Radiation environment in present and future particle colliders

(HL-LHC, FCC, Muon Collider)

A. Lechner (CERN), with the valuable input of many CERN colleagues

RADSUM25 workshop - 15/01/2025

Outline

- **Brief overview of high-energy collider landscape**
- **Interactions of high-energy particles in matter**
  - *Secondary particle production and showers*
  - *Radiation effects typically considered in collider magnet design*
- **Simulation tools (Monte Carlo radiation transport codes)**
- **Radiation load to superconducting magnets - representative examples:**
  - *High-Luminosity LHC – HL-LHC* (final focus magnets)
  - *Future Circular hadron-hadron Collider – FCC-hh* (final focus magnets)
  - *Muon Collider* (solenoids in muon production area, collider ring magnets)

Landscape of present & future high-energy colliders[#]

[#] this selection is not a complete list

Operational and upcoming (2030+) high-energy colliders

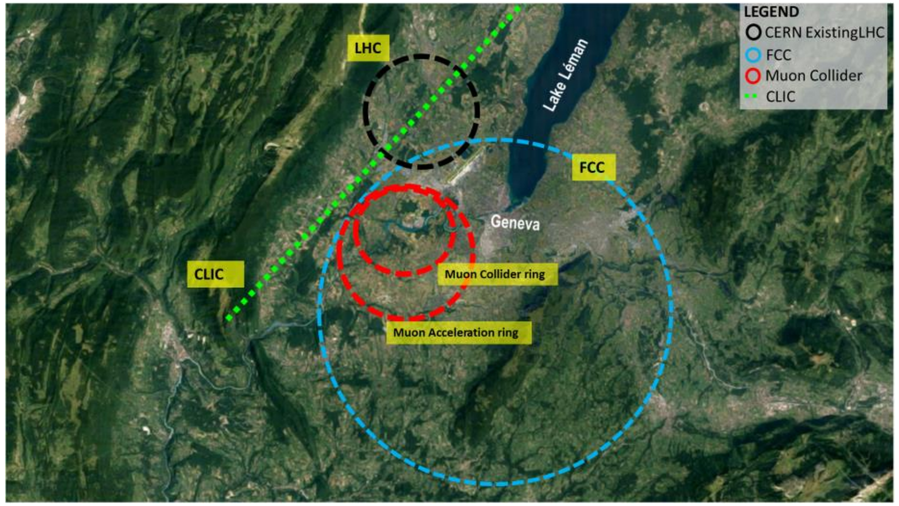
- **CERN:** LHC, HL-LHC ($\sqrt{s}$=13.6-14 TeV)
- **BNL (US):** RHIC, EIC ($\sqrt{s}$=20-140 GeV)

Different options for future colliders are presently being studied (timeline could be from 2040s)* **some earlier, some later*

- **Higgs and electroweak factories**
  - Circular or linear e^+e^- colliders ($\sqrt{s}$=90-380 GeV)
- **Beyond Higgs factories (energy-frontier machines)**
  - Linear e^+e^- colliders ($\sqrt{s}$=few TeV)
  - Circular pp ($\sqrt{s}$=O(100) TeV)
  - $\mu^+\mu^-$ collider ($\sqrt{s}$=O(10) TeV)

Red = superconducting rings

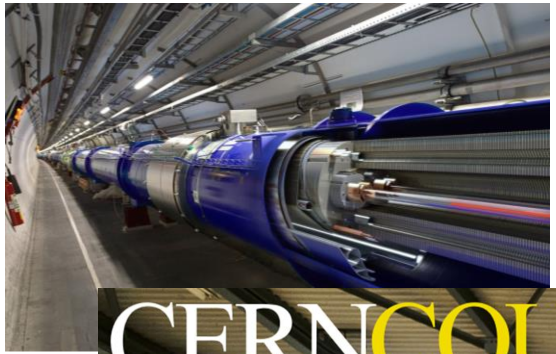
Acronyms:
LHC *= Large Hadron Collider*
HL-LHC *= High-Luminosity LHC*
RHIC *= Relativistic Heavy Ion Collider*
EIC *= Electron Ion Collider*
FCC *= Future Circular Collider*
CEPC *= Circular Elec. Pos. Collider*
CLIC *= Compact Linear Collider*
ILC *= International Linear Collider*
SPPC *= Super Proton-Proton Collider*
MC *= Muon Collider*



Rough comparison of sizes, does not show exact placement

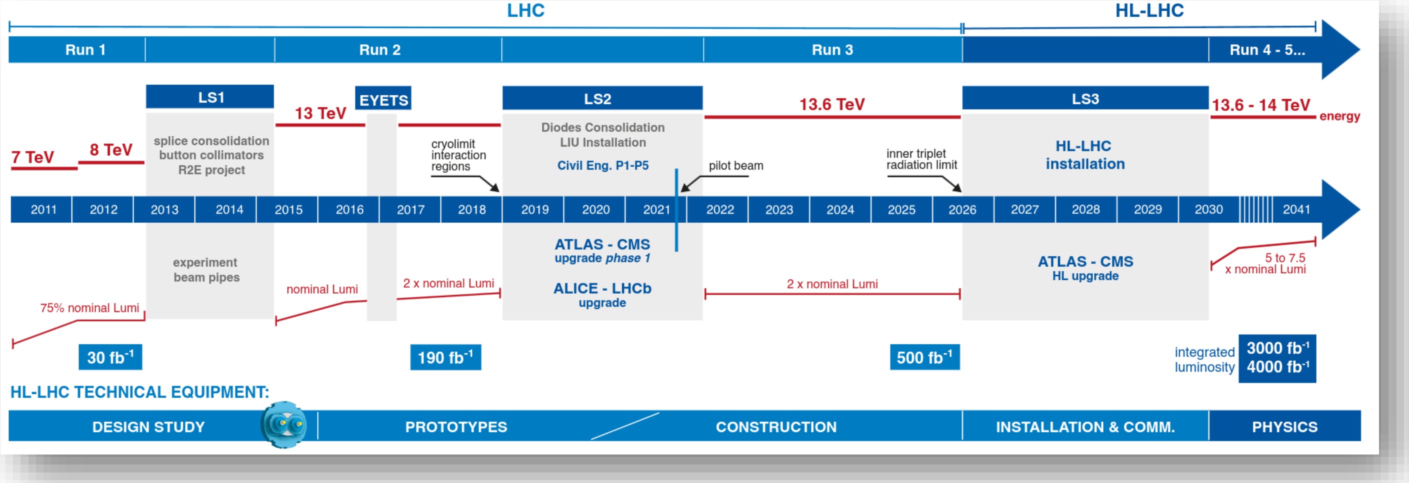
	Type	Particle species	Collision energy	Circumf. or length	Where
Proposals for future machines: Mature Higgs factory studies					
FCC-ee	Circ	**e+/e-**	91-365 GeV	91 km	Europe
CEPC	Circ	**e+/e-**	91-360 GeV	100 km	China
CLIC stage 1	Linear	**e+/e-**	380 GeV	11 km	Europe
ILC250	Linear	**e+/e-**	250 GeV	20 km	Japan
Proposals for future machines: Beyond Higgs factories					
CLIC stage 2/3	Linear	**e+/e-**	1.5/3 TeV	29/50 km	Europe
ILC upgrade	Linear	**e+/e-**	0.5/1 TeV	31/40 km	Japan
FCC-hh	Circ	**p**	81-115 TeV	91 km	Europe
SPPC	Circ	**p**	125 TeV	100 km	China
Muon Collider	Circ	**μ+/μ-**	3/10 TeV	4/10 km	US/Europe

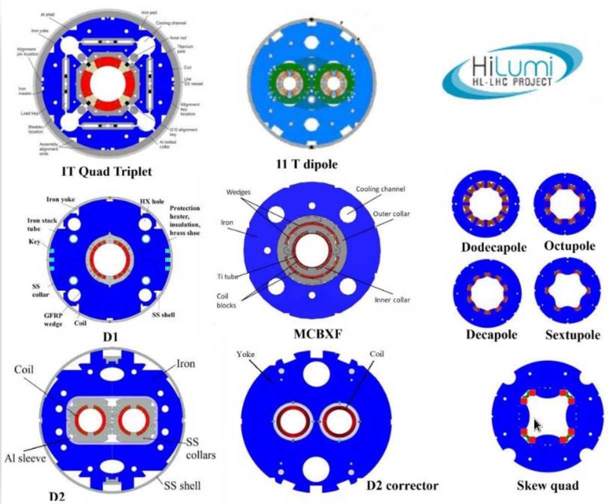
High Luminosity-Large Hadron Collider (HL-LHC)



The LHC is presently the highest-energy particle collider

- Collides **6.8 TeV protons** in four collision points **($\sqrt{s}$=13.6 TeV)**
- The **HL-LHC upgrade** will increase the collision rate (luminosity) in the ATLAS and CMS detectors (from 2030)
- Most of the LHC ring (**27 km**) is composed of SC magnets (all ***LTS***):
    - *Mostly **NbTi-based** (e.g. 8.7 T bending dipoles)*
    - *New **Nb3Sn-based** quadrupoles (and other magnets) will be installed near ATLAS/CMS*



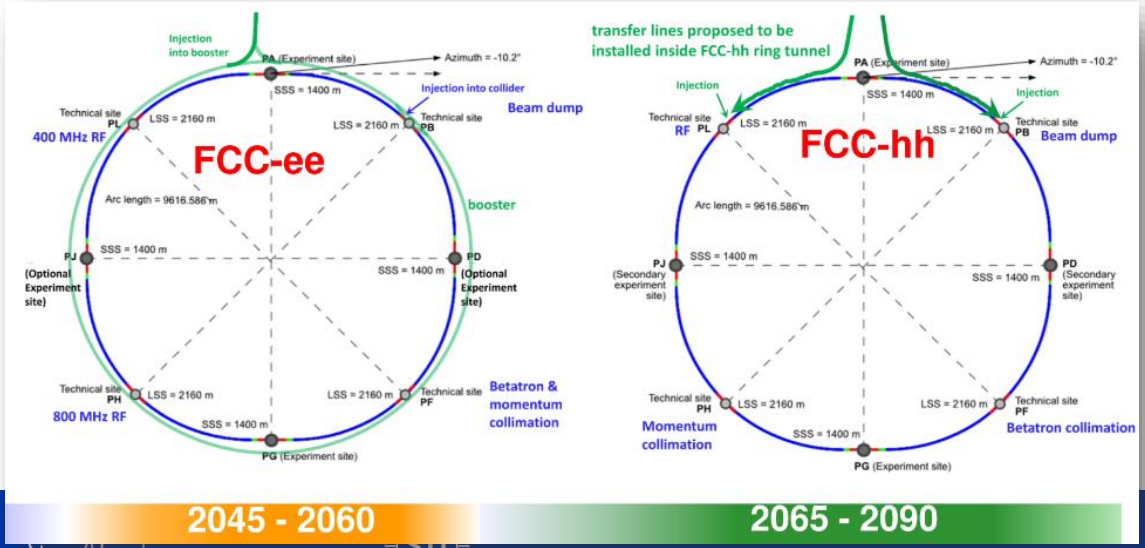


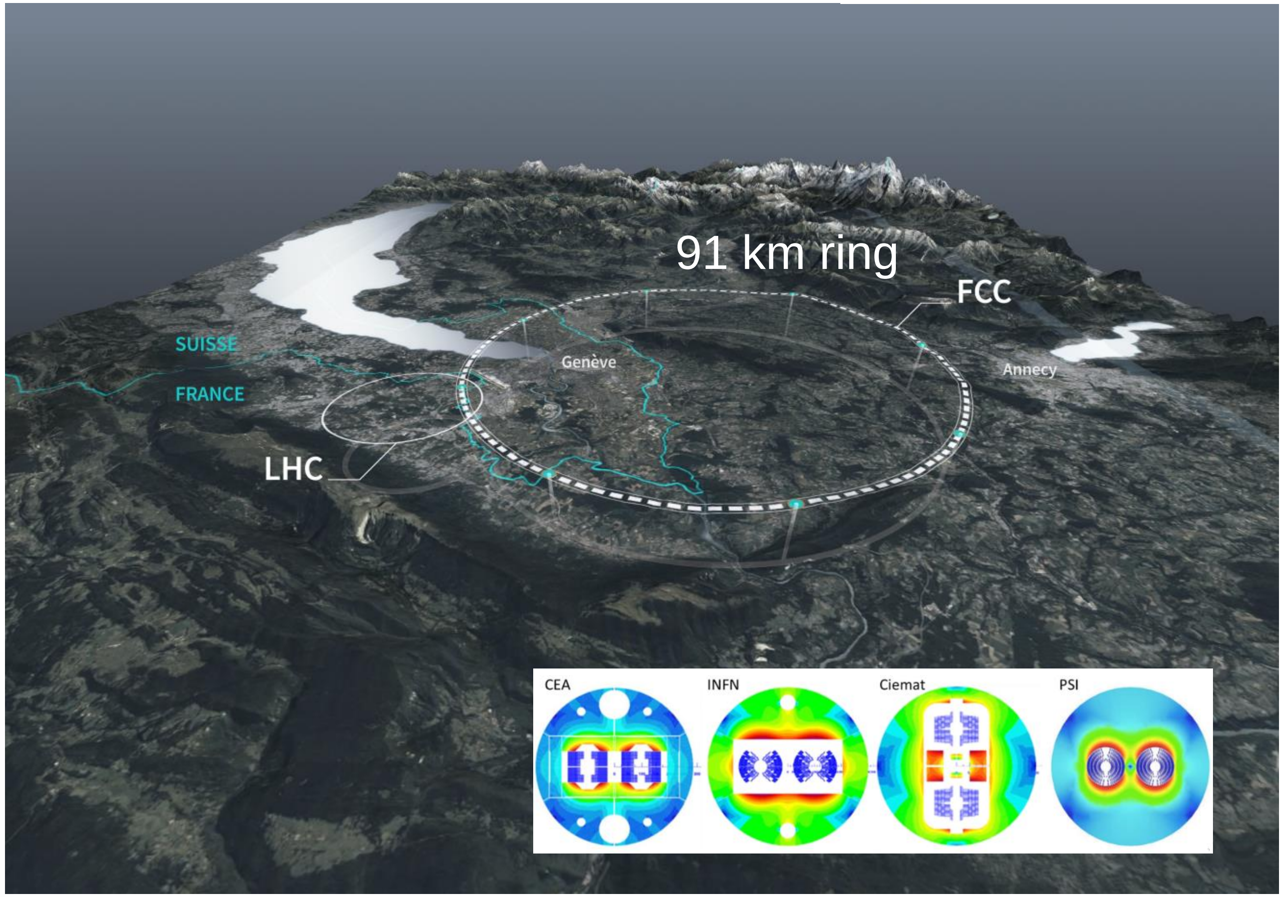
Future Circular Collider (FCC)

