International
MUON Collider
Collaboration

Radiation load studies for the proton target area of a multi-TeV muon collider

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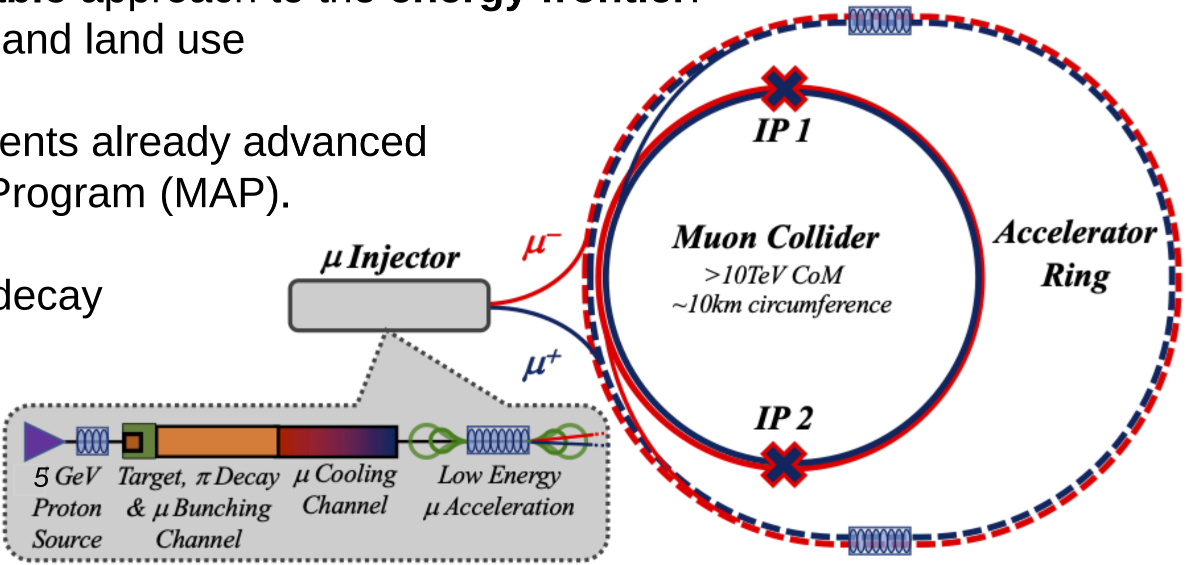
Proton-driven muon source for a multi-TeV muon collider

- Strong interest in the particle physics community in high-luminosity and high-energy lepton collider for the post-LHC era. The **International Muon Collider Collaboration was established in 2021** to explore the feasibility of a muon collider.

- Muon collider promises **sustainable** approach to the **energy frontier**: limited power consumption, cost and land use

- Technology and design requirements already advanced thanks to the Muon Accelerator Program (MAP).

- **A significant challenge**: muon decay (2.2 μs lifetime at rest)



Here, we investigate the feasibility of a **proton-driven** muon production for a muon collider.

Muon collider ring: key parameters

Preliminary parameters – may change as the design studies move on…

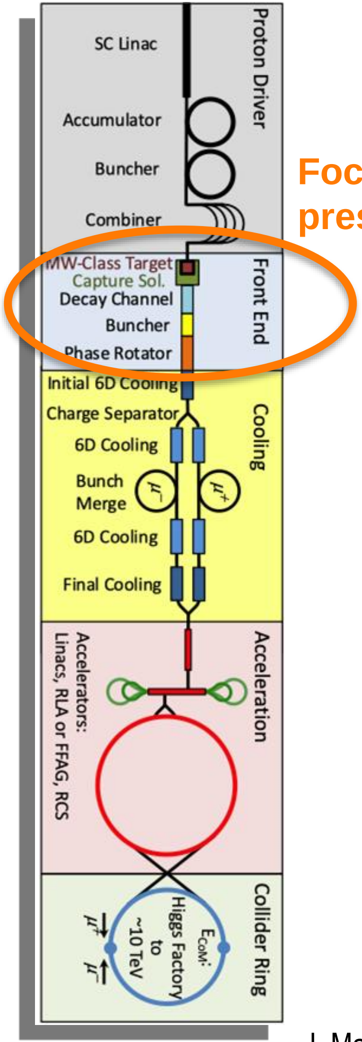
Parameter		Unit	3 TeV	10 TeV	14 TeV
Beam energy	E_{beam}	TeV	1.5	5	7
Relativistic factor	$\gamma=E_{beam}/m$	-	$1.4\cdot10^4$	$4.7\cdot10^4$	$6.6\cdot10^4$
Muon mean life (lab frame)	$\tau_{lab}=\gamma\cdot\tau$	s	0.03	0.10	0.15
Luminosity	L	10^{34} cm^{-2}s^{-1}	1.8	20	40
Injected muons per bunch	**N**	**10^{12}**	**2.2**	**1.8**	**1.8**
Injection frequency	**f_r**	**Hz**	**5**	**5**	**5**
Beam power	P_{beam}	MW	5.3	14.4	20
Circumference	C	km	4.5	10	14
Avg magnetic field	<B>	T	7	10.5	10.5

Currently the collaboration studies the feasibility of different designs

The required intensity poses a challenge for the muon production stage

Energy for discovery
10-14 TeV lepton collisions comparable to 100-200 TeV proton collisions

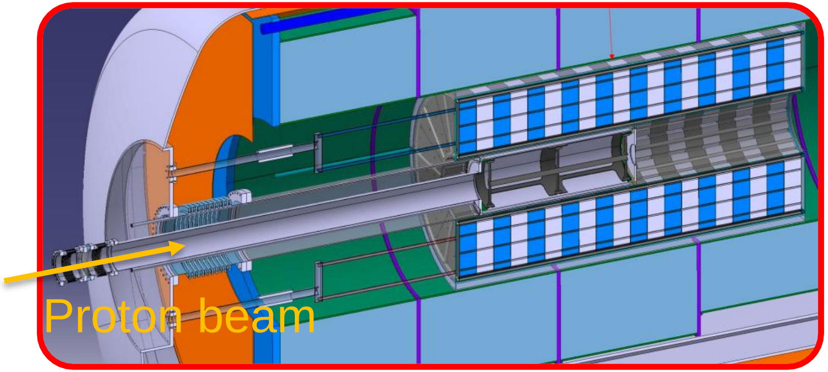
Presentation Outline



Focus of this presentation

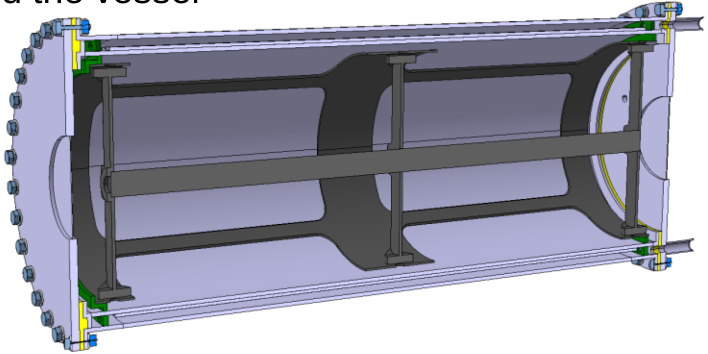
1. **Radiation load to the magnets in the proton target area.**
   - Systematic study of the dependence of the radiation load on the shielding design.
   - Improved target area magnet layout to meet the radiation load limits.
2. **Extraction channel for the primary protons that pass through the target (spent protons)**
   - Understanding the constraints.
   - Spatial separation of the extracted protons and the end of the chicane – how much space is available to place a beam dump.
   - Power deposition in the front-end equipment and the chicane solenoid magnets (normal conducting)

