Heat load and radiation damage studies for magnets in a muon collider

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Muon Collider Collaboration Meeting
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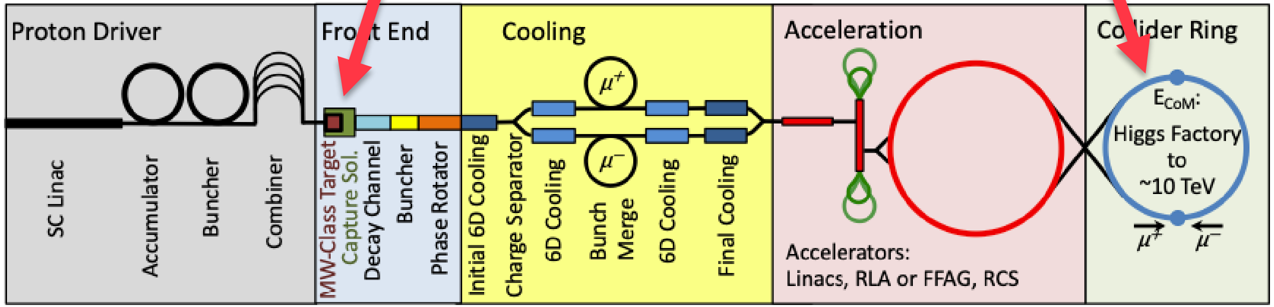
Introduction

- Particle-induced **heat load** and **radiation damage** in SC **magnets** pose a significant challenge for a muon collider
- For example*:

See talk of D. Calzolari Thu, 8h30

MW proton beam on target:
Hadronic & EM showers give rise to mixed radiation fields
→ radiation to solenoids

Beam losses (mainly muon decay):
EM showers, neutrons through photo-nuclear interactions
→ radiation to collider ring magnets



Main focus of this talk

*Cooling magnets, magnets in accelerators are also exposed to radiation, but are not discussed here.

Radiation to collider ring magnets

MW proton beam on target:
Hadronic & EM showers give rise to mixed radiation fields
→ radiation to solenoids

Beam losses (mainly muon decay):
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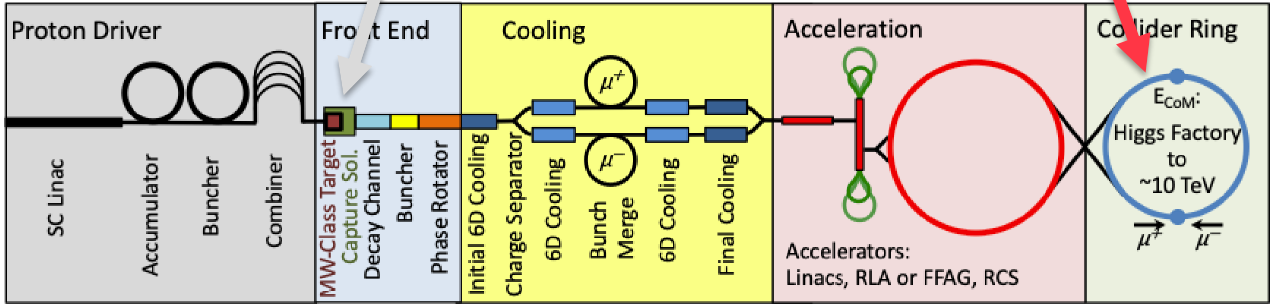
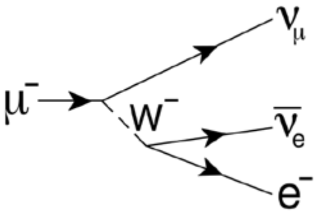
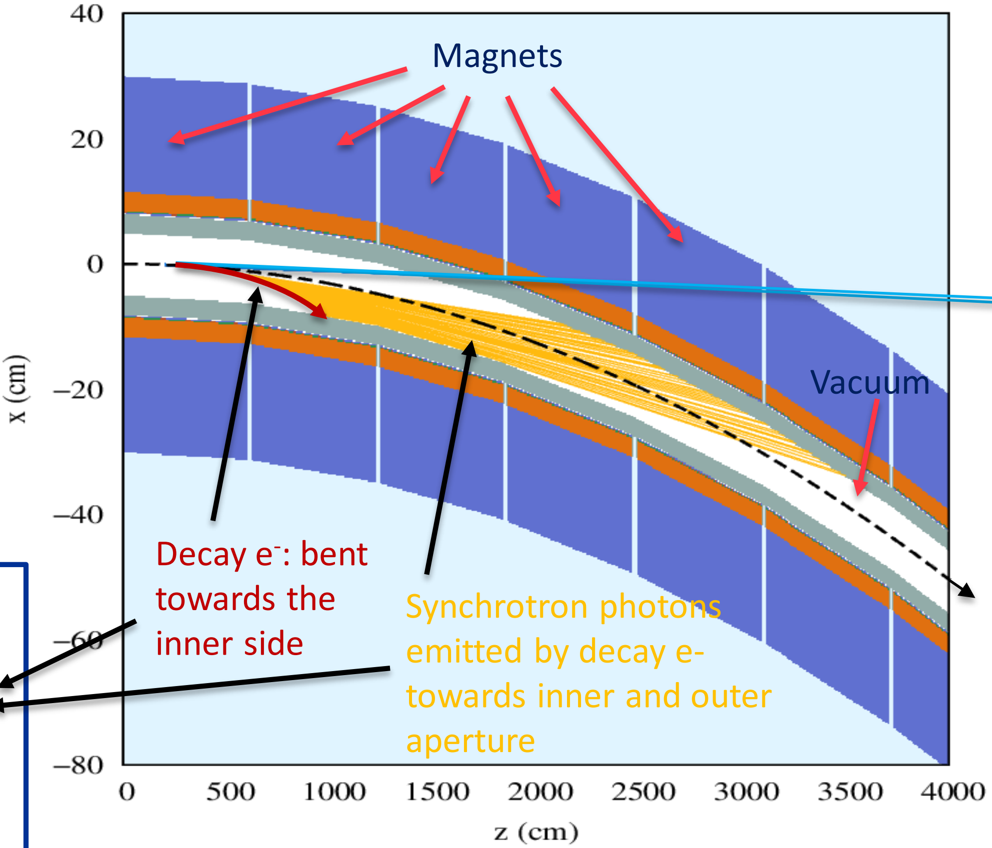
→ radiation to collider ring magnets



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

Inside magnets:

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

Similar picture applies to $\mu+$

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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

Muon decay, halo losses

**Point-like quantity*

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!), (*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 for full collider lifetime

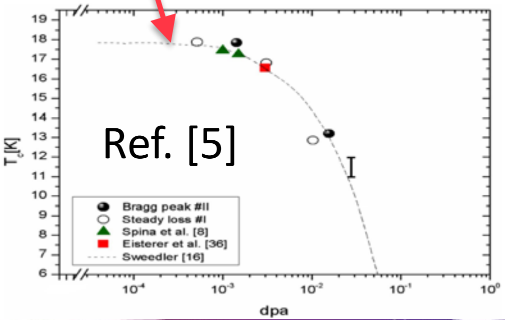
Radiation load on collider ring magnets – tolerable limits