FUTURE
CIRCULAR
COLLIDER

The Future Circular Collider (FCC) study led by CERN is developing a staged collider program for 2045-2090

- **Stage 1: FCC-ee** (Higgs, electroweak & top factory with $\sqrt{s}$**=91-365 GeV**) – *only a few superconducting magnets*
- **Stage 2: FCC-hh** (energy frontier proton-proton collider with $\sqrt{s}$**=80-115 TeV**) – *mostly superconducting magnets*





Options considered for FCC-hh:

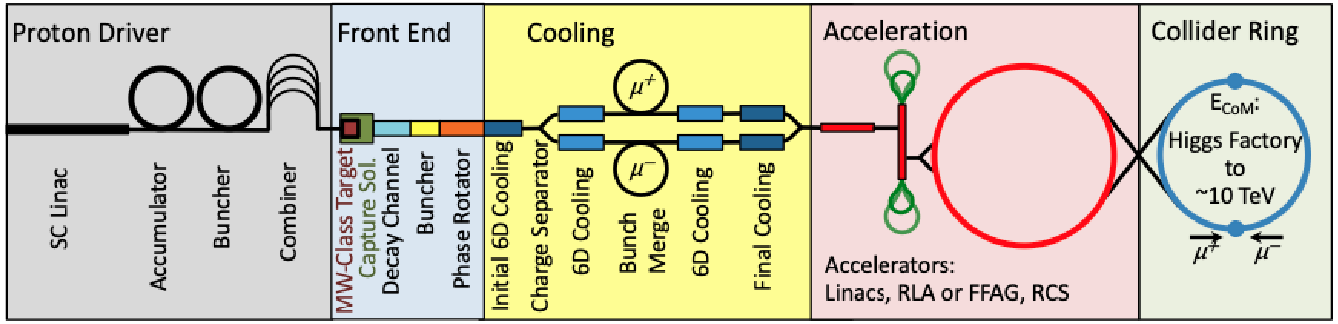
- ➢ ***LTS*** *(Nb3Sn) magnets (**14 T dipoles**)*
- ➢ ***HTS*** *(REBCO) magnets (**20 T dipoles**)*

Muon Collider

Proposal and studies for muon colliders exists since decades, several R&D efforts in the last 15 years

- **Muon Accelerator Program (MAP)** formed in the US in 2011 (now terminated)
- CERN-led **International Muon Collider Collaboration (IMCC)** formed in 2022, with the goal to study the feasibility of a $\sqrt{s}$**=10 TeV** muon collider
- Superconducting magnets are key for the entire Muon Collider complex
  - ➢ *Large aperture/high-field solenoids for the front-end and cooling (**HTS**)*
  - ➢ *High field magnets (e.g. **16 T dipoles**) in the collider ring (**LTS** or **HTS**)*

Schematic view of Muon Collider complex:



BCG vaccination for cattle pp. 1410 & 1433

Science

$15
29 MARCH 2024
science.org
AAAS

A radical new particle accelerator concept emerges. Call it physicists'

MUON SHOT

p. 1405

Home › The European Physical Journal C › Article

Towards a muon collider

Review | Open access | Published: 26 September 2023

Volume 83, article number 864, (2023) Cite this article

doi.org/10.1140/epjc/s10052-023-11889-x

Download PDF ⤓

✓ You have full access to this open access article

EPJ C

The European Physical Journal C

Aims and scope →

Submit manuscript →

Radiation to SC magnets in high-energy colliders

Beam particles circulating in an accelerator/collider can be lost or can emit secondary particles → radiation to magnets, for example:

- Hadron collider ring (e.g. HL-LHC, FCC-hh, SPPC):
  - Proton-proton collisions in detectors
- Electron/Positron collider ring (e.g. FCC-ee, CEPC)
  - Beam-beam effects (radiative Bhabha, Beamstrahlung)
  - Synchrotron radiation emission
- Muon collider ring
  - Muon decay

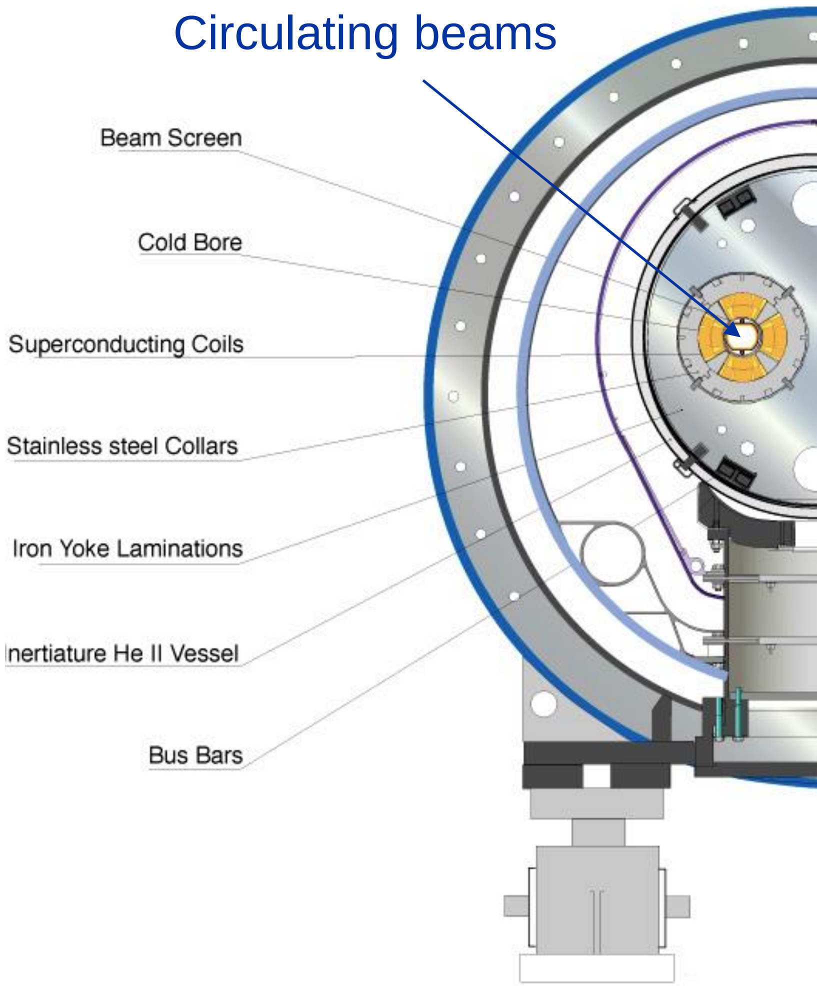
There are many other sources of beam losses

Superconducting magnets can also be subject to radiation in other parts of a collider complex, in particular in particle sources:

- Positron sources
- Muon sources

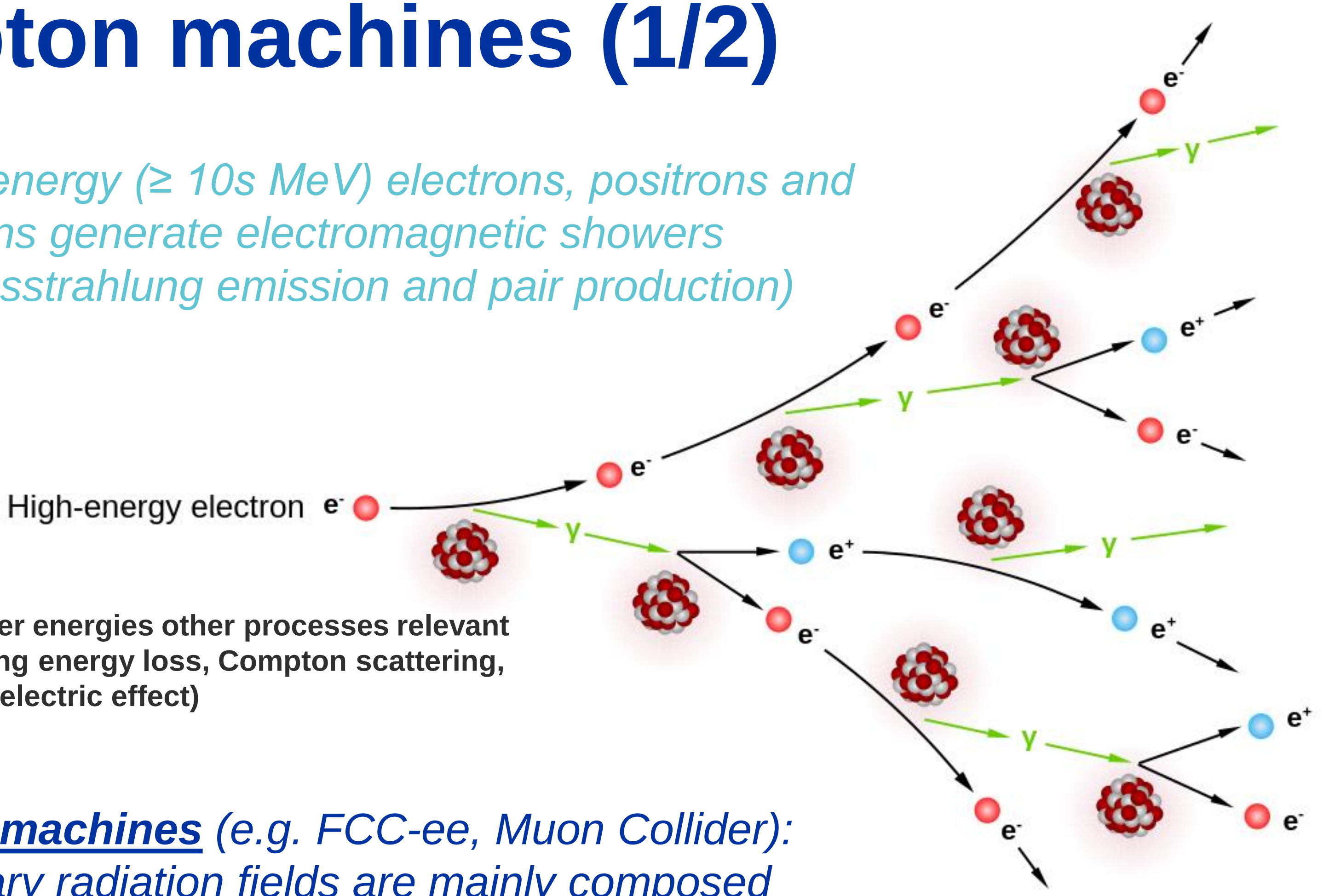
When high-energy particles interact with surrounding materials, they generate a **mixed radiation field** composed of **different particle types** and with a **wide energy spectrum**

LHC quadrupole cross section



Interactions of high-energy particles in matter – lepton machines (1/2)

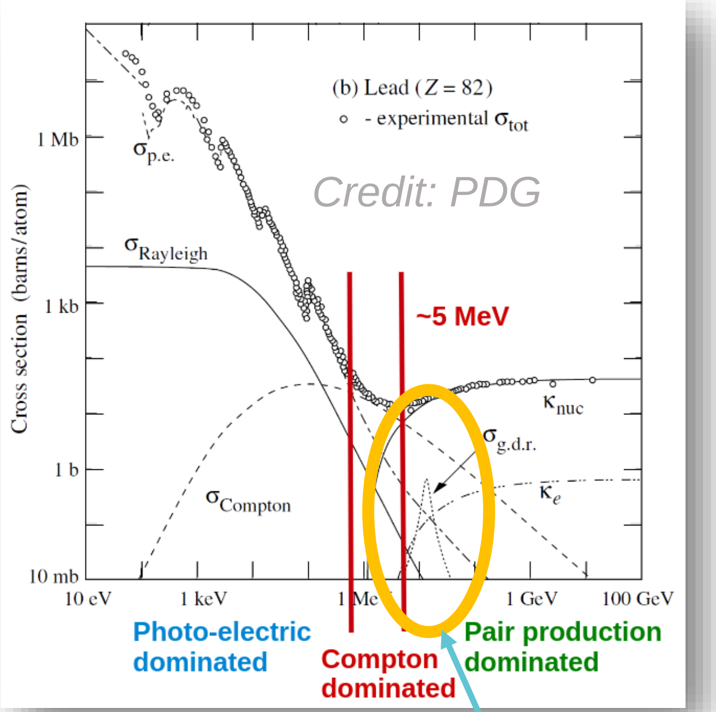
High-energy (≥ 10s MeV) electrons, positrons and photons generate electromagnetic showers (Bremsstrahlung emission and pair production)



At lower energies other processes relevant (ionizing energy loss, Compton scattering, photo-electric effect)

Lepton machines *(e.g. FCC-ee, Muon Collider): secondary radiation fields are mainly composed of* ***electrons, positrons, photons*** *and to a lesser extent also* ***neutrons*** *and* ***other hadrons***

roughly continues until electron/positron energy falls below below critical energy

