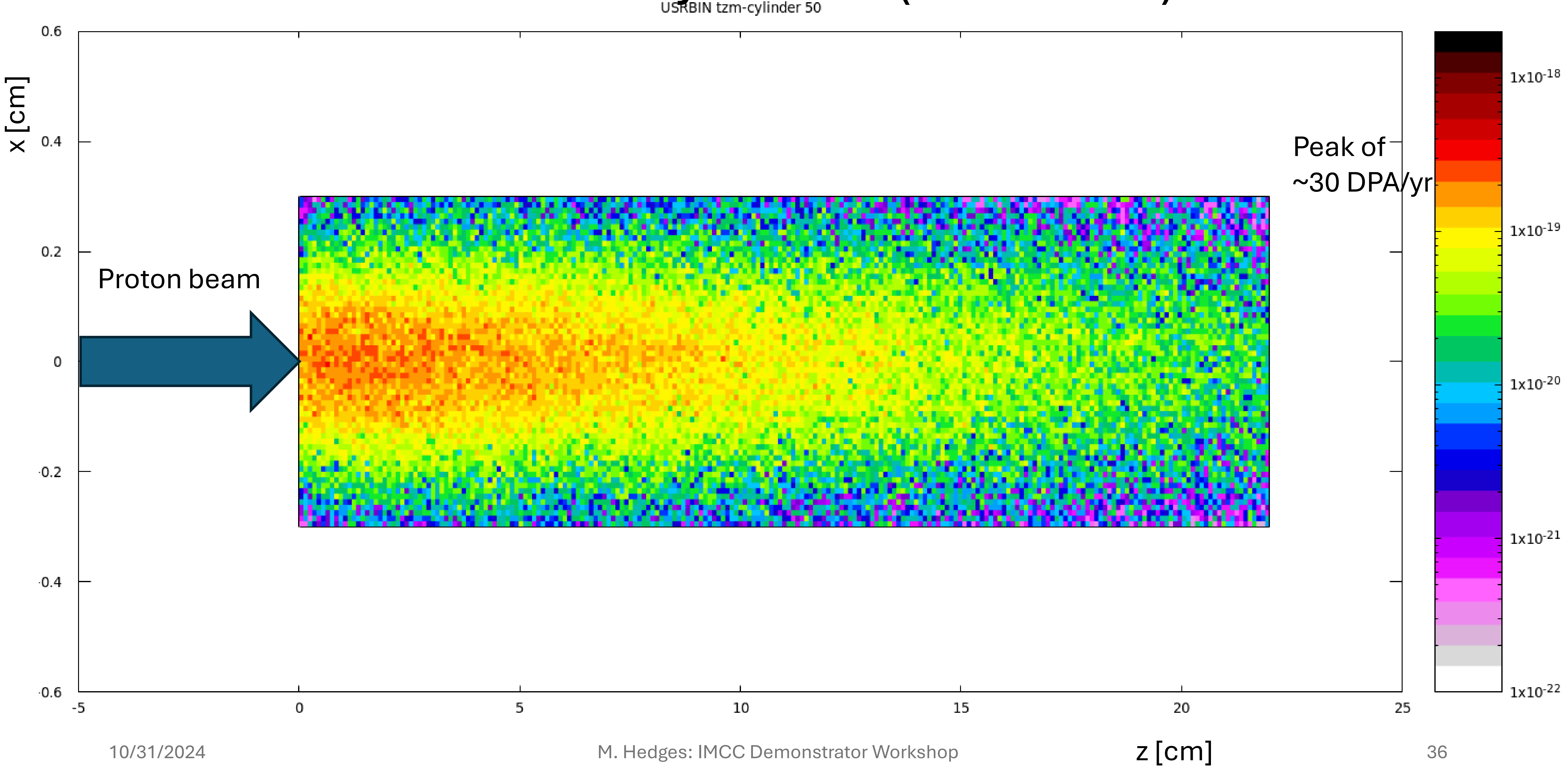
Proton beam
Peak of
< 1 DPA/yr
1x10-18
1x10-19
1x10-20
1x10-21
1x10-22
z [cm]