- Tolerable limits depend on the choice of coil technology & materials, i.e. superconductor (NbTi, Nb3Sn, HTS), stabilizer, impregnation, insulation, spacers
- A good knowledge of these limits is decisive for the collider shielding design
- For reference, some limits assumed for the (HL-)LHC magnets:

Quench
- **Local power density: 15-20 mW/cm³** (8.3 T NbTi) [1,2] … **70 mW/cm³** (11 T Nb3Sn) [3]

Magnet lifetime
- **Cumulative dose** (insulators, end spacers, resins): **few 10 MGy** (Kapton, epoxy, G11) [4]
- **Cumulative displacements** (superconductor): **few 10^{-3} DPA** (Nb3Sn) [5]

[1] B. Auchmann et al., Phys. Rev. Accel. Beam (18), 061002, 2015.
[2] L. Bottura et al., Phys. Rev. Accel. Beam (22), 041002, 2019.
[3] L. Bottura et al., https://indico.cern.ch/event/780182/
[4] L. Bottura https://indico.cern.ch/event/260492/contributions/159208
[5] R. Flükiger et al. Supercond. Sci. Technol. 30 054003 (2017)



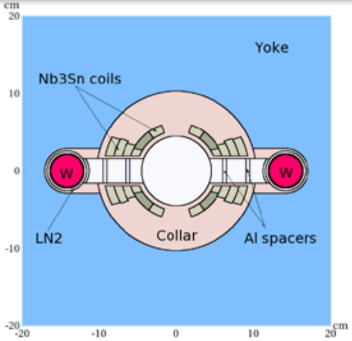
Degradation of bonding and fracture strength, materials become brittle.
**Premature quenches,*
**Failure of insulation,*
**Mechanical failures*

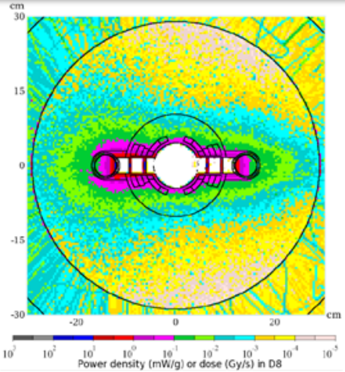
More input from the other talks in this session

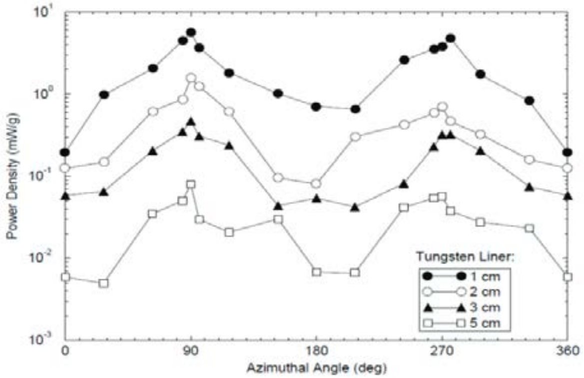
Radiation load on collider ring magnets – previous work in MAP

- Multiple studies done within MAP for $\sqrt{s}$= **1.5** and $\sqrt{s}$=**3 (4) TeV** (as well as for a lower energy Higgs factory)
- Heat load management with thick W shielding (few cm) or open-midplane magnets (dipoles)

Example: Power density in open midplane dipoles ($\sqrt{s}$ = 1.5 TeV)
N. Mokhov et al. “Radiation effects in a muon collider ring and dipole magnet protection”, IPAC 11, link.

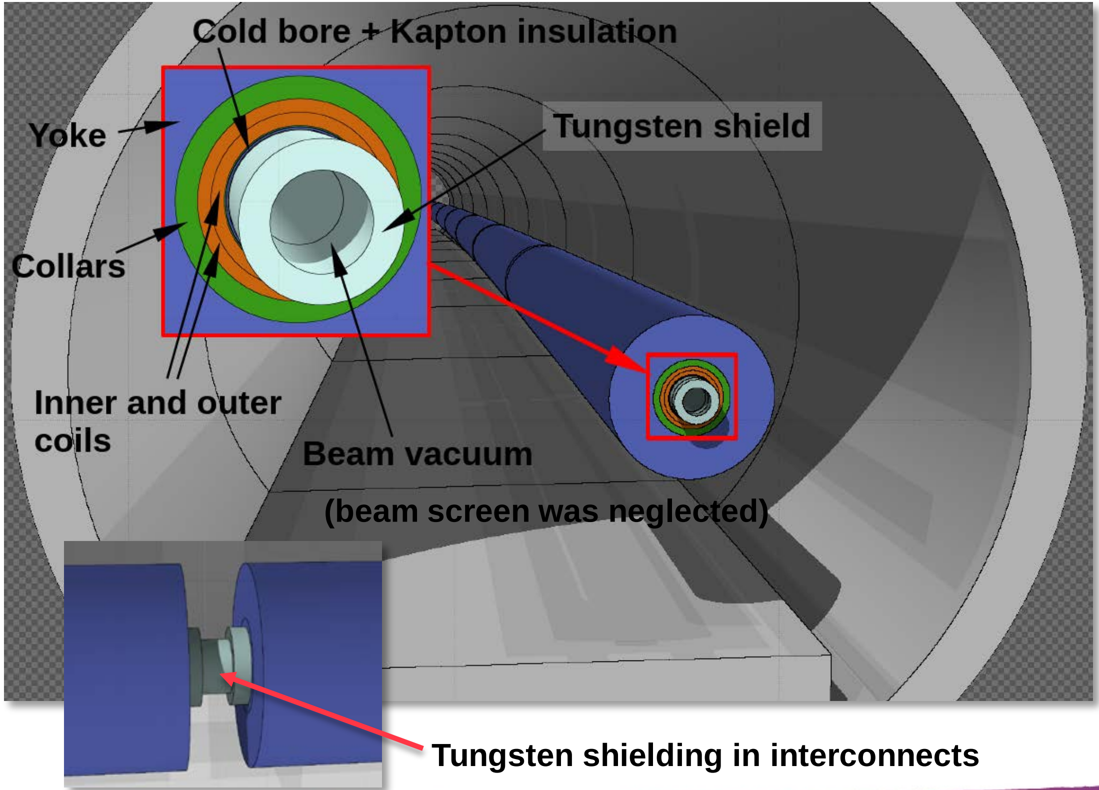






Example: Power density in coils vs W thickness ($\sqrt{s}$=4)
V.V. Kashikhin , Y.I. Alexahin, N.V. Mokhov, A.V. Zlobin, “High-Field Combined-Function Magnets for a 1.5 x 1.5 TeV Muon Collider Storage Ring”, IPAC12.

What are the magnet shielding requirements for a $\sqrt{s}$=10 TeV collider?

