Muon Cooling Demonstrator

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UK Muon Collider Collaboration, Daresbury Laboratory

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Muon Collider Cooling Scheme

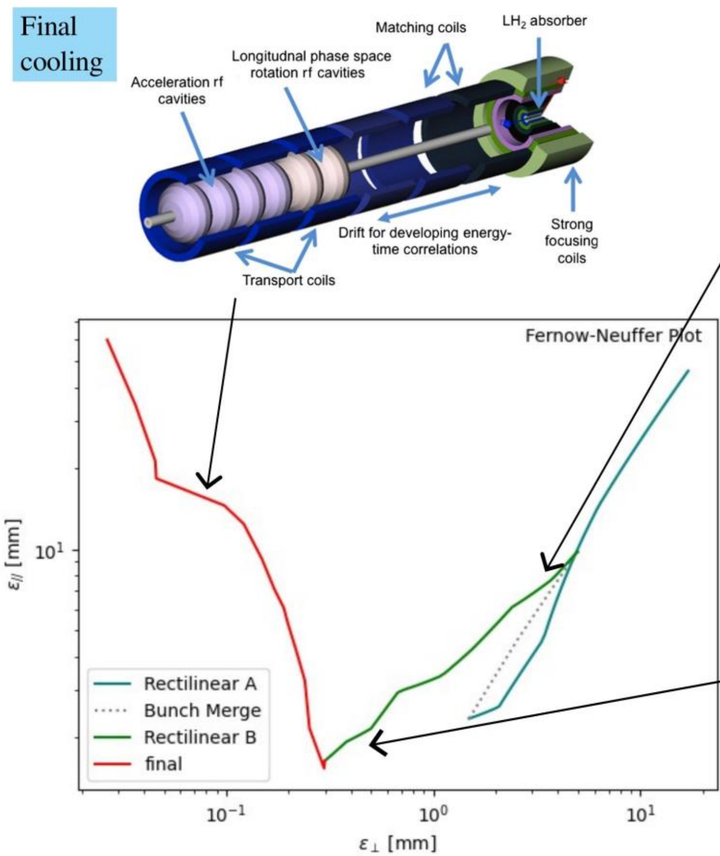
Ionisation cooling essential to achieve suitable collider luminosity

Challenges:

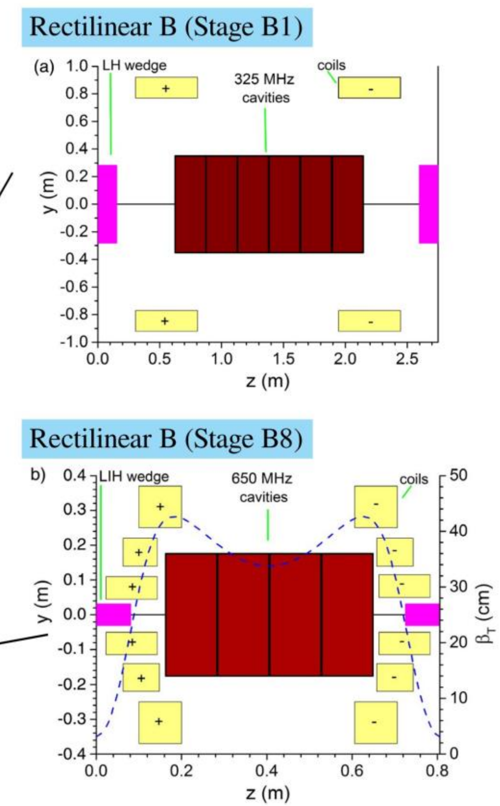
- Rectilinear cooling
  - Integration of magnets, absorbers and RF cavities in a **compact lattice**
  - High RF gradients in strong magnetic fields
  - Limited space for ancillary equipment (instrumentation, vacuum, etc.)

- Final cooling
  - Very high magnetic fields (~ 40+ T)
  - Management of longitudinal emittance growth
  - Liquid hydrogen absorber in the presence of high beam currents

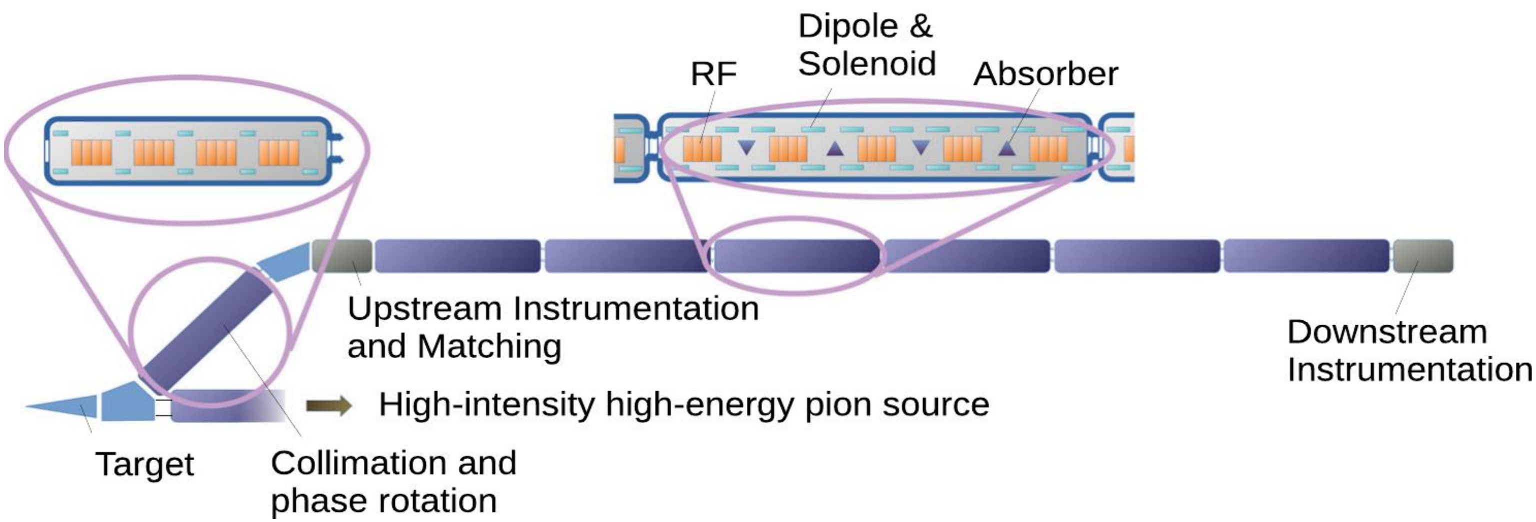
H. K. Sayed, R. B. Palmer, D. Neuffer
B. Stechauner, R. Taylor, E. Fol



D. Stratakis, R. B. Palmer
R. Zhu, C. Rogers

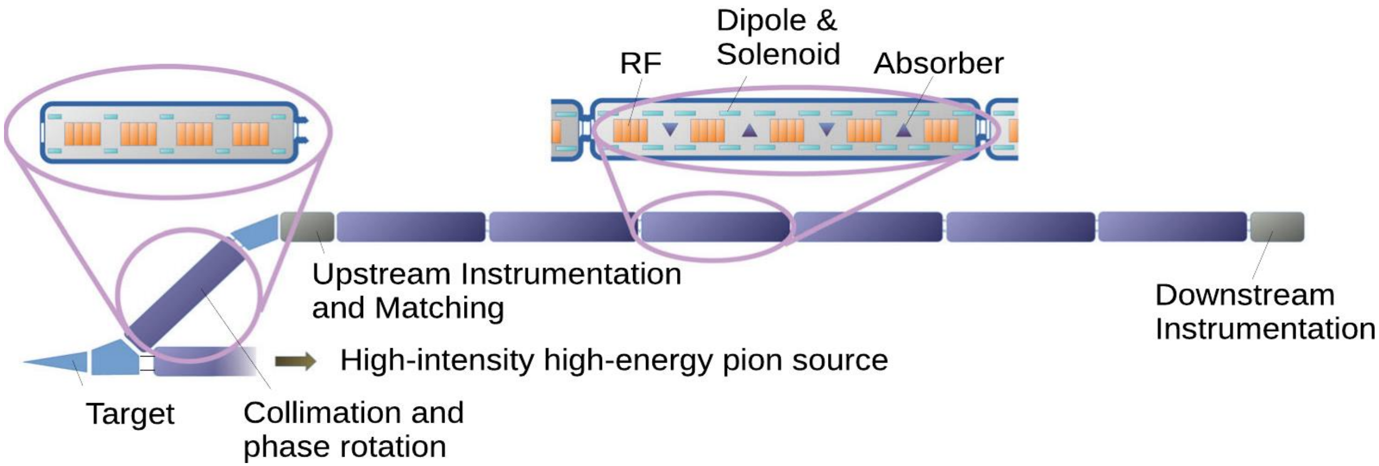


Muon Cooling Demonstrator



- Must demonstrate we can build a system that reliably delivers
  - Low 6D emittance
  - High intensity
- The muon cooling demonstrator will show
  - Successful integration of cooling equipment
  - Operation of cooling equipment with beam
  - Delivery of required luminosity performance

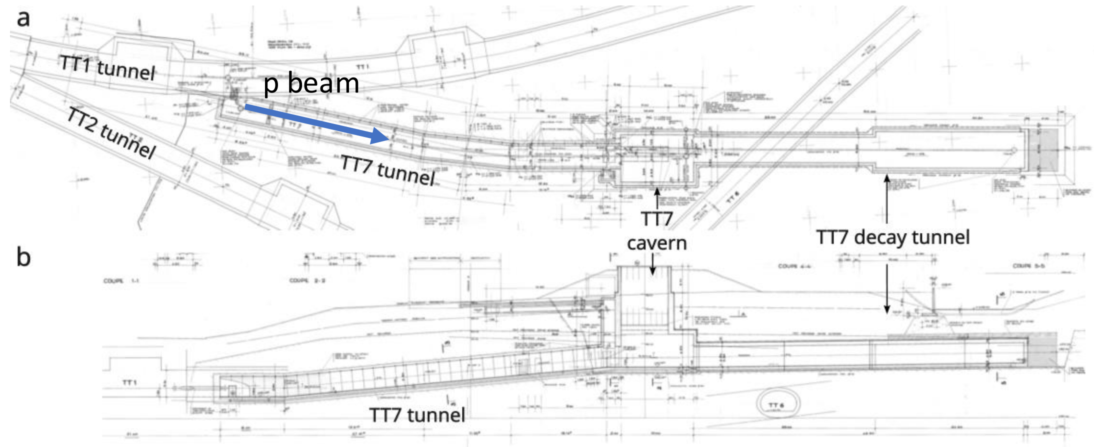
Muon Cooling Demonstrator



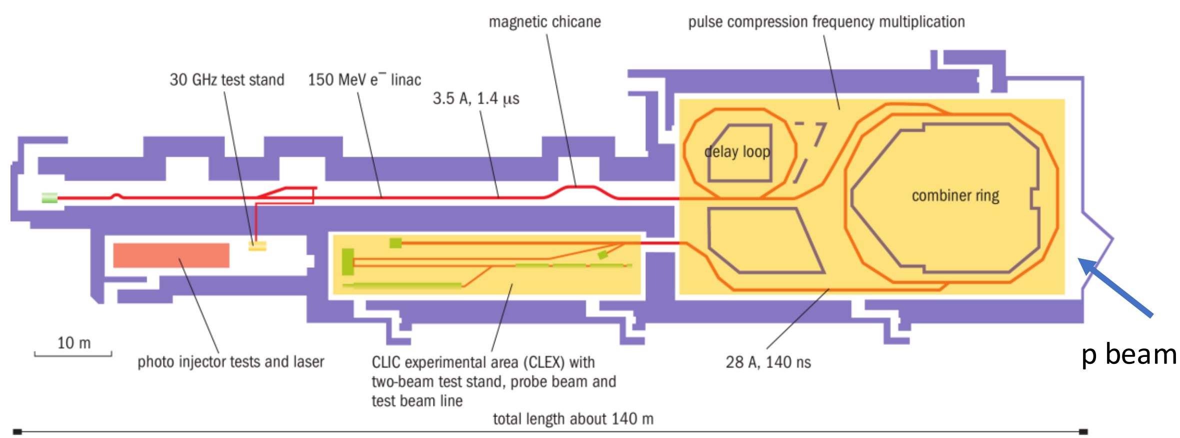
- UK team leading the Demonstrator design efforts
  - Aim to produce an integrated beam physics design of the facility
    - Target & Pion capture
    - Pion transport & decay
    - Muon transport, transverse and longitudinal preparation
    - Matching to cooling channel
    - Cooling cell
  - Facility integration: radiation protection
  - Code development: 6D cooling in BDSIM
  - Tolerance studies for beam instrumentation specs