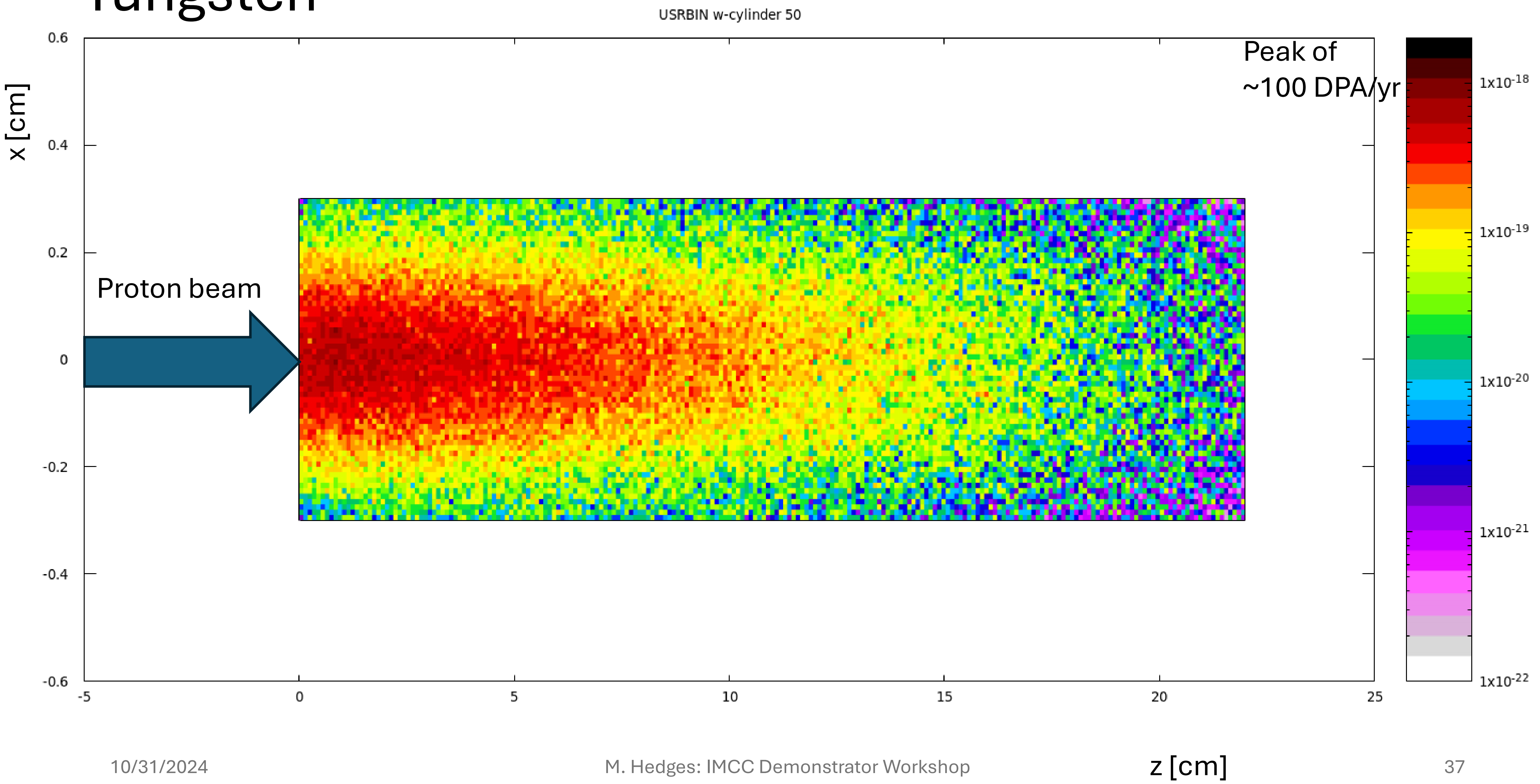
Inconel (Ni alloy)



