Study of the spent proton beam extraction channel and radiation load to the magnets in the target area

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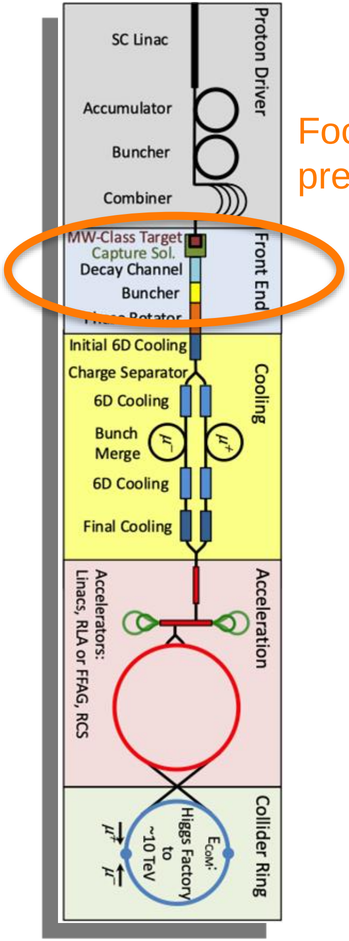
Presentation Outline

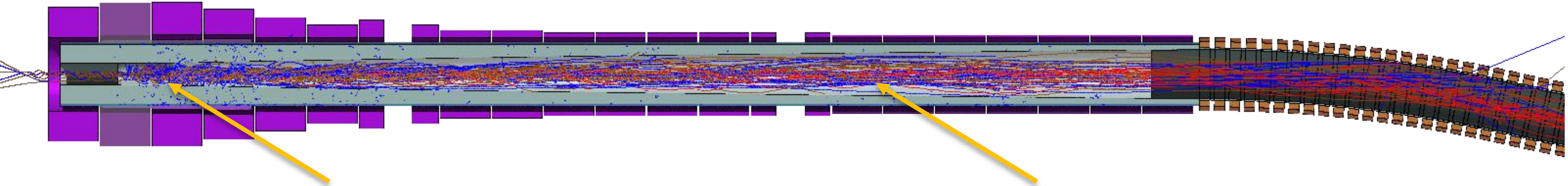


Focus of this presentation

1. **Radiation load to the magnets in the proton target area.**
   - Study of the previous design and the motivation for change.
   - Updated tapering magnet layout.
2. **Extraction channel for the primary protons that pass through the target (spent protons)**
   - Options for the chicane geometry allowing to incorporate space for an extraction window
   - Study of muon emittance and momentum spectra.
   - Spatial separation of the extracted protons and the end of the chicane – how much space is available to place a beam dump.
   - Energy deposition to the chicane solenoid magnets (normal conducting)

Introduction

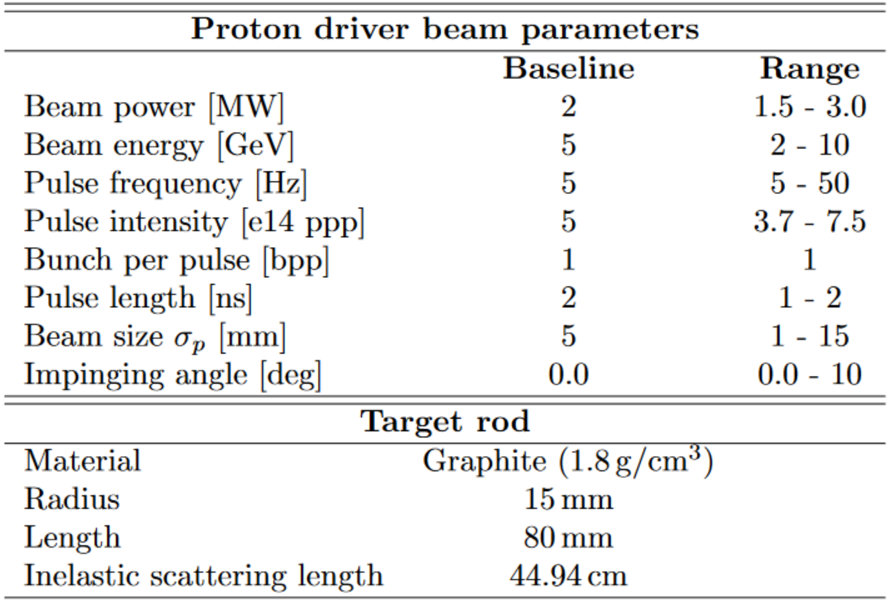
- The MC under current investigation is proton driven. **Protons** impact on a solid or liquid target **generating pions** by inelastic collisions.
- The generated pions travels through a tapering region where the **magnetic field** is **adiabatically decreasing**. The effect of this section is to decrease the angular divergence of the produced pions.
- Finally, the beam enters a **chicane** where the high momentum 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 magnets in the target area (target and magnets) and develop a shielding design.** All the simulation are conducted using **FLUKA**.
- All the **results** will be **normalized per 2 MW proton beam** intensity with 200 days of operation per year.



p impacting on a target, producing $\pi^{\pm}$

...decaying in μ^- and μ^+

Parameters



Proton driver beam parameters

	Baseline	Range
Beam power [MW]	2	1.5 - 3.0
Beam energy [GeV]	5	2 - 10
Pulse frequency [Hz]	5	5 - 50
Pulse intensity [e14 ppp]	5	3.7 - 7.5
Bunch per pulse [bpp]	1	1
Pulse length [ns]	2	1 - 2
Beam size σ_p [mm]	5	1 - 15
Impinging angle [deg]	0.0	0.0 - 10

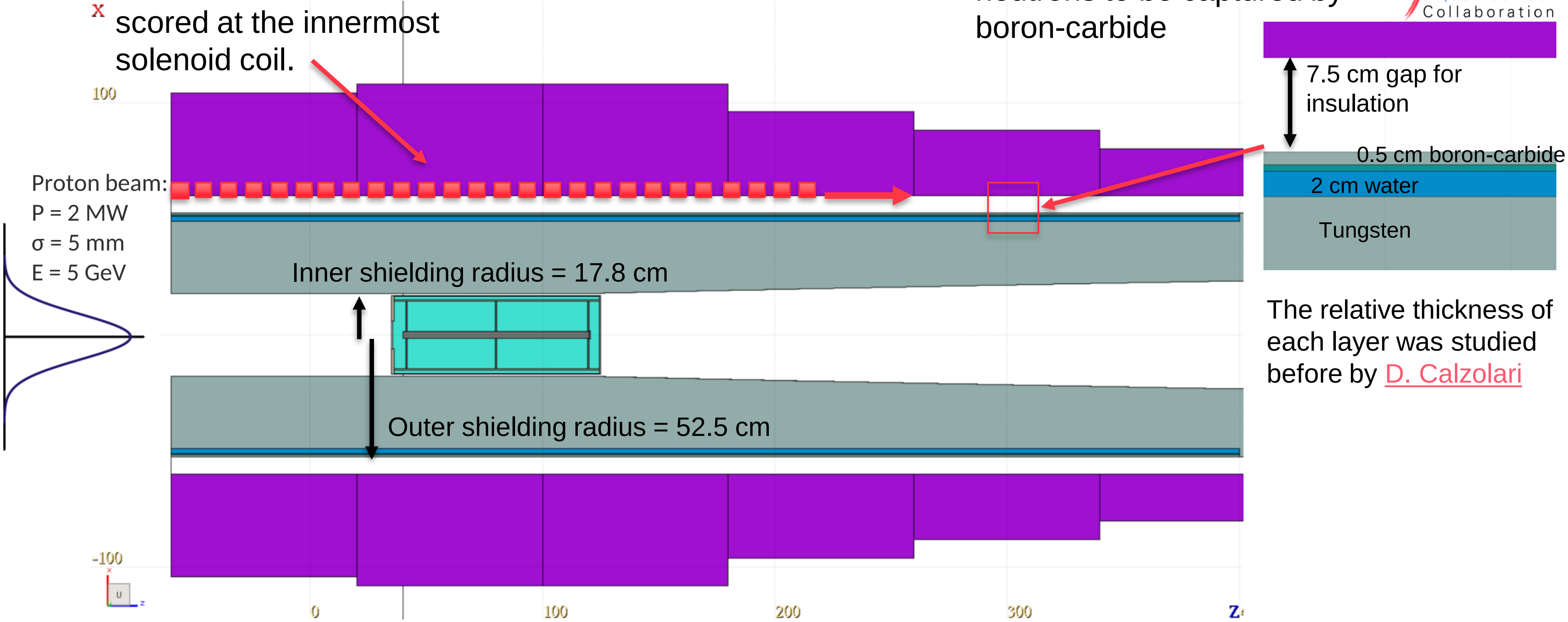
Target rod

Material	Graphite ($1.8\,\mathrm{g/cm^3}$)
Radius	15 mm
Length	80 mm
Inelastic scattering length	44.94 cm

Note on the long-term radiation damage: we considered 139 days of operation per year (1.2×10^7 s). In the general parameters table, we assume to operate for 10^7 s per year. All the results are given per year of operation.

Radiation load to the target solenoid magnets

Target area geometry



The DPA and the dose are scored at the innermost solenoid coil.