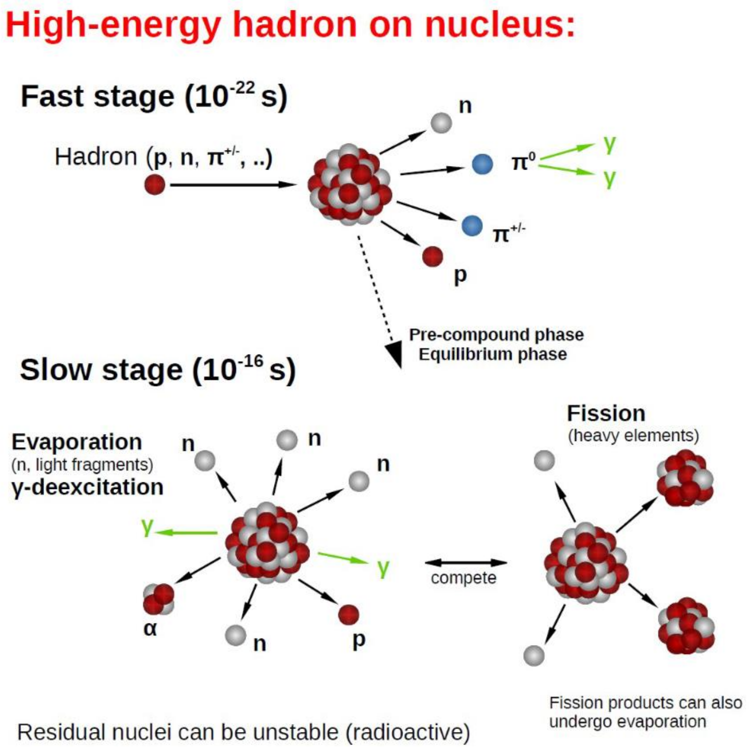


Credit: PDG

Neutron (and other hadron) production possible (≥ 5-10 MeV) due to photo-nuclear interactions

Interactions of high-energy particles in matter - hadron machines (2/2)

High-energy hadrons are subject to nuclear collisions, which give rise to hadronic showers and further to electromagnetic showers

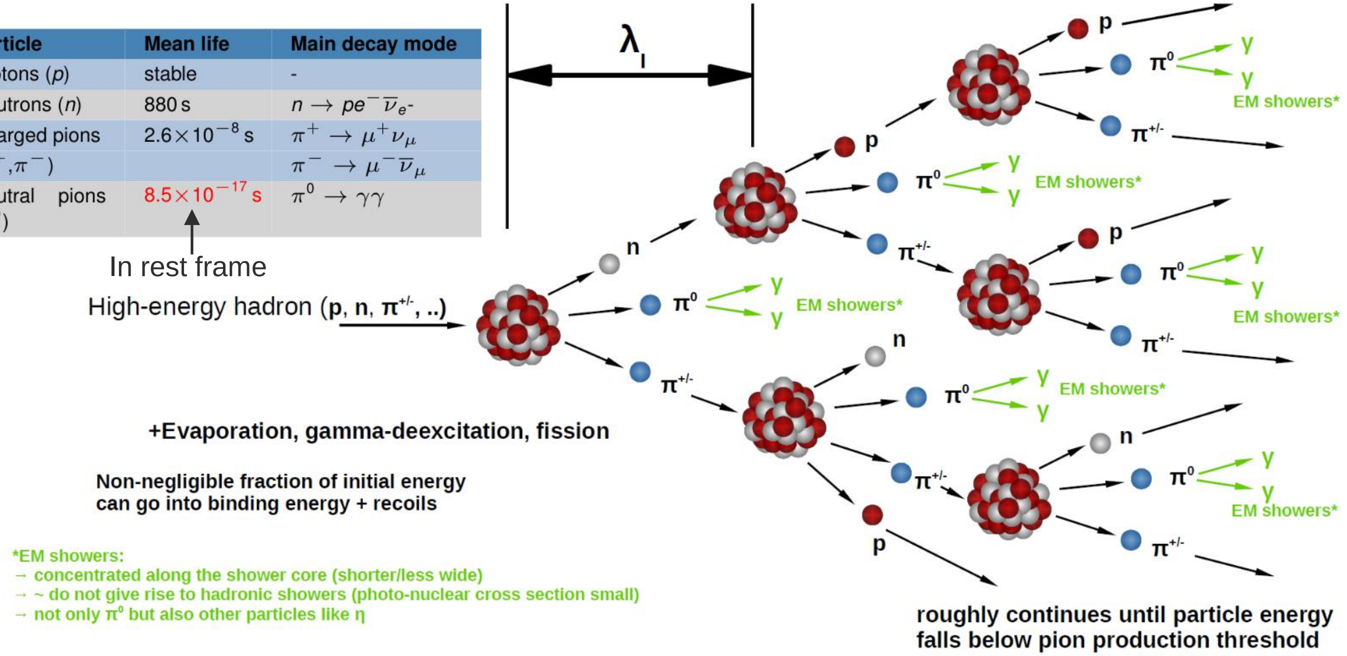


Fission products can also undergo evaporation

Residual nuclei can be unstable (radioactive)

Particle	Mean life	Main decay mode
Protons (*p*)	stable	-
Neutrons (*n*)	880 s	$n \to pe^-\overline{\nu}_e$-
Charged pions (π^+,π^-)	2.6×10^{-8} s	$\pi^+ \to \mu^+\nu_\mu$ $\pi^- \to \mu^-\overline{\nu}_\mu$
Neutral pions (π^0)	8.5×10^{-17} s	$\pi^0 \to \gamma\gamma$

In rest frame



+Evaporation, gamma-deexcitation, fission

Non-negligible fraction of initial energy can go into binding energy + recoils

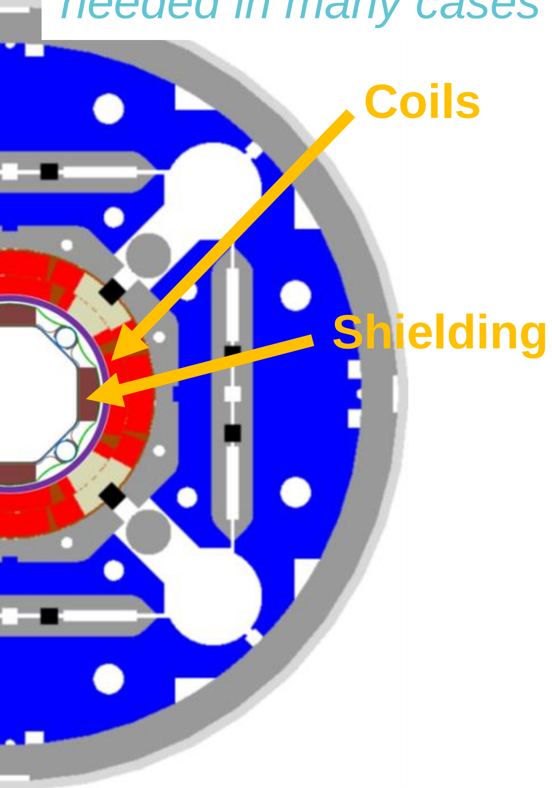
*EM showers:
- → concentrated along the shower core (shorter/less wide)
- → ~ do not give rise to hadronic showers (photo-nuclear cross section small)
- → not only π^0 but also other particles like η

roughly continues until particle energy falls below pion production threshold

Hadron machines *(HL-LHC, FCC-hh, but also hadron-driven particle sources like muon sources):*
secondary radiation fields are mainly composed of ***protons****,* ***neutrons****,* ***pions****,* ***photons, electrons/positrons***

Radiation effects relevant for SC magnets

Internal rad shielding needed in many cases



HL-LHC MQXF Nb3Sn magnet

Interaction of particles with matter

Depending on the machine, different effects might be dominant

Instantaneous

- **Power density in coils** **[mW/cm^3]**
  - ➢ *Can lead to magnet quenches (not destructive but can limit machine performance)*
- **Power deposition in cold mass** **[W]**
  - ➢ *Heat needs to be evacuated by the cryogenic system (performance limitation, cost)*

Need to avoid systematic performance limitations due to excessive heat deposition

Cumulative

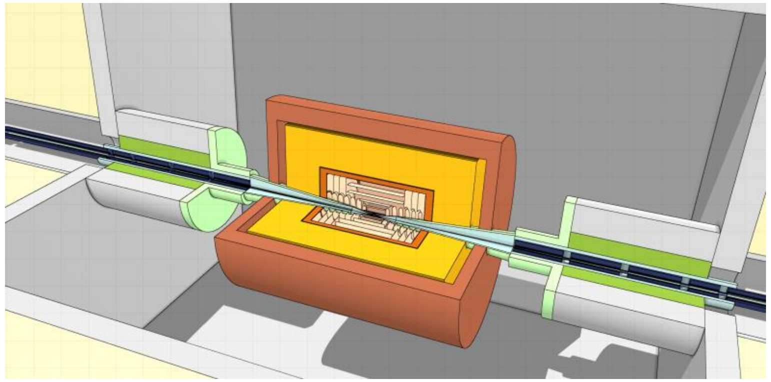
- **Ionizing dose** **[Gy]**
  - ➢ *Can affect material properties of organic materials (coil insulation, spacers, …)*
- **Atomic displacements** **[DPA]**
  - ➢ *Can affect the properties of superconductors (Tc, …)*
  - ➢ *Can affect structural materials*
- **Gas production** **[H / He appm]**
  - ➢ *Can lead to void formation, …*

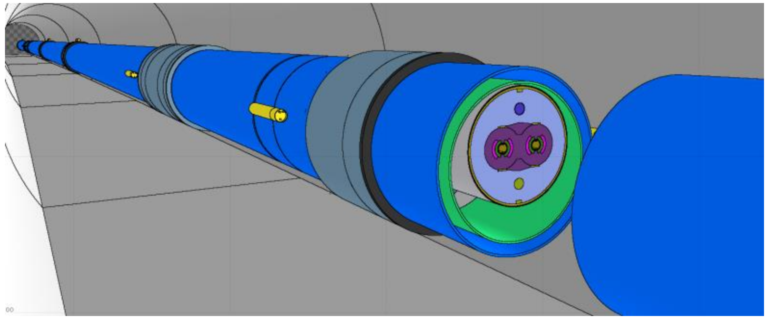
Need to avoid premature equipment failures (i.e. limited lifetime)

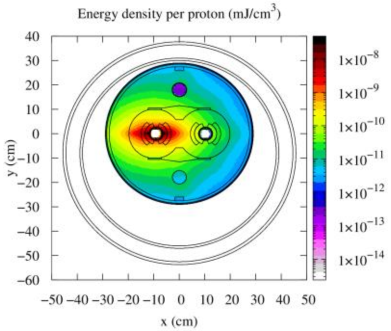
Radiation transport simulations

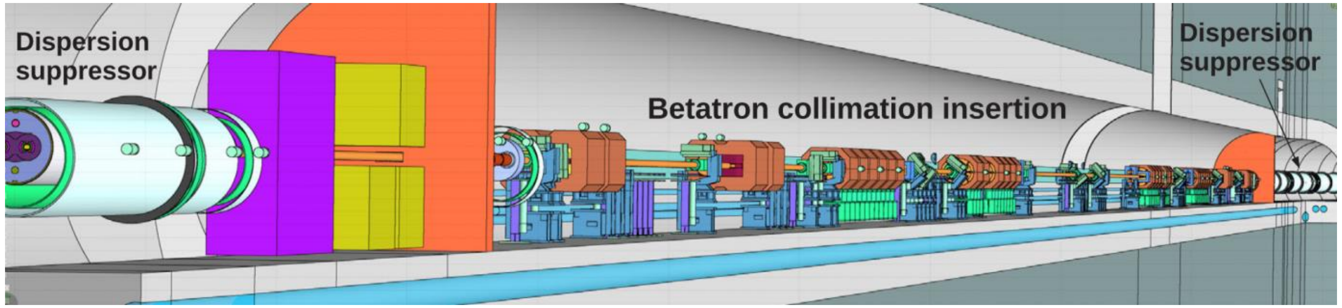
Monte Carlo radiation transport studies are fundamental for quantifying the radiation environment and for designing shielding for new colliders

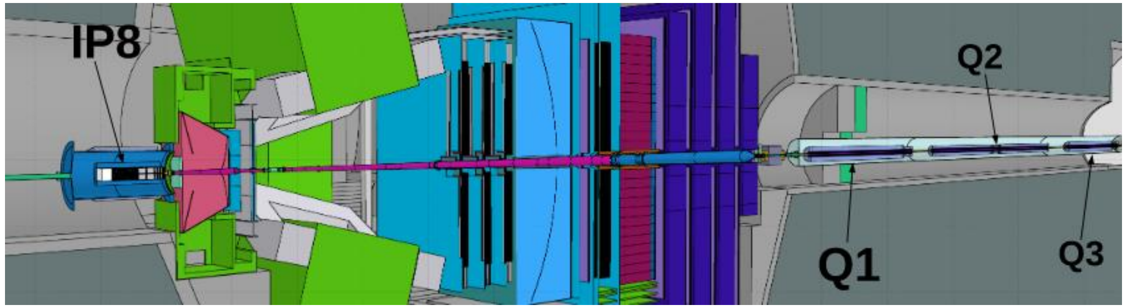
- Studies need to start early in the design phase of new machines
- Various codes exist (**FLUKA**, **Geant4**, **MARS**, **PHITS**), which enable a coupled transport of hadrons and leptons
- **FLUKA** is used the standard tool for CERN machines and facilities (from **targetry studies** to **beam losses in present and future colliders**)
    - ➢ Power deposition
    - ➢ Radiation damage (DPA and gas production)
    - ➢ Particle yield optimization for particle production sources
    - ➢ Radiation field and background characterization
    - ➢ Radiation to electronics
    - ➢ Radionuclide production and residual dose rates