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



Tungsten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Proton beam
Peak of
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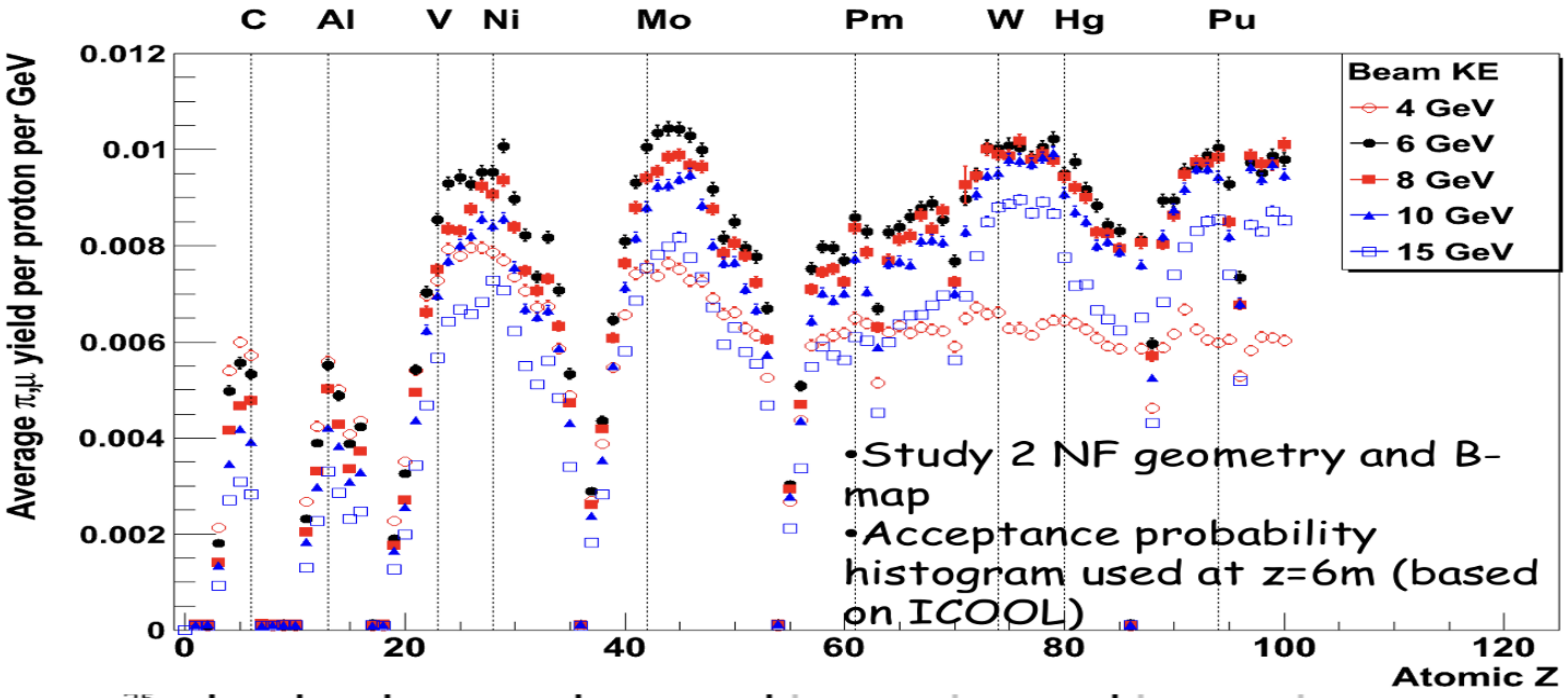
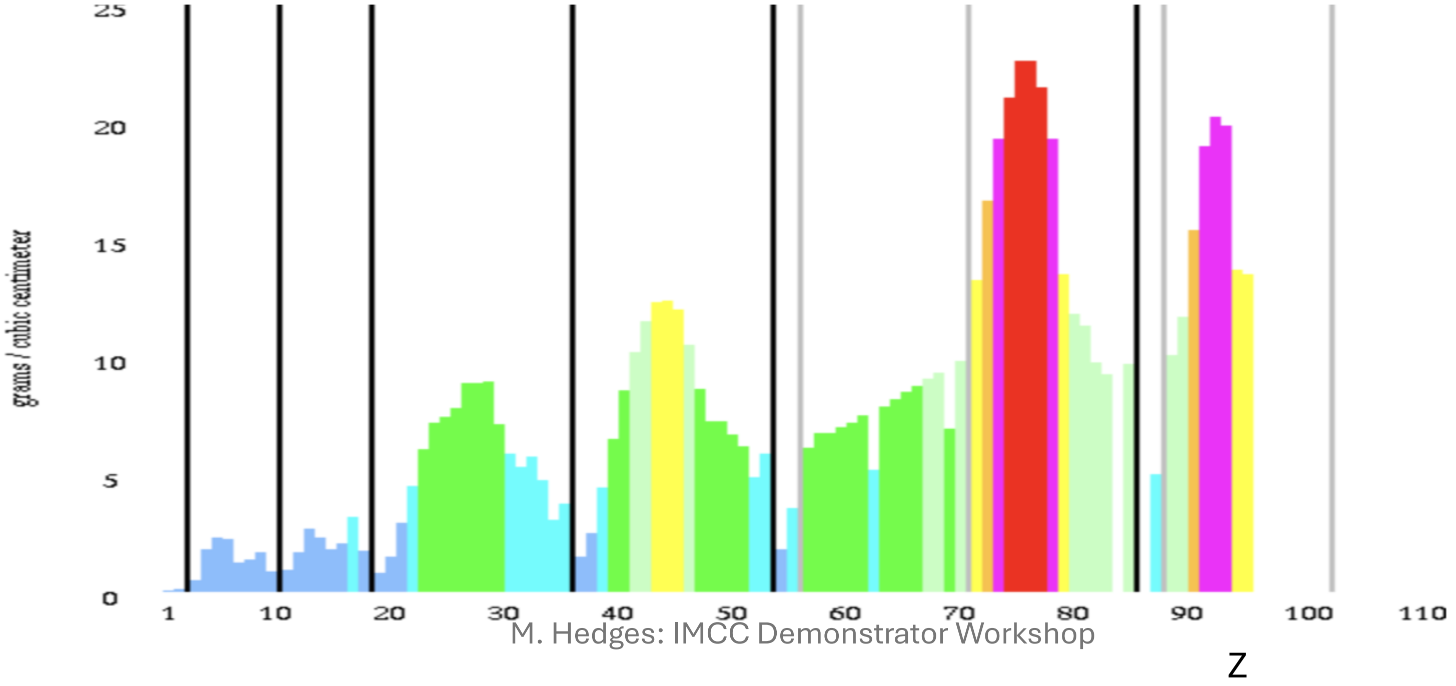
1x10-18
1x10-19
1x10-20
1x10-21
1x10-22

