International
MUON Collider
Collaboration

Report from IMCC WG on Beam-matter interactions / target systems*

****Transversal activity across many other WGs***

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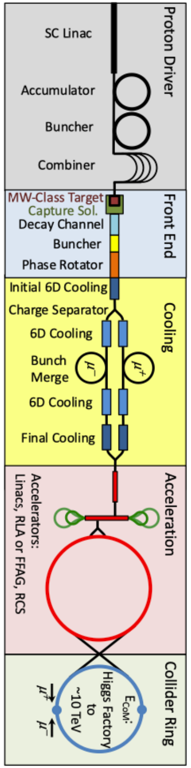
IMCC Accelerator Design Meeting
Feb 13 2023

Introduction



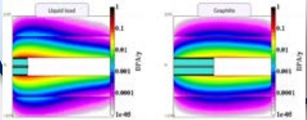
- **Particle-matter interactions** and **radiation effects** are relevant for many aspects of the muon collider, for example:
  - Muon production
  - Heat load and radiation damage in machine equipment (from the target and solenoids in the front end to the magnets in the accelerator and collider)
  - Physics background and radiation damage in the detector
  - RP*, in particular the off-site radiation hazard due to neutrinos
- In this presentation, I try to summarize the **ongoing studies** in the IMCC
- Could profit from the studies within MAP - MAP design often served as a starting point
- All studies shown are **work in progress**, some are more advanced than others

*RP studies are under the responsibility of the CERN HSE-RP group (contact: C. Ahdida)

The main subjects presently under study

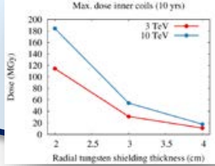
Muon production / heat load and radiation damage in the target area

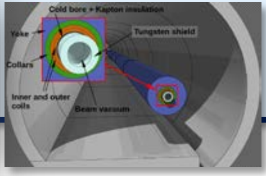
Develop a **target system**, which can sustain the thermal load and cumulative radiation damage, while delivering the required **pion/muon yield;** develop a **shielding design** for the solenoids.

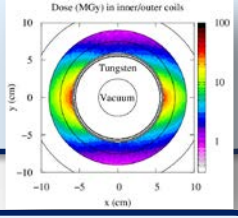


Heat load and radiation damage in accelerator/collider magnets

Develop a **shielding design** to sustain the thermal load and to prevent system (magnet) failures due to cumulative radiation damage

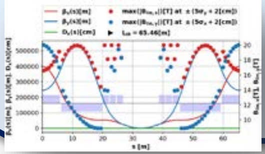


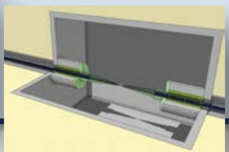


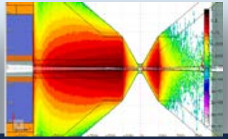


Physics background and radiation damage in detector

Develop a credible **interaction region (IR) design** that yields background levels compatible with detector operation

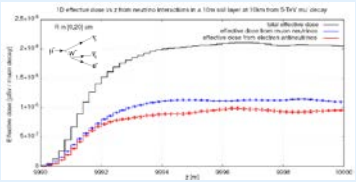


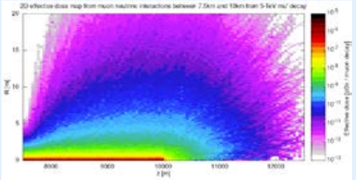




Neutrino hazard

Quantify the **neutrino-induced dose** and provide input for the development of mitigation techniques



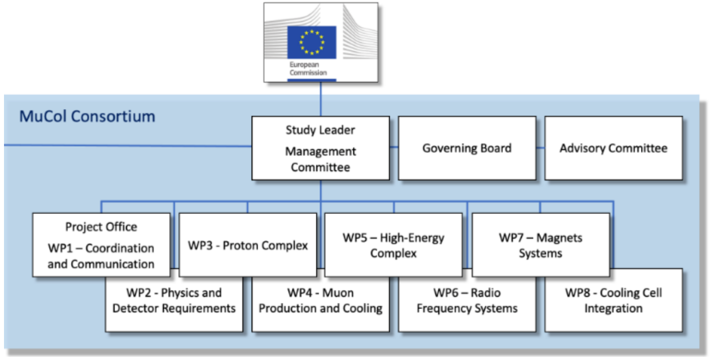


Meetings

- There is no dedicated meeting series for beam-matter interaction/radiation studies since the studies are deeply integrated with a variety of topics → the idea is to treat radiation studies within other WG meetings
- So far, the studies were mainly reported in:
  - **Muon Production and Cooling Working Group (target part):**
    - Indico event category: https://indico.cern.ch/category/12766/
  - **Muon Magnets Working Group:**
    - Indico event category: https://indico.cern.ch/category/13958/
  - **Machine-Detector Interface Working Group:**
    - Indico event category: https://indico.cern.ch/category/14574/

+ several informal meetings (e.g. concerning radial build of collider magnets)

Radiation studies in MuColl (EU study)

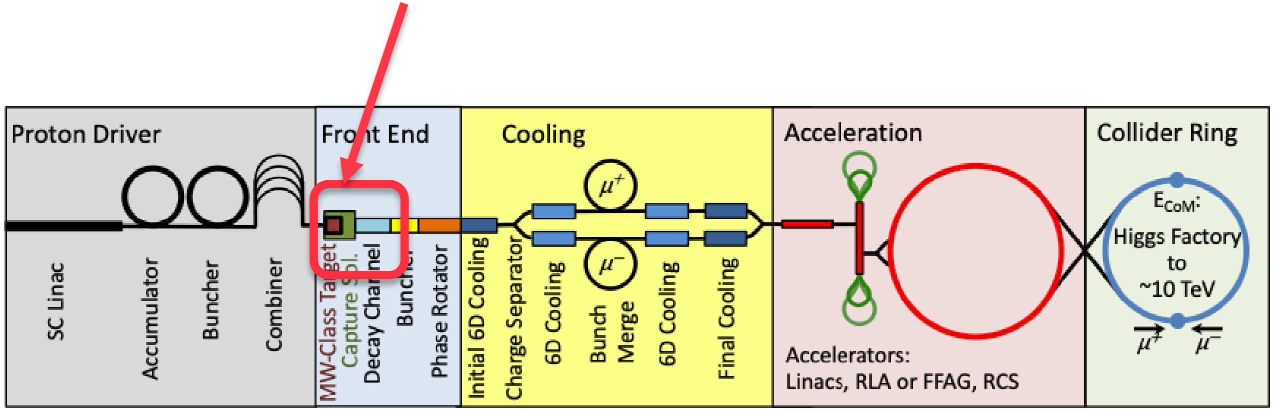


Beam-matter interaction/radiation studies are spread across several different WPs. Specific task activities within WP4 (Muon production) and WP5 (High-Energy Complex):

- **Target/absorber studies for muon production:**
  - Task 4.2 “Target system development” ⟷ **WP7** (Magnets)
- **Radiation/absorber studies for accelerators+collider***
  - Task 5.3 “Radiation studies for the accelerators” ⟷ **WP7** (Magnets)
- **Beam-induced background and MDI studies:**
  - Task 5.4 “MDI design & background to experiments” → Machine view on MDI, background generation for WP2 studies ⟷ **WP2** (Physics and Detector Requirements) → Detector view on MDI

*includes neutrino-induced dose studies

Part 1. Muon production and related radiation challenges in the target region



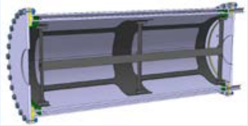
Muon production and capture – first evolution from US-MAP design

- **Key challenges:**
  - Target technology
  - Heavy radiation shielding
  - High-field, large aperture solenoids

US-MAP **2011:** mercury jet

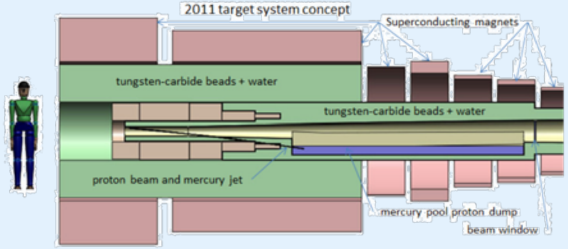
IMCC **2022** - different target technologies considered:

- Graphite target (CERN) – *baseline for studies*
- Liquid lead target (CERN, ENEA)
- Fluidized tungsten target (STFC)



Muon production & cooling working group
(C. Rogers & R. Franqueira Ximenes et al.)
https://indico.cern.ch/category/12766/

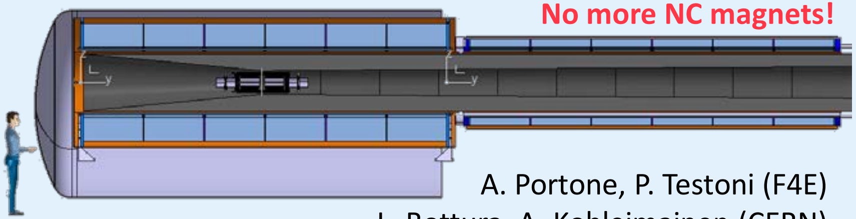
US-MAP **2011** design: LTS (14 T) + NC (6 T)



H.G. Kirk, PAC 2011

IMCC **2022** design: **HTS** (20 T, 20 K)

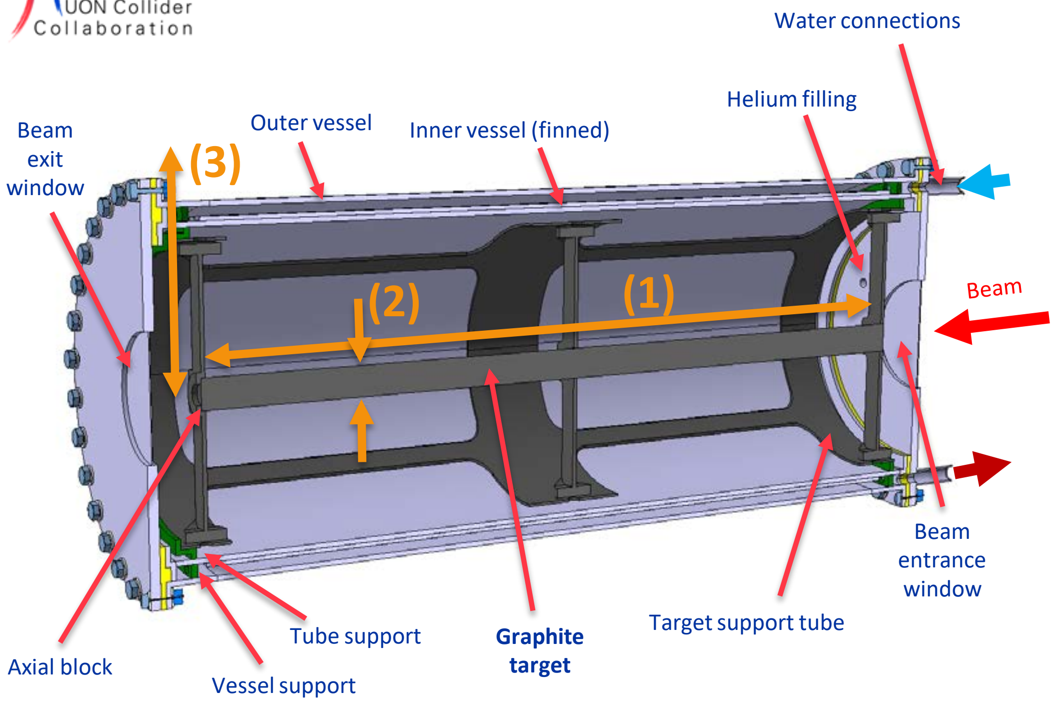
No more NC magnets!



A. Portone, P. Testoni (F4E)
L. Bottura, A. Kohleimainen (CERN)

Muon magnets working group (L. Bottura et al.)
https://indico.cern.ch/category/13958/

Graphite target assembly - concept



Present baseline parameters used in the target/radiation studies:

Target material	Graphite (1.8 g/cm^3)
Target length (1)	80 cm (=1.8 λ_{inel})
Target radius (2)	15 mm (=3σ)
Inner shielding radius around target (3)	17.5 cm

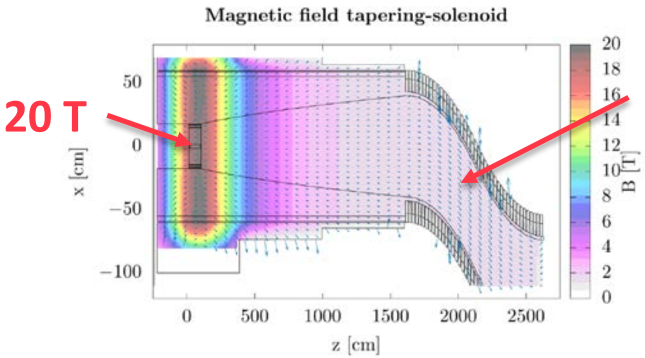
Two aspects to be considered when defining the inner shielding aperture:

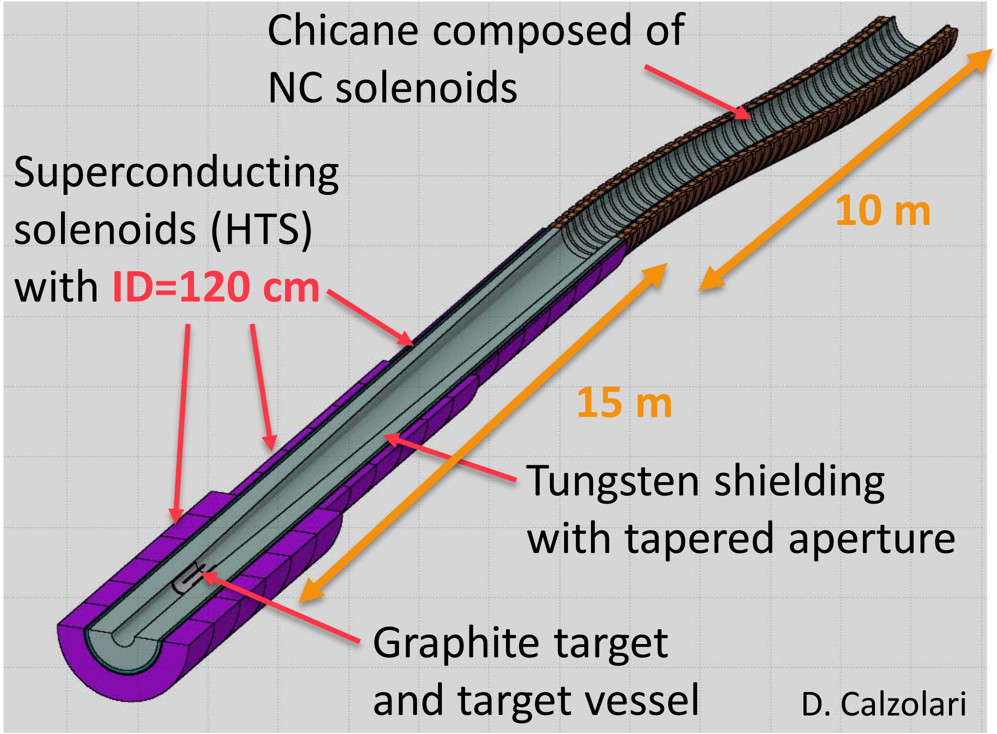
- Target vessel requirements
- Pion/muon yield (avoid losses on aperture)

From R. Franqueira Ximenes, F. J. Saura Esteban

Model for muon production and radiation studies

- First FLUKA model implemented up to end of the chicane (bulk structures only*)
- Beam aperture between target and chicane follows parabolic shape, with r_{min}=17.5 cm and r_{max}=40 cm
- Consider bulk W blocks for shielding (He gas cooled → see later), higher effective density than W beads in MAP study





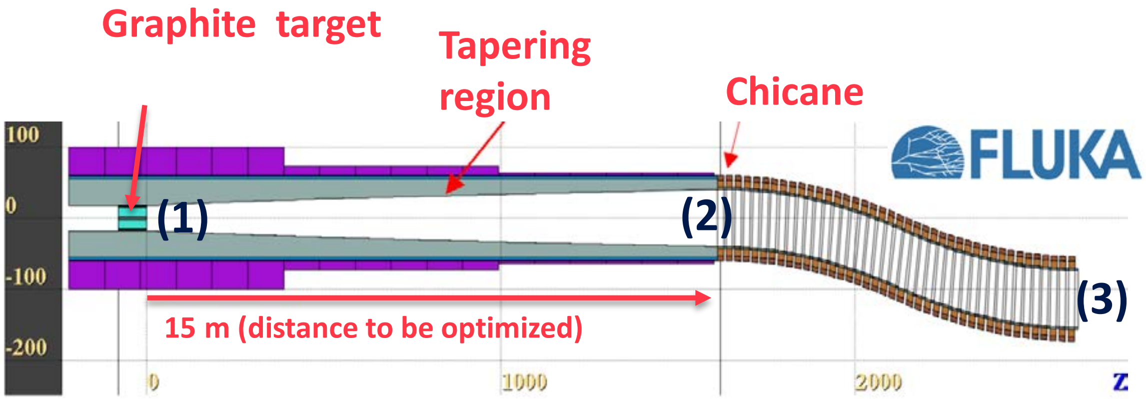
*without details like He cooling channels, thermal shields, gaps for supports, etc.

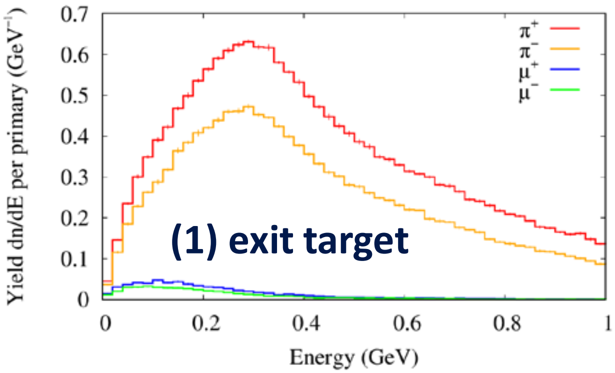
Evolution of pion/muon spectra along the line

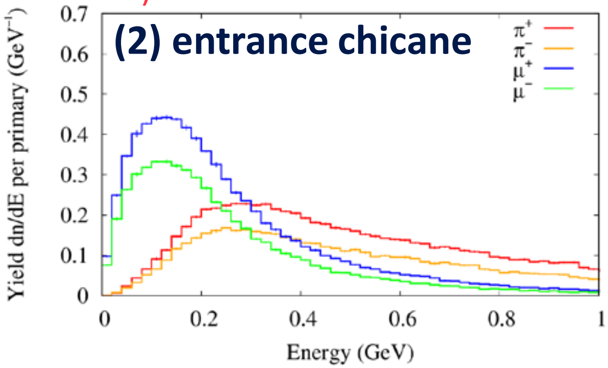
Present baseline beam parameters:

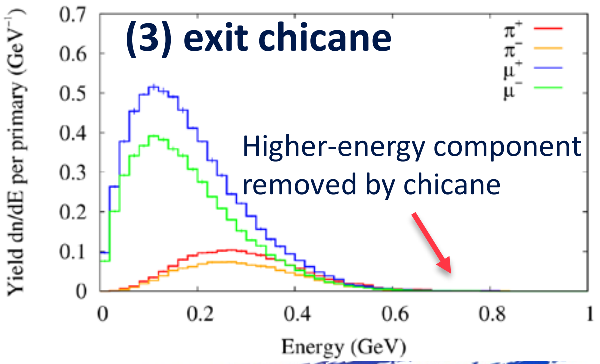
Proton drive beam parameters	
Beam energy	5 GeV
Beam sigma σ	5 mm
Pulse frequency	5 Hz
Beam power	1.5 MW

Keeping in mind the option to go up to 4MW (but: this affects many design choices)



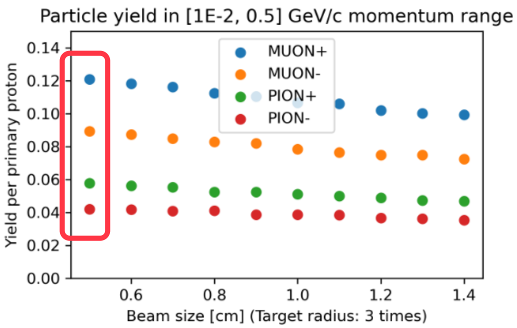


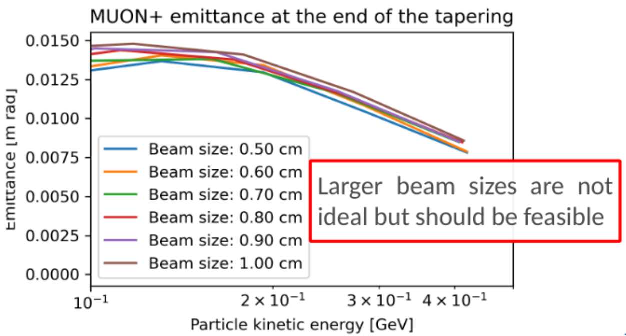




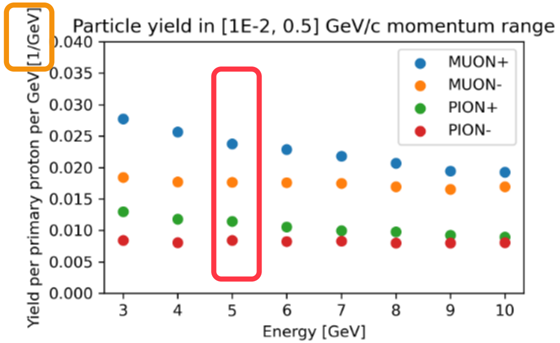
Physics output of Graphite target vs beam parameters

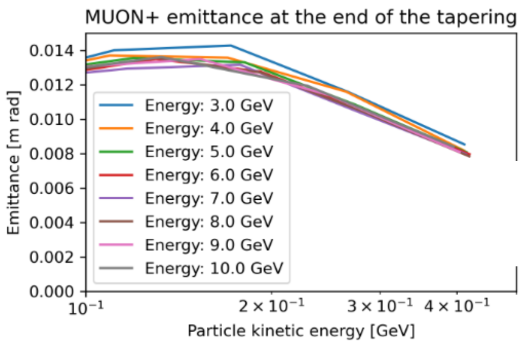
Beam σ (target radius: 3σ)





Proton beam energy





- Muon and pion yield at the entrance of the chicane (15m from target)
- Frames show yields for baseline parameters
- Could expect somewhat higher yield with lower beam energy*

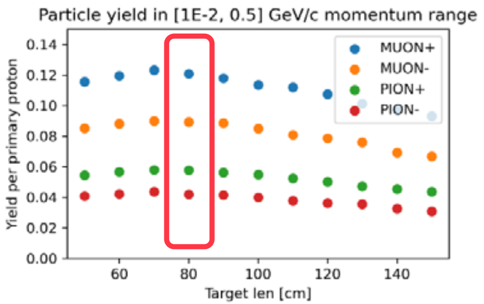
*Also found by J. Back (annual IMCC 2022 meeting, link)

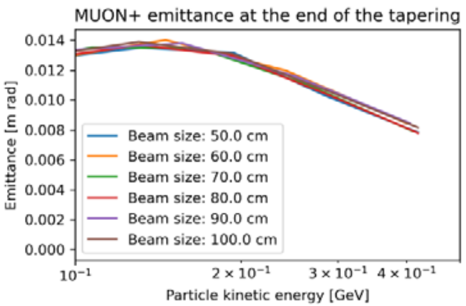
From D. Calzolari, Muon production & cooling meeting 12/01/2023

Physics output of Graphite target vs target dimensions and shielding aperture

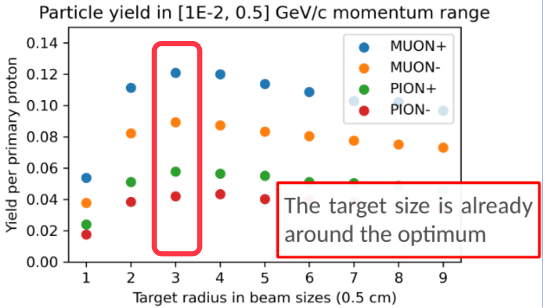
International MUON Collider Collaboration

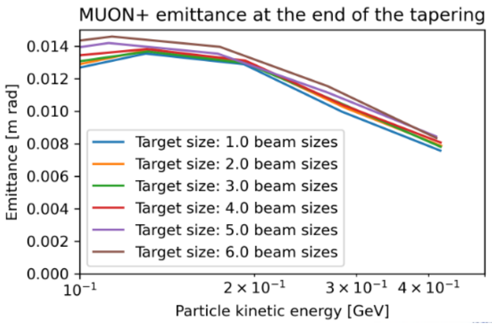
Target length



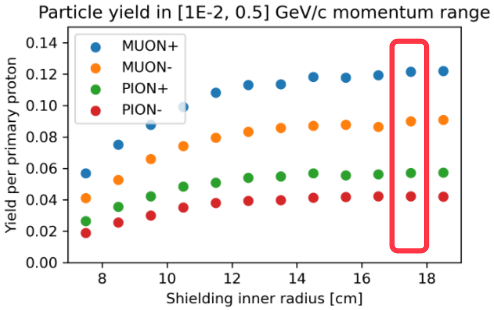


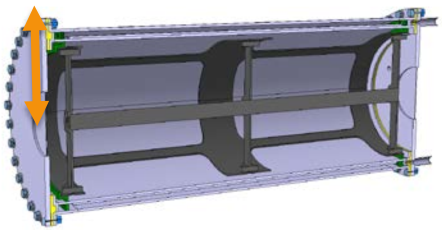
Target radius (multiples of σ)





Inner shielding aperture around target





The presently assumed dimensions are near the optimal ones for a Graphite target

From D. Calzolari, Muon production & cooling meeting 12/01/2023

Graphite target – engineering and lifetime considerations

- **Thermal load:**

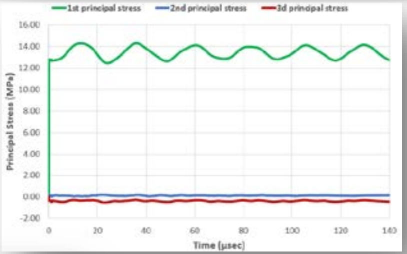
From R. Franqueira Ximenes, F. J. Saura Esteban ([IPAC22 paper](), [IMCC Annual Meeting 2022]())

  - With baseline beam parameters (σ=5mm, 1.5 MW), T_{peak} < 2800 °C (assuming radiative heat dissipation only)
  - Graphite sublimation in vacuum@high T: need inert atmosphere (He) around target

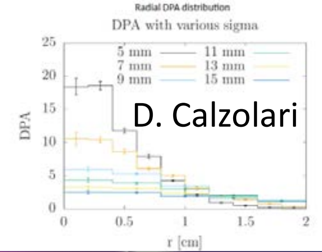
*Maximum temperature and power deposition for **1.5 MW** as function of the beam sigma, considering only radiative heat dissipation without direct cooling*

Tpeak (°C)	Transient				Steady state	Power deposited
σ_{beam} (mm)	5 Hz	10 Hz	20 Hz	50 Hz	Average	(W)
1	4301	3908	3735	3641	3583	44832
2	3318	3221	3177	3152	3135	59000
5	2740	2721	2713	2708	2704	90632
10	2305	2297	2293	2290	2288	129207
15	1947	1943	1940	1938	1938	163214

- **Structural considerations:**
  - Stresses were calculated for single shot with nominal parameters - no showstopper found



- **Lifetime consideration:**
  - Many cycles (10^8) per year at high temperature (fatigue)
  - Very high DPA values in beam windows
  - Design of remote handling system for target exchange is crucial



