Beam Matter studies for the target system

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1st Beam Dump Facility (BDF) Targetry Systems Advisory Committee (TSAC) – March 4-6, 2025

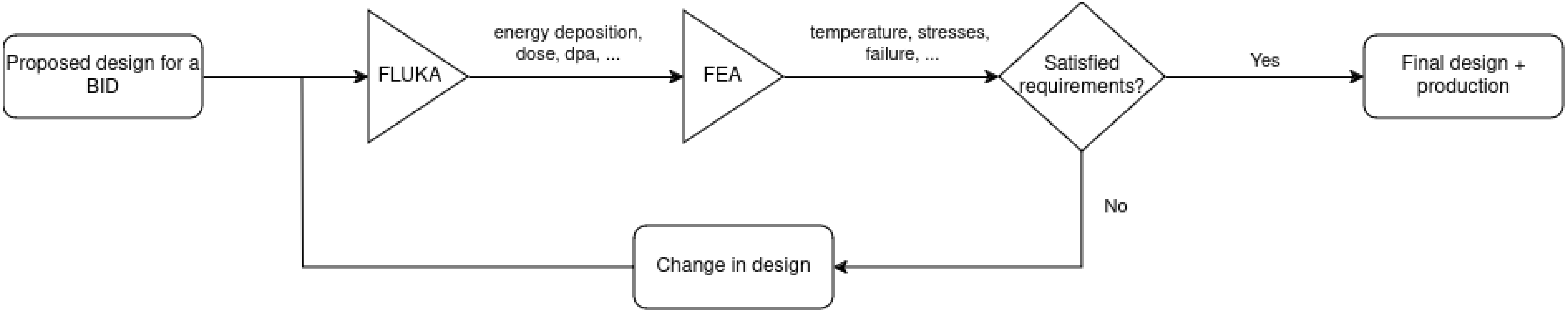
Outlook

- FLUKA simulations and motivation
- Geometry and beam parameters
- Particle yields and energy deposition in various systems
- DPA and gas production in target
- Radiation fields around target complex and R2E considerations
- Conclusion and outlook

FLUKA simulations and motivation

- **FLUKA is a general-purpose Monte Carlo code for particles transport and interaction with matter**

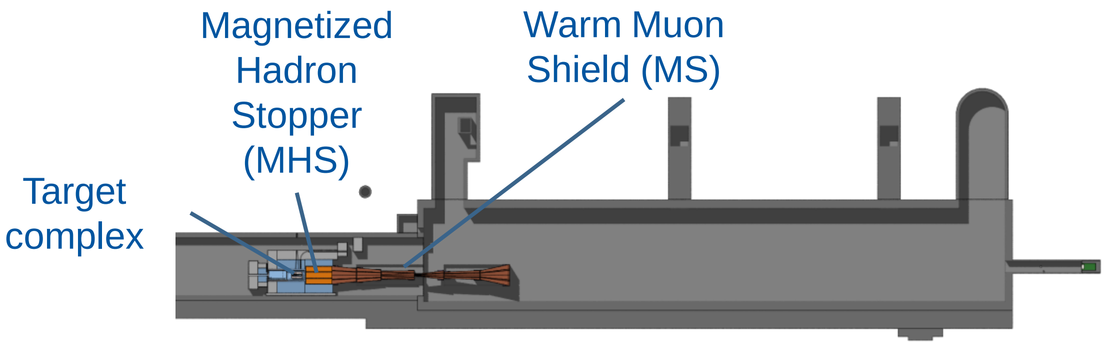
- Results coming from FLUKA.CERN simulations are used as input for Finite Element Analysis (FEA) to **validate the design** of different Beam Intercepting Devices (BID) distributed along the accelerator lines



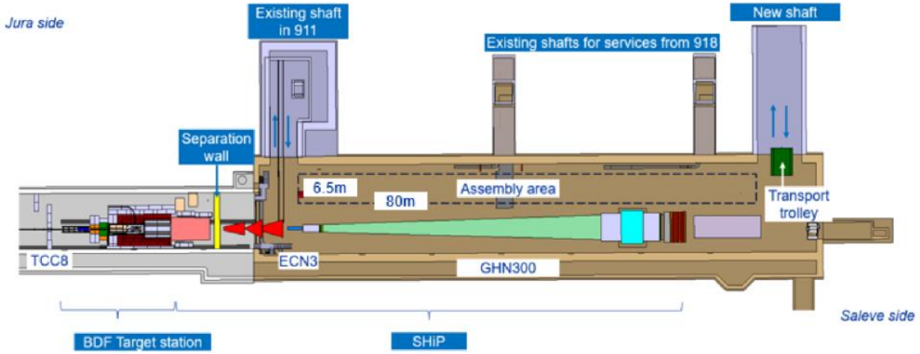
Geometry and beam parameters

Geometry design

Top view of FLUKA model for BDF/SHiP



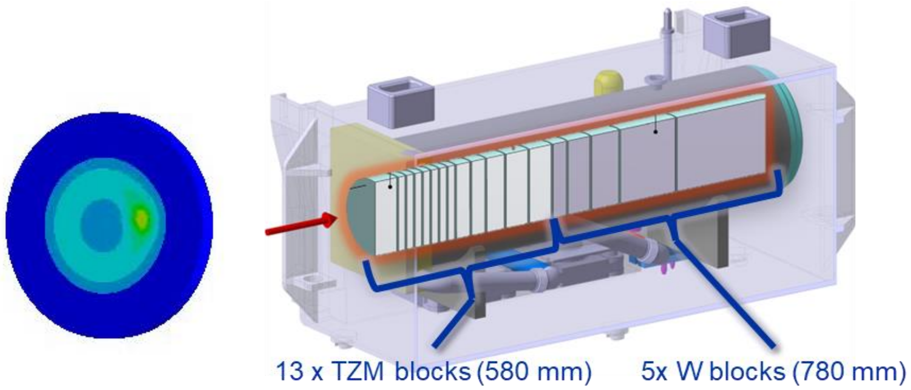
Top view of BDF/SHiP integration model – EDMS 2936008



Beam parameters

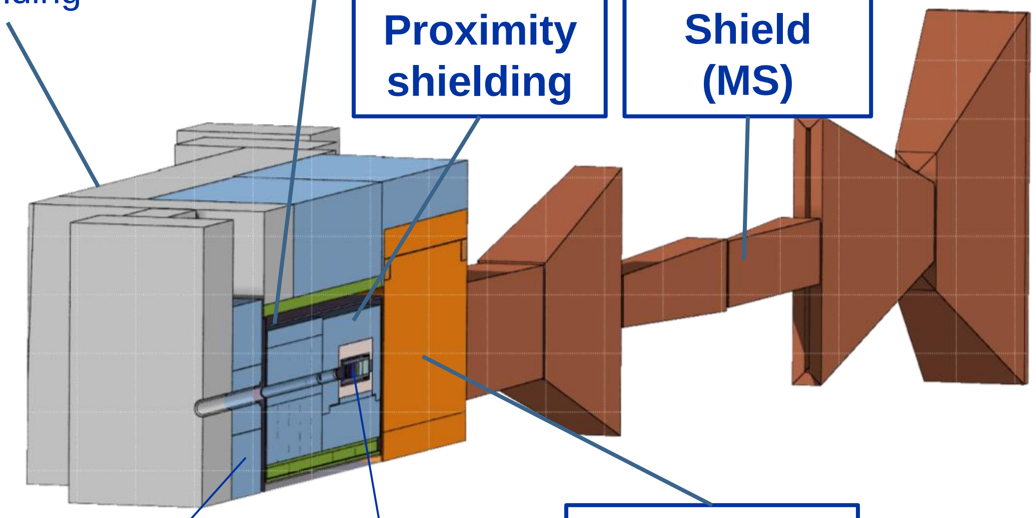
Beam parameters of the BDF target operation – CDS (Comprehensive Design Study) book

Parameter	Value	Unit
Proton momentum	400	GeV/c
Beam intensity	4e13	POT/cycle
Annual beam intensity	4e19	POT/year
Cycle length	7.2	s
Spill duration	1.0	s
Beam dilution patter	circular	-
Dilution circle radius	50	mm
Beam sigma (H,V)	(8, 8) or (16, 16)	mm



Representation of beam sweep (left) and CDS design target for BDF (right)

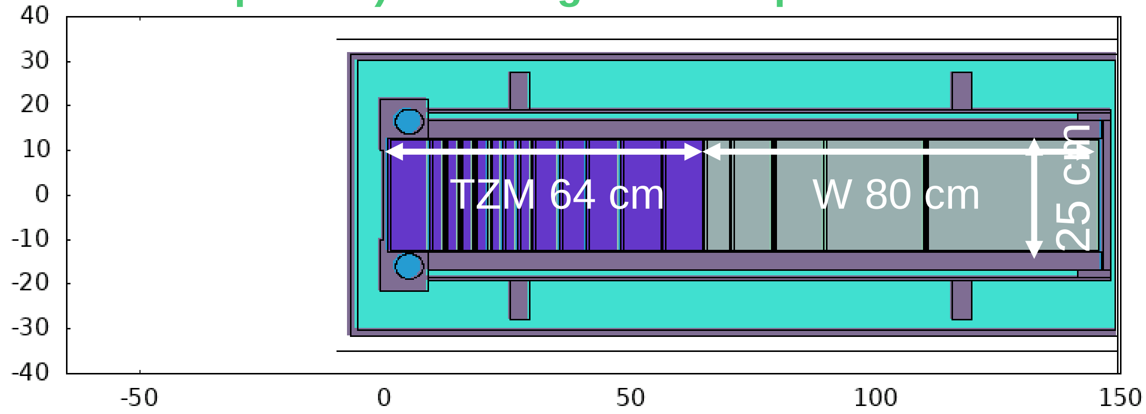
Particle yields and energy deposition in various systems



