FUTURE CIRCULAR COLLIDER

FCC-ee Radiation and Shielding Meetings:
https://indico.cern.ch/category/17958/

Radiation and shielding in the FCC-ee arcs

A. Lechner, B. Humann, A. Frasca, G. Lerner, R. Garcia Alia, M. Calviani, A. Perillo Marcone, S. Gilardoni, R. Kersevan, M. Mauro, C. Garion, J. Bauche, L. van Freeden, C. Jaermyr Eriksson, M. Widorski, G. Lavezzari, F. Valchkova-Georgieva, F. Carra, J.P. Burnet, S. Mazzoni, J. Gascon, and many more colleagues

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Introduction

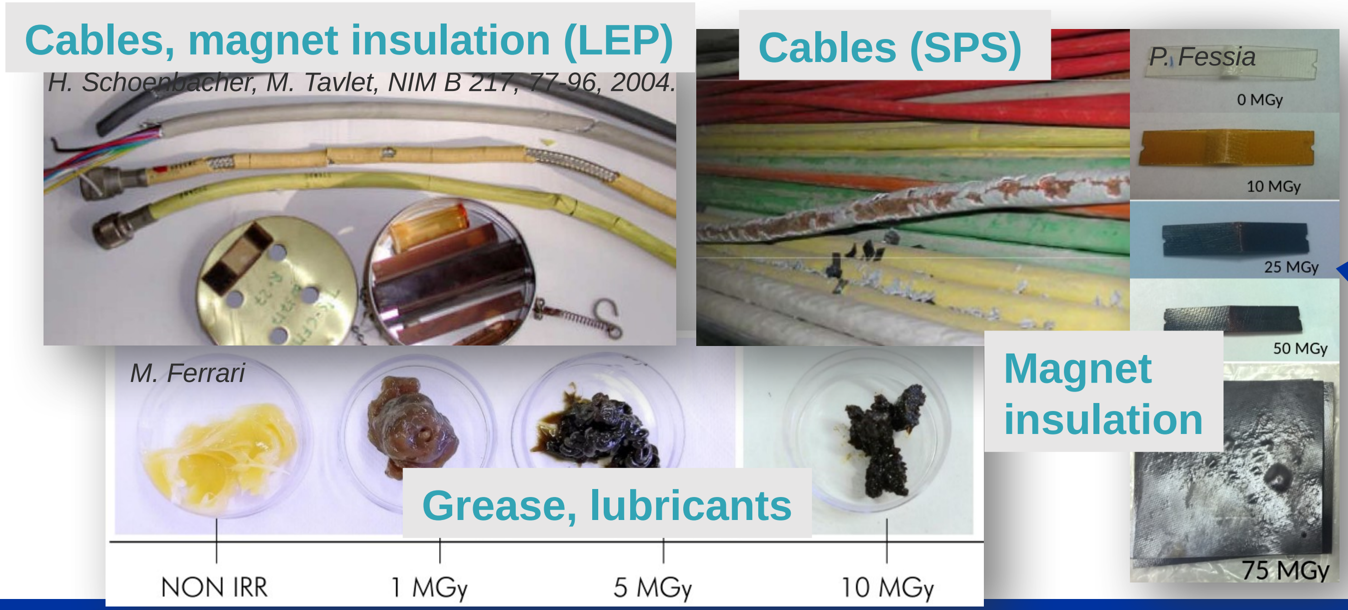
- **The radiation environment generated by synchrotron photons is a significant concern in FCC-ee**

- **Radiation can affect various machine components and other equipment in the tunnel**
    - Need to avoid equipment failures due to cumulative radiation damage
    - Need to avoid a degraded machine performance (e.g. single event effects)

- **Requires a concerted effort to find technically sound (and cost-effective) solutions**
    - **Decrease the overall radiation levels through additional shielding**
    - This shall reduce the need of (expensive) radiation-hard equipment
    - Nevertheless, some radiation-hard components/equipment will likely not be avoidable

Context: radiation effects in equipment

- **One of the main concerns in FCC-ee is the cumulative ionizing dose in machine components and equipment in the tunnel**
  - Affects organic materials (magnet insulation, cable insulation, optical fibers, seals, grease, lubricants etc.) and electronics → can limit the lifetime of equipment
- **Other instantaneous & cumulative radiation effects also have to be thoroughly assessed**
  - For example, single event effects, atomic displacements, radiation-induced corrosion etc.



In this presentation, the main focus is on the ionizing dose

Ionizing dose [Gy]

Can change mechanical, electrical and optical material properties of organic materials, can damage electronics

Typical dose limits

Sensitivity to ionizing dose depends strongly on type of equipment, for example:

- **Organic insulation of magnet coils/bus bars**
  - Typically **few 10s of MGy**
- **Insulation and sheating materials of cables***
  - Standard cables (Cat 1): up to **100 kGy** (to be qualified up to **500 kGy****)
  - Rad-tol cables (Cat 2): up to **700 kGy** (to be qualified up to **3.5 MGy****)
  - Rad-hard cables (Cat 3): up to **2 MGy** (to be qualified up to **10 MGy****)

Significantly higher cost, less choice

- **Electronics**
  - Rad-tol design based on Commercial-Off-The-Shelf (COTS) components: up to **0.5-1 kGy**
  - Rad-hard design based on Application-Specific Integrated Circuits (ASICs): typically **10 MGy**

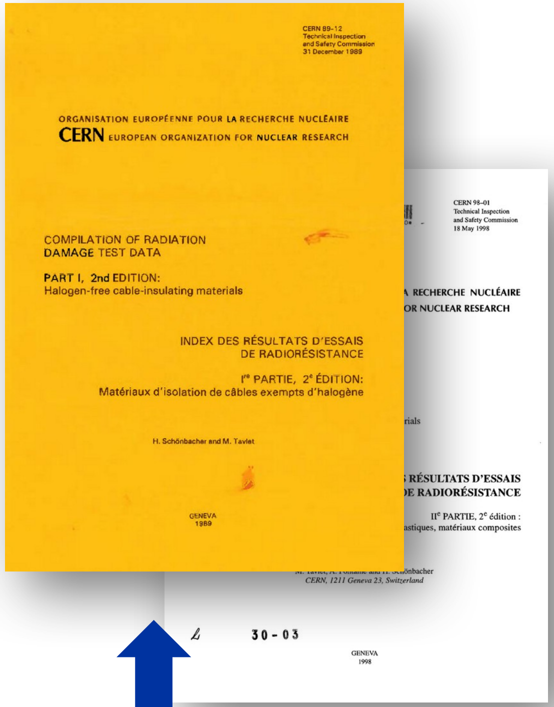
Longer development time and higher cost (cost strongly depends on the number of systems)

**See CERN Safety Guideline SG-FS-2-1-1 (EDMS 2669629), "Fire safety and radiation resistance requirements for cables"*

***Safety factor of 5 due to higher dose rate in irradiation tests*

Ionizing dose: examples from LEP

[1] H. Schoenbacher, M. Tavlet, Absorbed doses and radiation damage during the 11 years of LEP operation, NIM A 2017, pp 77-96, 2004
[2] G. de Rijk, "The LEP Magnet System at 100 GeV (or more)", Chamonix 1999.



Optical fibers [1]:

Standard optical fibre cables were installed in the tunnel on the side cable trays from the beginning. Loss of signal intensity, due to fibre darkening, was observed immediately at the start-up even at 45 GeV when the beam intensity was at low energy. The cables could no longer be used after only a few weeks. After this bad experience, more radiation-hard multi-

Covers of electrical junction boxes [1]:

The covers of electrical junction boxes installed on cable trays were made of translucent Makrolon (polycarbonate). They darkened with doses comparable to the ones absorbed by control cables, i.e., a few tens of kGy; they became brittle at a dose of about 500 kGy (see Ref. [10], Part 2, 2nd ed.).

Cables and cable connectors [1]:

In 1998, a red cable, of the type SVB 11, made by Intercond in 1986, was removed from cell 171 because of severe radiation damage. At its extremity towards the vacuum pump, the cable was very close to the beam pipe and presented important cracks on its outer sheath, while the inner insulations was brittle and fell apart. The maximum dose absorbed by this cable was of the order of 400 kGy [16].

