# Radiation challenges in the RCS accelerators

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# Introduction

- Different radiation aspects have to be considered in the RCS design (muon decay):
  - **Radiation load to magnets:**
    - Thermal load to SC magnets
    - Cumulative radiation damage in SC and NC magnets
  - **Radiation protection aspects***
    - One important aspect is the possible Co content in the NC dipoles
    - Neutrino flux

First considerations about the shielding requirements in this presentation

First considerations in this presentation

Not covered here

For the cumulative radiation damage and residual dose rates, we assume 140 days of operation/year

* Radiation protection aspects are under the responsibility of the HSE/RP group (C. Ahdida)

# Radiation load on magnets – what to consider

***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

Concerns SC and NC magnets!

- **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

DPA is likely not an issue (like in the collider) – not studied here

# Background

A muon collider brings the advantages of a lepton collider, without being affected by the severe synchrotron energy losses that an electron would experience in a similar machine.

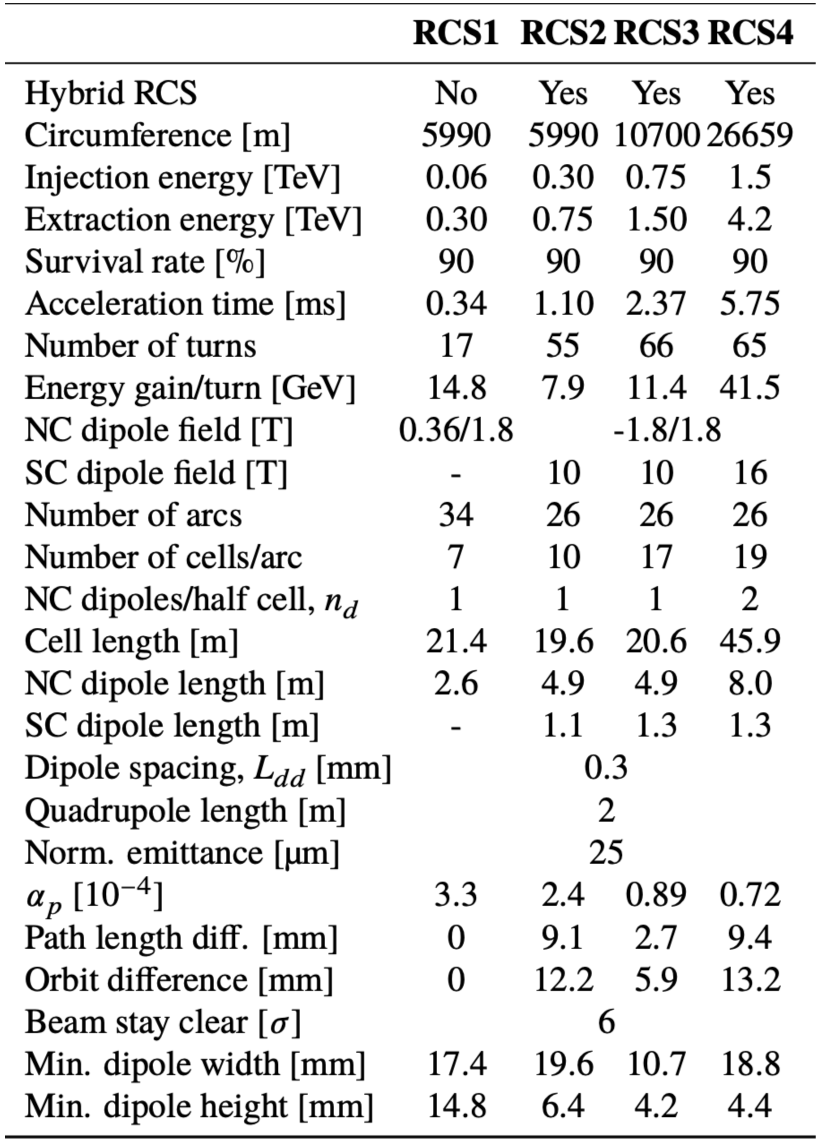
Muons accelerated from 60 GeV to 5000 GeV using recirculating synchrotrons

**However**, the decay of the muon

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_e + \nu_\mu$$

poses significant technological challenges.

- Electrons carry a fraction of the muon’s momentum and veer off the trajectory, colliding with the machine
- The interaction of high-energy electrons can cause radiations showers, which give rise to different issues summarized on the previous page



