Shielding requirements for the muon collider ring magnets

A. Lechner and D. Calzolari
With contributions from D. Amorim, L. Bottura, C. Carli, E. Metral, K. Skoufaris, D. Schulte, P. Tavares Coutinho Borges De Sousa, R. Van Weelderen, J. A. Ferreira Somoza and others

IMCC Collaboration Meeting
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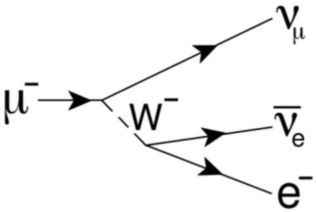
Introduction

- The superconducting magnets need to be shielded from muon decay products:
  - reduce the thermal load to the magnet cold mass
  - prevent magnet failures due to the cumulative radiation damage
- First **generic shielding studies** for the 3 TeV and 10 TeV collider arcs have been presented at the last IMCC annual meeting (Oct 2022), the Accelerator Design Meeting (Feb 2023) and in various informal meetings
- This presentation (main focus is on 10 TeV):
  - Update of generic shielding studies (new radial magnet build, updated operational scenario → important for scaling cumulative radiation effects)
  - First (preliminary) studies for a realistic arc lattice
  - Considerations about the absorber cross section

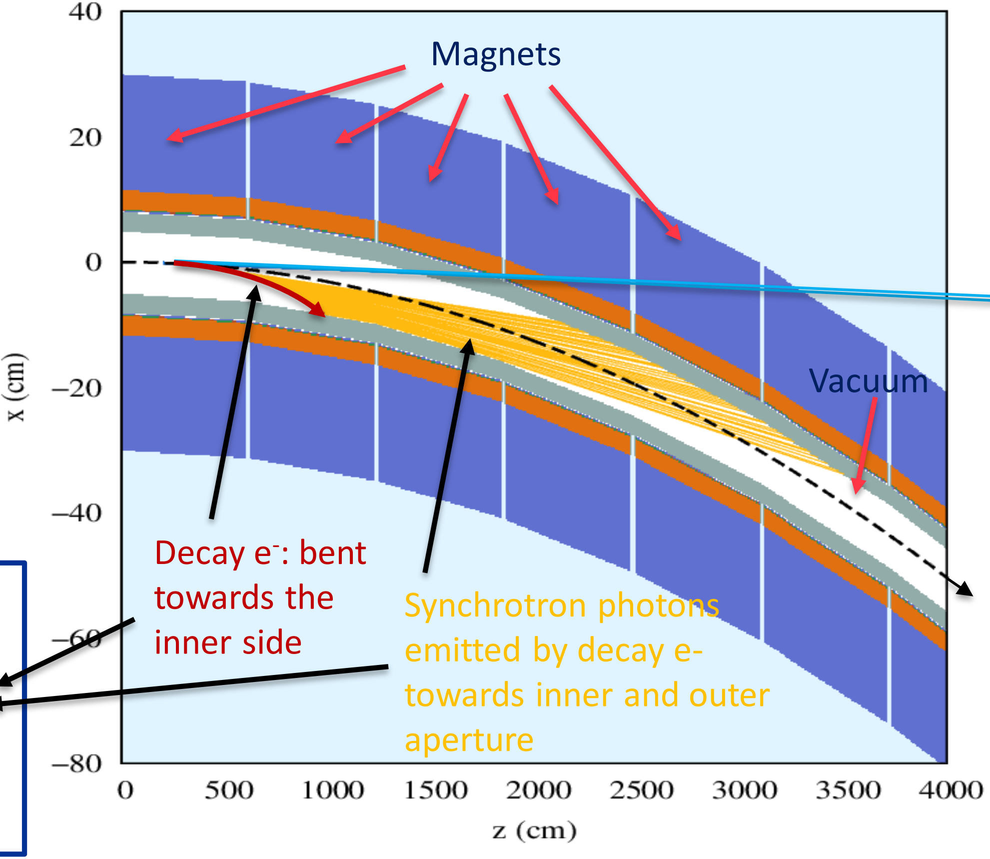
Open points (to be addressed soon):

- Shielding requirements for IR magnets in the collider
- Shielding studies for the accelerator

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

Decay e$^-$: bent towards the inner side

Synchrotron photons emitted by decay e- towards inner and outer aperture

Black dashed line: μ^- beam trajectory

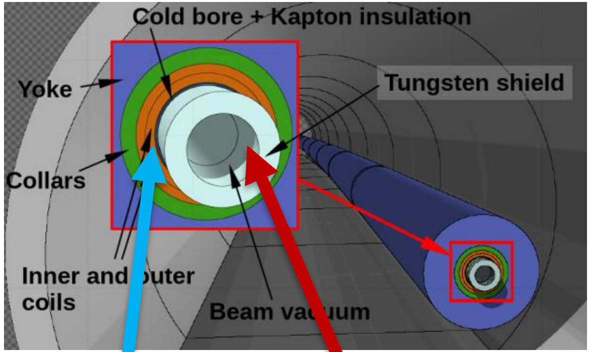
Inside magnets:

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

Similar picture applies to μ+

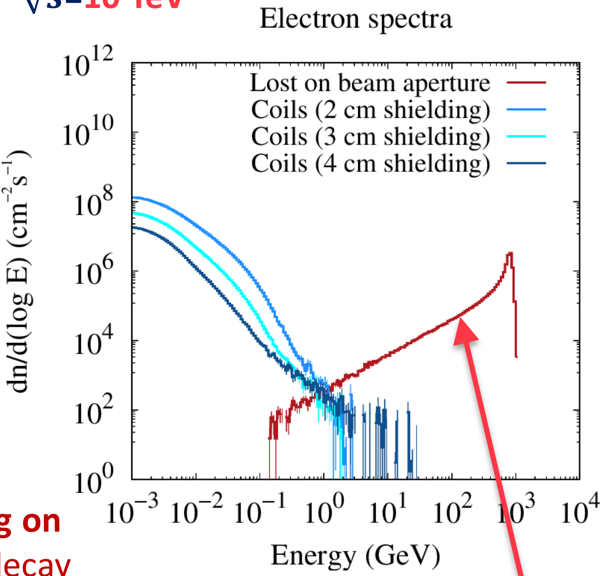
e-, e+, γ spectra in (generic) arc dipoles

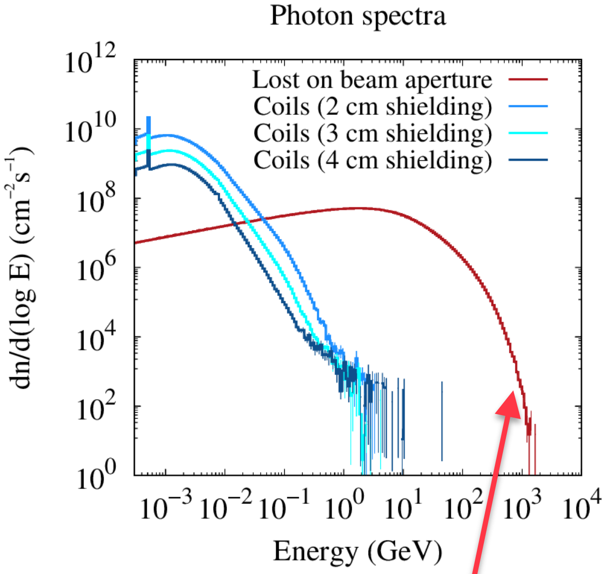
$\sqrt{s}$=10 TeV



Red curves: particles **impacting on the inner machine 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$^-$

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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 (mW/cm^3)*** → must remain safely below quench level of magnets
- **Total power deposition in cold mass (W/m)** → must be compatible with realistic cooling capacity (costs, electricity consumption!), (*most of the heat load must be extracted at higher T than the op. temp. of SC magnets*)

Long-term radiation damage

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

Parameters assumed for radiation studies

General assumption: All injected muons decay in the collider (luminosity burn-off is negligible, beams not extracted)

	Muon Collider ($\sqrt{s}$=3 TeV)	Muon Collider ($\sqrt{s}$=10 TeV)
Particle energy	1.5 TeV	5 TeV
Bunches/beam	1	1
Bunch intensity	2.2×10^{12}	1.8×10^{12}
Circumference	4.5 km	10 km
Normalization for instantaneous effects (heat load, power deposition density)		
Muon decay rate/meter*	4.9×10^{9} $m^{-1}s^{-1}$	1.8×10^{9} $m^{-1}s^{-1}$
Power (decay e-/e+)/meter*	**0.411 kW/m**	**0.505 kW/m**
Normalization for cumulative effects (ionizing dose, DPA)		
Operational years	5 years	5 years
Operational time/year (average)	1.2×10^{7} s (=139 days)	1.2×10^{7} s (=139 days)
Total decays/meter* (∑ all years)	2.93×10^{17} m^{-1}	1.08×10^{17} m^{-1}

*Includes contribution from both beams

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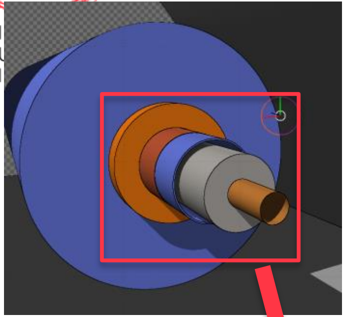
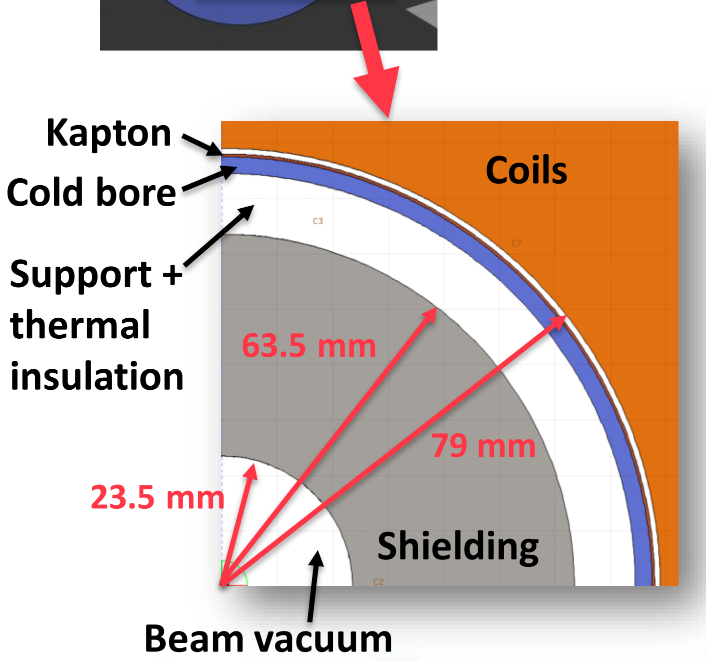
Circumference	4.5 km	10 km
Normalization for instantaneous effects (heat load, power deposition density)		
Mu	9×10^{9} m^{-1}s^{-1}	1.8×10^{9} m^{-1}s^{-1}
Po	**411 kW/m**	**0.505 kW/m**
No	DPA)	
Op	5 years	5 years
Op	0^{7} s (=139 days)	1.2×10^{7} s (=139 days)
Total	$.93\times10^{17}$ m^{-1}	1.08×10^{17} m^{-1}