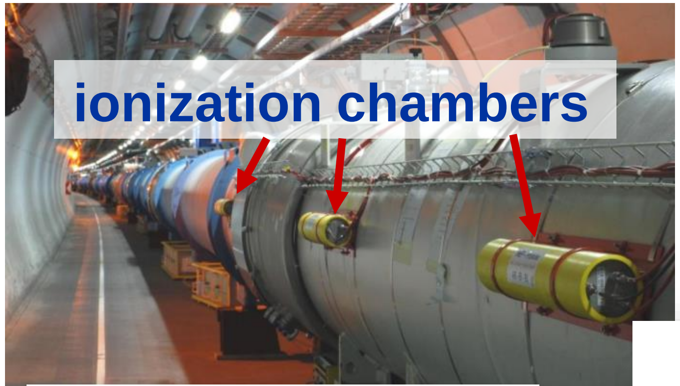




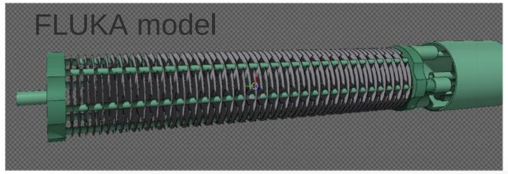


Benchmarking simulation models

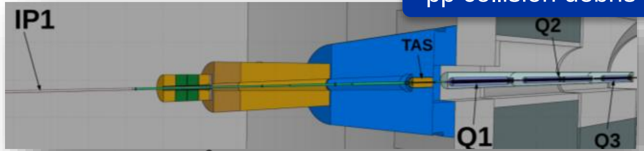
*Vast amount of ionization chamber measurements from **LHC operation**: many opportunities to benchmark energy deposition simulations*

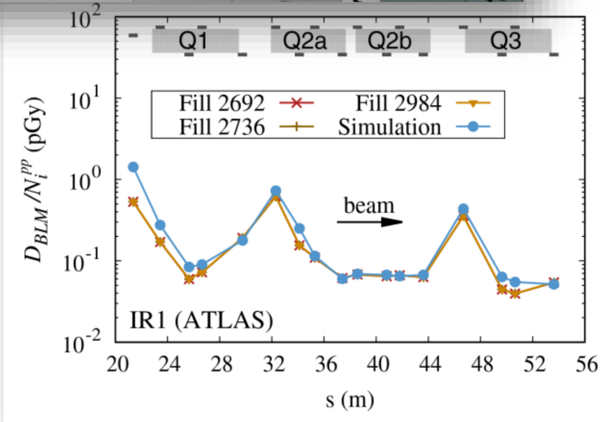


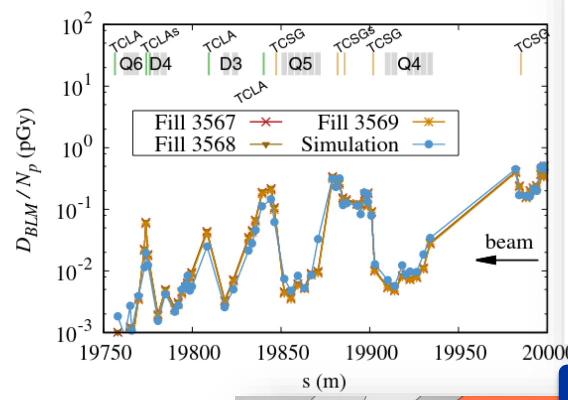

1500 cm^3, N_2 gas (@1.1bar)

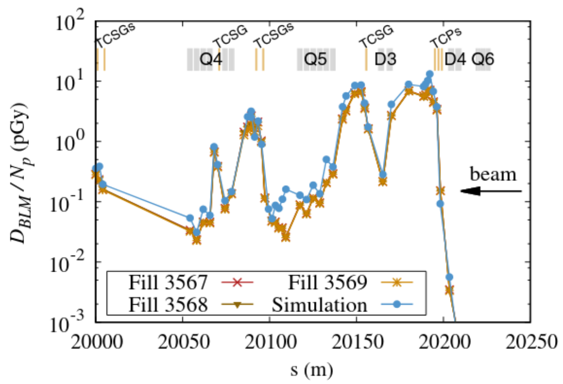


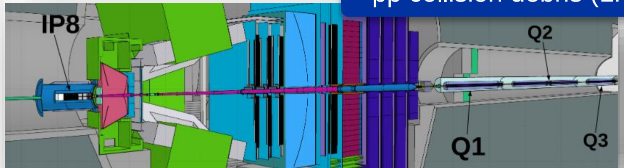
Agreement between FLUKA simulations and measurements typically within several 10%

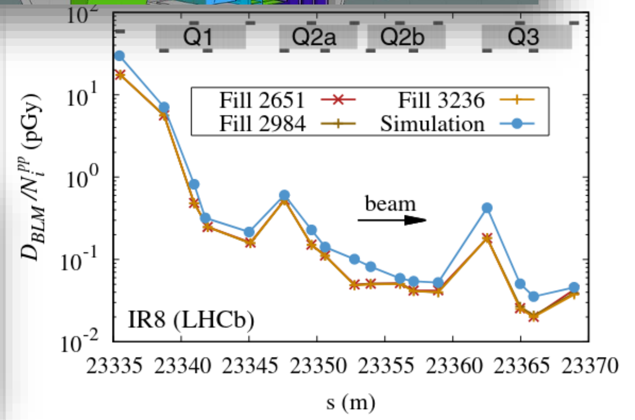

pp collision debris (ATLAS)

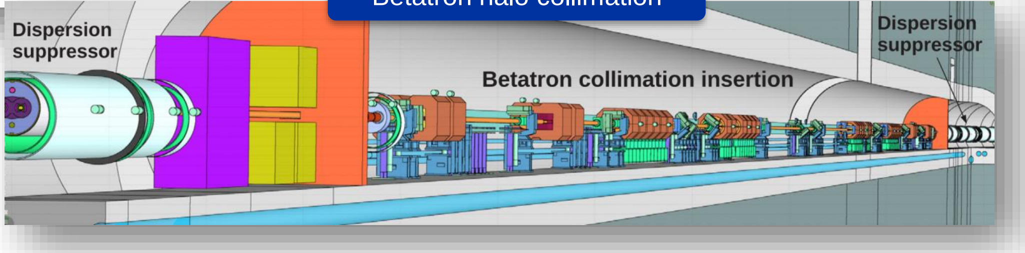


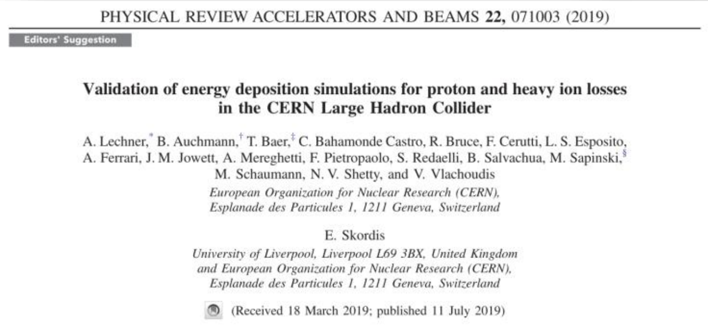





pp collision debris (LHCb)




Betatron halo collimation


PHYSICAL REVIEW ACCELERATORS AND BEAMS **22**, 071003 (2019)

Editors' Suggestion

Validation of energy deposition simulations for proton and heavy ion losses in the CERN Large Hadron Collider

A. Lechner,* B. Auchmann,† T. Baer,‡ C. Bahamonde Castro, R. Bruce, F. Cerutti, L. S. Esposito, A. Ferrari, J. M. Jowett, A. Mereghetti, F. Pietropaolo, S. Redaelli, B. Salvachua, M. Sapinski,§ M. Schaumann, N. V. Shetty, and V. Vlachoudis
European Organization for Nuclear Research (CERN), Esplanade des Particules 1, 1211 Geneva, Switzerland

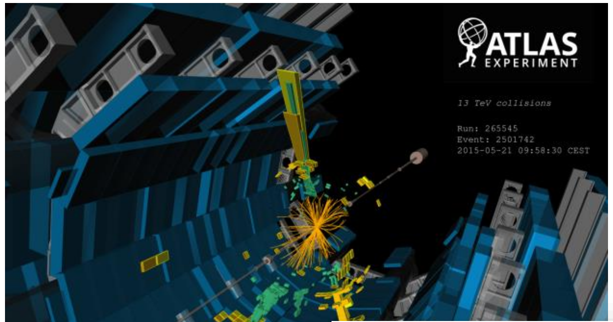
E. Skordis
University of Liverpool, Liverpool L69 3BX, United Kingdom and European Organization for Nuclear Research (CERN), Esplanade des Particules 1, 1211 Geneva, Switzerland

(Received 18 March 2019; published 11 July 2019)

Radiation to HL-LHC final focus magnets

The new HL magnets near the ATLAS and CMS detectors will be exposed to the highest radiation load in the entire HL-LHC ring

→ *proton-proton collision debris*



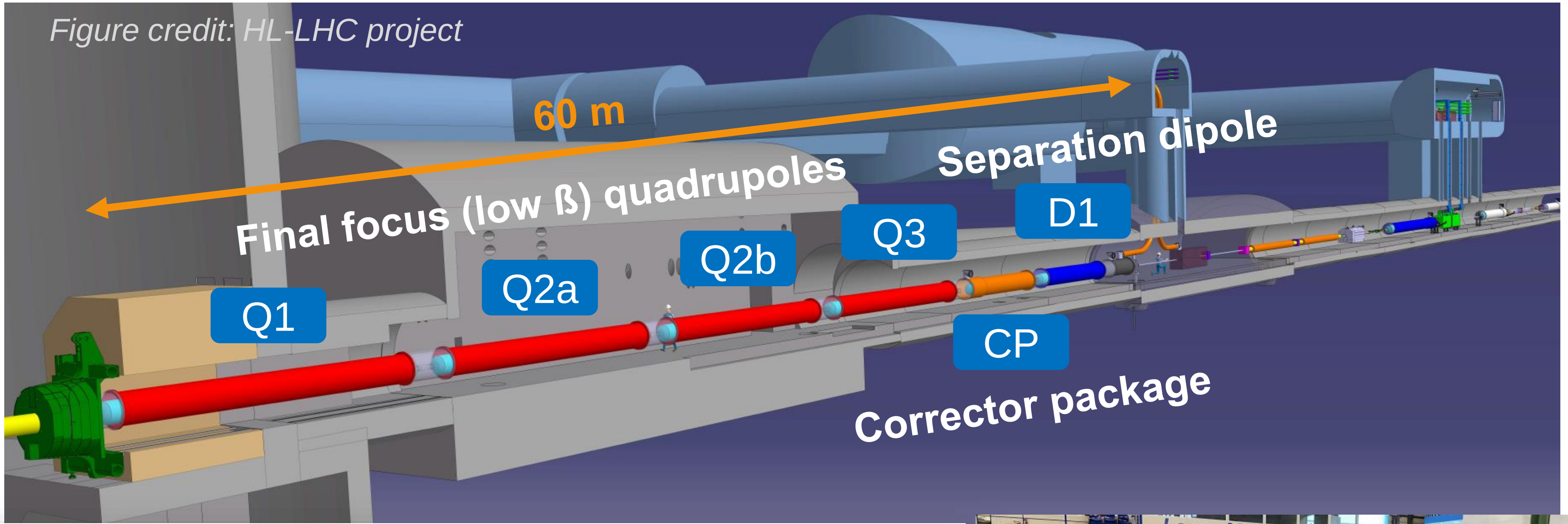
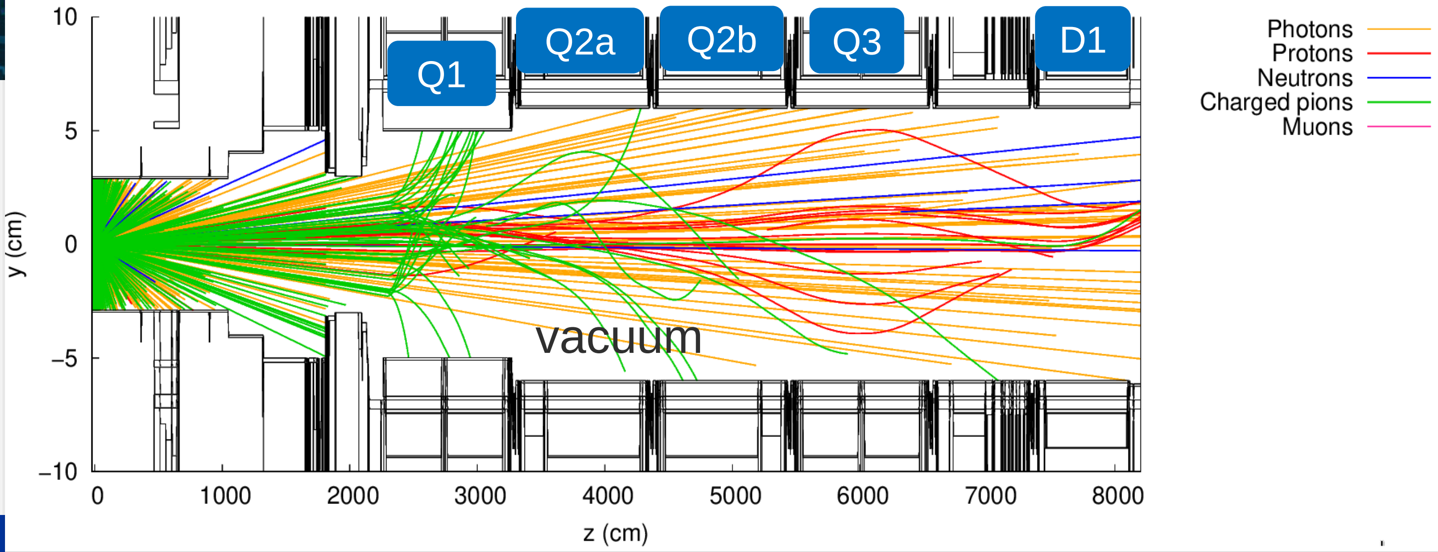
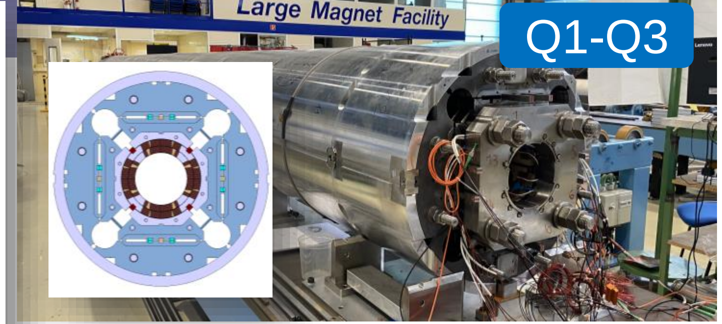