BUT THE MUON YIELDS!!!!

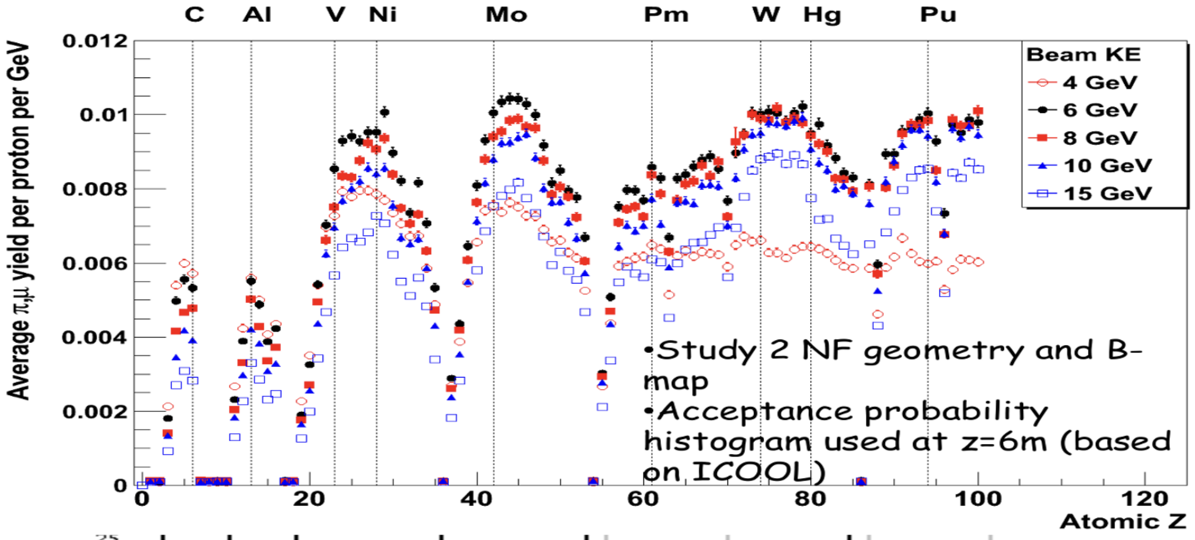


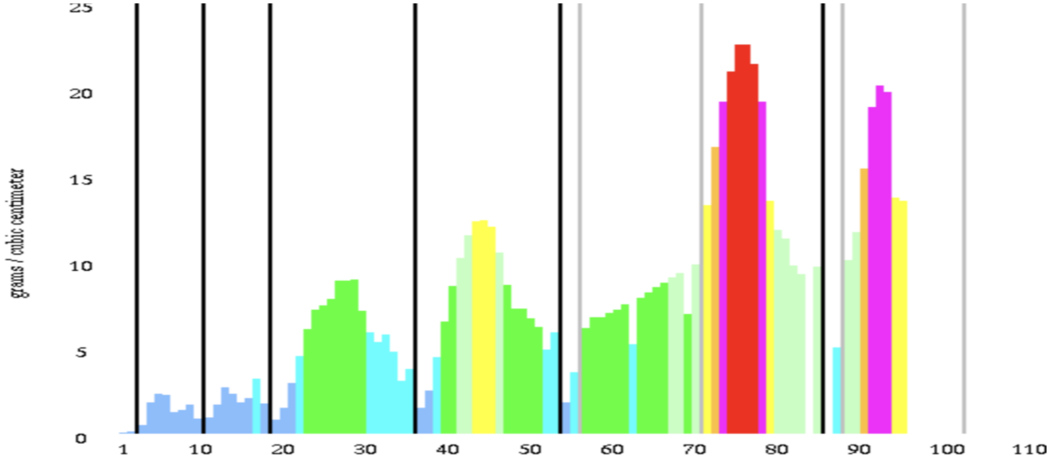


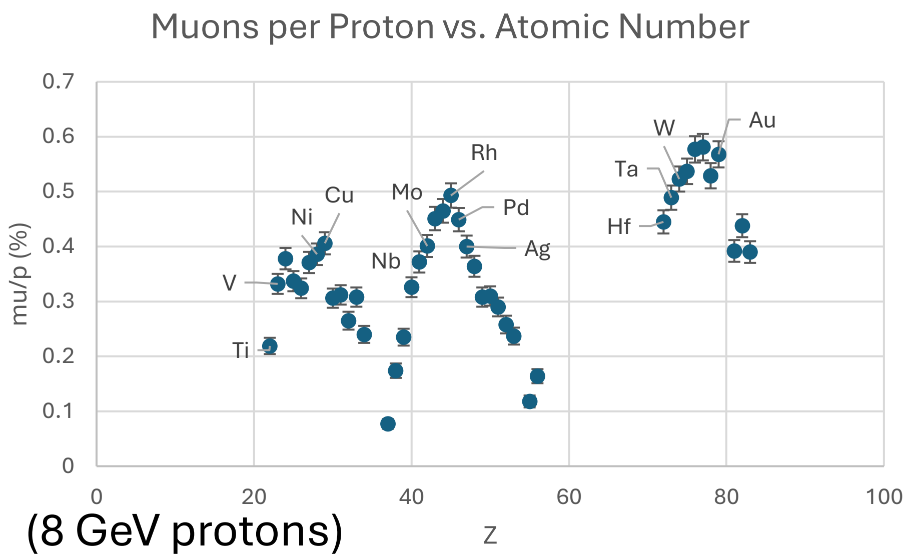
Source: IMCC meeting, talk on fluidized tungsten targets (2023)
https://indico.cern.ch/event/1250075/contributions/5348859/attachments/2670245/4628813/IMCC_fluidized-tungsten-target_v1.pdf