<u>IMCC annual meeting Oct 2022:</u>
We assumed 10 years of operation with 200 days/year (i.e. 2.88 x more decays in the collider than in the new parameter table)
→ our previous dose and DPA estimates were more conservative

*Includes contribution from both beams

Considered radial build (1D) of collider arc magnets

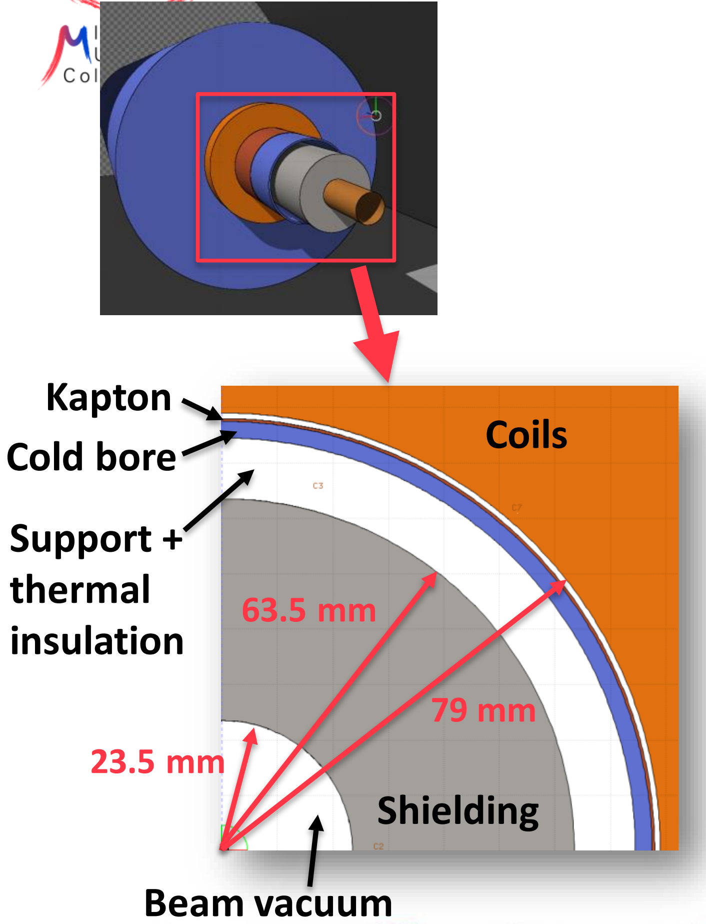




	Thickness	Outer radius	Comment
Beam aperture	23.5 mm	23.5 mm	Mainly governed by beam optics (see talk by K. Skoufaris)
Copper coating	0.01 mm	23.5 mm	Thin layer sufficient for impedance (see talk by D. Amorim)
W (alloy) shielding	40 mm	63.5 mm	Shielding thickness for keeping the decay-induced power leakage <1%
Shielding support + thermal insulation	11 mm	74.5 mm	See talk by P. Tavares Coutinho Borges De Sousa
Cold bore	3 mm	77.5 mm	Thicker than in LHC, considering the weight of the shielding
Kapton insulation	0.5 mm	78 mm	
Clearance to coils	1 mm	79 mm	

→ Coil aperture (radius) (**79 mm**)

Considered radial build (1D) of collider arc magnets



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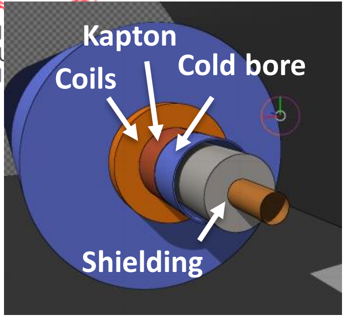
In the following slides, I will once more recall the results for different shielding thicknesses

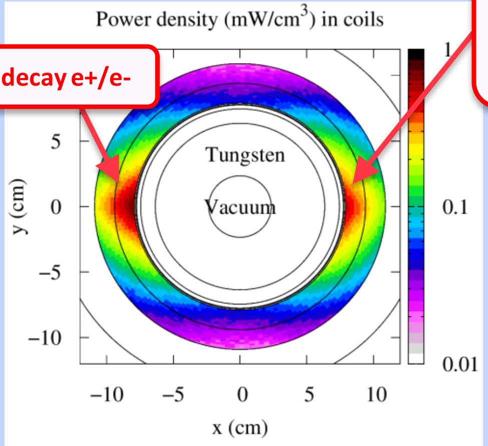
→ Coil aperture (radius) (**79 mm**)

Power deposition density in the coils of (generic) arc dipoles



Assumption:
Generic string of 16 T dipoles ($\sqrt{s}$=10 TeV)