During the 1999/2000 shut down, a campaign took place to cut the extremities of the control cables which came close to the beam pipe. This was decided because the degradation of the cables was severe at their connectors: the combination of radiation and mechanical stress damaged the sheath, while the open end of the cable allowed more radiation-oxidation of the inner insulations. Some 20 to 40 cm of cable extremities were cut, and the connectors were re-mounted on the less-damaged part of the cables.

At the decommissioning in 2001, some control cables were found severely damaged at places where absorbed doses exceeded some 300 kGy. The inner insulations of these cables were also heavily damaged; Fig. 17 shows a picture of some of these cables.

The multi-conductor cables (sheathed with polyolefins, made by Nokia and Pirelli) which were used as K-modulation coils on the quadrupole magnets were also found to be severely damaged. The levels of radiation absorbed by these cables are similar to those measured on quadrupole magnet coils, i.e., close to 1 MGy.

Interlock system [2]:

The LEP magnet coils each have a thermoswitch attached to provide an interlock protection against over-heating. Nearly 10000 thermoswitches are installed in the machine. These thermoswitches are sensitive to wear, due to the radiation dose. At present about 5 breakdowns per year occur. When this happens during the run this gives rise to several hours of downtime. The system is carefully

Significant effort to test beforehand dose limits of organic components, but some radiation damage due to SR was still unavoidable

LEP vs FCC-ee arcs: SR power

Indicative **peak value (beam current decreased from 98 GeV to 104.5 GeV)*

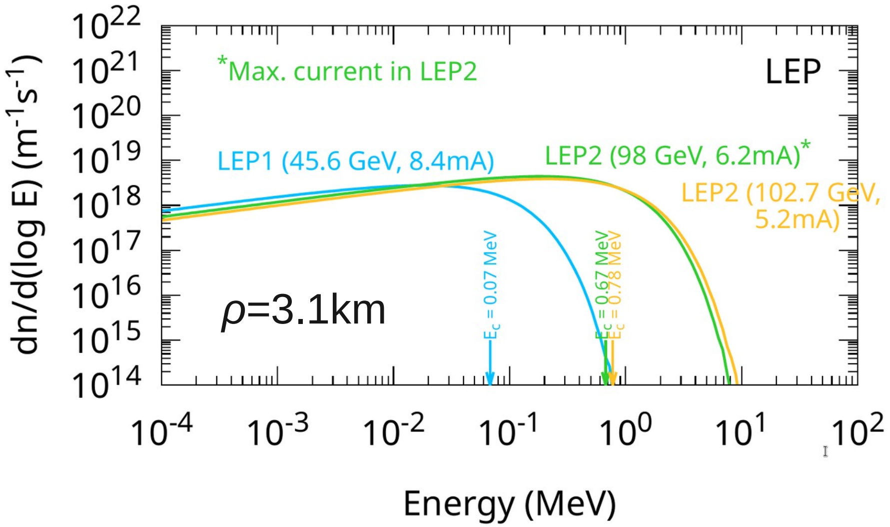
Energy loss per turn $U_0 \rightarrow E^4/\rho$

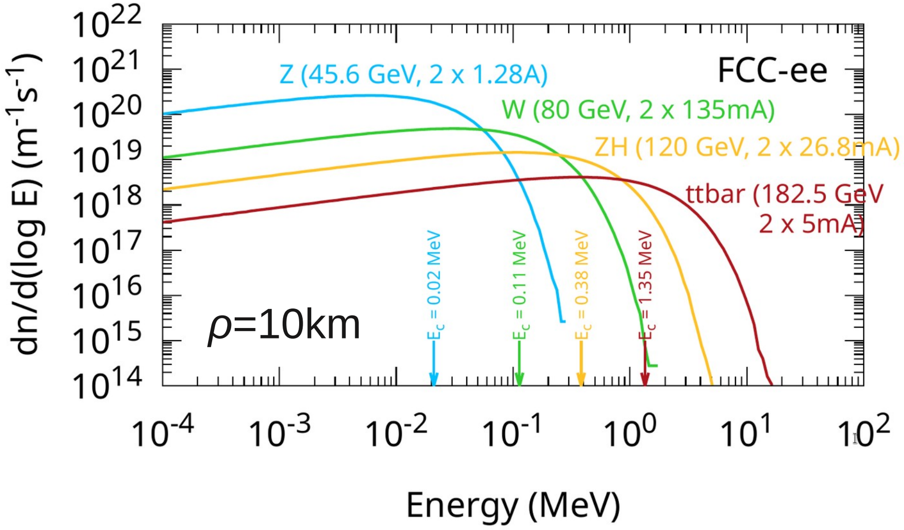
	LEP2 (1999-2000)	FCC-ee Z	FCC-ee W	FCC-ee ZH	FCC-ee ttbar
Beam energy E	98-104.5 GeV	45.6 GeV	80 GeV	120 GeV	182.5 GeV
Beam current I_b	6.2 mA (@98 GeV)	2 x 1280 mA	2 x 135 mA	2 x 27 mA	2 x 5 mA
Bending radius ρ	3.1 km	10 km			
Energy loss/turn (arcs) U_0	2.6 GeV (@98 GeV) 3.4 GeV (@104.5 GeV)	0.04 GeV	0.37 GeV	1.9 GeV	10.3 GeV
Power loss (arcs)	17 MW*	100 MW			
Total arc length	23 km	77 km			
Power loss/unit arc length	0.7 kW/m*	**1.3 kW/m**			

- **Power loss <u>per unit arc length</u> about two times higher in FCC-ee than in LEP2**
- **Also note that the <u>integrated power matters</u> for <u>cumulative radiation effects</u>:**
  - LEP was a cycling machine → beam current decayed during fills, time needed for turn-around
  - FCC-ee will use top-up injection → **always at max current, integrate more power over time**

LEP vs FCC-ee arcs: SR spectra and critical energy

Emitted SR photons per meter and second:

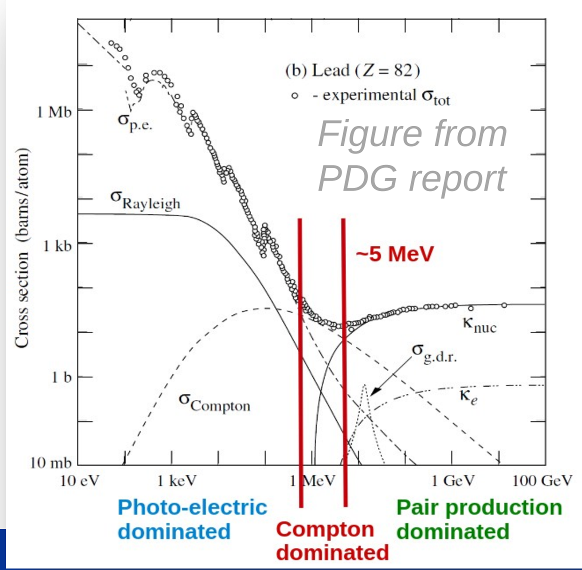




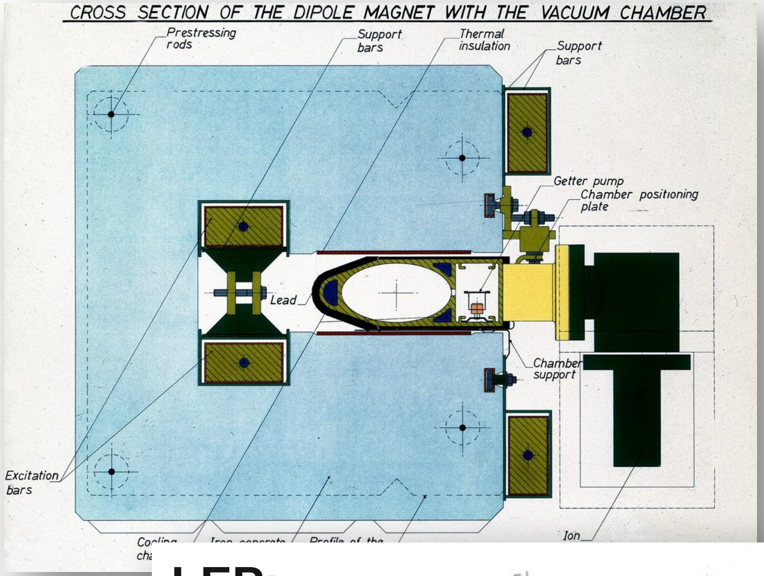
Critical energy $E_c \rightarrow E^3/\rho$