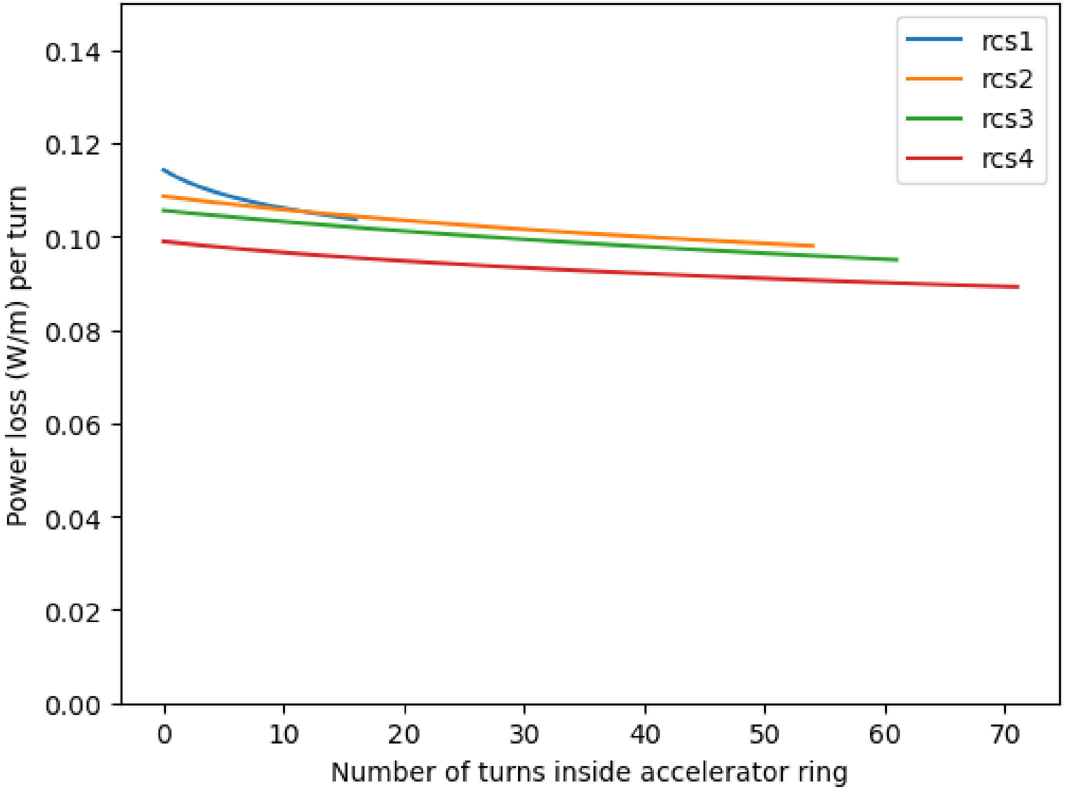
| | RCS1 | RCS2 | RCS3 | RCS4 |
|---|---|---|---|---|
| Hybrid RCS | No | Yes | Yes | Yes |
| Circumference [m] | 5990 | 5990 | 10700 | 26659 |
| Injection energy [TeV] | 0.06 | 0.30 | 0.75 | 1.5 |
| Extraction energy [TeV] | 0.30 | 0.75 | 1.50 | 4.2 |
| Survival rate [%] | 90 | 90 | 90 | 90 |
| Acceleration time [ms] | 0.34 | 1.10 | 2.37 | 5.75 |
| Number of turns | 17 | 55 | 66 | 65 |
| Energy gain/turn [GeV] | 14.8 | 7.9 | 11.4 | 41.5 |
| NC dipole field [T] | 0.36/1.8 | -1.8/1.8 | | |
| SC dipole field [T] | - | 10 | 10 | 16 |
| Number of arcs | 34 | 26 | 26 | 26 |
| Number of cells/arc | 7 | 10 | 17 | 19 |
| NC dipoles/half cell, $n_d$ | 1 | 1 | 1 | 2 |
| Cell length [m] | 21.4 | 19.6 | 20.6 | 45.9 |
| NC dipole length [m] | 2.6 | 4.9 | 4.9 | 8.0 |
| SC dipole length [m] | - | 1.1 | 1.3 | 1.3 |
| Dipole spacing, $L_{dd}$ [mm] | 0.3 | | | |
| Quadrupole length [m] | 2 | | | |
| Norm. emittance [µm] | 25 | | | |
| $\alpha_p$ [$10^{-4}$] | 3.3 | 2.4 | 0.89 | 0.72 |
| Path length diff. [mm] | 0 | 9.1 | 2.7 | 9.4 |
| Orbit difference [mm] | 0 | 12.2 | 5.9 | 13.2 |
| Beam stay clear [$\sigma$] | 6 | | | |
| Min. dipole width [mm] | 17.4 | 19.6 | 10.7 | 18.8 |
| Min. dipole height [mm] | 14.8 | 6.4 | 4.2 | 4.4 |

# Motivation and Prospect

We perform a preliminary radiation damage study on the RCS accelerator. We pick **conservative** parameters:

- Characterize upper limits on the radiation received by the machine’s equipment
- Identify radiation hot spots and design suggestions
- Validate shielding design and placement

We simulate a full cell of RCS-3, which is significantly shorter than RCS-4 and with a similar power deposition profile.

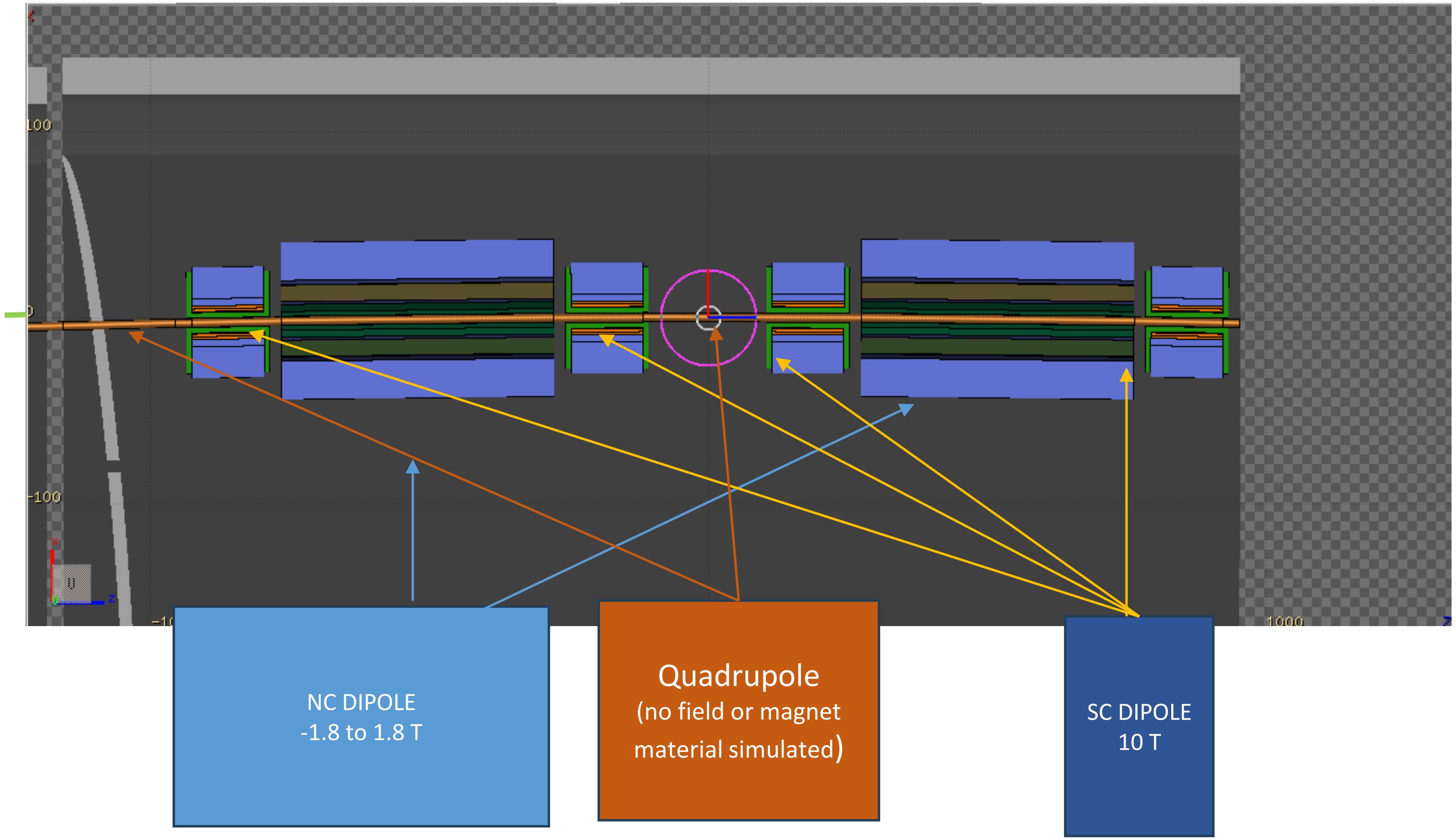


# Geometry

We simulate the full cell of a FODO geometry with hybrid SC and NC dipole magnets