CERN Site Options (low beam power)

- **TT7 tunnel**
  - Proton beam extracted from the Proton Synchrotron (PS)
  - Underground, close to surface level
  - ~ 1.5 kW average beam power
  - Limited space, tunnel expansion required

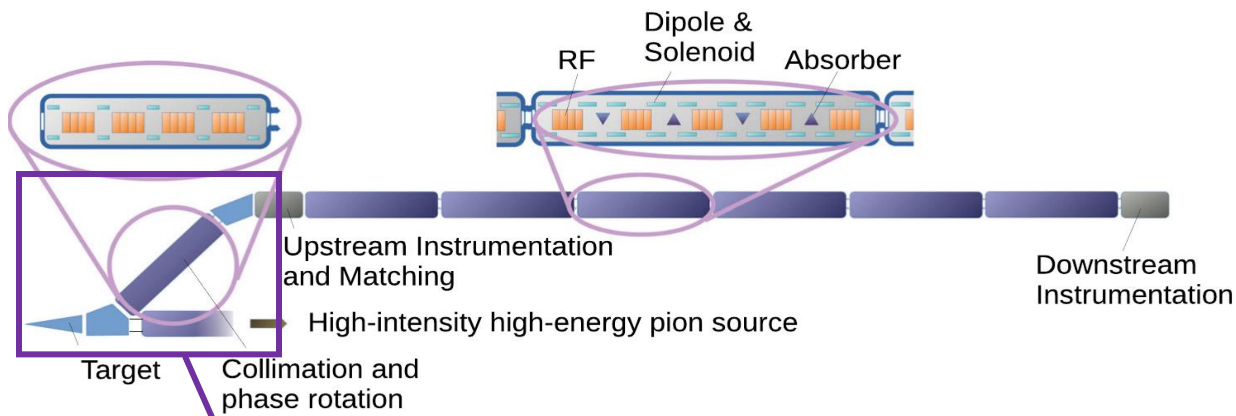


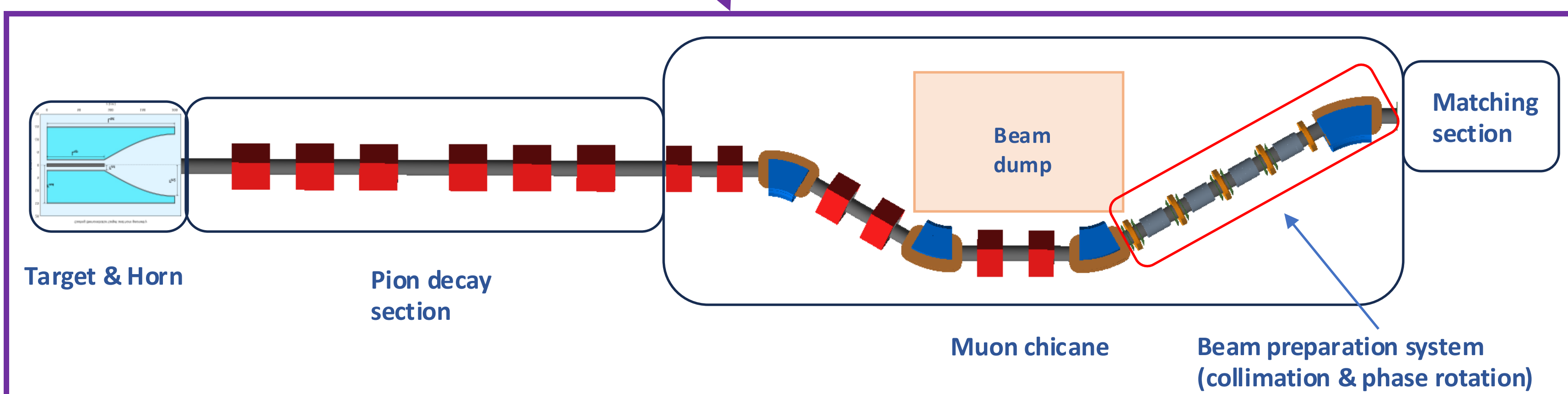
- **CTF3 area**
  - Proton beam extracted from the PS (under study)
  - Surface level
  - ~ 1.5 kW average beam power
  - More space for
    - Muon production
    - Cooling



Front End Complex

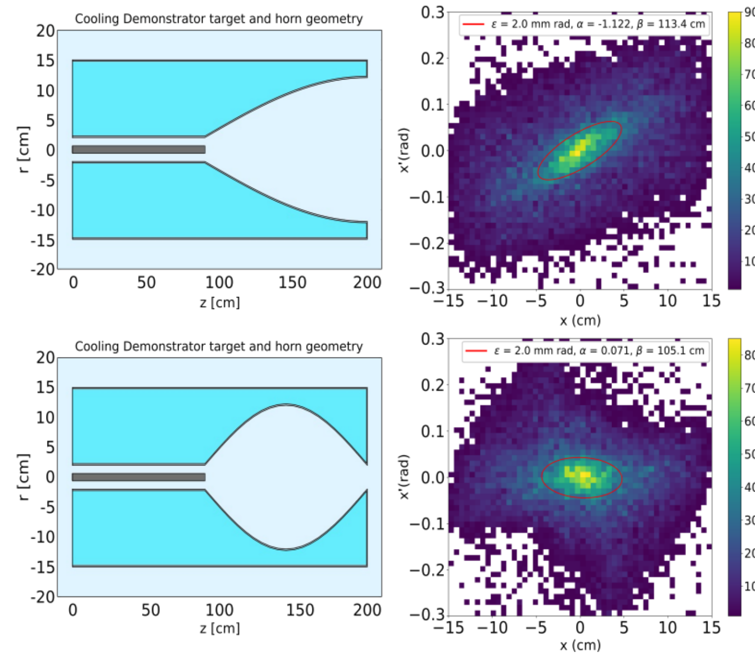
- Designed to deliver **200 MeV/c** muons to the cooling channel
- Challenging to achieve high intensity due to the intrinsically large muon beam emittance
- Layout may vary depending on site options

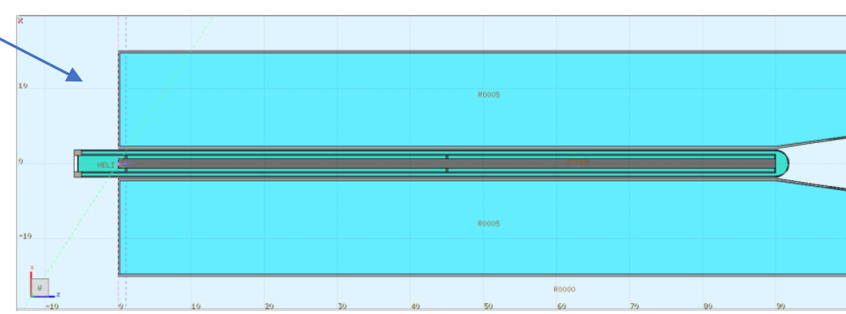




Target & Horn

- Currently optimized for using **14 GeV** proton beam to produce ~ **300 MeV/c** pions
- **Graphite** target (90 cm), **horn**-based pion capture (**I = 220 kA)**
- **Parabolic** and **ellipsoidal** inner conductor profiles considered
- Pion yield (in 210-330 MeV/c range and 2 mm rad transverse acceptance)
  - **8 x 10^{-4} π^+/POT** (parabolic profile)
  - Preliminary Bayesian optimisation of geometrical parameters shows ~20% pion yield improvements achievable (in progress)
- Force He convection target cooling system - integrated in the FLUKA model & under study
  - Challenge is to minimise the radial extent of the vessel – pion yield sensitive to the horn inner radius



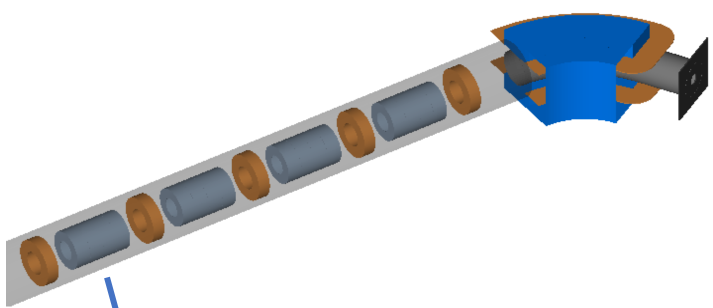


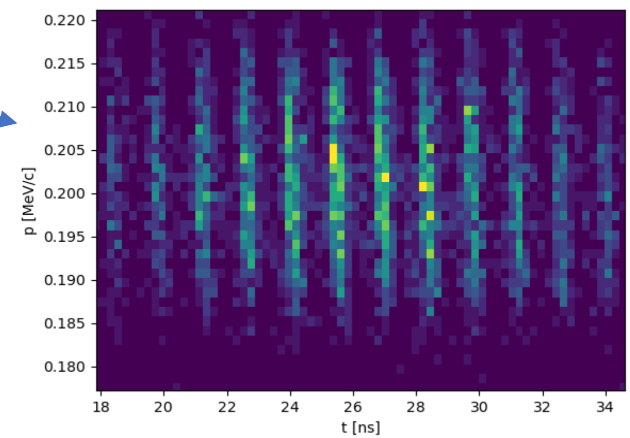
[Initial target thermal analysis (S. Candido, R. Ximenes)]

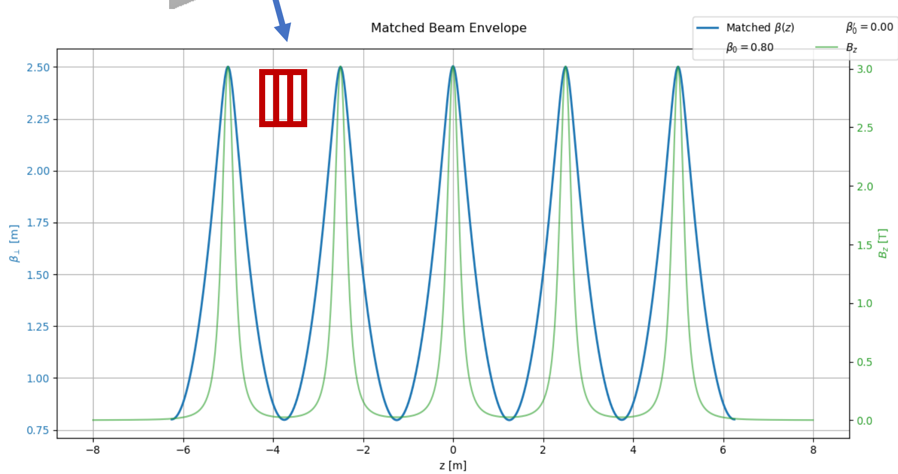
- No showstoppers

Beam Preparation System (BPS)

- Proton-driven muon beams have an intrinsically large transverse emittance
- Muon bunch length dependent on proton bunch length: expect 5-10 ns
- **Require**: ~ **2 mm** transverse emittance and ~ **100 ps** bunch length
  - Achieved through transverse collimation and longitudinal bunching
- **BPS**: sequence of RF cavities, solenoids, collimators and a dipole (momentum collimation)