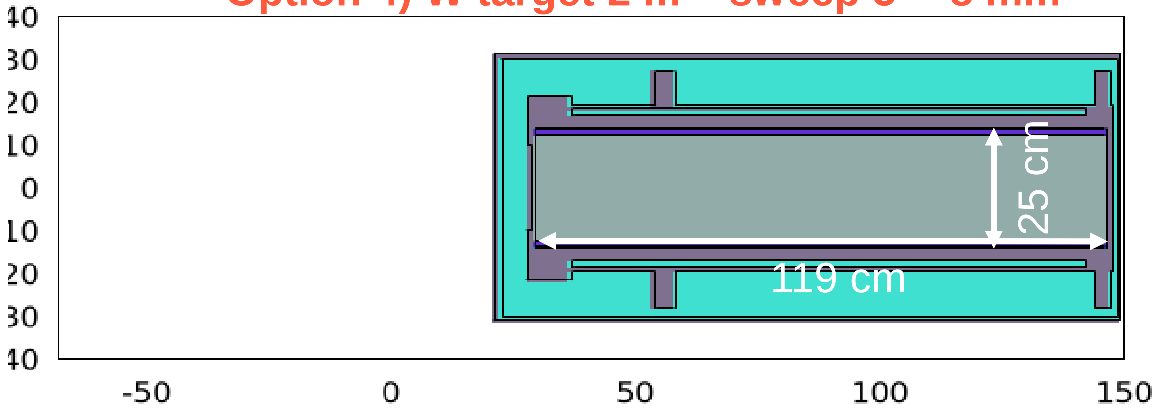
Geometry: Target core designs

Different core designs evaluated to maintain/improve the **SHiP physics reach** with respect to the CDS design

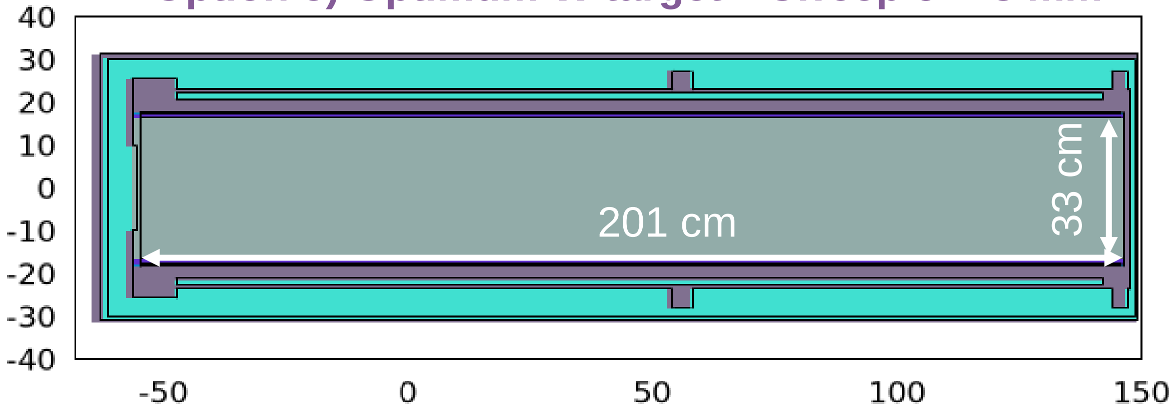
Option 1) CDS target – sweep σ = 8 mm
Option 2) CDS target – sweep σ = 16 mm



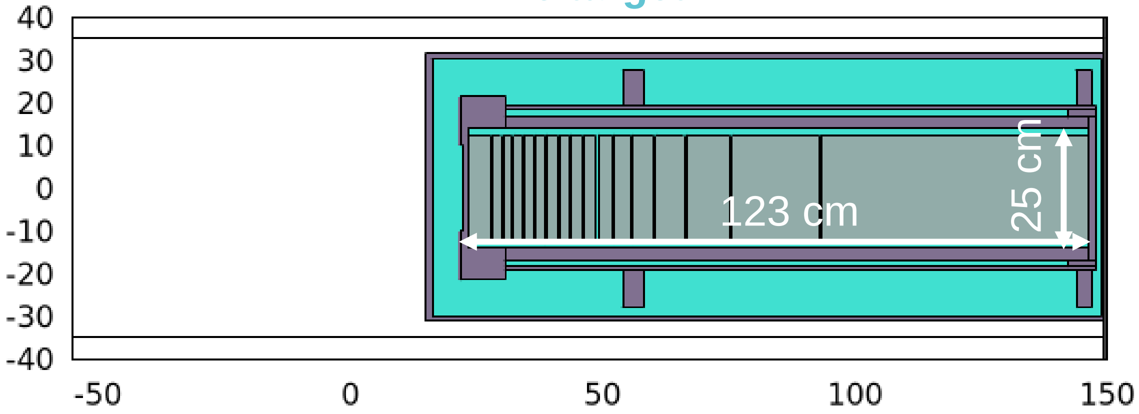
Option 3) W target 1.2 m – sweep σ = 8 mm
Option 4) W target 2 m – sweep σ = 8 mm



Option 5) Optimum W target – sweep σ = 8 mm



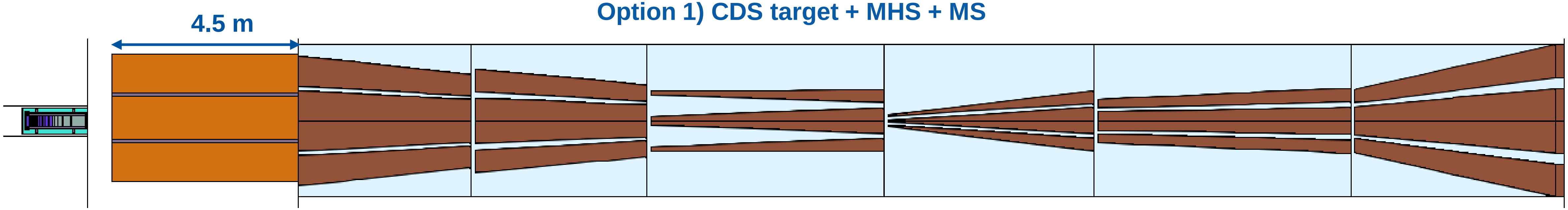
W-He target



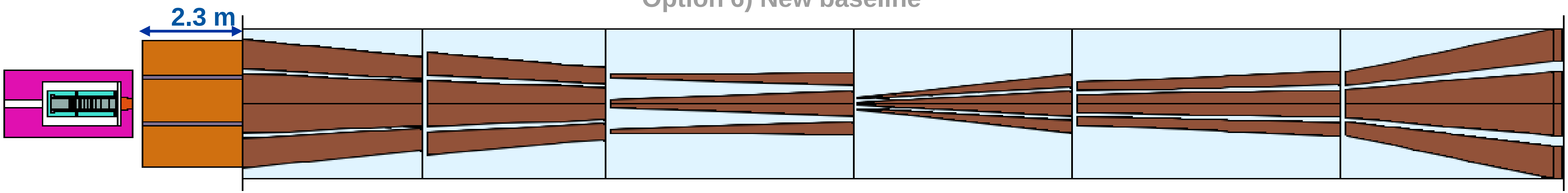
Geometry: Reduction of MHS length

- **As requested by SHiP, a shorter MHS would allow to reduce the aperture of the SC option:**
  - Full W target 1.5 m long, ρ = 19.3 g/cm^3, ⌀ = 25 cm
  - Cast-iron proximity shielding length downstream 25 cm
  - W plug ρ = 18.5 g/cm^3, ⌀ = 30 – 25 cm
  - Hadron absorber: 2.3 m long (from 4.5 m)
  - sweep σ = 8 mm

