International
UON Collider
Collaboration

# *Radiation studies for the target area*

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# Outline

- **Introduction**
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  - Target options for the radiation studies: graphite and liquid lead
- **Radiation load to the target**
  - Energy deposition and long-term radiation damage in the target
- **Radiation load to the target solenoid**
  - Heat load and long-term radiation damage in the superconducting coils
  - Total power to the cold mass
- **Adiabatic tapering and chicane (only for graphite target)**
  - Magnetic field modeling
  - Pions/muons energy spectrum
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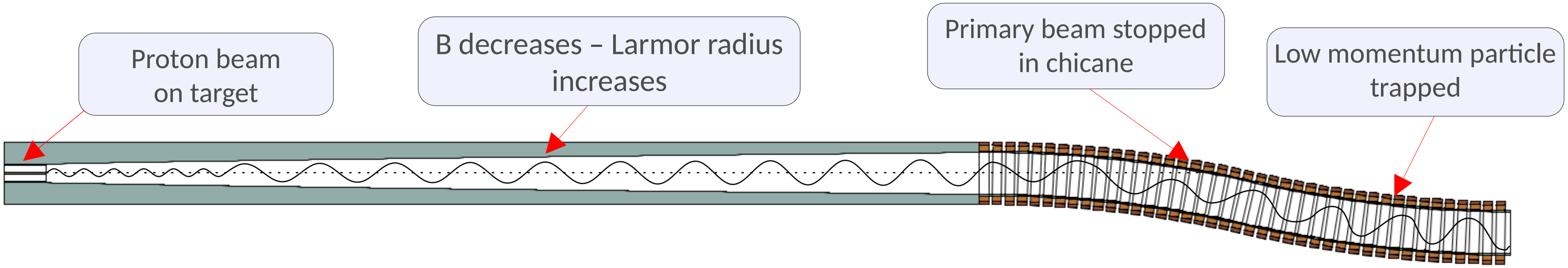
  - Energy deposition in the chicane
- **Conclusions**

# Introduction

- The MC under current investigation is proton driven. **Protons** impact on a solid or liquid target **generating pions** by inelastic collisions. [1]
- The generated pions travels through a tapering region where the **magnetic field** is **adiabatically decreasing**. The effect of this section is to decrease the angular divergence of the produced pions. [2,3]
- Finally, the beam enters a **chicane** where the high energy component of the beam is intercepted. Low momentum components (muons and pions) are forced to follow the field lines generated by a series of solenoids. [4]
- **The scope of these studies is to assess the radiation load to the equipment in the target area (target and magnets) and develop a shielding design.** The studies consider a generic setup as a **first step** using the MAP design as a starting point. All the simulation are conducted using **FLUKA**.
- All the **results** will be **normalized per unit MW proton beam** intensity with 200 days of operation per year.



Proton beam on target

B decreases – Larmor radius increases

Primary beam stopped in chicane

Low momentum particle trapped

# Parameters considered for these radiation studies

Table 1: Parameters table.

| Material | Graphite (1.8 g/cm$^3$) | Liquid lead (10.5 g/cm$^3$) |
|---|---|---|
| Inelastic scattering length | 44.94 cm | 17.34 cm |
| Target radius | 15 mm | 15 mm (+ 5 mm vessel) |
| Target length | 80 cm [3] | 29.7 cm (+2 cm vessel) |
| Beam size (round) | 5 mm | |
| Beam power (normalization purposes) | 1 MW | |
| Beam energy | 5 GeV | |
| Shielding thickness | 42.2 cm | |
| Magnet aperture (radius) | 60 cm | |
| Peak magnetic field | 20 T | |

Realistic values under consideration are higher (1.5-4 MW)

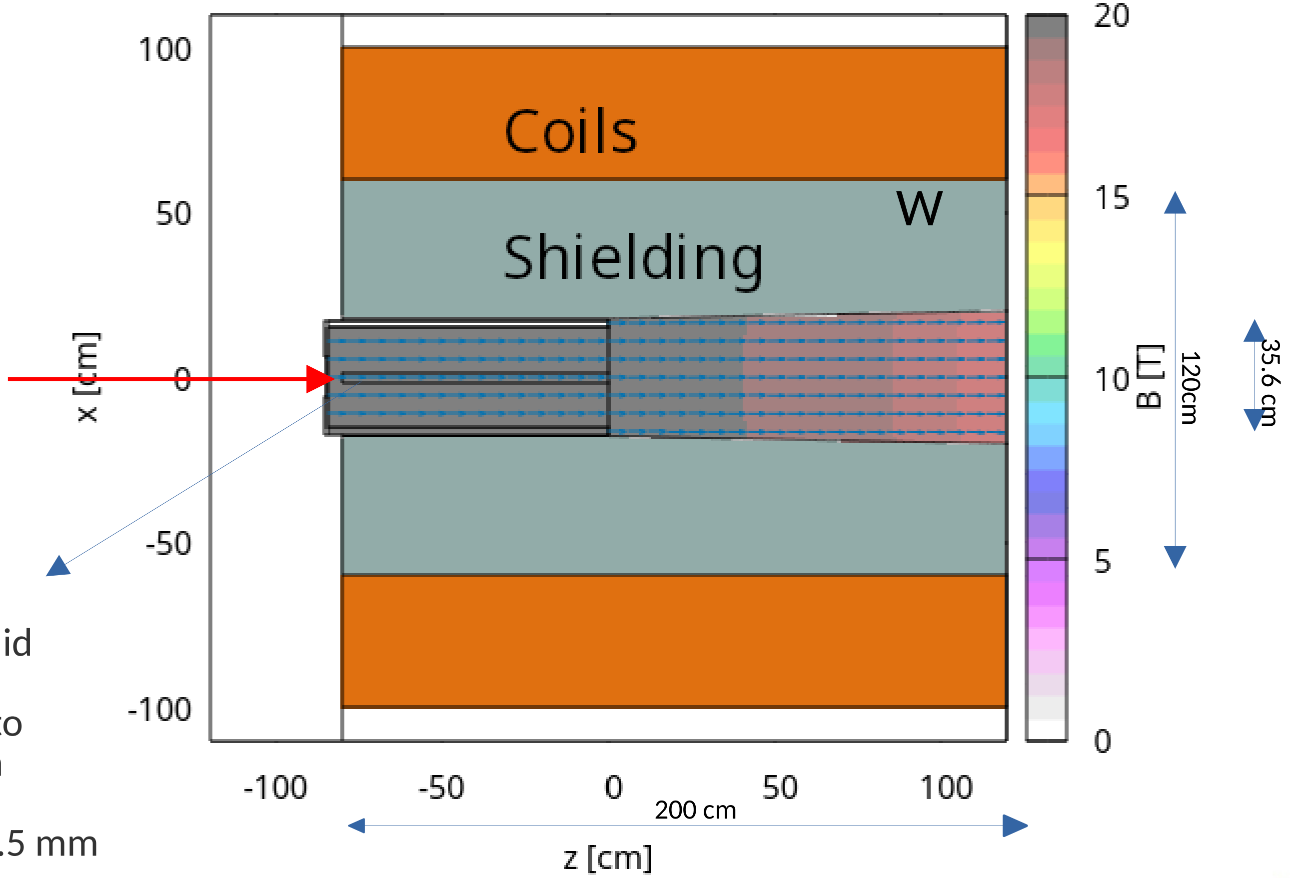
# Target geometry

Generic shielding and magnet geometry:

- Tungsten considered for the shielding (engineering and material aspects to be studied)
- No neutron absorber yet included

Proton beam (sigma 5 mm):

- 1 MW (normalization), to be scaled up to the real beam power.
- 5 GeV beam energy