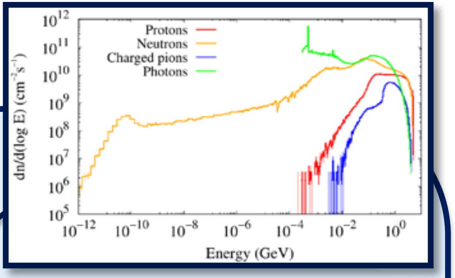
D. Calzolari

DPA/year in Window

Secondary radiation from the target

- Two main concerns:
  1. **Lateral leakage of secondaries** from the target gives rise to hot spot around the target
  2. **Spent proton beam and other secondaries** from the downstr. face of target → impact location depends on proton beam inclination → **need to design extraction channel + dump**
- The **solenoids** need to be shielded from the intense radiation load (heat, radiation damage)

Spectra of particles **lost on inner shielding aperture around the target** (p, n, γ from target give the largest contribution)



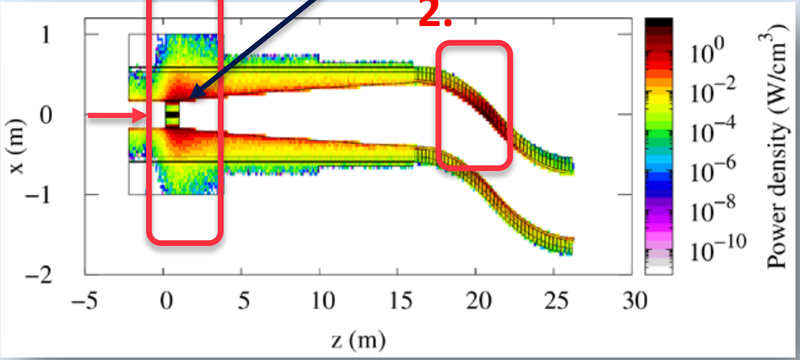
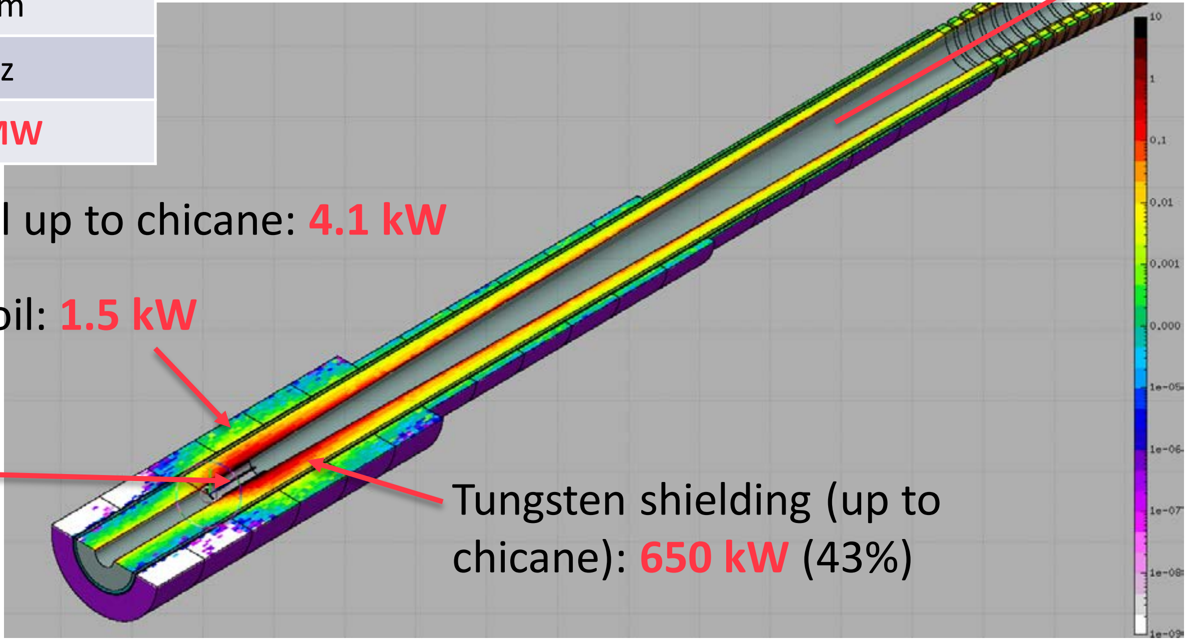


Figure: proton beam and Graphite target assumed to have no inclination wrt to solenoid axis → spent proton beam lost in chicane (note: the scoring in this figure is too coarse to resolve the peak power deposition density)

Power deposition in the target area

Proton drive beam parameters	
Beam energy	5 GeV
Beam sigma σ	5 mm
Pulse frequency	5 Hz
Beam power	**1.5 MW**



All HTS coil up to chicane: **4.1 kW**

Most loaded HTS coil: **1.5 kW**

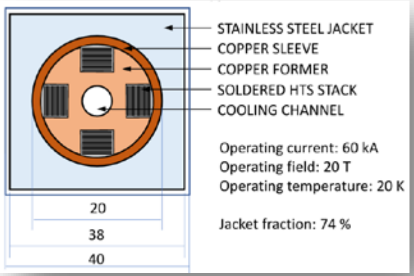
Target assembly:
110 kW (7%),
mainly Graphite (90 kW)

Tungsten shielding (up to chicane): **650 kW** (43%)

>500 kW

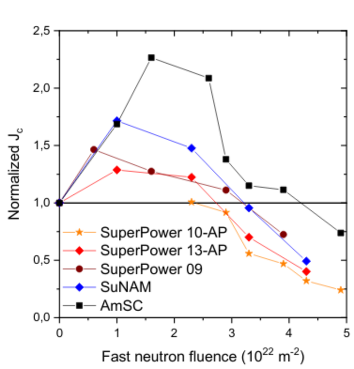
Radiation resistance of solenoids

- **Solenoid cables:**
  - MIT “VIPER” cables are considered
  - Standard HTS tapes from industry (Y, Gd, Eu)
- **Atomic displacements (DPA):**
  - Main concern is the degradation of J_c, T_c of HTS
  - **Annealing cycles will play an important role**
  - Possible degradation of electrical resistivity of the copper stabilizer not expected to be a main obstacle (Cu is there "only" for protection), but to be checked
- **Cumulative ionizing dose:**
  - Mainly concerns the coil insulation (kapton) and the coil impregnation (epoxy/cyanate-ester mix)
  - Acceptable limit could be O(50MGy)



Muon magnets working group (L. Bottura et al.)

Coated conductors (30 K, 15 T)
(Transport, 1 μV/cm)



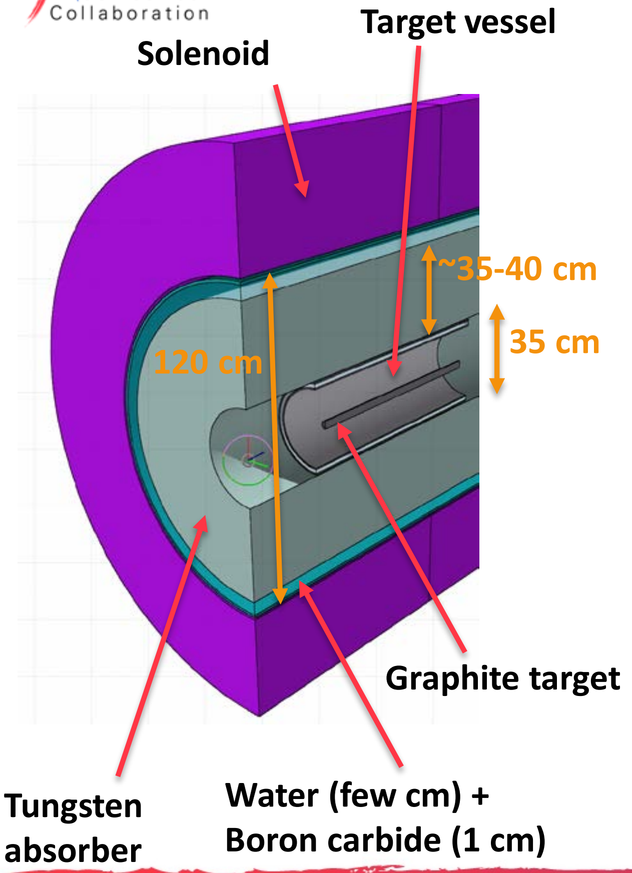
Most literature is focused on neutron irradiation (fusion community)

10^{22} n/m² gives roughly few 10^{-3} DPA

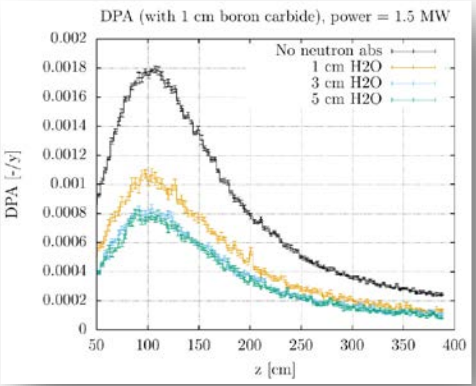
Beware: Gd has high capture xs for thermal neutrons (here: only fast neutrons are shown)

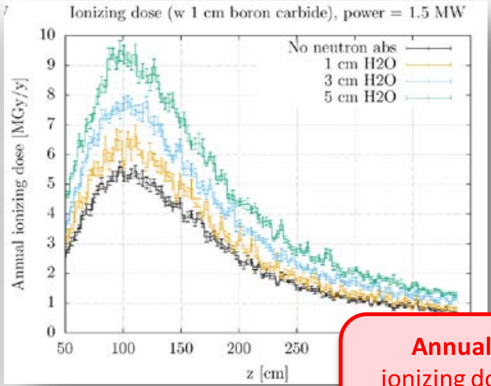
M. Eisterer, TU Wien (IMCC meeting 2022)

Conceptual shielding design for the 20 T solenoid around the target



- 35-40 cm solid W shielding, He gas cooled (5 kg/s at 1 bar)
- Water+boron around shielding for neutron moderation and capture (neutrons dominate source of DPA in solenoid)
- With this configuration, annual peak dose and DPA in solenoid at the limit (count on annealing for DPA in HTS) → required margins to better understood

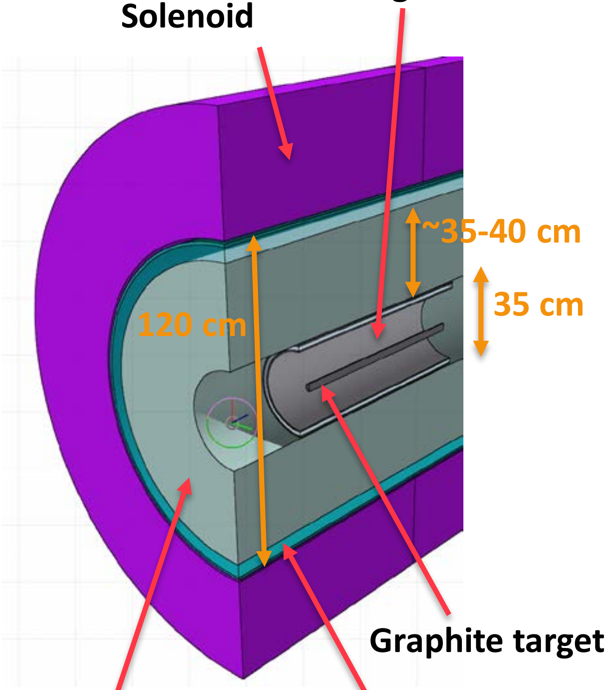




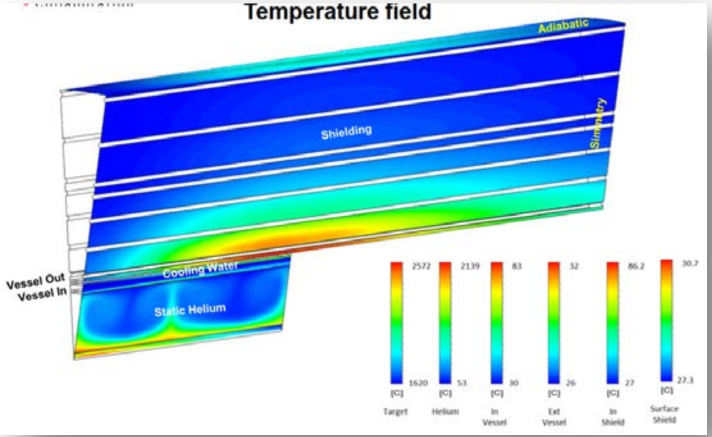
D. Calzolari

Annual DPA and ionizing dose in target solenoid (1.5 MW, 200 days of operation)

Conceptual shielding design for the 20 T SC solenoid around the target



- The W shielding up to the chicane absorbs 44% of the original proton beam power (650 kW)
- Peak temperature would reach 1200 °C, but can be reduced to less than 100 °C with the room-temperature He gas cooling
- First structural analysis for shielding started

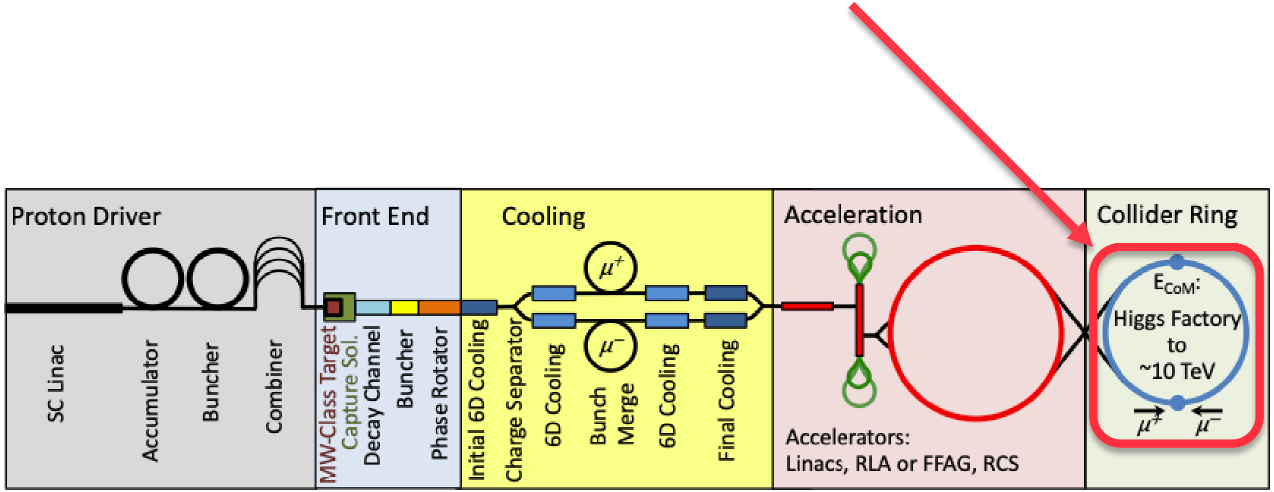


R. Franqueira Ximenes, F. J. Saura Esteban
Muon production and Cooling WG 12/01/2023

Next steps for the muon production and radiation studies

- **Upcoming topics:**
  - Iterate on the **radial build (dimensions)** of all components **around the target**, taking into account components such as thermal insulation etc. (which need space)
  - Address the extraction and disposal of the **spent proton beam**, which carries a non-negligible fraction of the original beam power
  - Start first **radiation protection studies** for the target area
  - Explore further the option of a **liquid lead target**
- **Drive beam power (1.5 MW – 4 MW):**
  - Has an impact on many design choices in the front end (no one-fits-all design), from target technology to shielding thickness and solenoid aperture
  - Which exact option(s) to study?