Option 1) CDS target + MHS + MS



Option 6) New baseline

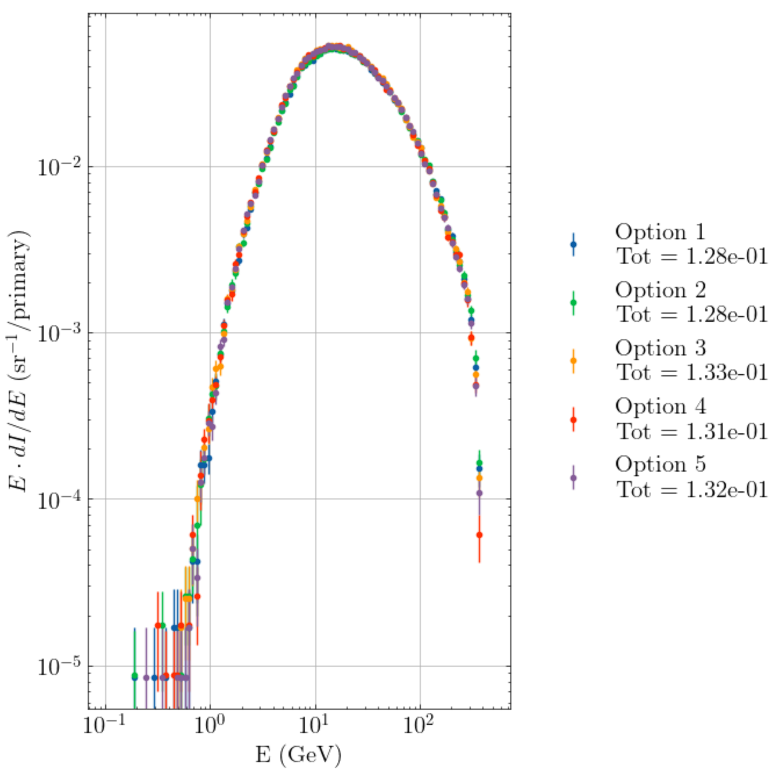


Target: Physics parameter metrics

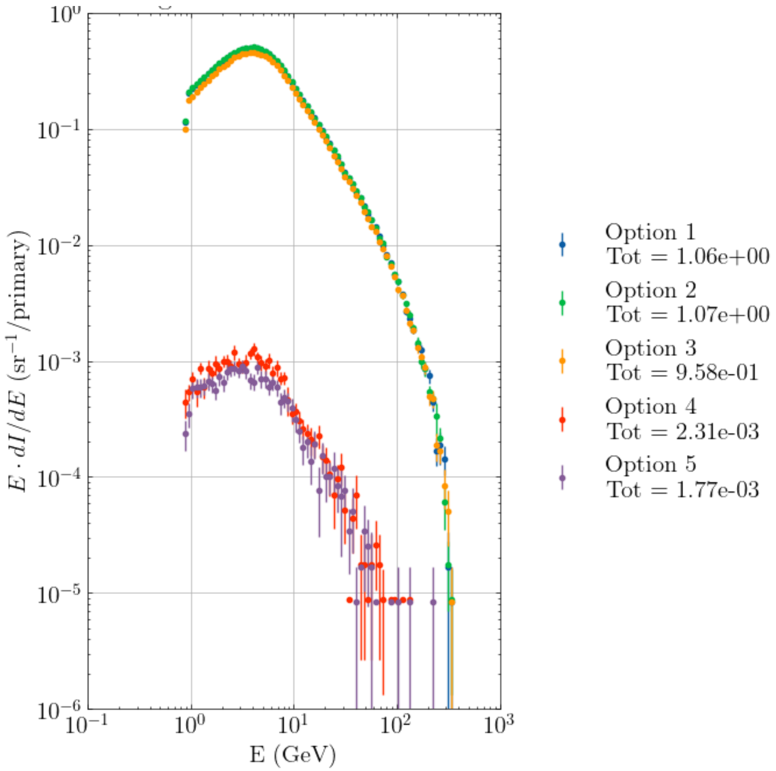
Option 1) CDS target – sweep σ = 8 mm
Option 2) CDS target – sweep σ = 16 mm
Option 3) W target 1.2 m – sweep σ = 8 mm
Option 4) W target 2 m – sweep σ = 8 mm
Option 5) Optimum W target – sweep σ = 8 mm
Option 6) W target 1.5 m – MHS 2.3 m – sweep σ = 8 mm

For each target design, **signal production** and **background suppression** are evaluated – SHiP CM

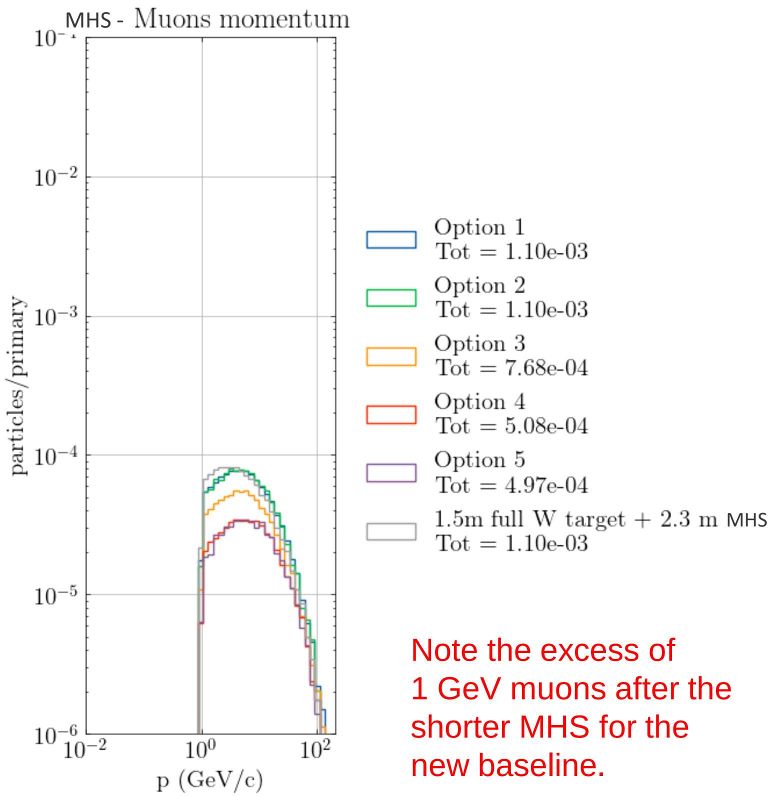
Spectra of charmed particles produced in target
Metrics used as trace for SHiP desired signal



Spectra of pions exiting target downstream
Metrics used for background suppression evaluation



Spectra of muons exiting MHS
Metrics used for background suppression evaluation

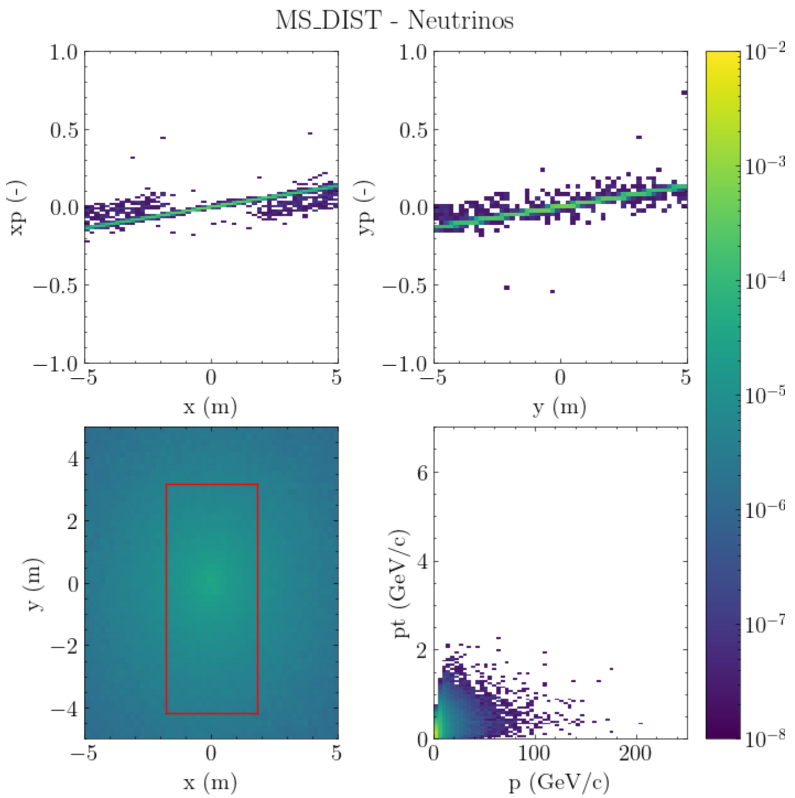


Note the excess of 1 GeV muons after the shorter MHS for the new baseline.

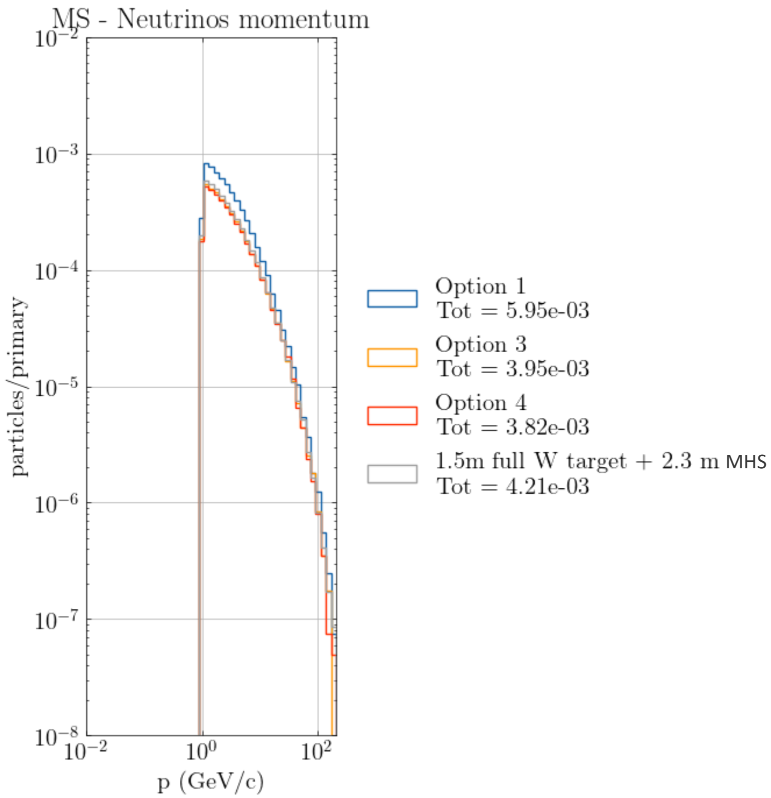
MS: Neutrino distributions

Option 1) CDS target – sweep σ = 8 mm
Option 2) CDS target – sweep σ = 16 mm
Option 3) W target 1.2 m – sweep σ = 8 mm
Option 4) W target 2 m – sweep σ = 8 mm
Option 5) Optimum W target – sweep σ = 8 mm
Option 6) W target 1.5 m – MHS 2.3 m – sweep σ = 8 mm