To RF

150 m of straight section



NC DIPOLE
-1.8 to 1.8 T

Quadrupole
(no field or magnet material simulated)

SC DIPOLE
10 T

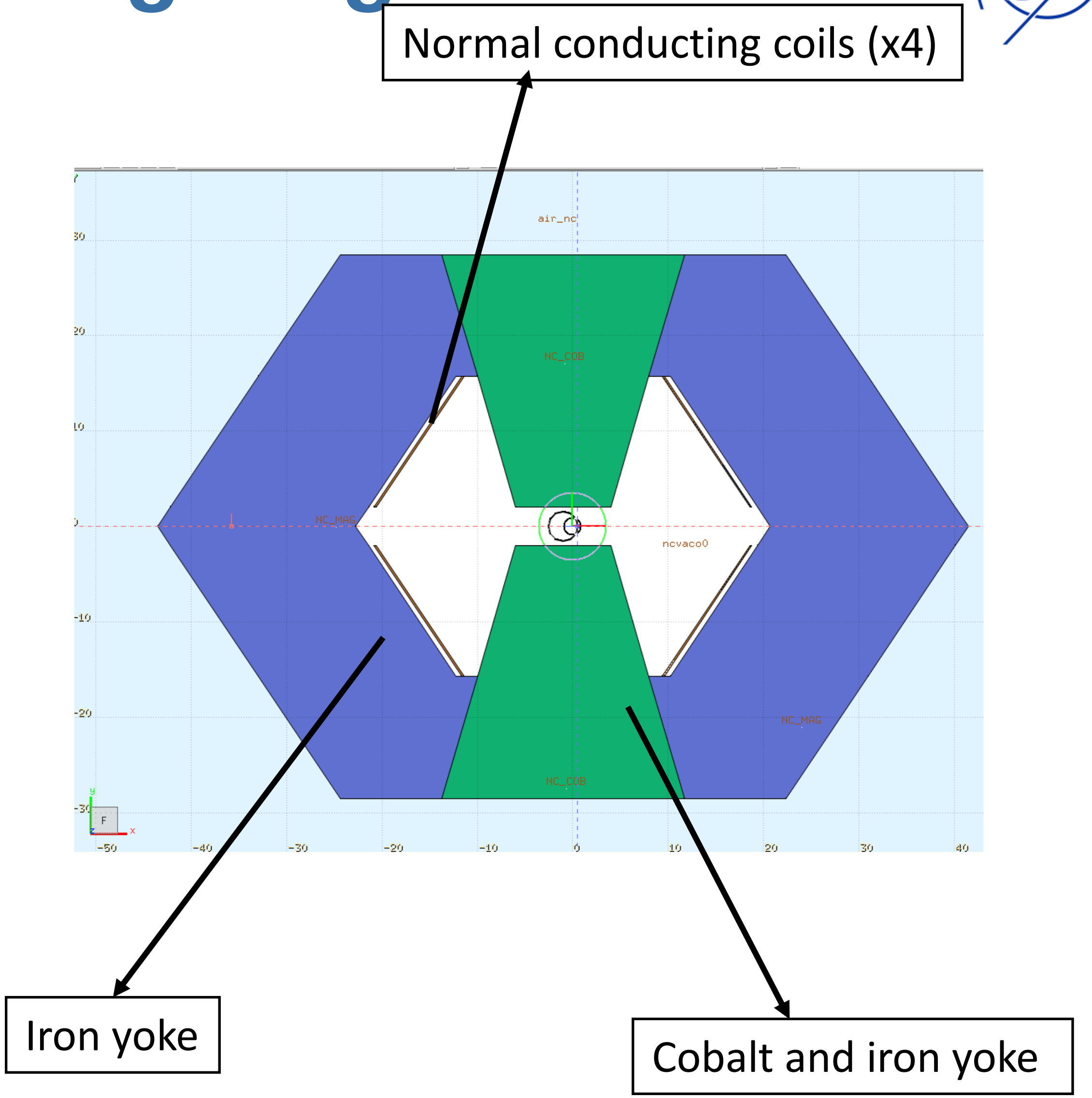
All simulation parameters from RCS-3 column from previous slide, and:

- Radius of beam pipe: 2.4 cm

# Normal conducting magnet

We obtained a preliminary NC magnet design from F. Boattini

- Coils on the side of the beam pipe generate the dipole magnetic field. Ionizing dose to coil insulation can cause mechanical failures.
- Due to the fast ramping of the magnetic field, eddy currents would generate too much power in shielding materials
- To increase the magnetic flux through the yoke, cobalt is mixed in the region closest to the beam pipe (assumed 50% ratio). However, neutron reactions on cobalt can generate long-lived $^{60}$Co



Normal conducting coils (x4)