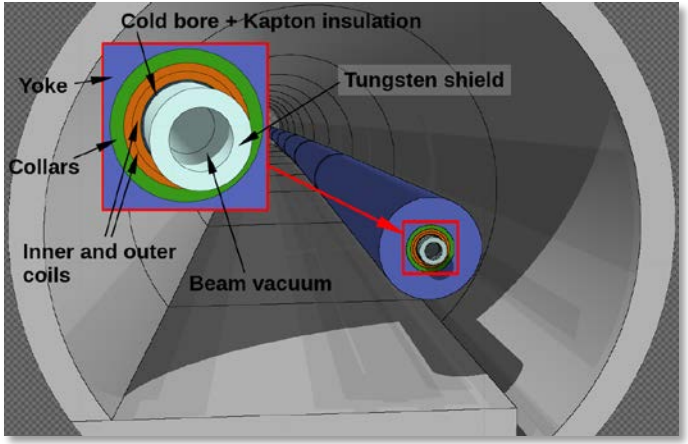


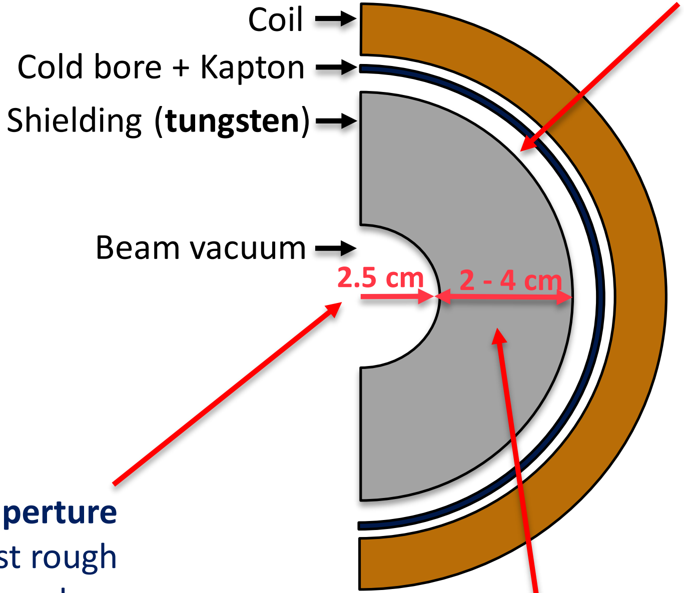
Performed first **generic shielding studies** for collider arc magnets with **FLUKA**, comparing 3 TeV and 10 TeV

- No real lattice/optics, just string of 6m-long dipoles:
  - 3 TeV: 7 Tesla
  - 10 TeV: ~11 Tesla*
- Generic dipole geometry (**WITH coils on mid-plane**)
- 20 cm long field-free regions in the interconnects

Goal: get a general understanding which quantity (**heat load**, **ionizing dose**, **DPA**) drives the shielding design

Radial magnet build assumed for generic shielding studies



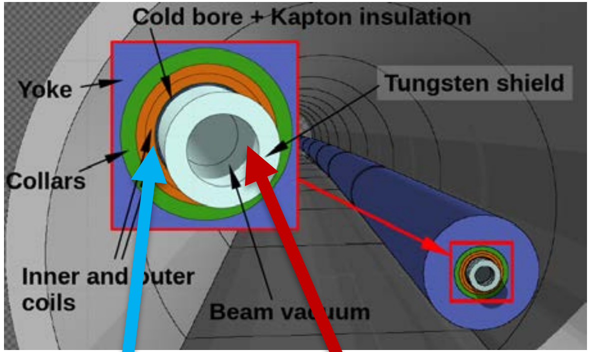


Thermal insulation between shielding and cold mass will take some space (NOT modelled here, we just assumed a small 1 mm gap)

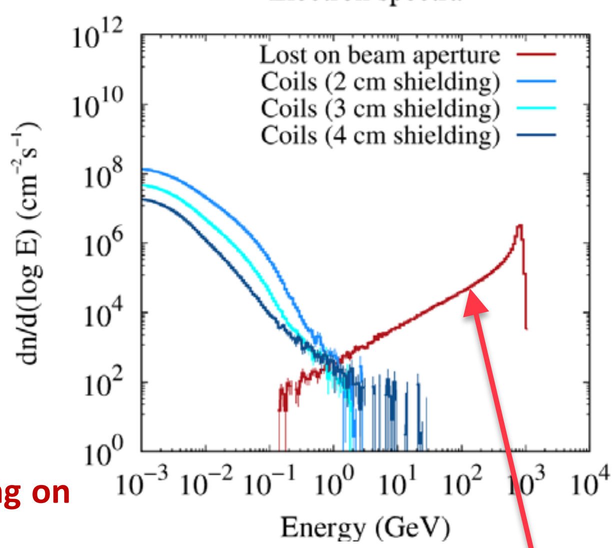
We assumed a **beam aperture** of **2.5 cm (radius)** – first rough guess from impedance and optics (note: in the 3 TeV MAP study, the aperture was 5.6 cm)

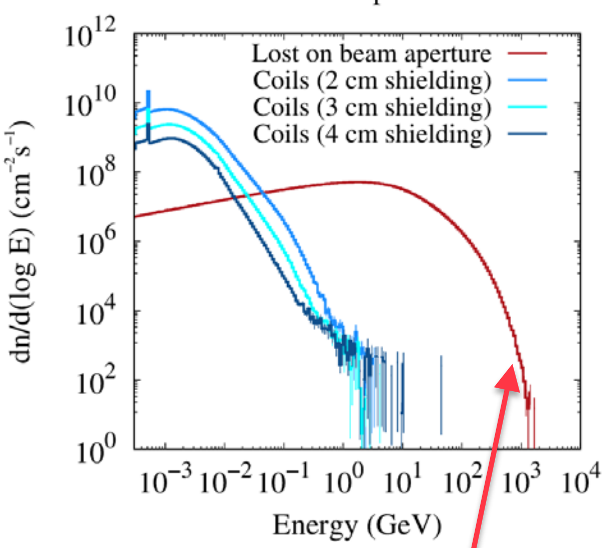
Considered **tungsten** shielding thicknesses **between 2 and 4 cm**

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



$\sqrt{s}$=10 TeV





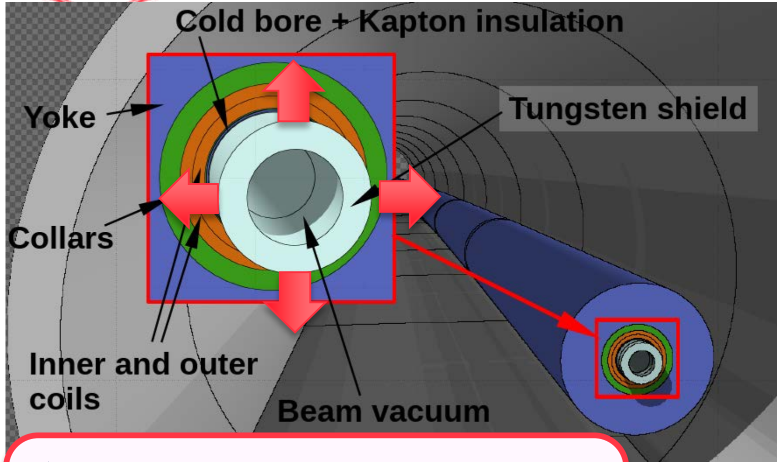
Red curves: particles **impacting on the inner shielding aperture** (decay e⁻, synchrotron photons)