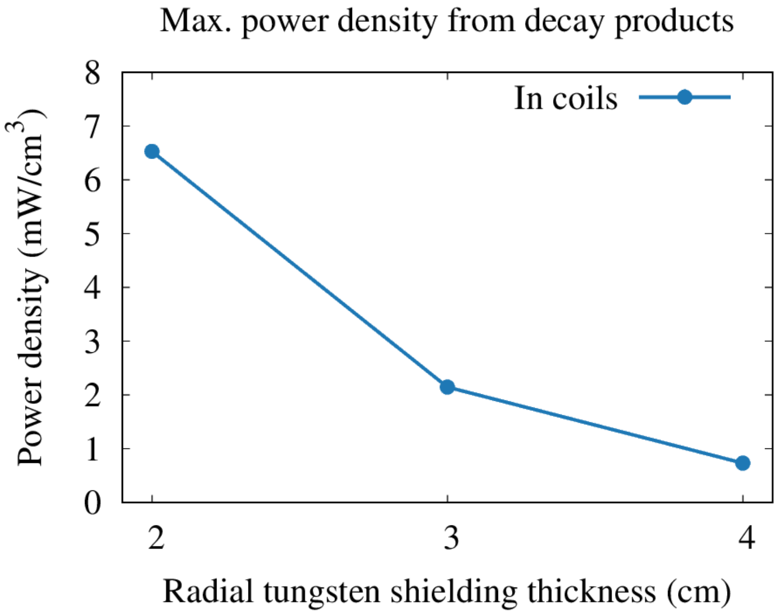
Power density map in coils:



Due to decay e+/e-

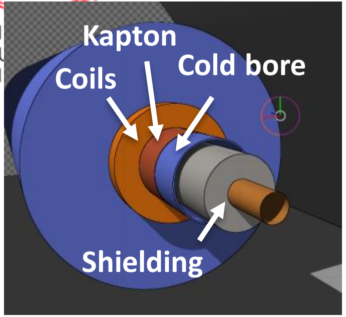
Due to synchrotron photons emitted by decay e+/e-

Center of collider ring



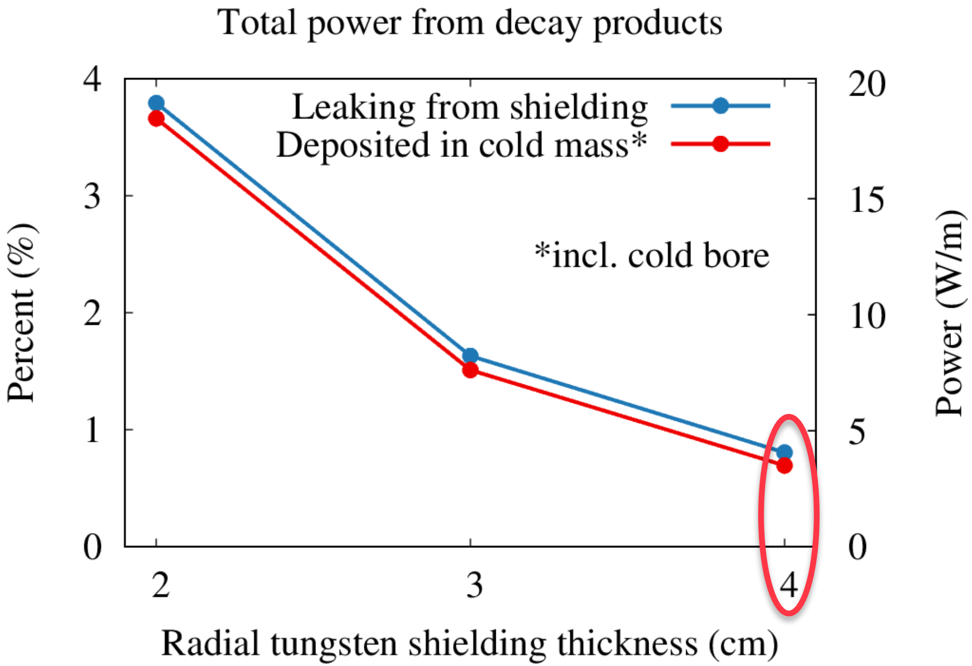
Quench level expected to be higher than 10 mW/cm^3 (achieved even with a 2 cm shielding)
The power density in the coils is not a driving factor for the shielding thickness

Total power deposition in the cold mass of (generic) arc dipoles

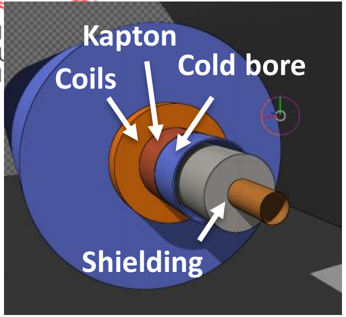


Assumption:
Generic string of 16 T dipoles ($\sqrt{s}$=10 TeV)

- Most of the power leaking from the shielding is deposited in the cold mass (rest: tunnel walls, molasse)
- Total power deposition in cold mass shall remain < 5W/m (see next talk by Patricia Tavares Coutinho Borges De Sousa)
  → **4 cm W shielding** needed