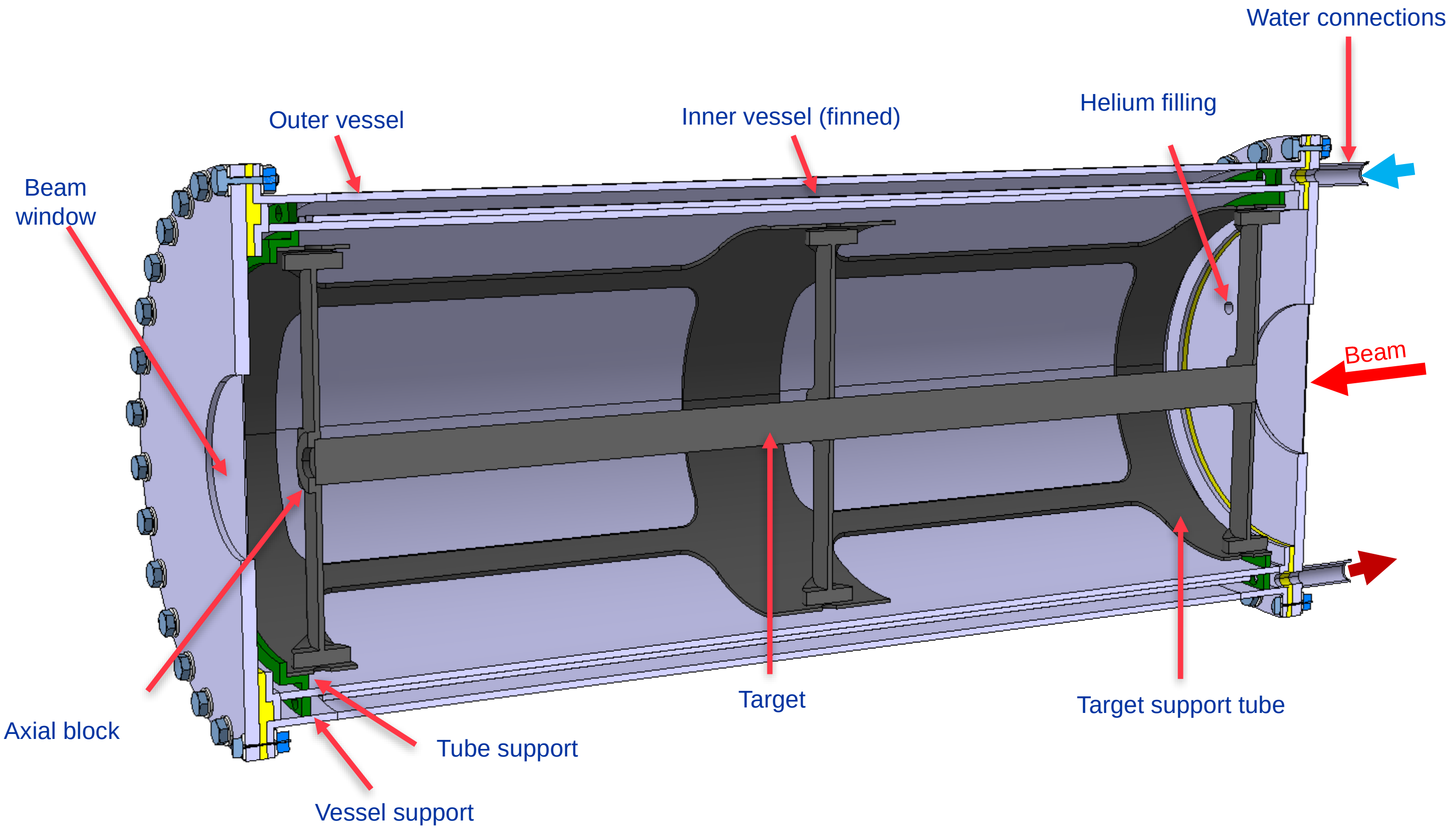


Target:

- Graphite or liquid lead
- It corresponds to 1.78 interaction lengths
- Target radius: 1.5 mm

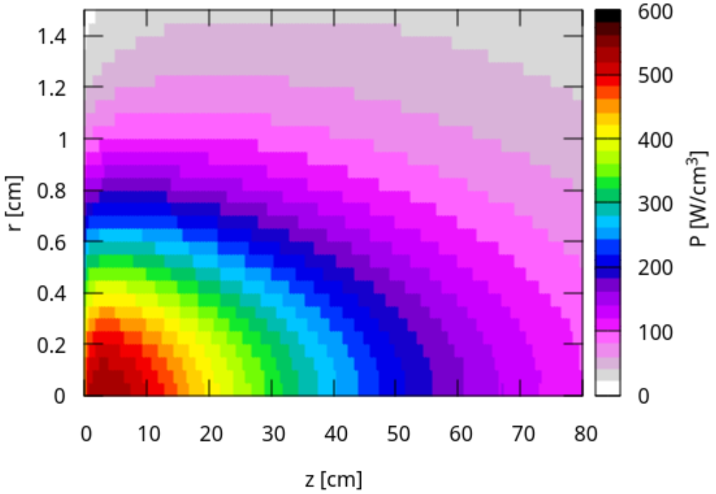
# Target geometry

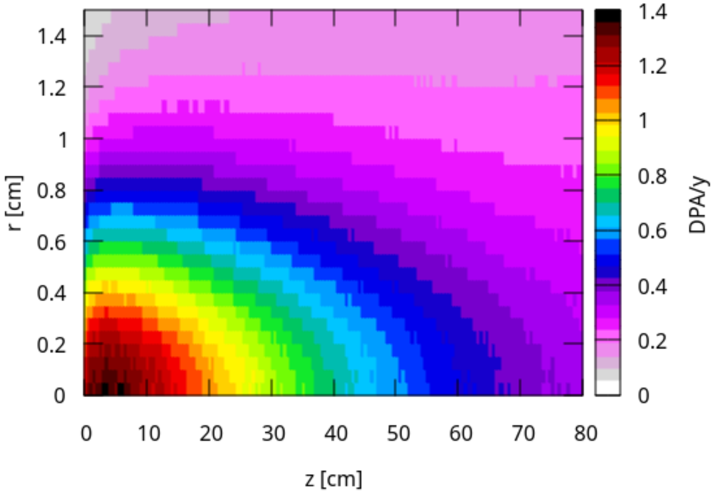
- The graphite target and vessel geometry has been studied by means of thermomechanical simulations (see the presentation of Rui Franqueira Ximenes)



# Graphitic target: heat deposition and displacement damage

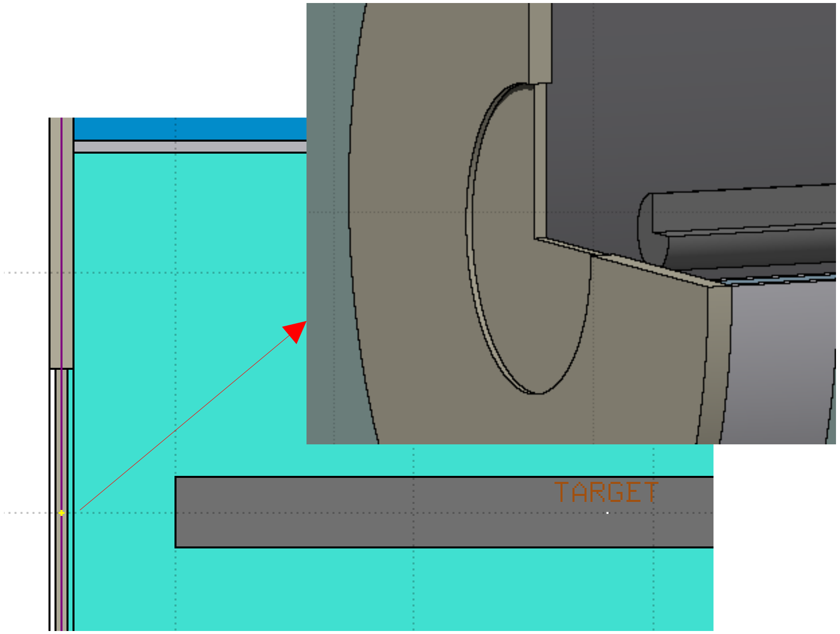
- In a **graphitic** target, the energy deposition is mostly concentrated in the first section of the target.
- Values up to **600 W/cm$^3$** are observed per MW proton beam.
- The displacement damage follows the same profile, with values up to **1.5 DPA per year** per MW beam.
- The total power deposition in the target is **5.5%** of the proton beam power. (34% goes in the shielding surrounding the target and 0.2% in the coils)


Power deposition in target

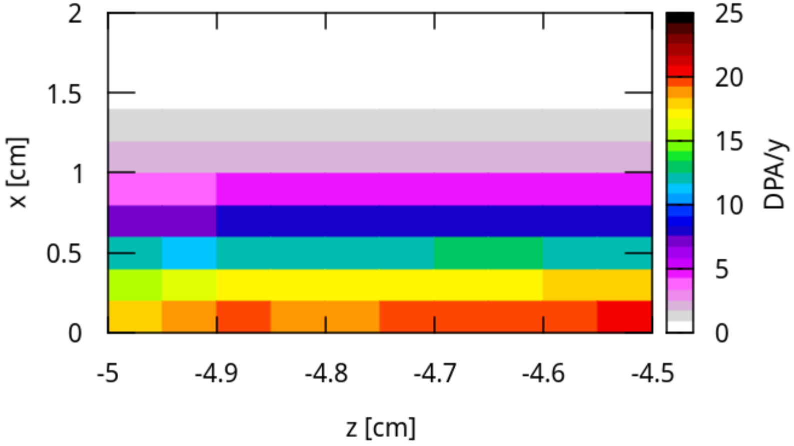

Displacement damage in target

# Window for the graphite target

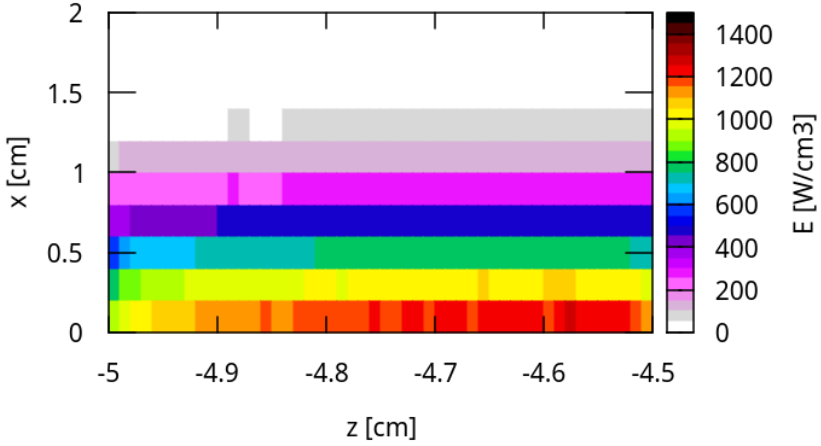
- Various **windows** option are under exploration. Current possibilities are **Ti based materials** with thickness ranging from 1 to 5 mm (with a C target, smaller targets can be foreseen). (Ti DPA energy threshold: 30 eV)
- They will need to withstand **high power deposition values** and **intense radiation damage**.
- Based on the current configuration, the displacement damage might be too excessive. To reduce this value, **larger beam sizes** might be needed.
- The possibility of a windowless target could be explored.