Water is needed to thermalize neutrons to be captured by boron-carbide

Proton beam:
P = 2 MW
σ = 5 mm
E = 5 GeV

Inner shielding radius = 17.8 cm

Outer shielding radius = 52.5 cm

7.5 cm gap for insulation

0.5 cm boron-carbide

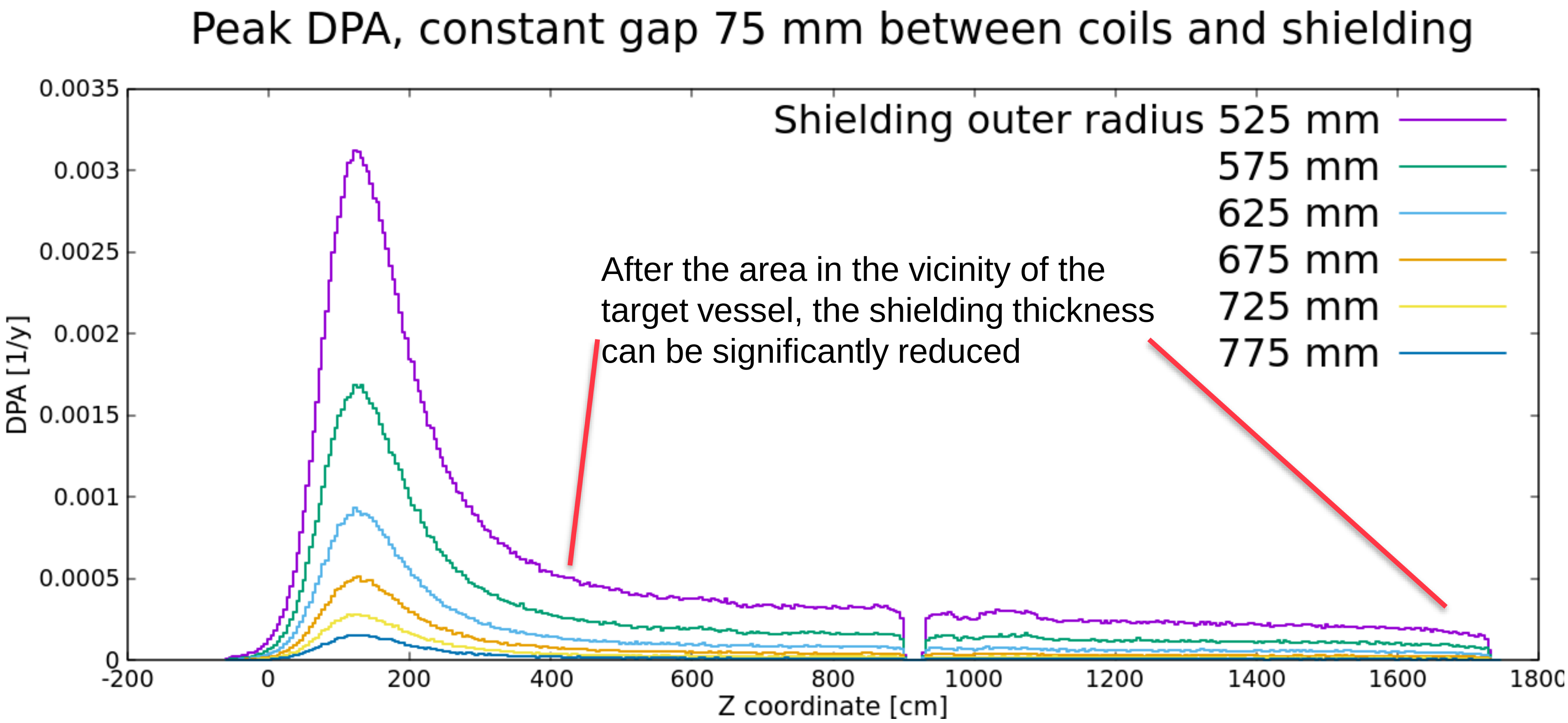
2 cm water

Tungsten

The relative thickness of each layer was studied before by D. Calzolari

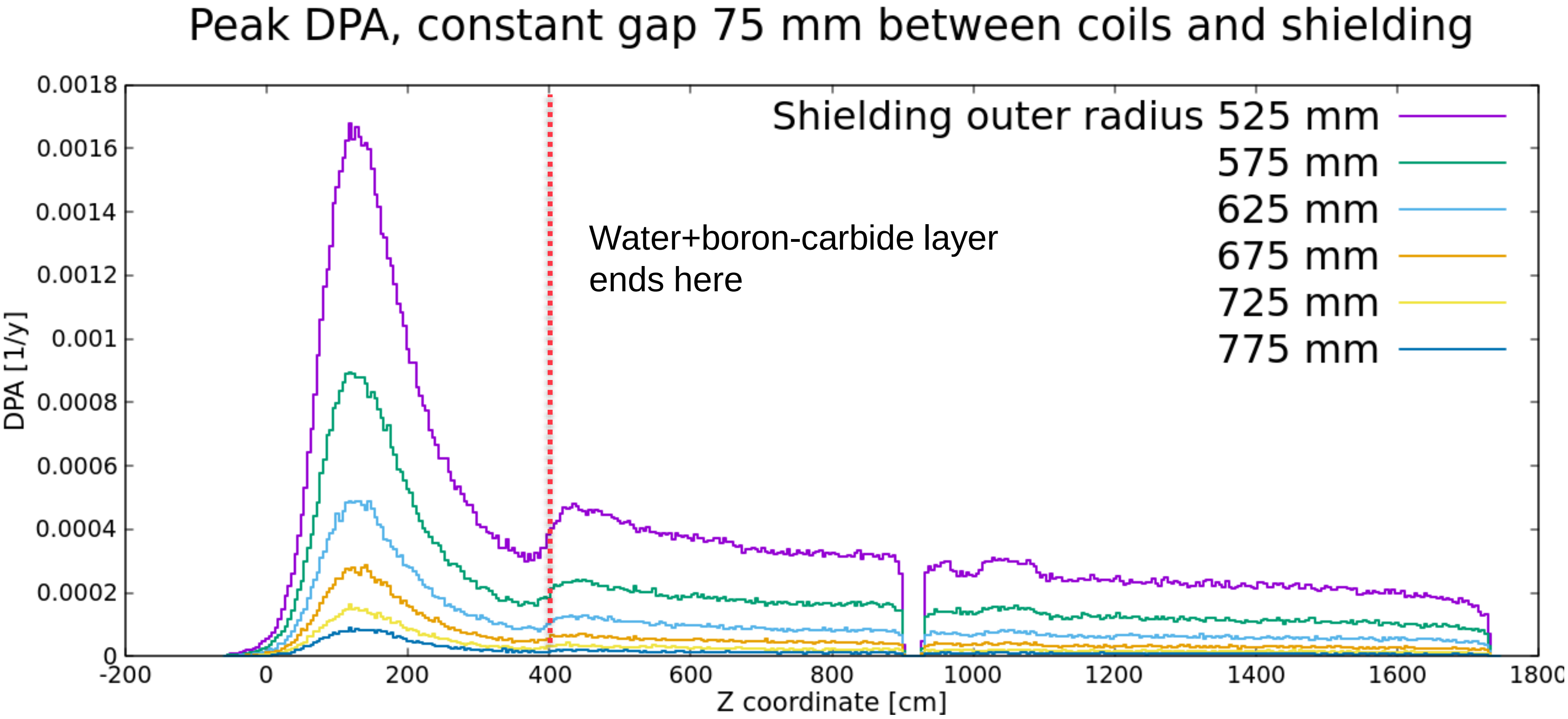
This is still the old magnet layout!

DPA/year pure tungsten



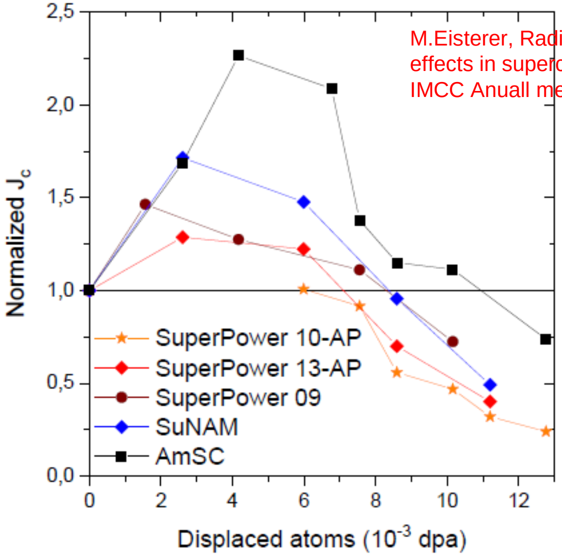
After the area in the vicinity of the target vessel, the shielding thickness can be significantly reduced