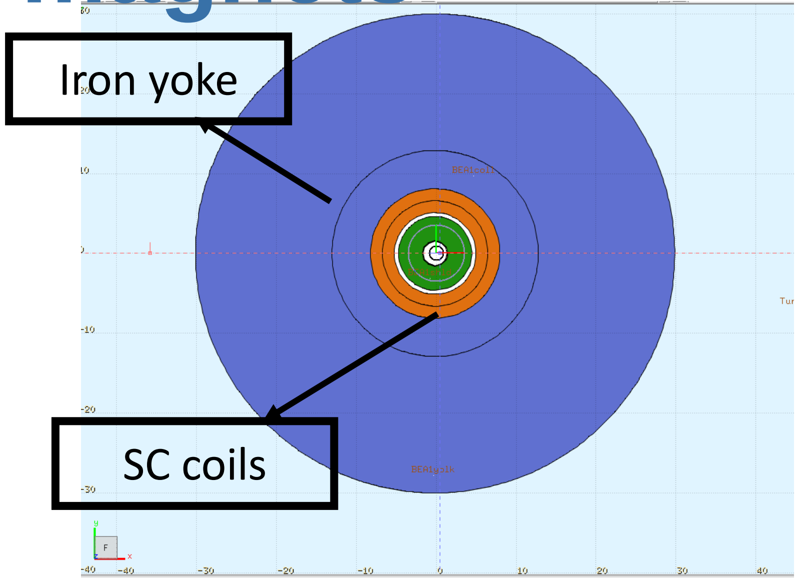
Iron yoke

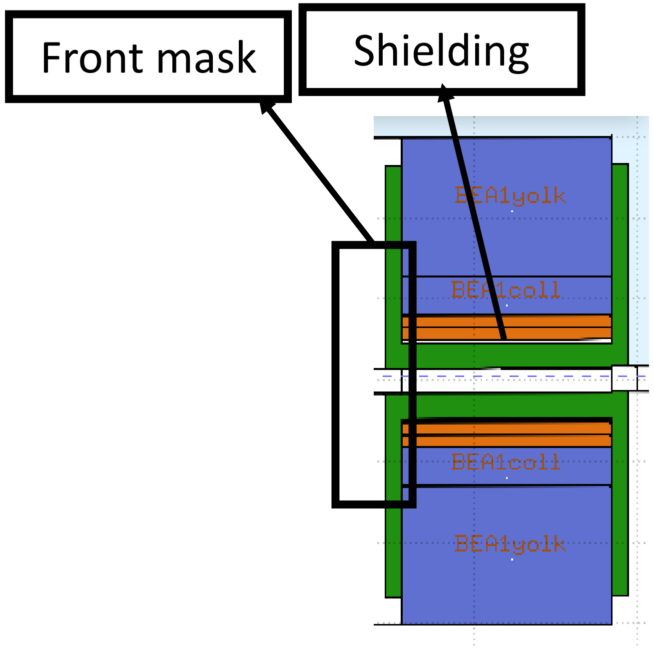
Cobalt and iron yoke

# Superconducting magnets

Superconducting magnets are used to exert a much stronger bending force on the muons.

- Radiation heating of superconducting coils can lead to quenching. Heavy shielding is needed to prevent this
- The aperture of the SC magnets is kept as tight as possible around the shielding





**Beam aperture: 2.4 cm radius**

Here we assume the following shielding parameters:

- 3 cm of internal shielding
- 10 cm of front mask shielding

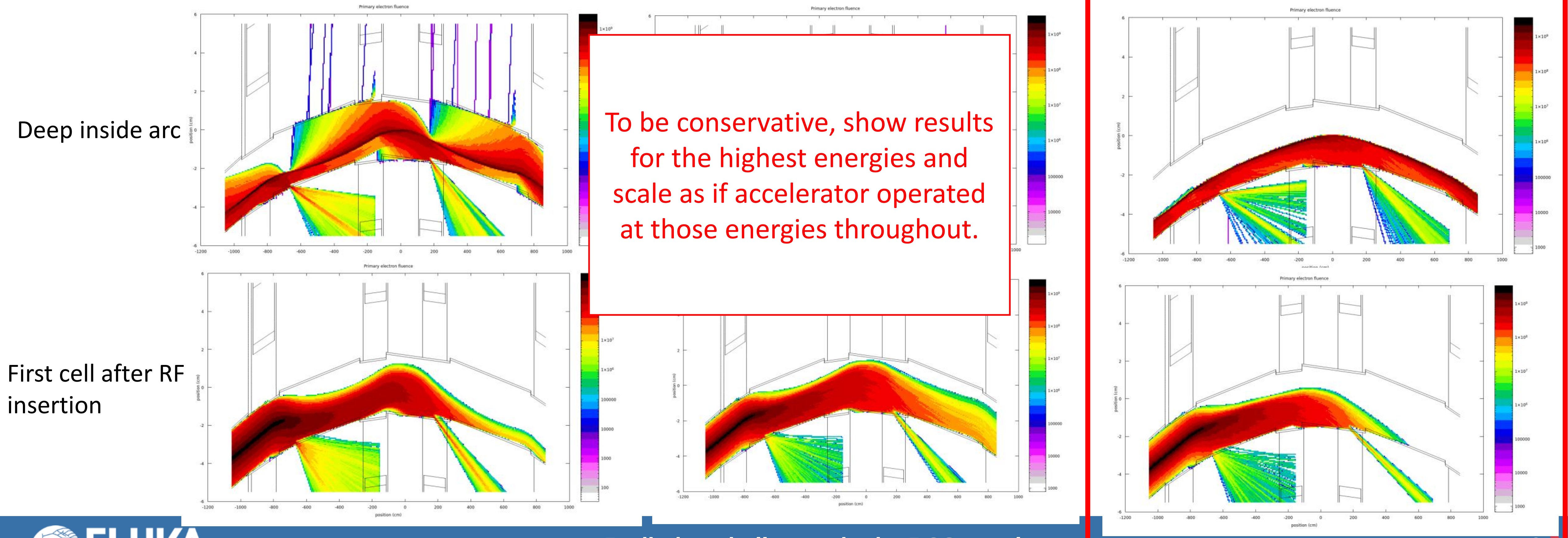
All shielding is made of tungsten (19.1 $\frac{g}{cm^3}$)

# Source

Two separate sets of simulations, for the **negative muon beam**

- Muon decaying inside the arc cell, simulated as a continuous lattice (steady state decay)
- Muon decaying inside RF insertion, large power delivered to the first few magnets after the acceleration stage

$E_\mu =$ 750 GeV 1150 GeV 1500 GeV

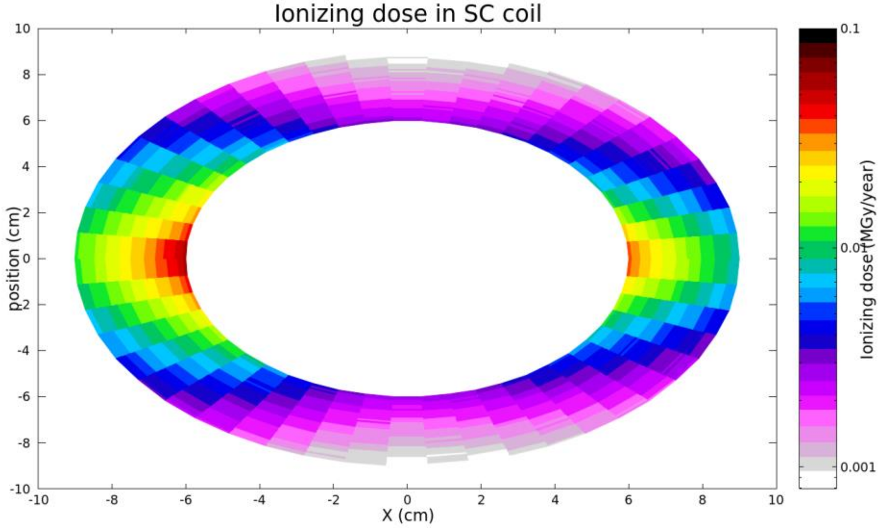


To be conservative, show results for the highest energies and scale as if accelerator operated at those energies throughout.