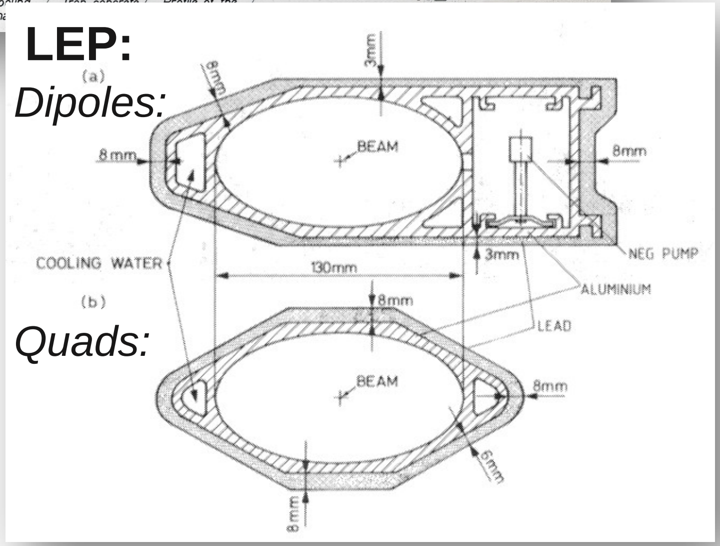
	LEP2 (1999-2000)	FCC-ee Z	FCC-ee W	FCC-ee ZH	FCC-ee ttbar
E	98-104.5 GeV	45.6 GeV	80 GeV	120 GeV	182.5 GeV
ρ	3.1 km	10 km			
E_c	0.7 – 0.8 MeV	0.02 MeV	0.1 MeV	0.4 MeV	**1.35 MeV**

Higher photon energy = reduced shielding efficiency



LEP vs FCC-ee arcs: intercepting SR photons





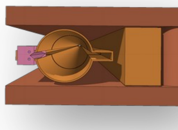
LEP:

- SR photons impacted directly on water-cooled Al vacuum chambers
- A **continuous Pb shielding** (**3-8 mm**) was cladded on the chambers to reduce the radiation leakage

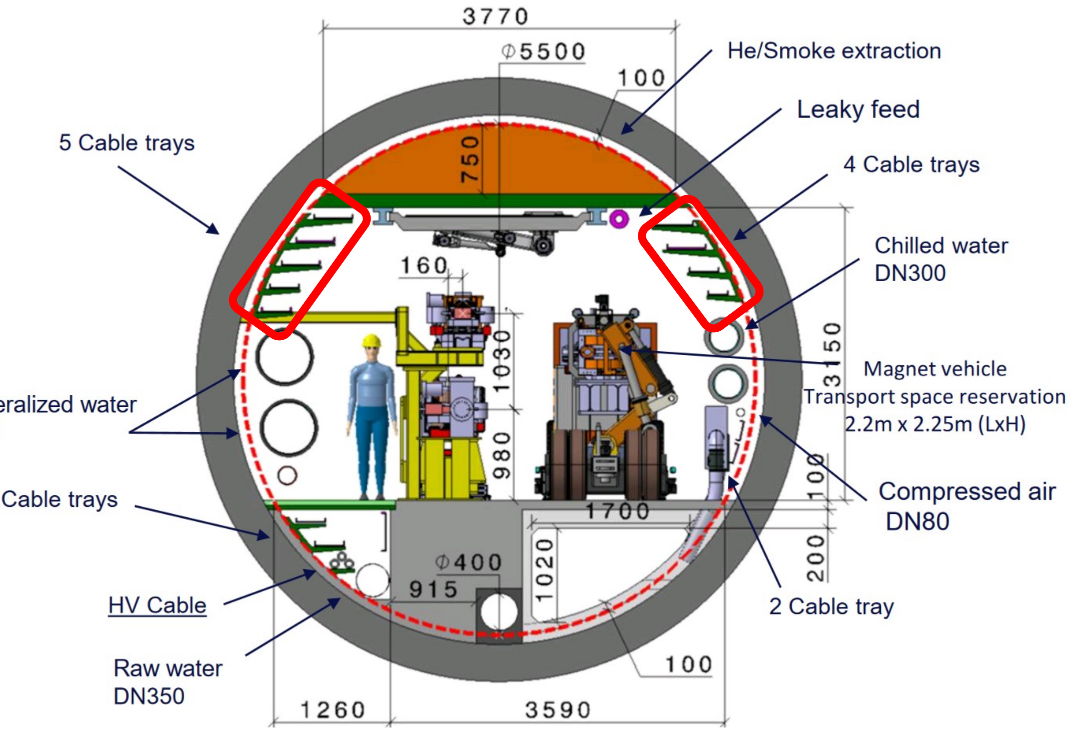
FCC-ee: *(see presentation of M. Mauro in this session)*

- **Discrete photon stoppers** made of **copper-alloy (CuCrZr)** intercept the primary SR fan (stopper length: about 30 cm)
- Placed in the winglets of the Cu vacuum chamber of dipoles (typical distance between stoppers: 4-5 meters), shadowing also the SSS
- The radiation leakage from the photon stoppers **becomes important at higher beam energies**

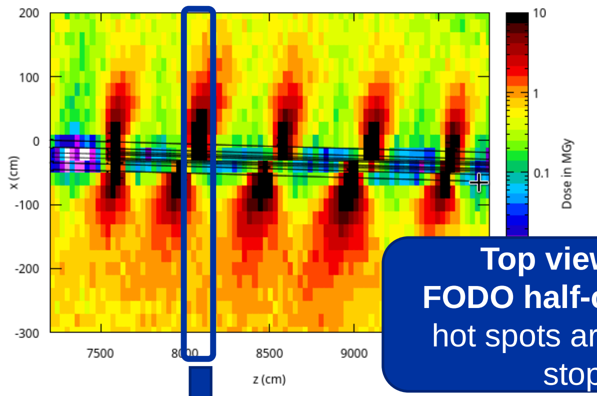
Annual ionizing dose in FCC-ee arc tunnel



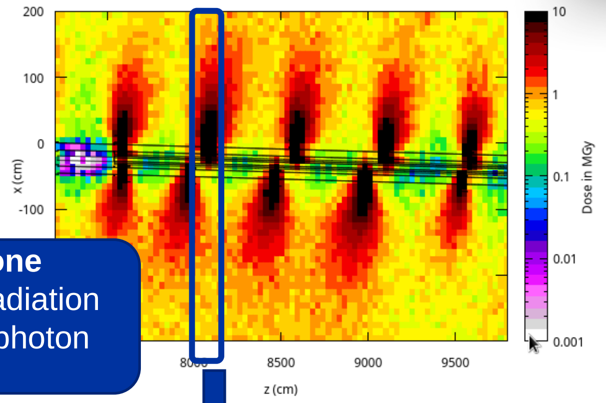
- Annual ionizing dose is excessive for equipment, **both at ZH and ttbar**
- **Need a significant reduction** of the radiation levels through **additional shielding**