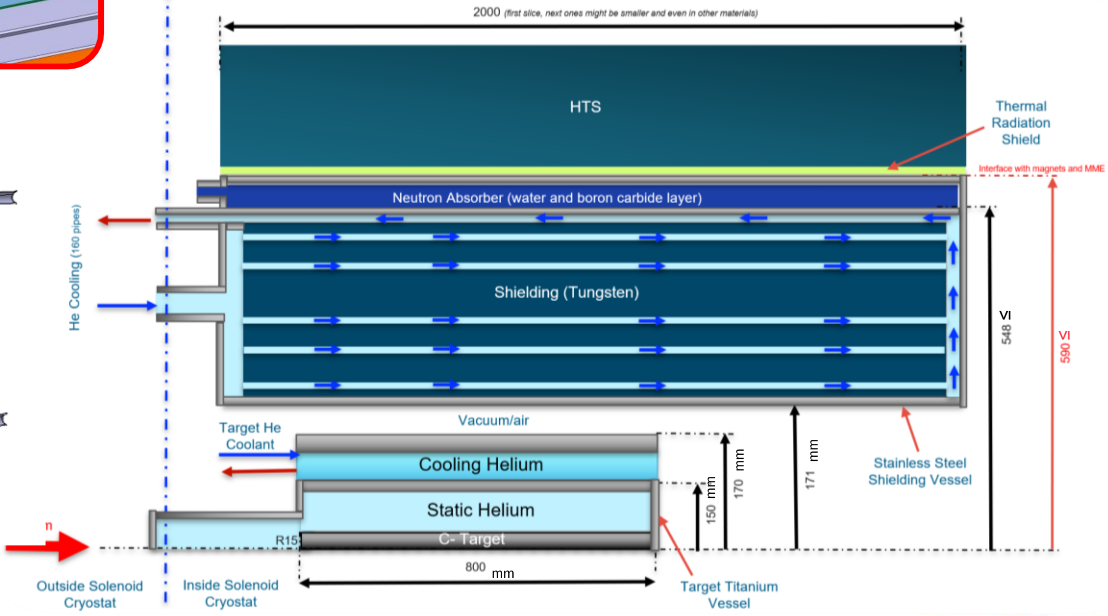
Proton target area



- The solenoids embed a radiation shielding made of helium gas-cooled tungsten segments.
- The HTS coils are made of the VIPER material*

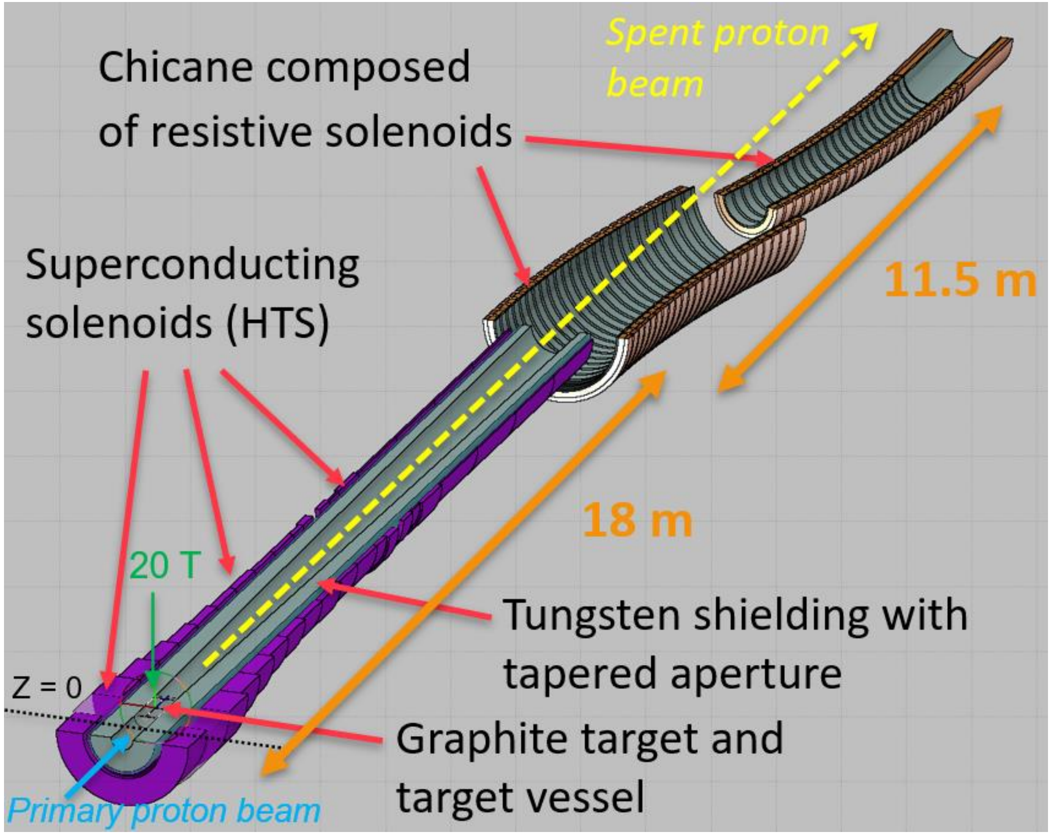
Graphite target rod with supporting structure and the vessel





*Z. Hartwig et al.,doi:10.1088/1361-6668/abb8c0

Front-end layout model in FLUKA



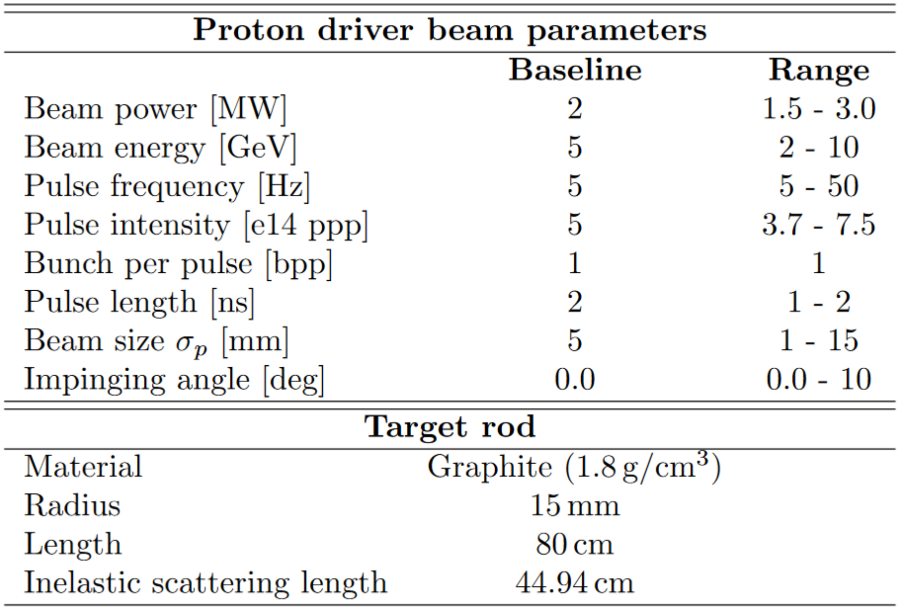
- **Protons** impact the target and **generate pions** in inelastic interactions.

- The shielding has a tapered aperture downstream of the target to confine the secondary pions and the muons emerging from pion decay

- The HTS coils must stay functional for about **10 years of operation**.

- **A chicane** made of resistive solenoids is placed after the tapered region to **filter out the high-momentum particles**. At the same time, the chicane has to accommodate space for **the extraction channel of the spent primary protons**.