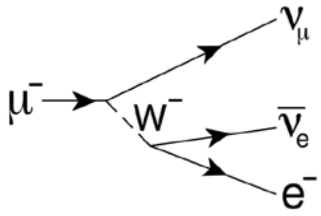
Part 2. Radiation impact on collider ring magnets



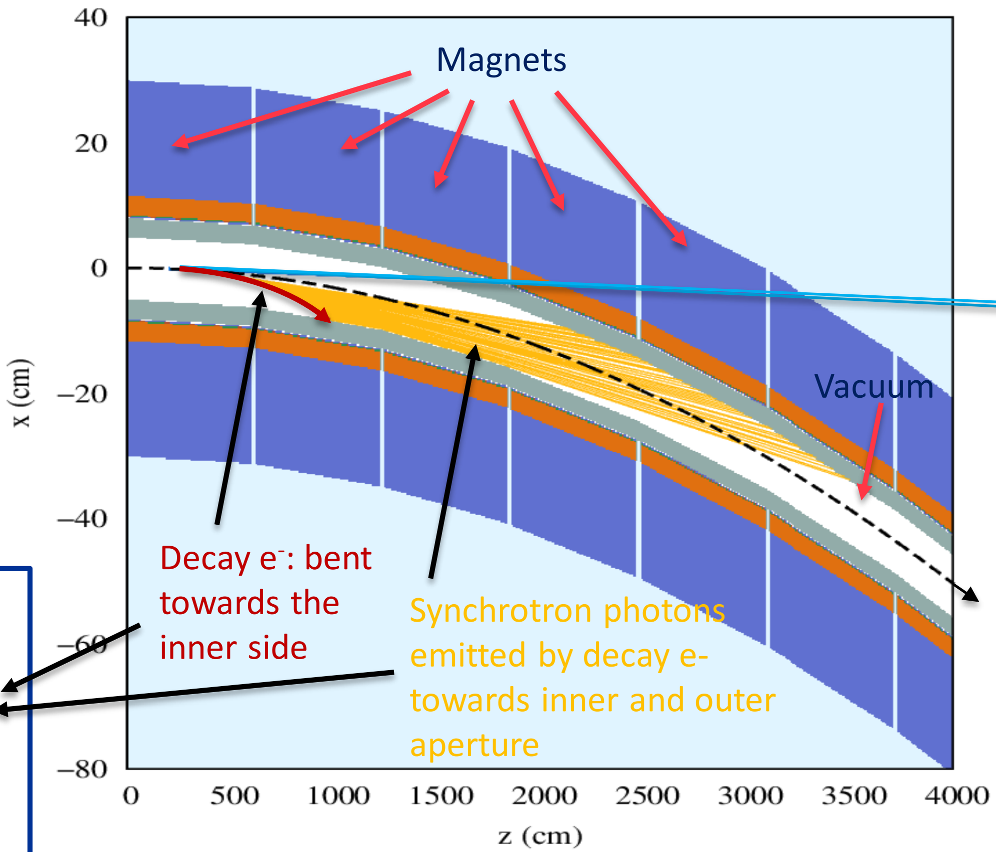
Radiation load to collider ring magnets

- **Objectives:**
  - Quantify the radiation load to superconducting magnets due to muon decay (and beam halo losses)
  - Develop a **shielding design** to sustain the thermal load and prevent magnet failures due to the cumulative radiation damage
- Performed **generic shielding studies** for the arc regions of the 3 TeV and 10 TeV colliders (considering dipoles only)
- Together with lattice, magnet, cryo, vacuum experts, a first radial build of arc magnets is presently being developed (beam aperture – shielding – cold bore – coil), including aspects like the operating temperature of the shielding

Muon decay in the collider – a qualitative view



e^- carries on average 35% of muon energy



Picture shows the horizontal plane of a generic arc section (dipoles only)

Decay neutrinos: irrelevant for radiation load to machine

Black dashed line: μ^- beam trajectory

Similar picture applies to μ^+

Inside magnets:
- Secondary EM cascades (e^-, e^+, γ)
- Neutron production (photo-nuclear interactions)

Power load on magnets in different circular machines

(assuming 5 Hz injection frequency)

	HL-LHC		FCC-ee (CDR)	MC ($\sqrt{s}$=3 TeV)	MC ($\sqrt{s}$=10 TeV)
Particles	p		e-/e+	μ-/μ+	μ-/μ+
Particle energy	7 TeV		45.6 … 182.5 GeV	1.5 TeV	5 TeV
Bunches/beam	2760		16640 … 48	1	1
Bunch intensity	2.2×10^{11}		1.8×10^{11} … 2.3×10^{11}	2.2×10^{12}	1.8×10^{12}
Circumference	26.7 km		97.8 km	4.5 km	10 km
Main heat source	pp debris	E-cloud	Synchrotron rad.	Muon decay	Muon decay
Region	Triplet+D1	Arcs	arcs	entire ring	entire ring
Power/meter*	**few 10^{-2} kW/m**	**few 10^{-3} kW/m**	**1.2 kW/m**	**0.4 kW/m****	**0.5 kW/m****
Magnets	**superconducting**		**warm**	**superconducting**	**superconducting**

* Includes contribution from both beams

** Values correspond to **power carried by decay e-/e+** (=1/3 of muon energy)
Here it is **NOT** assumed that the beam is **extracted after a certain number of turns**.

MC = unprecedented power load in a cold machine!

Radiation impact on collider ring magnets

International MUON Collider Collaboration

Muon decay, halo losses

Decay rate, halo loss rate

Integral number of decays, integral halo losses (over collider lifetime)

Instantaneous heat deposition

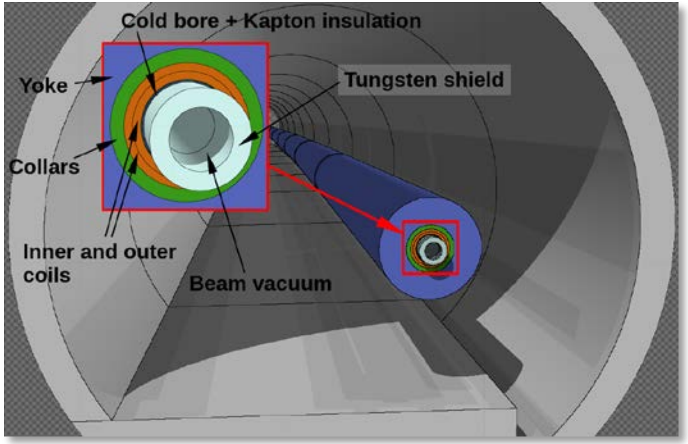
- **Power density in coils*** → must remain safely below quench level of magnets
- **Total power deposition in cold mass** → must be compatible with realistic cooling capacity (costs, electricity consumption!), (*most of the heat load must be extracted at higher temperature than the op. temp. of SC magnets*)

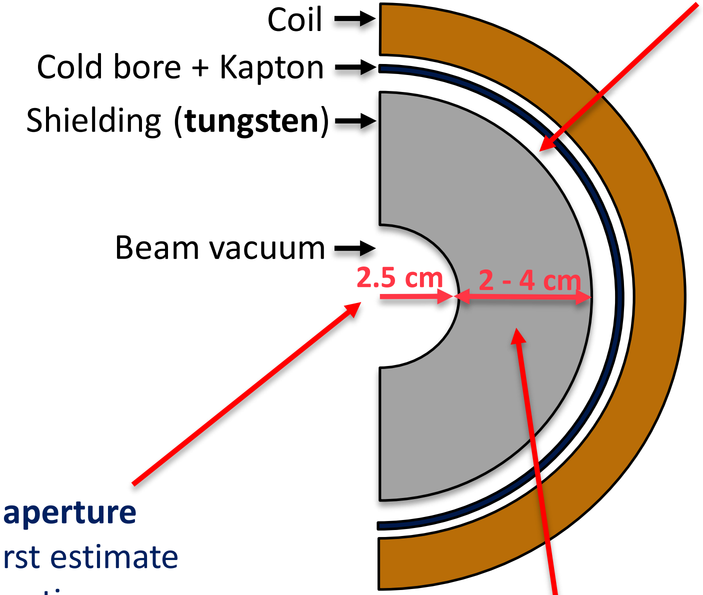
Long-term radiation damage

- **Ionizing dose*** (organic materials for *insulation, coil impregnation, etc.*) → must remain below critical level for full collider lifetime
- **Atomic displacements*** (*superconductor, stabilizer*) → must remain below critical level, partial mitigation with annual annealing cycles

**Point-like quantity*

Radial magnet build assumed for generic shielding studies





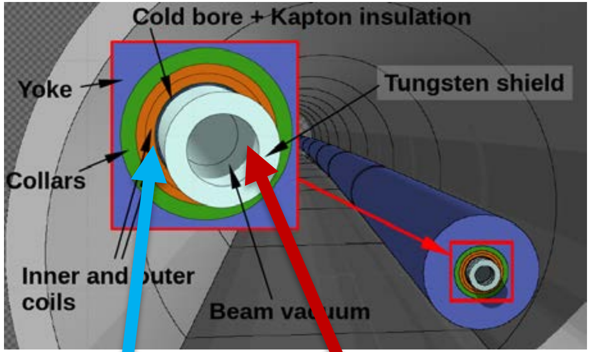
Thermal insulation between shielding and cold mass will take some space (NOT modelled here, we just assumed a small 1 mm gap)

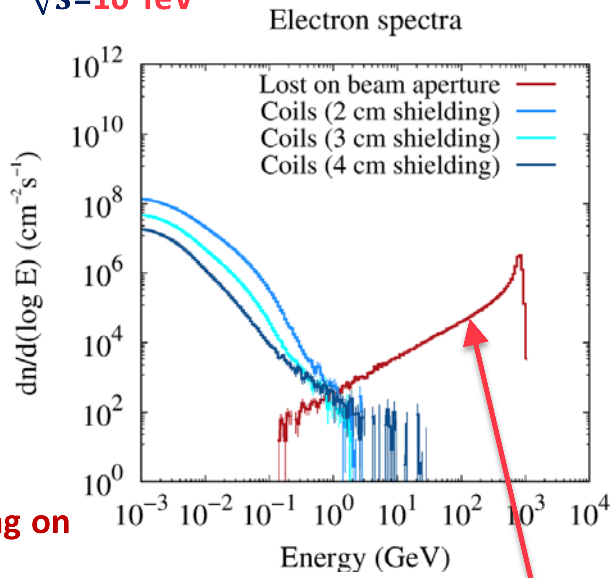
We assumed a **beam aperture** of **2.5 cm (radius)** – first estimate from impedance and optics (note: in the 3 TeV MAP study, the aperture was 5.6 cm)

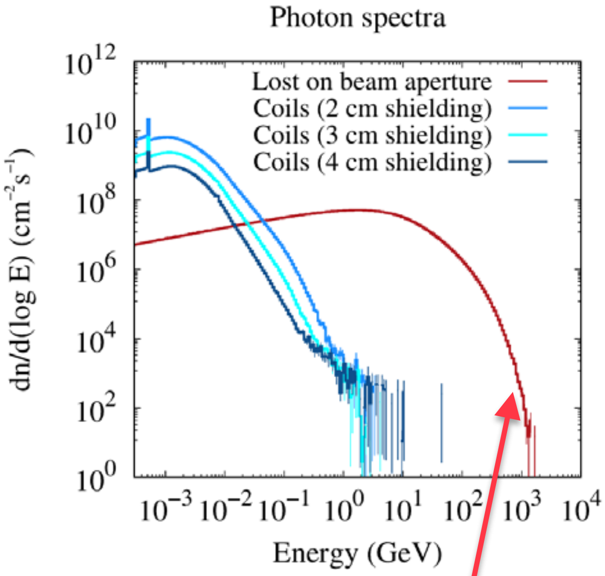
Considered **tungsten** shielding thicknesses **between 2 and 4 cm**

e-, e+, γ spectra in (generic) arc dipoles

$\sqrt{s}$=10 TeV







Red curves: particles **impacting on the inner shielding aperture** (decay e^-, synchrotron photons)

Blue curves: particle spectra **inside the inner coils** (for different shielding thicknesses)