5 mm DPA in window per year

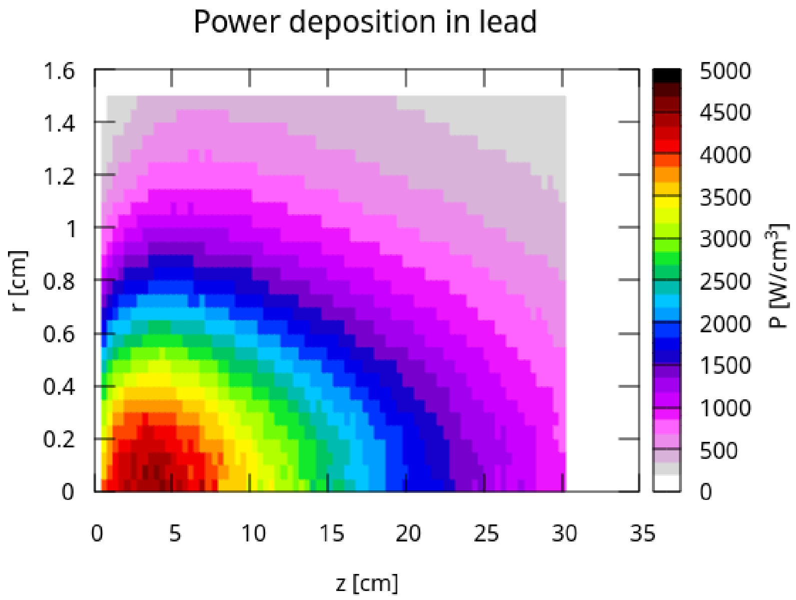


5 mm energy deposition in window per MW beam



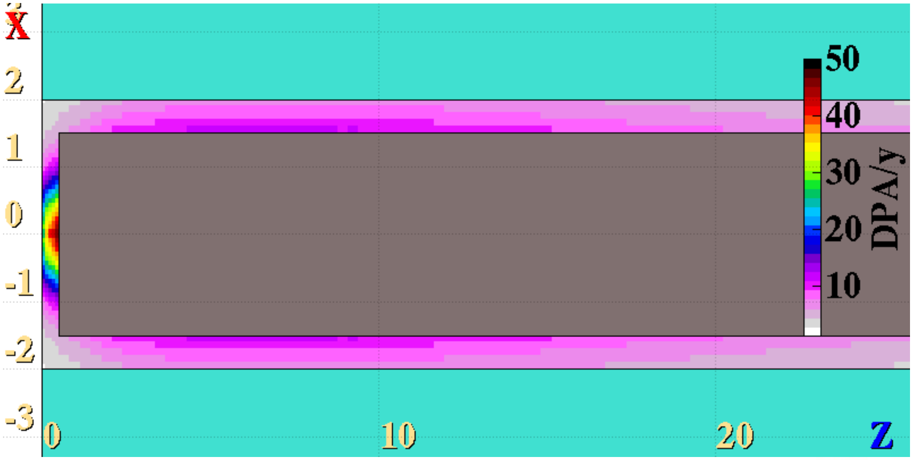
# Liquid lead target and vessel: radiation effects

- In a liquid lead target, the **power densities are higher** in comparison with the graphite target due to the high Z and material density.
- Values up to **4500 W/cm$^3$** are observed per MW proton beam.
- The total power deposition in the target is **20%** of the proton beam power. (32% goes in the shielding and 0.28% in the coils)

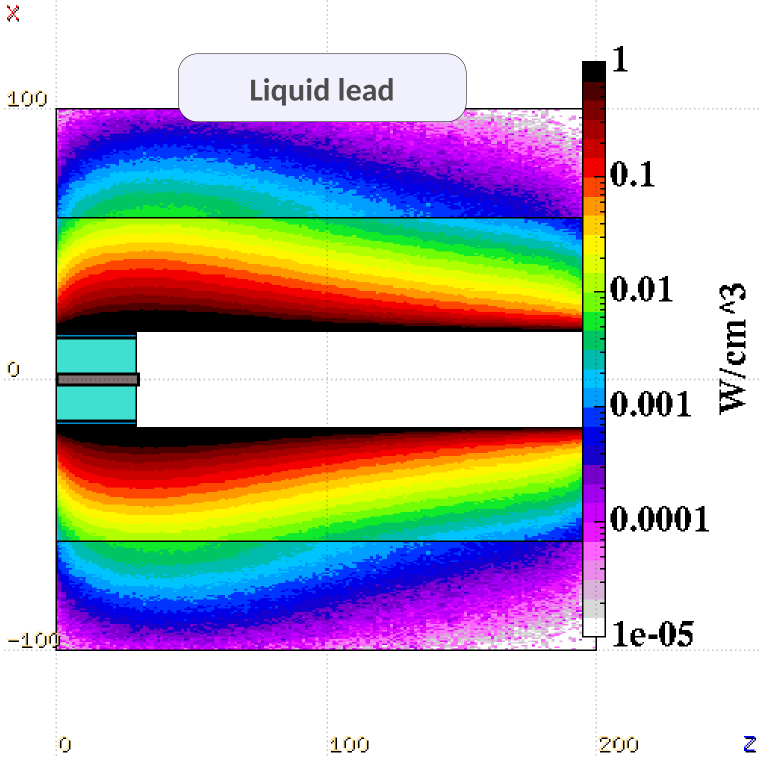


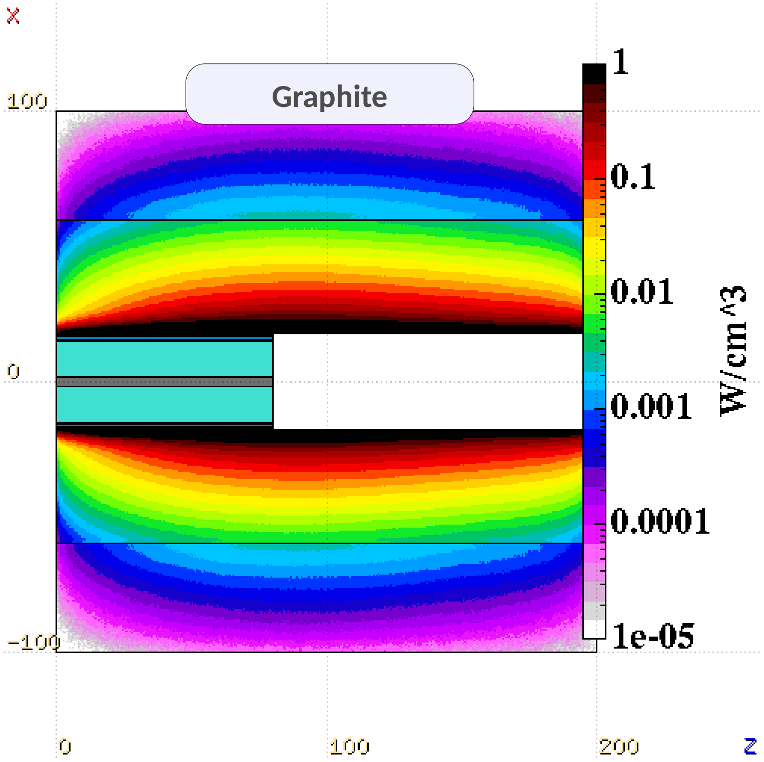
**The vessel is assumed to be made of stainless steel.**

- Due to the small beam size, **DPA** peaks in the **front window** are up to **30-40** per year. Larger beam sizes might be needed.
- The **lateral side** of the vessel is exposed to the shower products. We observe DPA values up to **8-10**, which would potentially require a larger vessel
- The **downstream** window shows values of **~1s DPA** per year per MW beam



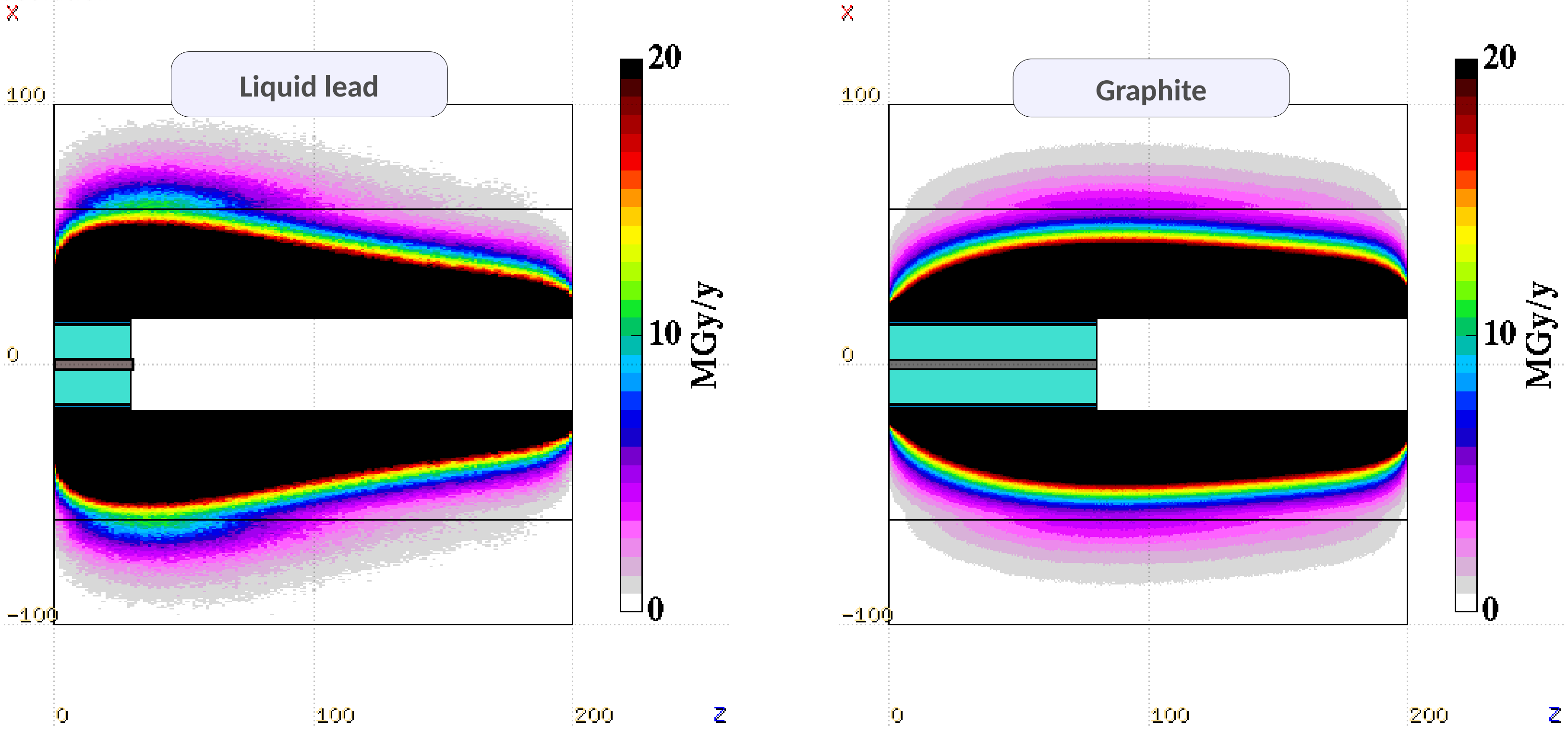
# Energy deposition in coils: graphite and liquid lead