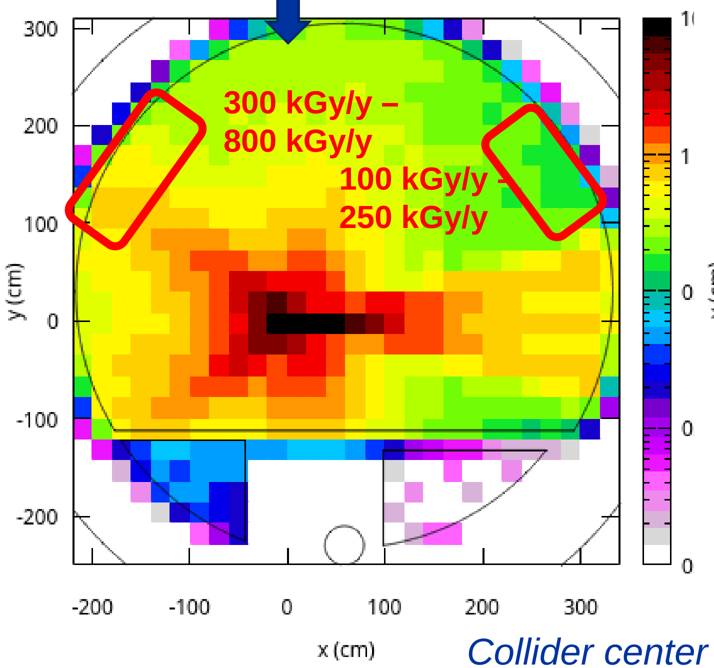
ZH (120 GeV):

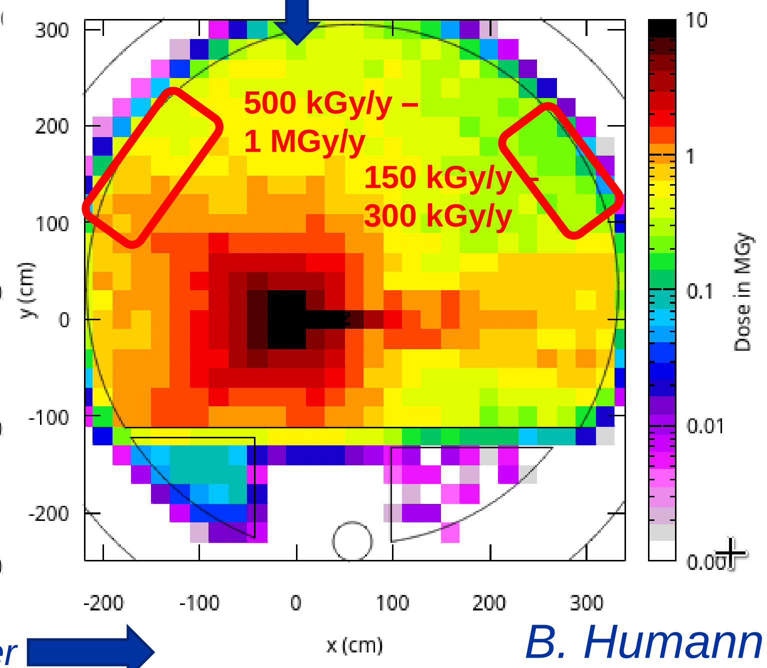


ttbar (182.5 GeV):



Top view on one FODO half-cell: radiation hot spots around photon stoppers



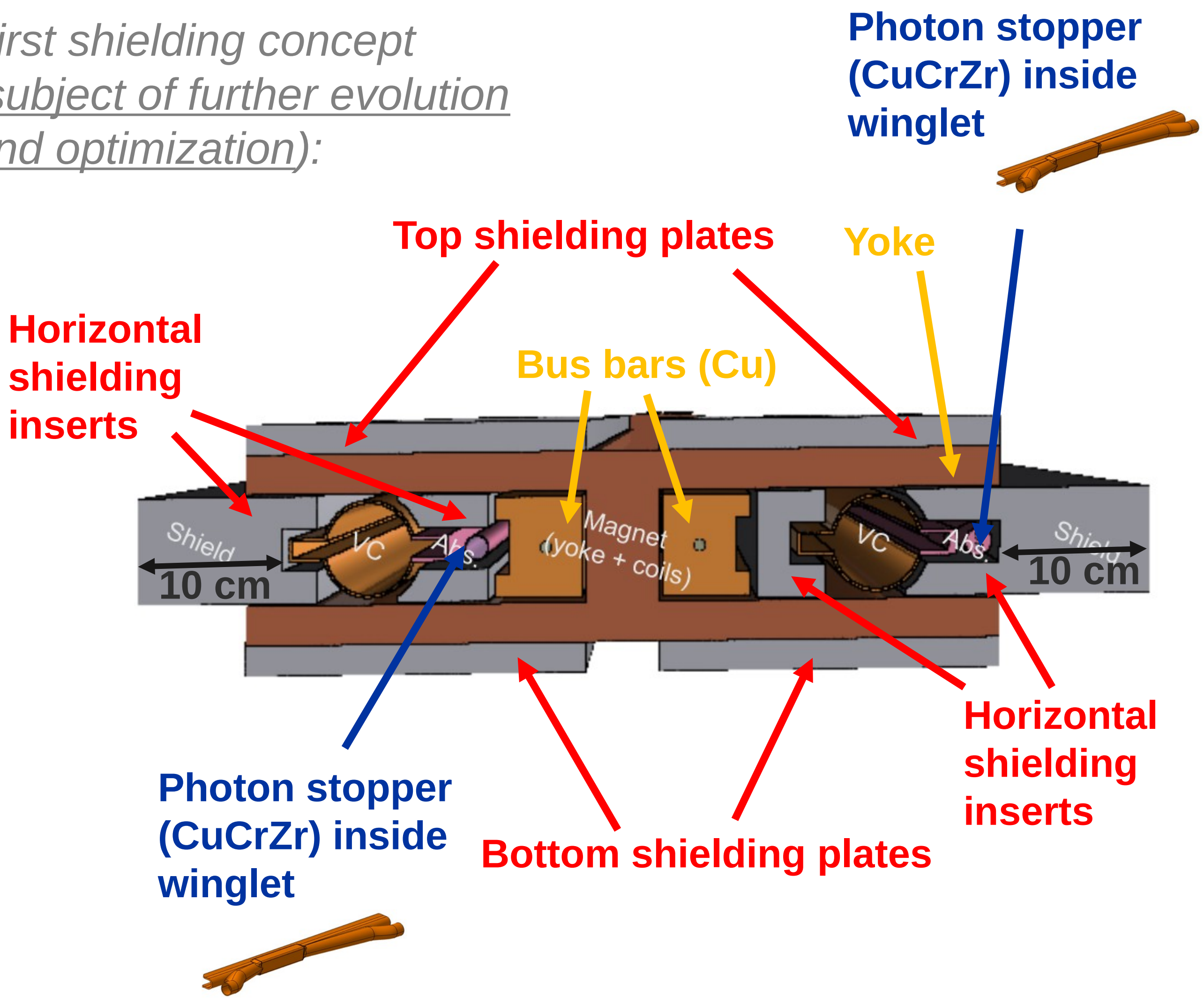


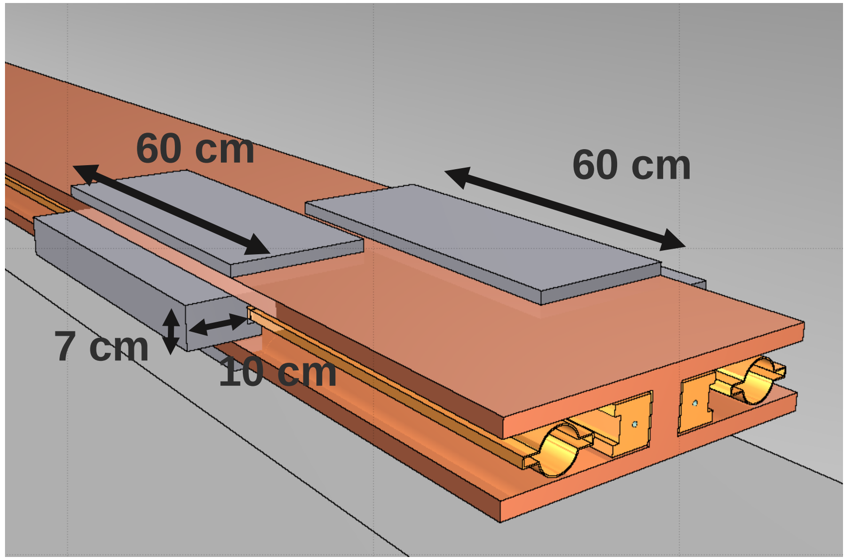
Collider center →

B. Humann

Tentative shielding concept

First shielding concept (subject of further evolution and optimization):





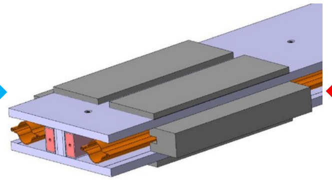
- Each photon stopper enclosed by horizontal shielding inserts + top & bottom shielding plates
- Shielding should have at least double the length of the photon stoppers
- **Tentatively assumed Pb-based shielding material** (dimensions/weight will depend on final material choice)

Considerations about shielding material

Material selection is a trade-off between:

Shielding efficiency (prefer high density)

Engineering aspects (fabrication, machining, cooling, ...)