Decay e^-

Synchrotron photons emitted by decay e^+/e^-

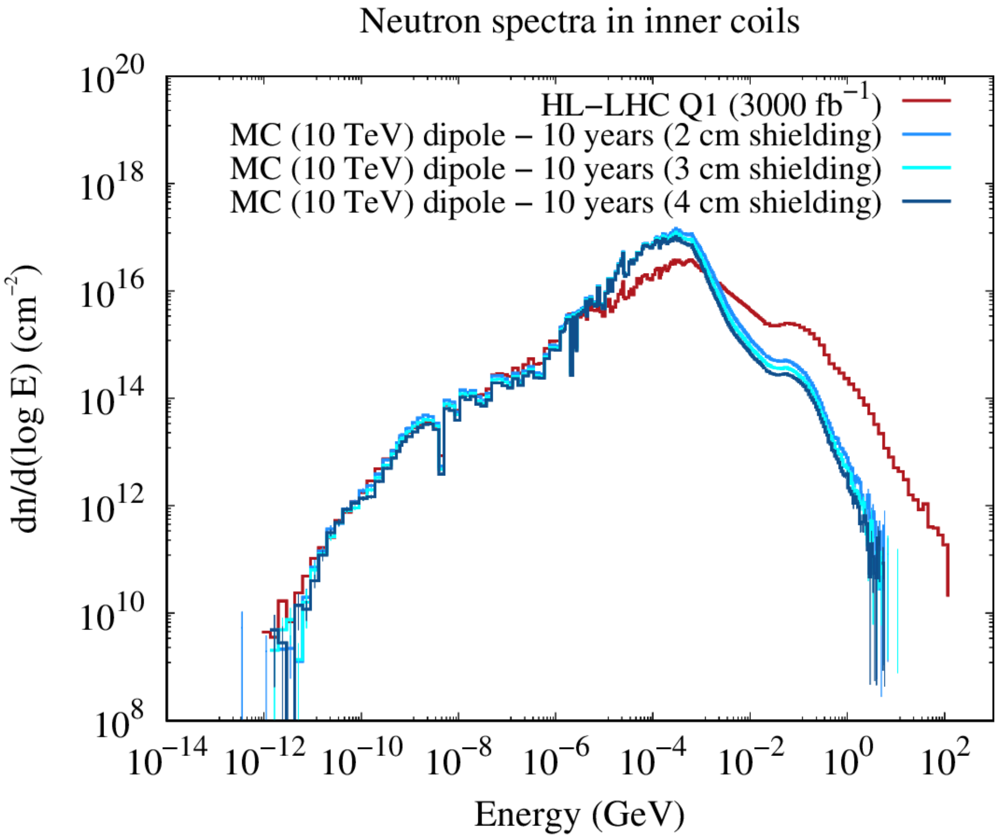
Neutron spectrum in coils of (generic) arc dipoles

- Photo-nuclear interactions → non-negligible neutron flux
- **Neutrons** are the **main source of displacement damage** (DPA) in muon collider magnets

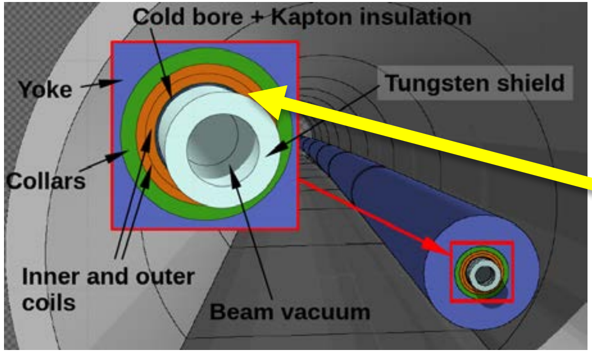
❖ **Neutron fluence in MC magnets shows only small dependence on shielding thickness**

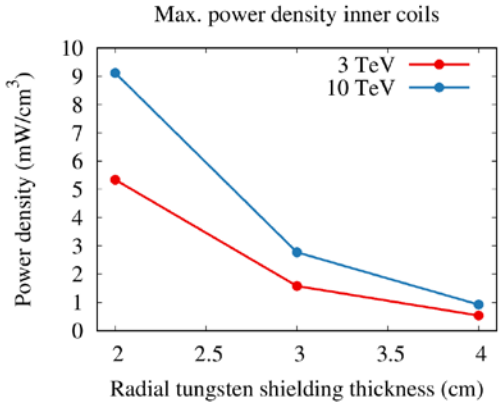
❖ Spectrum similar for 3 TeV as for 10 TeV collider

For comparison, the figure shows the neutron fluence in the Q1 (triplet) coils of the HL-LHC after 3000 fb^{-1}



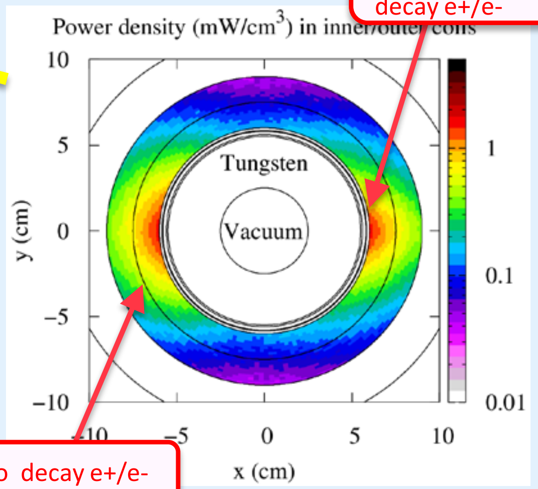
Power density in coils of (generic) arc dipoles



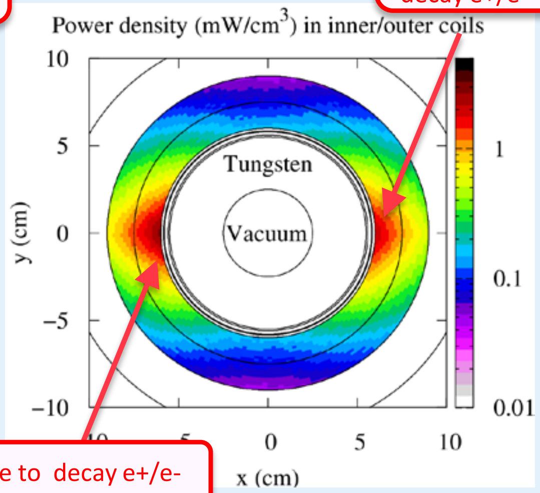


Power density map (transverse coil cross section):

$\sqrt{s}$=3 TeV:
2.5 cm beam aperture
3 cm W shielding

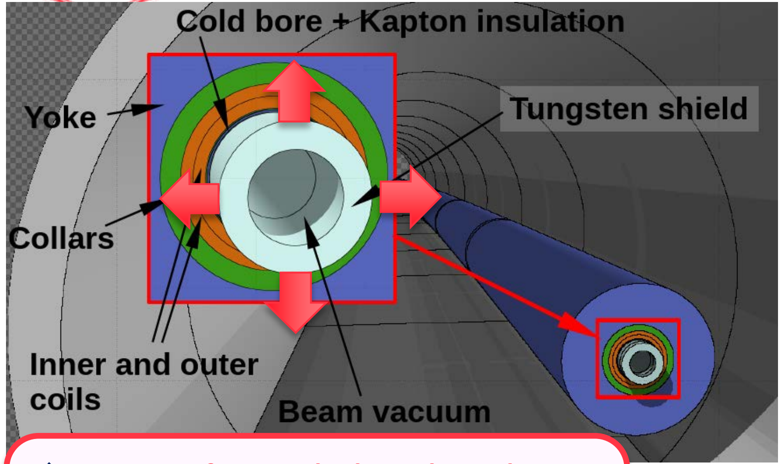


$\sqrt{s}$=10 TeV:
2.5 cm beam aperture
3 cm W shielding

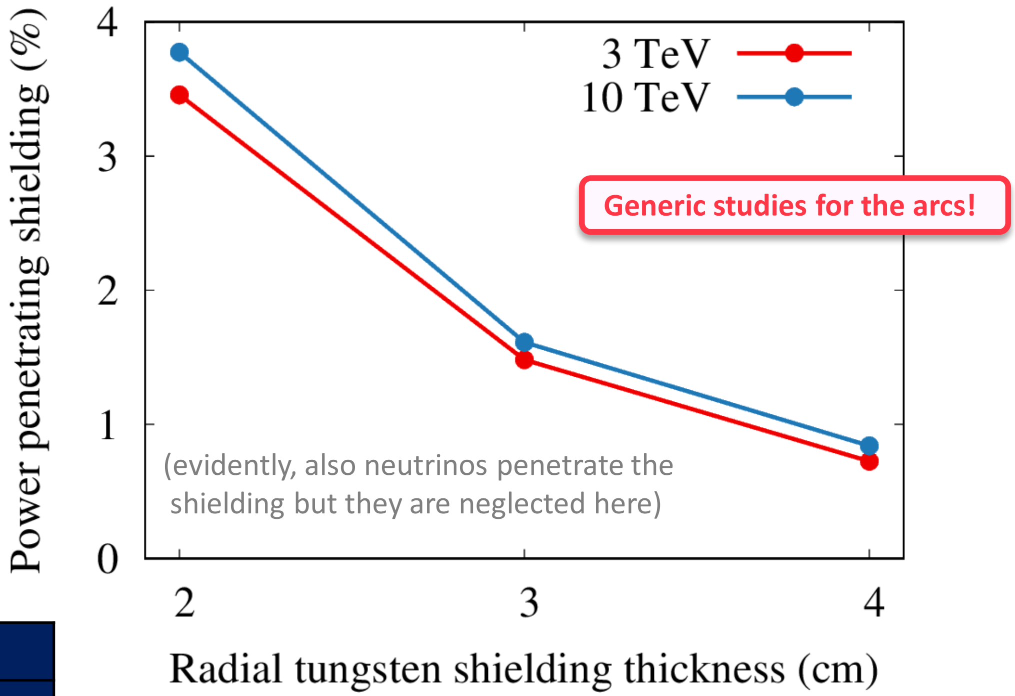


Even with 2 cm W shielding **power density is <10 mW/cm^3**
→ power density (quench margin) not the driving quantity for the shielding thickness

Muon decay: power penetrating shielding



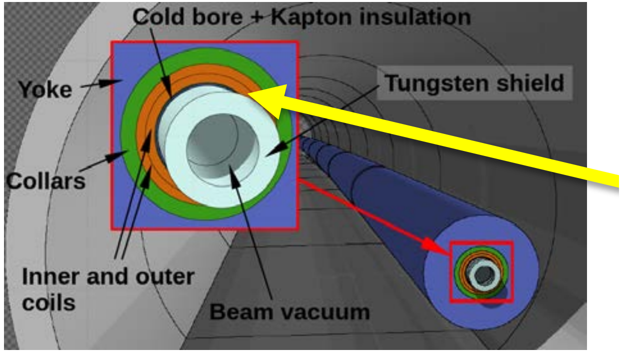
- Fraction of power leaking through shielding similar for 3 TeV & 10 TeV
- This power is mostly deposited in cold mass (including cold bore)

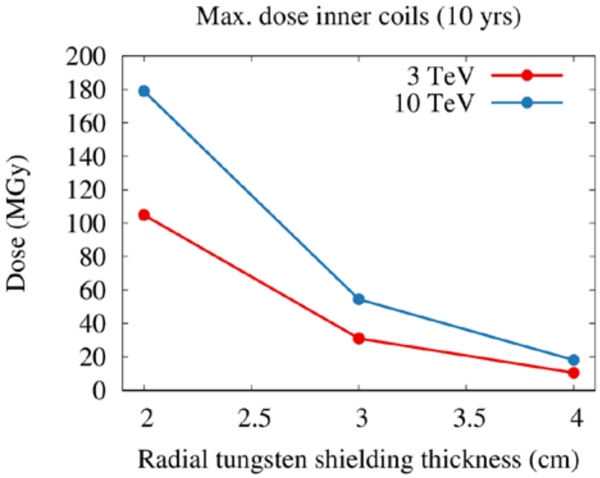


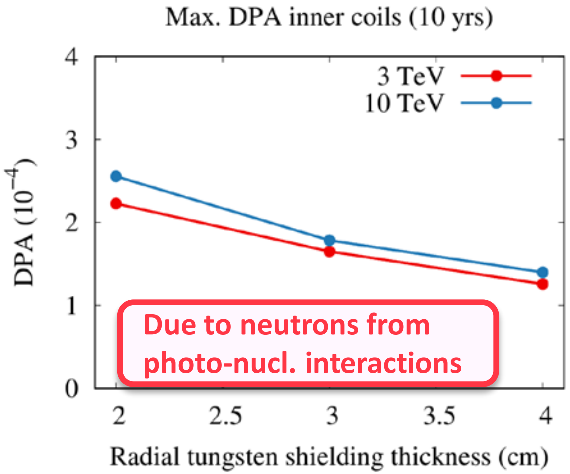
	Power carried by decay e^-/e^+:	Power penetrating shielding		
		2 cm	3 cm	4 cm
3 TeV	410 W/m	14 W/m	6 W/m	3 W/m
10 TeV	500 W/m	18 W/m	8 W/m	4 W/m

Ideally should stay below 1-2%: **can be achieved with 3-4 cm of W shielding**

Muon decay: cumulative dose and DPA in coils of (generic) arc dipoles







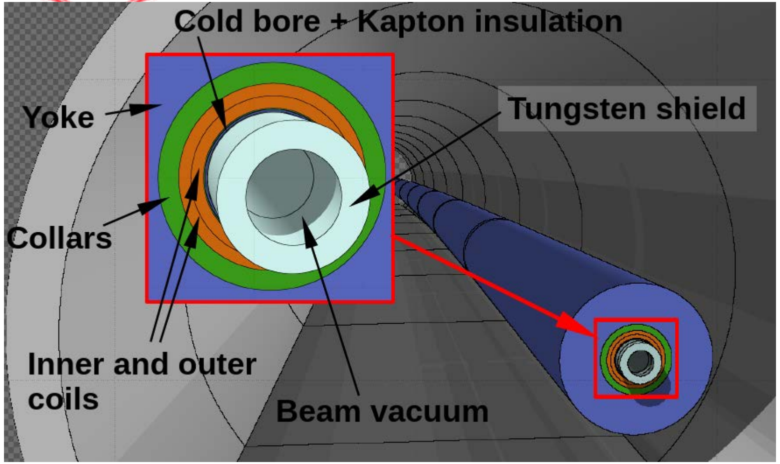
Assumptions:

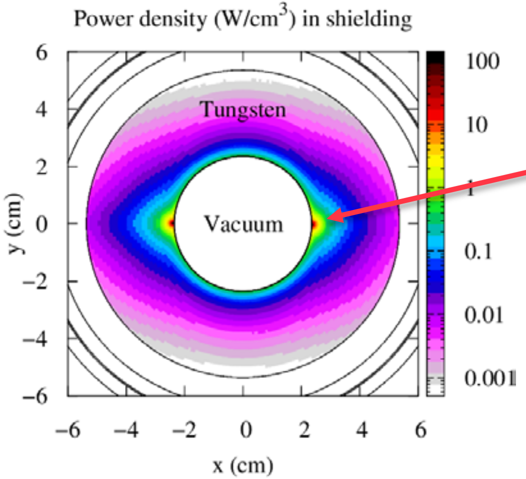
- **200 days operation/year** (conservative 100% machine availability)
- **10 years** of operation

With **3-4 cm W shielding**, the ionizing dose is **20-60 MGy** in coils after 10 years → careful choice of insulation materials

Neutron fluence/DPA shows (as expected) small dependence on shielding thickness: **2-5x10^{17}n/cm^2** / **1-3x10^{-4} DPA** (10 years) → values acceptable for superconductors

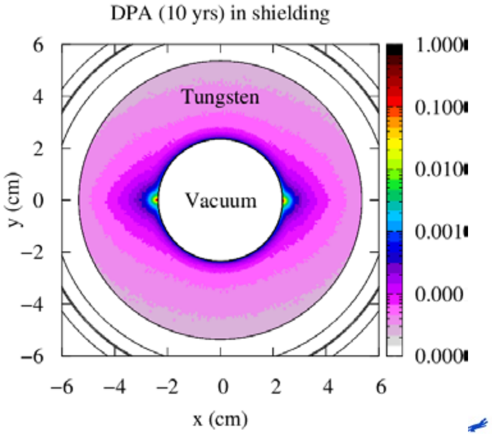
Muon decay: radiation load on shielding





Generic studies for the arcs assuming a vertical beam sigma of 100 μm

High (100 W/cm^3), but localized peak power density in coils



Realistic shielding design to be developed, including cooling channels (operating temperature of shielding to be decided)

Note: magnet interconnects need to be short due to neutrino hazard (field-free regions of 30 cm) and need to be shielded → heat extraction to be studied

Local displacement damage in W shielding (H plane) → concern for thermal conductivity of W?