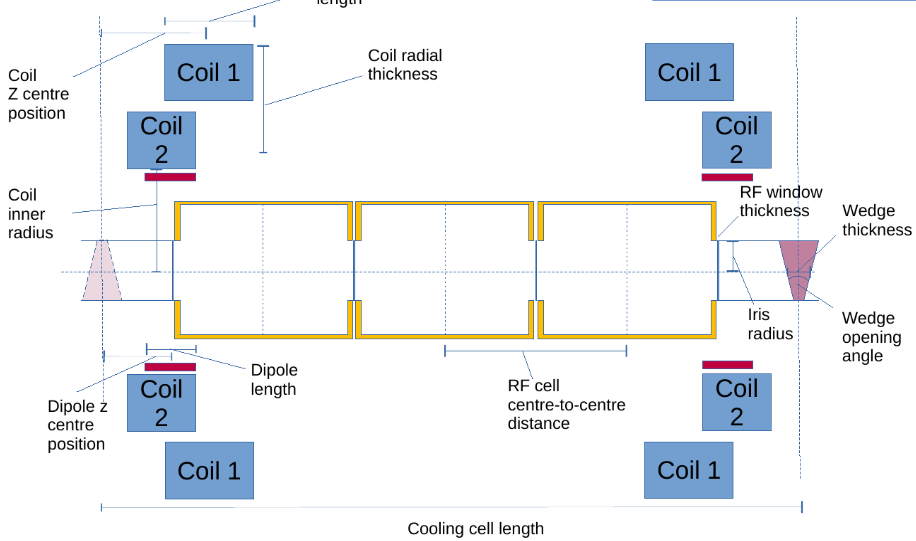


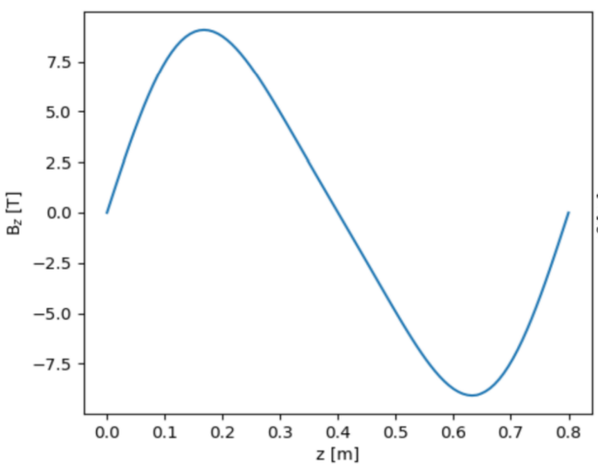


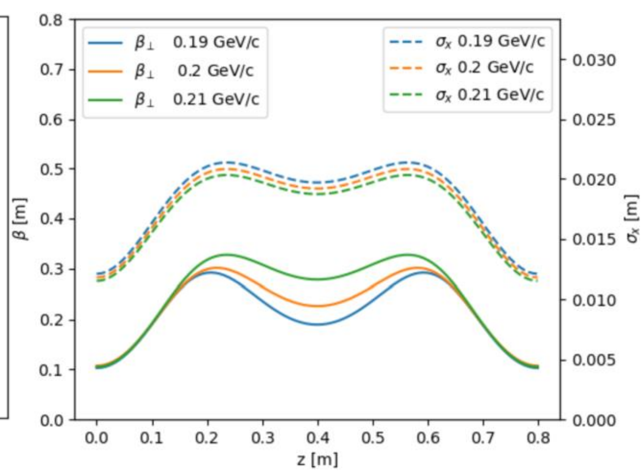
- Need ~ 2 mm beam to pass through the BPS
  - Optics design to account for this and avoid overcollimation
- Limiting aperture – RF cavity iris <= **81.6 mm** (at 704 MHz)
- ~ 3+ T fields allow **β < 1 m** in the RF region

Cooling Cell

[**Version**: 2025-11-24-release](#) (C. Rogers)



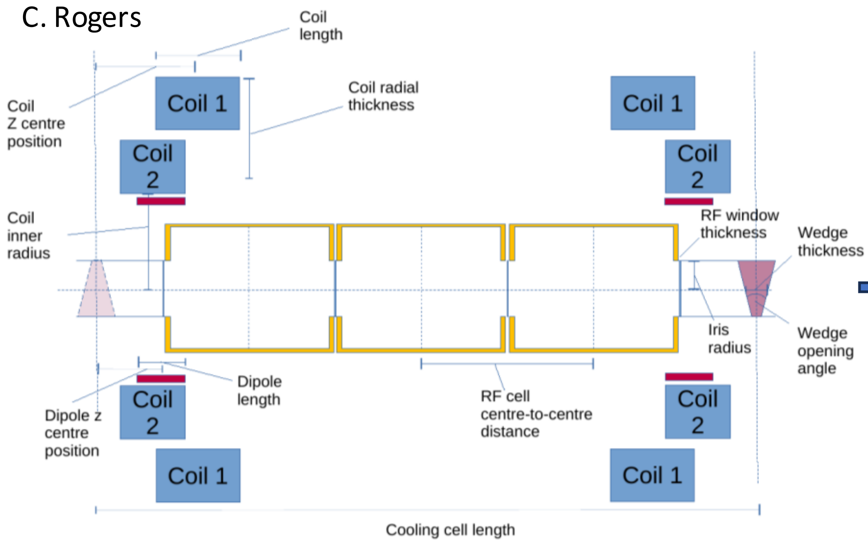




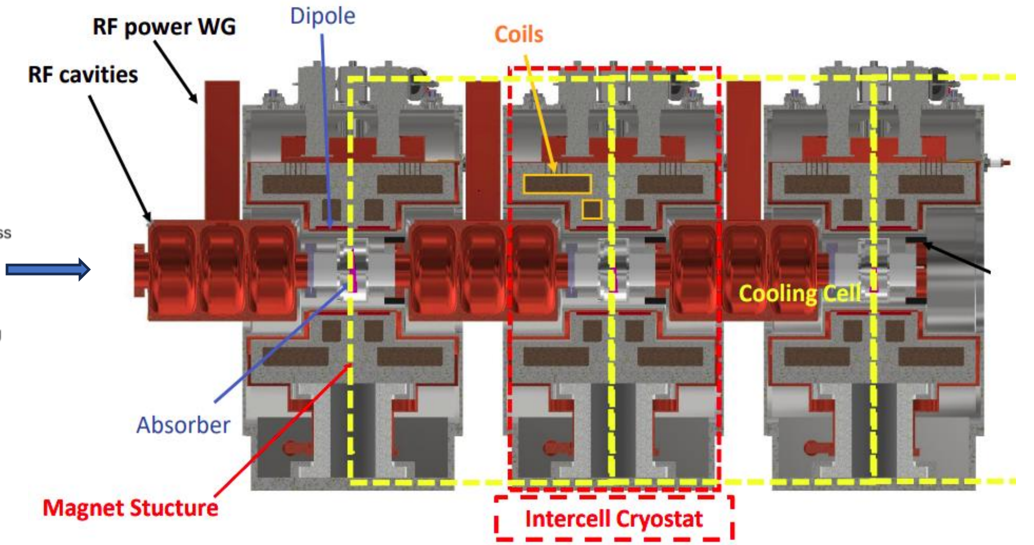
Parameter	Unit	Value	
Cooling Cell Length	mm	1000	
Beam Physics			
Momentum	MeV/c	200	
Twiss beta function	mm	130	
Dispersion in X	mm	-61.5	
Dispersion in Y	mm	-19.7	
Beam Pipe Radius	mm	81.6	
Solenoid Parameters			
	Unit	Value	Tol
B0	T	7	0.25
B0.5	T	0	0.02
B1	T	1	0.025
B2	T	0	0.5
Coil Geometry			
Parameter	**Unit**	**Coil 1**	**Coil 2**
Geometry	–	B5-DEMO-MAG-2.4	
Inner Radius	mm	285	185
Length	mm	211	63.4
Radial Thickness	mm	76.2	71.7
Z Centre Position	mm	251.8	88.1
Pancake length	mm	12	12
Spacer length	mm	7.9	13.7
Number pancakes	–	11	3
Current Density	A/mm^2	403.5	632.3
RF Cavity			
Center-to-centre distance	mm	188.6	
Gradient E0	MV/m	30	
Iris Radius	mm	81.6	
Number of RF Cells		3	
Frequency	GHz	0.704	
Synchronous Phase	degree	20	
Window Thickness	mm	0.1	
Window Material		Beryllium	
Wedge			
Material		LiH	
Opening Angle	degree	10	
Thickness	mm	20	
Alignment		Horizontal	
Dipole			
Length	mm	100	
Polarity		+ - - +	
Field	T	0.2	
Z Centre Position	mm	160	
Field Direction		Vertical	

Cooling cell

C. Rogers

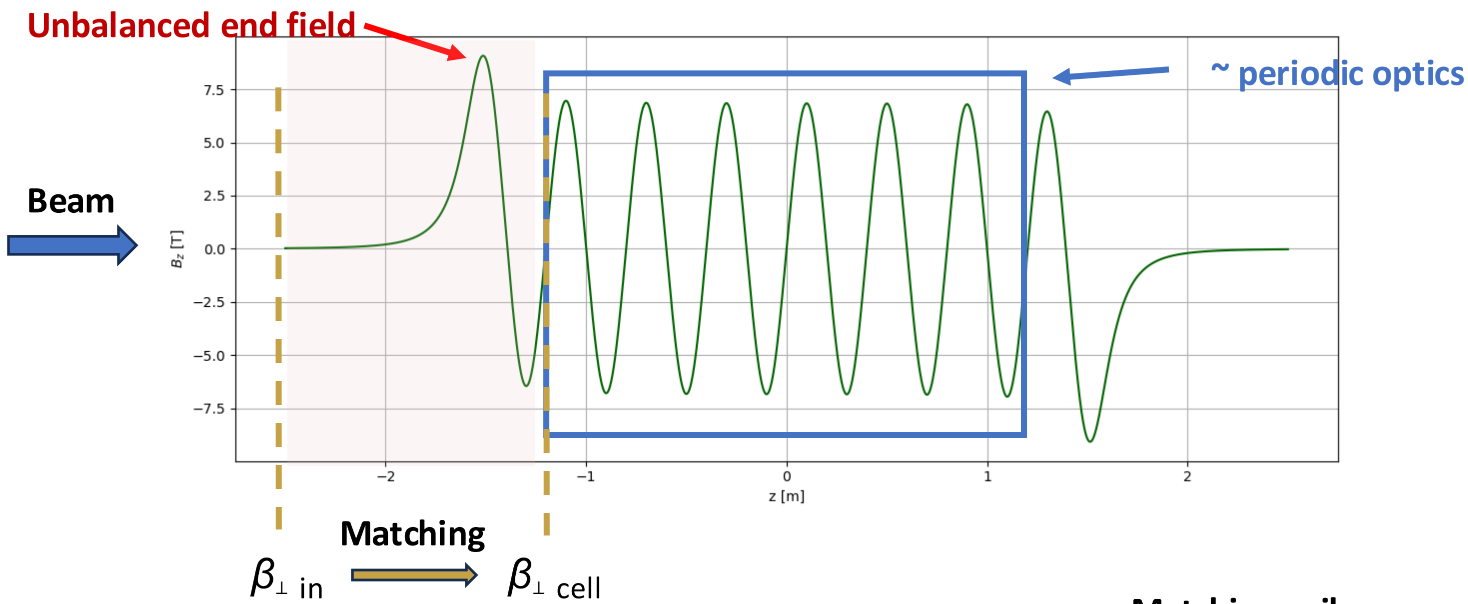


L. Rossi et al.

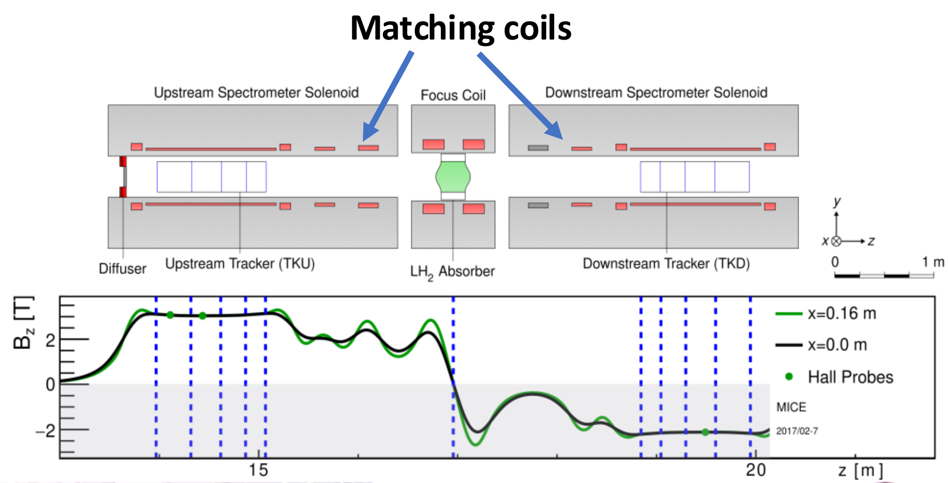


- Maturing beam physics design, multiple iterations including engineering constraints
  - Longitudinal dynamics optimisation ongoing
- Engineering design & integration of main components showing good progress
  - Compact build!
- Limiting apertures – RF cavities
  - Additional constraint to the optics, on top of the tight focus at the absorber