Option 1
Phase space distribution ν



Comparison
Spectra of ν exiting MS



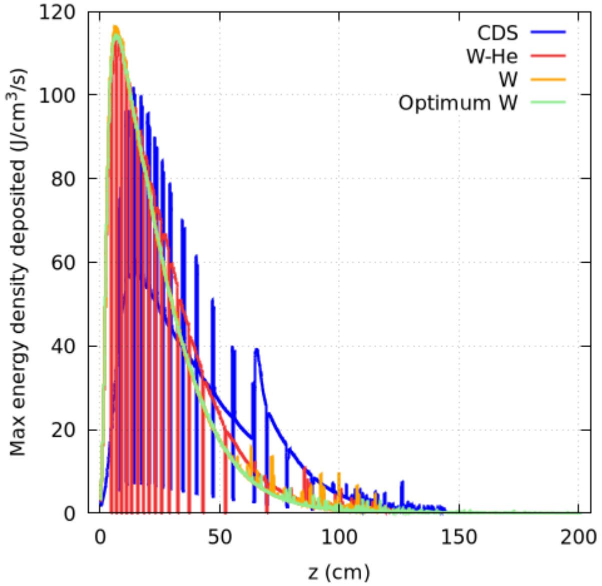
- Considered all neutrinos and anti-neutrinos flavors
- Simulated 40 M protons on target
- Downstream the MHS, similar reduction factor obtained going from CDS to full W target
- The new baseline sits in between CDS and Options 3/4

Target: Energy deposition

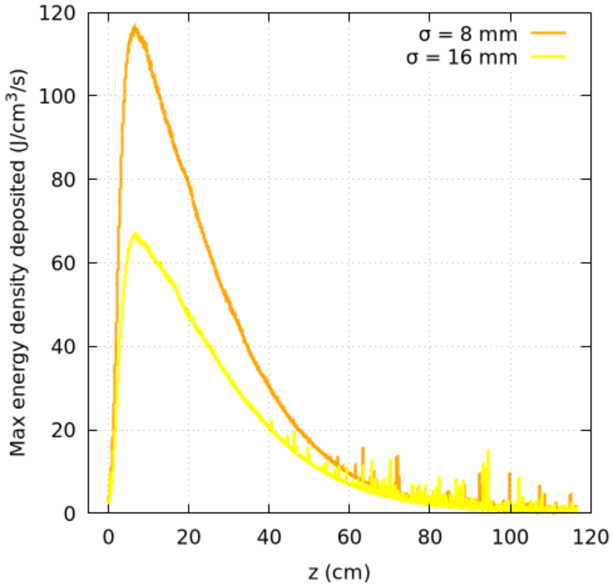
- Evaluation of energy deposited in the core for the different target designs

Verification of thermo-mechanical properties and design optimization

Maximum energy density deposited by beam
For all designs same beam delivery
(sweep 50 mm radius, 8 mm σ)



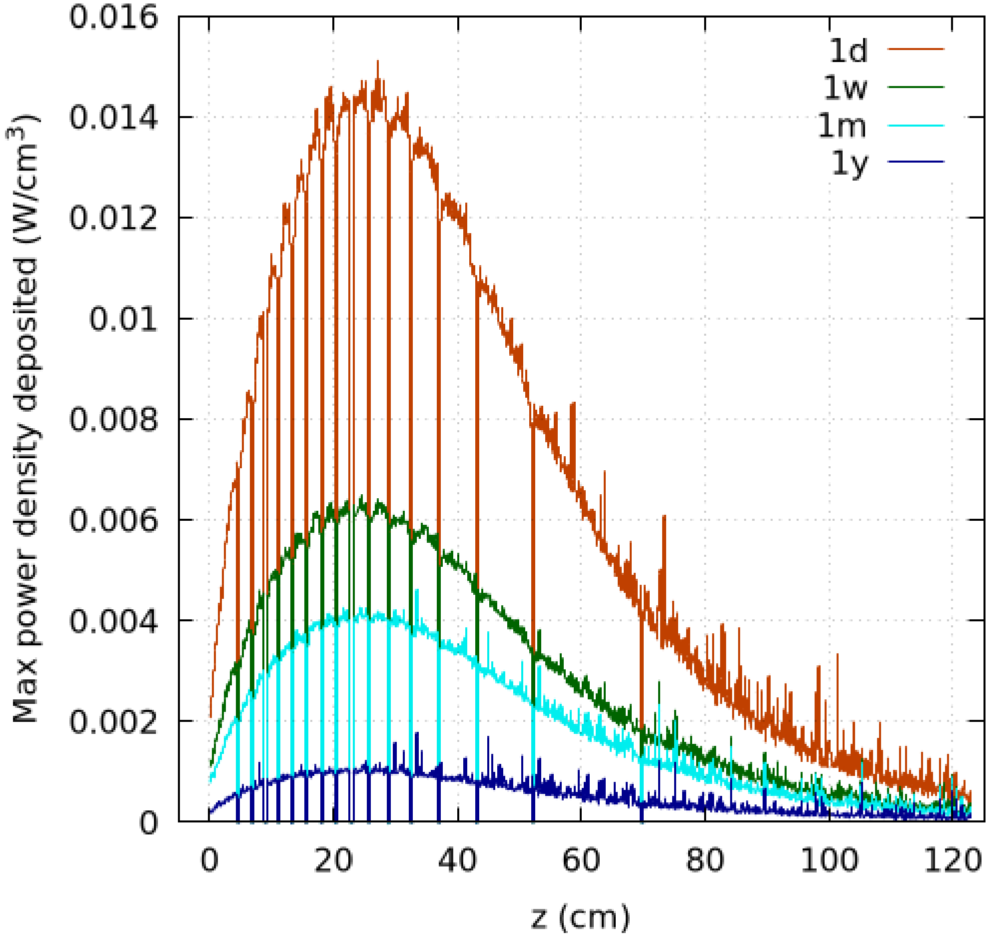
Maximum energy density deposited by beam
W target with different beam delivery
(sweep 50 mm radius, 8 mm and 16 mm σ)



Results normalized to 4e13 p/cycle with 7.2 s/cycle

Target: Decay heat

Residual maximum power density deposited
W-He target, beam sweep 50 mm radius 8 mm σ
for 5 years with 4e19 p/year

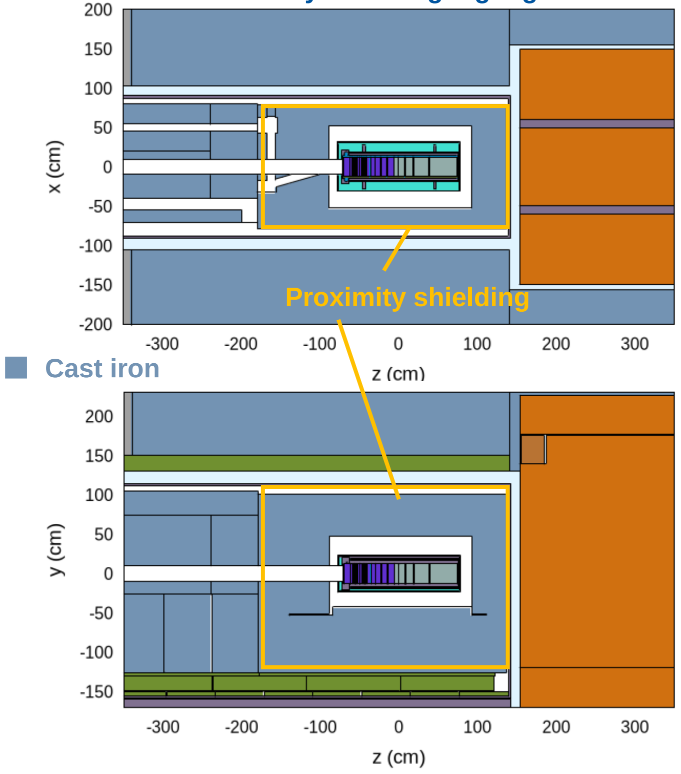


- For CDS design, the decay heat in the target material is considerable and it is significantly driven by the cladding.
- The possibility of a Loss-of-Coolant Accident (LOCA) poses a critical safety risk. This risk leads to several potential problems
  - Uncontrolled temperature and pressure increase
  - Potential risk of core melting (due to decay heat)
  - In case of cladding rupture, the release of radioactive material
- **Reducing/avoiding Ta cladding as mitigation strategy**