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

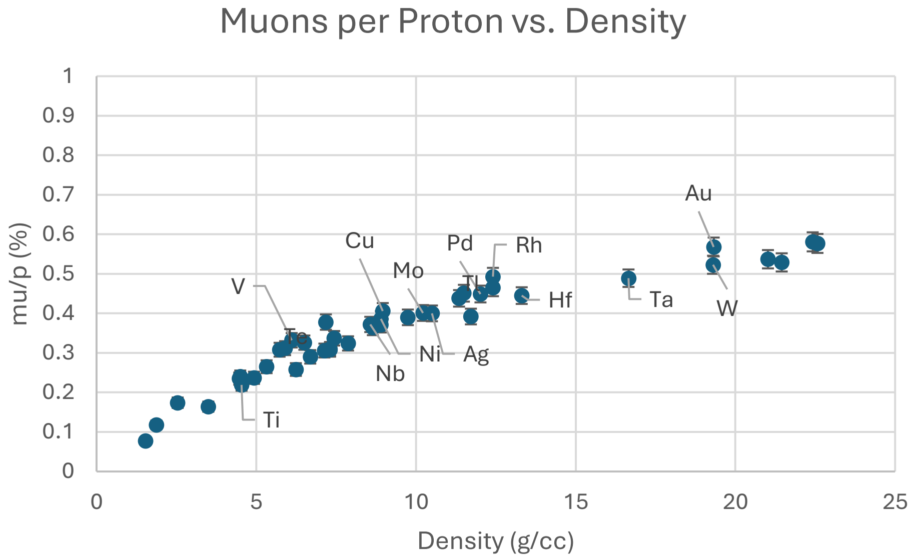
G4Beamline yield validation







(8 GeV protons)