Figure credit: HL-LHC project





MQXF nominal operation (7 TeV): 16.23 kA, 132.2 T/m; 11.3 T B_{peak}

Radiation to HL-LHC final focus magnets

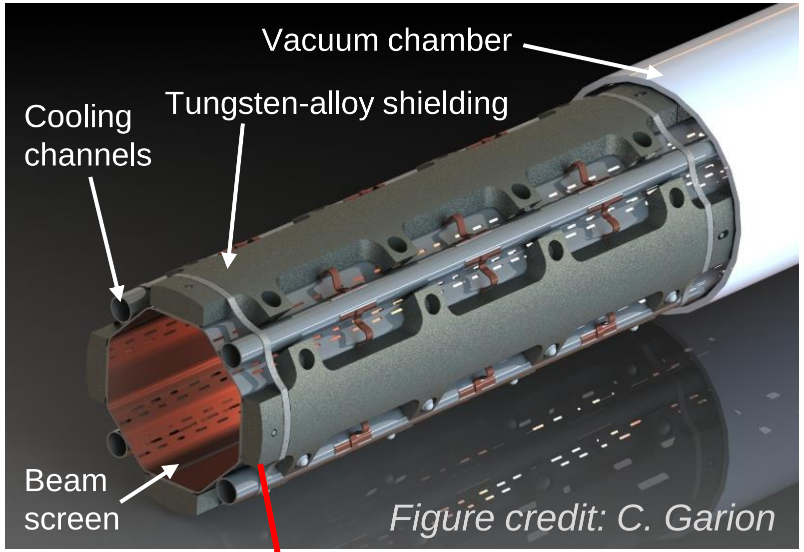
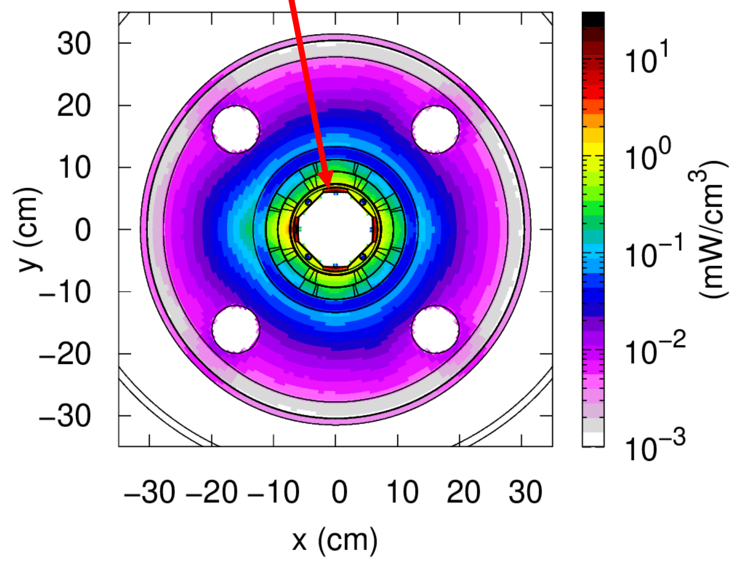
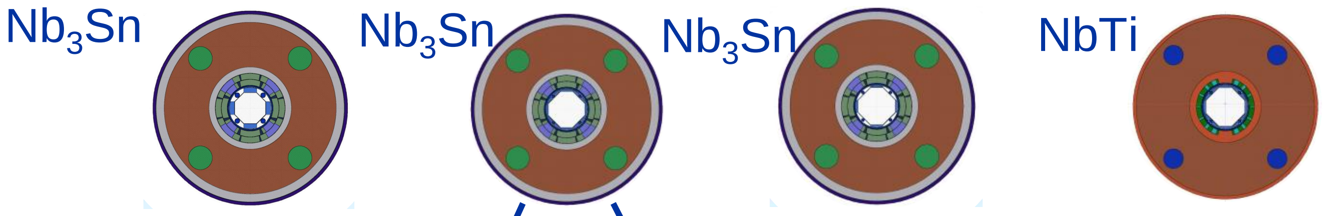


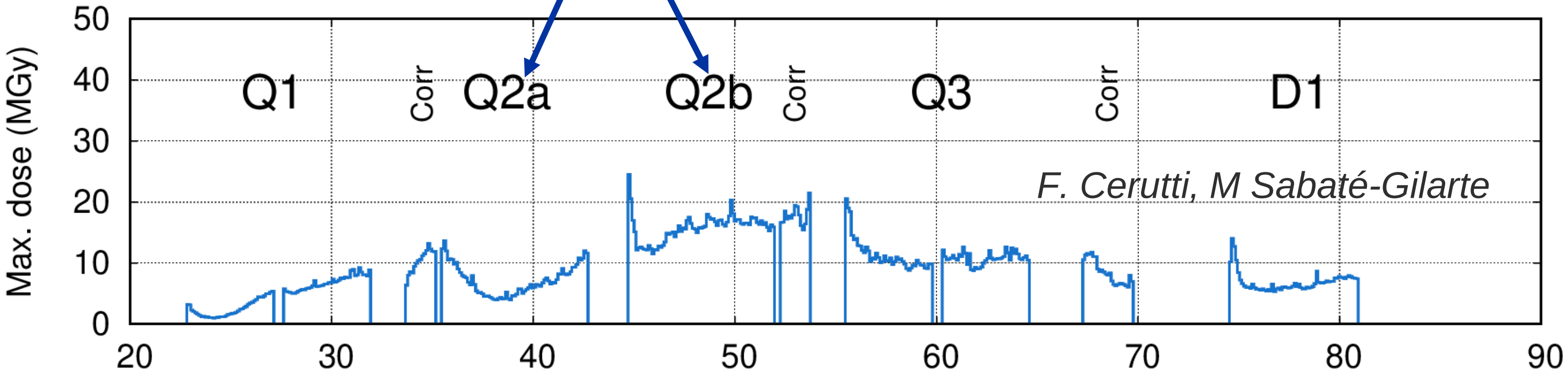
Figure credit: C. Garion

Power density in Q2B magnet (mW/cm^3)



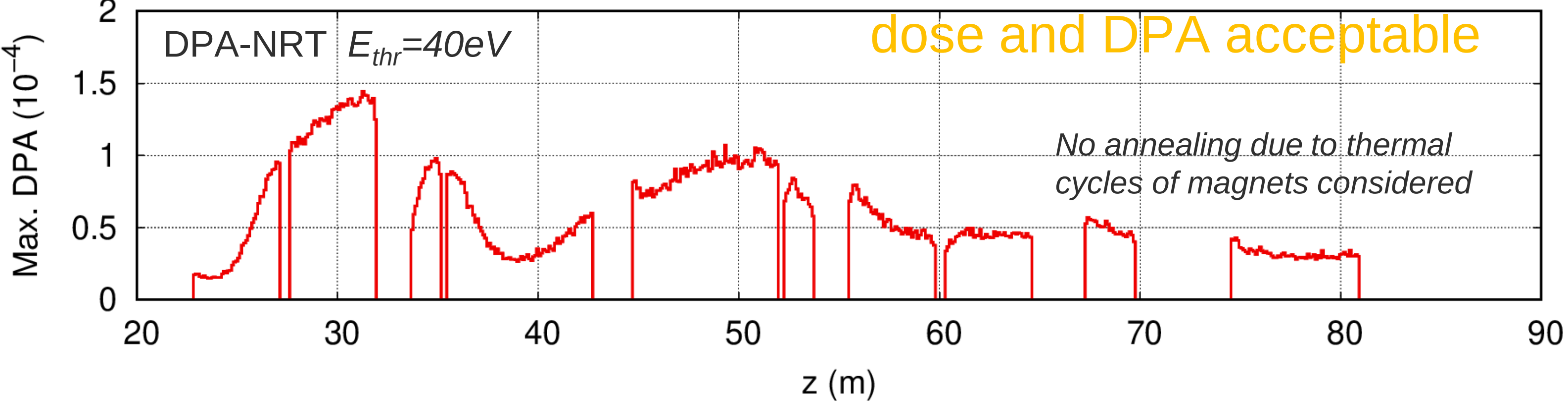
*Cumulative dose and DPA in triplet coils after 10 yrs – 3000 fb^{-1} (**with 0.6-1.6 cm internal tungsten shielding**):*





F. Cerutti, M Sabaté-Gilarte

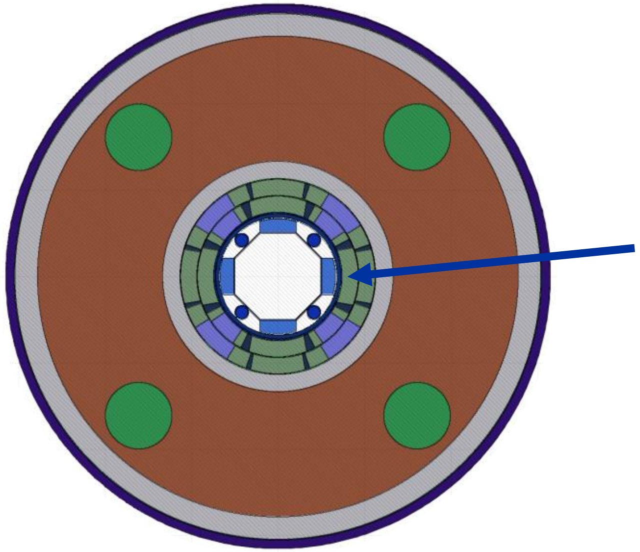
With cm tungsten shielding, dose and DPA acceptable

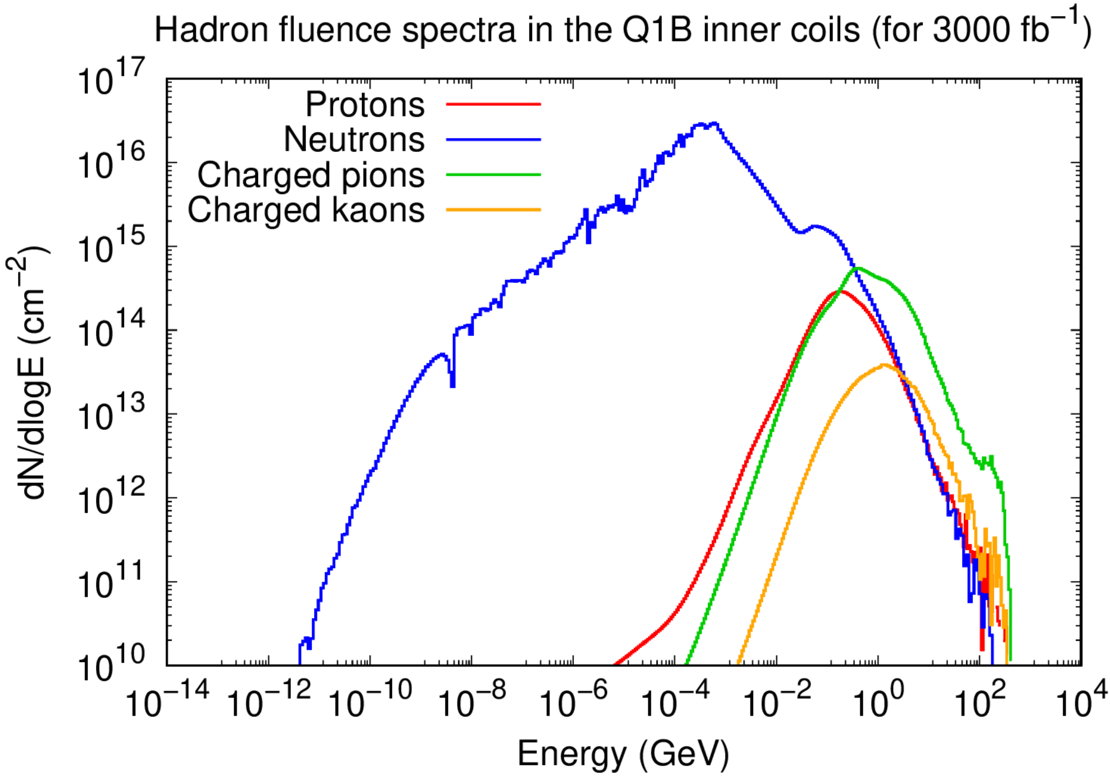


No annealing due to thermal cycles of magnets considered

Radiation to HL-LHC final focus magnets

MQXF (Nb_3Sn)