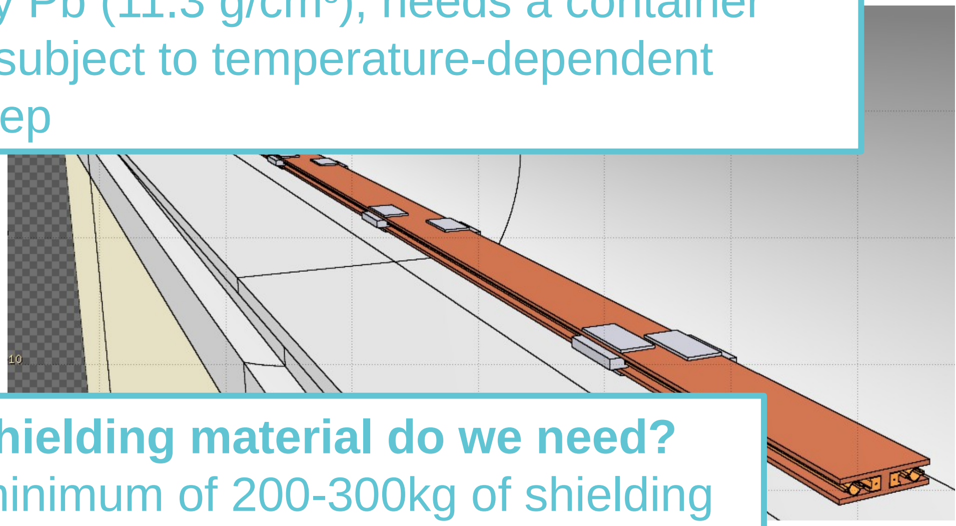


Raw material costs and material availability

Radiation protection considerations and radioactive waste production (impurities matter)

Possible materials: *High density, but expensive…*

- W-heavy alloys (17-18.5 g/cm³), typically >90%W in Ni,Fe or Ni,Cu matrix
- PbSb alloys (9-10 g/cm³), fraction of Sb can vary
- High-purity Pb (11.3 g/cm³), needs a container since it is subject to temperature-dependent plastic creep



How much shielding material do we need?

- Expect a minimum of 200-300kg of shielding per photon stopper
- 10 photon stoppers per dipole x 2840 dipoles
- *Need at least **5500 to 8500 tons****

**Estimate only for arcs, does not include IRs*

Need to consider real material compositions, including trace amounts

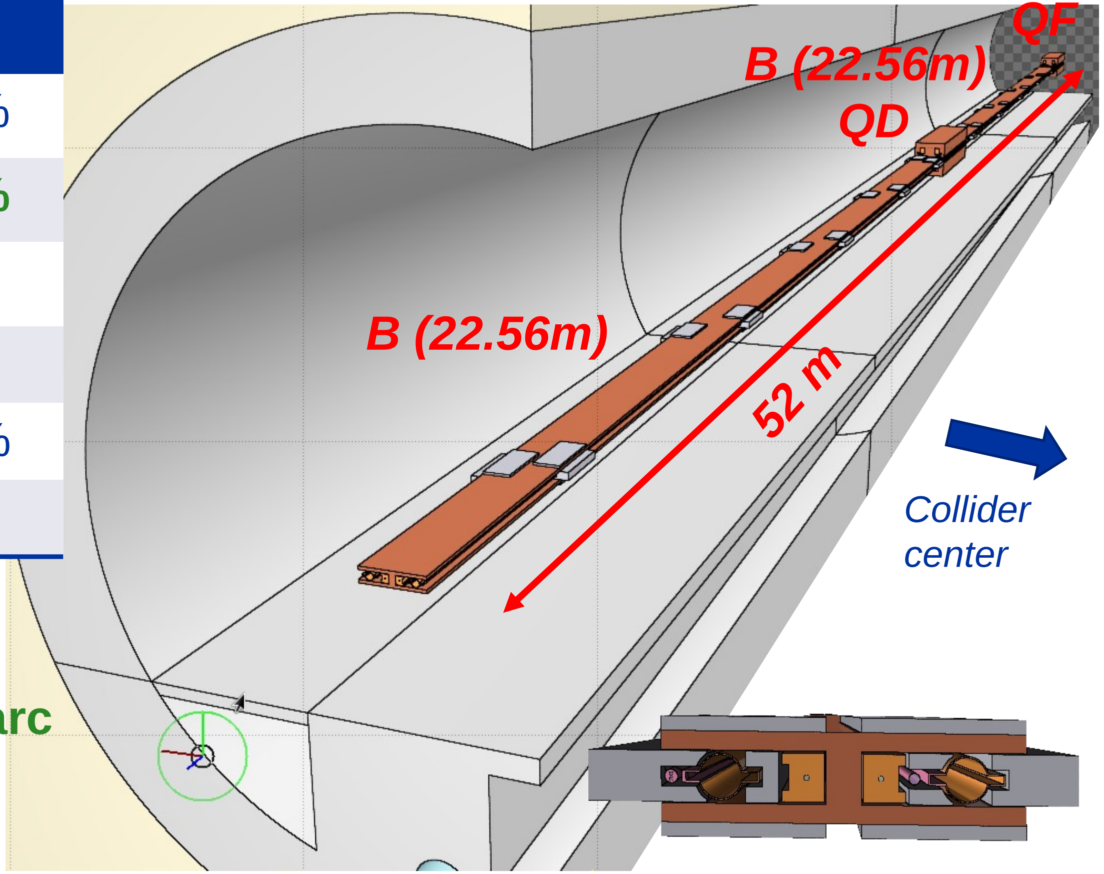
SR-induced power deposition in the FCC-ee arcs

Relative power deposition with and w/o radiation shielding:*

	ZH (120 GeV)		ttbar (182.5 GeV)	
Radiation shielding:	*w/o*	*with*	*w/o*	*with*
Photon stoppers	74.3%	74.0%	70.1%	69.8%
Radiation shielding	N/A	**19.4%**	N/A	**21.6%**
Vacuum chambers	3.3%	3.0%	3.5%	3.3%
Dipoles	17.0%	3.2%	18.6%	4.3%
Quadrupoles	<0.1%	<0.1%	<0.1%	<0.1%
Environment	**5.3%**	**0.4%**	**7.8%**	**1.0%**

0.7 MW/arc **0.05 MW/arc** **1 MW/arc** **0.13 MW/arc**

5 photon stoppers per dipole and per beam
→ 20 photon stoppers in FODO cell



Studied one type of FODO cell (w/o sextupoles) of GHC lattice, results can be somewhat different for other cells*