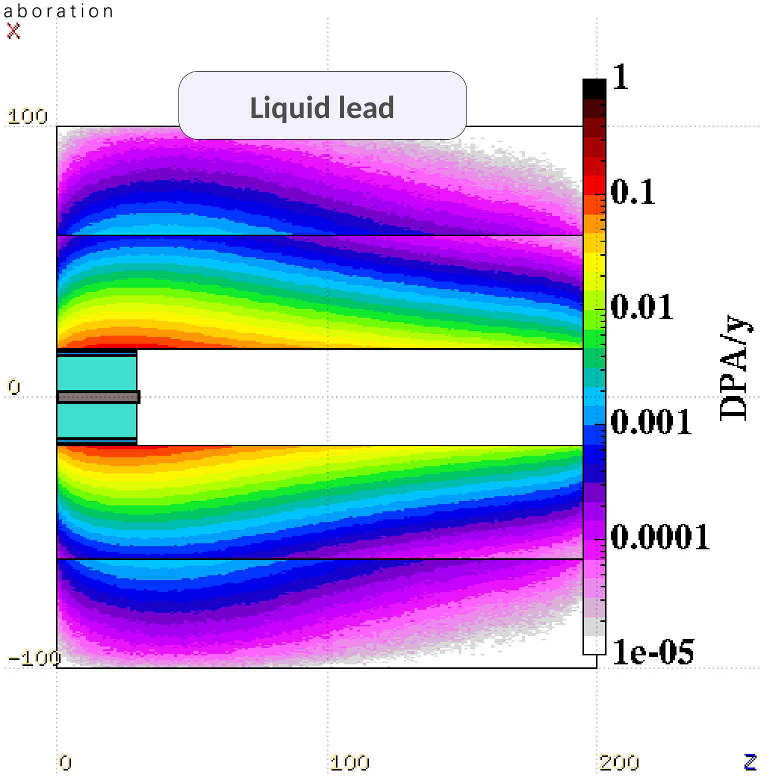
- Considering the **same number of inelastic scattering lengths** (1.78) the **energy** deposition **distribution** is **different** when considering a graphite and a liquid lead target.
- The **lead** target produces a **shorter shower** development, therefore the hotspot in the coils is closer to the target.

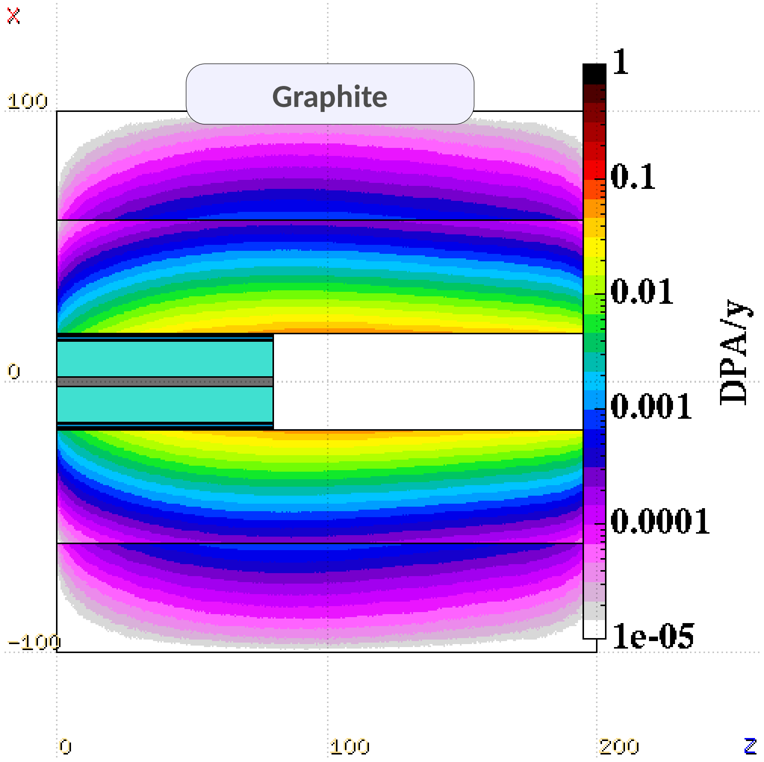
# Ionizing dose in coils: graphite and liquid lead



- Since the shielding and coils geometry are the same, the total ionizing dose is 1-to-1 function to the power deposition.
- The scale chosen for these plots **highlight** the **effect on the coils**.
- After 1 year with 1 MW power, the coils receive **~10 MGy** in a case of a **liquid lead** target. This might be **not sustainable** with the **material degradation.**
- Additional shielding can be positioned in the liquid lead target case, since the cooling capability is provided by the liquid lead circuit itself.

# Displacement damage in coils: graphite and liquid lead

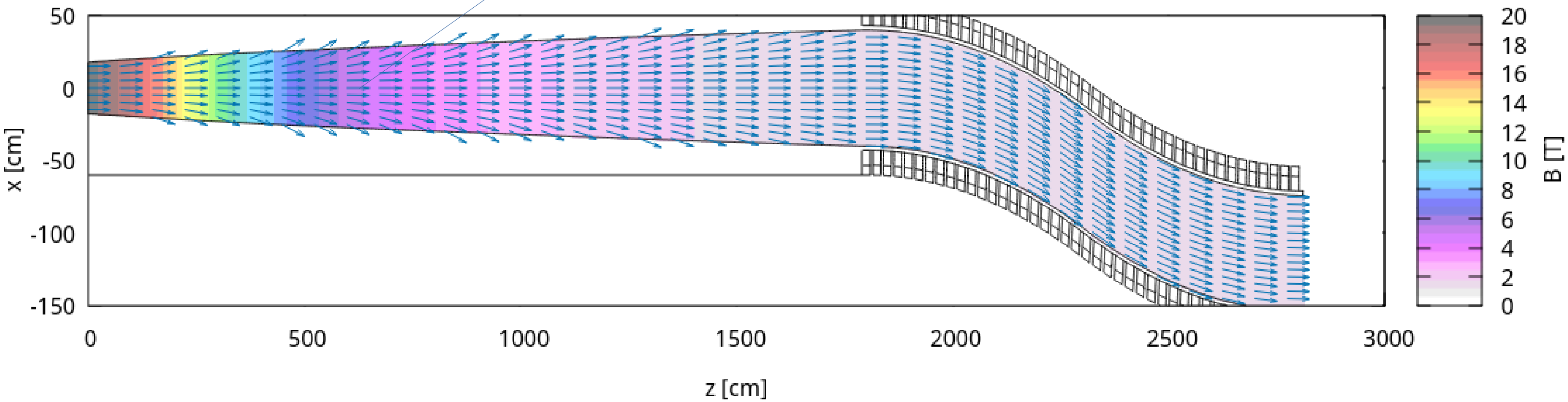




- The damage profile follows the energy distribution one. Again, the liquid **lead** target cause an **higher displacement damage** in the coils.
- **No neutron absorber yet included**! This can significantly change the picture.