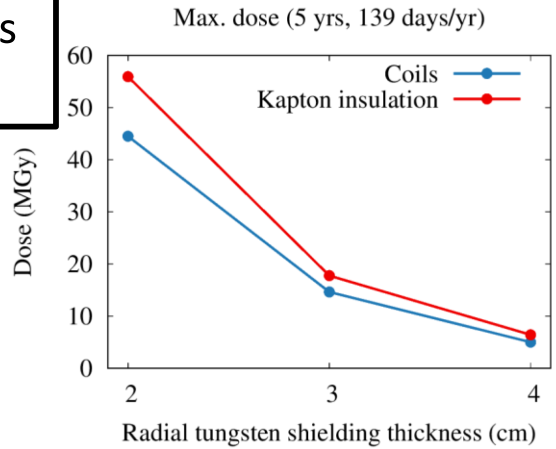


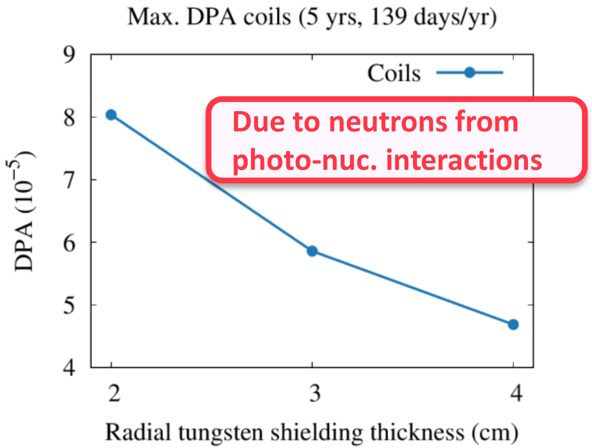
Cumulative dose and DPA in coils of (generic) arc dipoles



Assumption:
Generic string of 16 T dipoles
($\sqrt{s}$=10 TeV)

Scenario:
- **139 days operation/year**
- **5 years** of operation





Due to neutrons from photo-nuc. interactions

- With **4 cm W shielding**, the ionizing dose is **<10 MGy** in coils and insulation after 5 years → acceptable for commonly used materials (even a 3 cm W shielding would be fine)
- Neutron fluence/DPA shows (as expected) smaller dependence on shielding thickness: **<2x10^{17}n/cm^2** / **<1x10^{-4} DPA** (5 years) → values should be acceptable for superconductors

Summary of required shielding thickness

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 (mW/cm^3)***

Likely 2 cm W would be enough for power density in coils

- **Total power deposition in cold mass (W/m)** → must be … ling … *heat load must … than the o*

4 cm W needed to stay below 5 W/m in cold mass (incl cold bore)

The total power in the cold mass is the driving factor for the shielding thickness

Long-term radiation damage

- **Ionizing dose (MGy)*** (organic … *, coil* … must remain … full collider lifetime

With 3 cm, stay below 20 MGy in Kapton insulation after 5 yrs

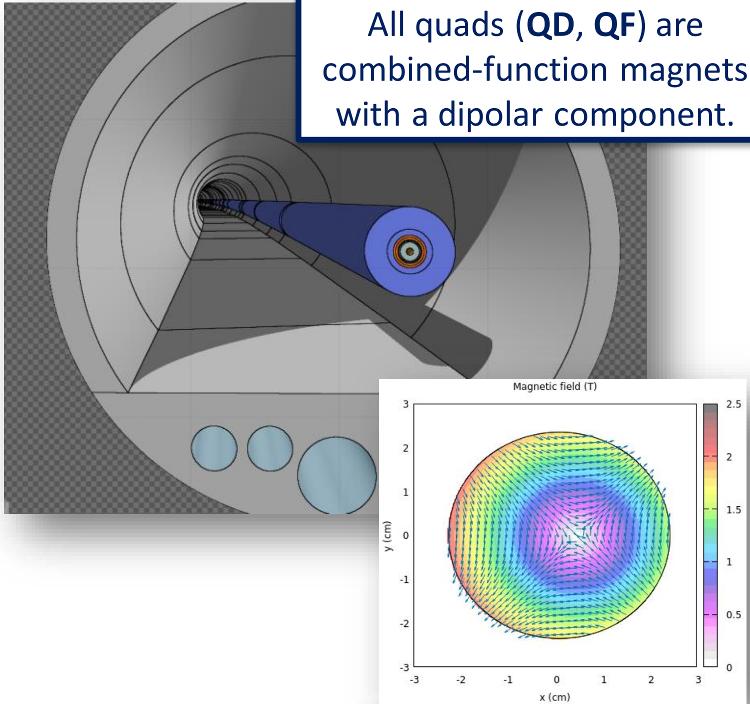
- **Atomic displacements (DPA)*** (*superconductor, stabilizer*) → must

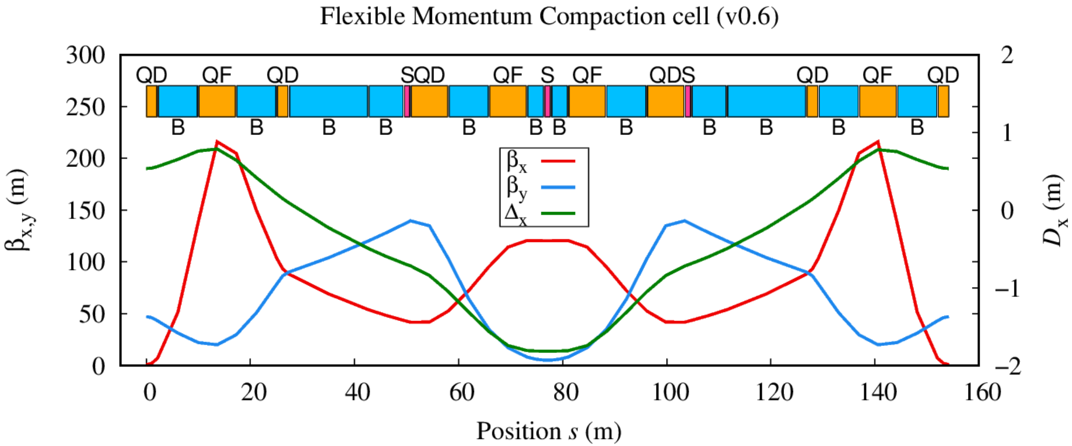
Less dependent on shielding thickness, 2 cm acceptable for DPA in coils (<10^{-4} DPA after 5 yrs)

Shielding studies: from a generic string of magnets to a realistic arc cell (10 TeV)

Pure dipoles (**B**) have a field strength of about 16 T.