B. Humann

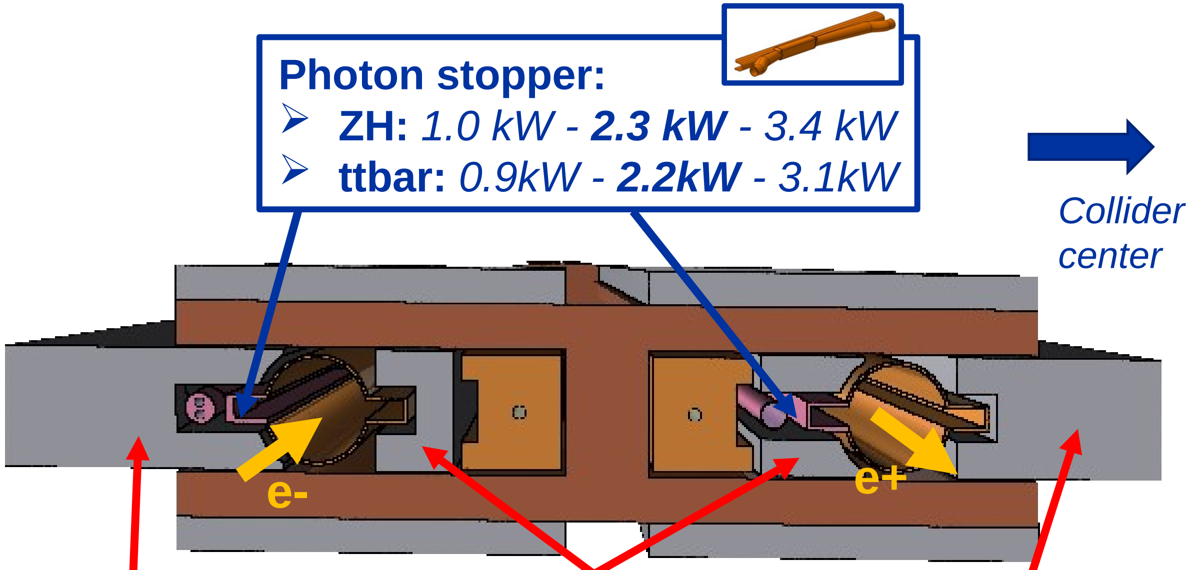
Power absorption in photon stoppers and shielding

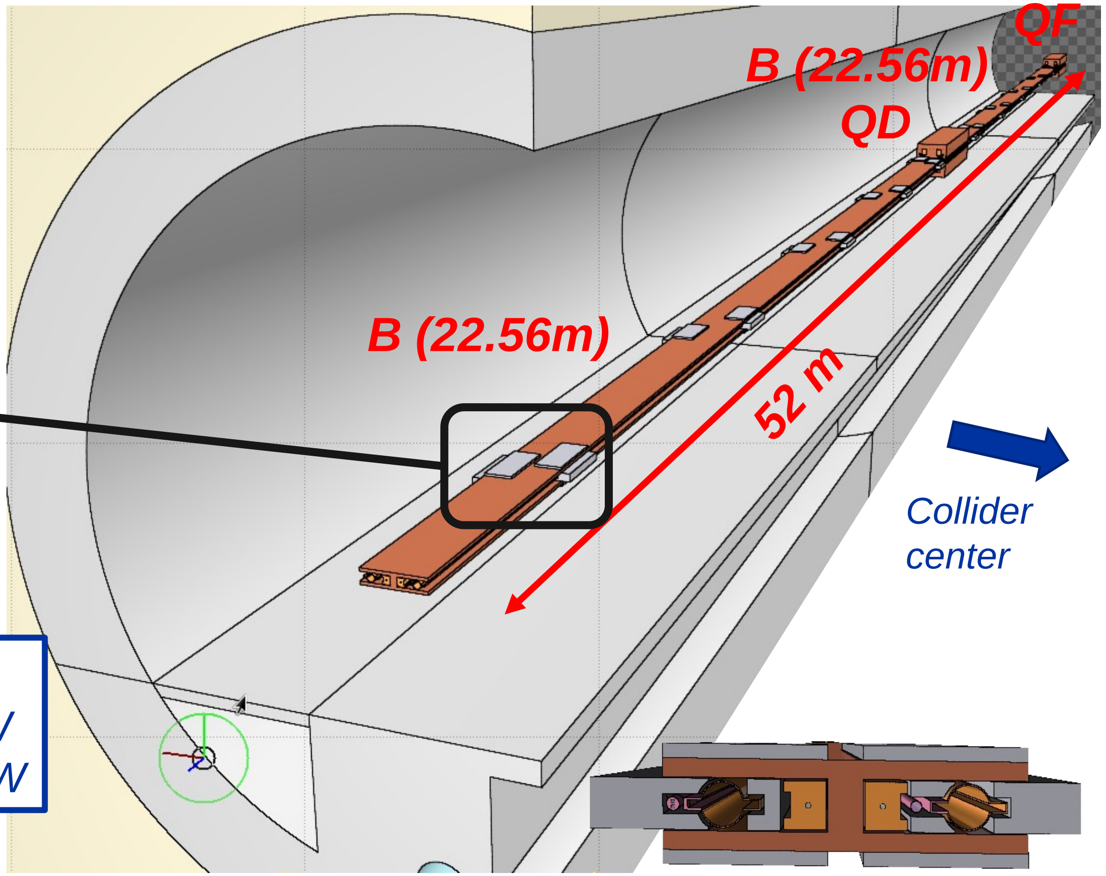
*Power absorption **per** photon stopper and radiation shielding (min-**average**-max):*

Absorbed power depends on longitudinal position (varies along cell)

5 photon stoppers per dipole and per beam
→ 20 photon stoppers in FODO cell

Photon stopper:
- **ZH:** *1.0 kW - **2.3 kW** - 3.4 kW*
- **ttbar:** *0.9kW - **2.2kW** - 3.1kW*





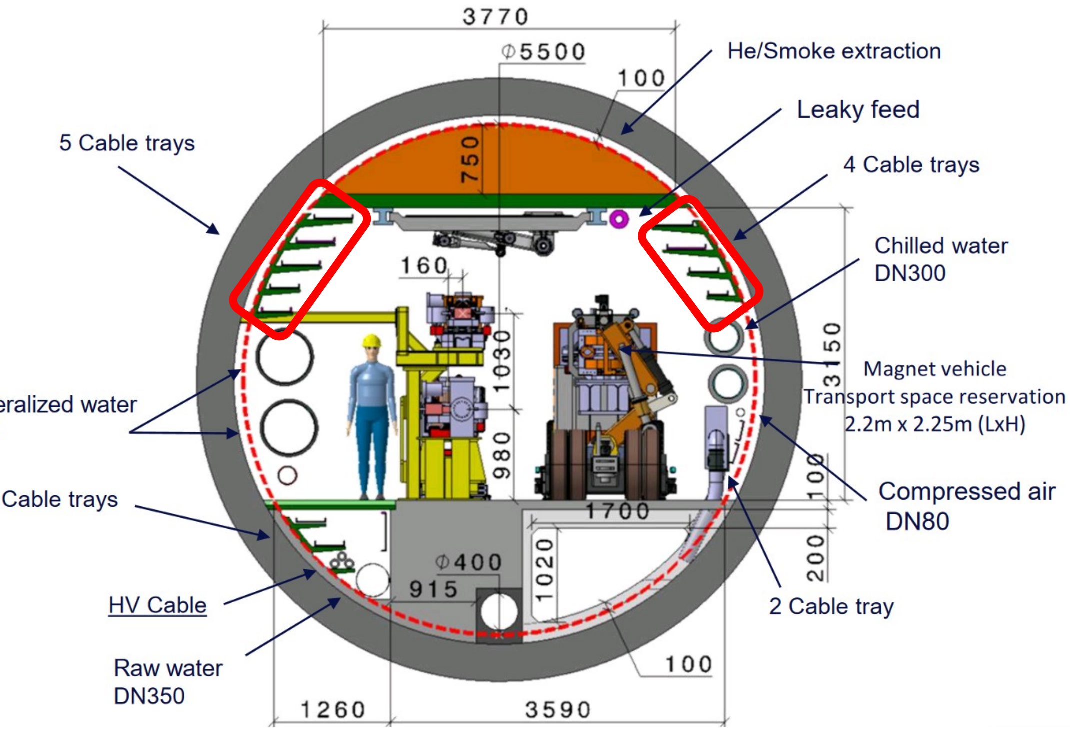
Shielding (external wrt beam):
- **ZH:** *0.4kW - **0.5kW** - 0.7kW*
- **ttbar:** *0.4kW - **0.6kW** - 0.8kW*

Shielding (internal wrt beam):
- **ZH:** *0.05kW - **0.12kW** - 0.17kW*
- **ttbar:** *0.06kW - **0.13kW** - 0.2kW*