Radiation load to collider ring magnets – next steps

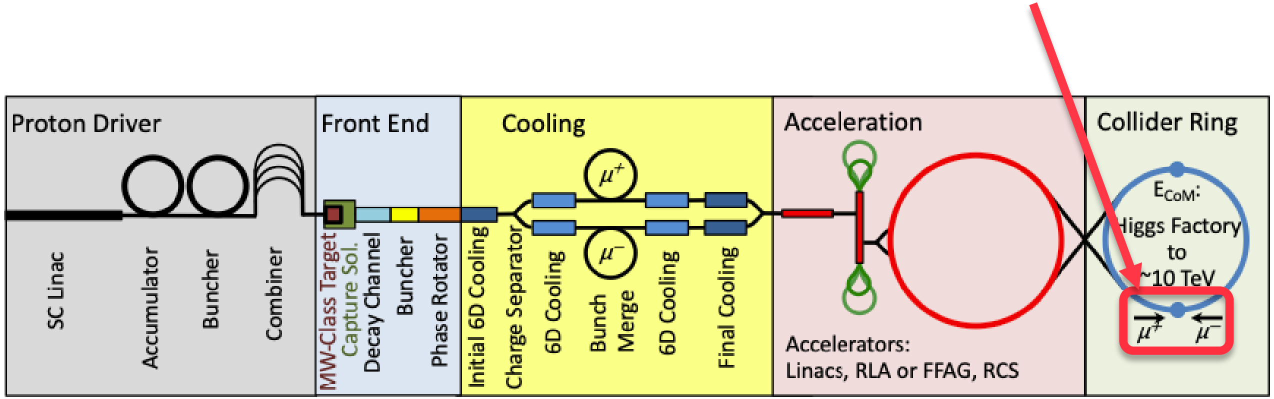
General remarks about the shielding requirements for collider magnets:

- Are mainly driven by A) the **total power leaking through the shielding** and B) **the cumulative ionizing dose in coils**, while the power density and cumulative DPA in coils appear to be somewhat less limiting
- The studies showed that we need **3-4 cm** of **tungsten** in the arcs

Next steps:

- Together with the other teams, progress on the radial magnet build (including thermal considerations)
- Perform shower studies for a realistic arc lattice to refine the shielding requirements for quadrupoles/combined function magnets
- Repeat radiation load studies with a more realistic shielding design (including cooling channels, revised transverse cross section, etc)
- Extend the studies to the IR magnets

Part 3. Beam-induced background and Machine-Detector Interface (MDI)



Beam-induced background (BIB) and Machine-Detector Interface (MDI)

- **Main objectives:**
  - Study the beam-induced background (BIB) and identify mitigation strategies for the **3 TeV** and **10(+) TeV** collider options.
  - Develop a credible **interaction region (IR) design** that yields background levels compatible with detector operation (1. enabling physics performance reach, 2. reducing radiation damage to acceptable levels)
- **MDI Working Group**:
  - Formed last year in course of the Muon Collider Community meetings
  - Shall bring together expertise from different areas (lattice design, particle-matter interactions, detectors etc.)
  - Meetings every last Friday of a month (Indico event category)
  - Please subscribe to the **muoncollider-mdi** e-group to receive invitations

IR lattices used for background studies

- $\sqrt{s}$ = 3 TeV IR lattice taken from US-MAP (Y. Alexahin et al 2018 JINST 13 P11002):
  - L* = **6 m**
  - **Quadruplet** final focus with combined function magnets (ß* = **5 mm**)
  - Maximum field at inner bore is **12 T**
- $\sqrt{s}$ = 10 TeV IR lattice was developed from scratch within IMCC:
  - L* = **6 m** as baseline
  - **Triplet layout** (ß* = **1.5 mm**), optionally with and without dipolar component
  - Max field at inner bore is **20 T**

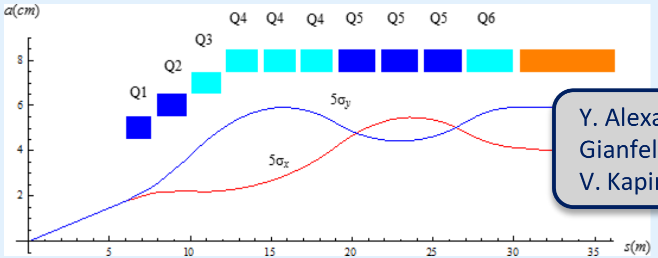
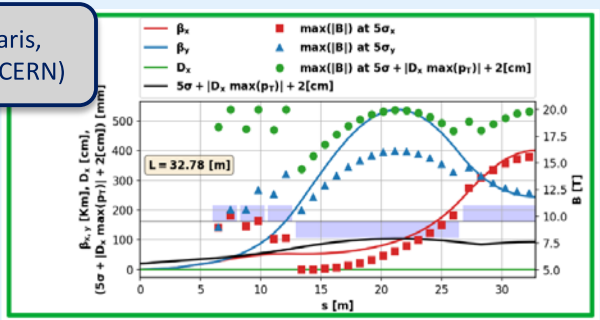


Figure 3. Quadruplet FF quadrupole apertures and 5σ beam envelopes for $E_{c.o.m.}$ = 3 TeV and β^* = 5 mm. Defocusing magnets with 2 T dipole component are shown in cyan. Beam parameters are given in the summary table of section 5.

Y. Alexahin, E. Gianfelice-Wendt, V. Kapin (Fermilab)

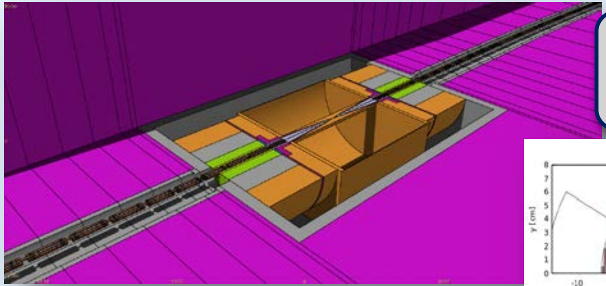
K. Skoufaris, C. Carli (CERN)



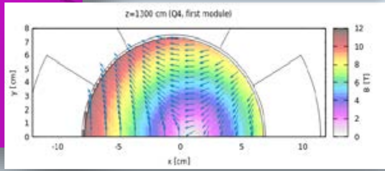
Status of the background studies for the $\sqrt{s}$ = 3 TeV collider

- $\sqrt{s}$ = 3 TeV BIB studies with FLUKA:
  - The procedure used to verify the beam-induced background at $\sqrt{s}$ = 1.5 TeV (F. Collamati et al 2021 JINST 16 P11009) is being used to study background at $\sqrt{s}$ = 3 TeV
  - Nozzle inspired by 1.5 TeV MAP design (N. Mokhov)
  - Particle distributions were used for first detector studies
  - Dose/neutron fluence maps for detector

FLUKA model of 3 TeV interaction region:



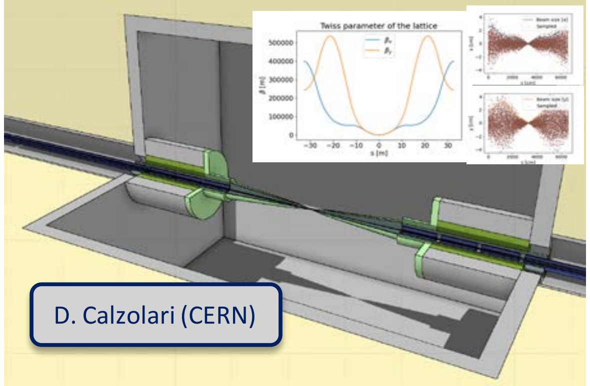
A. Mereghetti (CNAO),
C. Curatolo (INFN),
F. Collamati (INFN) et al.



See presentation of D. Lucchesi in the IMCC Accelerator meeting Nov 14, 2022

Status of the background studies for the $\sqrt{s}$ = 10 TeV collider

- Simulation model (FLUKA):
  - Started with a nozzle inspired by 1.5 TeV MAP design (N. Mokhov)
  - Conical W liners in magnets which follow **5σ beam envelope**
  - Muon decay sampling → fully matched beam phase space distr.



- Topics addressed so far for the 10 TeV collider:
  - Is the decay-induced background worse than in a 3 TeV collider? → Results with MAP-like nozzle yield similar number of particles entering detector for 3 TeV and 10 TeV:
  - **Impact of lattice design choices on the decay background**
  - First assessment of the nozzle optimization potential for 10 TeV
  - First assessment of the contribution of incoherent electron-positron pair production
  - First estimate of the cumulative radiation damage in the detector
  - First study of forward muons from IP (muon tagging)

(Impact of lattice design choices; nozzle optimization potential:) See next slides

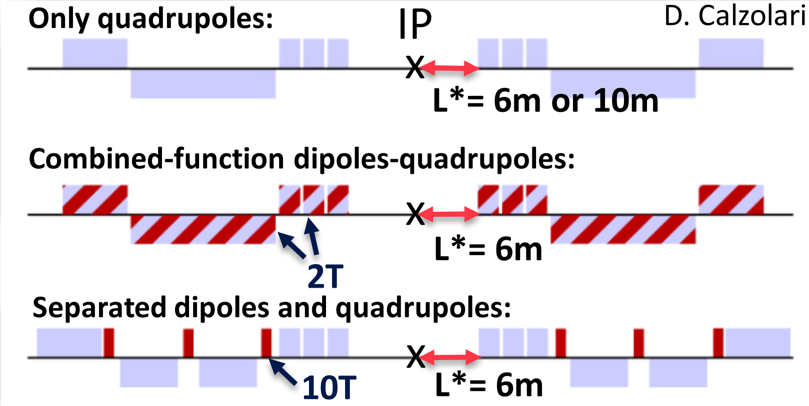
Monte Carlo simulator	FLUKA	FLUKA
Beam energy [GeV]	1500	5000
μ decay length [m]	$93.5 \cdot 10^5$	$311.7 \cdot 10^5$
μ decay/m/bunch	$2.1 \cdot 10^5$	$0.64 \cdot 10^5$
Photons ($E_\gamma > 0.1$ MeV)	$70 \cdot 10^6$	$107 \cdot 10^6$
Neutrons ($E_n > 1$ MeV)	$91 \cdot 10^6$	$101 \cdot 10^6$
Electrons & positrons ($E_{e^\pm} > 0.1$ MeV)	$1.1 \cdot 10^6$	$0.92 \cdot 10^6$
Charged hadrons ($E_{h^\pm} > 0.1$ MeV)	$0.020 \cdot 10^6$	$0.044 \cdot 10^6$
Muons ($E_{\mu^\pm} > 0.1$ MeV)	$0.0033 \cdot 10^6$	$0.0048 \cdot 10^6$

From Snowmass white paper.