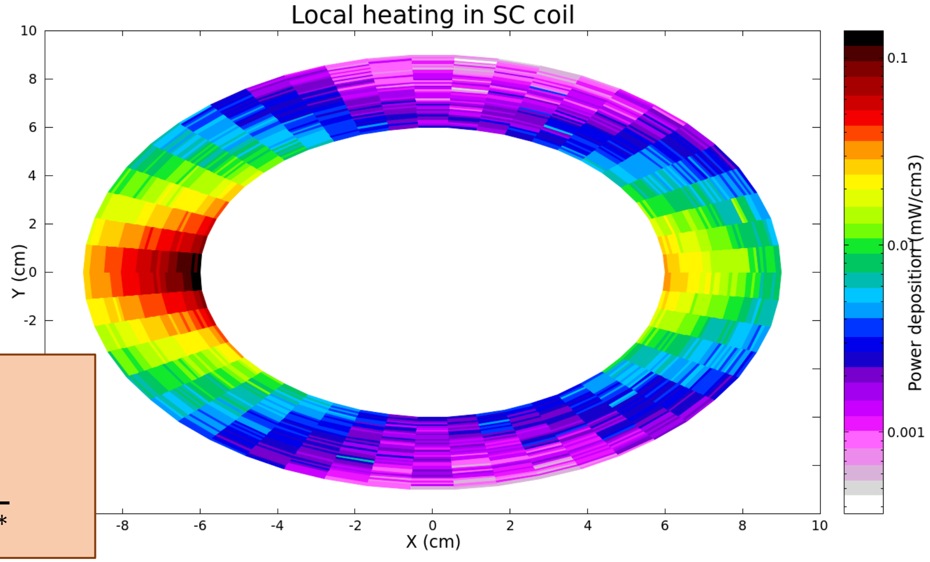
# Radiation to SC coils – deep inside arc

Only $\mu^-$ beam

- Heating due to radiation energy deposition can cause the SC coils to quench
- Ionizing dose can damage the coils and the surrounding materials



In either case, deep within the arcs, the radiation damage is well below the limits of few $10s\frac{mW}{cm^3}$ and 5 $\frac{MGy}{year}$, by several orders of magnitude.



*For these conditions/materials:*

$$1\frac{kW}{cm^3} \approx 1.4\frac{\mathrm{MGy}}{year^*}$$

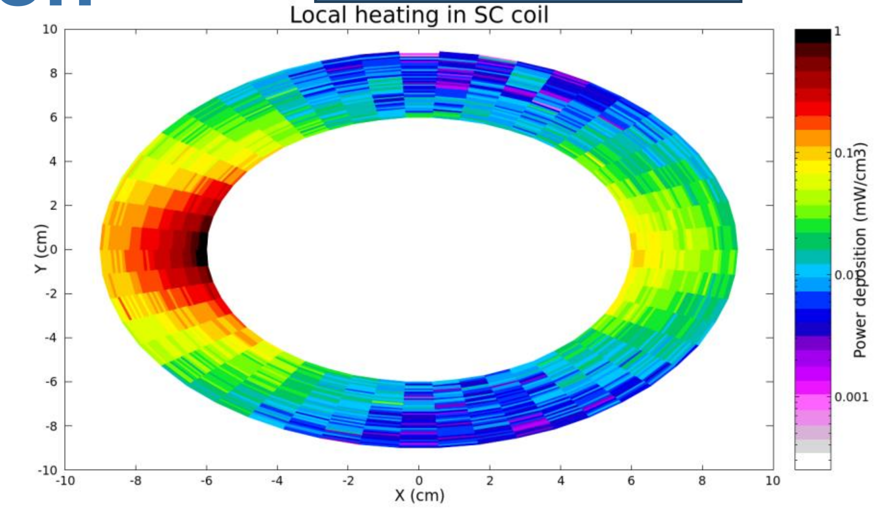
# Radiation to SC coils – first cell after RF insertion