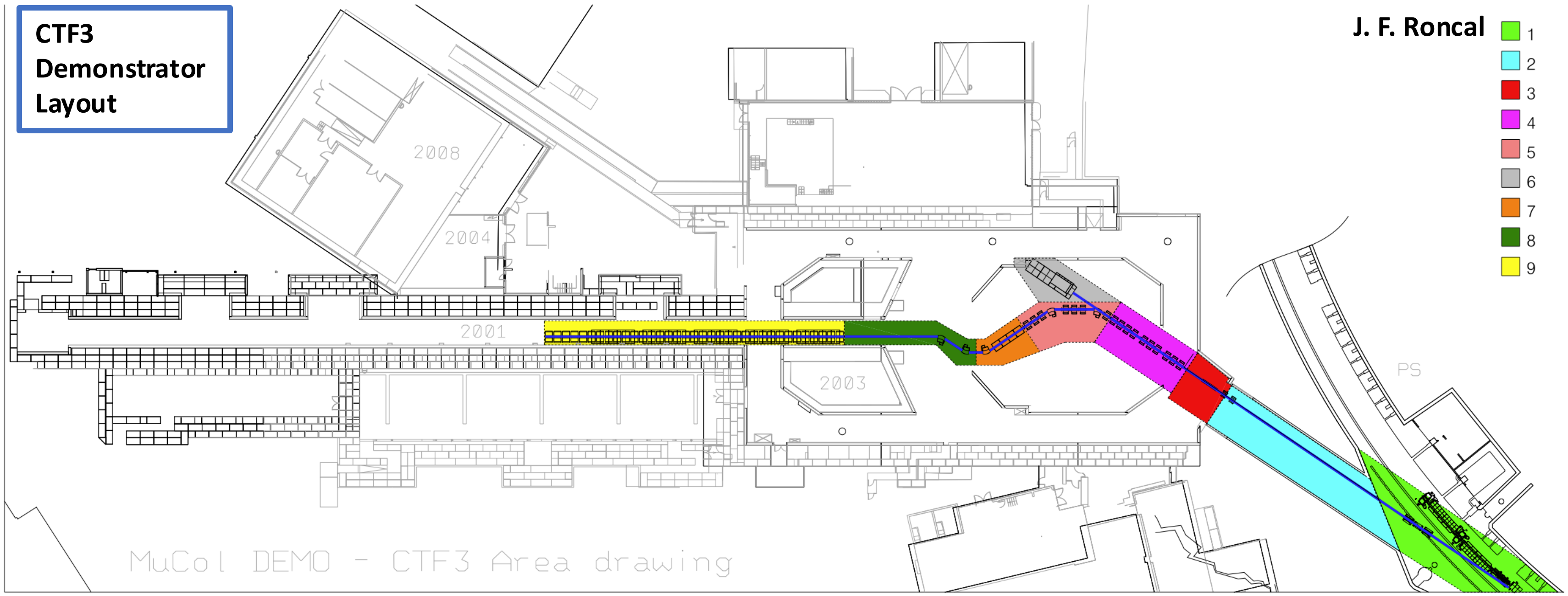
Cooling channel – end fields



- Unbalanced field at the entrance into the cooling channel
  - Optics
  - Unbalanced magnet forces
- Additional coils required to match the optics of the input beam to the optics of the channel while managing forces on magnets
- Example: **MICE** matching



CTF3 radiation protection study

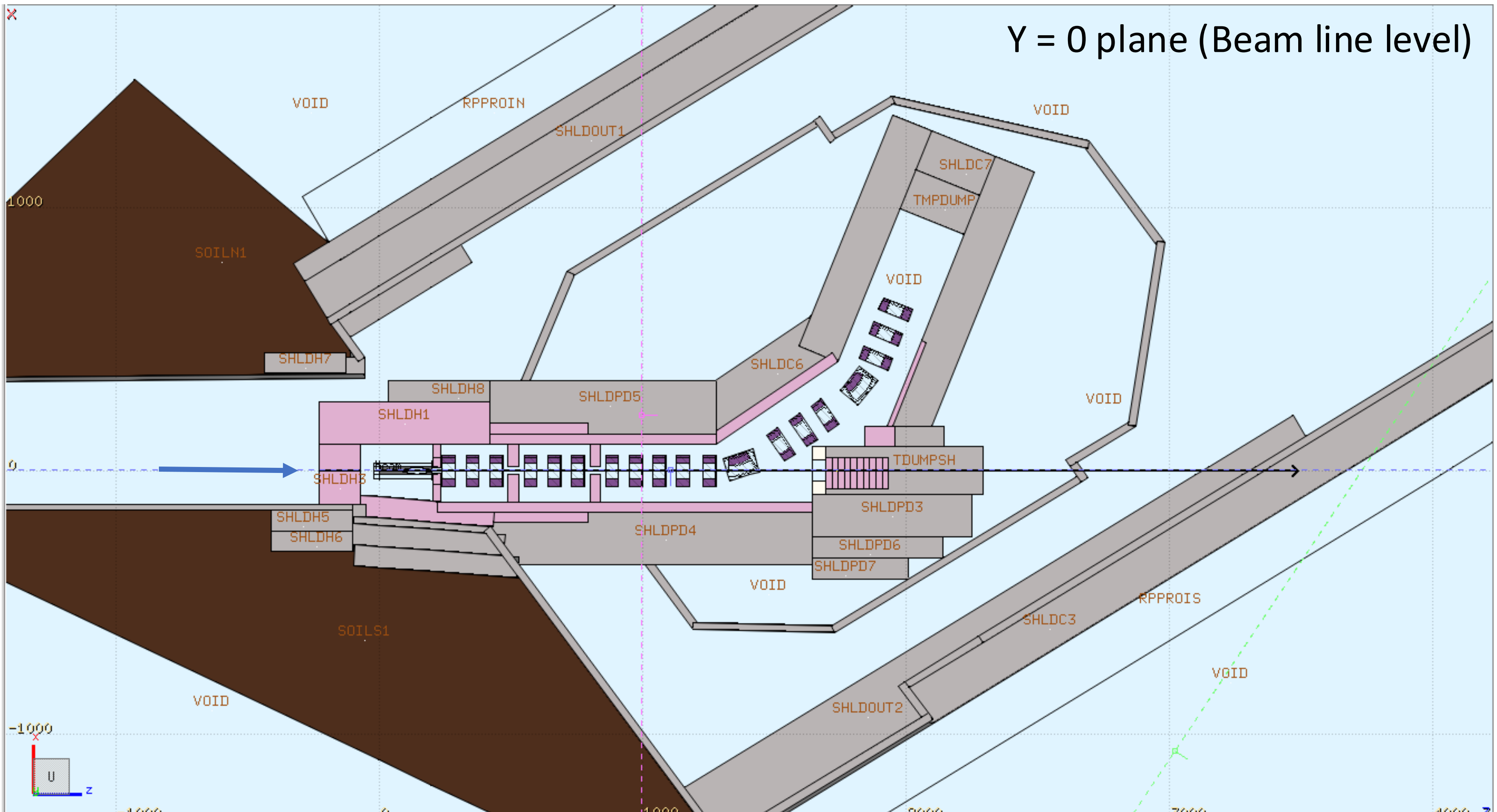


- Provide input to the CTF3 Demonstrator costing exercise, and beyond
  - Simulation-based estimation of shielding configuration, materials and volumes
  - Identify potential civil engineering requirements (e.g. reconfiguration of existing building, trench digging, roof/sarcophagus)
- Identify any potential radiation-related constraints/requirements on the beamline design (e.g. from shielding, collimators, high loads on magnets etc.)

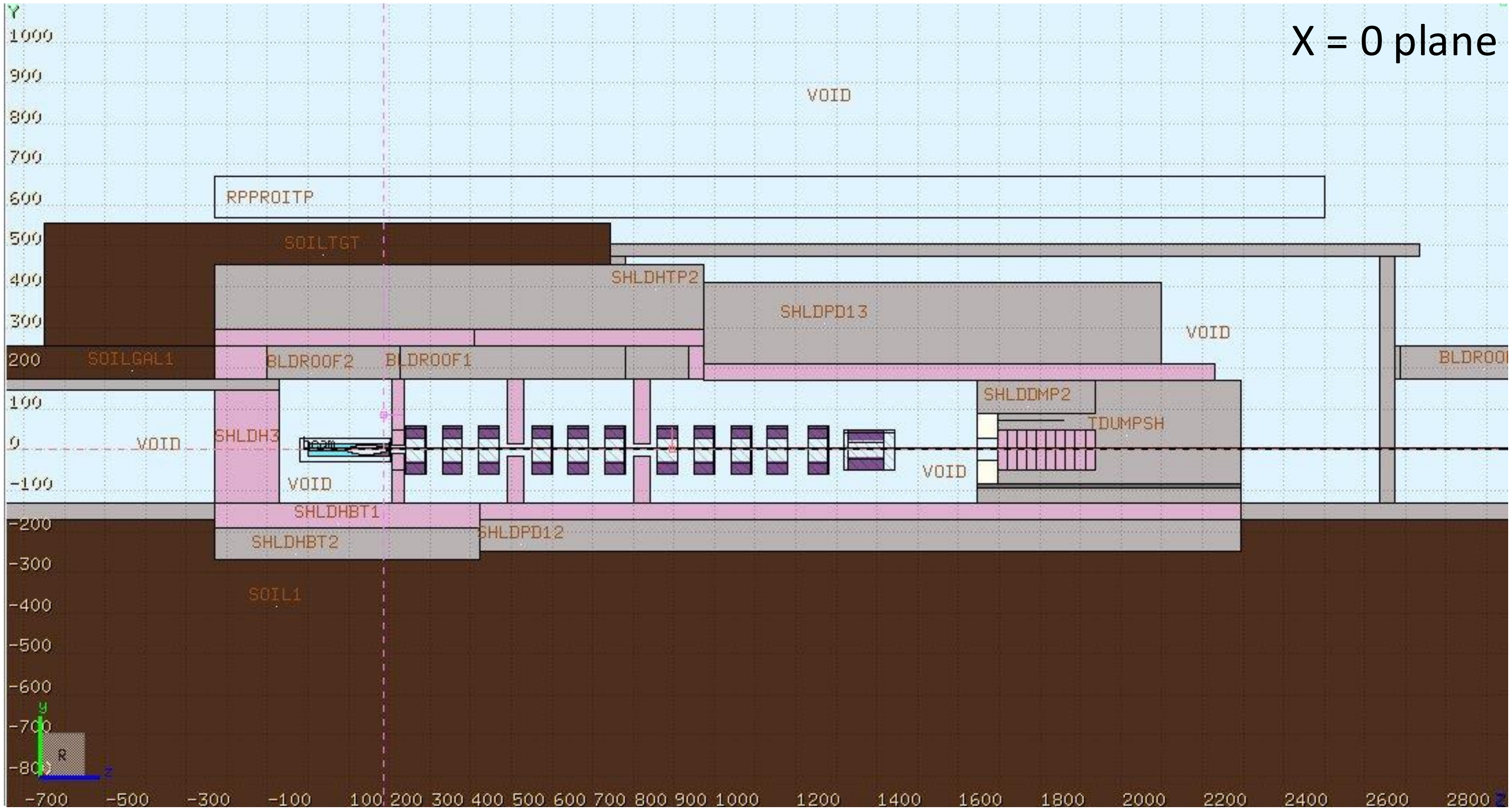
Target area FLUKA model

- Based on existing civil engineering infrastructure and current target and beam line models:
  - Graphite target + horn
  - Beam line, from horn to the exit of the chicane (matching section to be designed)
    - Assumed 20 cm radius apertures
  - CTF3 building, higher fidelity near the patio area
  - AD beam dump model
  - Layered shielding around target, beamline, dump, building
    - Cast iron (GG20)
    - Concrete
  - Three iron large-aperture (10-15 cm) 'collimators'