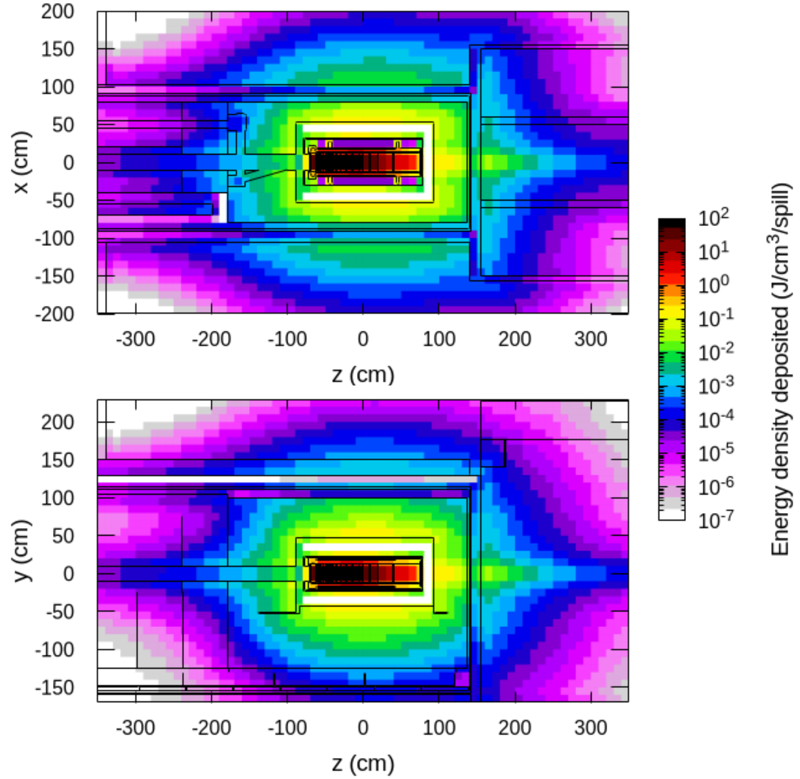
Proximity shielding: Energy deposition

- The proximity shielding is placed inside the vacuum vessel, and it surrounds the whole target → **high energy deposited, and active cooling required**

Top view and side view of BDF target complex
Proximity shielding highlighted



Top view and side view for energy density deposited in BDF target complex. Results normalized with 4e13 p/spill



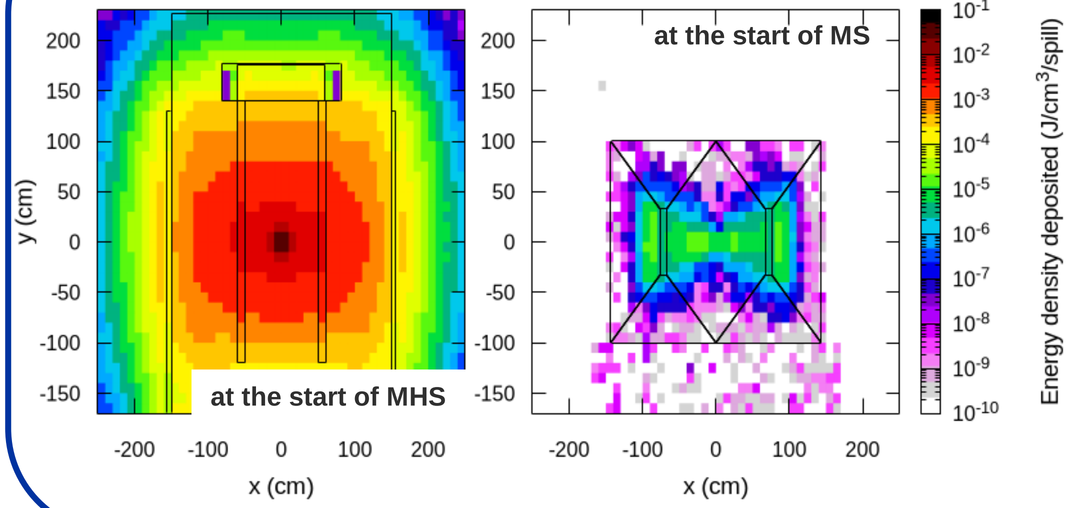
Parameters and integral energy deposited in proximity shielding

Proximity shielding		
Parameter	Value	Unit
Volume	~1e7	cm^3
Beam intensity	4e13	POT/spill
Spill duration	1	s
Energy deposited	1.62e5	J/spill

MHS and MS: Energy deposition

- The **Magnetized Hadron Stopper (MHS)** and the **Muon Shield (MS)** are fundamental elements in the **background suppression for SHiP**:
  - MHS aims to stop all hadrons escaping the target and applies a first sweep to the muons through a magnetic field. Energy deposition evaluated in the coil and yoke to appropriately design the element.
  - MS is composed by a series of magnetized blocks which sweep horizontally the muons exiting downstream BDF creating the “ship” shape. Options for a fully warm and hybrid (super conducting + warm) MS are being investigate.

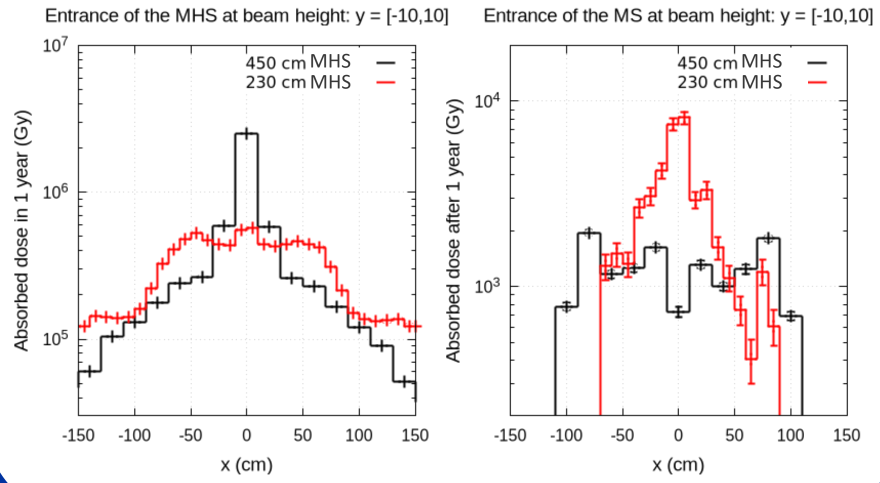
CDS geometry. Cross section for energy density deposited.
Results normalized to 4e13 p/spill



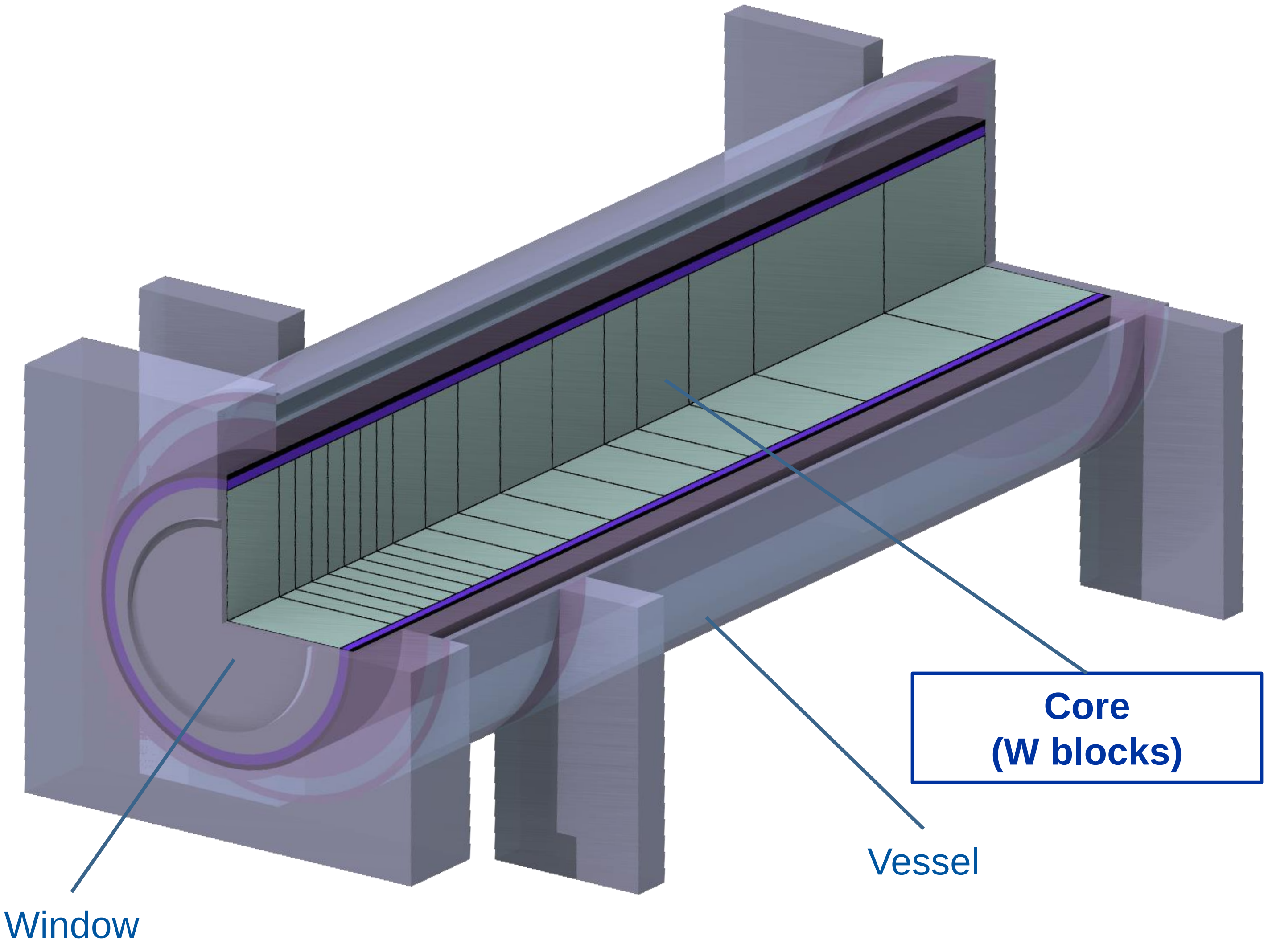
Yearly value of TID for the coil and yoke’s center at start and at the end of MHS. 4e19 p/year considered.