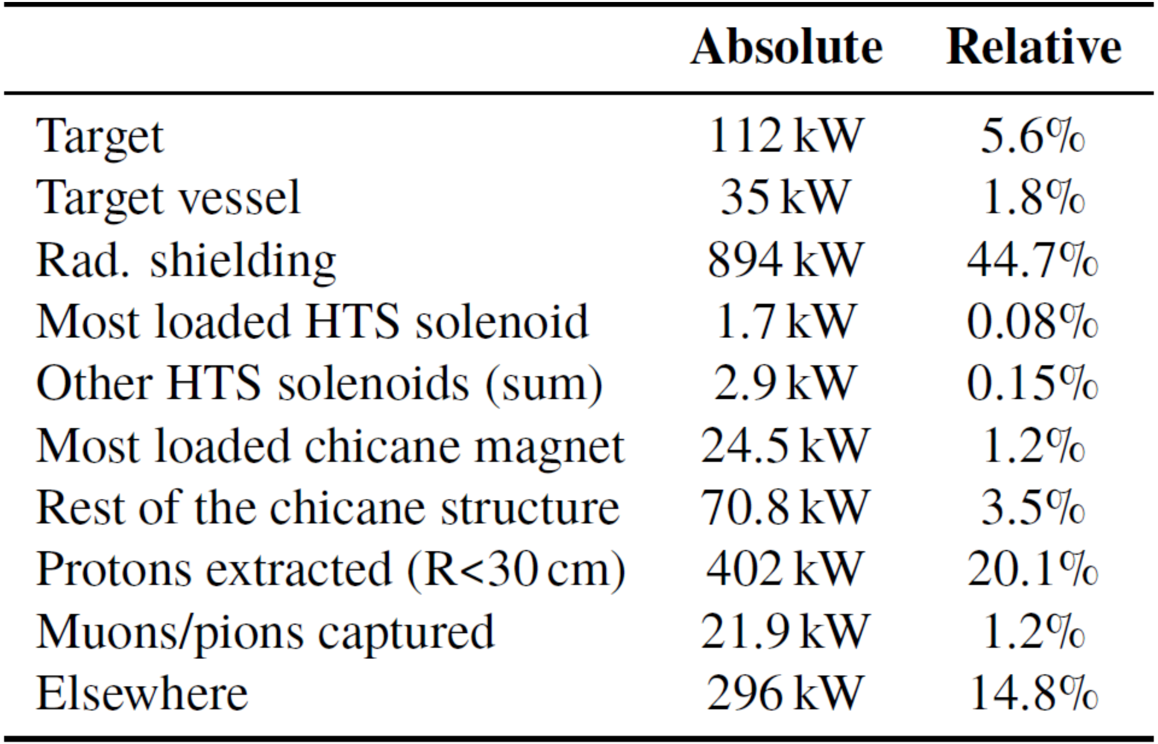
Parameters



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 g/cm^3)	
Radius	15 mm	
Length	80 cm	
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.

Power deposition in the target area



	Absolute	Relative
Target	112 kW	5.6%
Target vessel	35 kW	1.8%
Rad. shielding	894 kW	44.7%
Most loaded HTS solenoid	1.7 kW	0.08%
Other HTS solenoids (sum)	2.9 kW	0.15%
Most loaded chicane magnet	24.5 kW	1.2%
Rest of the chicane structure	70.8 kW	3.5%
Protons extracted (R<30 cm)	402 kW	20.1%
Muons/pions captured	21.9 kW	1.2%
Elsewhere	296 kW	14.8%

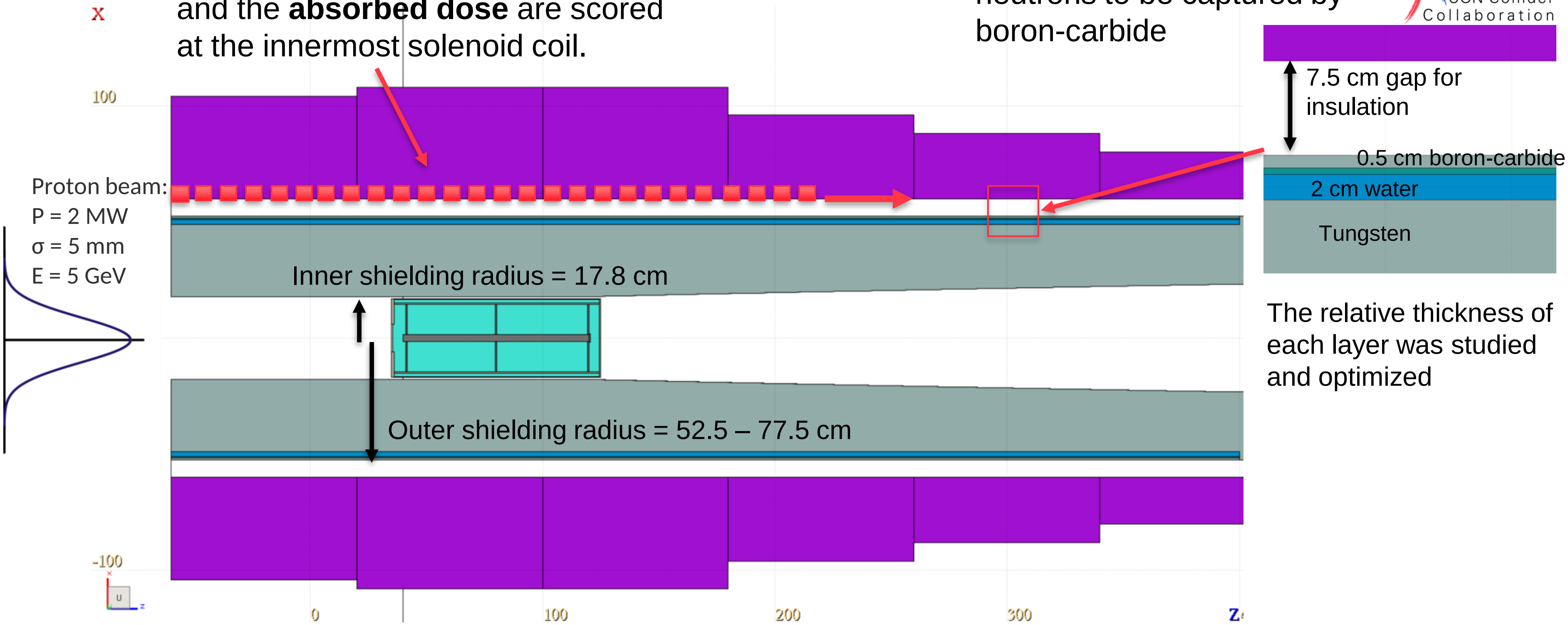
- **The shielding dissipates almost half (45%) of the initial proton beam power**, while only **7.4% is deposited in the target rod and vessel**.
- In total, the power load on HTS solenoids is less than 5 kW, which is considered acceptable for the heat evacuation from the cold mass.
- Only 22 kW is converted into useful pions and muons, while **402 kW is carried by spent and high-energy secondary protons.**
- About 95 kW is deposited in the chicane.

Radiation load to the target solenoid magnets

Target area geometry

The **Displacement per Atom (DPA)** and the **absorbed dose** are scored at the innermost solenoid coil.

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



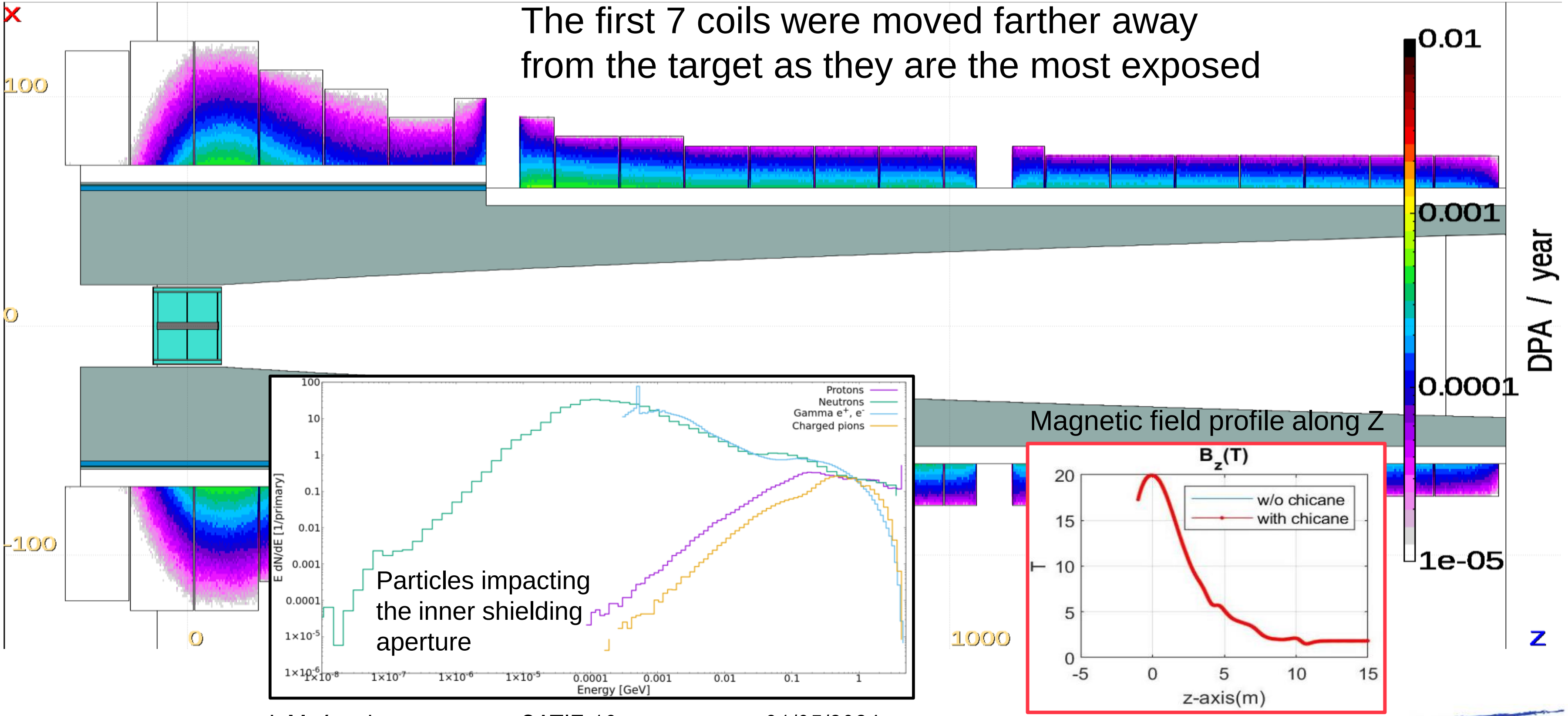
Proton beam:
P = 2 MW
σ = 5 mm
E = 5 GeV