Decay e⁻

Synchrotron photons emitted by decay e⁺/e⁻

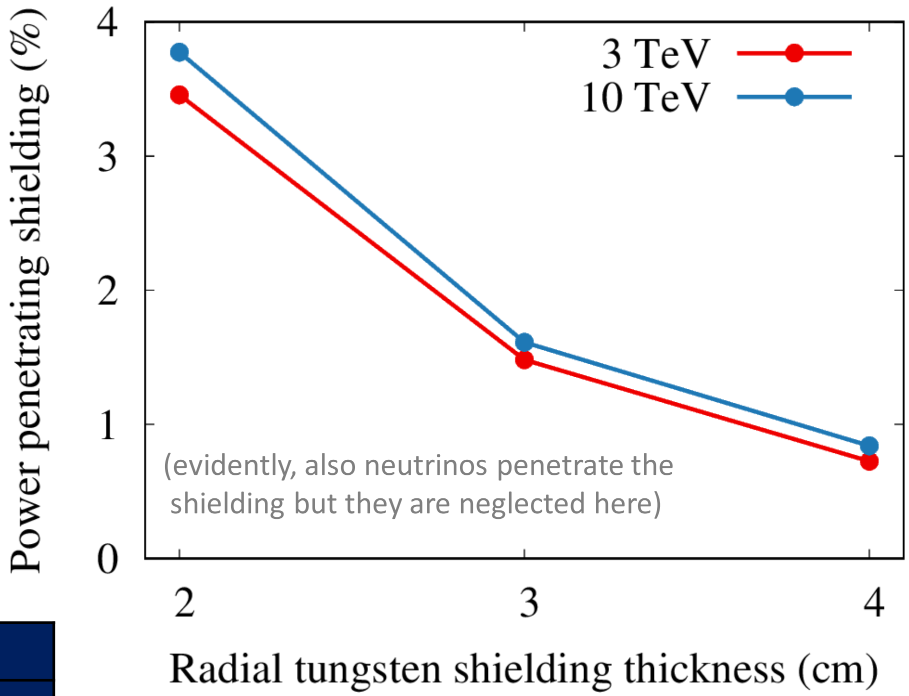
Blue curves: particle spectra **inside the inner coils** (for different shielding thicknesses)

Muon decay: power penetrating W shielding



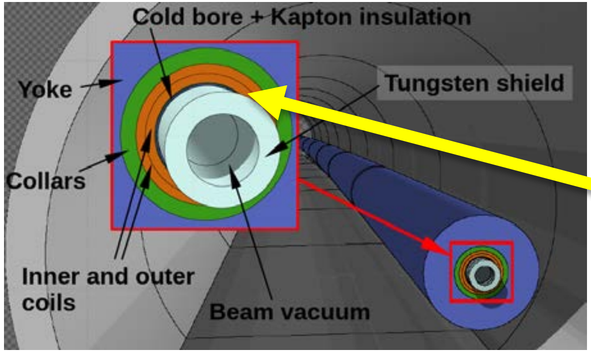
- **Fraction of power leaking through shielding similar for 3 TeV & 10 TeV**
- This power is mostly deposited in cold mass (including cold bore)

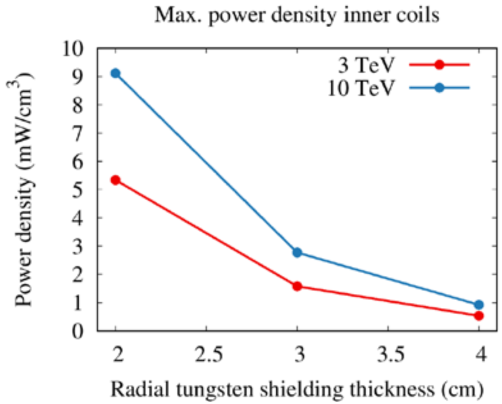
	Power carried by decay e^-/e^+:	Power penetrating shielding		
		2 cm	3 cm	4 cm
3 TeV	410 W/m	14 W/m	6 W/m	3 W/m
10 TeV	500 W/m	18 W/m	8 W/m	4 W/m



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

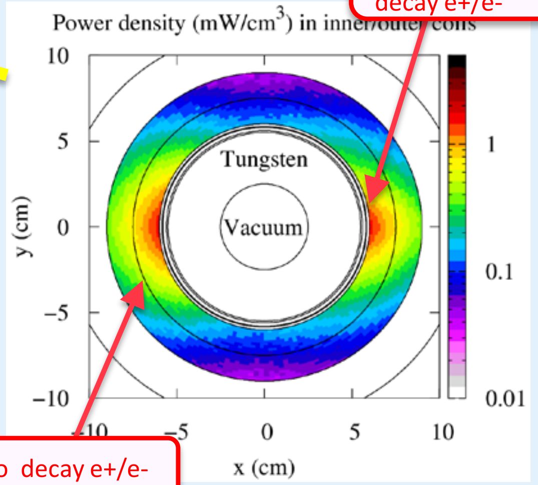
Power density in coils of (generic) arc dipoles



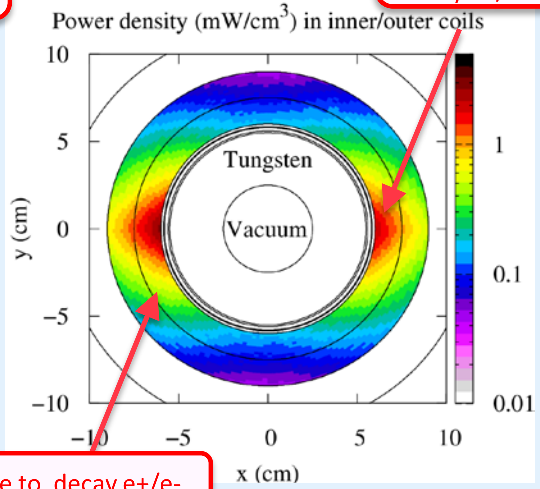


Power density map (transverse coil cross section):

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

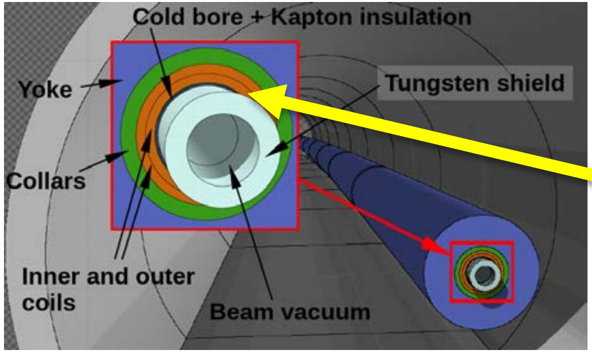


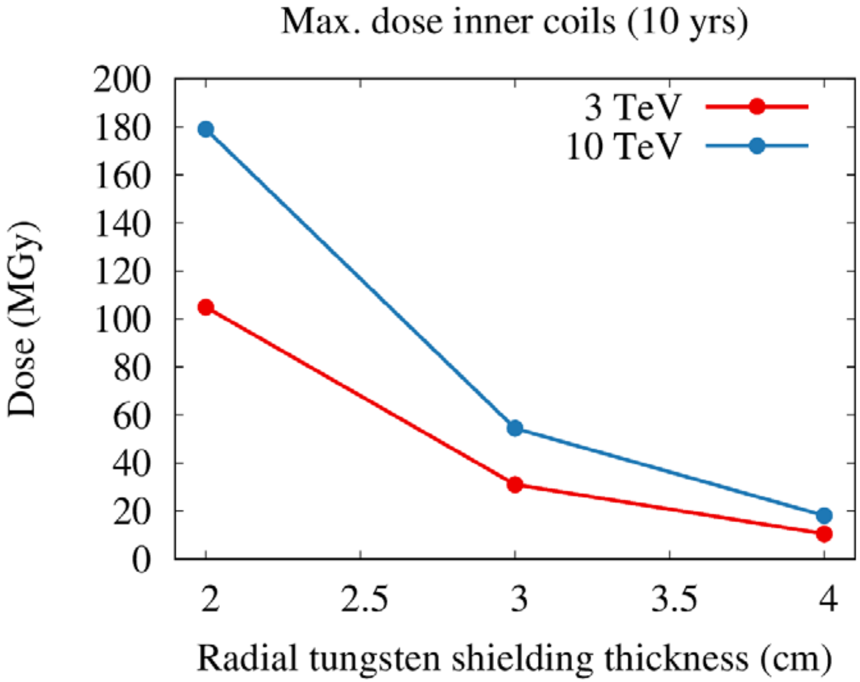
$\sqrt{s}$=10 TeV:
2.5 cm beam aperture
3 cm W shielding