Pions dominate above 200 MeV

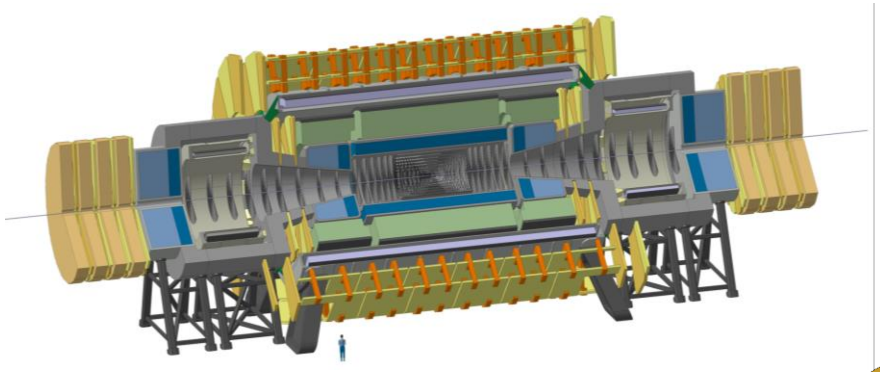
Neutrons (<20MeV) nevertheless DPA

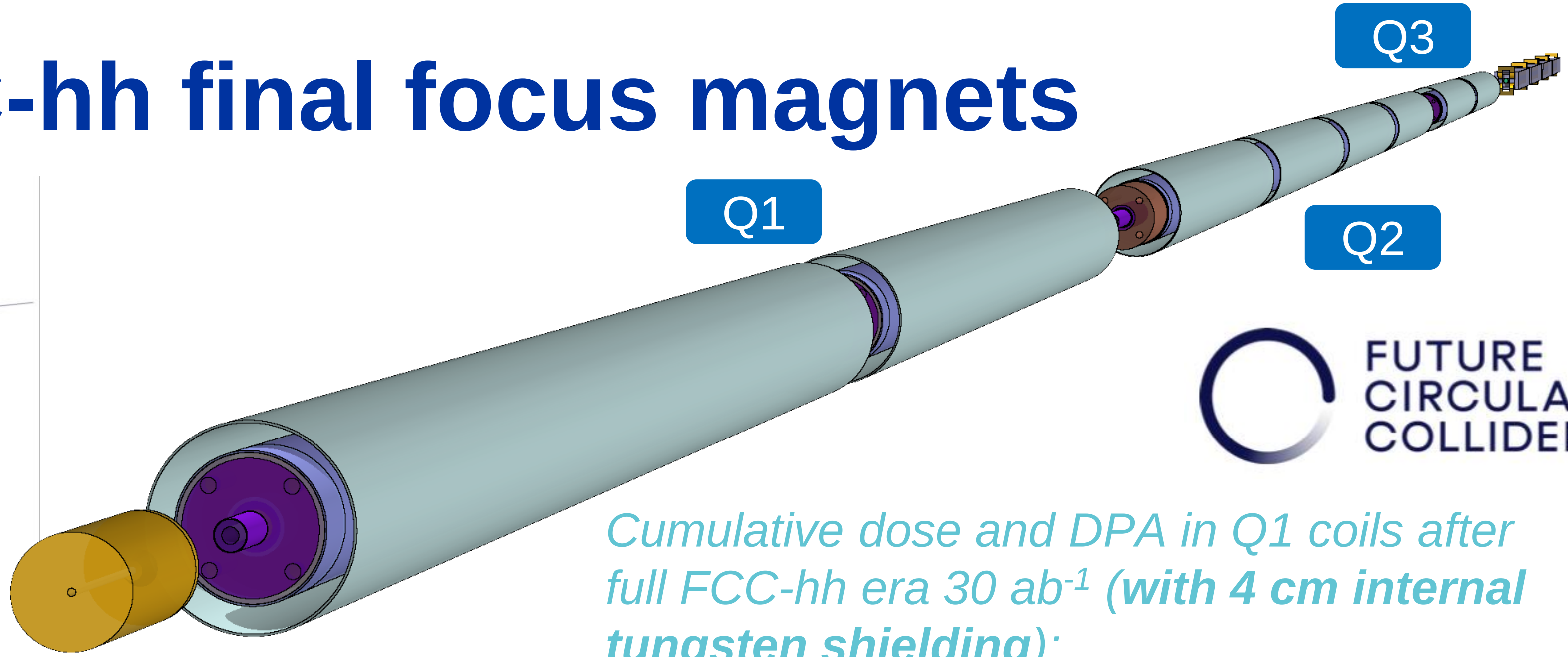
Fluence accumulated over full HL-LHC era

Q1b inner coils (averaged over coil volume):

Neutrons	Protons	Charged pions	Charged kaons
1.1×10^{17} cm^{-2}	8.3×10^{14} cm^{-2}	1.7×10^{15} cm^{-2}	1.2×10^{14} cm^{-2}

Radiation to FCC-hh final focus magnets

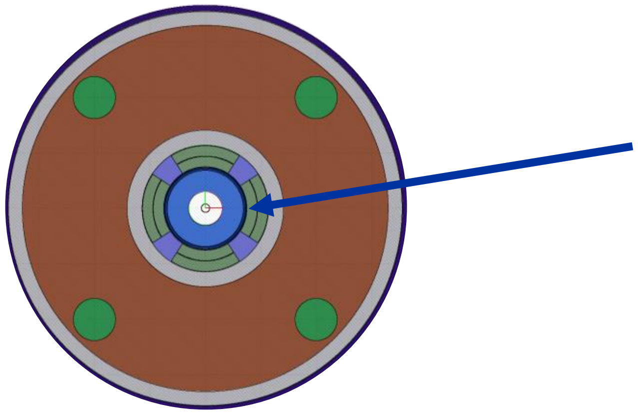


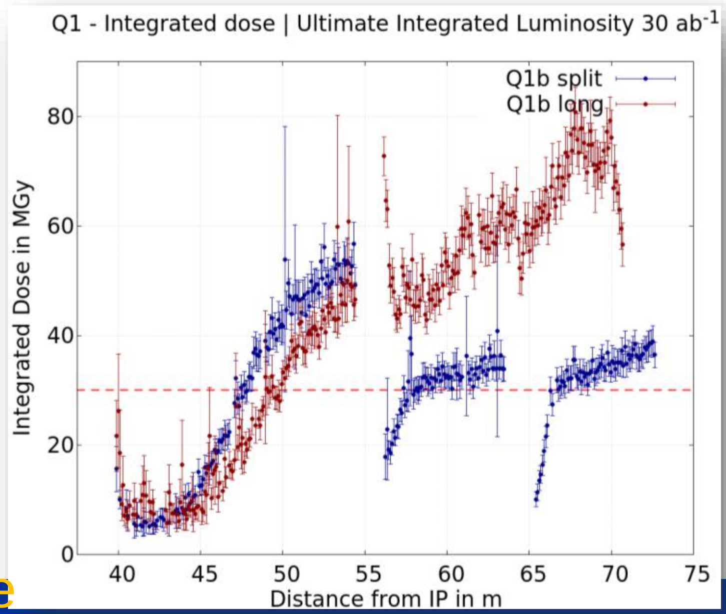


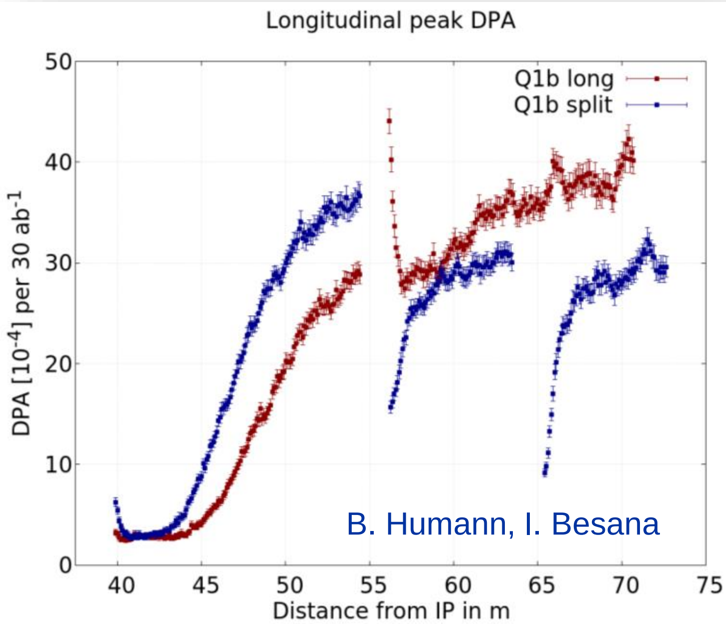
Like for HL-LHC, the final focus quadrupoles near the FCC-hh detectors are exposed to the highest radiation load in the FCC-hh ring

→ proton-proton collision debris

*Cumulative dose and DPA in Q1 coils after full FCC-hh era 30 ab^{-1} (**with 4 cm internal tungsten shielding**):*



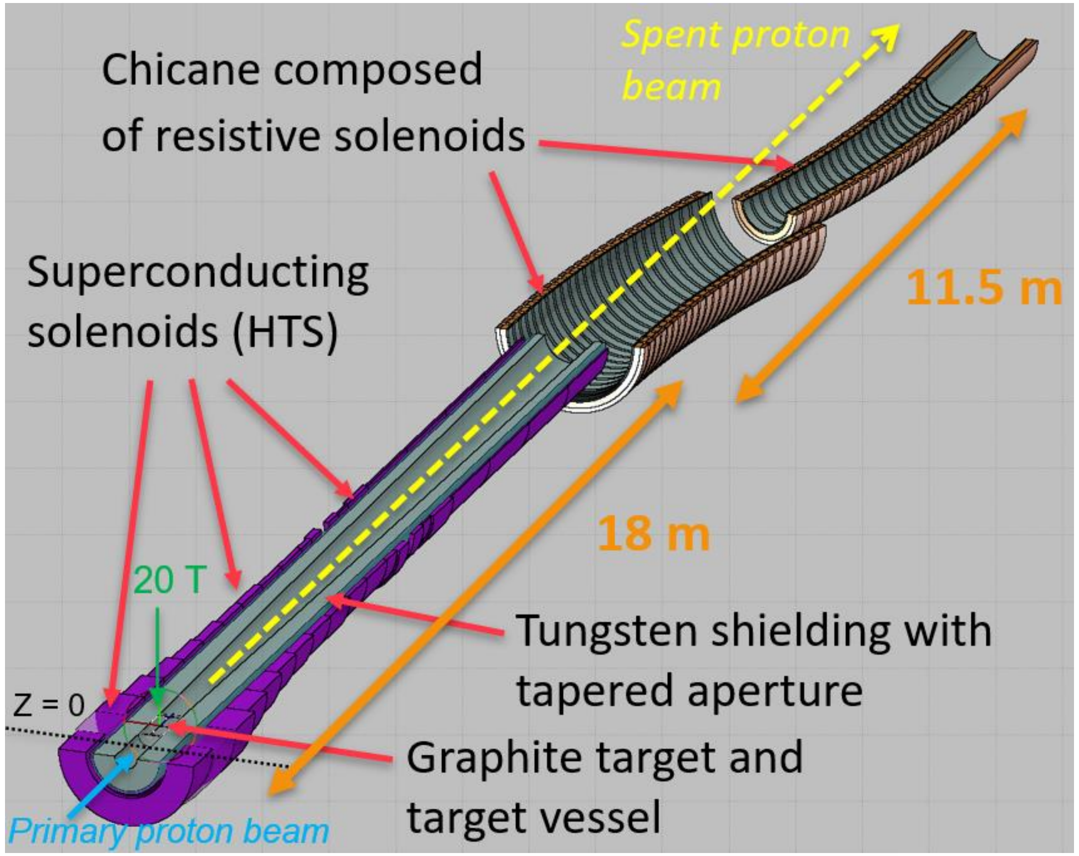


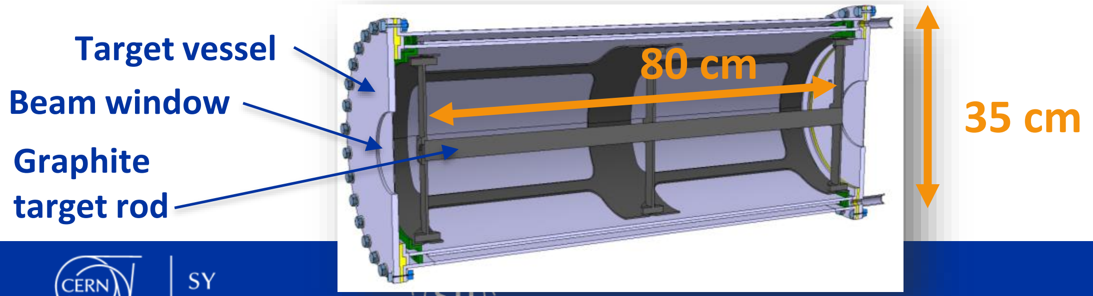


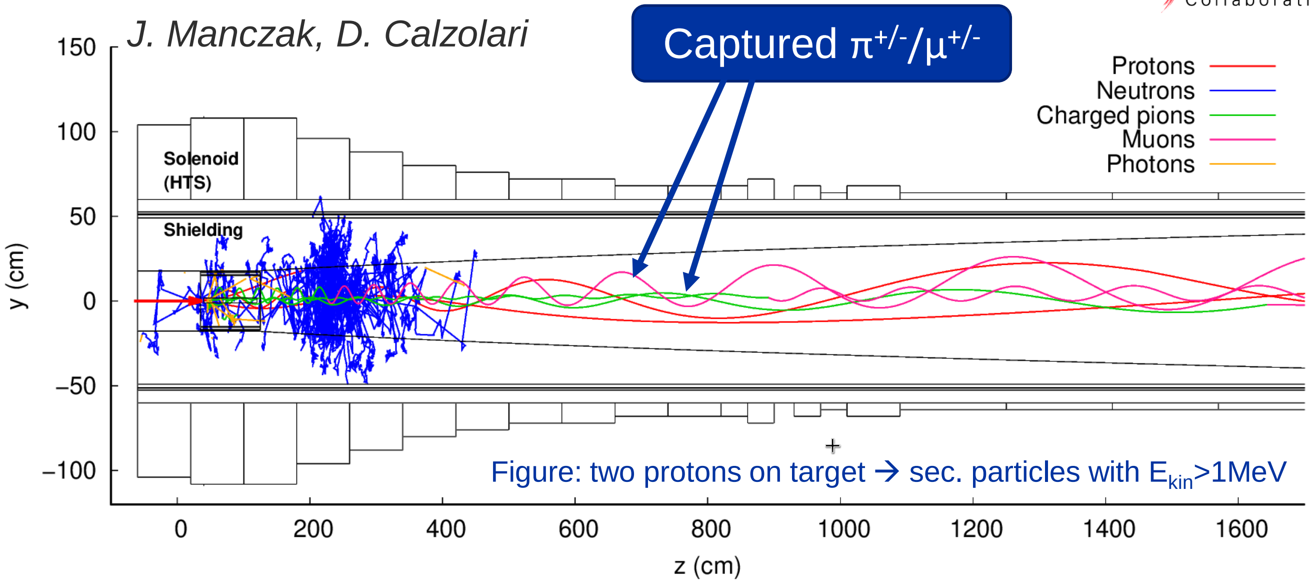
B. Humann, I. Besana

With 4 cm shielding, dose and DPA remain high

Muon collider front end (muon production)