Inner shielding radius = 17.8 cm

Outer shielding radius = 52.5 – 77.5 cm

The relative thickness of each layer was studied and optimized

Improved tapering magnet layout

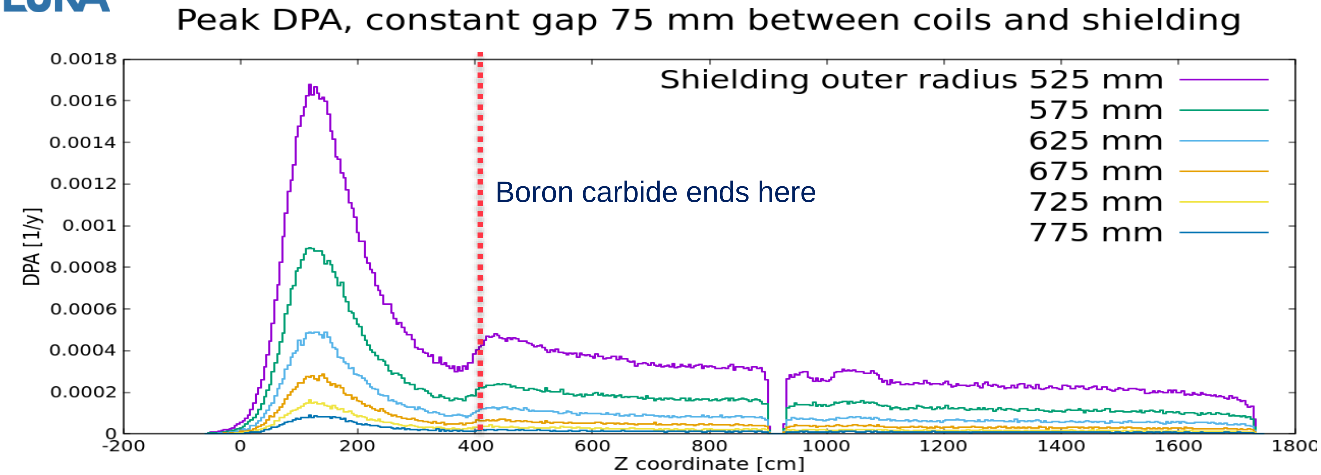


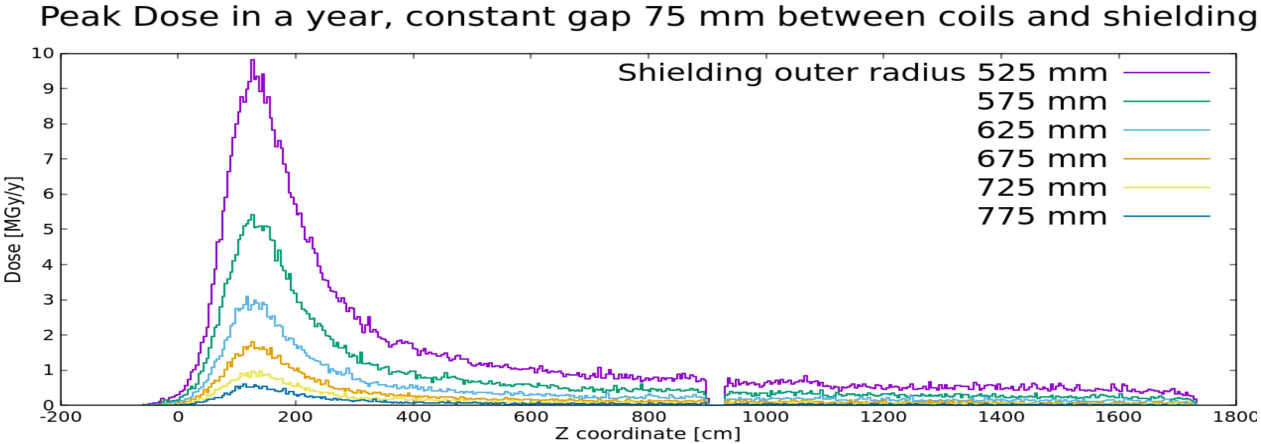
The first 7 coils were moved farther away from the target as they are the most exposed

Particles impacting the inner shielding aperture

Magnetic field profile along Z

Radiation load in the HTS coils



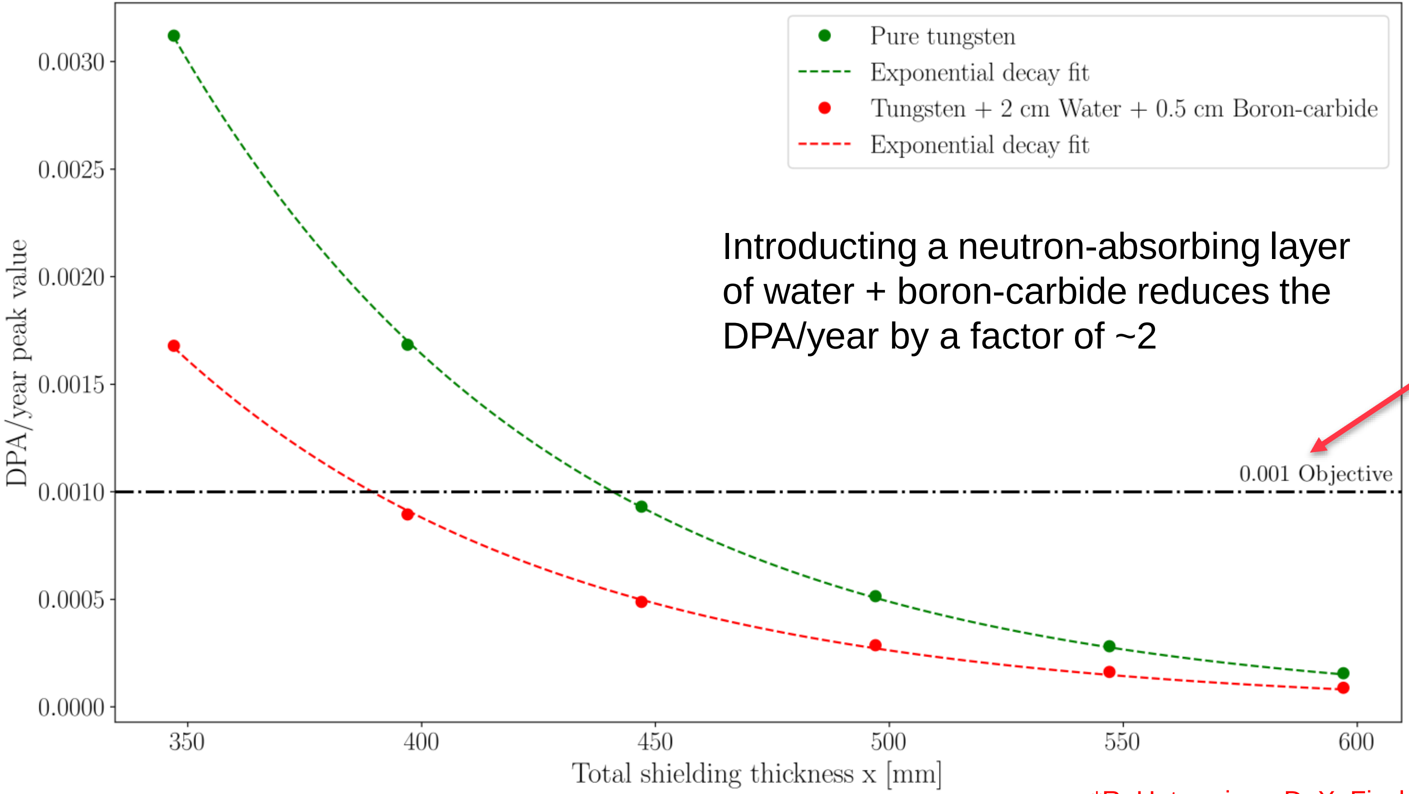


DPA-NRT model [1] with material specific energy thresholds from [2].