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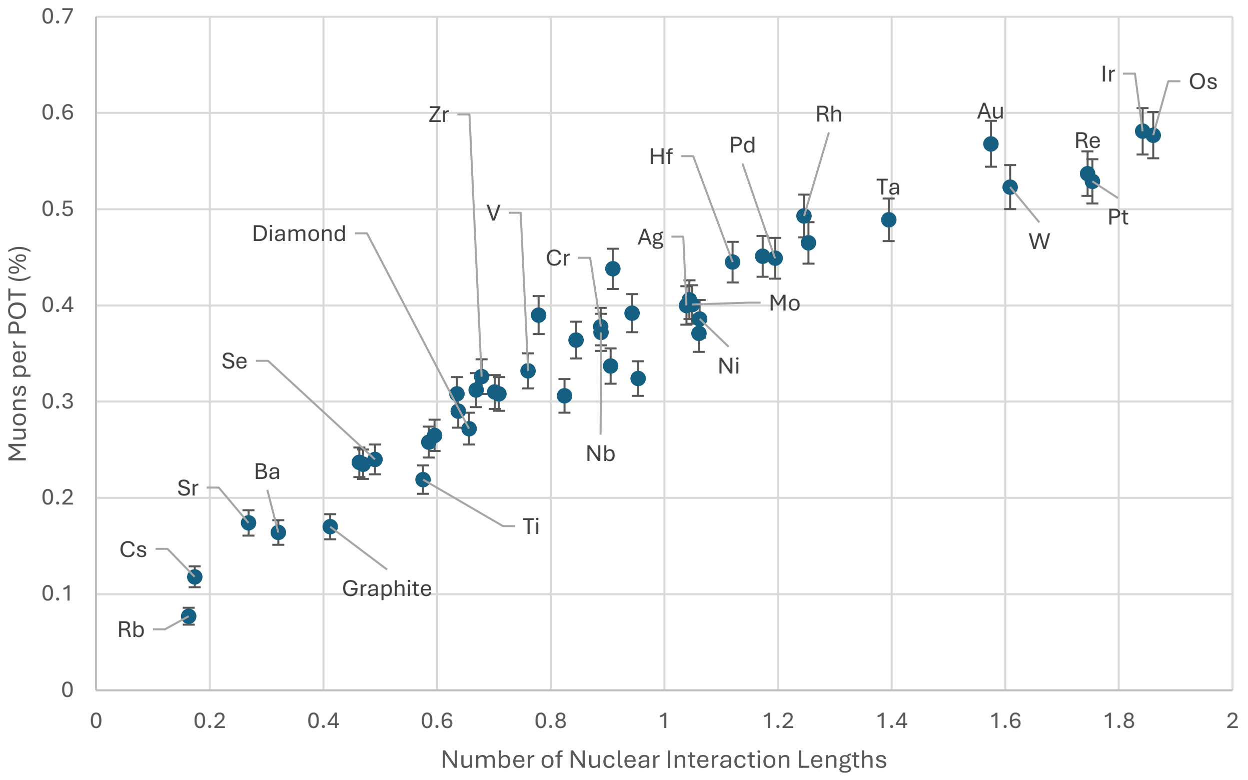