# Tapering and chicane

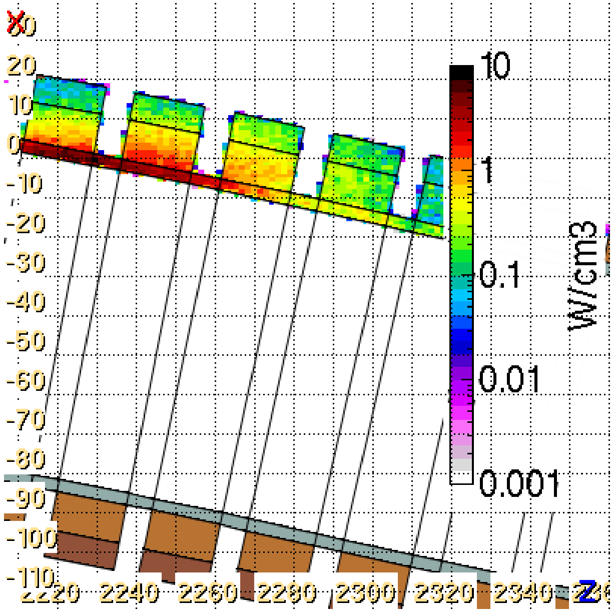
$$B_z(0, z_1 < z < z_2) = \frac{B_1}{[1 + a_1(z - z_1) + a_2(z - z_1)^2 + a_3(z - z_1)^3]^p}$$

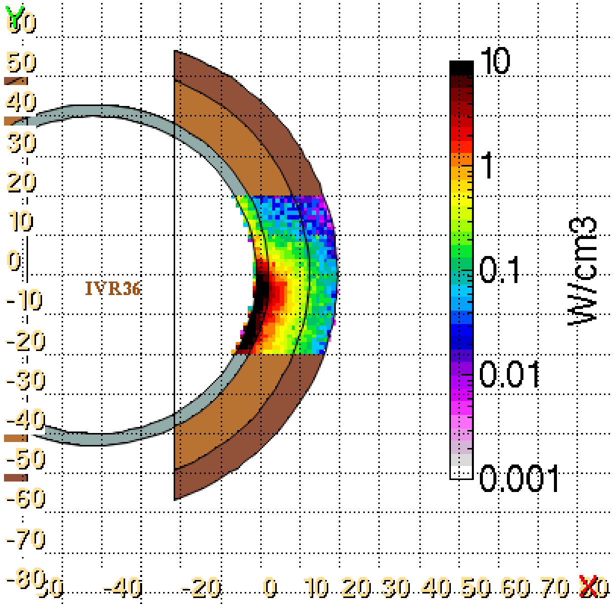

Tapering magnetic field

- All the results are simulated considering the **graphite target**.
- The magnetic field chosen for adiabatic section is an **inverse cubic tapering**.
- The chicane coils are 18 cm long, placed at 0.625° intervals (25 cm in s). The inner radius of the coils is 43 cm. A **tungsten shielding of 3 cm** is placed uniformly inside the chicane.

# Energy deposition in the chicane

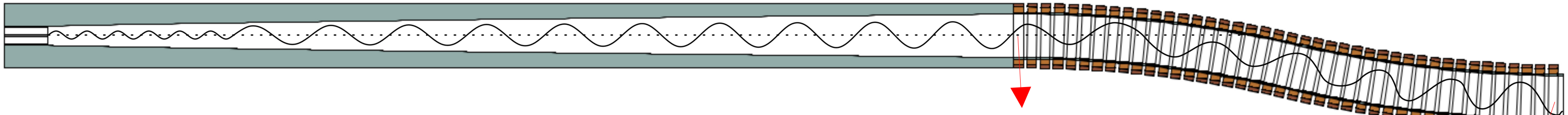
- More than 50% of the power is going in the shielding before the chicane!
- The total power deposited in the chicane region is 12.4% of the one from the primary beam. This corresponds to a few 100 kW. **A dedicated beam dump might be needed**

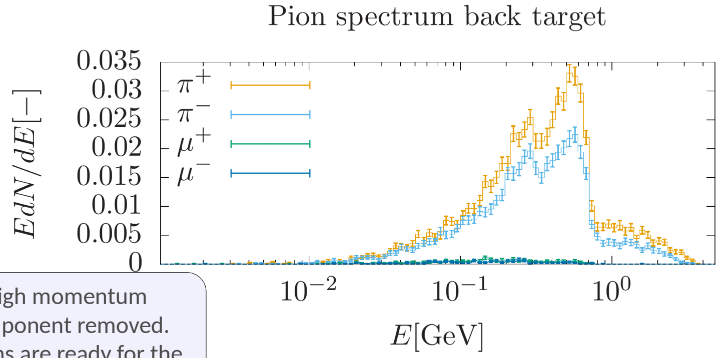




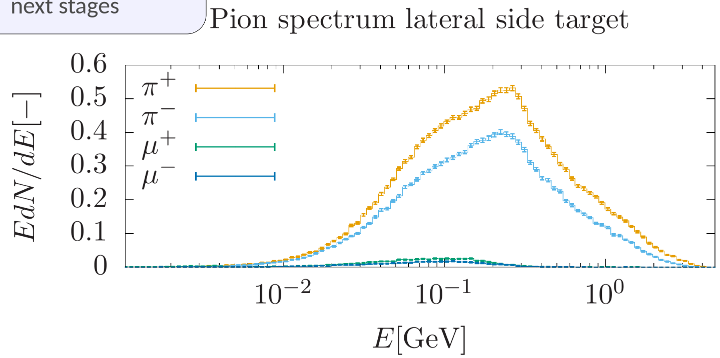
# Tapering effect: transverse momentum correction.

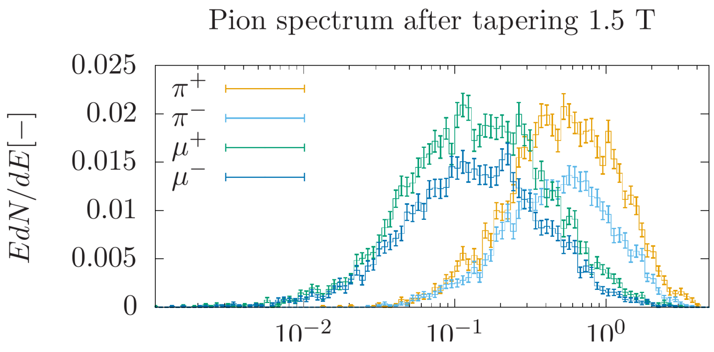
- Here there are reported the secondary spectra **per primary particle of the proton beam**. (normalization factor: 1.25E15 particle per second per MW of beam power with 5 GeV protons)
- The physic optimization should be perform together with the shielding design.

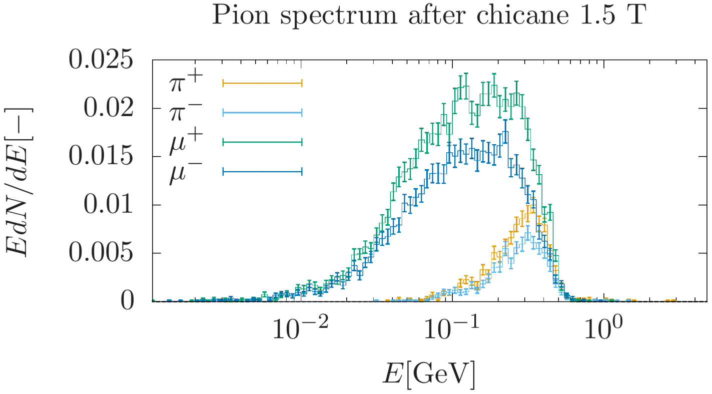



Pion spectrum back target

High momentum component removed. Muons are ready for the next stages


Pion spectrum lateral side target


Pion spectrum after tapering 1.5 T


Pion spectrum after chicane 1.5 T

# Conclusions

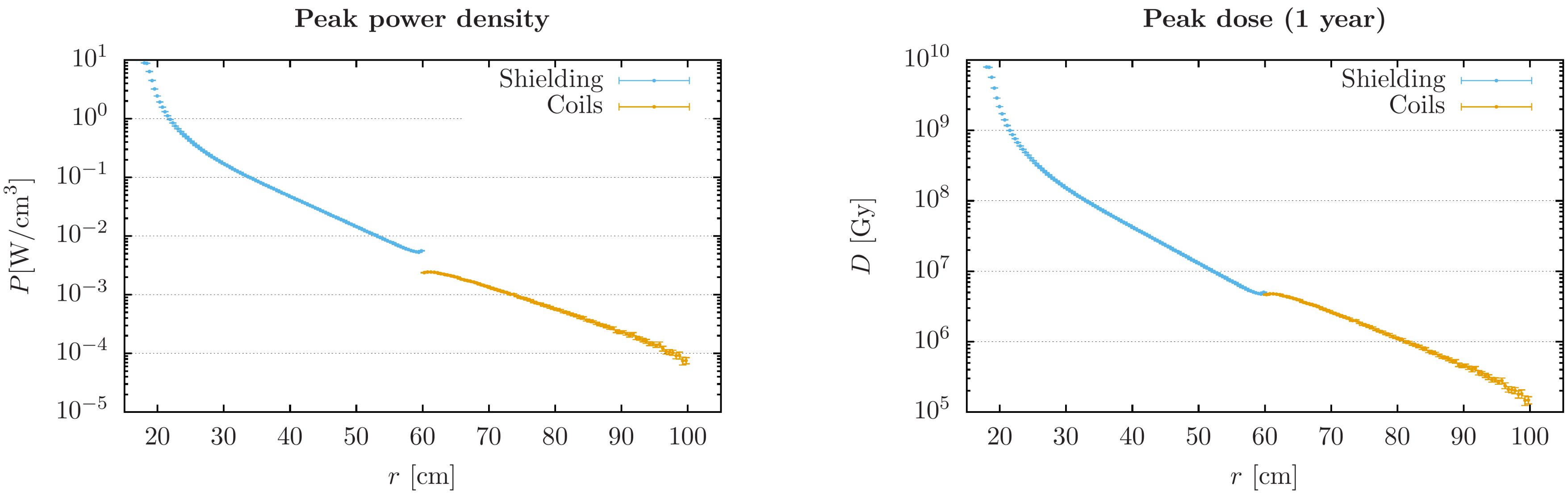
- **Target**:
  - **Radiation load studies** for the target area have been started simultaneously with the **thermomechanical calculations** to assess various target options.
  - Radiation load on **graphite** and **liquid lead target** has been studied with a fixed beam size.
  - In both cases, the **containment** structure (a window to enclose an helium athmosphere for graphitic materials and the vessel for the liquid lead option) are subject to intense **displacement** damage. This might be a possible lifetime limitation of the target assembly.
- **Coils of target solenoid**:
  - The **energy deposition** and **long term damage** in the shielding and the superconducting coils has been assessed, assuming a generic geometry.
  - The liquid lead target induces shorter shower development and the radiation load to the coils is a factor 1.5 higher.
- **Chicane**:
  - With a simple geometry, the **particle yield** after the chicane has been obtained. A dedicated **beam dump** might be needed