Cylindrical binning assuming axial symmetry, Bin size in R = 1 cm

[1] M. Norgett, M. Robinson, I. Torrens, doi: 10.1016/0029-5493(75)90035-7
[2] R. MacFarlane and A. Kahler, doi:10.1016/j.nds.2010.11.001

Max DPA/year in the HTS target solenoid magnets



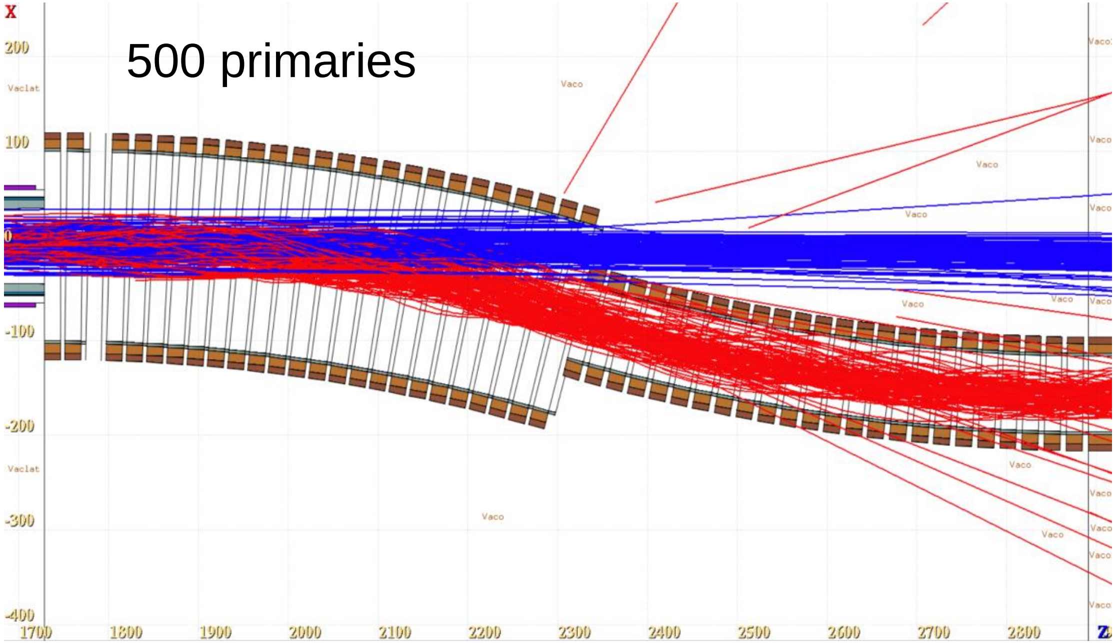
Introducting a neutron-absorbing layer of water + boron-carbide reduces the DPA/year by a factor of ~2

This value will depend on the **annealing effect*** of the chosen magnet technology.

*R. Unterrainer, D. X. Fischer, A. Lorenz, and M. Eisterer, doi:10.1088/1361-6668/ac4636

Spent proton beam extraction

Chicane design

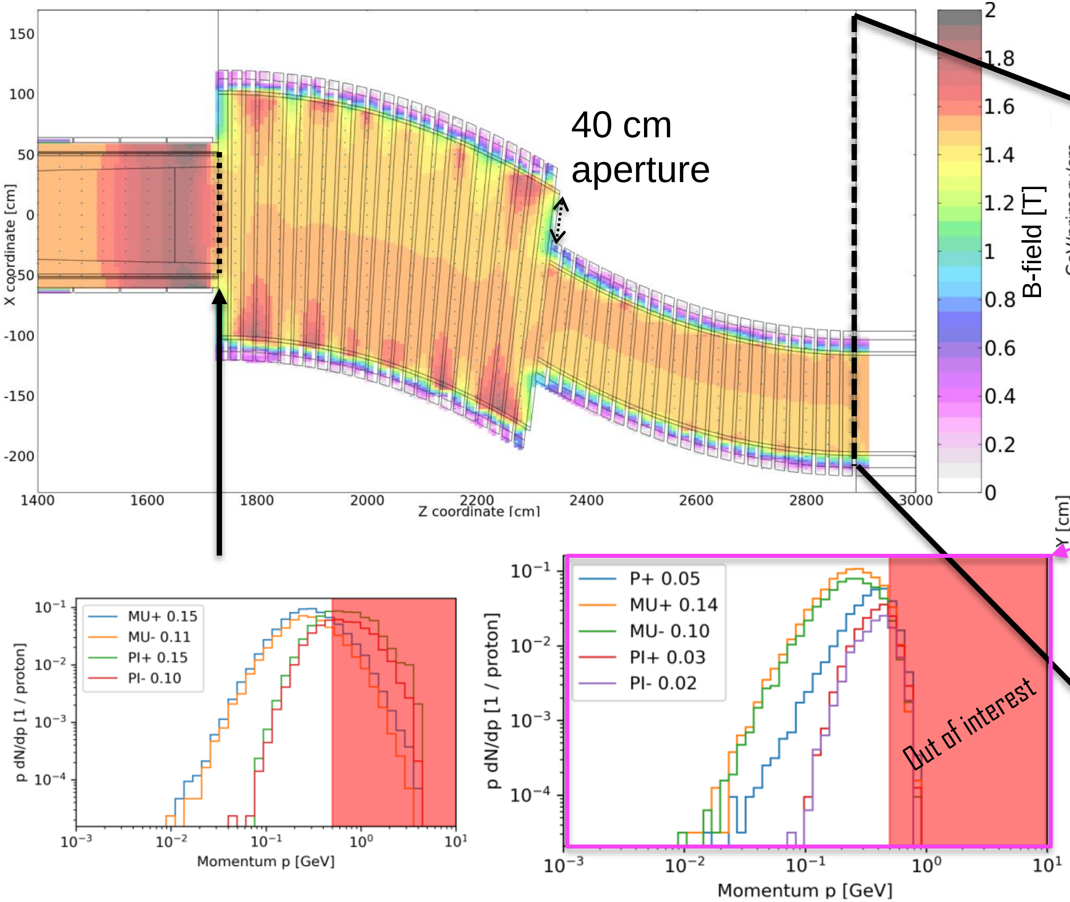


🟦 Protons with E > 4 GeV 🟥 Muons

Spent protons still focused when entering the chicane, high energy density can damage the coils if not properly extracted.

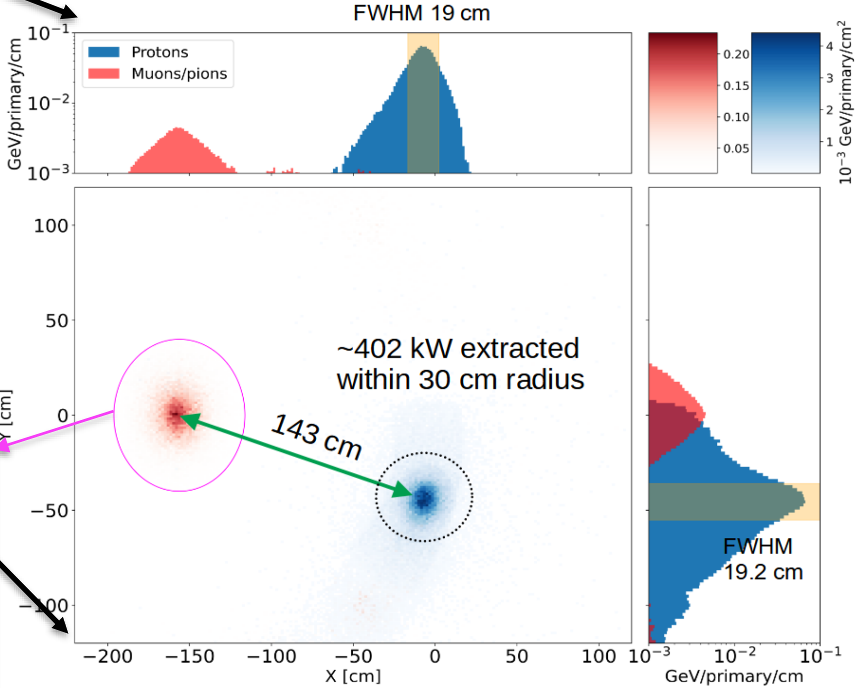
The challenge: Extract the protons while keeping the muon distribution within the desired spectrum.