DPA/year tungsten+water+boron-carbide



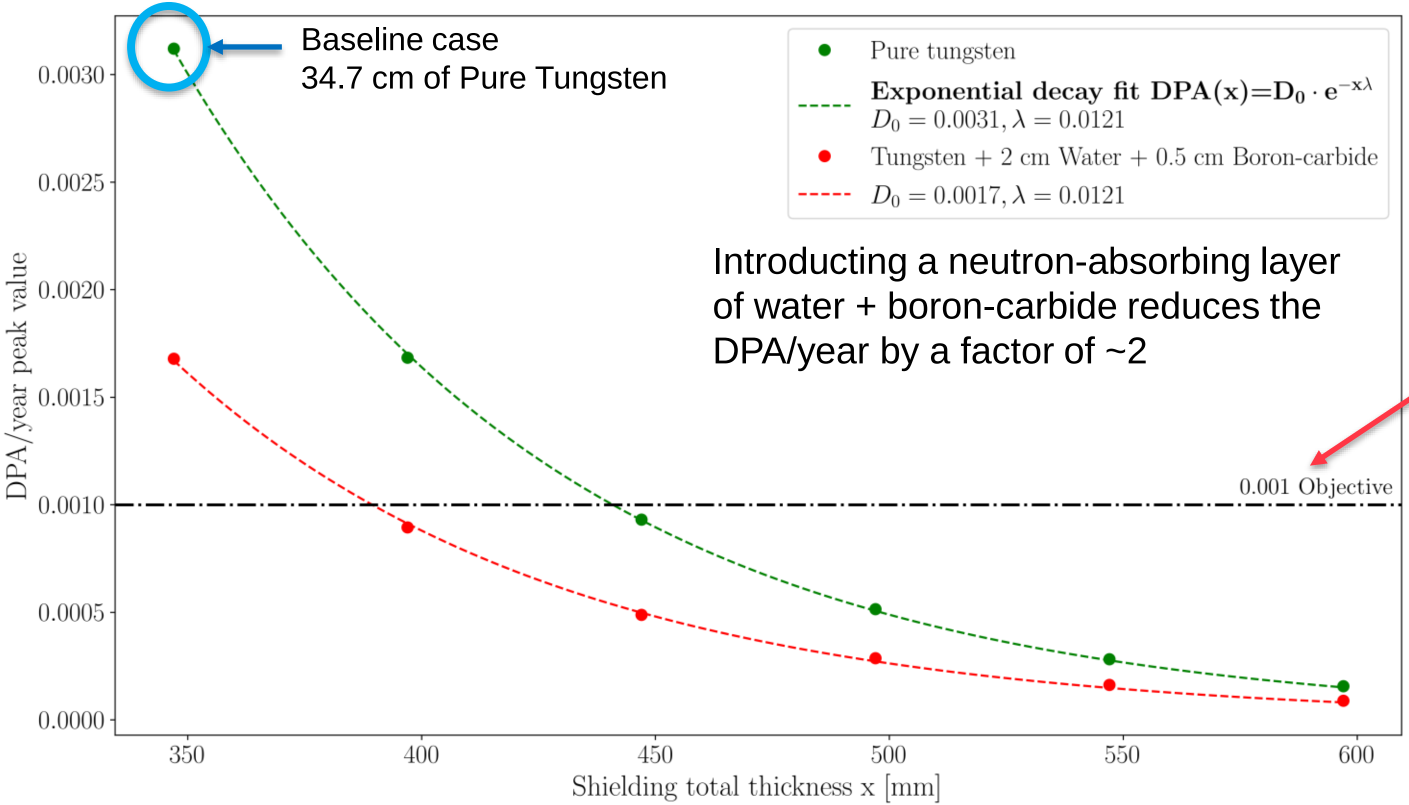
DPA limits in HTS

- From the study by M. Eisterer, a rather conservative limit for DPA/year in high temperature superconductors used in the MuColl target area can be set at the order of 10^{-3}, assuming 10 years of operation.
- This study however was performed using reactor neutron spectrum which does not correspond to what we expect in our target area. The effects might vary depending on the energy of the neutrons causing the DPA.
- The DPA might not be the best metric to evaluate long term radiation effects on HTS, but it's easily accessible in FLUKA and with a conservative limit still allows us to assess preventive measures.
- The effects of accumulated DPA can be partially reversed using **annealing** procedure (heating up the magnet coils between operation). The efficiency of this method depends on the coil material, but possibly also on the damage characteristic. For details, see the study by M. Eisterer.



M.Eisterer, Radiation effects in superconductors IMCC Anuall meeting 2022

Max DPA/year in the HTS target solenoid magnets

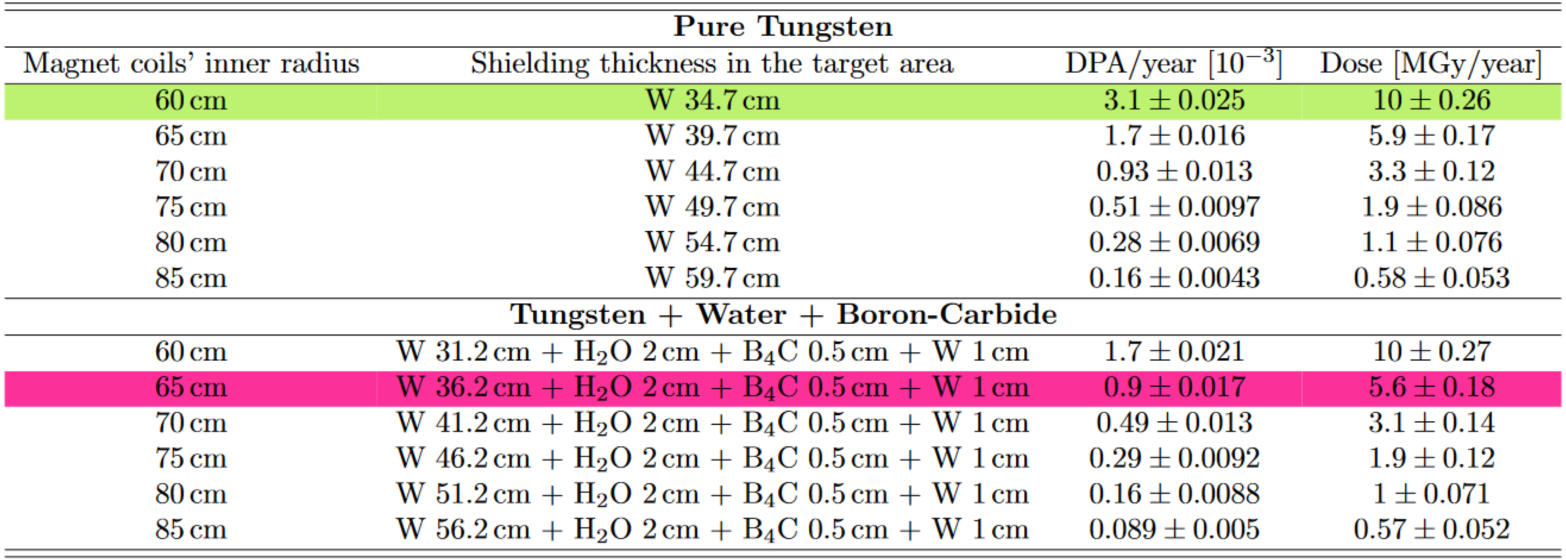


Baseline case
34.7 cm of Pure Tungsten

Introducting a neutron-absorbing layer of water + boron-carbide reduces the DPA/year by a factor of ~2

This value will depend on the annealing capabilities of the future design.

Radiation studies to the target magnets – results



Magnet coils' inner radius	Shielding thickness in the target area	DPA/year $[10^{-3}]$	Dose [MGy/year]
Pure Tungsten			
60 cm	W 34.7 cm	3.1 ± 0.025	10 ± 0.26
65 cm	W 39.7 cm	1.7 ± 0.016	5.9 ± 0.17
70 cm	W 44.7 cm	0.93 ± 0.013	3.3 ± 0.12
75 cm	W 49.7 cm	0.51 ± 0.0097	1.9 ± 0.086
80 cm	W 54.7 cm	0.28 ± 0.0069	1.1 ± 0.076
85 cm	W 59.7 cm	0.16 ± 0.0043	0.58 ± 0.053
Tungsten + Water + Boron-Carbide			
60 cm	W 31.2 cm + H_2O 2 cm + B_4C 0.5 cm + W 1 cm	1.7 ± 0.021	10 ± 0.27
65 cm	W 36.2 cm + H_2O 2 cm + B_4C 0.5 cm + W 1 cm	0.9 ± 0.017	5.6 ± 0.18
70 cm	W 41.2 cm + H_2O 2 cm + B_4C 0.5 cm + W 1 cm	0.49 ± 0.013	3.1 ± 0.14
75 cm	W 46.2 cm + H_2O 2 cm + B_4C 0.5 cm + W 1 cm	0.29 ± 0.0092	1.9 ± 0.12
80 cm	W 51.2 cm + H_2O 2 cm + B_4C 0.5 cm + W 1 cm	0.16 ± 0.0088	1 ± 0.071
85 cm	W 56.2 cm + H_2O 2 cm + B_4C 0.5 cm + W 1 cm	0.089 ± 0.005	0.57 ± 0.052

Dose does not seem to be problematic here

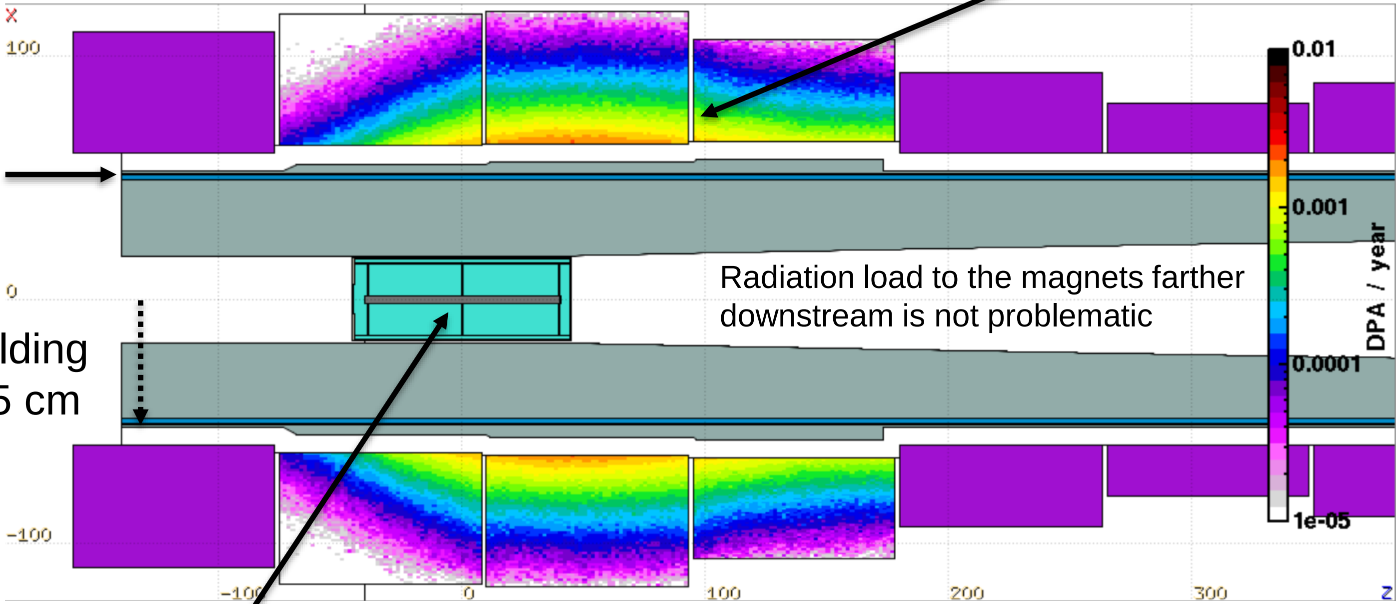
This result concluded the necessity for increase of the target solenoid inner radius AND incorporation of the neutron-capturing layer.