# *Thank you!*

# References

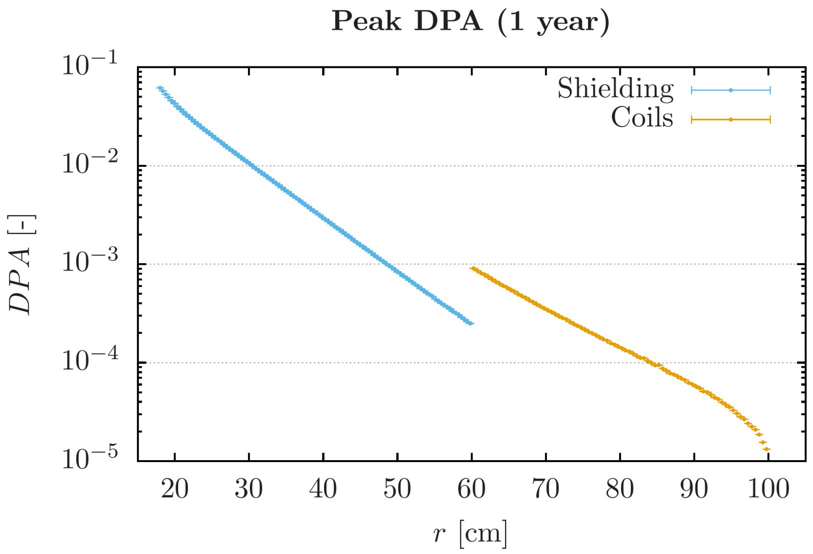
- [1] Considerations on Muon Collider Targetry, Marco Calviani.
- [2] Analytic Forms for an Adiabatic Tapered Solenoid, McDonald. https://www.hep.princeton.edu/mumu/target/taper.pdf
- [3] Preliminary Optimization of the Pion Capture and Decay Channe, Paul et al.  https://doi.org/10.1063/1.1818427
- [4] The Target System Baseline, Kirk er al. https://inspirehep.net/files/8020cfe9d0e3474c15ecbf2a5bb29f1a
- [5] CARBON AND MERCURY TARGET SYSTEMS FOR MUON COLLIDERS AND NEUTRINO FACTORIES, McDonald et al. doi:10.18429

# Main solenoid: energy deposition and ionizing dose peak



- The small bump in the power deposition in the interface between shielding and coils is mostly due to the difference in density.
- With 40 cm W shielding, the peak dose reaches 4-5 MGy in the coils after 1 year of operation (assuming 1 MW beams)

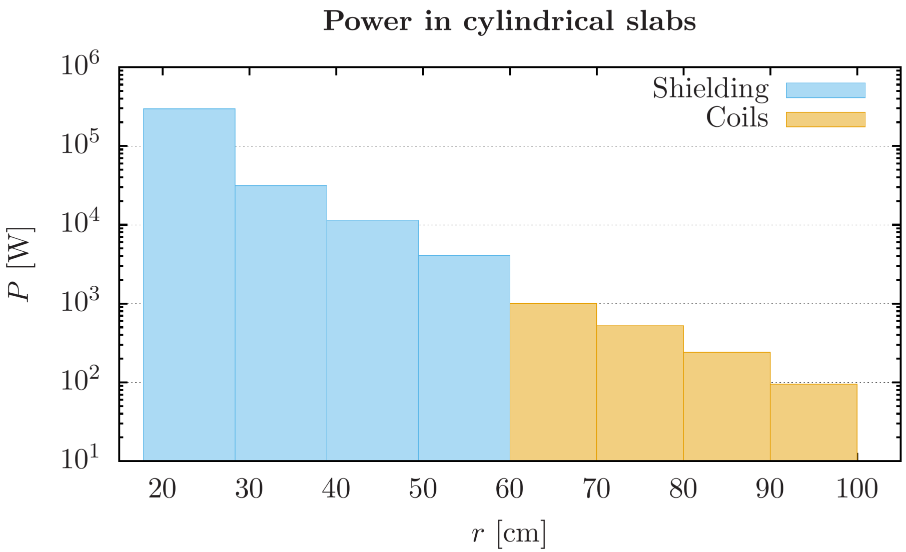
# Radial profile of the peak displacement damage



- The considered energy threshold for inducing a displacement is 40 eV for the superconductive coils and 90 eV for the tungsten shielding.
- The gap in the DPA values at the interface is due to:
  1) The different values in the energy thresholds (you need to deposit less energy to induce a displacement in the coils).
  2) The neutron elastic cross section is larger for light elements.

- With 40 cm W shielding, the peak DPA reaches $10^{-3}$ in the coils after 1 year of operation (assuming 1 MW beams)

# Power in cylindrical slabs



The (integrated) **power deposition** for the 2 m (longitudinal coordinate) **coils** is reported for each cylindrical slab of the magnet.

For example: a cylindrical coil with $r_{min}$=60cm and $r_{max}$=70cm (length of 2m) would absorb 1 kW.

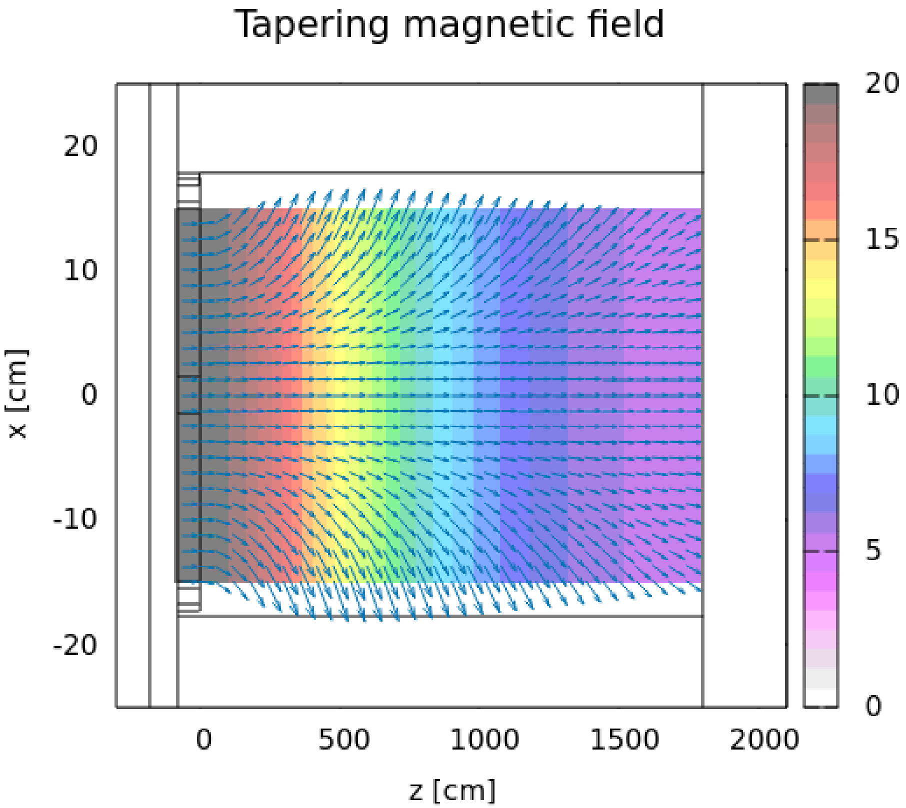
# Tapering field: inverse cubic taper

$$B_z(0, z_1 < z < z_2) = \frac{B_1}{[1 + a_1(z - z_1) + a_2(z - z_1)^2 + a_3(z - z_1)^3]}$$

$$B_z(r, z) = \sum_n (-1)^n \frac{a_0^{(2n)}(z)}{(n!)^2} \left(\frac{r}{2}\right)^{2n},$$

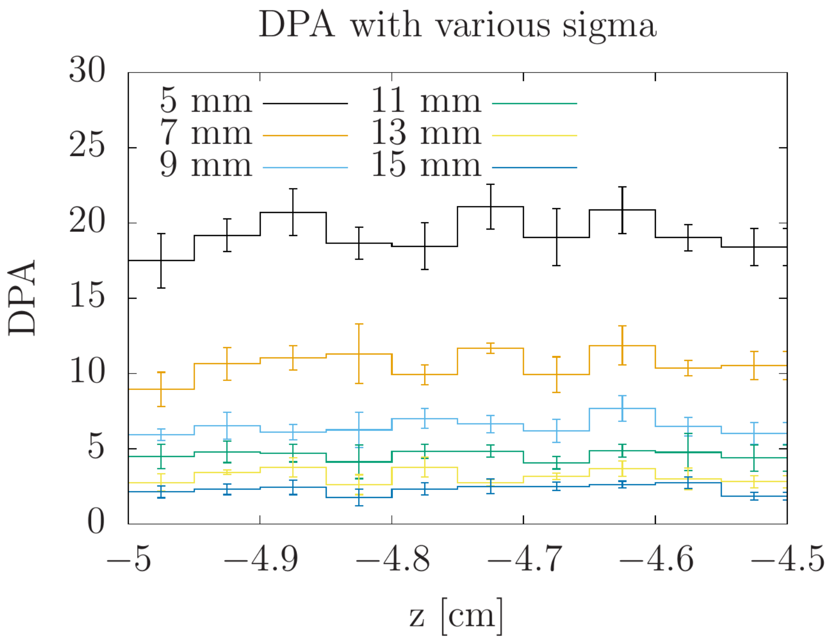
$$B_r(r, z) = \sum_n (-1)^{n+1} \frac{a_0^{(2n+1)}(z)}{(n+1)(n!)^2} \left(\frac{r}{2}\right)^{2n+1},$$