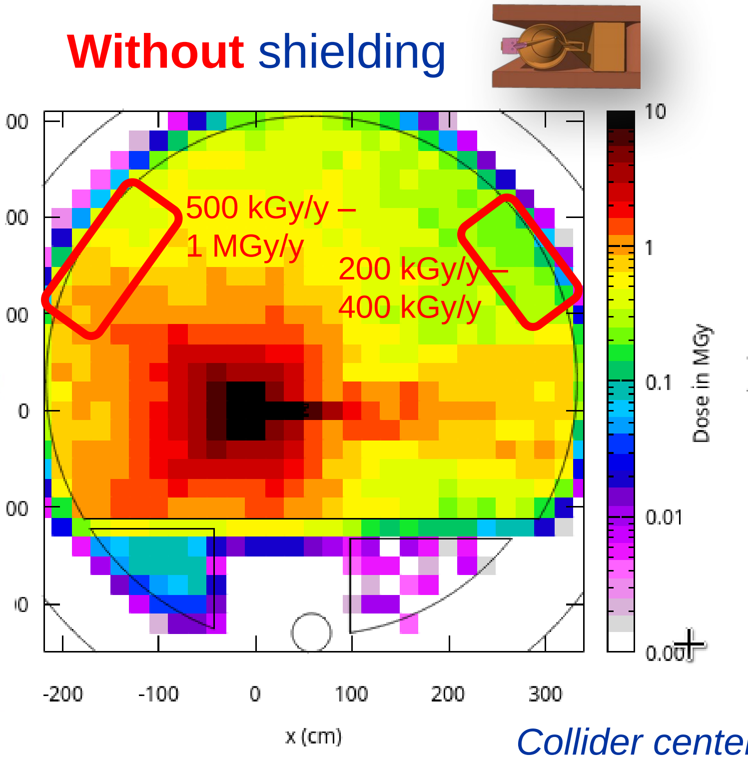
→ Shielding needs to be actively cooled (like the photon stoppers)

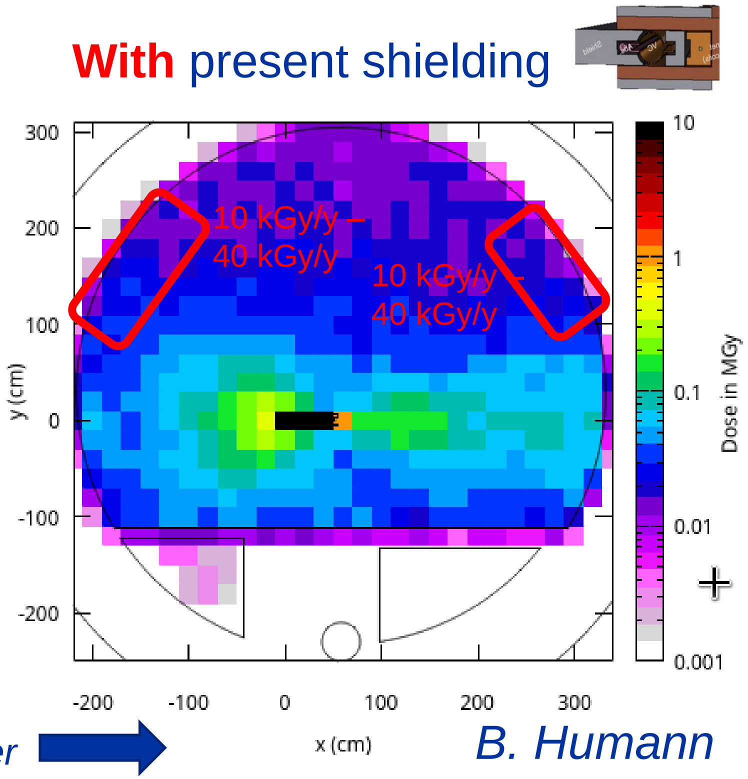
Annual ionizing dose with shielding (ttbar)

- The proposed shielding shows a promising but not yet sufficient reduction of the annual dose levels
- A further improvement of the shielding efficiency is needed → need to work on shape, dimensions, material budget of the shielding



ttbar (182.5 GeV):



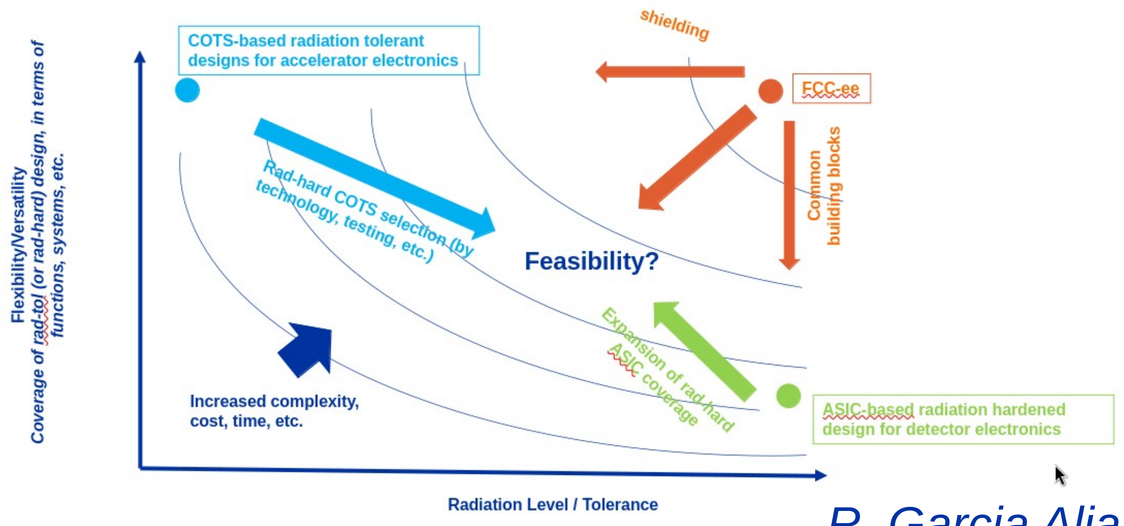


Collider center →

B. Humann

What target dose values should we aim for?

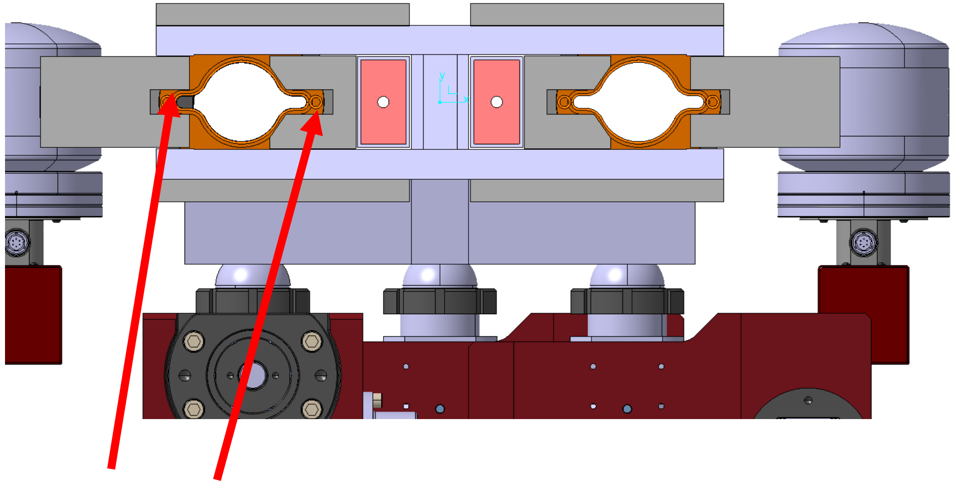
- **The exact shielding requirements need to be elaborated further in the Radiation and Shielding WG**
- **A first few considerations:**
  - For **machine components** (e.g. dipole busbar insulation) or **equipment near the machine** (e.g. cables and cable connectors for BPMs, vacuum gauges, pumps), rad-hard solutions are likely unavoidable even with radiation shielding; nevertheless the shielding is still beneficial for these components
  - It seems possible to reduce the cumulative ionizing dose for most **cable trays** to <100 kGy for the full collider lifetime (<10 kGy per year for ttbar), which **shall allow the use of Cat 1 cables**
  - For **electronics** (e.g. racks for beam instrumentation, vacuum equipment), it is **still unclear** if dose levels compatible with **COTS-based systems** are in reach (which would require <1kGy for the full collider lifetime, or <100 Gy per year of ttbar)
    - *We will explore locally shielded volumes at quadrupoles possibly integrated into the girder*
    - In any case, need an integral approach to FCC-ee electronics design, as shown in the sketch