J. Manczak, D. Calzolari

Captured $\pi^{+/-}/\mu^{+/-}$

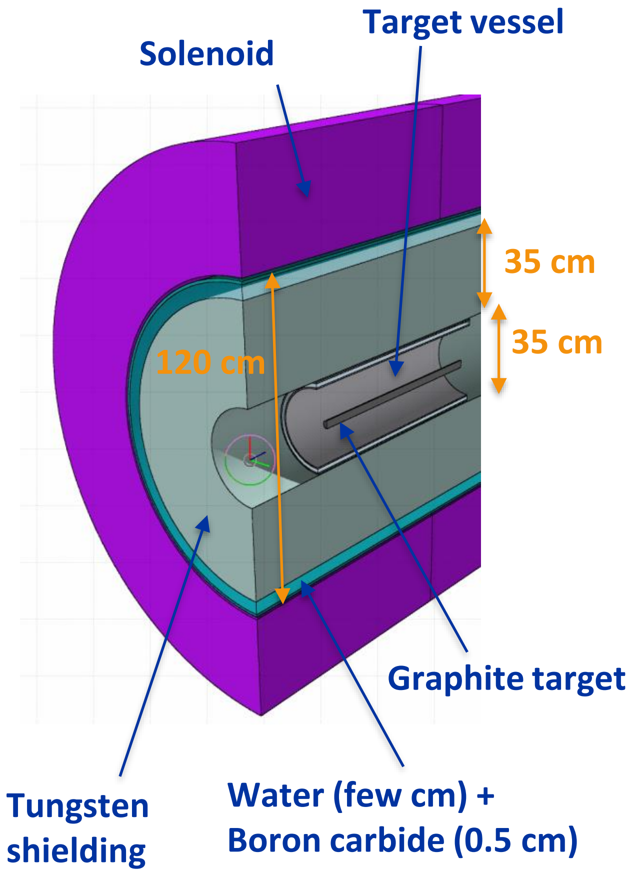
Figure: two protons on target → sec. particles with E_{kin}>1MeV

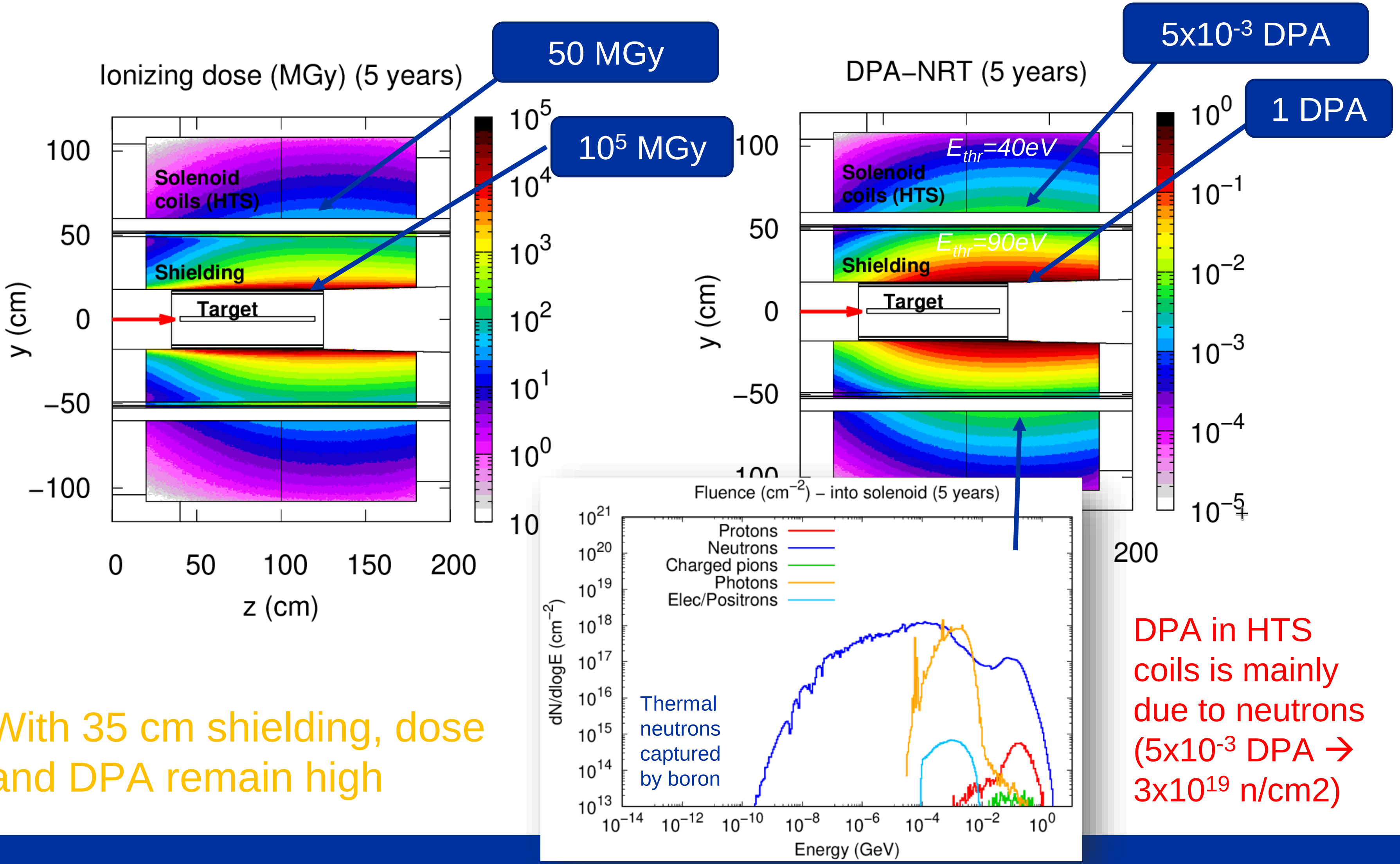
- **5 GeV proton beam (2 MW)** on **graphite target rod**
- Production of **charged pions →** captured by **solenoid** fields (20 T peak field at target) **→** decay into **muons**
- Only a tiny fraction of the power is converted into useful muons **→ most of the power dissipated in target area**
- **Significant radiation shielding needed to protect magnets**

Radiation to solenoid around π/μ production target

J. Manczak, D. Calzolari

*Cumulative dose and DPA around target with **35 cm shielding** (after 5 yrs):*



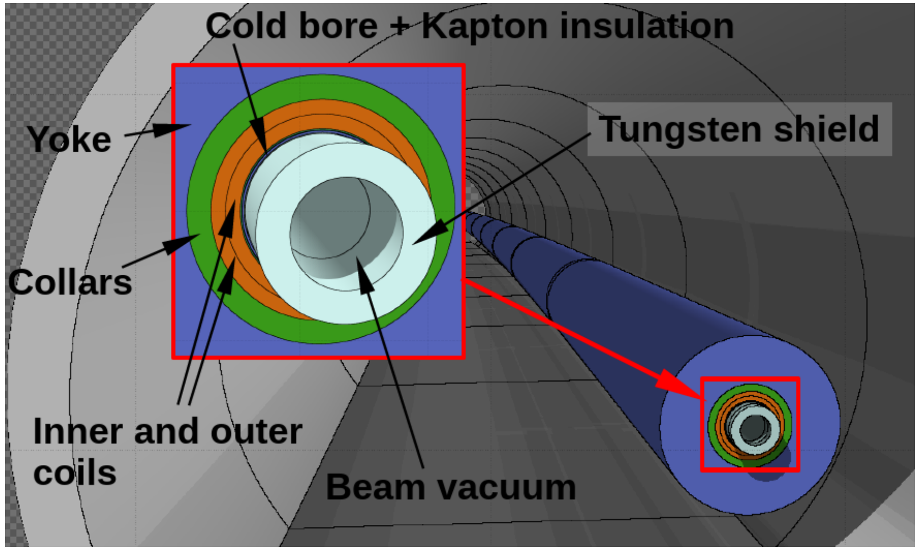


With 35 cm shielding, dose and DPA remain high

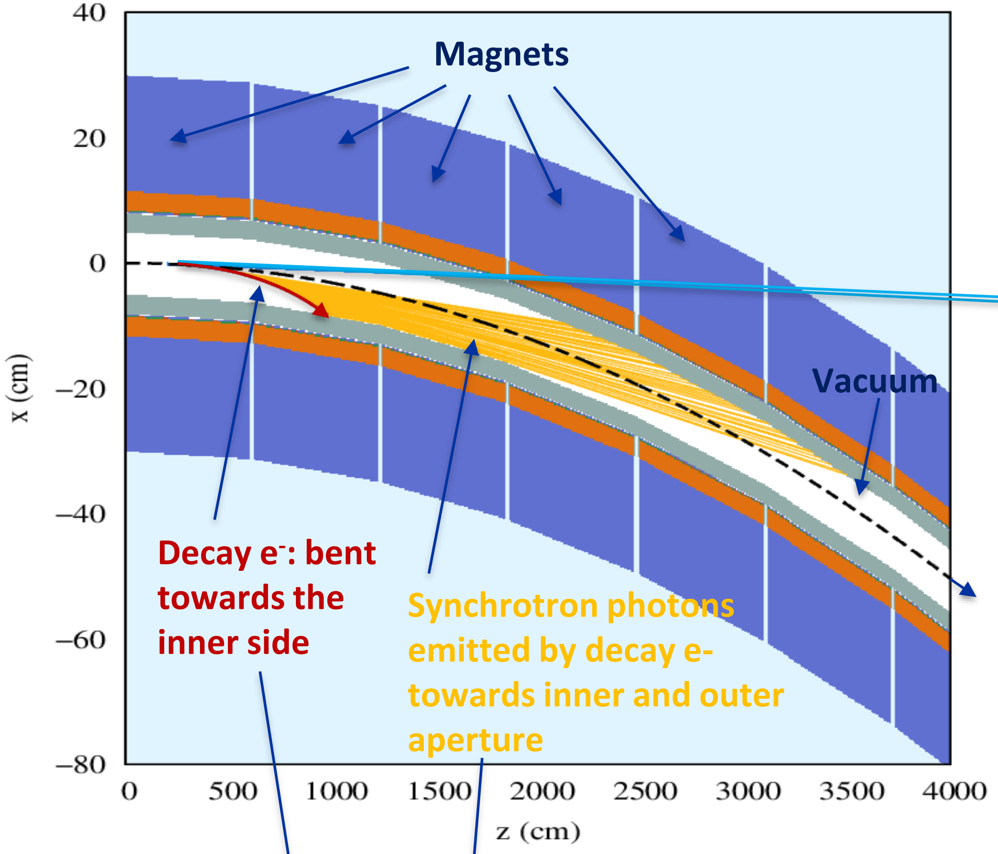
DPA in HTS coils is mainly due to neutrons (5×10^{-3} DPA → 3×10^{19} n/cm2)

Assuming 5 years with 140 days of operation per year

Radiation to muon collider ring magnets



- Collider ring: circumference of **10 km, B=16T**
- **Muons are unstable → τ_{av}=0.1s** at **5 TeV**
- Decay $e^{-/+}$ are a very significant source of radiation in the collider ring → **500 W/m**
- **Continuous shielding inside magnets needed along the full ring to reduce heat load and radiation damage**



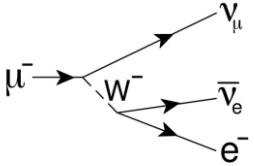
Picture shows the horizontal plane of a generic arc section (dipoles only)

Decay neutrinos: irrelevant for radiation load to machine

Similar picture applies to μ+

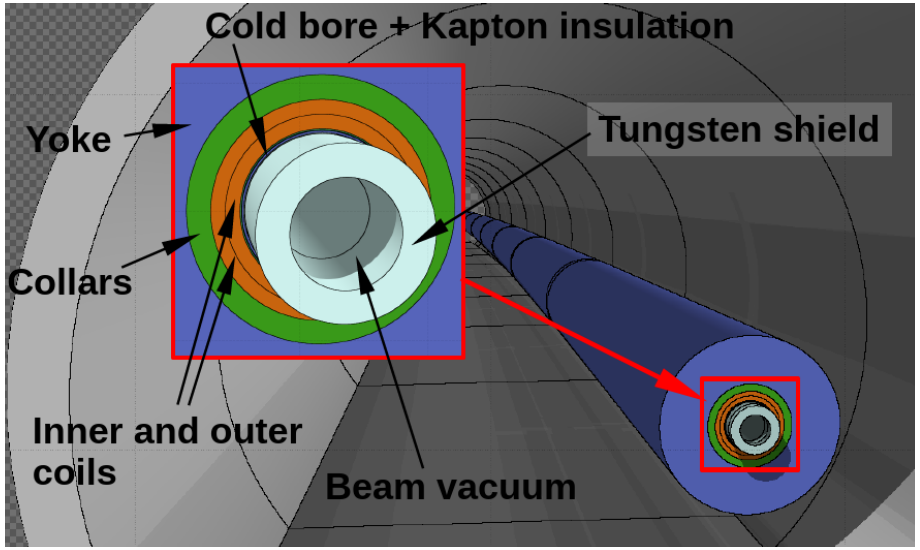
Inside magnets:

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



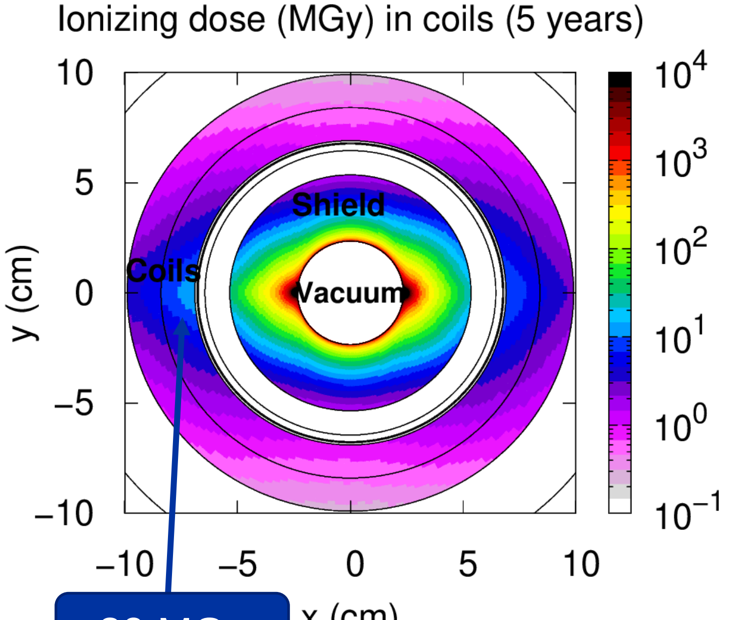
e^- carries on average 35% of muon energy