$$a_0^{(n)} = \frac{d^n a_0}{dz^n} = \frac{d^n B_z(0, z)}{dz^n},$$

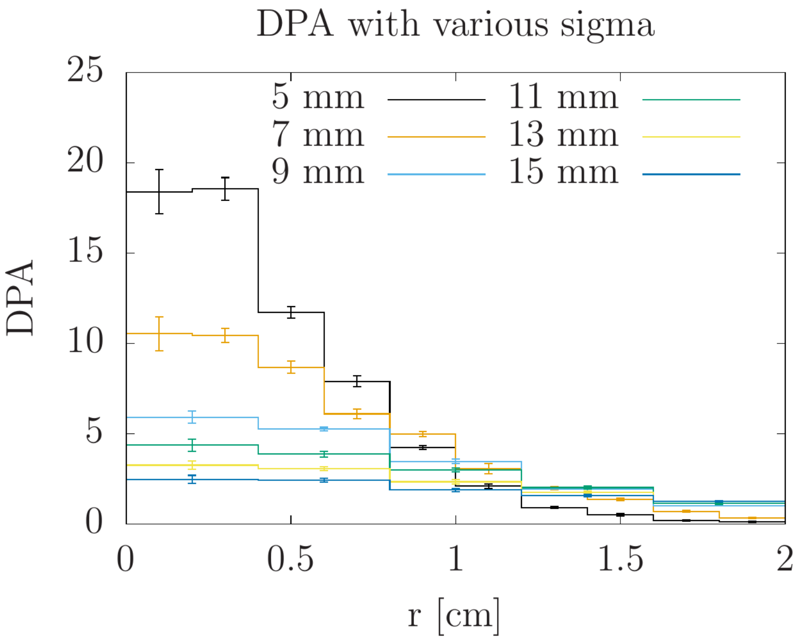


# DPA in window (graphite target)

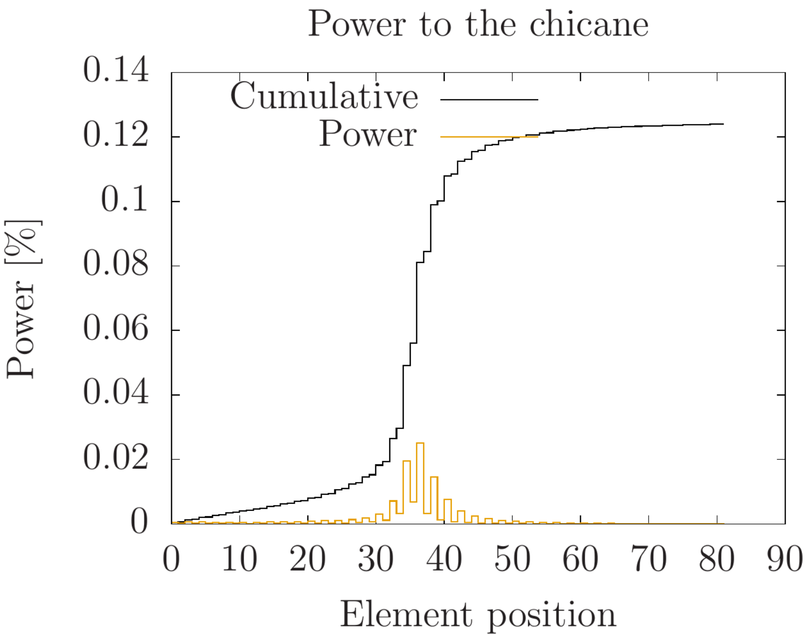
Longitudinal DPA distribution (uniform)



Radial DPA distribution

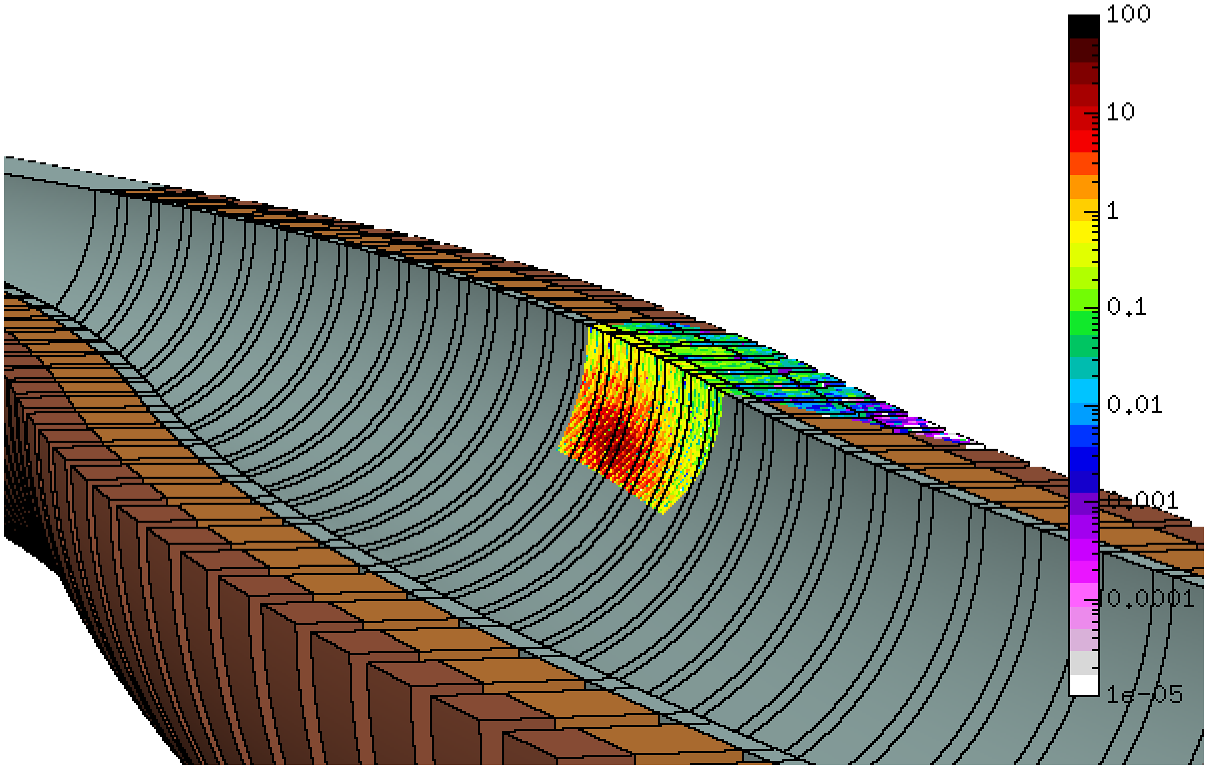


# Power to the chicane



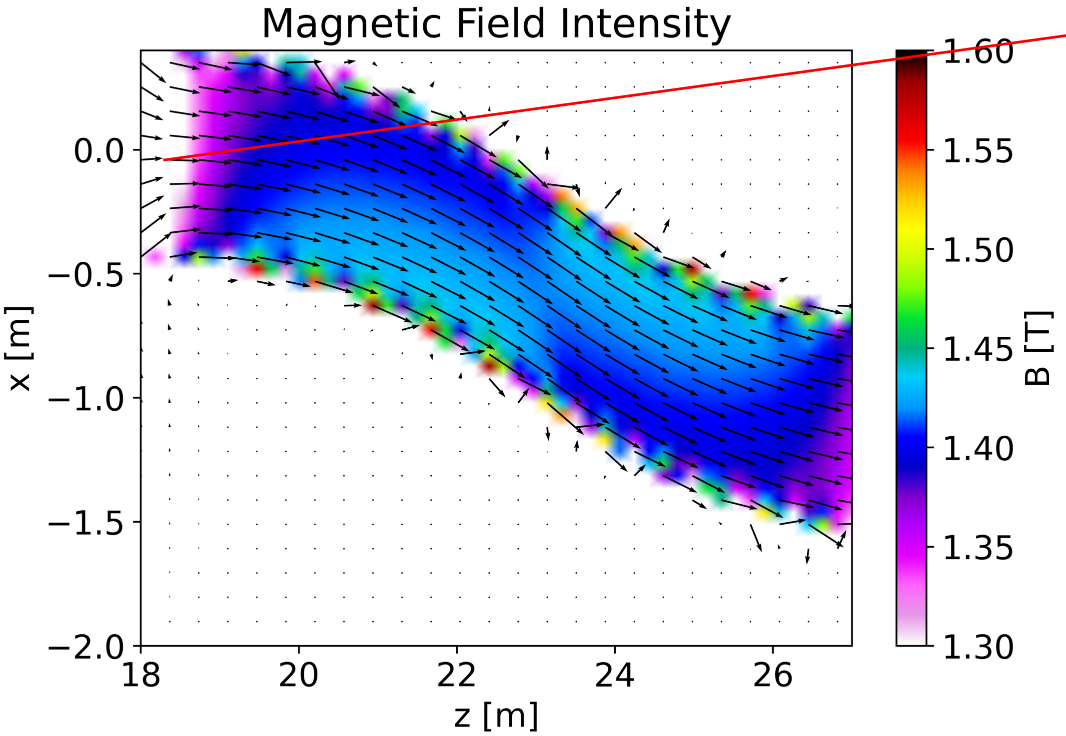
# Heat deposition in the chicane

Considering a 1 MW beam, the heat deposition is concerning, a much thicker shielding is required. Since the structure is quite localized, we can implement an asymmetrical shielding if needed.