Particle spectra in the chicane



40 cm aperture

Out of interest



FWHM 19 cm

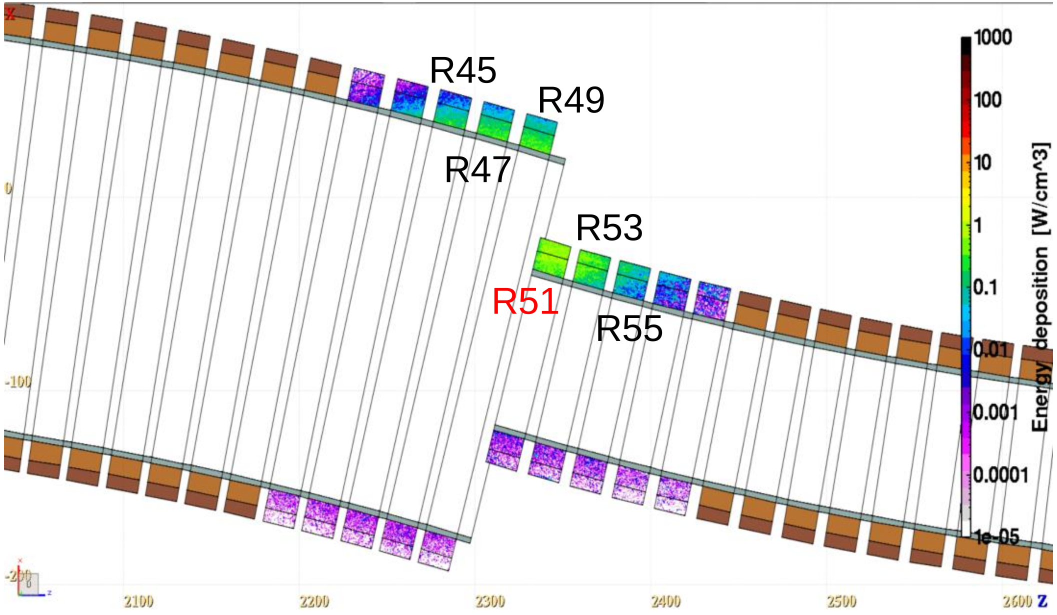
~402 kW extracted within 30 cm radius

143 cm

FWHM 19.2 cm

Momentum spectrum gets truncated by the chicane at around 500 MeV

Power density in the chicane



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.

Summary

- The challenge of radiation load to the HTS magnets in proton-driven muon production phase of a muon collider was studied and addressed in the design.
- The magnet bore of the proton target area in the tapering region requires a diameter of 1.3-1.4 meters.
- 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.
- Next steps: include structural and insulating materials, consider engineering constraints in the model.

Thank you for your attention!

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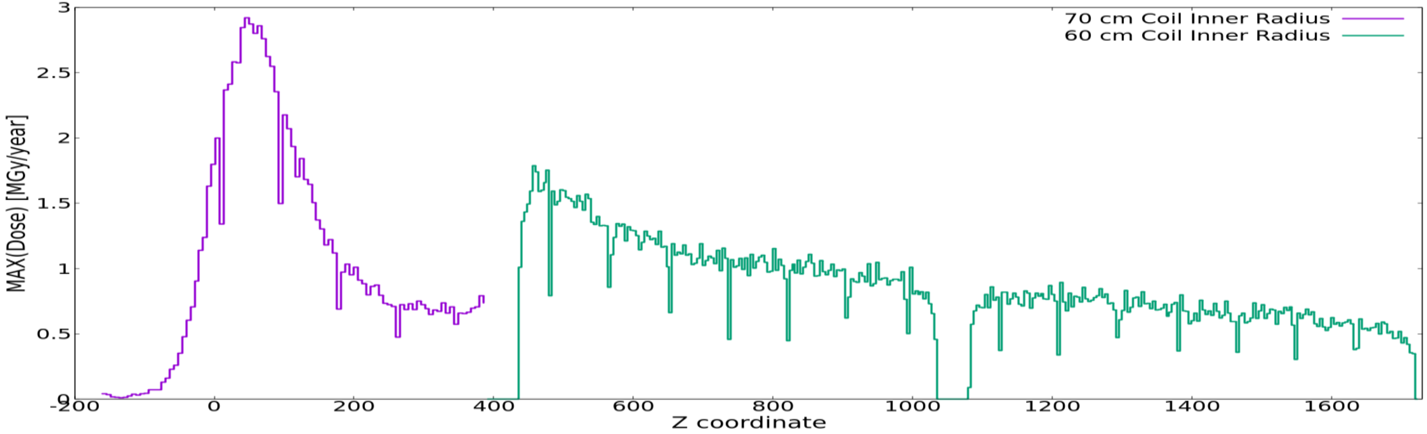
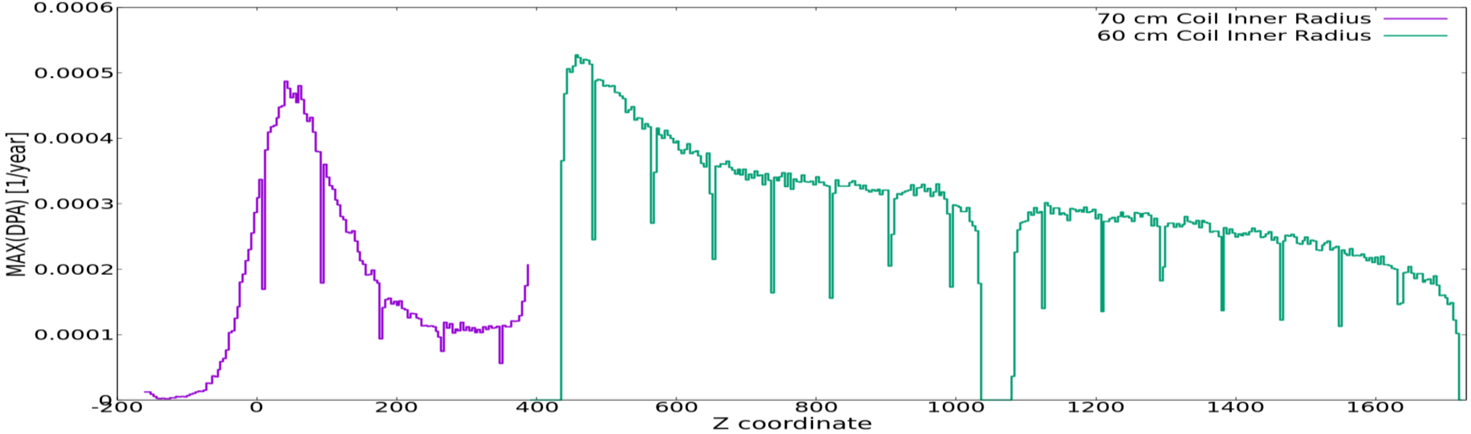
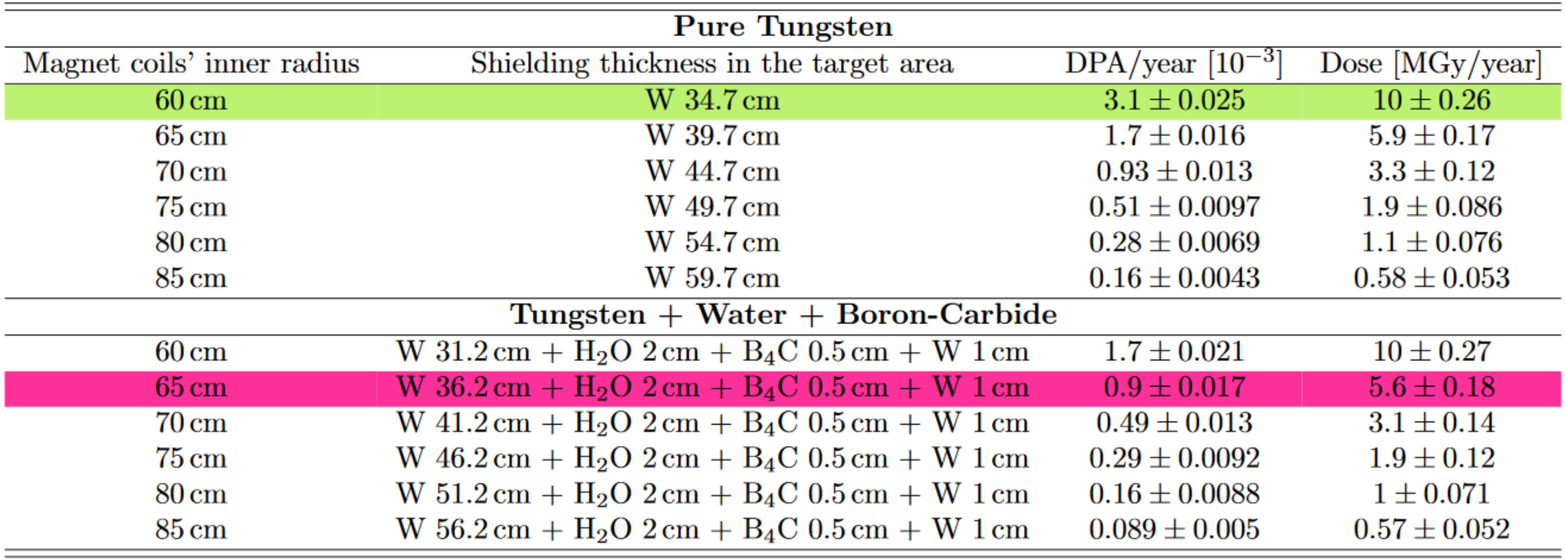
Backup