CTF3 target area FLUKA model – top view

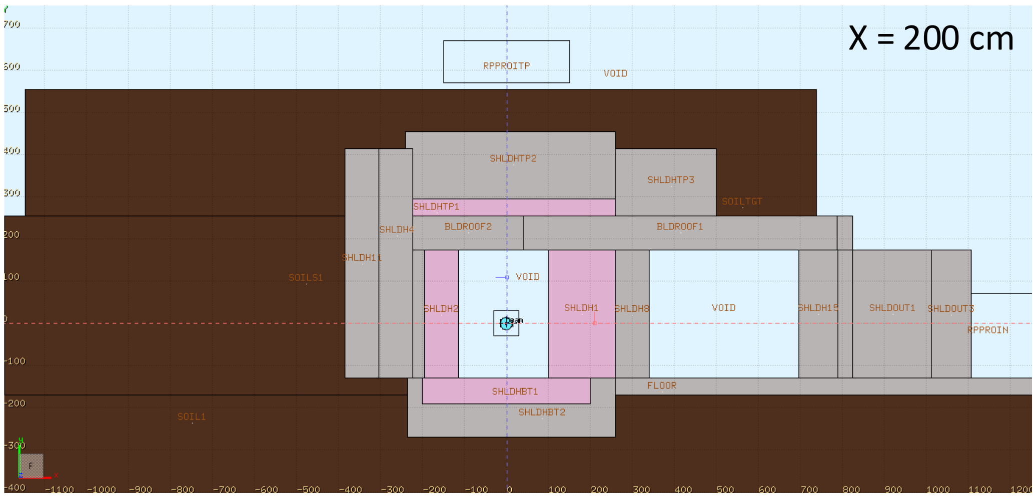


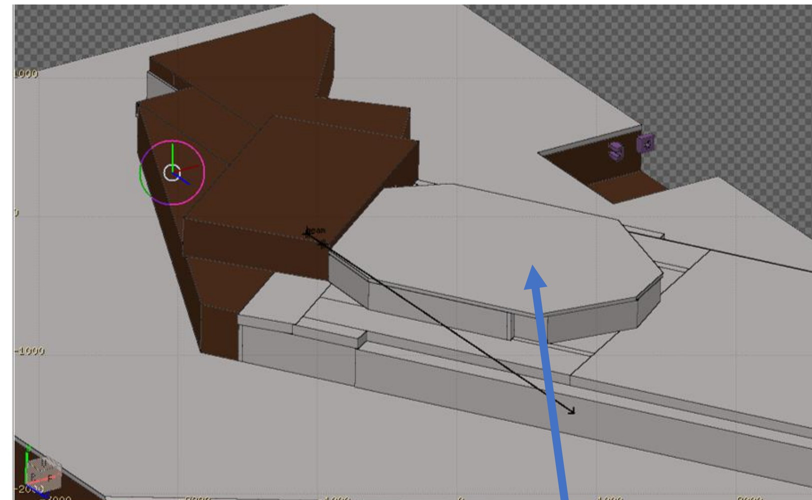
Target area FLUKA model – side view

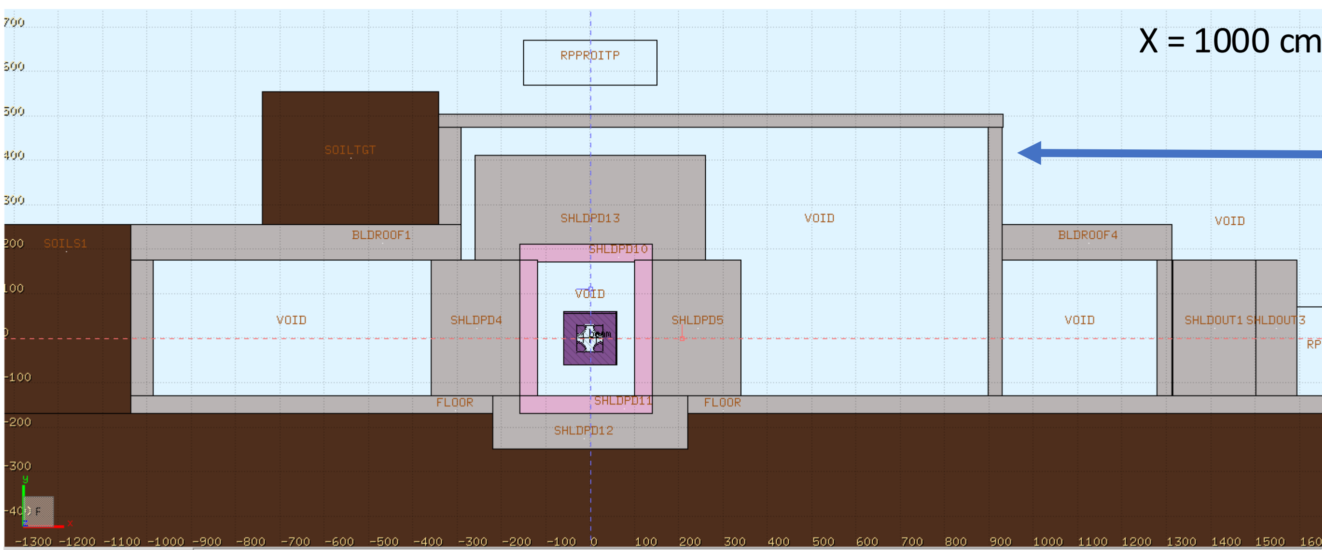


- Added shielding below target area and beam line -> trench
- Minimally sealed the 'patio area'

Target area FLUKA model







'Sarcophagus' placeholder – to be defined

Prompt dose (x-z)

- Radiation dominated by neutrons

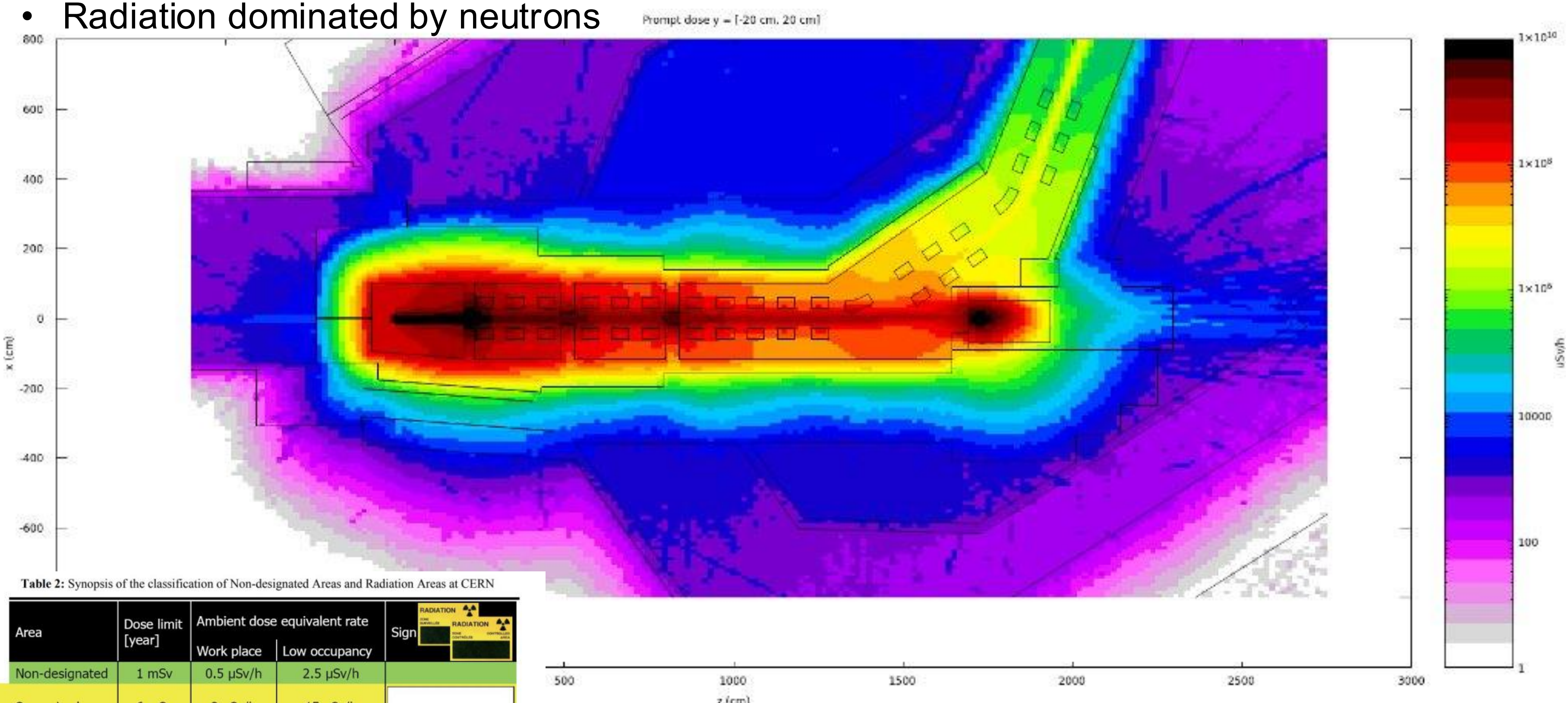
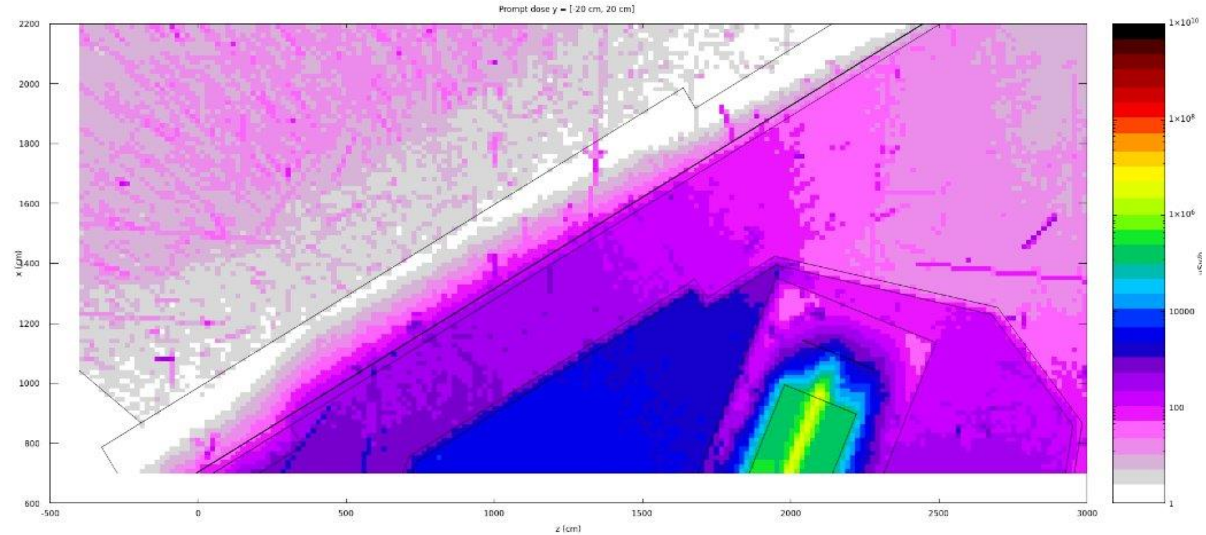


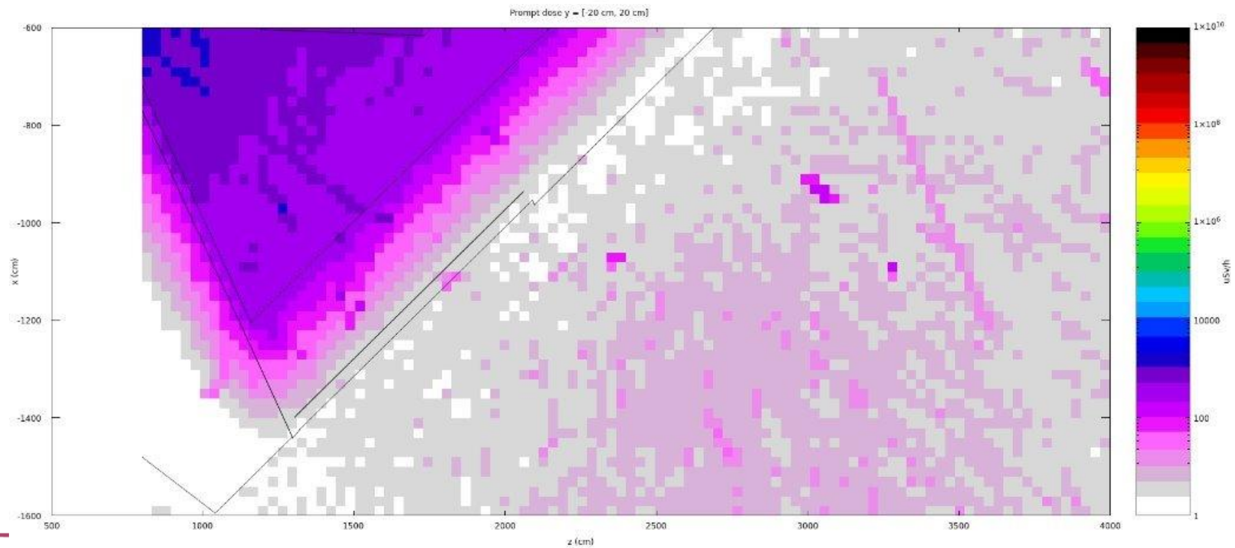
Table 2: Synopsis of the classification of Non-designated Areas and Radiation Areas at CERN