# Tentative magnetic field implementation

I tried to implement all the different magnets in a numeric way. The source code can be shared upon request. **This shouldn't change anything for the heat deposition!**



**I'm working to include the magnetic field**

From communications with Chris Rogers, I am trying to **replicate past studies.**

G4BL chicane coils have:
**Inner radius**: 430 mm
**Outer radius**: 530 mm
**Length:** 180 mm
**Current Density:** 16.57 A/mm$^2$
Placed at 0.625° intervals (250 mm in *s*)

# Realistic solenoid (infinitesimal cylinder)

$$B_\rho = \frac{\mu_0 I}{4\pi}\frac{2}{l}\sqrt{\frac{R}{\rho}}\left[\frac{k^2-2}{k}K(k^2)+\frac{2}{k}E(k^2)\right]_{\zeta_-}^{\zeta_+},$$

$$B_z = \frac{\mu_0 I}{4\pi}\frac{1}{l}\frac{1}{\sqrt{R\rho}}\left[\zeta k\left(K(k^2)+\frac{R-\rho}{R+\rho}\Pi(h^2,k^2)\right)\right]_{\zeta_-}^{\zeta_+}.$$

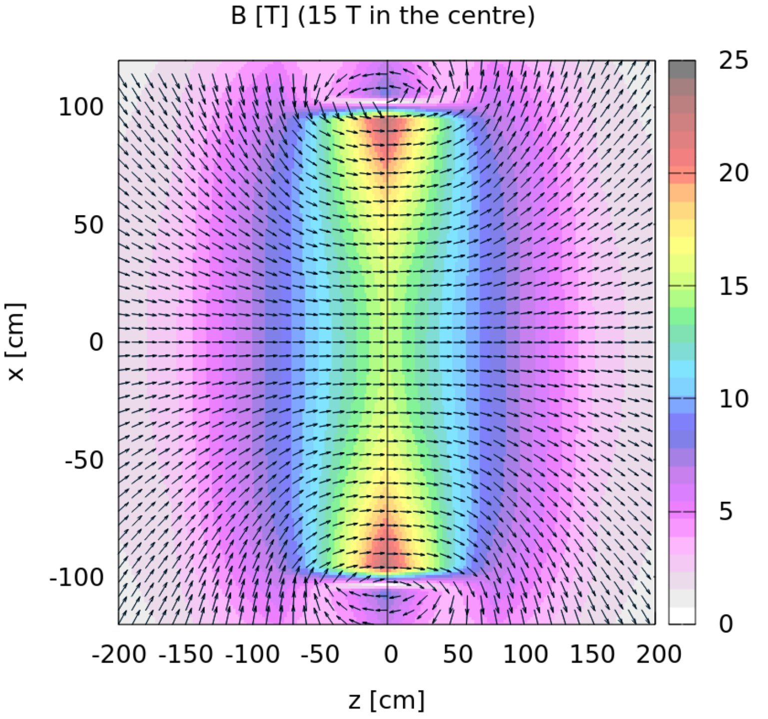
$$\zeta_\pm = z \pm \frac{l}{2},$$

$$h^2 = \frac{4R\rho}{(R+\rho)^2},$$

$$k^2 = \frac{4R\rho}{(R+\rho)^2+\zeta^2},$$

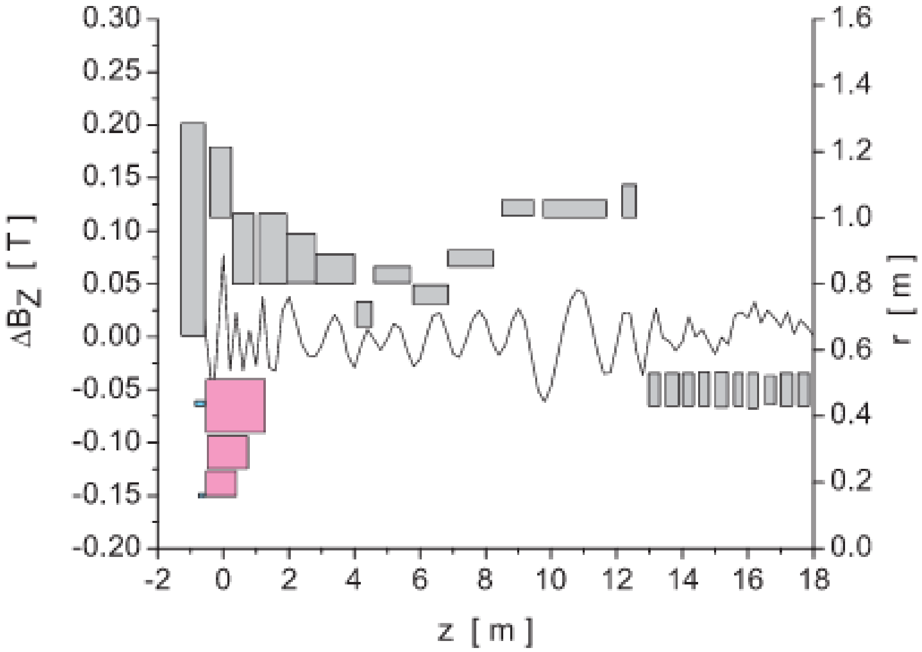
Good: they are exact. We can numerically integrate to get a thick solenoid.

Bad: we need to know how the magnet looks like



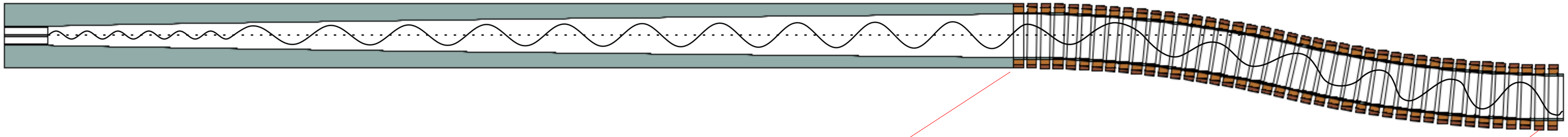
# Tapering field: achievable?

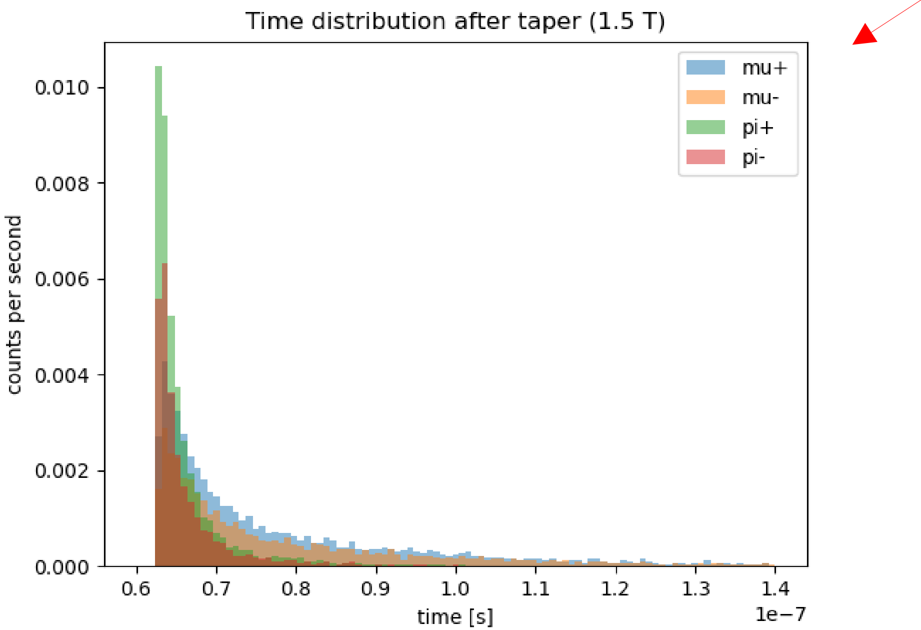
- Past studies affirm that, with a proper solenoid configuration, the difference between the actual magnetic field and the needed one is minimal. https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.9.011001



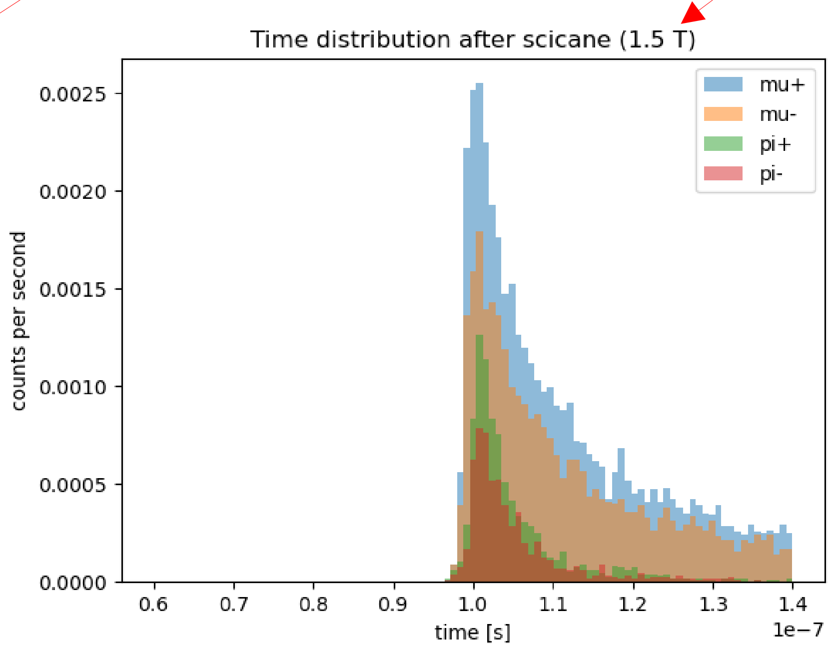
# Tapering effect: particle time of arrival

With 1.5 T chicane magnetic field, the time of arrival distribution (0 RMS proton beam)





Time distribution after taper (1.5 T)



Time distribution after scicane (1.5 T)