Radiation load in the HTS coils


Peak Dose in the HTS coils of the target area


Peak DPA/year in the HTS coils of the target area

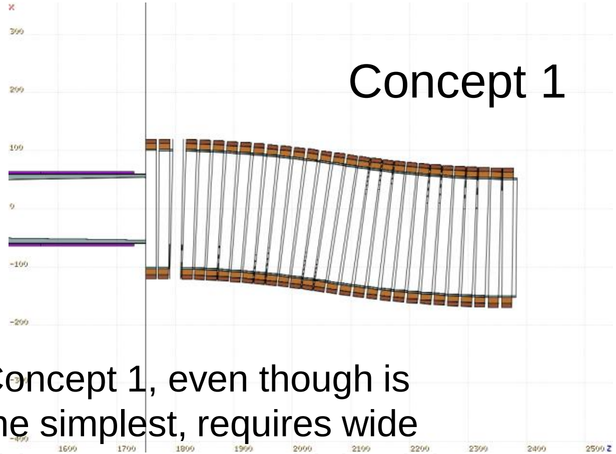
Radiation studies to the target magnets – results



Pure Tungsten			
Magnet coils' inner radius	Shielding thickness in the target area	DPA/year $[10^{-3}]$	Dose [MGy/year]
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

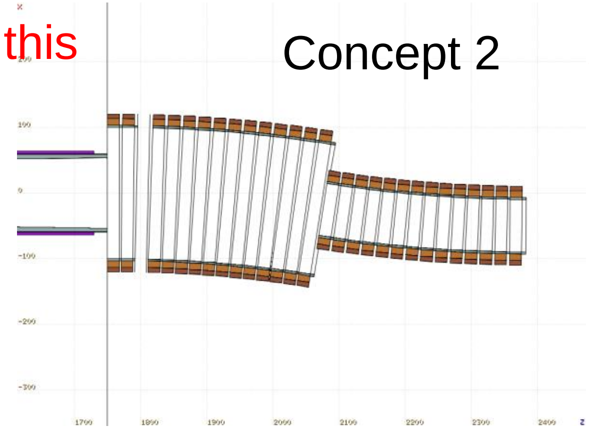
This result concluded the necessity for increase of the target solenoid inner radius AND incorporation of the neutron-capturing layer.

3 main concepts for the proton extraction



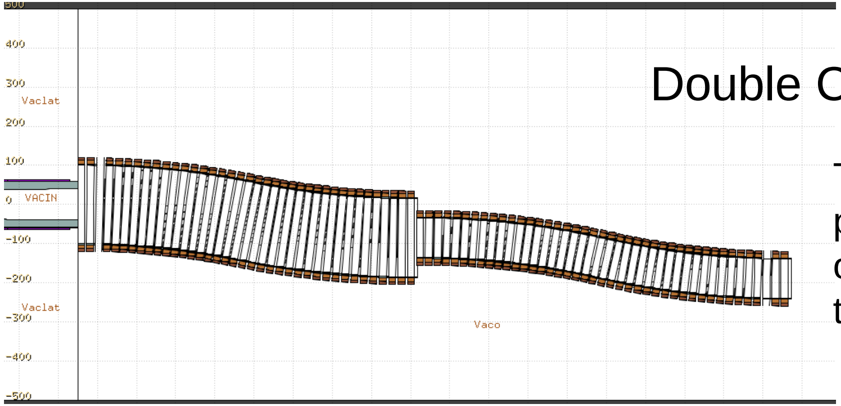
Concept 1

The focus of this presentation!



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

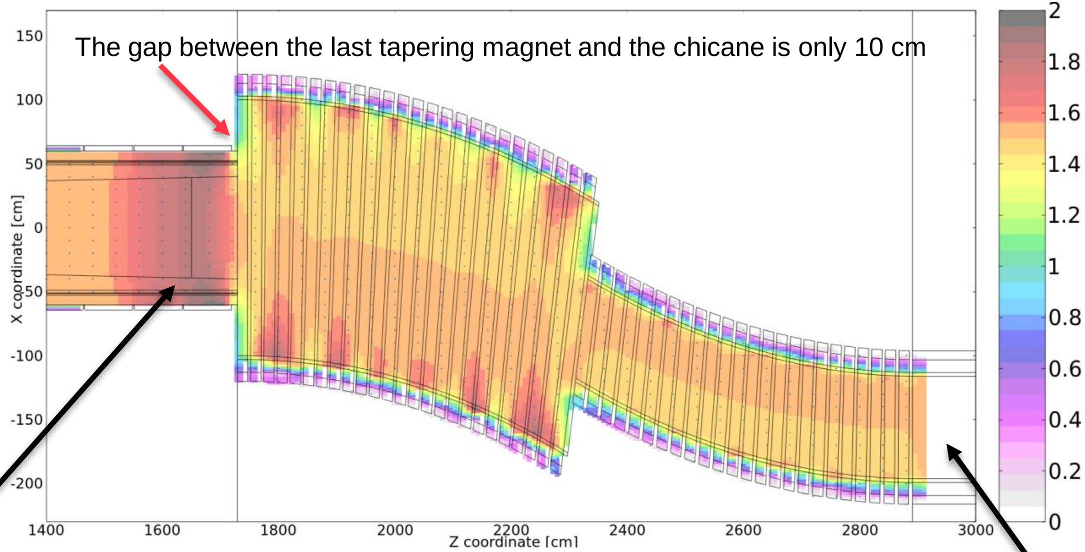
This option gives the best platform for the spatial separation of the spent proton beam after the extraction