Radiation to muon collider ring magnets

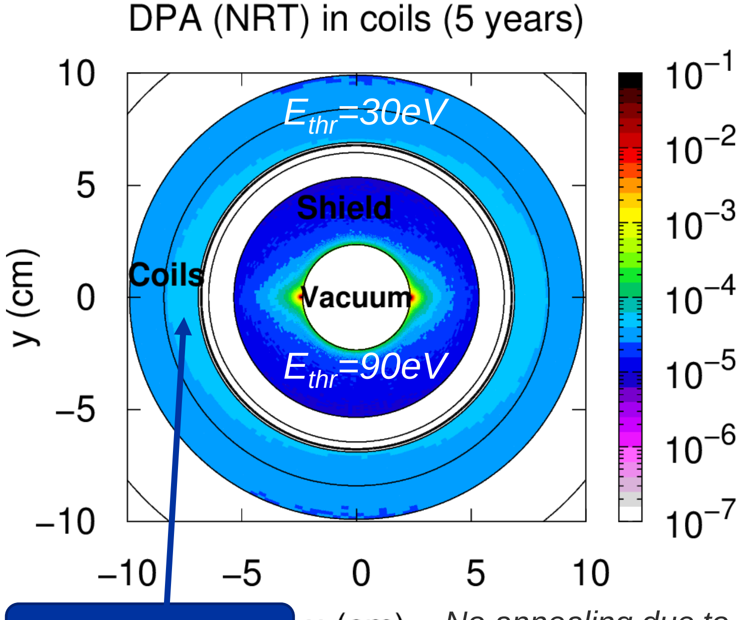


*Cumulative dose and DPA in coils of arc dipoles after 5 yrs (with **3 cm thick tungsten shielding**):*

Assuming 5 years with 140 days of operation per year

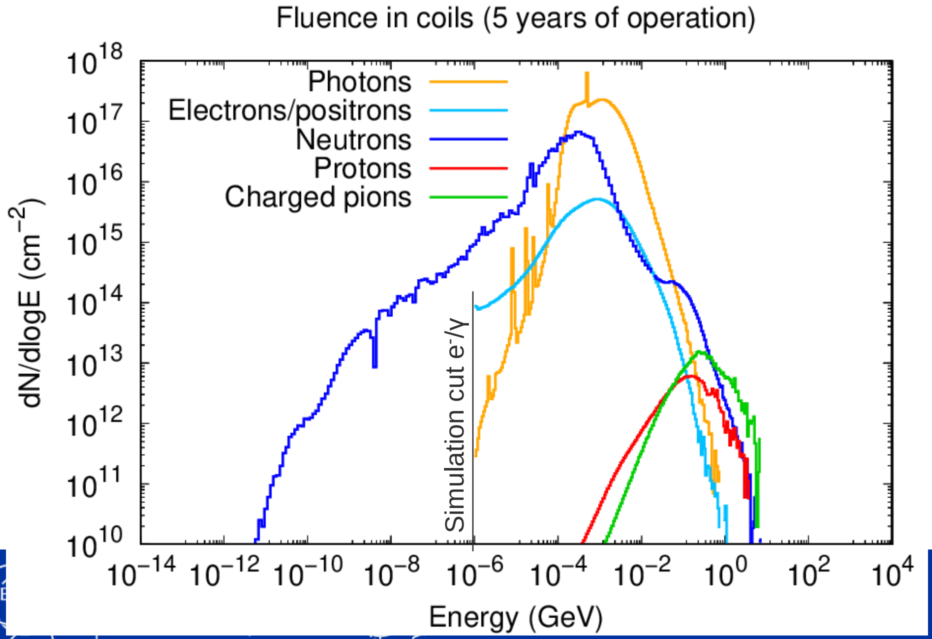


20 MGy



$<10^{-4}$ DPA

No annealing due to thermal cycles of magnets considered



With 3 cm shielding, dose and DPA acceptable

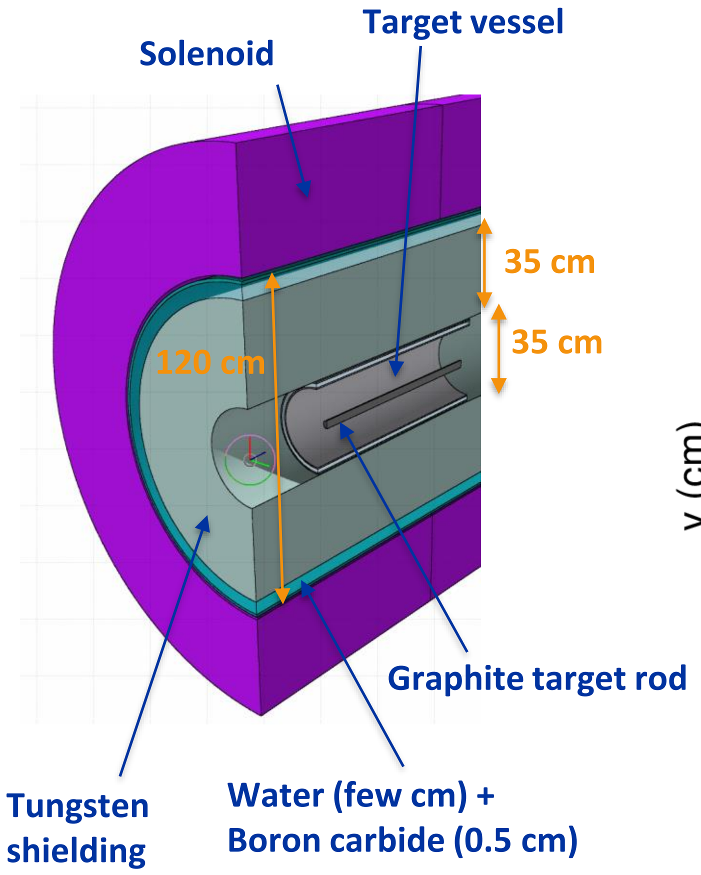
DPA in HTS coils is mainly due to neutrons (10^{-4} DPA → 2×10^{17} n/cm^2)

Conclusions

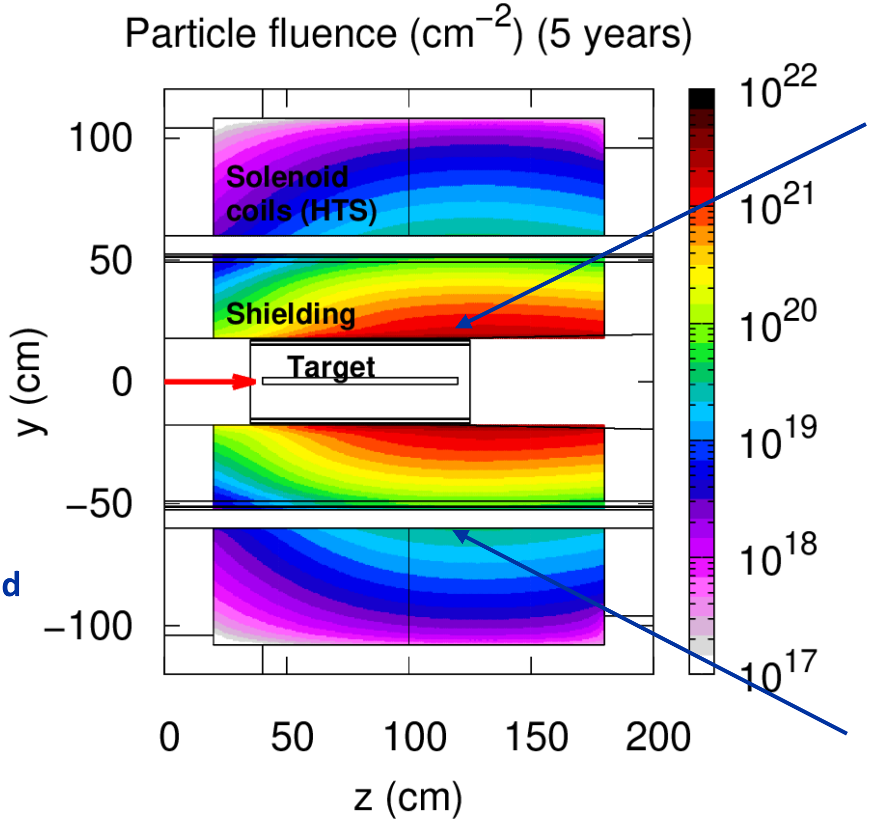
- Superconducting magnets in high-energy collider facilities are exposed to mixed radiation fields (hadrons, electrons/positrons, photons)
- Radiation damage studies (Monte Carlo transport simulations) are essential from the early design phase of a machine
- I many cases, the ionizing dose in the coils (insulation materials) is driven by secondary photon/electron fields produced in secondary EM cascades
  - ➢ can reach excessive values, but can often be well reduced with shielding
- Displacement damage in superconductors is often dominated by secondary neutrons despite the mixed radiation fields
  - ➢ shielding evidently more difficult; understanding of acceptable limits is essential for the design of new collider facilities

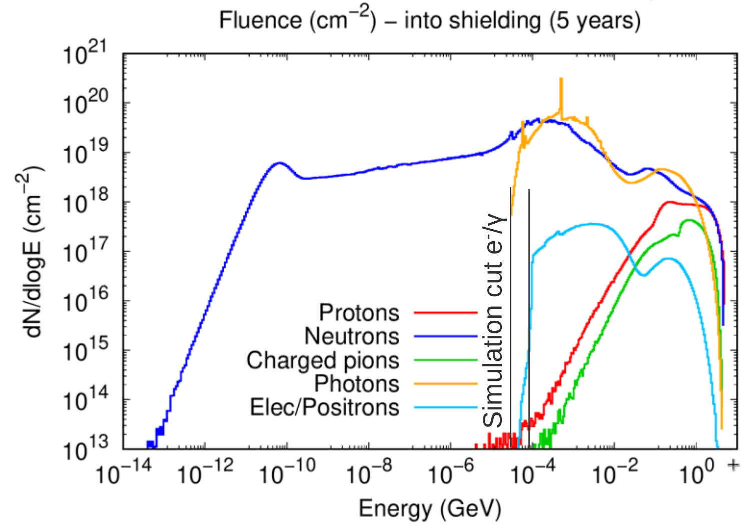
home.cern

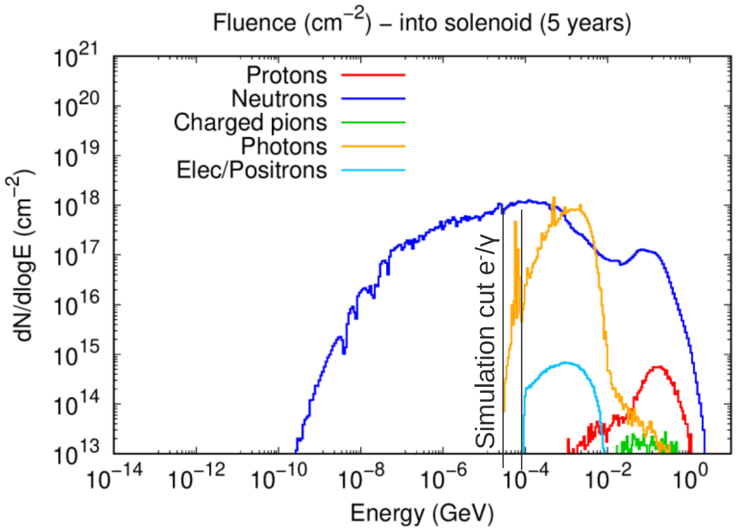
Radiation to solenoid around π/μ production target



Secondary particle fluence around target:







Assuming 5 years with 140 days of operation per year

Comparison of selected circular colliders

	Operational	Construction	Possible future project		Possible future project	
	Large Hadron Collider (LHC)		**Future circular colliders (FCC)**		**Muon Collider (MC)**	
	LHC (2024)	**HL-LHC**	**FCC-ee**	**FCC-hh**	**MC ($\sqrt{s}$=3 TeV)**	**MC ($\sqrt{s}$=10 TeV)**
Type	**Hadron collider**		**Lepton collider**	**Hadron collider**	**Lepton collider**	
Particle species	p*	p*	e-/e+	p*	μ-/μ+	μ-/μ+
Particle energy	6.8 TeV	6.8-7 TeV	45.6 … 182.5 GeV	40.5 – 57.5 TeV	1.5 TeV	5 TeV
Bunches/beam	2350	2760	11200 … 64		1	1
Bunch intensity	1.6x10^{11}	2.2x10^{11}	2.16x10^{11} … 1.48x10^{11}	1.0x10^{11}	2.2x10^{12}	1.8x10^{12}
Circumference collider ring	26.7 km		90.66 km		4.5 km**	10 km**
Collider ring magnets	Mostly **SC** [LTS (NbTi)]	Mostly **SC** [LTS (NbTi + few Nb3Sn magnets)]	Mostly **NC**, except final focus [LTS (NbTi) or HTS considered]	Mostly **SC** [LTS (Nb3Sn) or HTS considered]	Mostly **SC** [LTS (Nb3Sn) or HTS considered]	Mostly **SC** [LTS (Nb3Sn) or HTS considered]
Dipole field collider ring (arcs)	8.1 T	8.1-8.33 T	61 mT	14 T - 20 T	10 T	16 T
SC magnets in injector complex and transfer lines?	None		Only for positron source (solenoid) [HTS]	Possibly for pre-accelerators and transfer lines	In front-end, cooling section, and accelerators	

* Also ion collider (parameters not shown)

** The rapid cycling synchrotrons of the injector have a larger circumference