All quads (**QD**, **QF**) are combined-function magnets with a dipolar component.

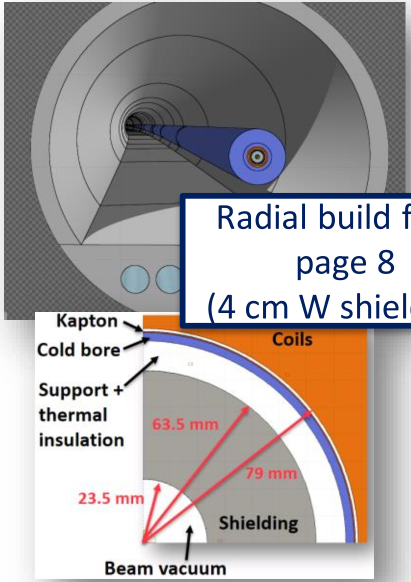




- The previous shielding studies did not consider a real lattice, but just a generic string of dipoles
- Performed a first FLUKA study for a realistic arc cell (lattice from *K. Skoufaris*), still with some simplifications*

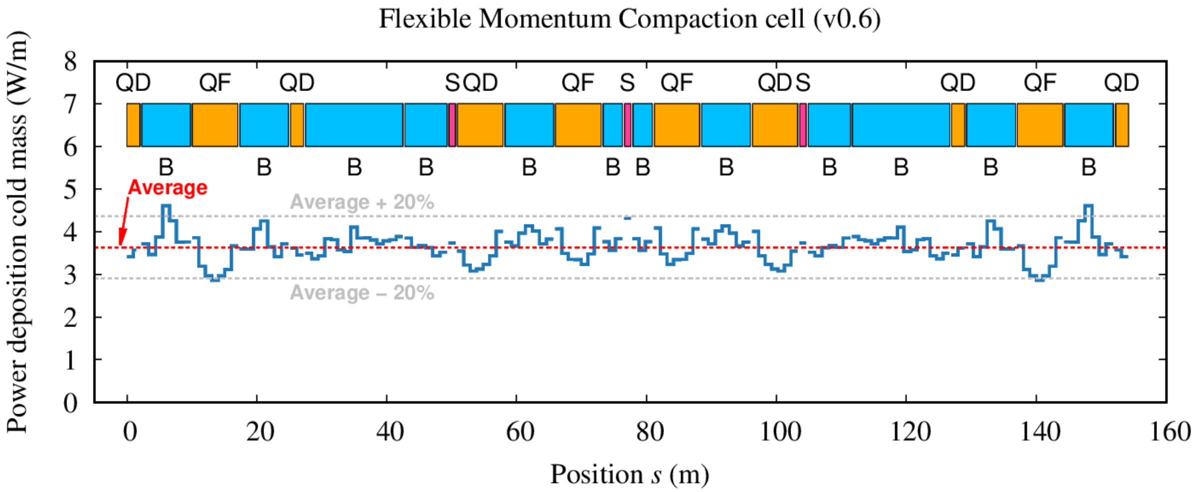
*Assumed constant beam size along cell, magnet aperture was modelled to be straight (i.e. no SBENDS, except for the two 15 m long dipoles)

Shielding studies: from a generic string of magnets to a realistic arc cell (10 TeV)



Radial build from page 8
(4 cm W shielding)

Power deposition/meter in the cold mass of magnets (incl. cold bore) along the arc cell (blue curve):

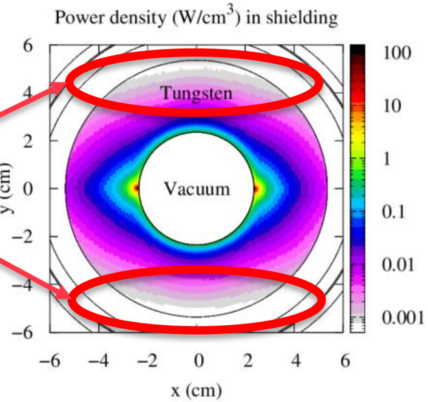


- The average power deposition/meter for the realistic cell is very similar to the generic studies
- The profile varies within 20% around the average

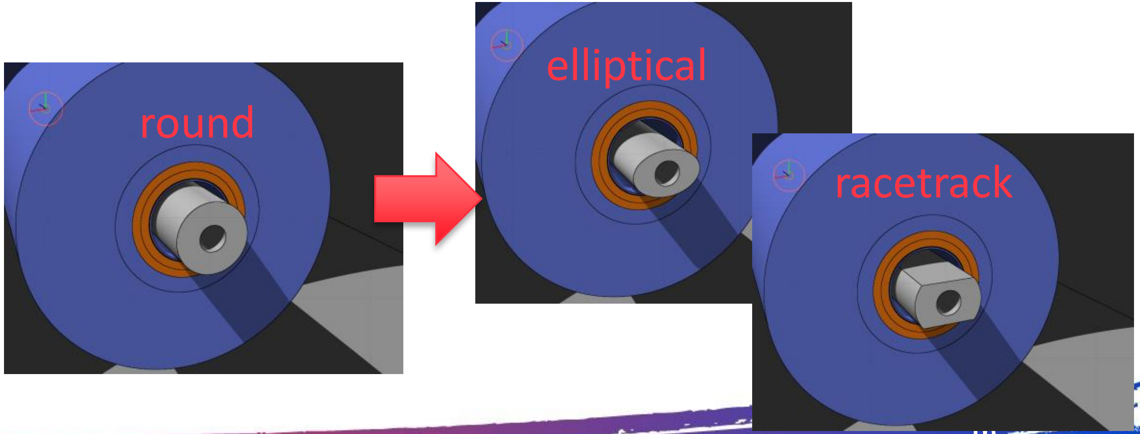
Can still rely on generic model for optimization studies (faster simulation)