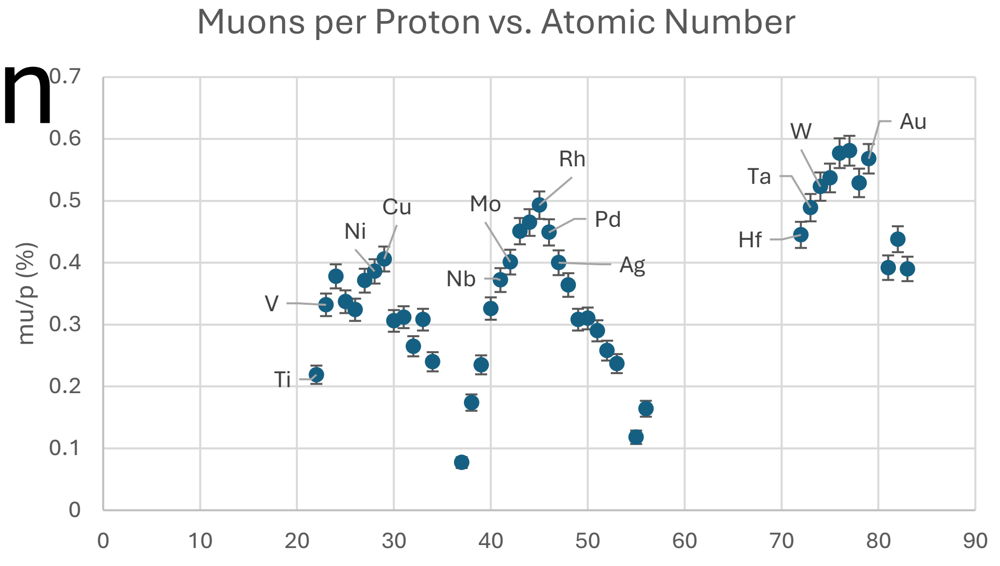
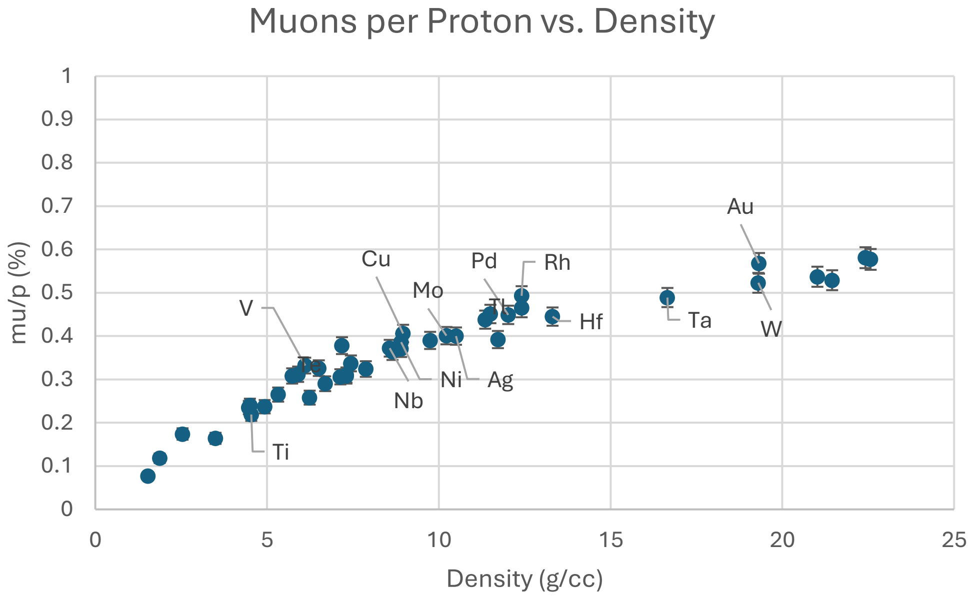