MHS		
Element	Gy/year at start	Gy/year at end
Coil	$\sim$4e+3	$\sim$1e-2
Center	$\sim$1e+6	$\sim$1e+4

Effect of 1.5 m W target + plug + reducing the MHS



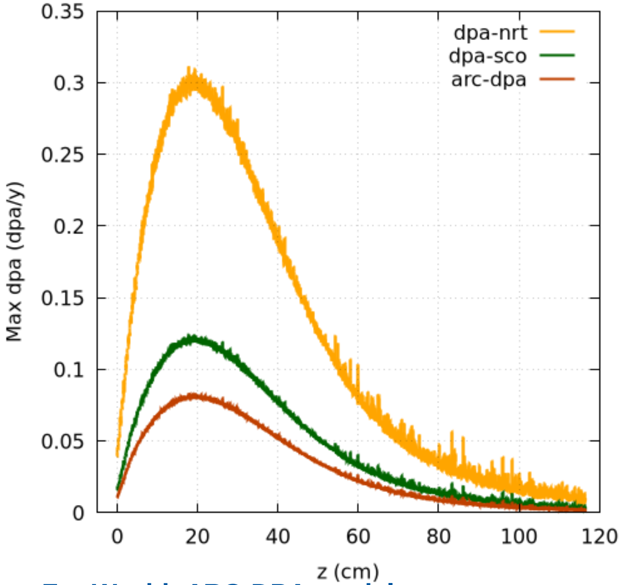
DPA and gas production in target



DPA in target

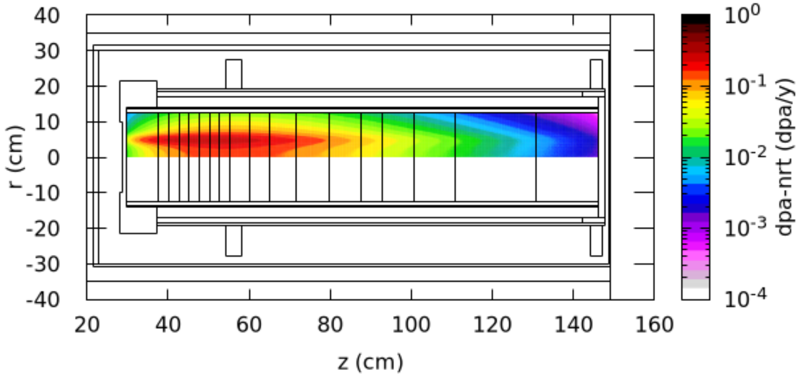
- Evaluation of **displacement per atom in the target's core** evaluated with different models and used as figure of merit for the **radiation induced damage**:
  - ARC-DPA model assigns an energy-dependent damage cross section. Parameters are needed for DPA evaluation.

Maximum yearly DPA, computed with different models, along W target
Beam sweep 50 mm radius, 8 mm σ

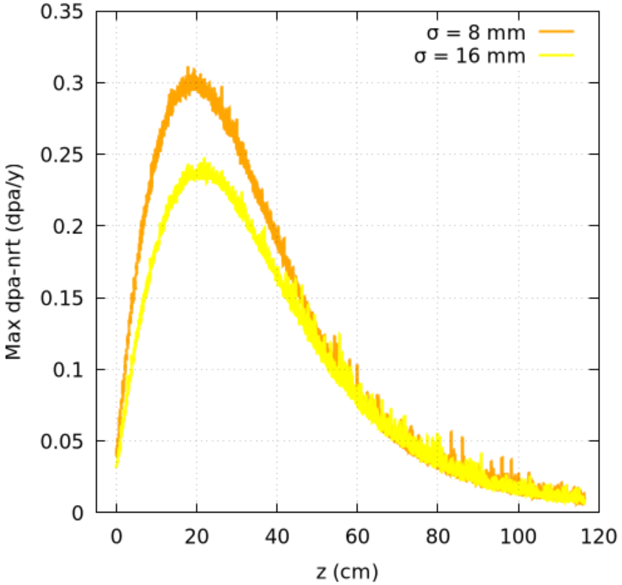


For W with ARC-DPA model, parameters:
E_d = 70 eV, b_{arc} = -0.564 and c_{arc} = 0.119 (ref)

Distribution of DPA-NRT in
W target with beam sweep 50 mm radius,
8 mm σ. Values averaged angularly.



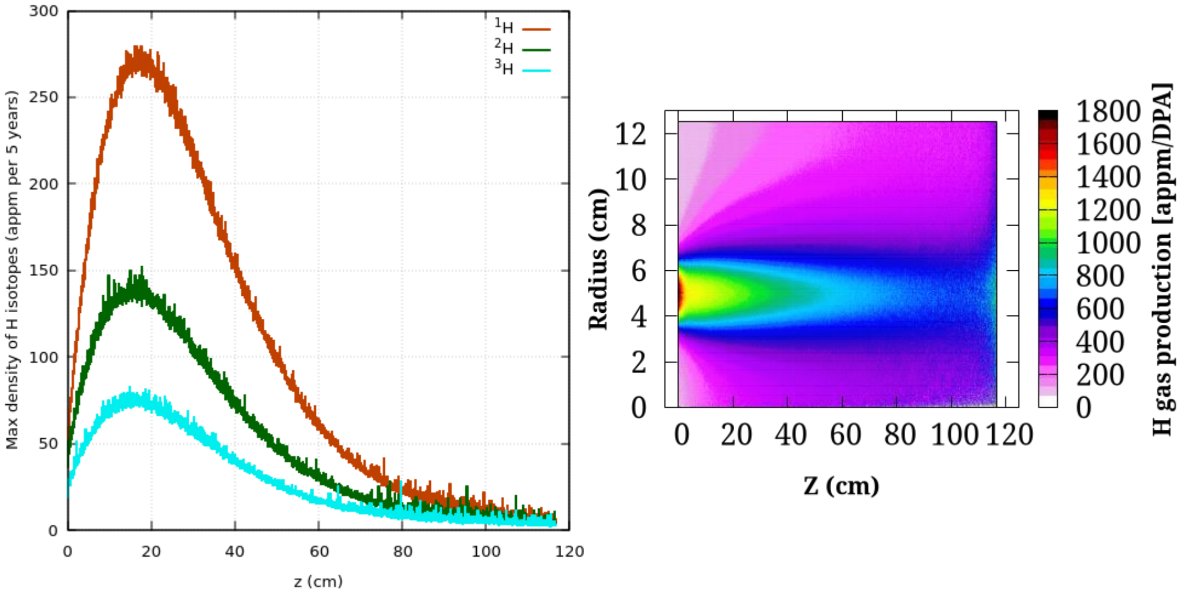
Maximum yearly DPA-NRT along W target with different beam delivery (sweep 50 mm radius, 8 mm and 16 mm σ)



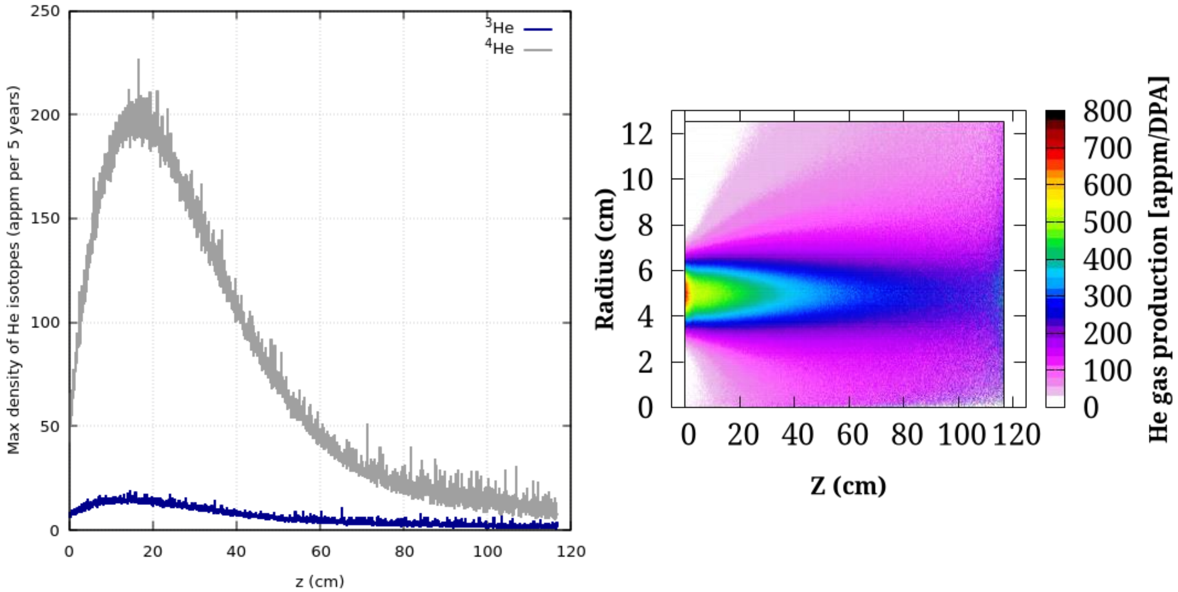
Gas production in target

- Evaluation of **residual gas (H and He) production in target core**. Gas production can generate concern in **safety** and can change **material properties**