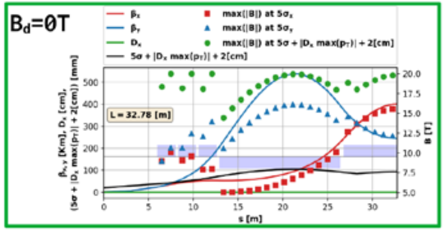
Impact of lattice design choices on the decay-induced background (10 TeV)

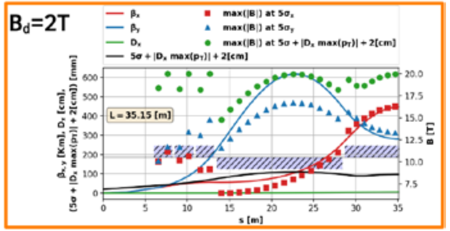
- *Can the decay-induced background be reduced by adjusting the lattice design?*
- Two key aspects were investigated:
  - Dipolar component in the final focus triplet (combined function magnets or separate dipoles)
  - Distance between IP and final focus magnets (L*)

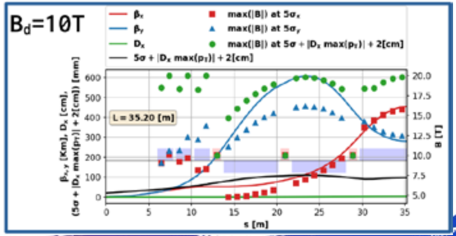
Layouts considered for the BIB studies:



Lattices with and without dipolar component (L=6m):*





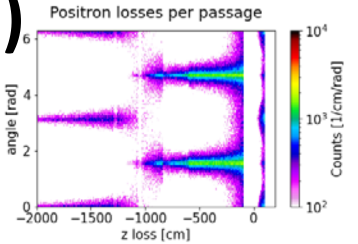


K. Skoufaris

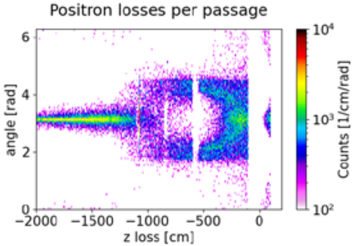
Impact of dipolar component on the decay-induced background (10 TeV)

- The presence of a dipolar component changes the loss distribution of decay-e^-/e^+ on the aperture
- Some reduction of the contribution from distant decays
- However, the overall benefits are limited

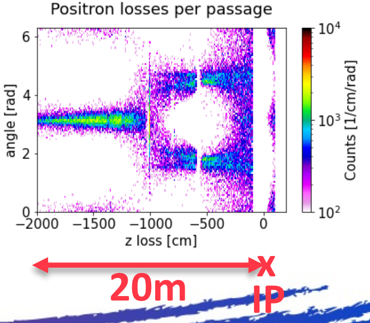
Only quadrupoles

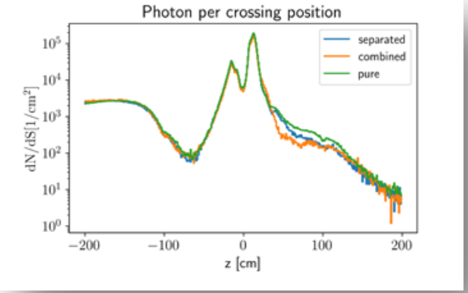


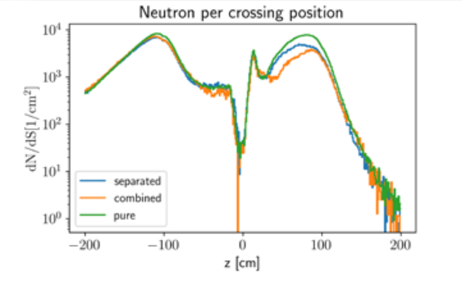
Combined-function dipoles-quad.



Separated dipoles and quadrupoles:



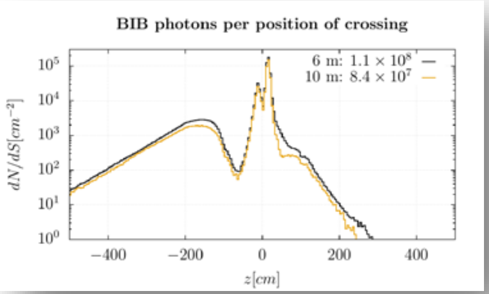


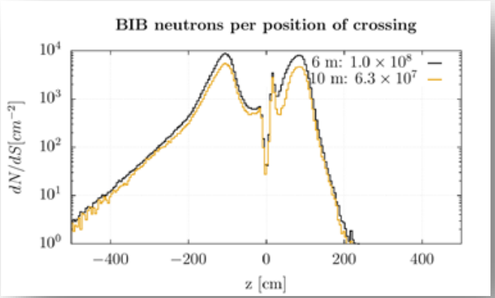


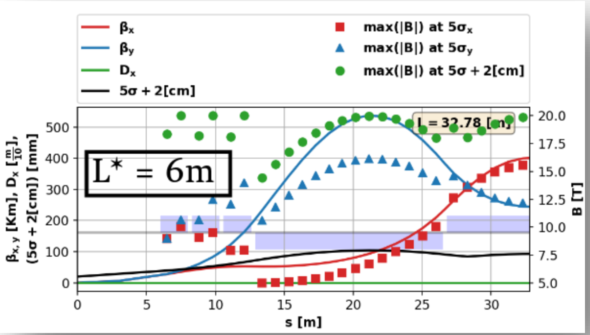
Particles crossing into the detector around the IP (with and without dipolar component):

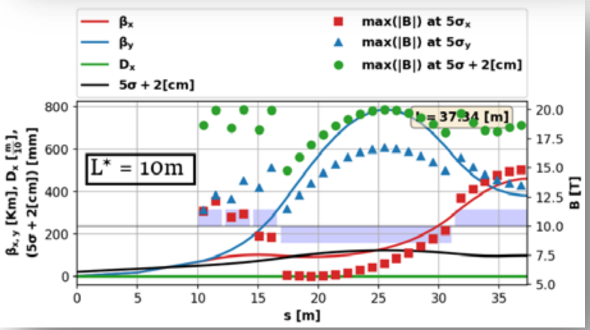
Impact of L* on the decay-induced background

- The 10 TeV MDI studies show that μ-decays between IP and first quad contribute little to the BIB – is it beneficial to increase L*?
- With **L*= 10 m**, some reduction of the particle fluence is found around the IP compared to **L*= 6 m**
- Nevertheless, the gain is not large enough to justify the increase of L*





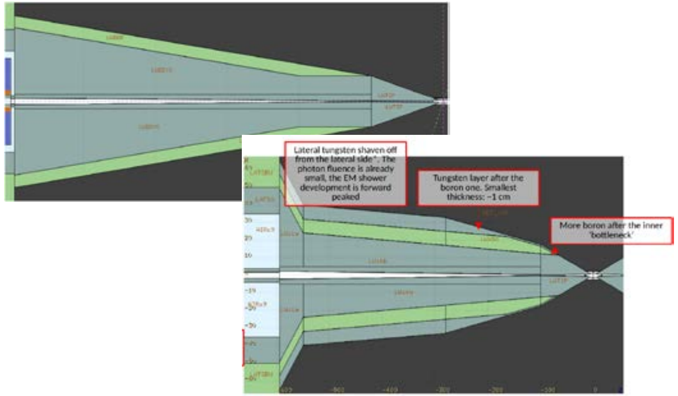


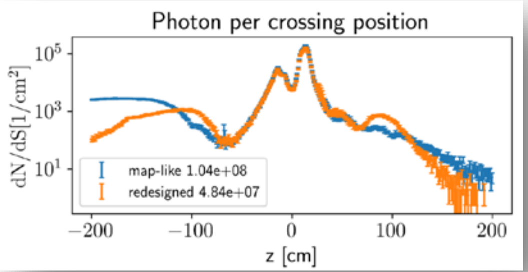


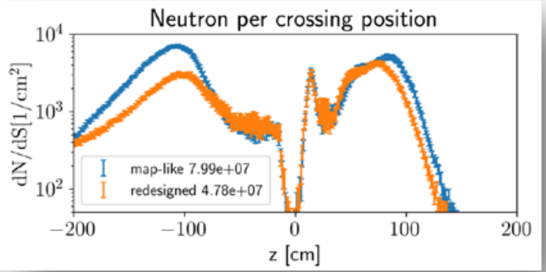
K. Skoufaris

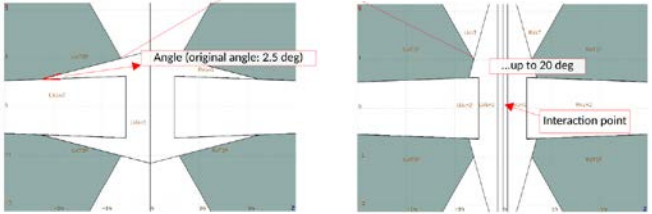
Towards an optimized nozzle for the 10 TeV collider

- The nozzle geometry developed within MAP (N. Mokhov) was customized for a 1.5 TeV collider
- Preliminary studies@10 TeV suggest that there is potential to decrease the particle fluence into the detector by changing the nozzle shape and adjusting the material layers









D. Calzolari MDI meeting #6, 29/06/2022

Next steps for the background studies

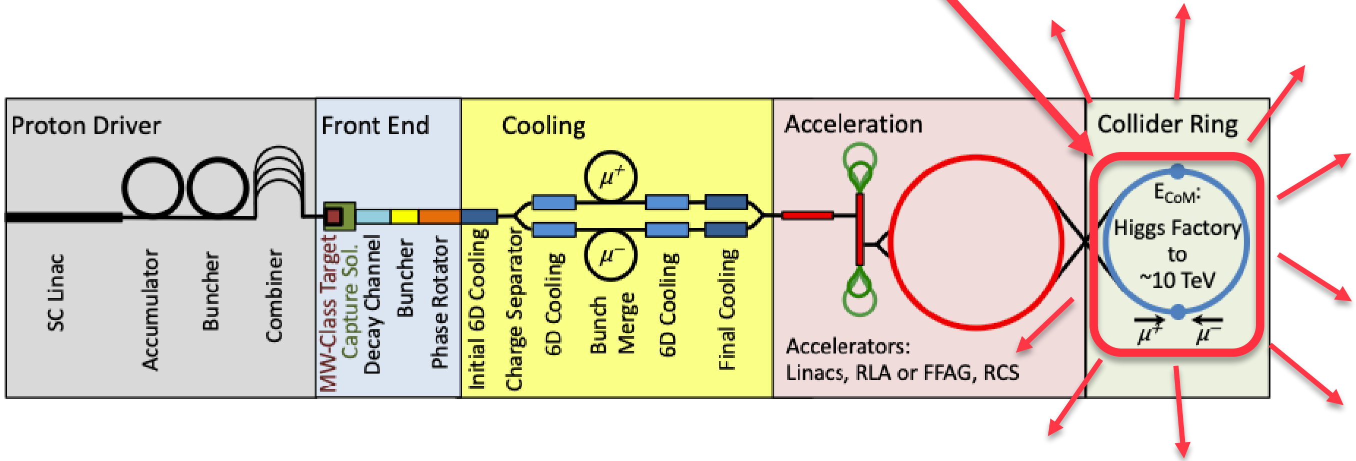
3 TeV collider:

- Revive the BIB studies
- **Progress on the optimization of the nozzle for 3 TeV**

10 TeV collider:

- **Progress on the optimization of the nozzle for 10 TeV**
- Evaluate in more detail the contribution of other background sources:
  - Assess the acceptable level of beam halo losses on the aperture near the IP
  - Update the studies for incoherent e^-/e^+ pair production
- Progress on the forward muon studies

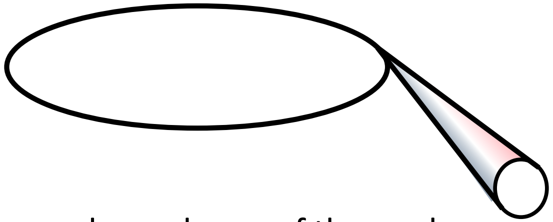
Part 4. Neutrino-induced dose



Neutrino radiation at a muon collider

- Neutrinos from $\mu^{\pm}$ decays can lead to significant dose levels when emerging on the earth's surface:
  - Narrow neutrino cone (width ~ $1/\gamma$)
  - Cross section growing linearly with the energy
  - No benefit from shielding (possibly detrimental)

Strong dependence of the peak dose on the muon energy



- FLUKA simulations framework put in place to study the effective dose in soil:

1st STEP: MUON DECAY

- Samples the muon decay products yielding a **list of decay neutrinos** with their flavor, energy, and angle of emission
- Yields a **list of interacting neutrinos** by filtering the above list based on the interaction probability in soil (via the macroscopic cross section)

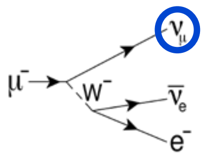
2nd STEP: NEUTRINO INTERACTIONS IN SOIL

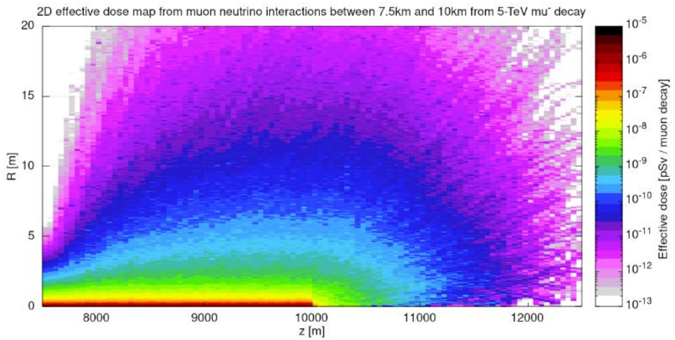
- Simulates neutrino interactions in soil by sampling the distance of the interactions from the muon decay point within a user-defined range, and using the output of the 1st step to obtain the (x,y,z) position of the interaction
- Yields the scoring of relevant quantities (e.g., absorbed dose, effective dose, particle spectra) per unit muon decay

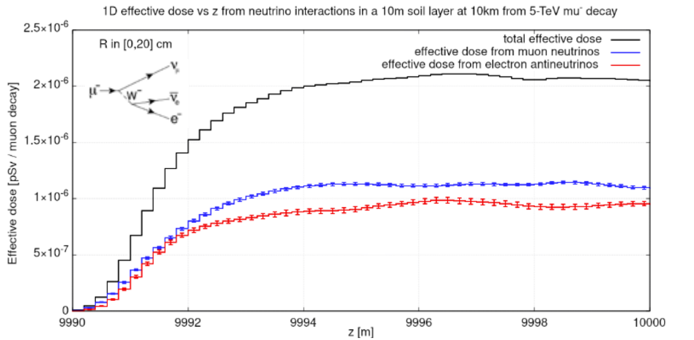
International MUON Collider Collaboration

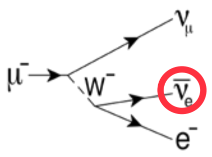
Effective dose build-up in soil and attenuation in air

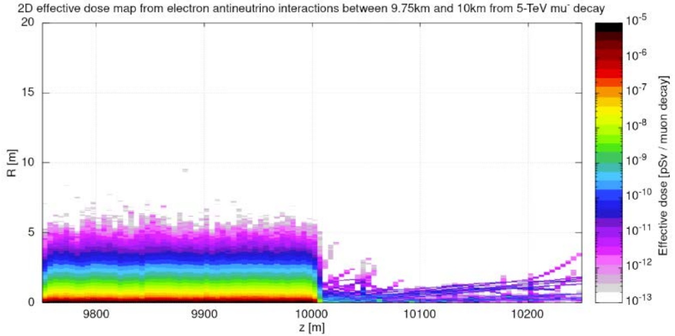
- The build-up of effective dose in soil occurs over a few meters, while the muon flux build-up occurs over longer distances (but yields a small contribution to the dose). The effective dose decreases rapidly in air.