New tapering magnet layout

The most exposed coils were moved farther away from the target

Coil 3 is the most exposed

Layer of Water + Boron-Carbide



Radiation load to the magnets farther downstream is not problematic

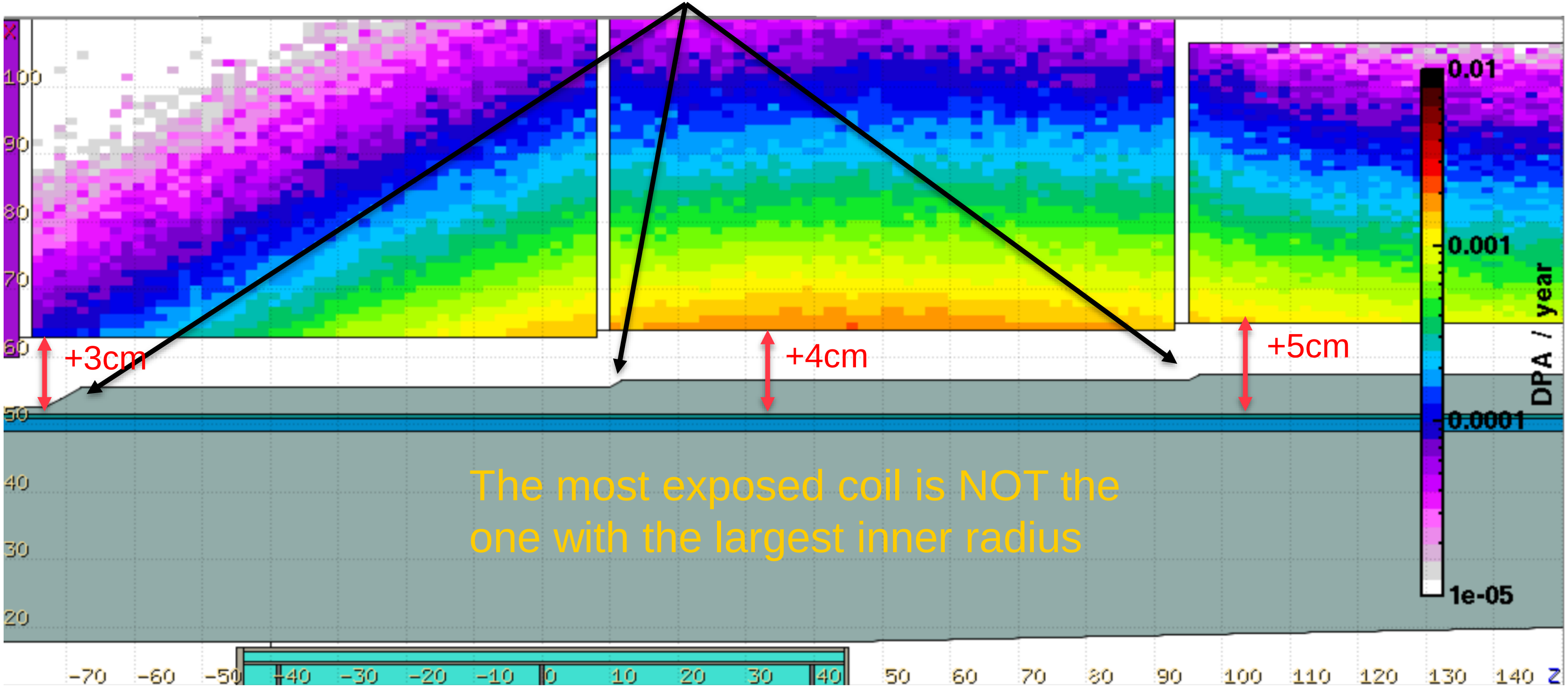
Outer shielding radius 52.5 cm

Target centered at Z=0

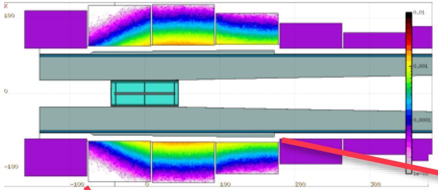
Details of the newest target magnet design can be found in the presentation by A. Portone, J. Lorenzo, P. Testoni (F4E)

New tapering magnet layout

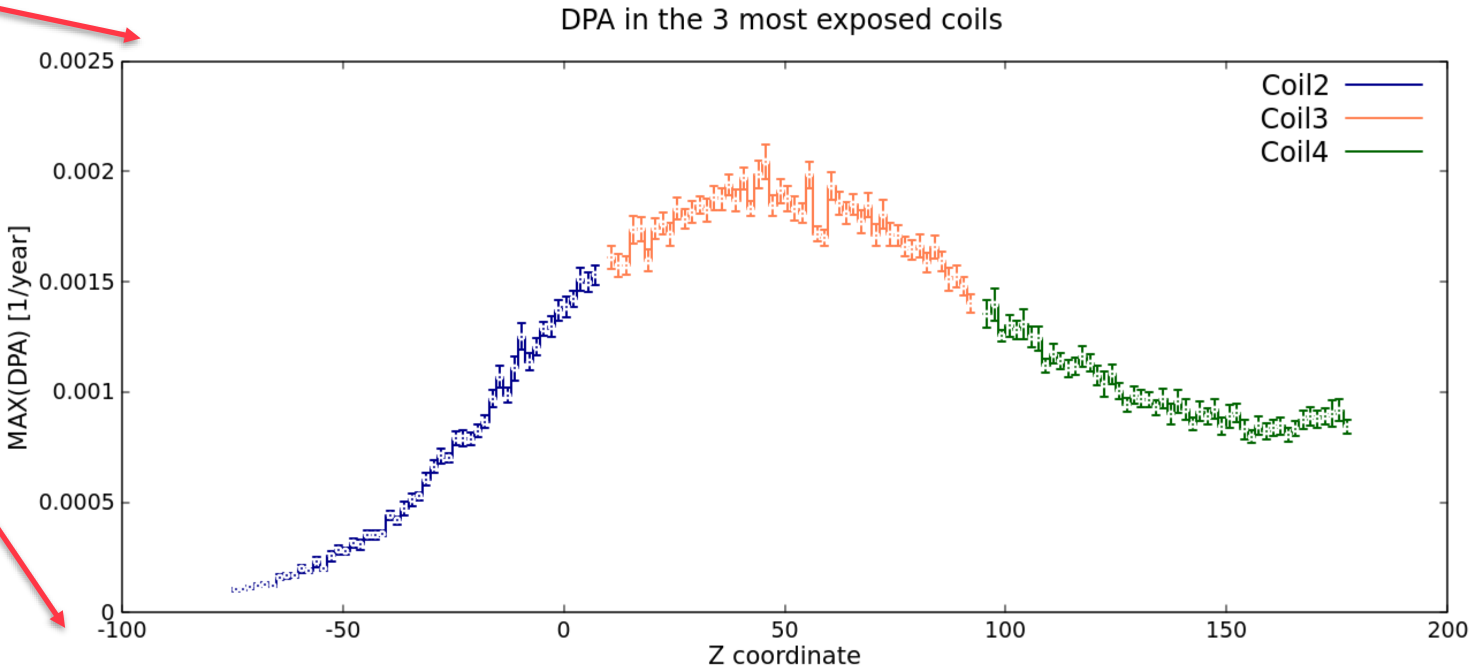
The edges are shaped so that the closest distance between the shielding and the magnets is always 7.5 cm.



Displacement per atom in the magnets

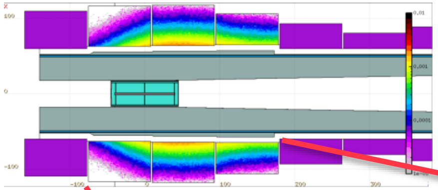


Only tungsten for shielding!

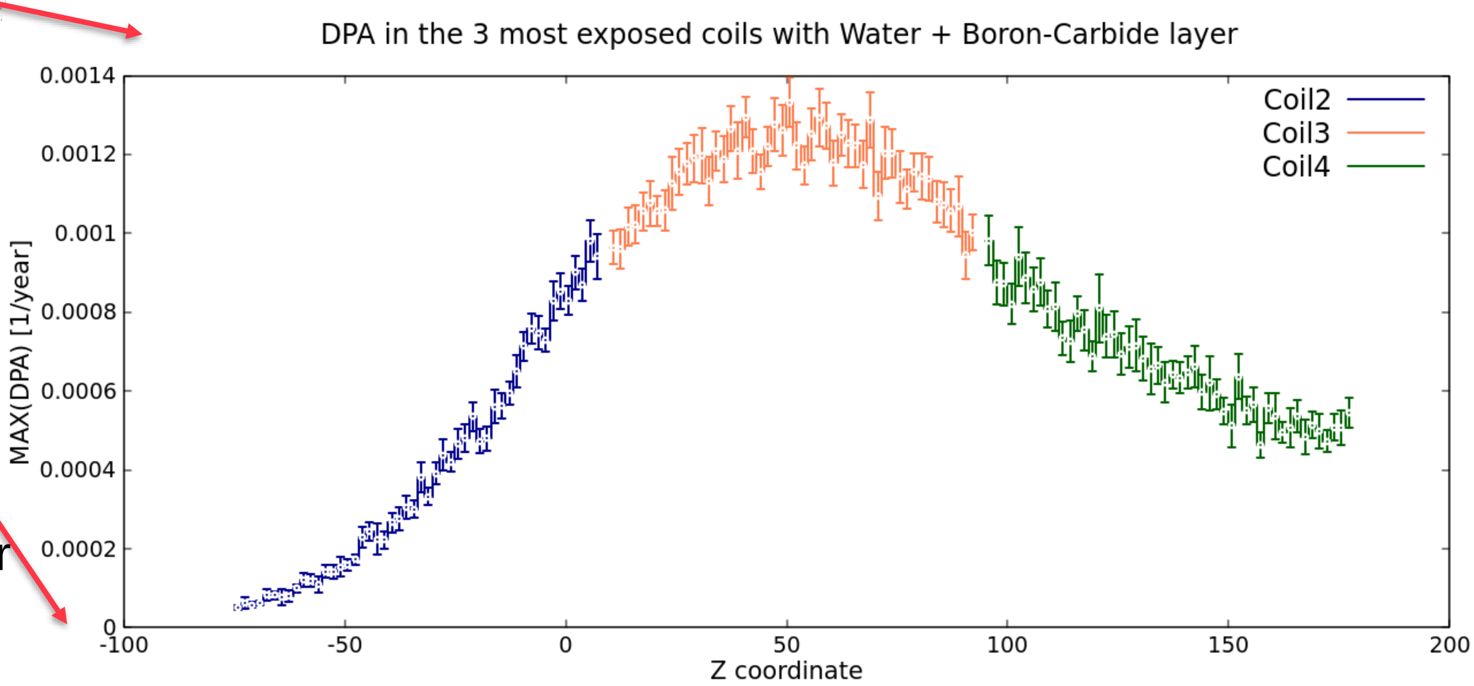


The DPA/year is most likely still too high

Displacement per atom in the magnets



Tungsten + Water + Boron-Carbide



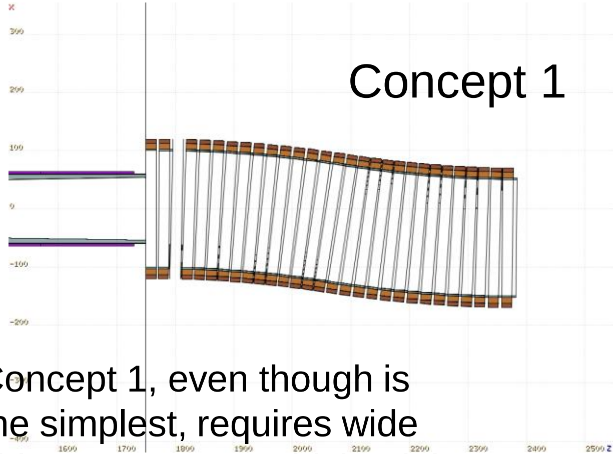
Still the DPA might be too high – further studies needed!