	Area	Dose limit [year]	Ambient dose equivalent rate		Sign	
			Work place	Low occupancy		
	Non-designated	1 mSv	0.5 μSv/h	2.5 μSv/h		
Radiation Area	Supervised	6 mSv	3 μSv/h	15 μSv/h	Dosimeter obligatory / Dosimètre obligatoire	
Radiation Area	Simple	20 mSv	10 μSv/h	50 μSv/h	Dosimeter obligatory / Dosimètre obligatoire	Controlled Area
Radiation Area	Limited Stay	20 mSv		2 mSv/h	LIMITED STAY / SÉJOUR LIMITÉ	Controlled Area
Radiation Area	High Radiation	20 mSv		100 mSv/h	HIGH RADIATION / HAUTE RADIATION	Controlled Area
Radiation Area	Prohibited	20 mSv		> 100 mSv/h	PROHIBITED AREA / ZONE INTERDITE	Controlled Area

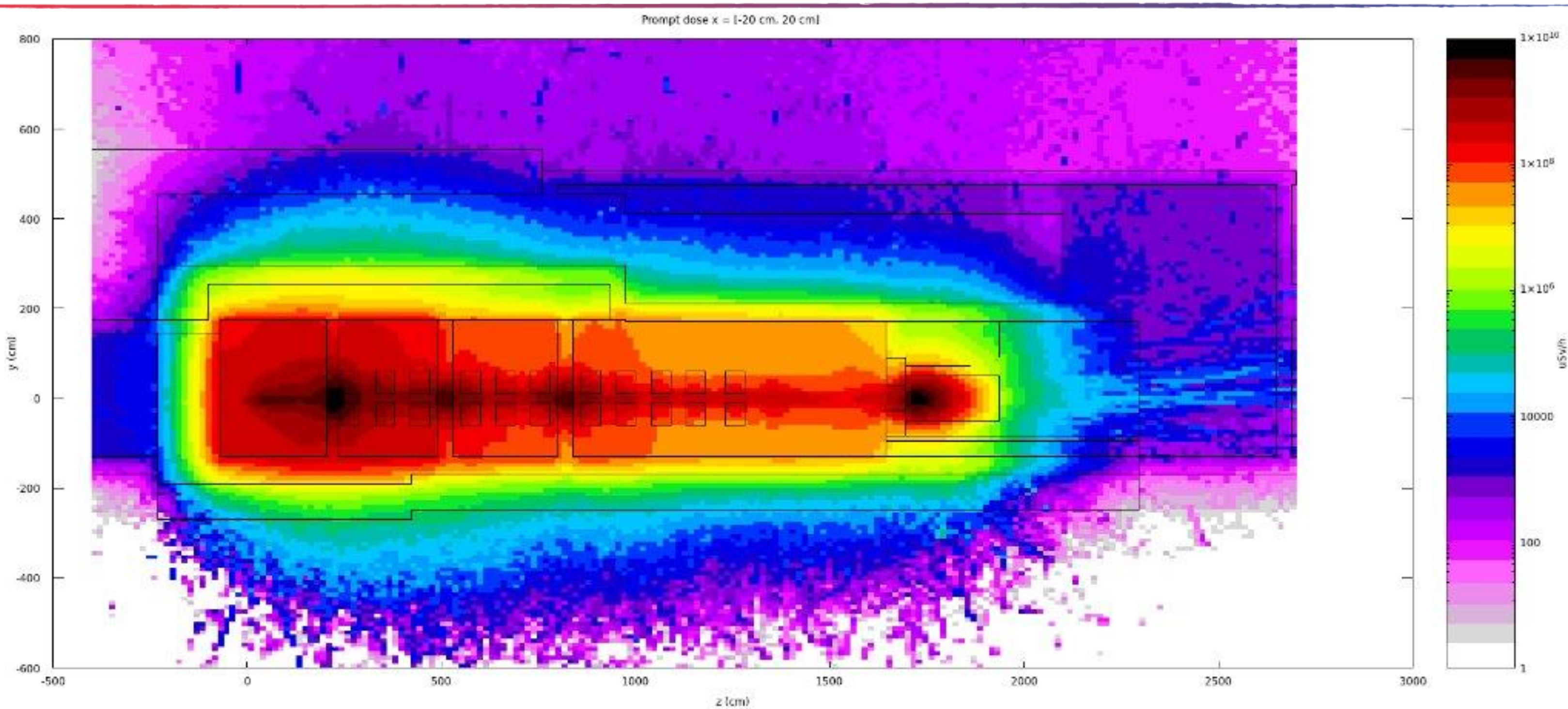
Prompt dose (x-z) - Building proximity

- ~3-4 uSv/h achieved at the building boundary
- **Skyshine** observed further away from the building - neutrons that escape vertically and scatter in air back to ground level





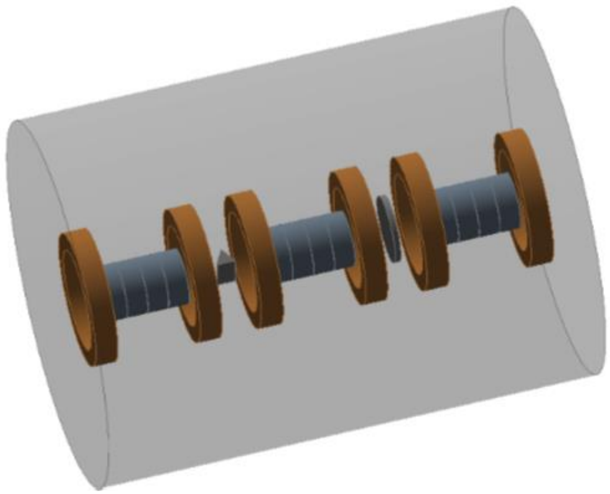
Prompt dose (y-z)



- ~400-500 uSv/h observed in air, close to the top building boundary
  - Skyshine source
  - Requires shielding enhancement/optimisation
- Current dose rate in the soil below target/beam line is high, but soil activation estimations not yet performed
  - Requires defining operating scenarios, TBD

Muon cooling in BDSIM

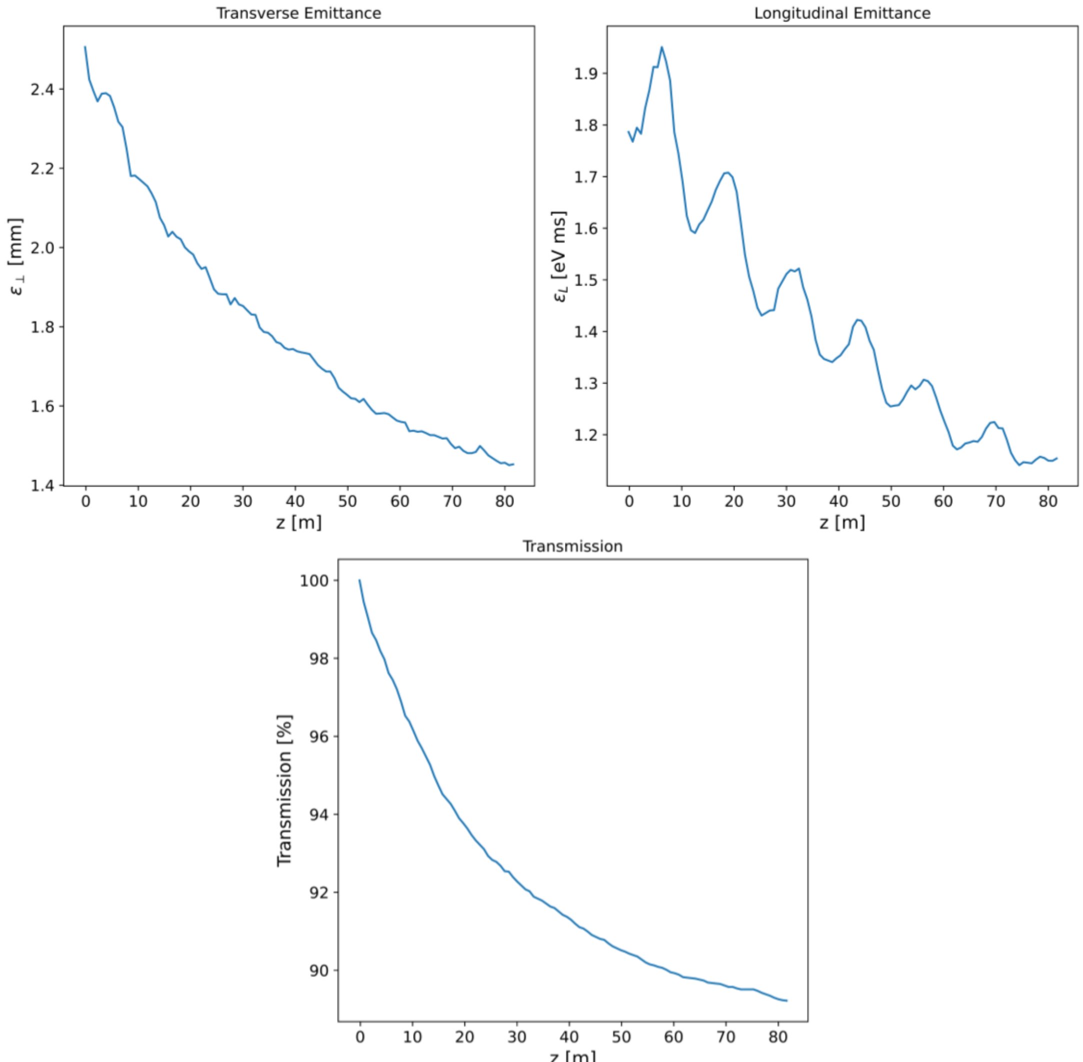
- A new BDSIM element, **muoncooler**, has been implemented to support the simulation of 6D muon cooling systems
- This element allows the definition of an entire cooling lattice within BDSIM, and it can include:
  - Solenoids
  - Dipoles (field only, no physical magnet)
  - RF cavities
  - Absorbers (wedge or cylinder shaped)
- Fields from each cooling cell component (magnets, RFs) are summed to compute a 6-vector electromagnetic field spanning the element volume.
  - Fringe effects from all magnets are accurately accounted for across the lattice



Cooling example – Demonstrator lattice

- ~ 80 m long channel
- Initial longitudinal mismatch leads to oscillating behaviour in longitudinal emittance
- **Preliminary**: Emittance reduction observed, accompanied by beam losses in the tails

- Study on tolerances and beam instrumentation specs using BDSIM initiated (R. Kamath)



Summary

- Efforts to produce an integrated start-to-end design & simulation for the Muon Cooling Demonstrator underway
- Two CERN sites considered: **TT7** tunnel, **CTF3** area (currently in focus)
- **Cooling cell** design in a mature state
  - Longitudinal dynamics optimisation
  - Tolerance study and beam instrumentation specs
- **Front end complex**
  - **Target + Horn**
    - Bayesian optimisation to improve beam intensity
    - Horn geometry refinement, explore different target materials
    - Develop the model including ancillary systems that impact performance
  - **Transport line**
    - Preliminary pion decay channel & chicane solutions
    - Beam preparation system -> Exploring stronger focusing solutions, underway
  - **Pre-cooling-channel matching section**
    - To match the beam exiting the beam preparation system to the cooling channel
- Radiation protection
  - Lower bound on shielding requirements estimated
  - Iterate the target area radioprotection study to finalise the shielding requirements
    - Investigate radiation loads on magnets & collimator configurations
- Implemented 6d ionisation cooling simulation capabilities in BDSIM

Thank you

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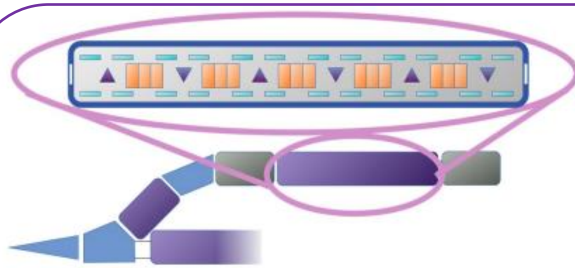
6D cooling R&D Plan