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

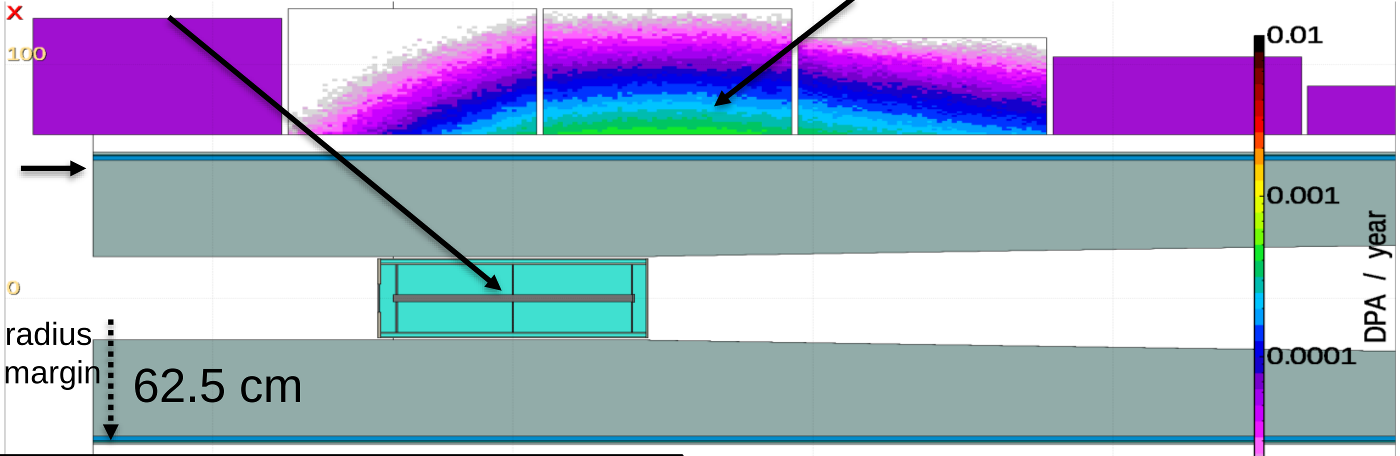


The gap between the last tapering magnet and the chicane is only 10 cm

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

Improved tapering magnet layout



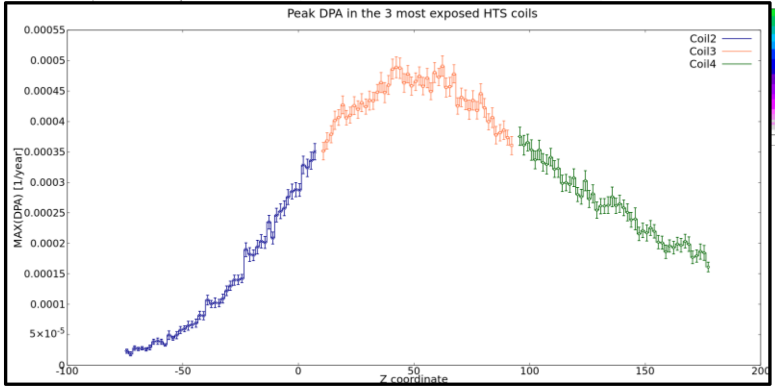
Target centered at Z=0

Coil 3 is the most exposed

Layer of Water Boron-Carbide

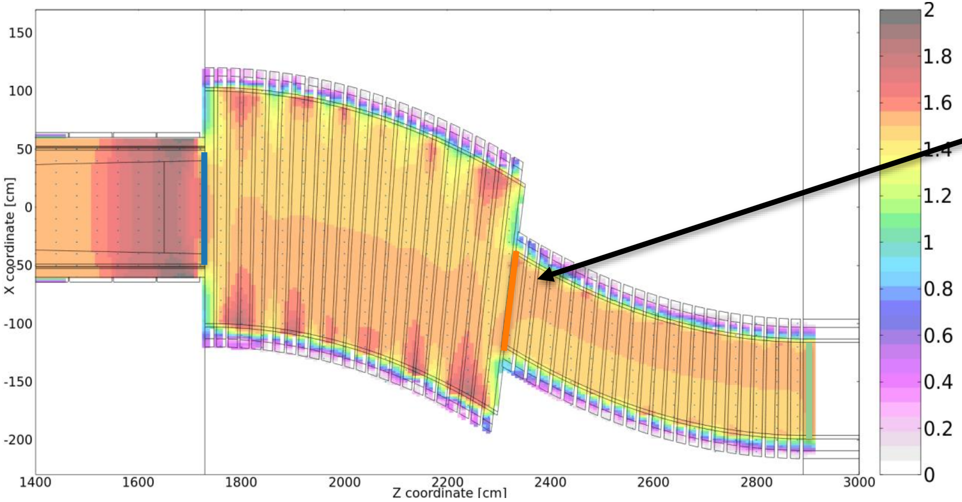
Outer shielding radius leaves a safety margin and still proven feasible.

62.5 cm

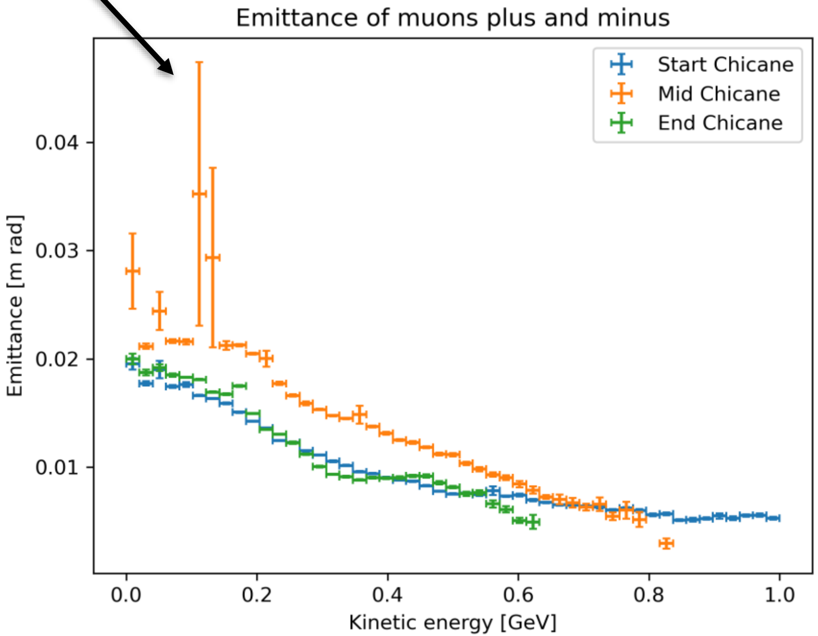

Peak DPA in the 3 most exposed HTS coils

The DPA well a control even without relying on annealing!

Figure of merit – muon emittance

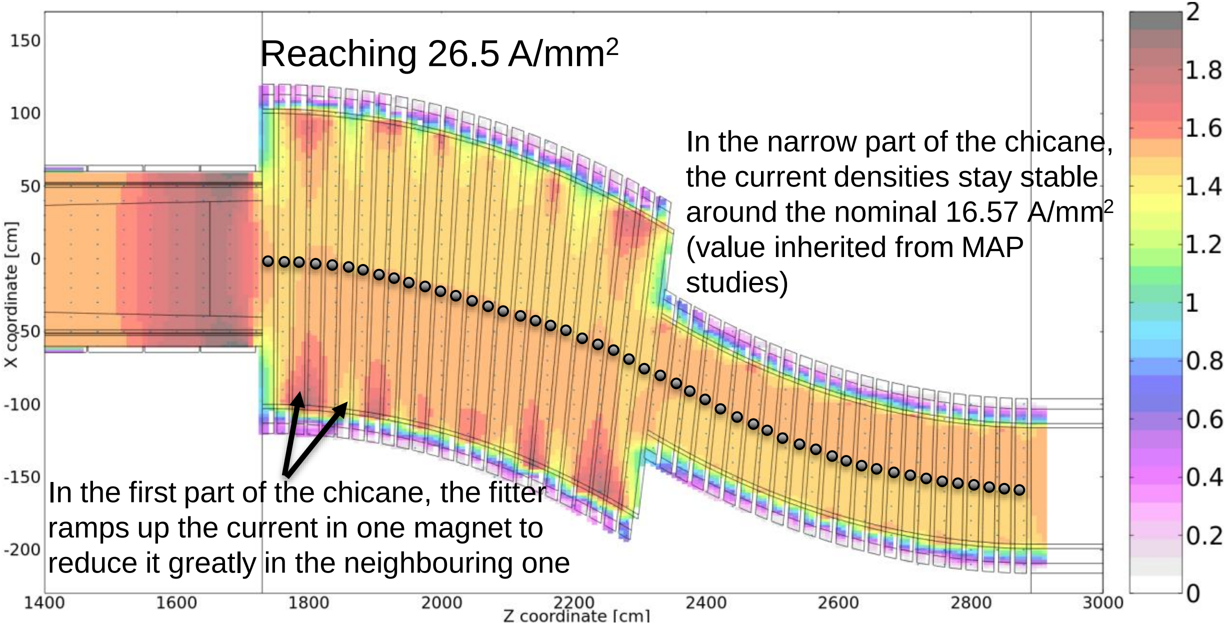


The beam has the maximum divergence in Y at the center of the chicane.



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

Fitting the field



Reaching 26.5 A/mm^2

In the narrow part of the chicane, the current densities stay stable around the nominal 16.57 A/mm^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/mm^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