Radiation load to the target magnets - summary

- The dependence of the radiation load to the target area magnets on the shielding thickness and composition was evaluated.
- The newest target magnet design was implemented in FLUKA.
- The increased distance of the most exposed coils from the target might still be insufficient to keep the DPA at a tolerable level.
- Possibly, the shielding layers in the new magnet design can still be optimized. To be checked.

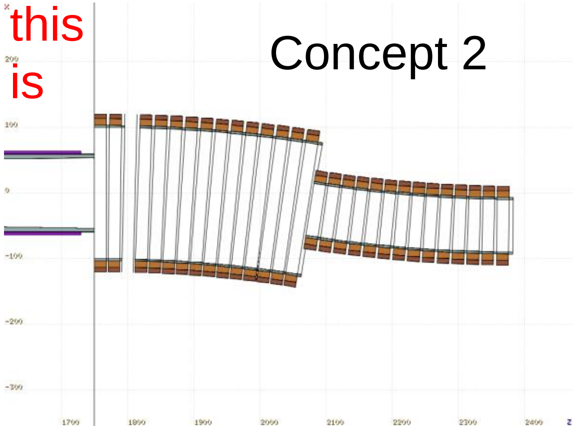
Spent proton beam extraction

3 main concepts for the proton extraction



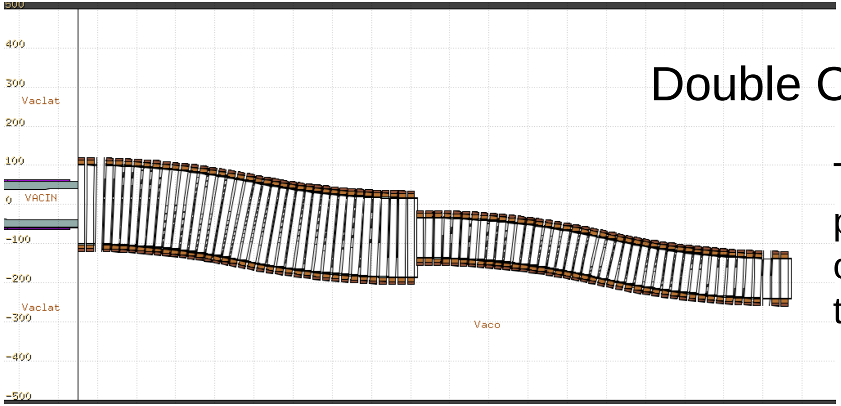
Concept 1

The focus of this presentation is Concept2



Concept 2

Concept 1, even though is the simplest, requires wide chicane aperture which might become costly in terms of keeping the desired field strength



Double Chicane

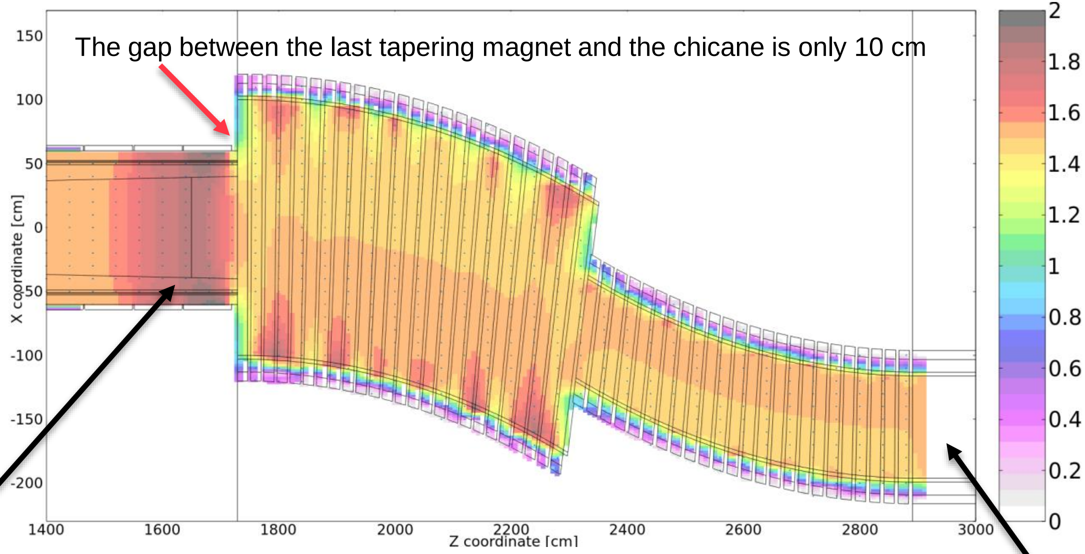
This option gives the best platform for the spatial separation of the spent proton beam after the extraction

Concept 2 investigated

Parameters in the model:

- Bending radius
- Opening angle
- First half aperture
- Second half aperture
- Relative shift between the two halfs
- Magnetic field / current density in each coil

Current densities in the solenoid magnets have been fitted with the MINUIT2 minimizer to achieve 1.5T along the center line of the chicane

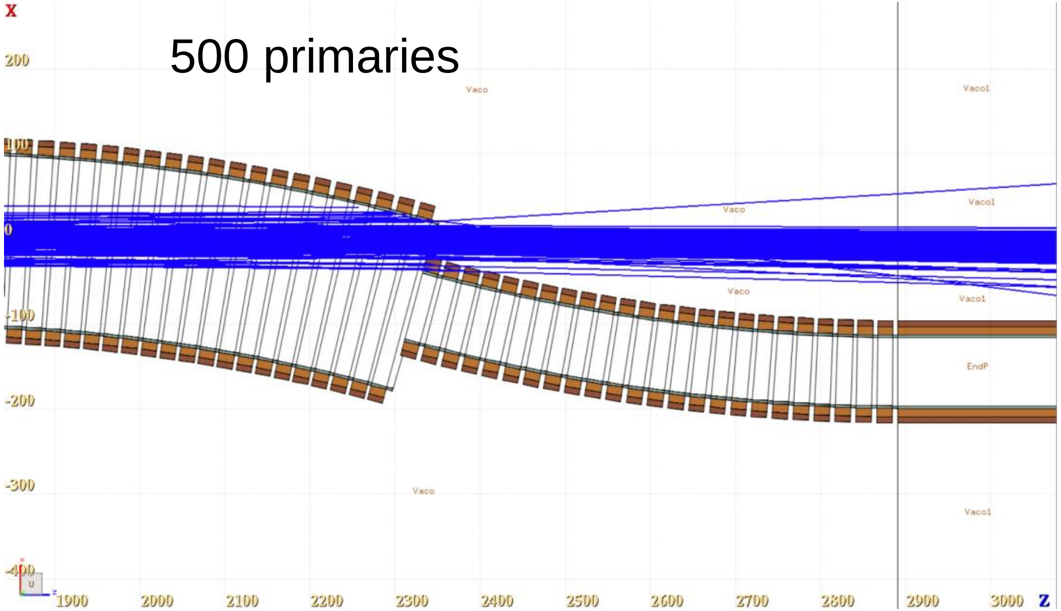


The gap between the last tapering magnet and the chicane is only 10 cm

This increase in the field strength comes from the fact that the current densities in the tapering magnets were not varied in the fit. The attempt to include just the last magnet did not improve the result.

Long straight element with a fixed current density to stabilize the field at the of the chicane

Chicane parameter adjustment



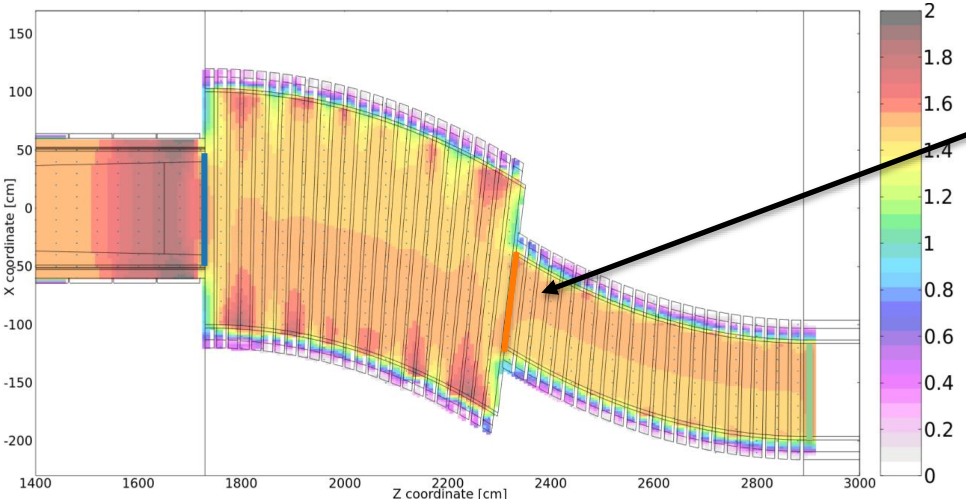
500 primaries

🟦 Spent primary protons with E > 4 GeV

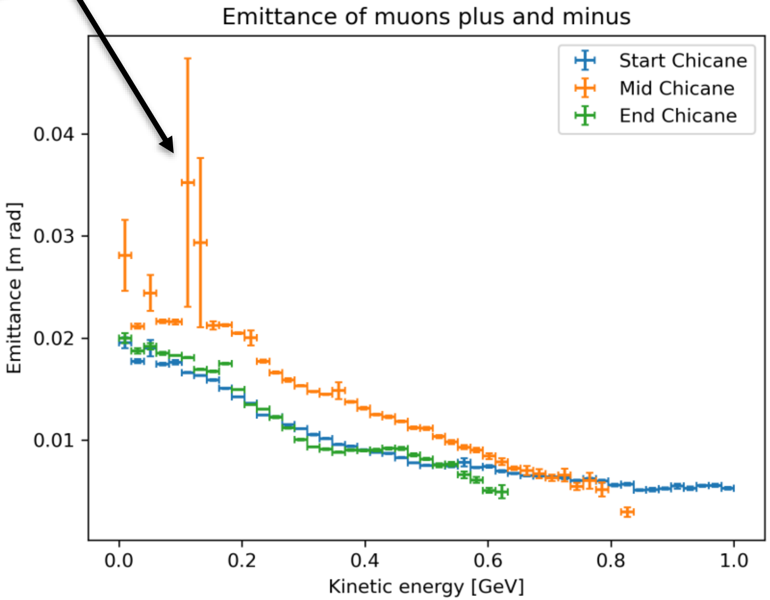
Geometry prepared for a straight target configuration