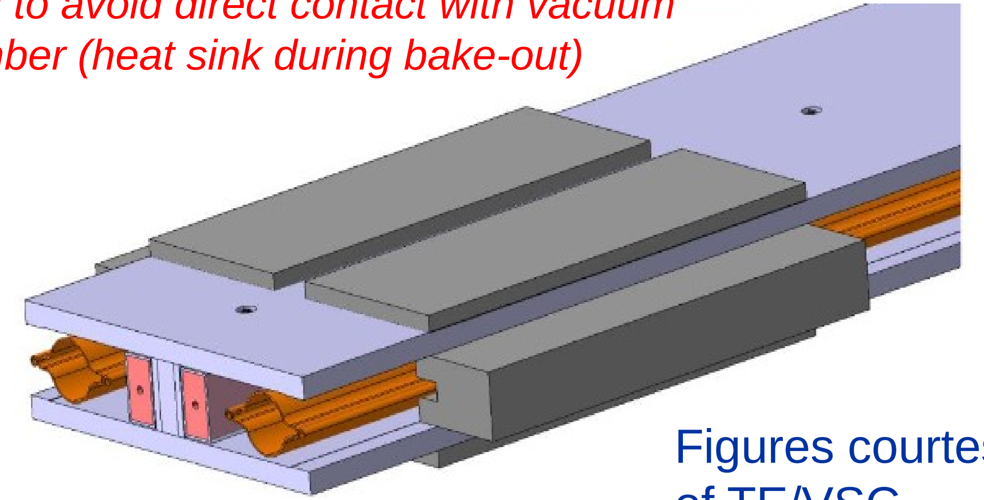
R. Garcia Alia

Technical shielding design & integration

- **Some of the high-level objectives for the <u>technical</u> shielding design in 2024:**
  - Cost estimate for shielding → important input for FCC feasibility study
  - Define space requirements and integration of shielding in the magnets
- **Next steps:**
  - **Material selection and shielding optimization**
  - Mechanical shielding design including thermal simulations and cooling circuit design
  - Shielding integration, supports, assembly procedure, definition of tolerances and alignment requirements
  - Structural consideration for magnets and their supports considering the shielding weight of O(2-3 tons/20m)



Need to avoid direct contact with vacuum chamber (heat sink during bake-out)

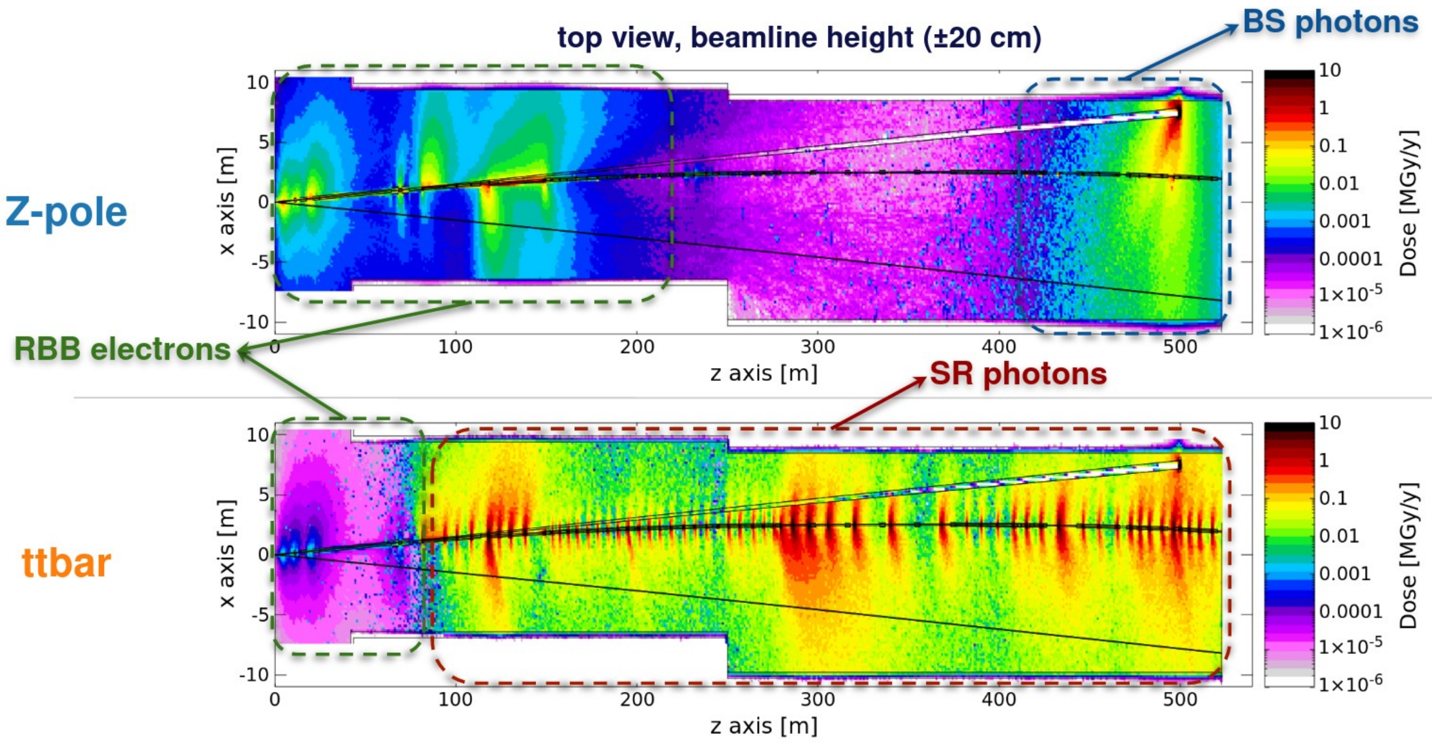


Figures courtesy of TE/VSC

Shielding needs in the insertion regions

- **Experiment IRs:**
  - Besides the arcs, the radiation levels are also significant in the tunnel of the experimental IRs
  - Different radiation sources contribute (see figure)
  - Need to develop dedicated shielding, following similar principles as for the arcs
- **Technical IRs**:
  - In addition to the experimental IRs, shielding might also be needed to the technical insertions
  - For the moment, do not have any estimates yet

Experimental IRs: annual ionizing dose due to radiative Bhabha electrons (RBB), Beamstrahlung (BS) and synchrotron radiation (SR) emission in magnets:

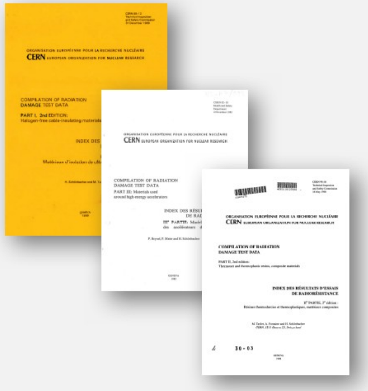


A. Frasca

Conclusions

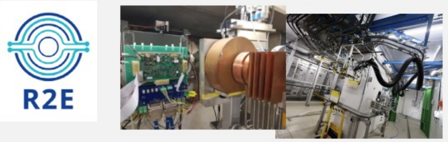
- **Radiation shielding is inevitable** for both **ZH** and **ttbar** operation modes; it is highly desirable that the shielding is installed for all operation modes to keep the dose levels as low as possible
- A first shielding design was proposed, which shows a promising but not yet sufficient reduction of the radiation levels in the tunnel
- A further improvement of the shielding efficiency is needed while considering at the same time **technical, financial and radiation protection aspects** related to the shielding design
- The exact shielding requirements need to be elaborated further in the Radiation and Shielding WG
- At the same, need an integral design approach for rad-hard FCC-ee equipment (in particular electronics)

From LEP times …



… to HL-LHC times, for example:

- R2E/M (Radiation to Electronics/Materials)



- CARE (Cable Ageing Research project)

Radiation effects assessment and equipment qualification at CERN, from LEP to HL-LHC. Evidently, also of high relevance for FCC-ee.