Mask design studies – from 1D to 2D

- So far, we only performed generic studies with a **round mask cross section** (one free parameter → radial thickness)
- The required material budget can still be optimized without compromising significantly the shielding efficiency
- In order to explore the **potential for optimization** (material reduction), we considered different outer shapes (**elliptical**, **racetrack**) while keeping a round beam aperture

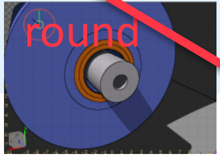


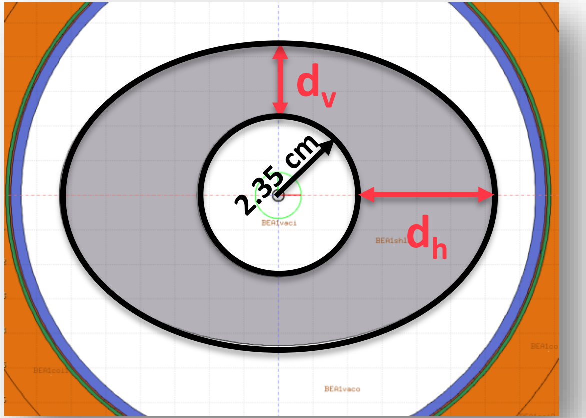
Less material needed for shielding



Round vs elliptical shape: power penetrating shielding (muon decay)

Power penetrating shielding (10 TeV collider)		Horizontal shielding thickness d_h 2 cm	3 cm	4 cm
Vertical shielding thickness d_v	2 cm	3.8% (19.1 W/m)		1.4% (6.9 W/m)
	3 cm		1.6% (8.2 W/m)	1.0% (4.9 W/m)
	4 cm			0.8% (4.1 W/m)



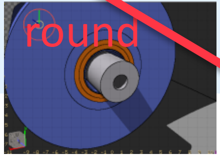


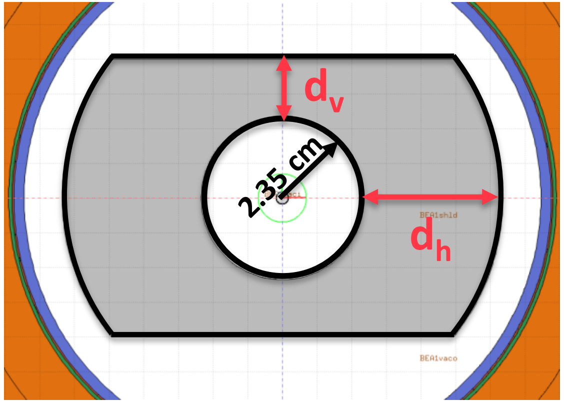
Tungsten weight		Horizontal shielding thickness d_h 2 cm	3 cm	4 cm
Vertical shielding thickness d_v	2 cm	81 kg/m		134 kg/m
	3 cm		140 kg/m	173 kg/m
	4 cm			211 kg/m

Remember: power deposition in cold mass is slightly lower than the power penetrating shielding (since some power escapes from magnets)

Round vs racetrack shape: power penetrating shielding (muon decay)

Power penetrating shielding (10 TeV collider)		Horizontal shielding thickness d_h 2 cm	3 cm	4 cm
Vertical shielding thickness d_v	2 cm	3.8% (19.1 W/m)		1.1% (5.4 W/m)
	3 cm		1.6% (8.2 W/m)	0.8% (4.2 W/m)
	4 cm			0.8% (4.1 W/m)





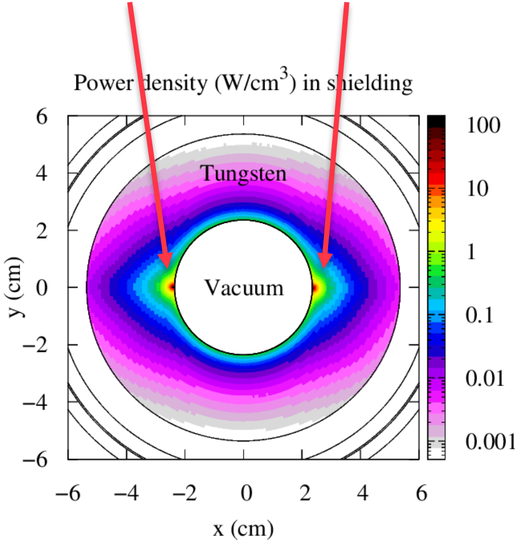
Tungsten weight		Horizontal shielding thickness d_h 2 cm	3 cm	4 cm
Vertical shielding thickness d_v	2 cm	81 kg/m		162 kg/m
	3 cm		140 kg/m	193 kg/m
	4 cm			211 kg/m