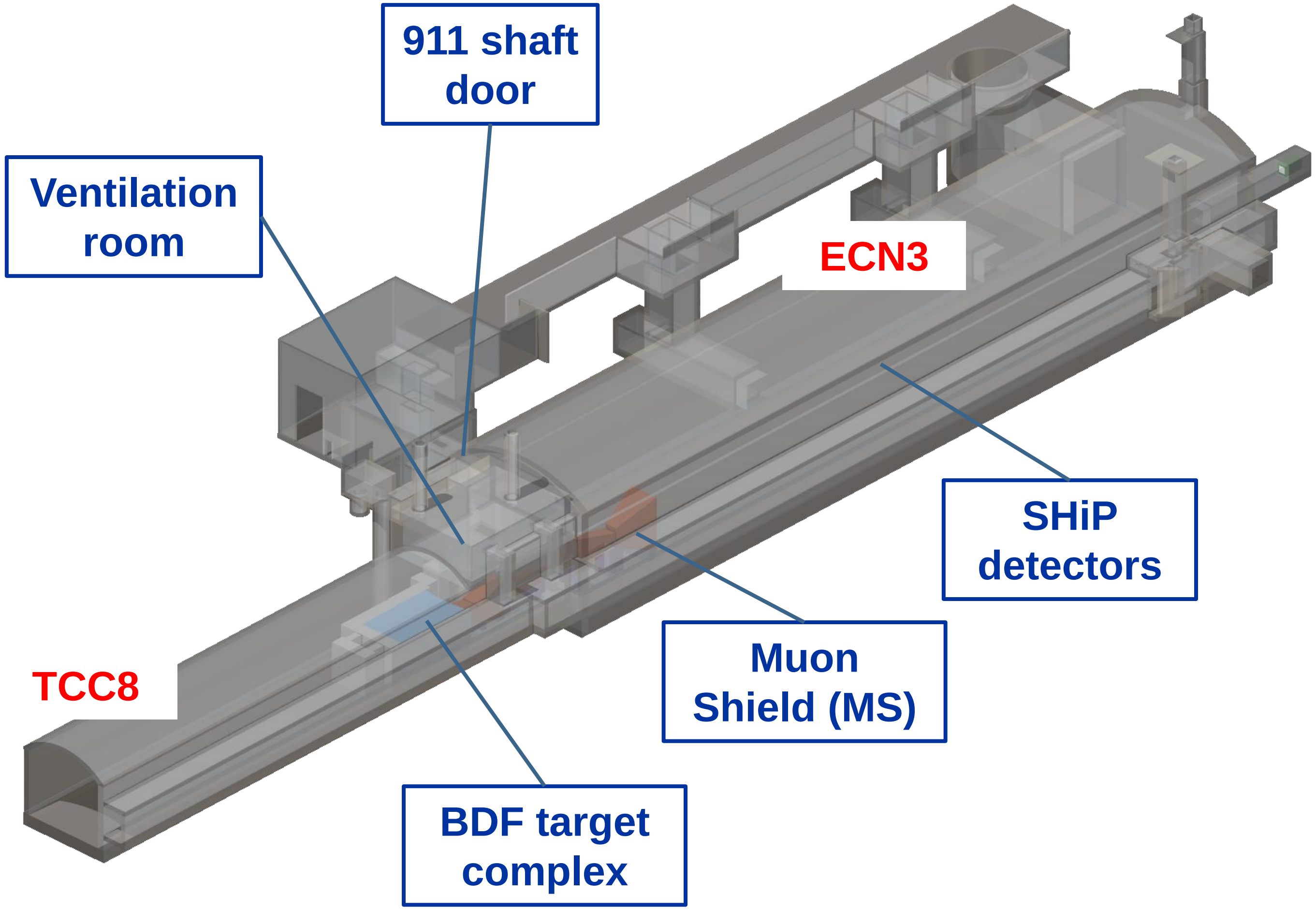
Maximum density of hydrogen isotopes along W target with beam sweep 50 mm radius, 8 mm σ after 5-year operation



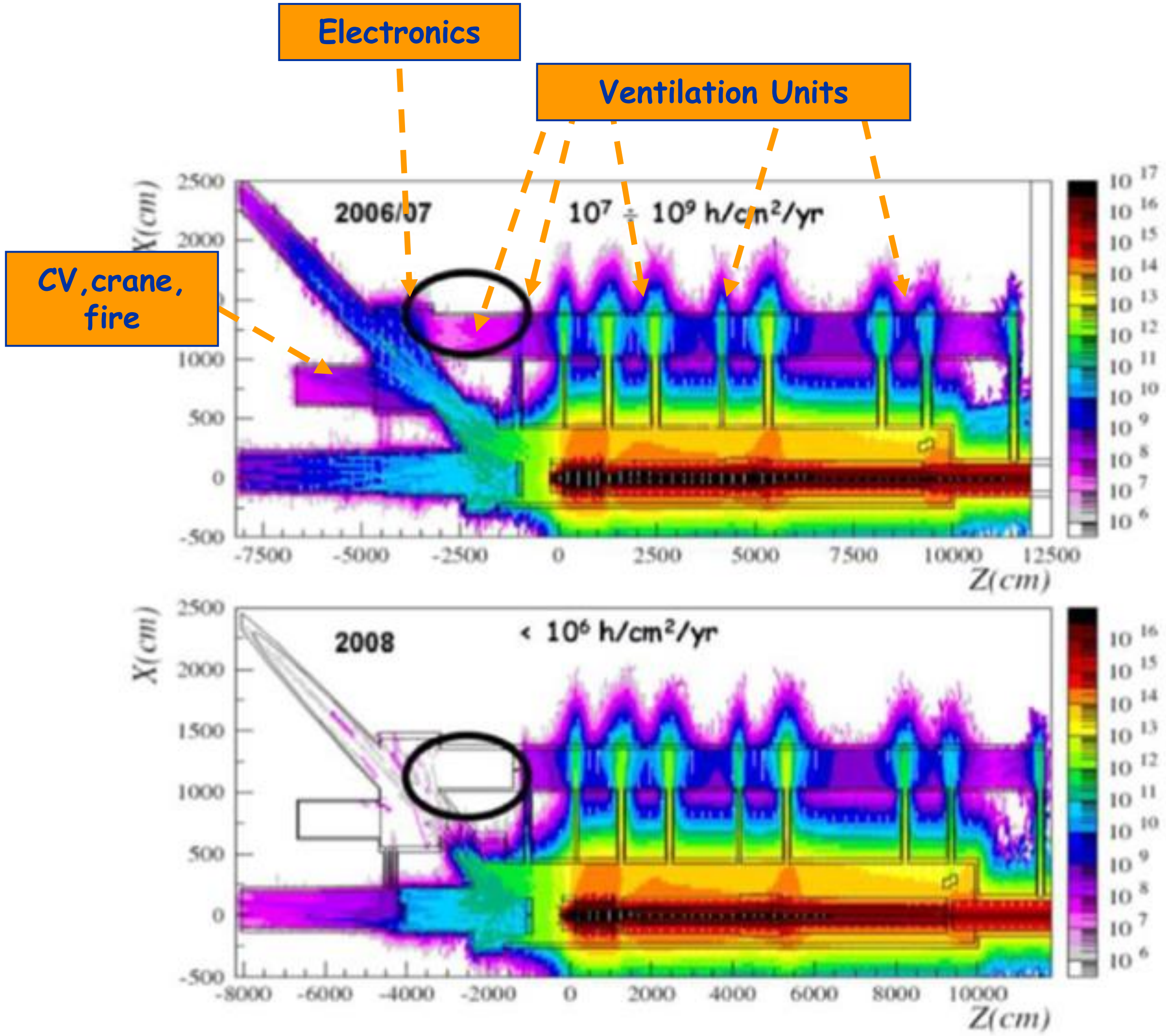
Maximum density of helium isotopes along W target with beam sweep 50 mm radius, 8 mm σ after 5-year operation



Radiation fields around target complex and R2E considerations



R2E lesson from CNGS experience



During the 2007 CNGS physics run, 8×10^{17} p.o.t. delivered, i.e., ~2% of a nominal CNGS year

Single event upsets (SEU) in the electronics of the ventilation units caused control failure and interruption of communication

Critical review of installation of all electronics in CNGS:

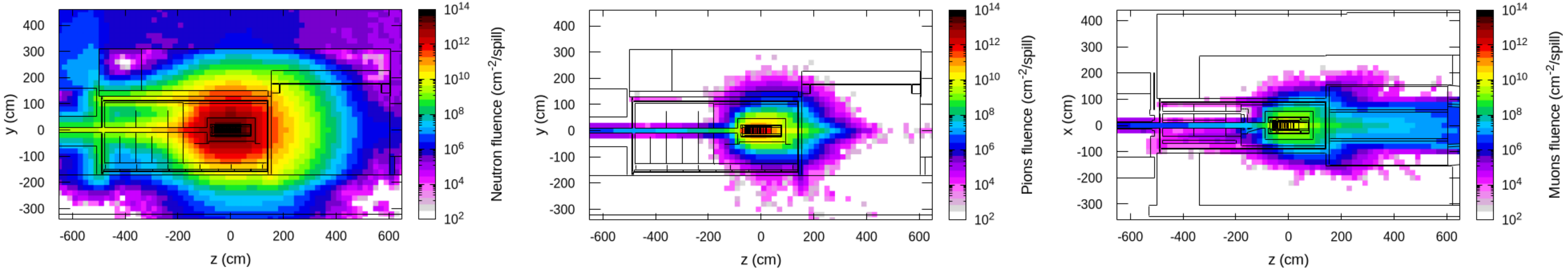
- installing thick radiation shields in situ
- moving all the control systems into a protected area

This triggered the creation of the R2E Project, with large impact for LHC operation and HL-LHC
→ **This must be considered for any new facilities**

Radiation field around the target complex

- Protons of 400 GeV/c impacting on a 12 λ long target (CDS) generate a **high radiation field** all around the target and the target complex
  - Constraints for radiation protection and radiation to electronic aspects → **Great amount of shielding required**
  - On the other side, the radiation field can be exploited for material and electronics irradiation tests → (backup slide)

Side view of neutron (left) and pions (middle) around target complex. Right, top view of muons fluence.
Results normalized considering 4e13 p/spill. Plots averaged around BDF target (CDS design).



Radiation field results to be dominated by neutrons, pions stopped in MHS while muon exit downstream BDF

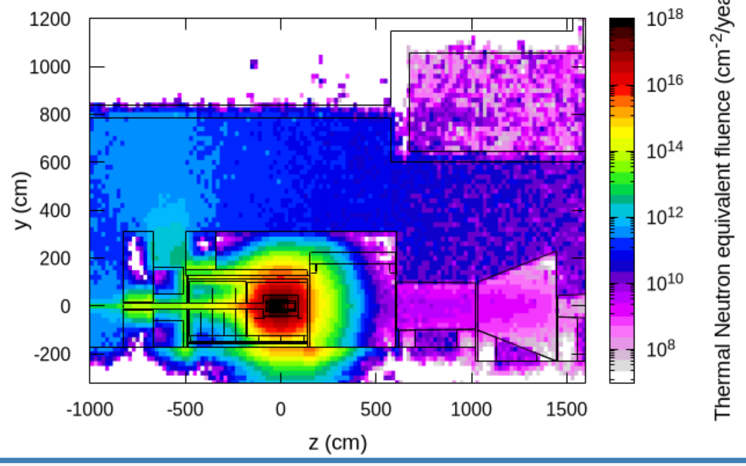
R2E in TCC8

General limits for R2E considerations

Effects	R2E quantity	Limit value	Unit
Cumulative	TID	1 - 10	Gy/(10 years)
	Si1MN	1e10 - 1e11	cm^{-2}/(10 years)
SEE	HEH	3e6	cm^{-2}/year
	ThNeu	3e7	cm^{-2}/year

- The radiation field generates constrains due to **radiation to electronic effects** mainly leading to **cumulative damage** and **Single Event Effect (SEE)**
- Some **general limits** (EDMS) are defined for specific **R2E quantities** (Indico) to characterize an area as **radiation-safe** for electronics.
- The **radiation levels** in different areas which will store active electronics has been evaluated:
  - *Ventilation room above BDF in TCC8*
  - 911 shaft door
  - SHiP detector in ECN3

Side view of BDF and ventilation room in TCC8.
ThNeu yearly fluence averaged along target.
Grey color represents the limit of 3e7 cm^{-2}/year



Similar plots present also in BDF/SHiP proposal, considering previous integration model of BDF

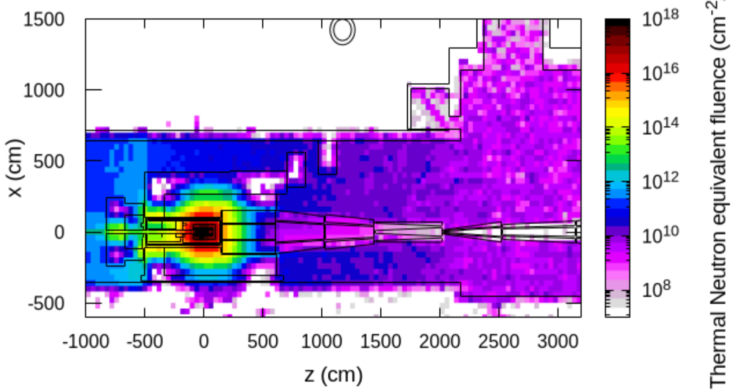
R2E in 911 shaft and ECN3

General limits for R2E considerations

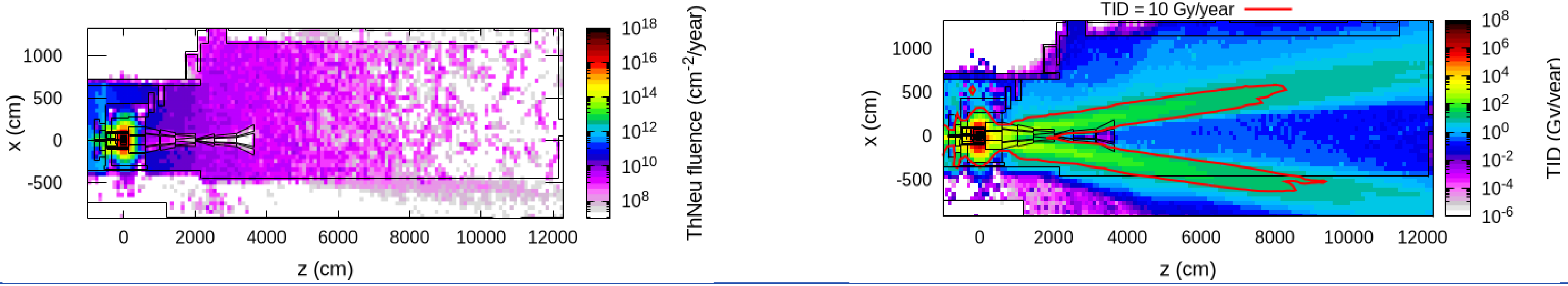
Effects	R2E quantity	Limit value	Unit
Cumulative	TID	1 - 10	Gy/(10 years)
	Si1MN	1e10 - 1e11	cm^{-2}/(10 years)
SEE	HEH	3e6	cm^{-2}/year
	ThNeu	3e7	cm^{-2}/year

- The **radiation levels** in different areas which will store active electronics has been evaluated:
  - Ventilation room above BDF in TCC8
  - *911 shaft door*
  - *SHiP detector in ECN3*

Top view of BDF and 911 access shaft.
ThNeu yearly fluence averaged at beam height.
Grey color represents the limit of 3e7 cm^{-2}/year



Top view of yearly thermal neutron equivalent fluence (left) and Total Ionizing dose in one year (right) in ECN3.
For left plot, the grey color represents the limit of 3e7 cm^{-2}/year. In the right plot, value of 10 Gy/year represented by red contour



Conclusion and outlook

- Different studies have been conducted for BDF target: building upon the **solid baseline design (CDS)**, the goal was to **optimize it** and **explore new solutions**
- This presentation summarizes the **main results** (energy deposition, DPA, and radiation levels).
- In addition, studies have been performed on future **targets for irradiation**, the **SC MS**, and **parasitic irradiation facilities** (info in backup slide)
- Target design optimization is nearly finalized. A tungsten-helium (W-He) cooled target offers promising benefits in terms of mechanical properties and background reduction
- **New simulations are planned after incorporating the updated design into the target facility model for the TDR**

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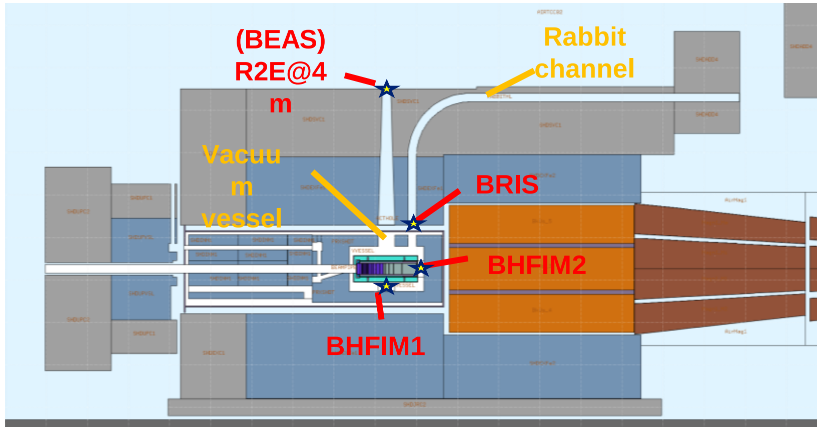
Radiation field and irradiation stations

- The neutron-dominated radiation field generated around BDF is of interest for Electronics and Materials irradiation and Nuclear Activation

Parasitic irradiation of samples in well-defined irradiation stations
HI-ECN3 Irradiation Opportunities Workshop

Top view of the BDF target complex with CDS design for target. Highlighted the proposed irradiation stations.



Integral particles fluence in different irradiation stations