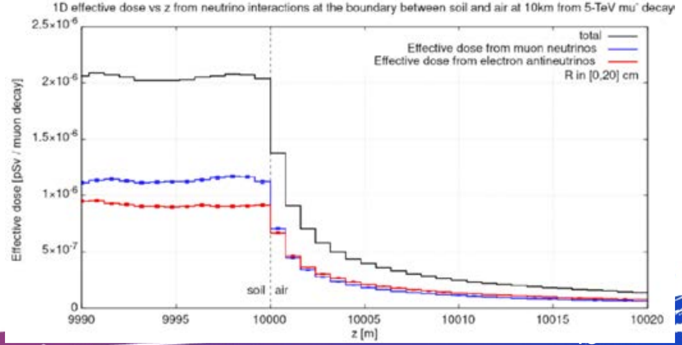










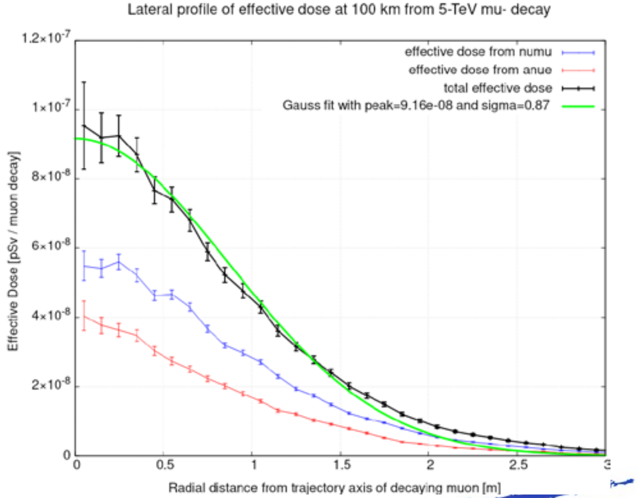


G. Lerner

Result: effective dose kernel in soil

- Effective dose in soil vs longitudinal and lateral distance from the decay of muons of given energy and trajectory, serving as the basis for calculations taking into account the beam divergence in more complex geometries
- Simulated with FLUKA for positive and negative muon beams and for two energies (1.5 TeV, 5 TeV)
- Presented at the international muon collider meeting in October 2022 (link)

	μ^-		μ^+	
Distance	Peak eff. dose [pSv / decay]	σ [m]	Peak eff. dose [pSv / decay]	σ [m]
5 km	$1.57 \cdot 10^{-5}$	0.05	$1.63 \cdot 10^{-5}$	0.05
10 km	$4.86 \cdot 10^{-6}$	0.10	$5.38 \cdot 10^{-6}$	0.10
15 km	$2.54 \cdot 10^{-6}$	0.15	$2.70 \cdot 10^{-6}$	0.14
20 km	$1.56 \cdot 10^{-6}$	0.19	$1.55 \cdot 10^{-5}$	0.20
40 km	$4.80 \cdot 10^{-7}$	0.37	$4.62 \cdot 10^{-6}$	0.38
60 km	$2.33 \cdot 10^{-7}$	0.54	$2.22 \cdot 10^{-6}$	0.55
80 km	$1.38 \cdot 10^{-7}$	0.71	$1.31 \cdot 10^{-7}$	0.73
100 km	$9.16 \cdot 10^{-8}$	0.87	$8.63 \cdot 10^{-8}$	0.90



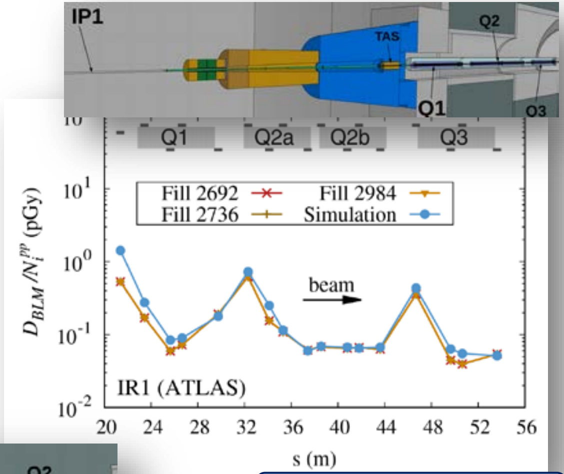
G. Lerner

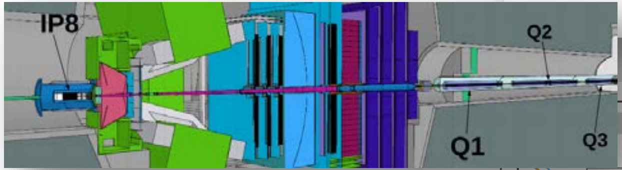
International
MUON Collider
Collaboration

Thank you
for your attention!

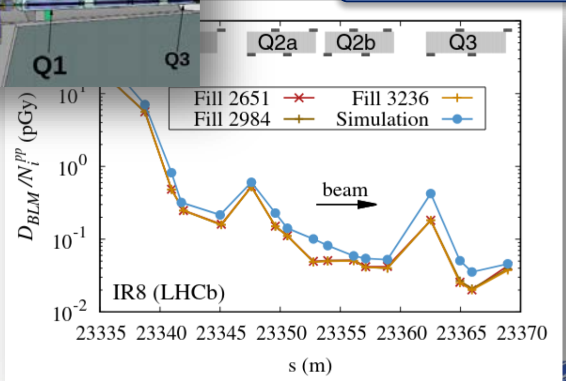
Studying beam losses in colliders – simulation tools

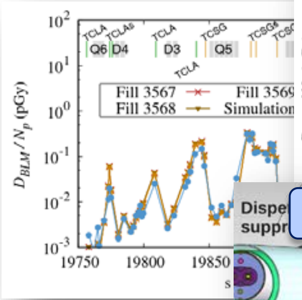
- FLUKA Monte Carlo code is widely used for collider studies (LHC, HL-LHC, FCCee/hh, …)
- Vast experience from LHC operation: agreement with beam loss monitor measurements typically within few 10%

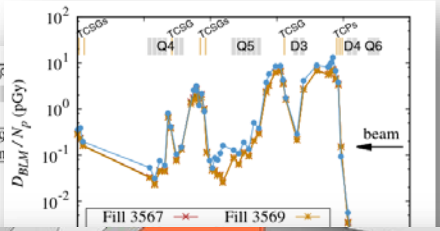




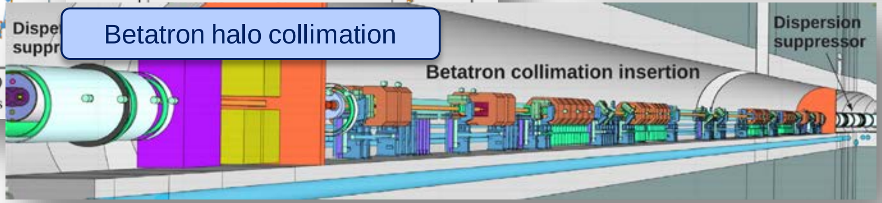
pp collision debris







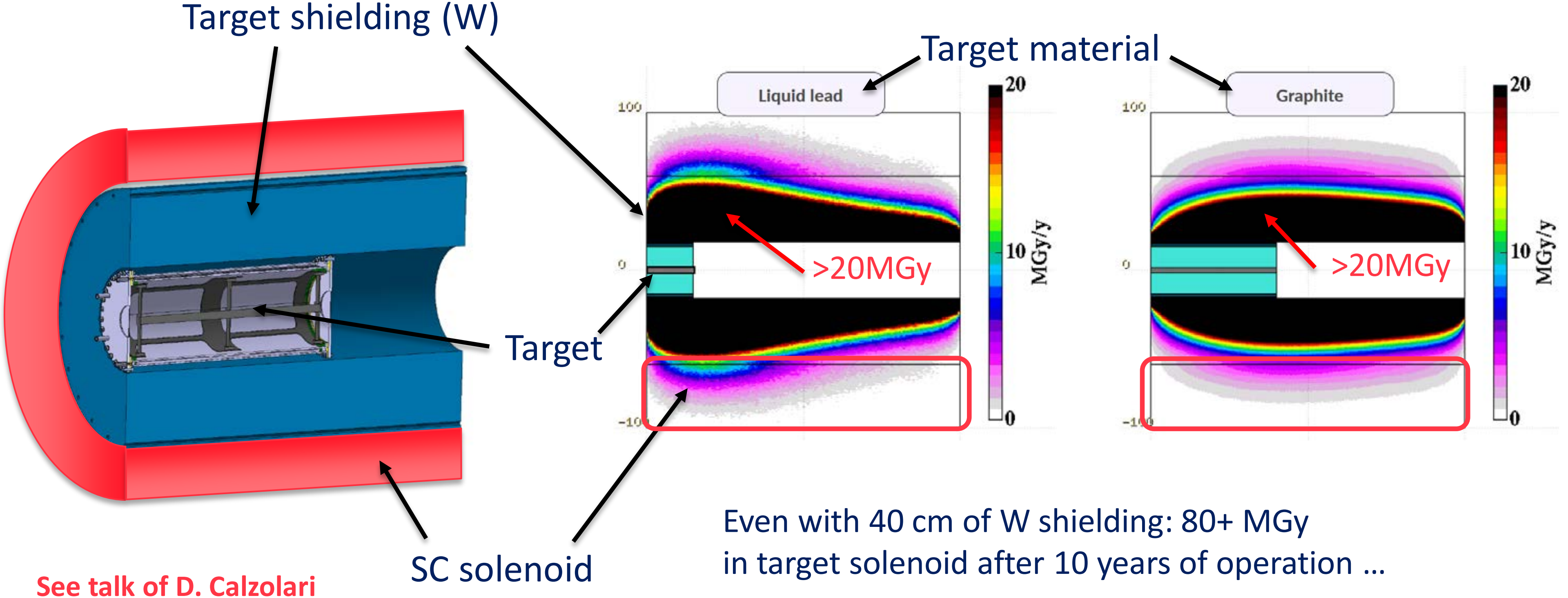
Betatron halo collimation



A. Lechner et al., Phys. Rev. Accel. Beam (22), 071003, 2019.

Radiation load to target solenoid – ionizing dose

Results normalized to 1 year of operation with 1 MW proton drive beam (actual beam power expected to be 1.5 MW+)

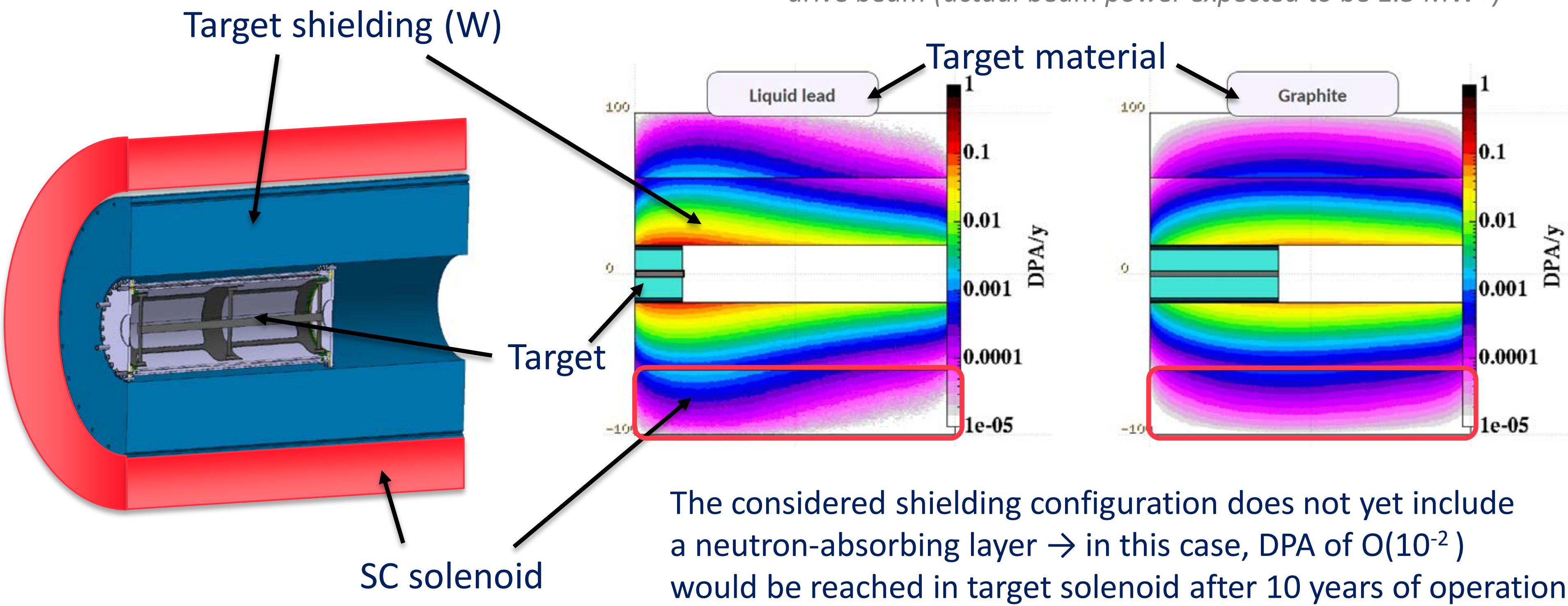


Even with 40 cm of W shielding: 80+ MGy
in target solenoid after 10 years of operation …

See talk of D. Calzolari Thu morning

Radiation load to target solenoid – DPA

Results normalized to 1 year of operation with 1 MW proton drive beam (actual beam power expected to be 1.5 MW+)



The considered shielding configuration does not yet include a neutron-absorbing layer → in this case, DPA of O(10^{-2}) would be reached in target solenoid after 10 years of operation

DPA with neutron absorber to be studied

Work in progress