- Angle = 15 deg
- Bending Radius = 22 m
- Big aperture = 100 cm
- Small aperture = 50 cm
- Center of the narrow part aligned wit the center of the wide part

Figure of merit – the muon emittance

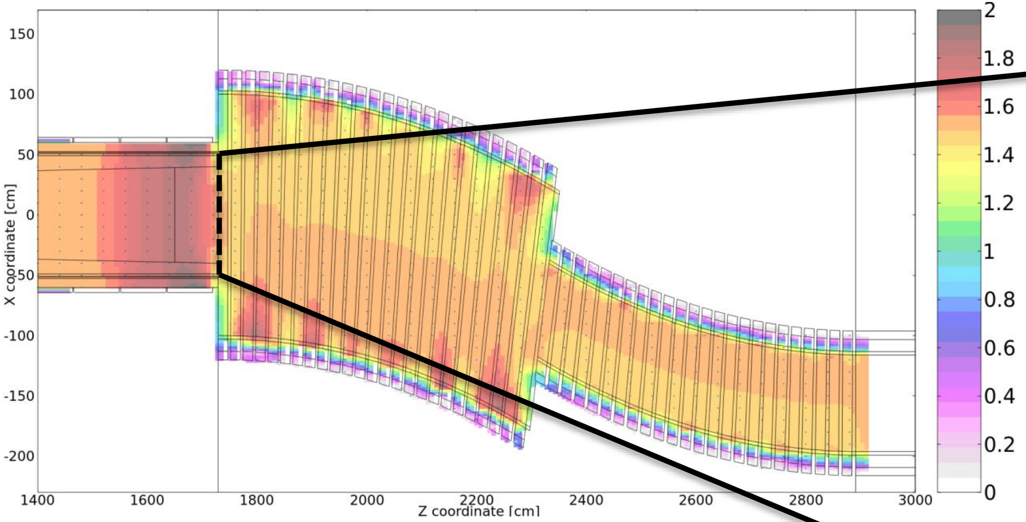


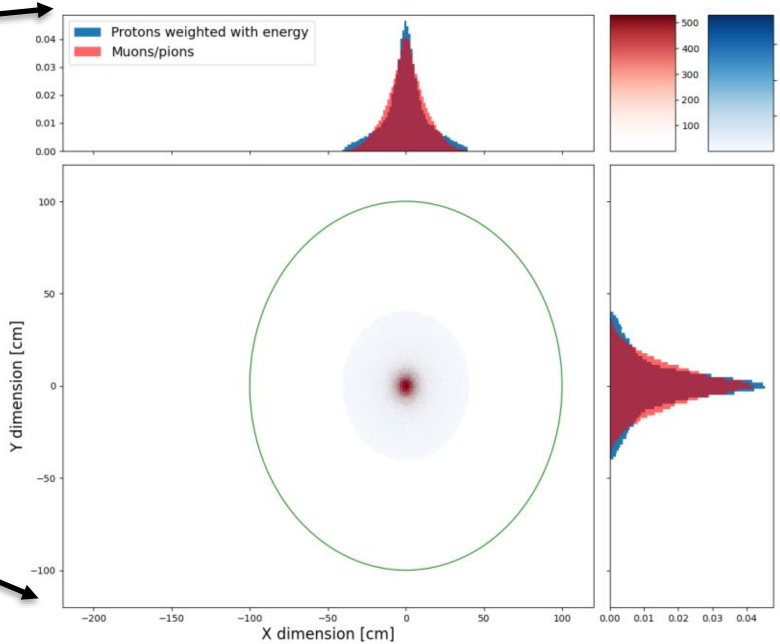
In the following slides we will see what's happening here



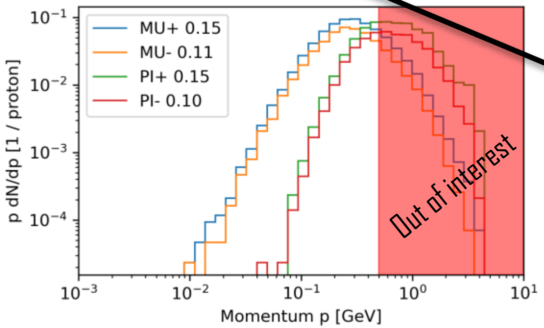
Muons with $E_k > 600$ MeV basically do not reach the end of the chicane, they are dumped in the chicane walls.

Concept 2, beam shape



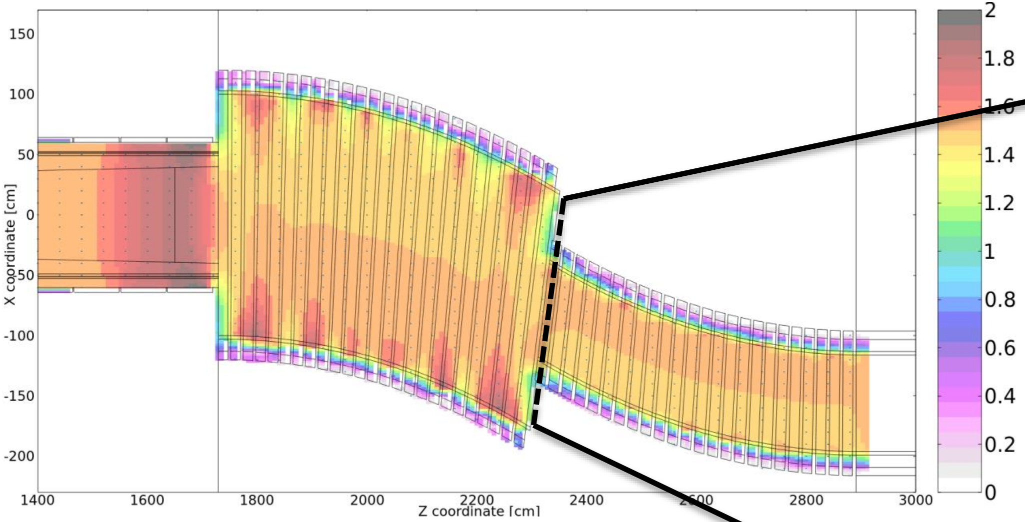


Particles entering the chicane are nicely centered.