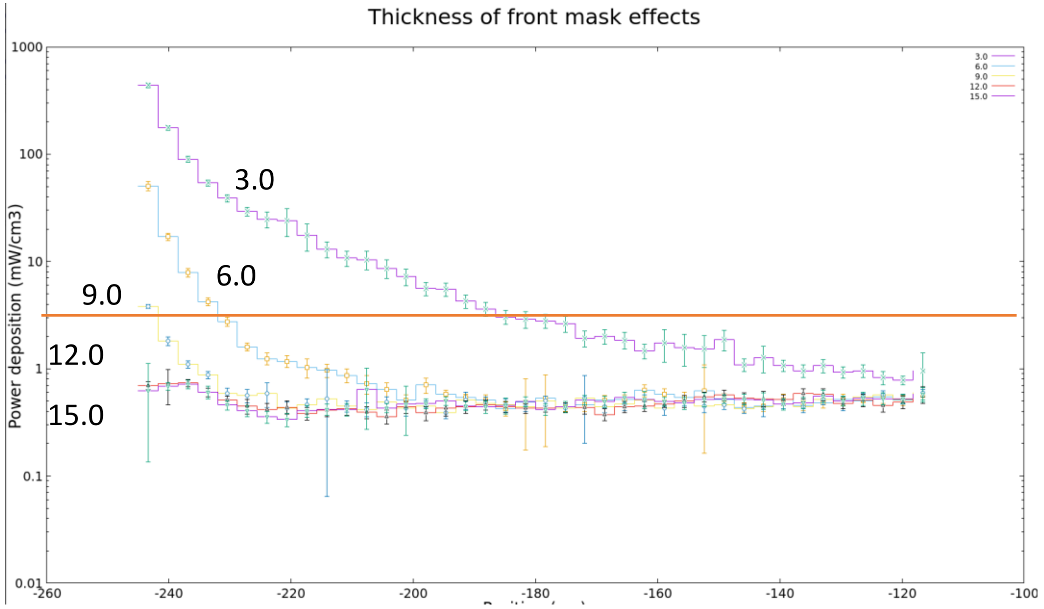
Only $\mu^{-}$ beam

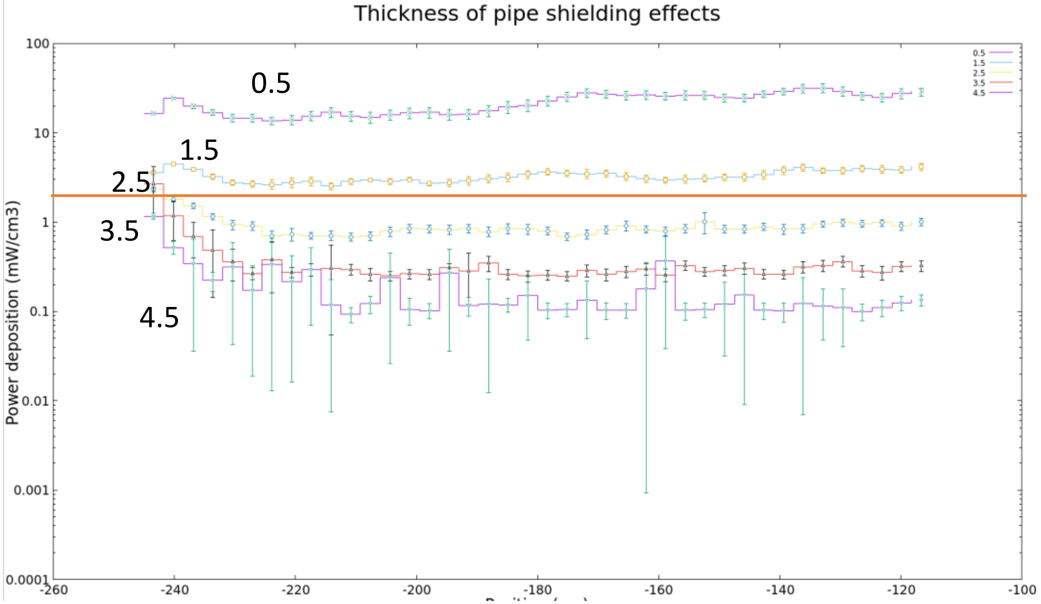
For the first magnet after the RF insertion, the radiation field is significantly more intense, but still within the limits.

Limited by yearly dose limits, but safe within the prescribed shielding.

Should be feasible as long as the front mask shield is kept deep (~7-10 cm) and the shielding around the beam pipe is at least 2-3 cm.



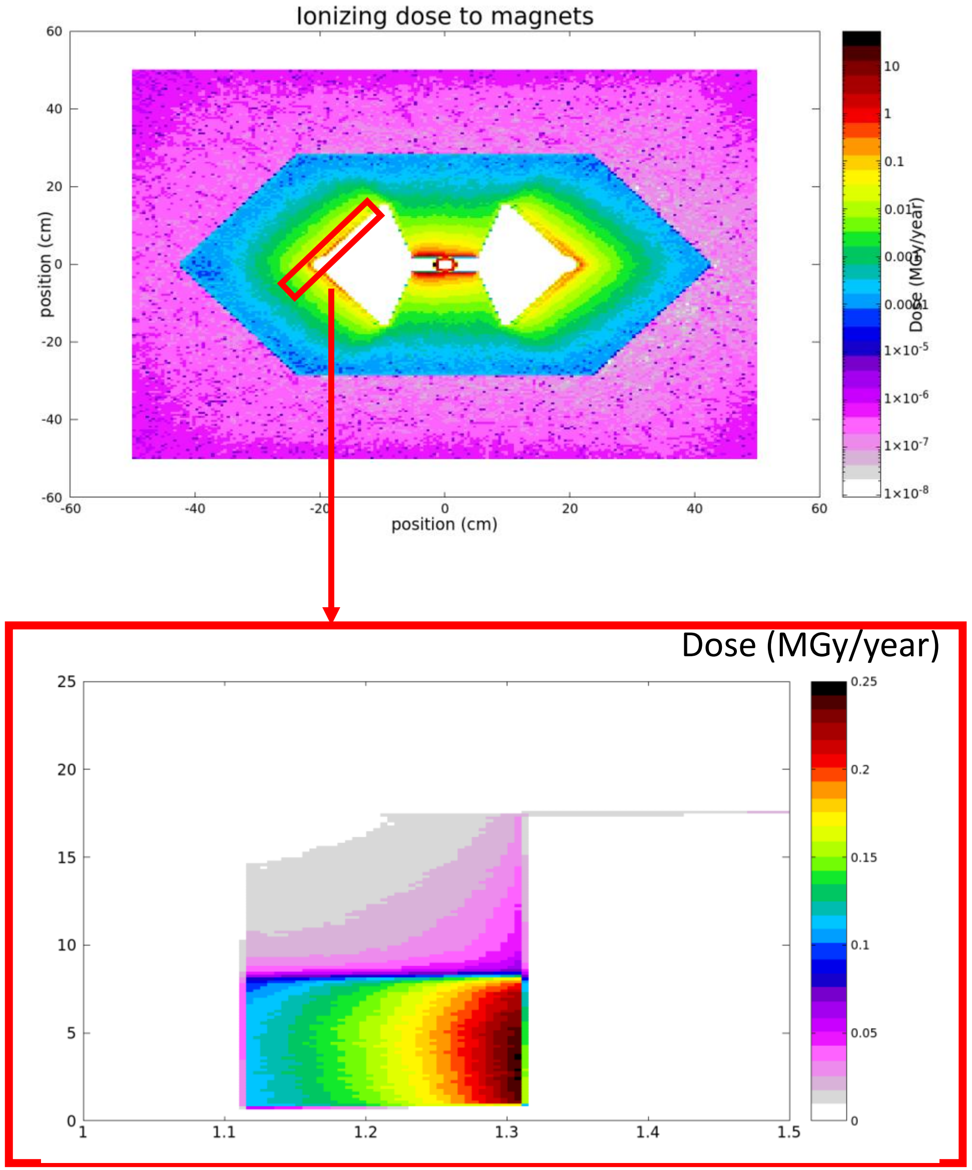




# Radiation to NC coils - deep inside arc

NC magnets do not suffer from quenching, but high doses of radiation to the coils can degrade their operation.

Even without any shielding, the ionizing dose to the coils remains small (due to the larger distance from coil to beam).