RF Test stands, to develop novel RF and magnet technologies

One-cell module to test RF in operational magnetic environment

Multi-cell module to demonstrate integration of absorber, RF and magnets

Require beam



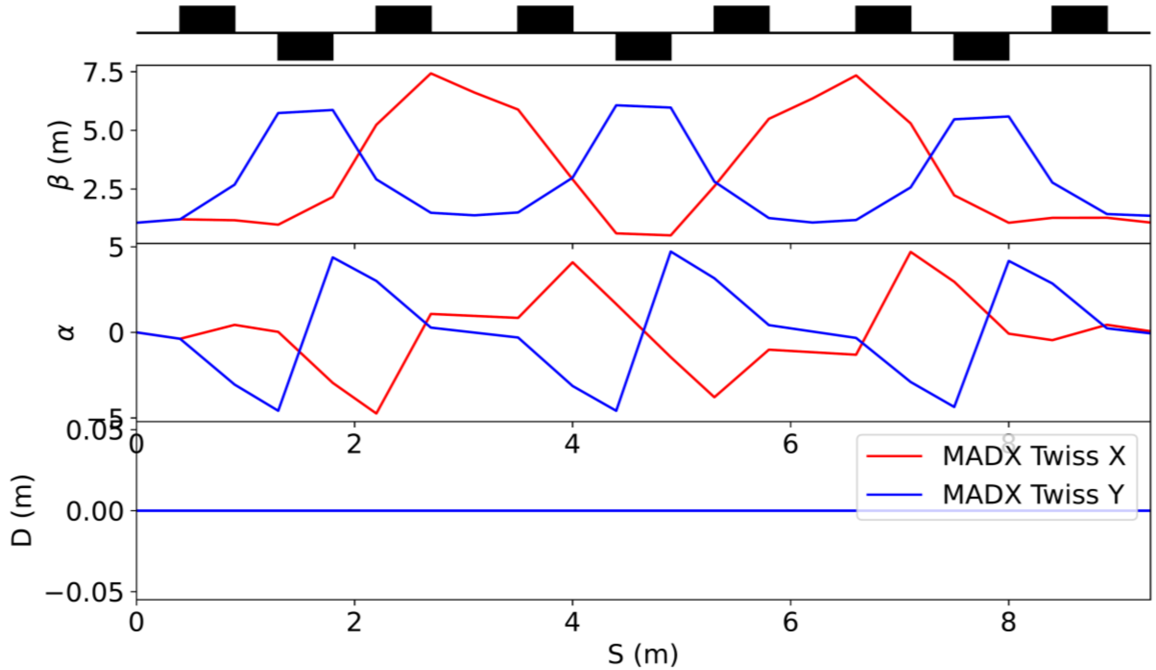
Demonstration of cooling module to show operation with beam

Demonstration of cooling to demonstrate beam physics performance

C. Rogers

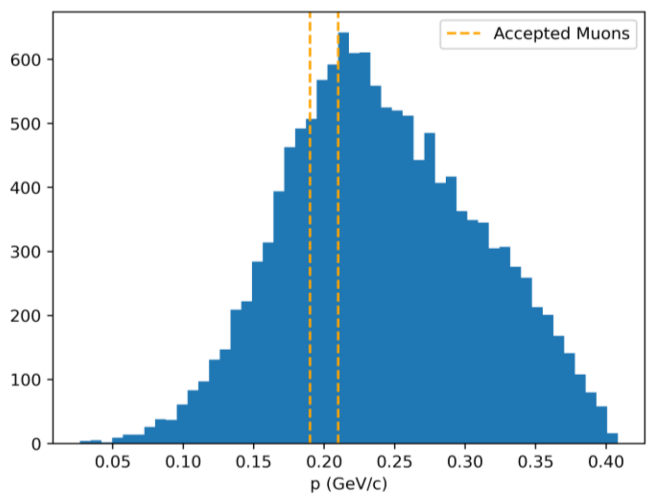
Pion decay channel - Optics

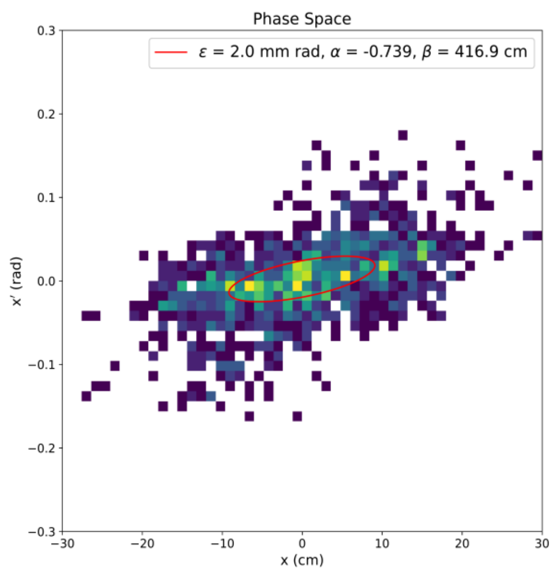
- Based on three **quadrupole triplets**
  - Same solution currently considered for **TT7** and **CTF3**
  - 9.5 m lattice, ~ **40%** pions decay at 300 MeV/c
- Large pion momentum acceptance: ~ ± 50%
- Low pion beta function to reduce losses

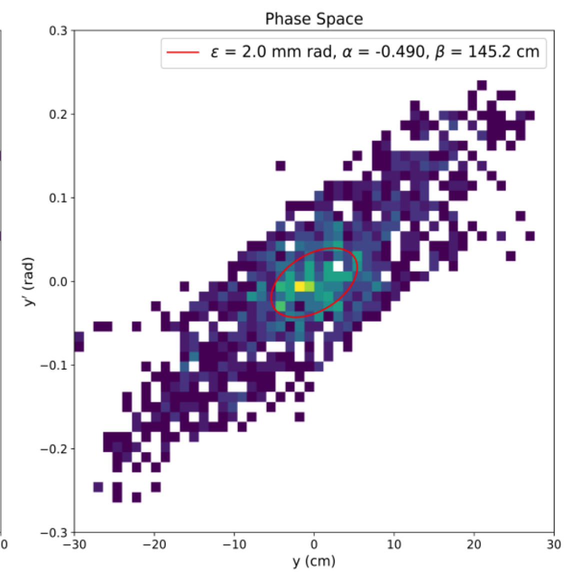


Pion decay channel – Muons

- Muons from decays of pions with **270 ± 50% MeV/c** momentum and maxiumum **2 mm rad** single particle emittance
- Muons with **190-210 MeV/c** momentum
  - diffuse beam – **red** ellipse indicates **2 mm rad** single particle emittance





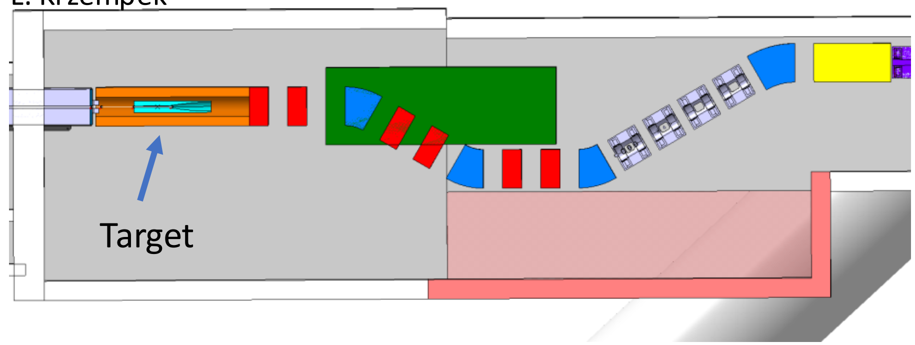


Chicane

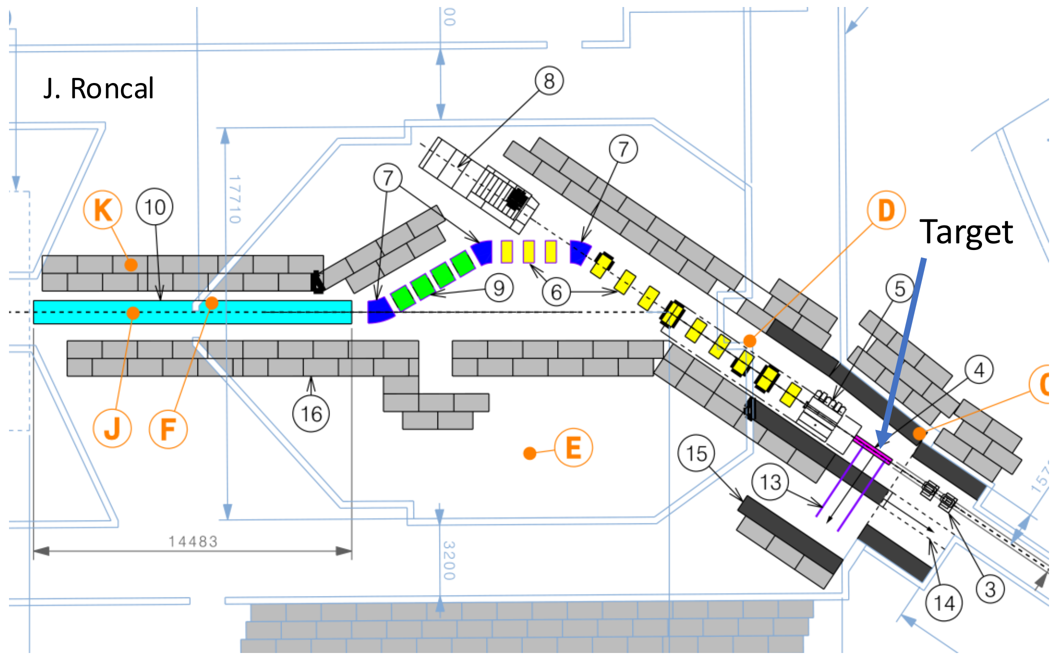
- Muon momentum selection (**190 – 210 MeV/c**), proton beam dump & muon beam preparation
- Significant space constraint in TT7
  - Requires tunnel expansion
- More flexibility in CTF3 assuming the target can be situated closer to PS extraction
- **NOTE**: Figures only show a placeholder lattice

L. Krzempek

TT7

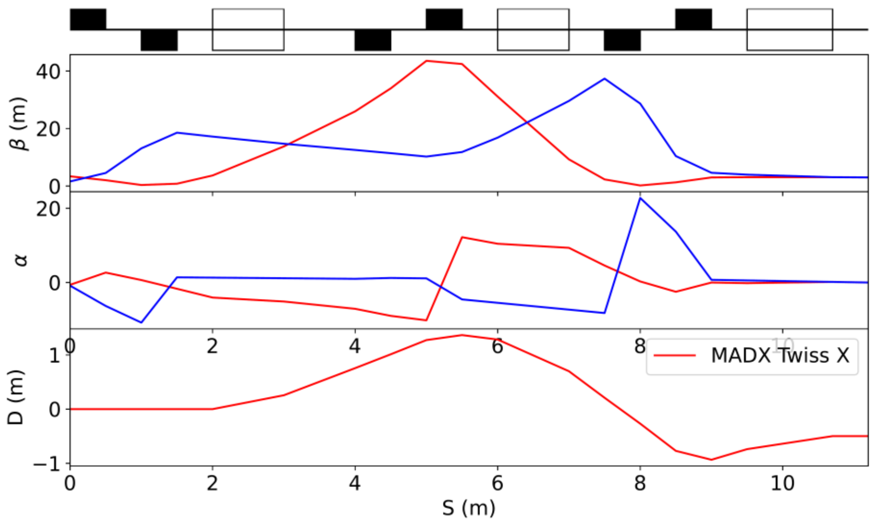


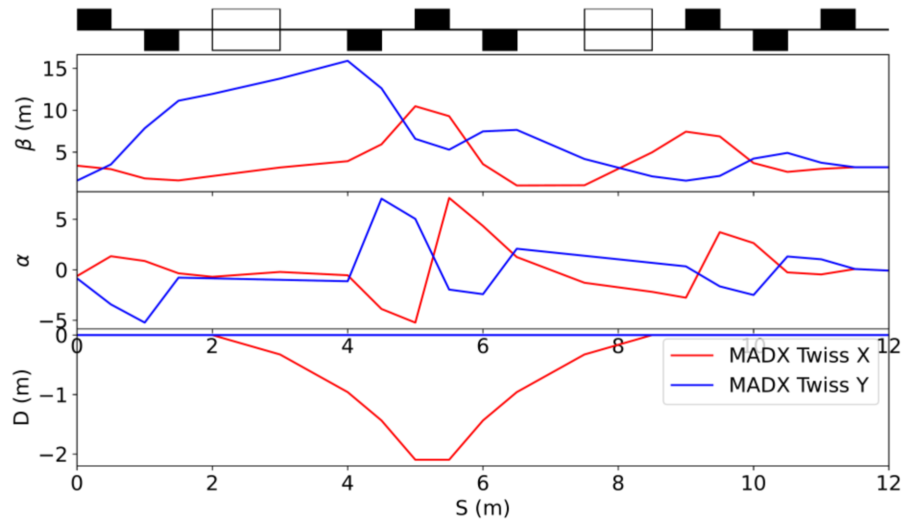
CTF3



Chicane – Optics Matching

- Performed exploratory chicane lattice design to verify if the muon beam can be matched into the Beam Preparation System (BPS)
- Optic plots shown here assume a beam with $\beta_{x,y}$ = 3 m and $\alpha_{x,y}$ = 0 required at BPS