Remember: power deposition in cold mass is slightly lower than the power penetrating shielding (since some power escapes from magnets)

Next steps for magnet shielding design

- **More realistic shielding design to be developed (requires input from different experts):**
  - Iteration on the **transverse cross section** (2D shape)
  - Integration of **cooling channels**, choice of cooling fluid/gas
  - Shielding material: choice of **tungsten heavy alloy** (e.g. W with Ni and Cu (or Fe)), which grants better machining and ductility than pure tungsten ⟶ small caveat: W-alloys have a slightly small density than pure W (i.e. slightly reduced shielding efficiency)
  - Design of **shielding supports**
- **Other important points:**
  - Likely need a curved magnet aperture (sagitta of beam trajectory →beam clearance), which means a curved shielding
  - Magnet interconnects (in particular magnet front face) needs to be shielded as well

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



Summary and conclusions

Shielding for collider arc magnet:

- A continuous shielding is needed inside magnets (and interconnects) to cope with the decay-induced radiation load
- The shielding requirements are mainly driven by the **total power leaking through the shielding**, while the power density, cumulative dose in insulation and DPA in coils appear to be somewhat less limiting
- The studies showed that we need **4 cm** of **tungsten (alloy)** in the arcs is needed to remain <5W/m of decay-induced power in the cold mass

Next steps:

- Together with the other experts, progress on a more realistic shielding design (shape, material, cooling channels, support, …)
- Extend the studies to the IR magnets and the accelerator

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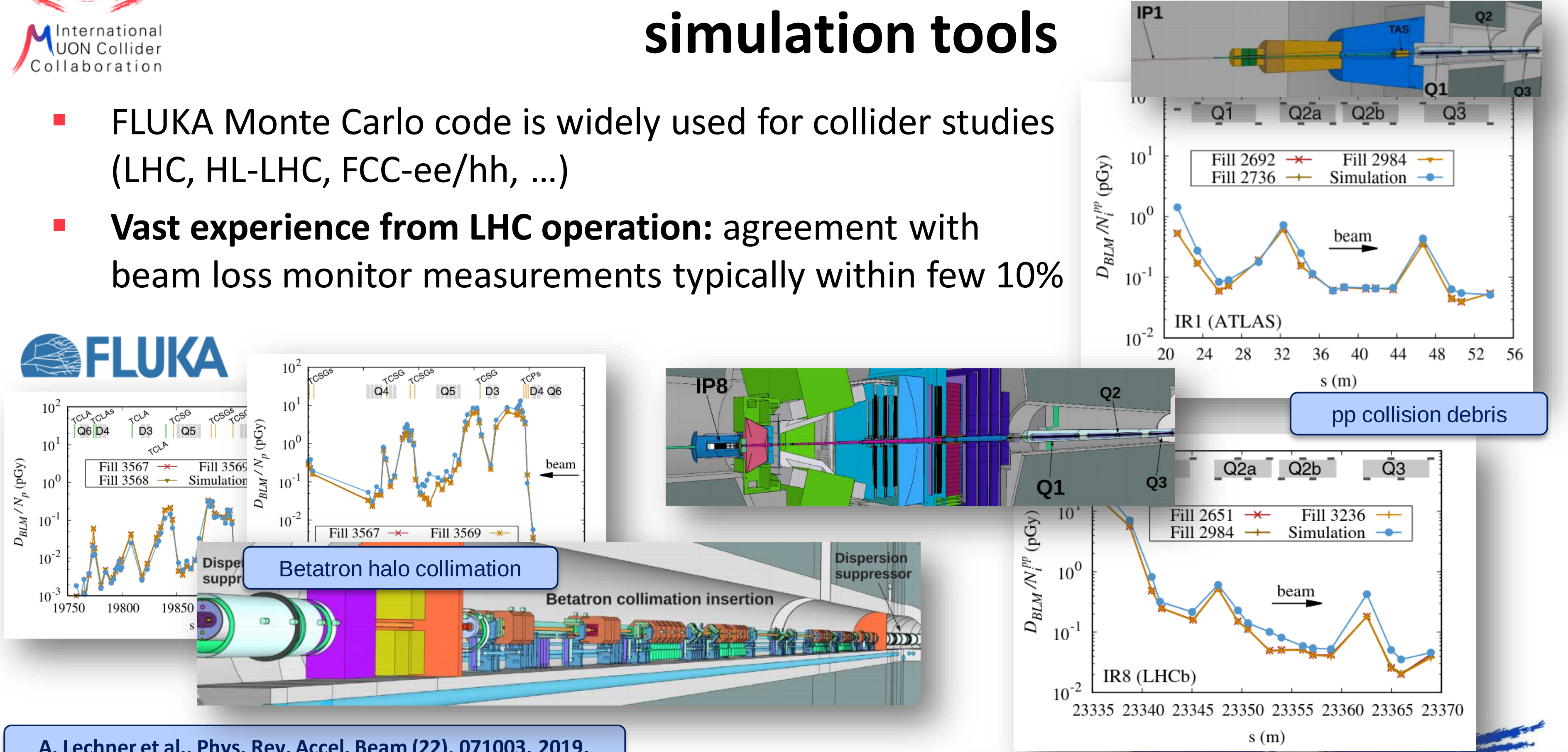
***Thank you
for your attention!***

Studying beam losses in high-energy colliders – simulation tools

- FLUKA Monte Carlo code is widely used for collider studies (LHC, HL-LHC, FCC-ee/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.