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

Cumulative dose in coils of (generic) arc dipoles





Assumptions:

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

Need at least 4 cm W shielding to **stay below 20 MGy** in 10 yrs,
→ cumulative ionizing dose one of the main driving factors for the shielding design

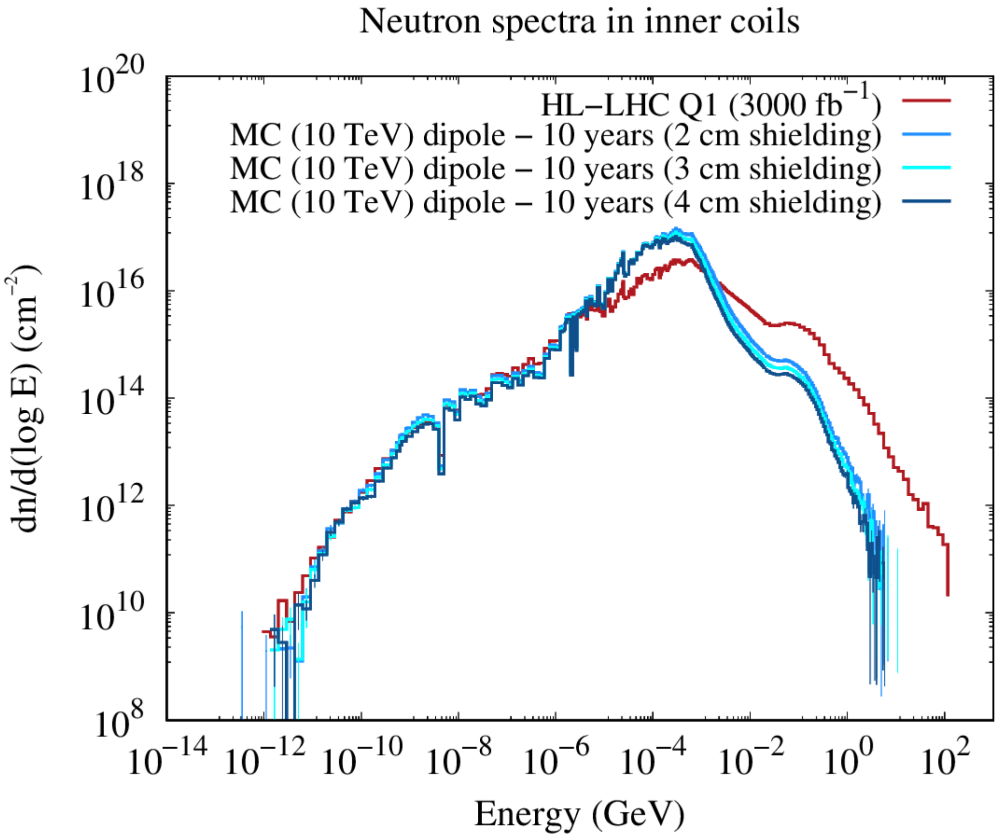
Neutron fluence in coils of (generic) arc dipoles

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

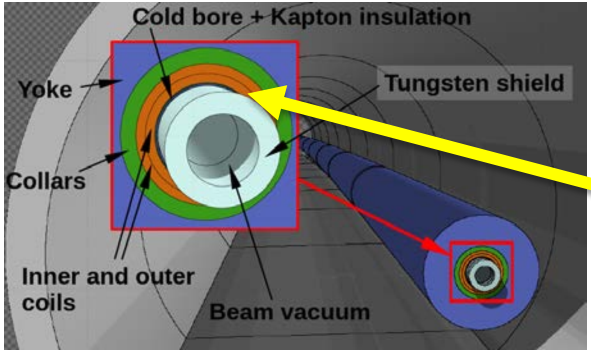
❖ **Neutron fluence in MC magnets shows only small dependence on shielding thickness**

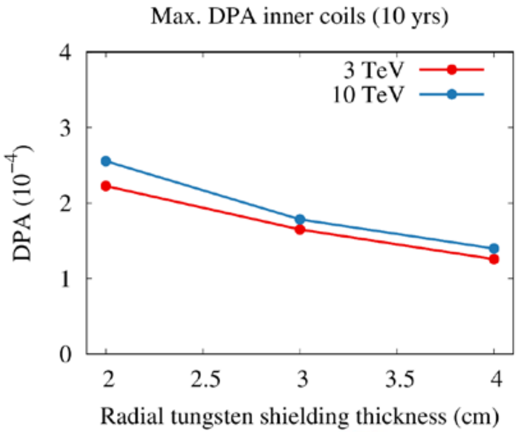
❖ Spectrum similar for 3 TeV as for 10 TeV collider

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



Cumulative DPA in coils of (generic) arc dipoles

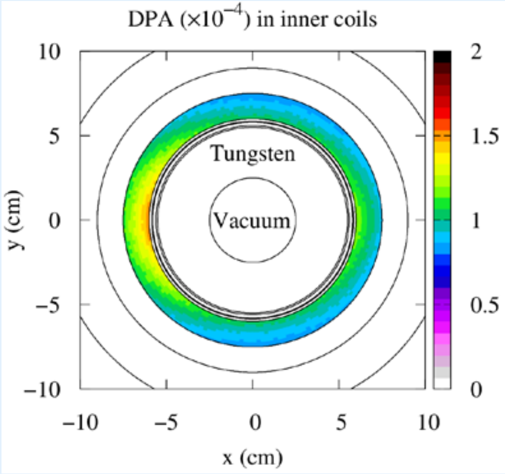




$\sqrt{s}$=3 TeV:

2.5 cm beam aperture

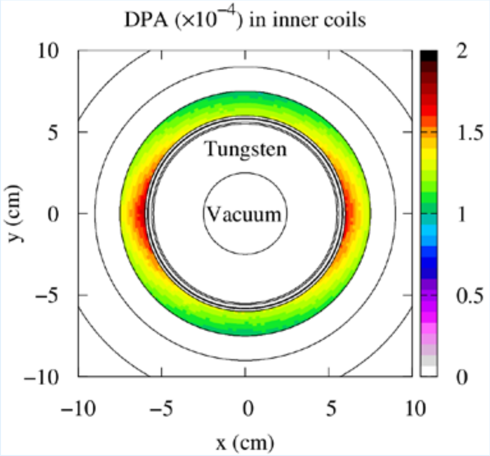
3 cm W shielding



$\sqrt{s}$=10 TeV:

2.5 cm beam aperture

3 cm W shielding

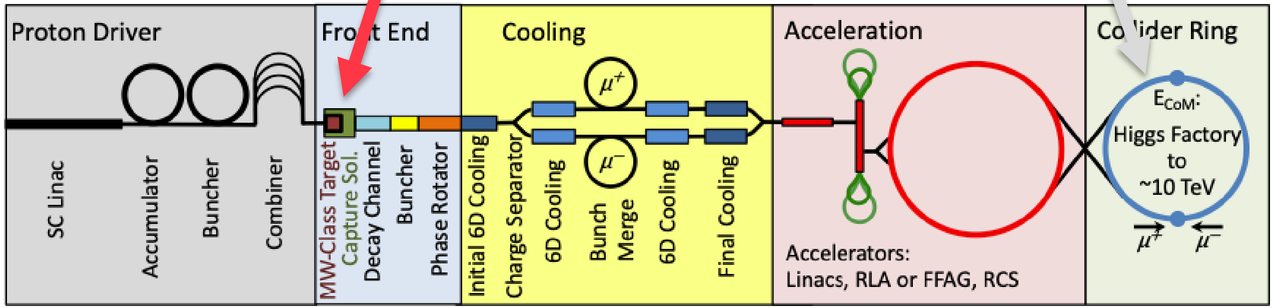


Max. 1-3x10^{-4} DPA in coils after 10 yrs (with 2-4 cm W shielding), appears to be less limiting than the ionizing dose

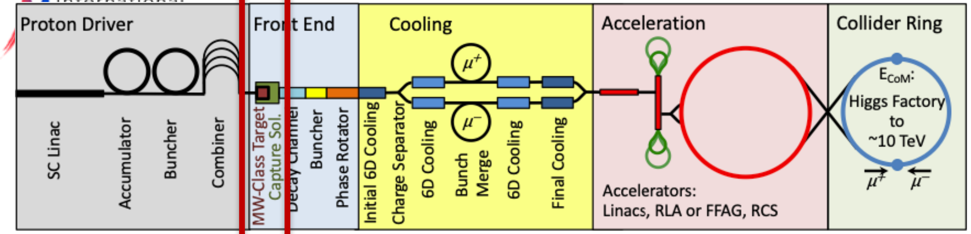
Radiation to the target solenoid

MW proton beam on target:
Hadronic & EM showers give rise to mixed radiation fields
→ radiation to solenoids

Beam losses (mainly muon decay):
EM showers, neutrons through photo-nuclear interactions
→ radiation to collider ring magnets

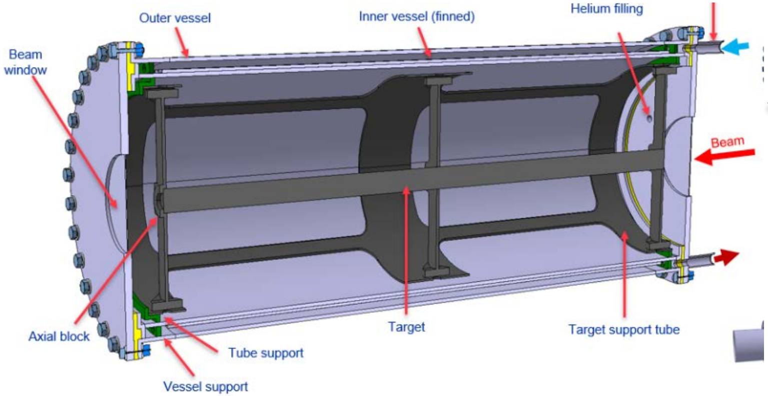


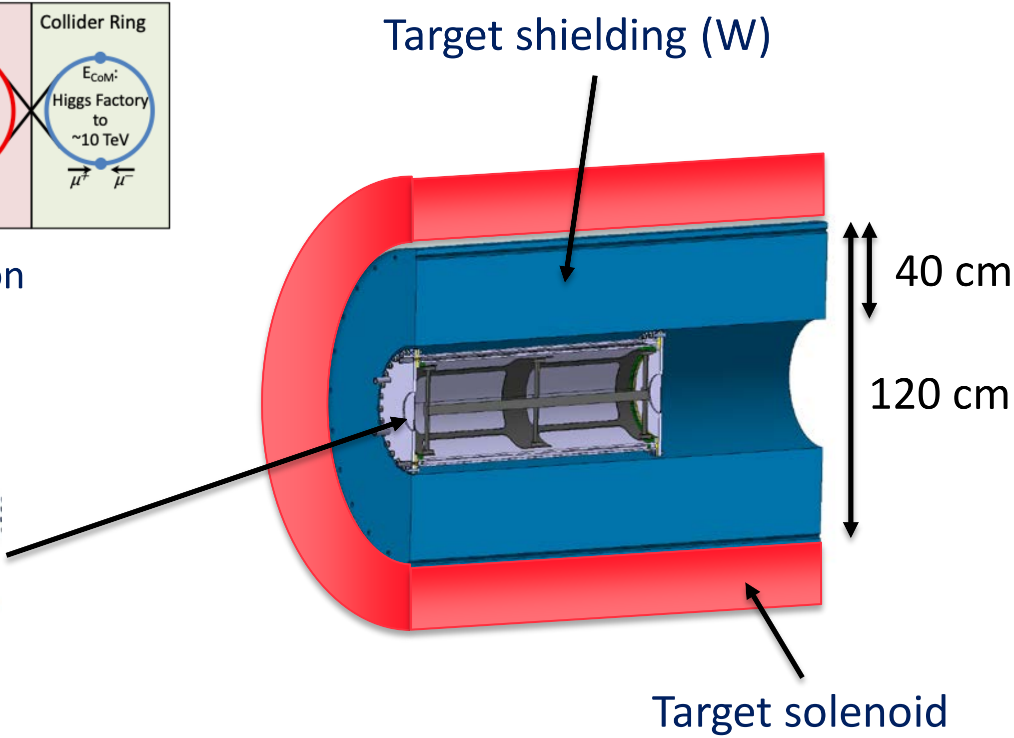
Radiation load to target solenoid



Different target materials under consideration (e.g. Graphite, liquid metals)

First concept of Graphite target + He vessel:





See talk of R. Franqueira Ximenes Wed morning

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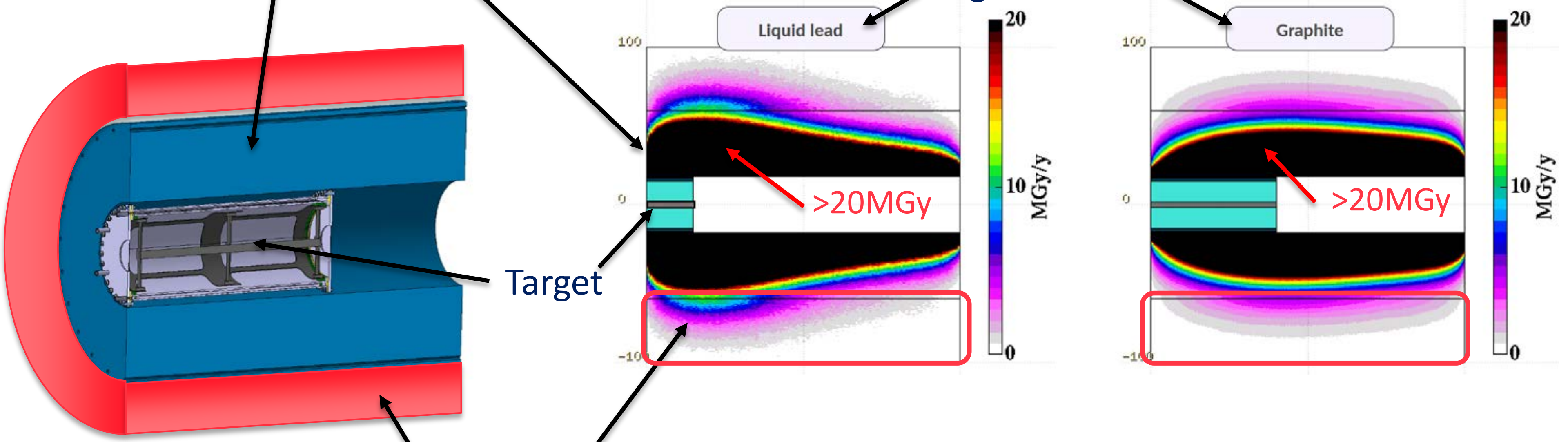
Radiation load to target solenoid – ionizing dose

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

Target shielding (W)

Target material



Target

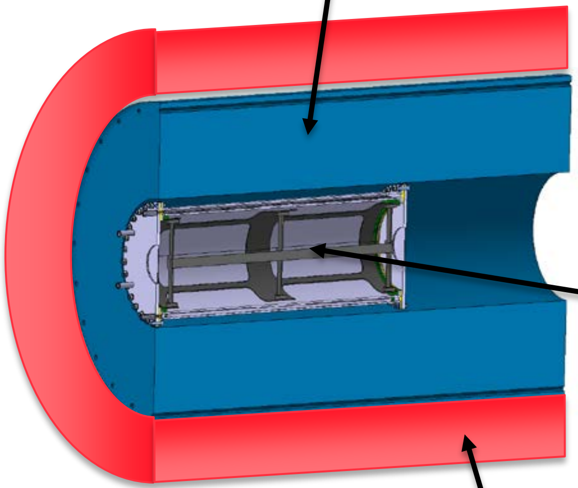
SC solenoid

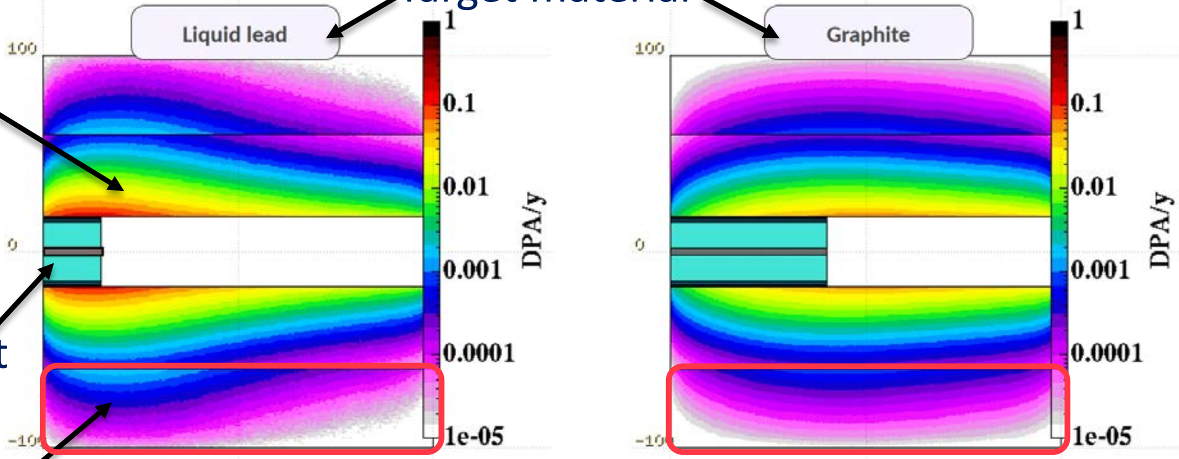
Even with 40 cm of W shielding: 80+ MGy in target solenoid after 10 years of operation …

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

Summary

Collider ring magnets:

- All magnets in the collider ring will be exposed to a high radiation load due to muon decay
- The shielding requirements are mainly driven by A) the total power leaking through the shielding and B) the cumulative ionizing dose in magnets, while the power density and cumulative DPA in coils appear to be somewhat less limiting
- With a ~4 cm thick W shielding, we expect that the radiation loads to magnets can be reduced to acceptable values (<5W/m to cold mass, <20 MGy/10 yrs, < 2×10^{-4} DPA/10 yrs)
- Possible benefits of other configurations (open mid-plane dipoles a la MAP) to be assessed

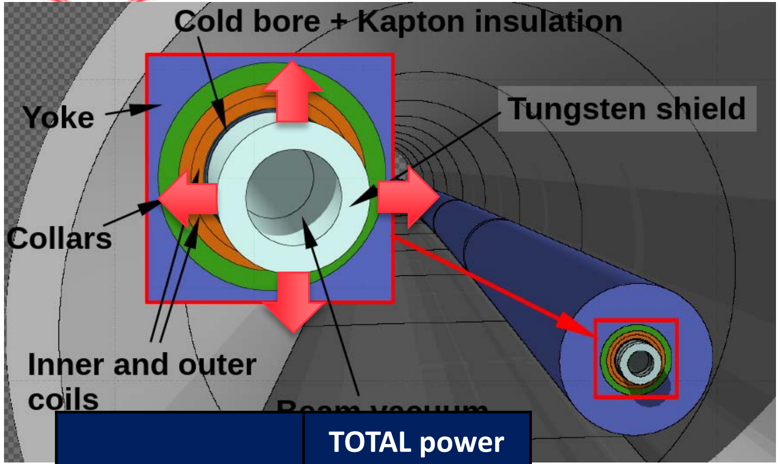
Target solenoid:

- Very high cumulative ionizing dose and DPA – feasible to operate magnets for the full collider lifetime?
- *More radiation resistant magnets would be highly beneficial*

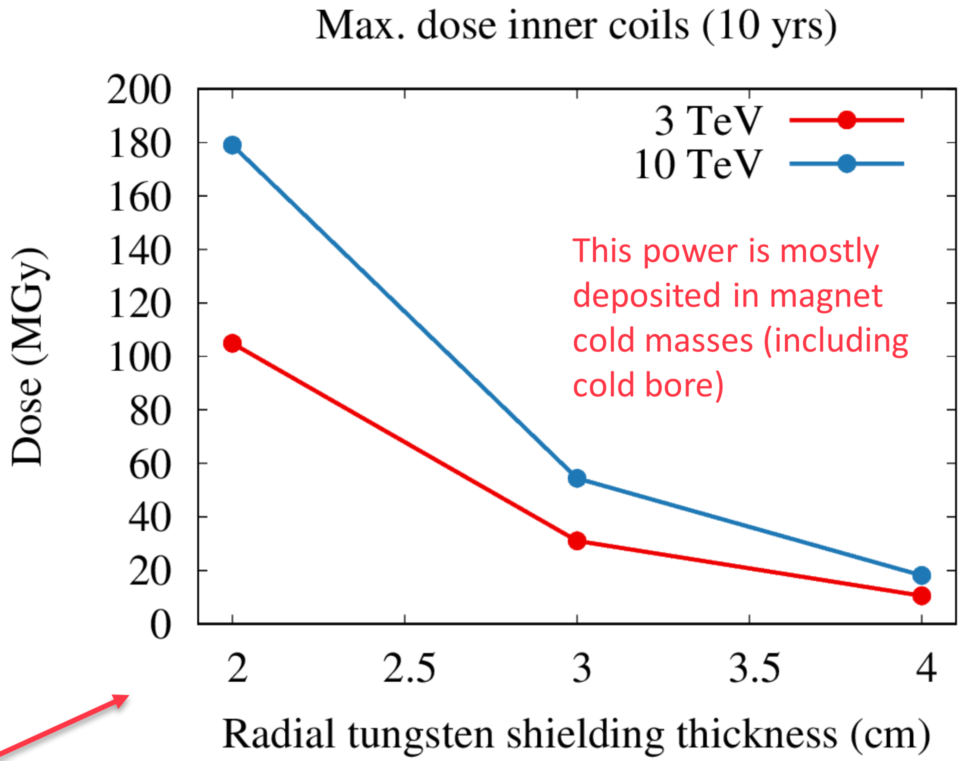
A close collaboration with magnet and cryo experts is crucial to advance together on the design considerations for the shielding requirements