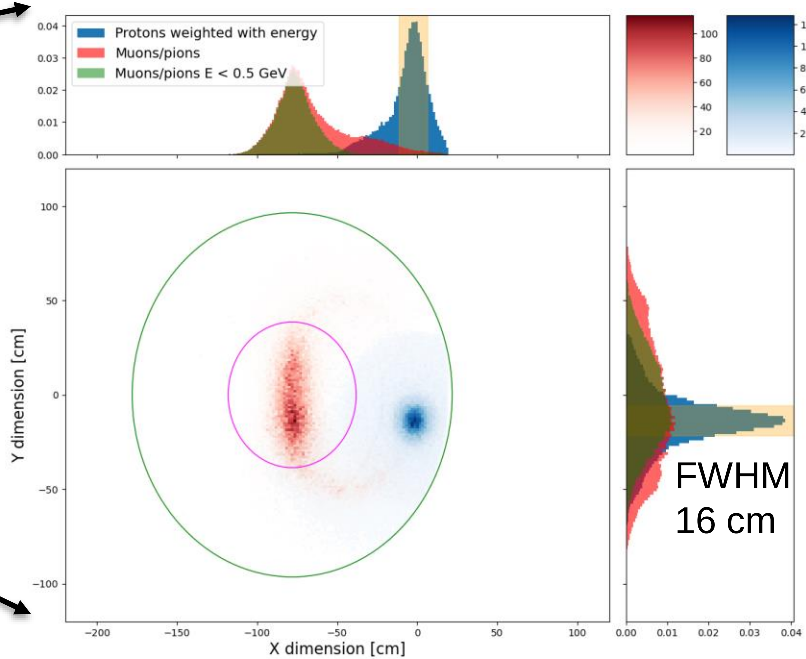


Momentum spectrum

Concept 2, beam shape



FWHM 17.7 cm

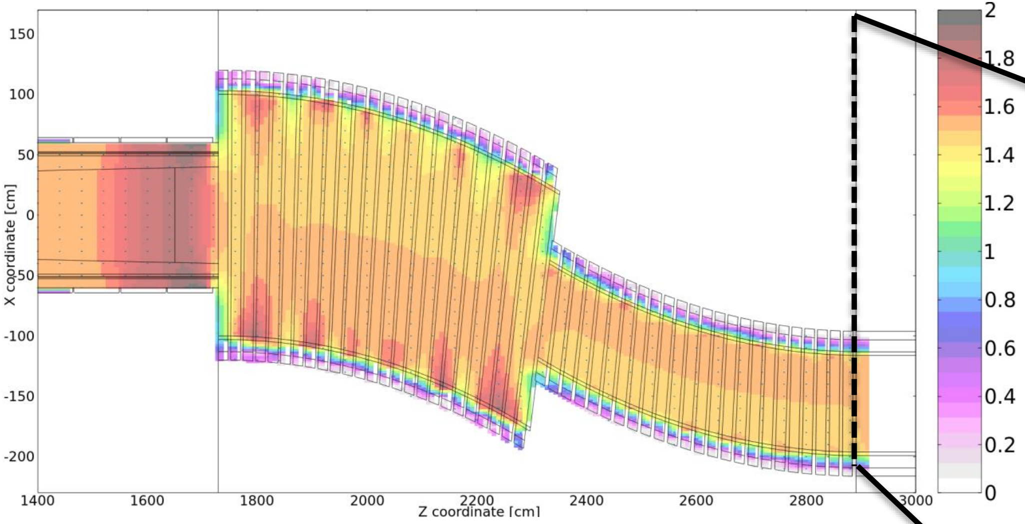


FWHM 16 cm

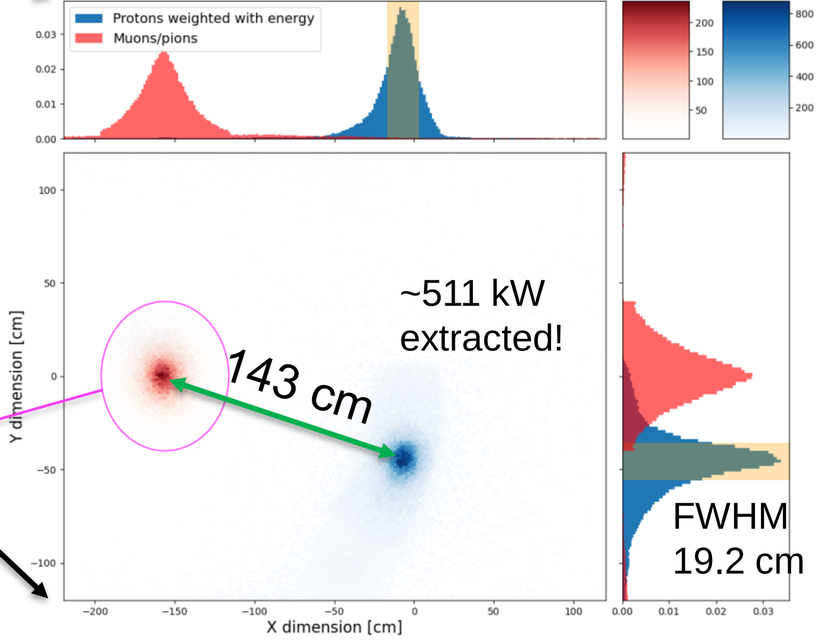
At it was shown before, the transverse emittance of muons in the center of the chicane blows up – here we can see it happens due to the vertical elongation. However, it gets compensated by the end of the chicane.

Here we observe all the particles crossing the dashed line **including** the ones hitting the magnets

Concept 2, beam shape



FWHM 19 cm

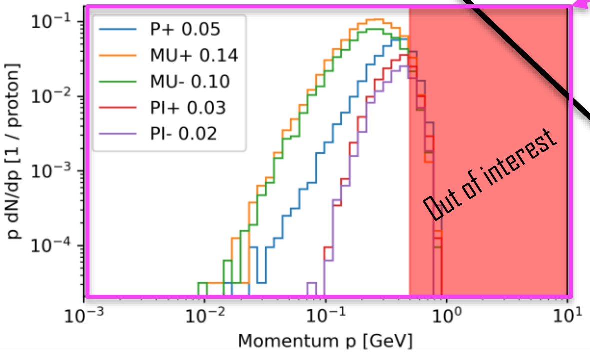


~511 kW extracted!

143 cm

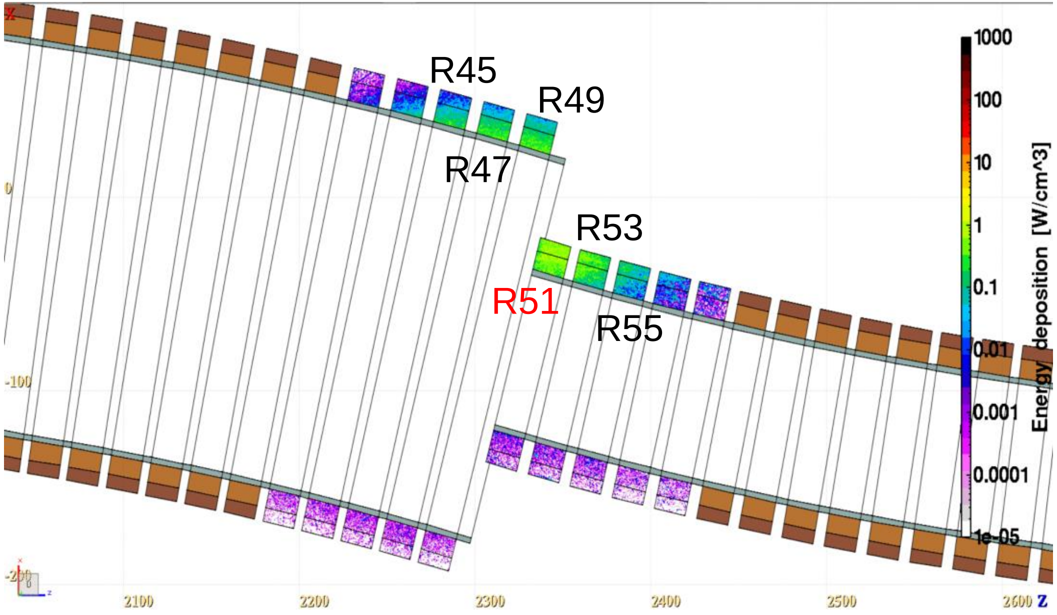
FWHM 19.2 cm

The spent proton beam exiting the chicane is inclined slightly down – its center moves down **in Y by 35 cm** over a distance of **~5 m in Z**.



Momentum spectrum of particles only inside the solenoid!

Concept 2, energy deposition to the most exposed magnets



Magnet	Integrated energy deposition [kW]
MagR45	2.09
MagR47	3.73
MagR49	5.32
MagR51	24.5
MagR53	8.63
MagR55	2.51
Total	46.8

Possibly, the shape can be fine-tuned to reduce the energy deposition or spread it more evenly between the magnets.

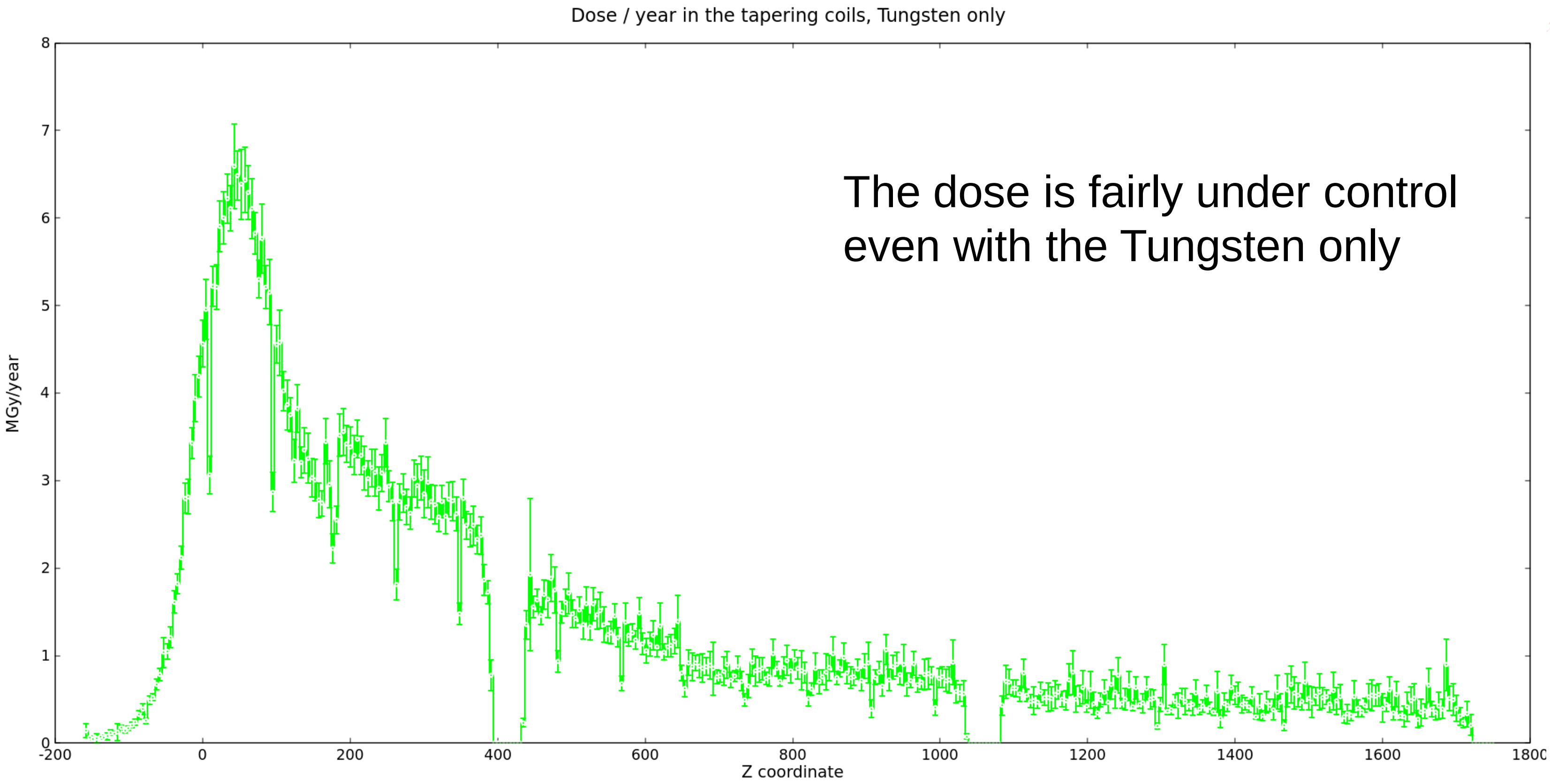
Spent proton beam extraction channel study - summary

- An example chicane configuration was investigated in the scope of spent proton beam extraction.
- A figure of merit for optimization and future comparisons was developed in the process.
- Once the geometry of the chicane and the proton extraction channel is established, the magnetic field at the end of the tapering region should be adjusted considering the chicane magnets. Also, the minimum gap between the last tapering magnet and the chicane should be established.
- Magnetic field in the chicane was calculated assuming relatively liberal constraints on the current density and the big solenoid aperture radius 100 cm. The feasibility of this solution should be verified.

Thank you for your attention!