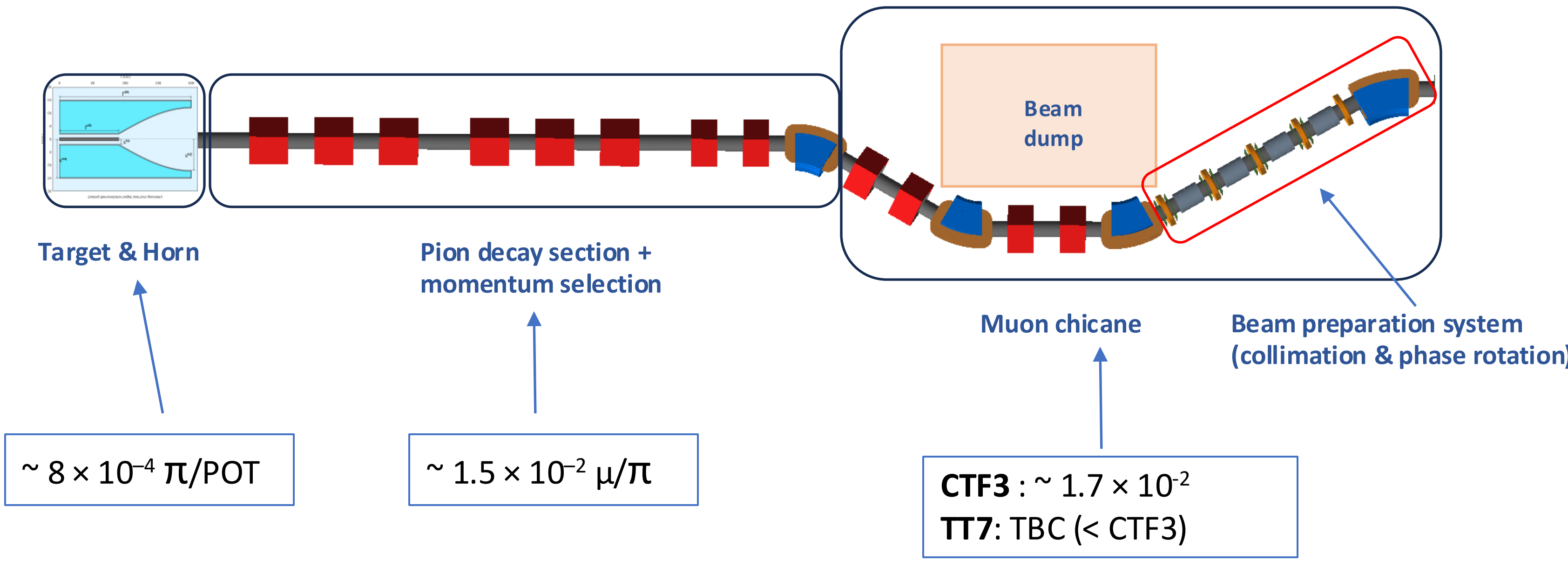
TT7

- 3-bend configuration
- Dispersion (X) not fully suppressed (~ - 0.4 m)
- Challenging to maintain a low beta to avoid losses in the magnet apertures

CTF3

- 2-bend configuration
- Zero dispersion
- Beta < 15 m can be achieved throughout
- Smaller beams can be delivered to the BPS ($\beta_{x,y}$ < 1 m)
  - Flexible lattice

Beam intensity

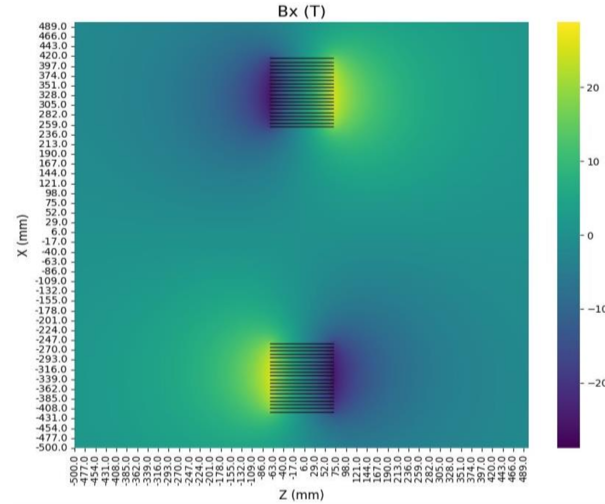


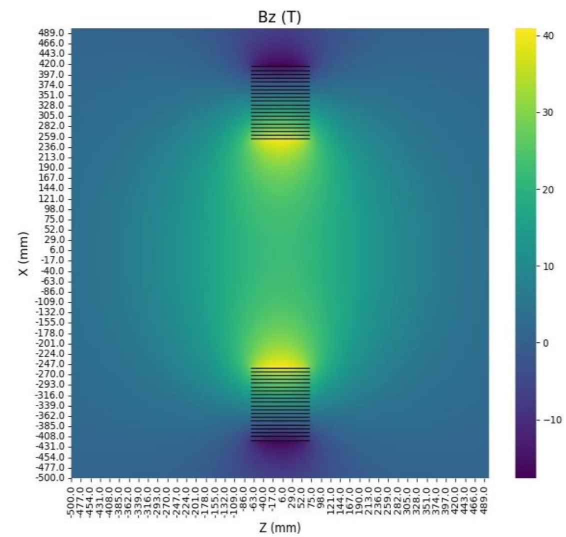
- For a proton bunch intensity of **10^{13}** ⟶ **~ 2 × 10^{6} muons/bunch** (CTF3)
  - Lower intensity expected in TT7 – under assessment
  - **Note**: BPS section needs further development and detailed tracking studies

BDSIM 'muoncooler' - Solenoid Models

- Two dedicated solenoid field models have been written:
  - Sheet Model (cylindrical current carrying sheet)
  - Block Model
- **Sheets** are modelled following the treatment outlined by [Derby et al].
- A bounding box optimisation to speed up computation has been implemented.
- **Solenoid Blocks** are implemented by layering sheets one on top of another for a more realistic 3D representation.

Parameter	Unit	Magnitude
Coil inner radius	mm	250.0
Coil radial thickness	mm	169.3
Coil outer radius	mm	419.3
Coil length	mm	140.0
Current density	A/mm^2	500.0





BDSIM 'muoncooler' - Dipole

- Two dipole field models implemented:
  - Hard edge
    - Constant B_y within the bore of the magnet (defined by length and aperture radius parameters)
  - Enge-type fringe fields
    - Following the treatment in B. D. Muratori, et al
    - Currently only one Enge polynomial term included, fields of the form:

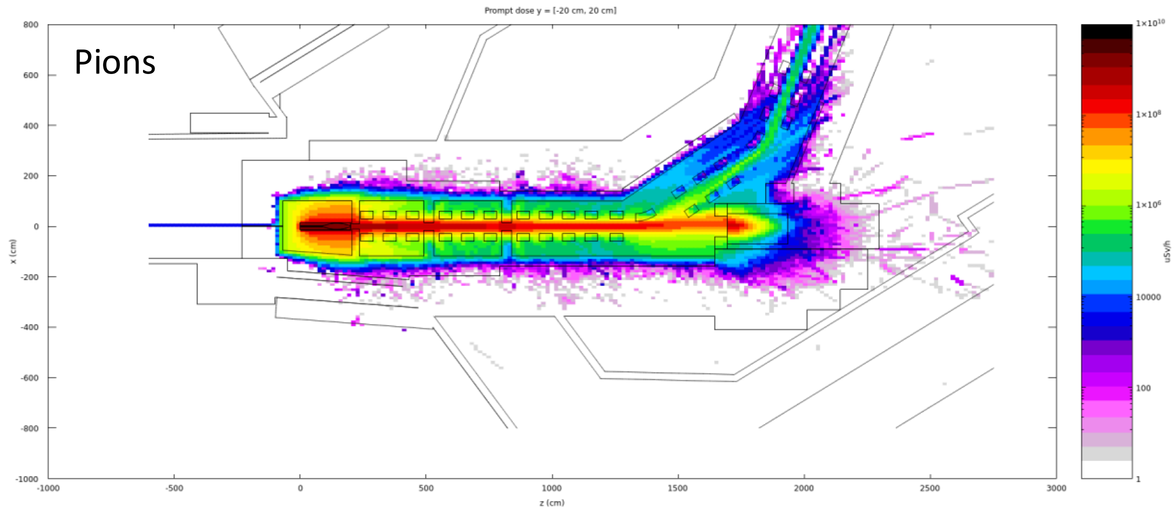
$$B_y = \frac{1 + e^{\alpha z} \cos \alpha y}{1 + 2e^{\alpha z} \cos \alpha y + e^{2\alpha z}}$$

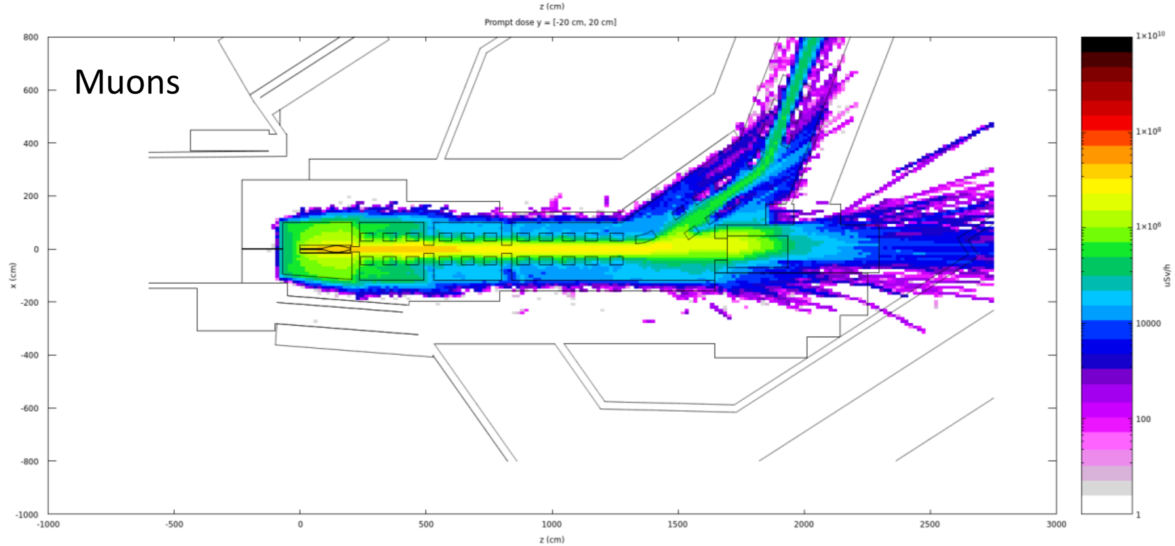
$$B_z = \frac{-e^{\alpha z} \sin \alpha y}{1 + 2e^{\alpha z} \cos \alpha y + e^{2\alpha z}}$$

where $\alpha = a_1/D$, D - magnet aperture, a_1 - coefficient of the first order Enge term

Prompt dose (x-z) - Pions/Muons

- Well contained, except for high energy muons
  - To investigate muon energy spectrum to inform mitigation strategy
- Note pion background





Prompt dose (x-z) - Protons/Neutrons

- Neutrons main radiation contributors
- AD dump ~ effective for both species
  - Potential widening to be investigated