Thank you for your attention!

Muon decay: power penetrating shielding



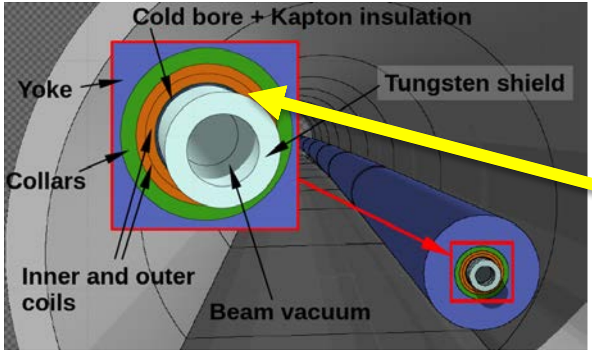
	TOTAL power carried by decay e^-/e^+:
3 TeV (4.5 km)	1.9 MW
10 TeV (10 km)	5 MW

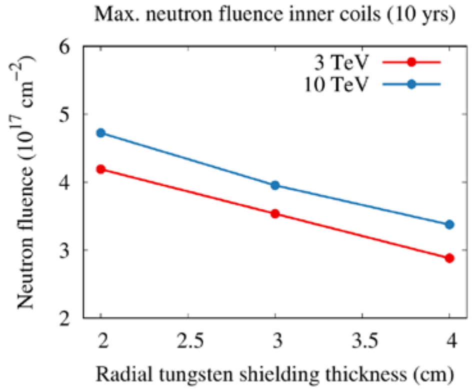


Estimates for the full collider:
numbers simply scaled from genericarc studies
→ these are just **ballpark numbers** without accounting for the detailed collider layout

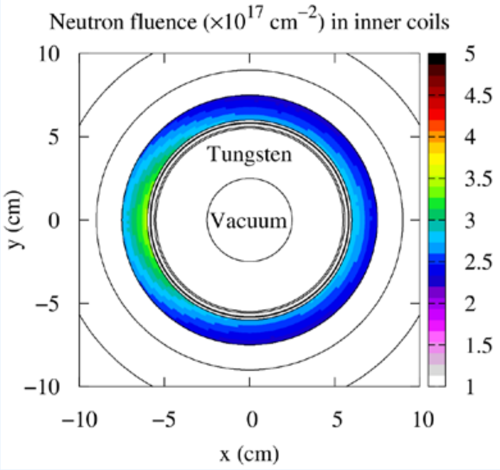
(evidently, also neutrinos penetrate the shielding but they are neglected here)

Neutron fluence in coils of (generic) arc dipoles

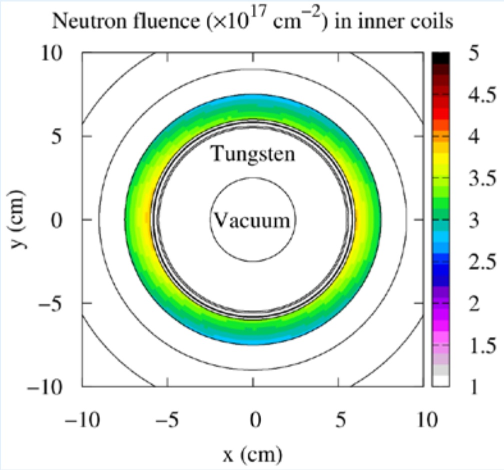




$\sqrt{s}$=3 TeV:
2.5 cm beam aperture
3 cm W shielding



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

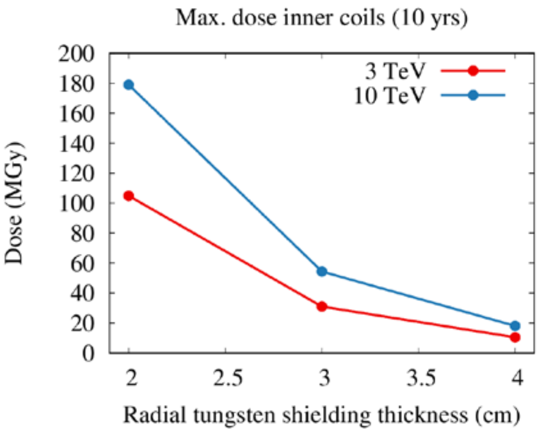


Max. 2-4x10^{17} n/cm^{-2} for in coils after 10 yrs (with 2-4 cm W shielding)

Cumulative dose in coils of (generic) arc dipoles

Assumptions:

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



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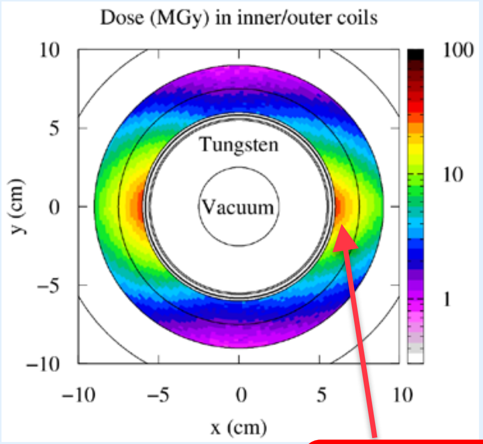
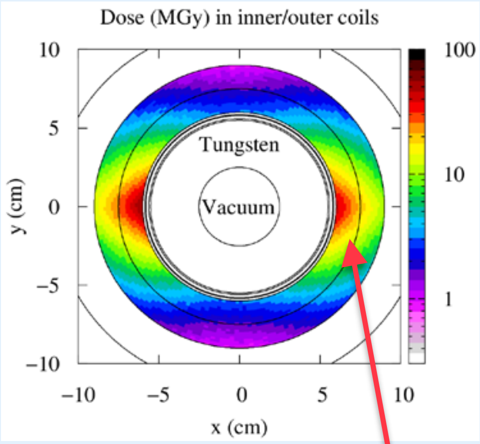


Due to synchrotron photons emitted by decay e+/e-

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



Due to synchrotron photons emitted by decay e+/e-

With 4 cm W shielding, **can stay below 20 MGy** in 10 yrs