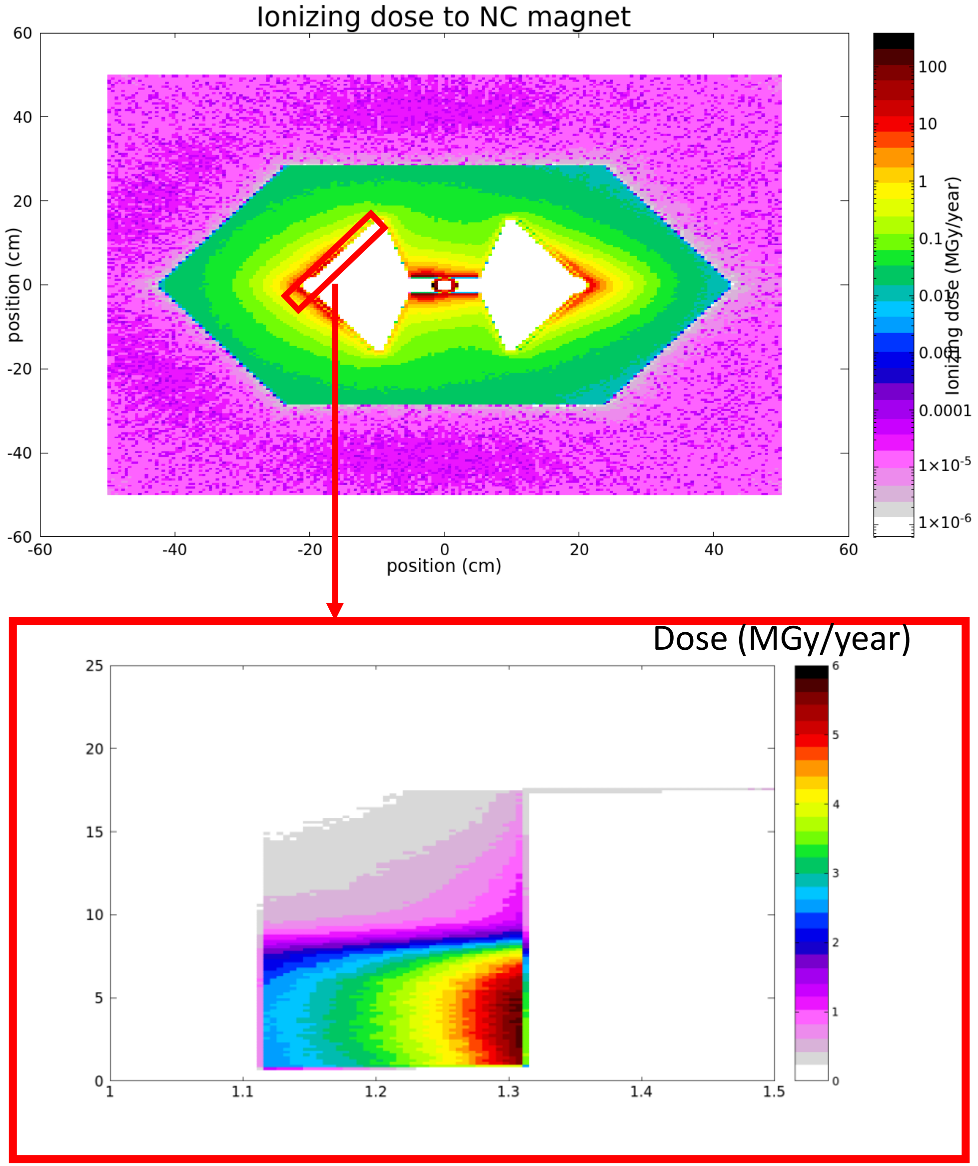
Only $\mu^-$ beam

# Radiation to NC coils - first cell after RF insertion

Only $\mu^-$ beam

For the NC magnets after an RF insertion, the ionizing dose is higher, close to the limit of 5 $\frac{MGy}{year}$.

Either shielding or a repositioning of the coils may be needed to reduce dose.



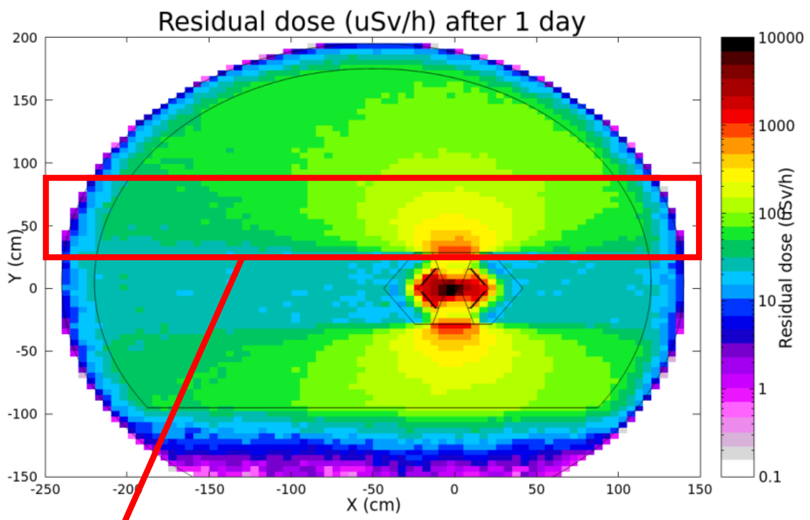
# Co60 production

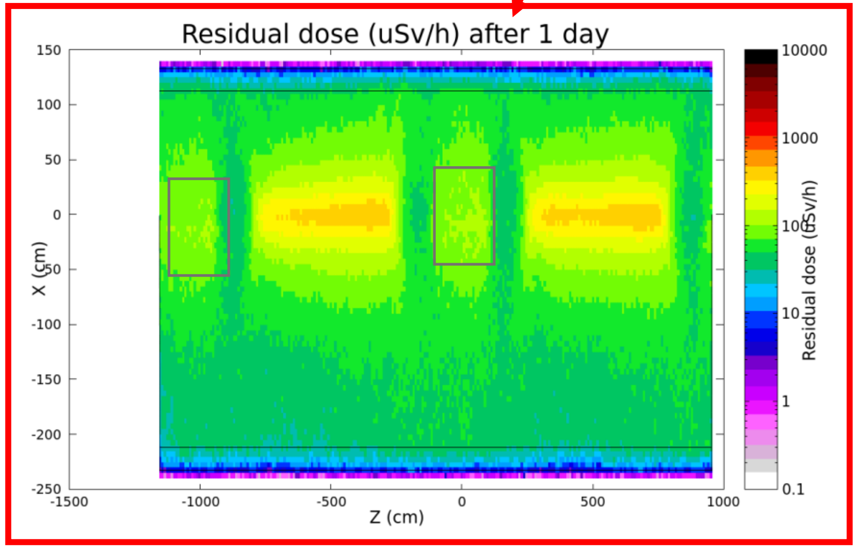
Photonuclear effects can generate an intense neutron radiation field in the cells. These neutrons can interact with the NC magnet yoke, which is composed of up to 50% of cobalt, and produce $^{60}$Co.

We study an irradiation of **5 years of operations** (140 days + 225 days shutdown), with cooldown times of 1 day, 1 month, 6 months, and 1 year

We consider **two beams.**

The yoke provides considerable self shielding, so the highest dose is received just above the cobalt yoke.