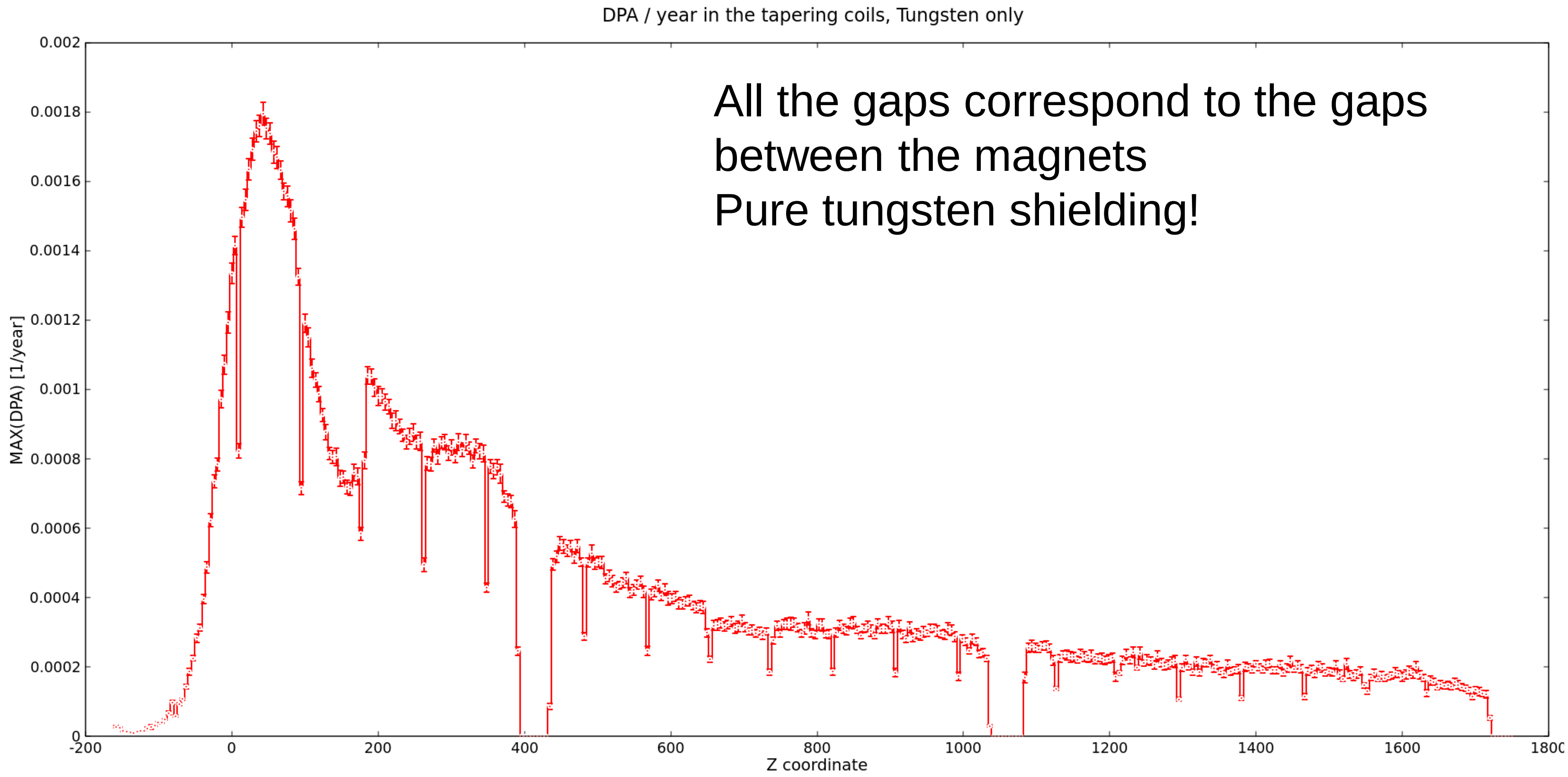
Backup

Dose in the magnets



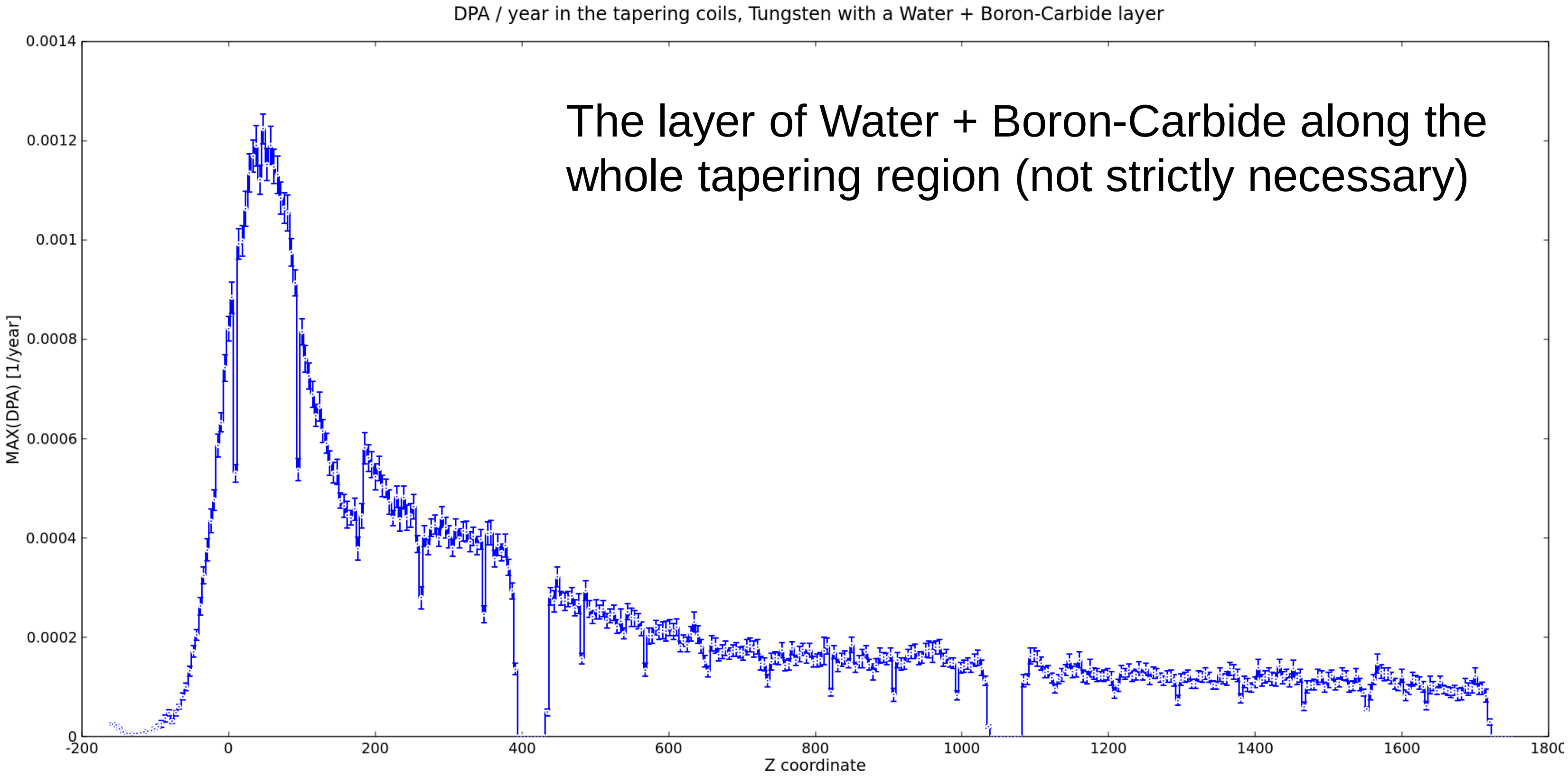
The dose is fairly under control even with the Tungsten only

Displacement per atom in the magnets – new layout



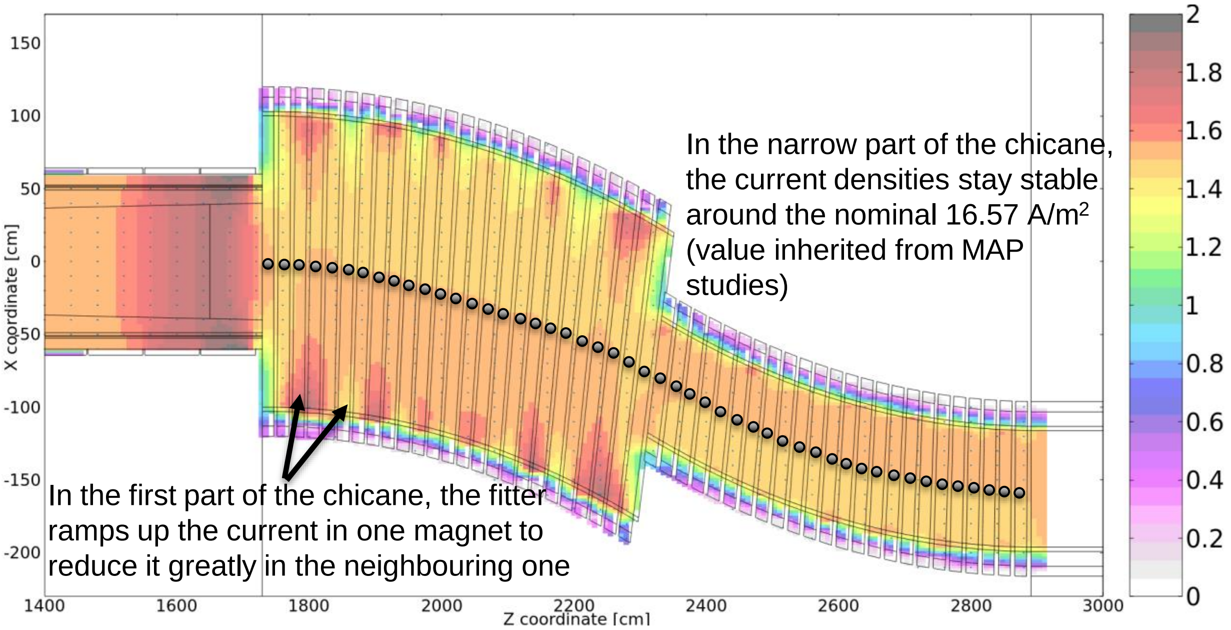
All the gaps correspond to the gaps between the magnets
Pure tungsten shielding!

Displacement per atom in the magnets – new layout



The layer of Water + Boron-Carbide along the whole tapering region (not strictly necessary)

Fitting the field



In the narrow part of the chicane, the current densities stay stable around the nominal 16.57 A/m^2 (value inherited from MAP studies)

In the first part of the chicane, the fitter ramps up the current in one magnet to reduce it greatly in the neighbouring one

The fit limits the parameters (current densties) to **16.57 A/m^2 +/-60%**

Field calculation based on the script developed by D. Calzolari

● Data points corresponding to the center of each solenoid magnet and the field strength of 1.5T

The number of fit parameters is equal to the number of data points – the parameters are the current densities of each magnet