https://pdg.lbl.gov/2024/AtomicNuclearProperties/



8 GeV protons



Takeaways

- Mu2e will probably be the last attempt of a solid, fixed, radiatively cooled target (high-Z or otherwise) for muon production
- 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 Tevatron 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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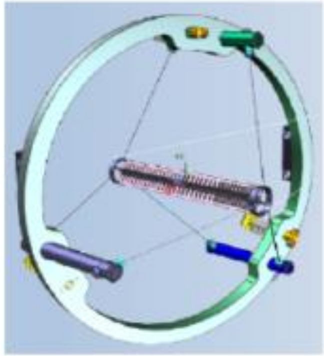
- Pbar group expected a small beam would cause a "molten channel" to form in the target and decrease antiproton yield

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

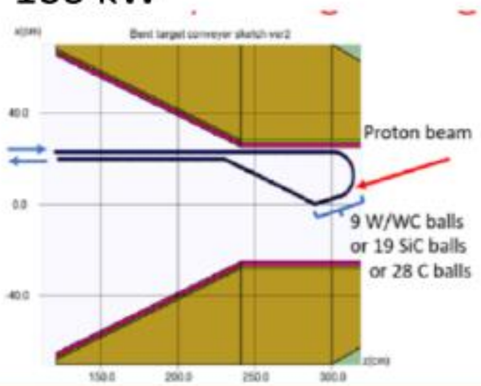
While the Nickel target was in use, the proton beam intensity at times reached 5.0E12 protons per pulse with a RMS beam size of σ_{xy} = 0.15, 0.16. The beam models, as represented by figure 1, would estimate a peak energy deposition of 1,500 joules/gram. This should be above the melting point of nickel 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

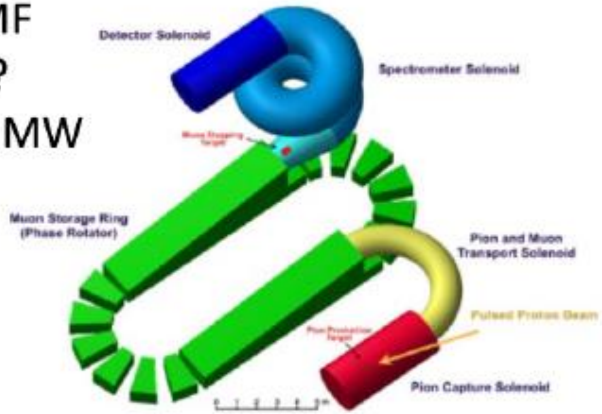
Mu2e
Tungsten, 6.3 mm x 220 mm
8 kW beam in 4.5 T



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



AMF
???
~1 MW

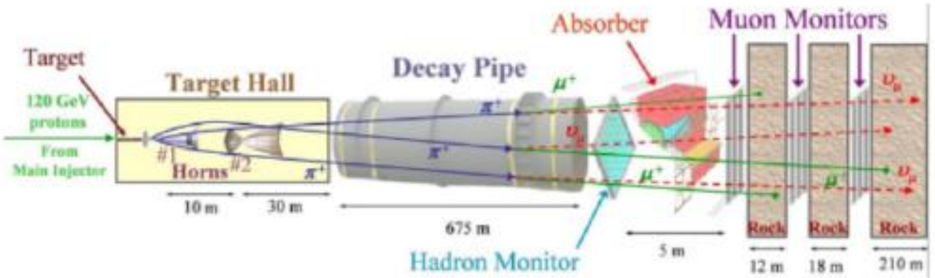


Compact, high-power targets and accompanying beam-intercept devices inside extraction solenoid

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

Short → Near → Long

NuMI



LBNF