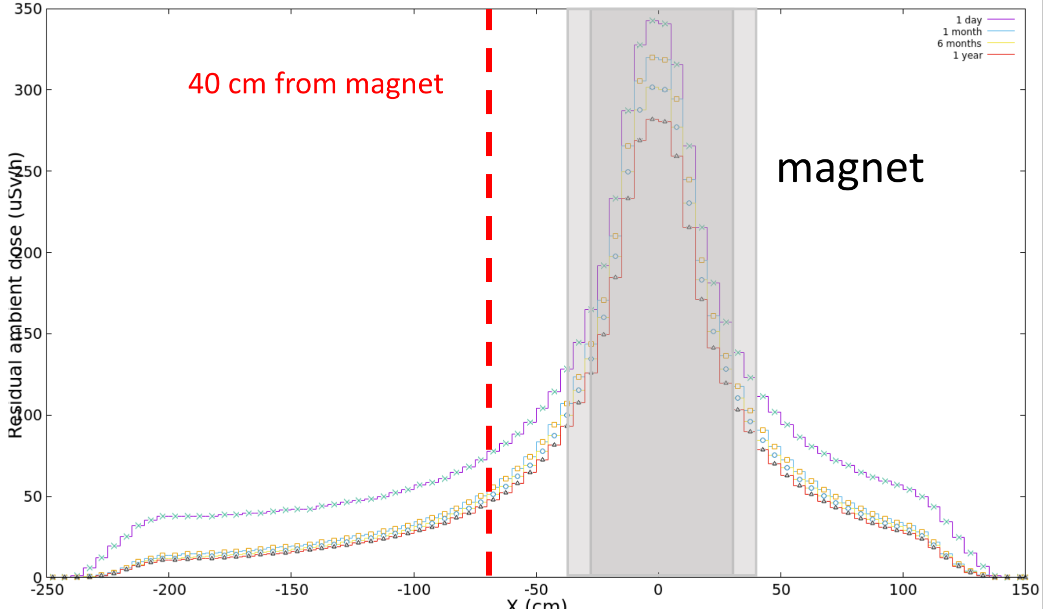


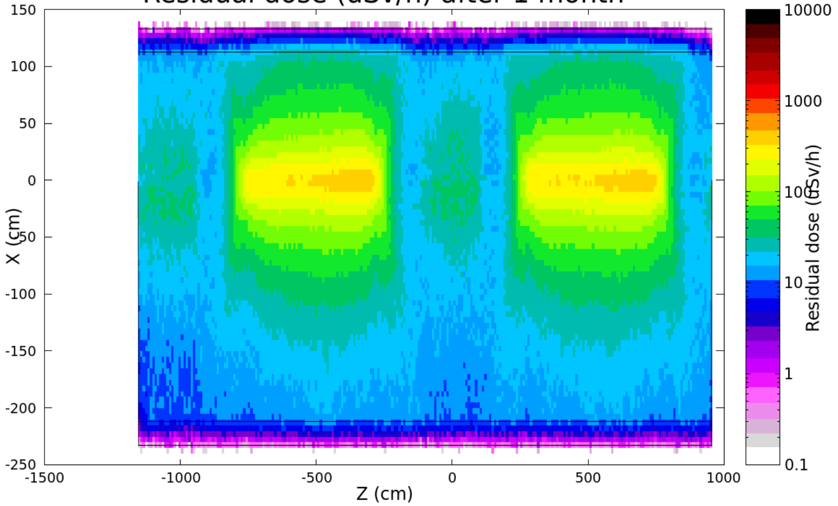
Quadrupole magnet is simulated as vacuum, in reality some shielding would be provided.

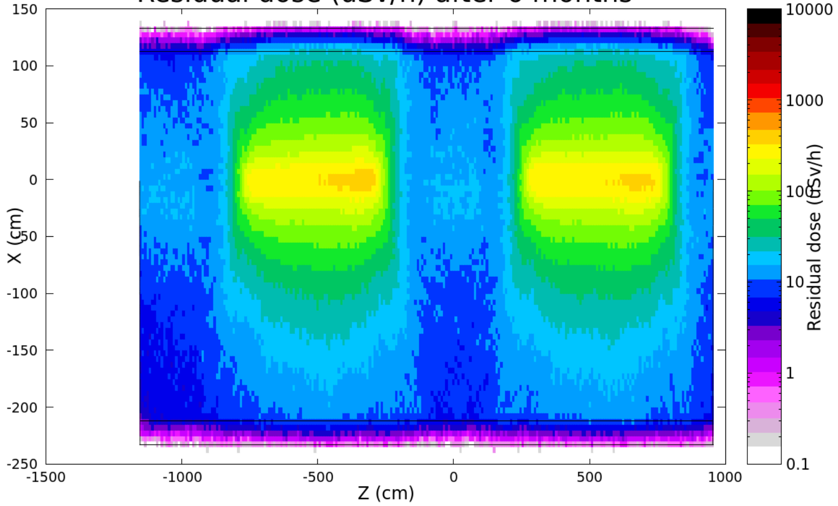
# Residual dose rates

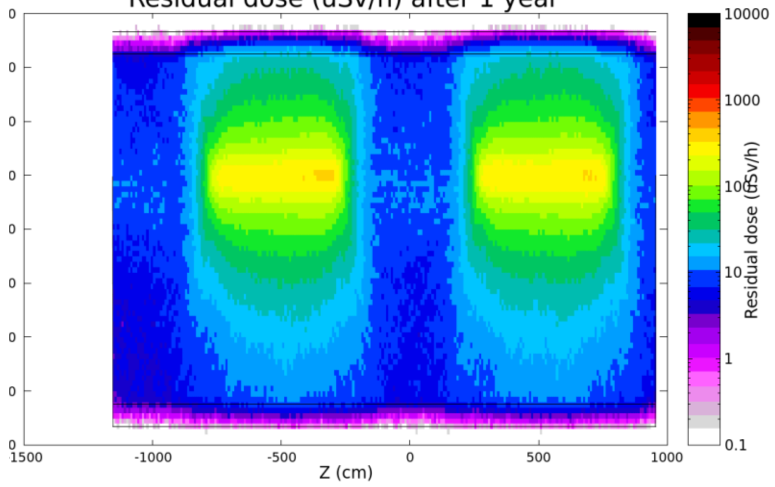
After a period of cooling down, the ambient dose of ~30 uSv/h in the vicinity of the NC magnet (40 cm from surface).

These values are comparable to the doses observed in the collider ring.


Residual ambient dose close to magnet


Residual dose (uSv/h) after 1 month


Residual dose (uSv/h) after 6 months


Residual dose (uSv/h) after 1 year

# Conclusions

Radiation load to the magnets:

- The ionizing dose to the normal conducting coils remains acceptable deep in the arcs; shielding might be needed for the first cell after the RF insertion
- The ionizing dose to the superconducting coils requires shielding of at least 2 cm around the beam pipe and 10 cm of front shielding.

Radiation protection:

- First preliminary studies showed that the residual dose levels of the NC magnets are significant
- Nevertheless, at a distance of 40 cm from the magnets they are not significantly higher than in the collider ring
- Further aspects need to be studied (e.g. radioactive waste production) in order to give a conclusive answer if such a high cobalt content is acceptable