Radiation-related challenges and shielding design

A. Lechner on behalf of **SY/STI** and the **FCC-ee Radiation and Shielding WG**

In close collaboration with TE/VSC, TE/MSC, HSE/RP, EN/MME, EN/ACE, BE/CEM, R2E, FCC-ee TIWG, FCC-ee ATDC, MDI WG etc.

Introduction

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

FCC-ee Radiation and Shielding meetings

FUTURE CIRCULAR COLLIDER

September 2024
Sep 25 9th FCC-ee Radiation and Shielding Meeting

July 2024
Jul 17 8th FCC-ee Radiation and Shielding Meeting

May 2024
May 22 7th FCC-ee Radiation and Shielding Meeting

April 2024
Apr 24 6th FCC-ee Radiation and Shielding Meeting
Apr 10 5th FCC-ee Radiation and Shielding Meeting
Apr 09 Discussion about technical SR shielding design

March 2024
Mar 27 4th FCC-ee Radiation and Shielding Meeting
Mar 13 3rd FCC-ee Radiation and Shielding Meeting

February 2024
Feb 28 2nd FCC-ee Radiation and Shielding Meeting
Feb 14 1st FCC-ee Radiation and Shielding Meeting

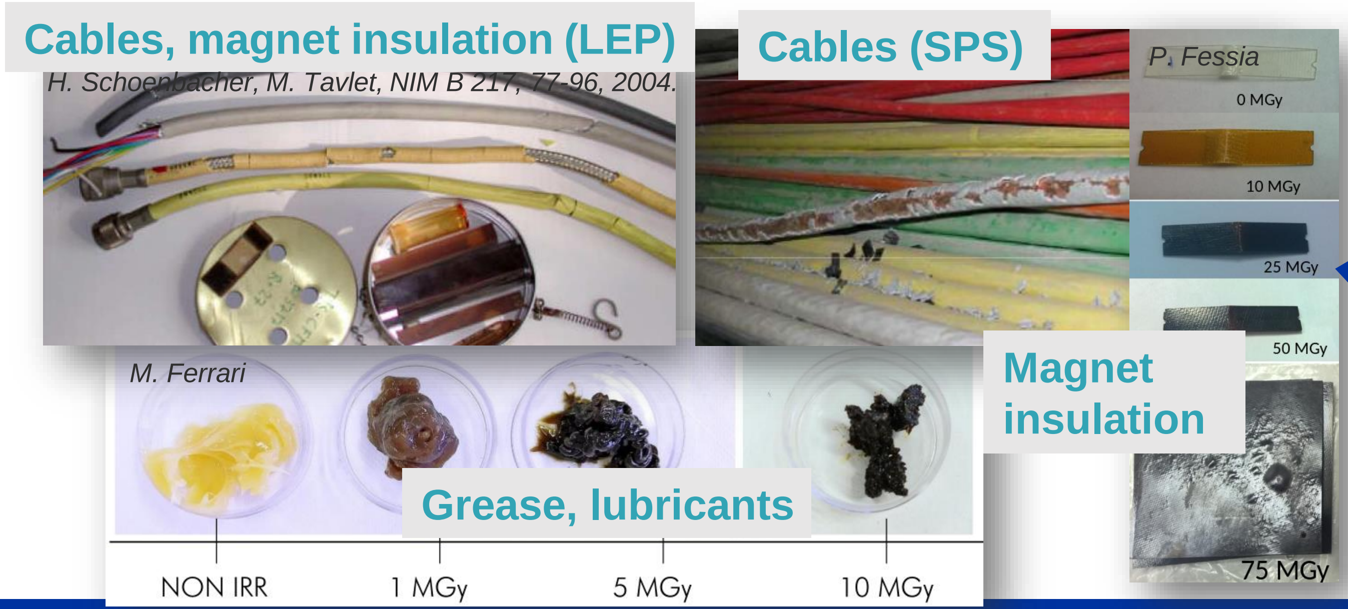
- **The radiation environment generated by synchrotron photons is a significant concern in FCC-ee**

- **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.


Cables, magnet insulation (LEP)

H. Schoenbacher, M. Tavlet, NIM B 217, 77-96, 2004.

Cables (SPS)

P. Fessia

Magnet insulation

M. Ferrari

Grease, lubricants

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

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.


CERN 89-12
Technical Inspection
and Safety Commission
31 December 1989

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

COMPILATION OF RADIATION
DAMAGE TEST DATA

PART I, 2nd EDITION:
Halogen-free cable-insulating materials

INDEX DES RÉSULTATS D'ESSAIS
DE RADIORÉSISTANCE

Ire PARTIE, 2e ÉDITION:
Matériaux d'isolation de câbles exempts d'halogène

H. Schönbacher and M. Tavlet

GENEVA
1989

CERN 98-01
Technical Inspection
and Safety Commission
18 May 1998

RECHERCHE NUCLÉAIRE
OR NUCLEAR RESEARCH

RÉSULTATS D'ESSAIS
DE RADIORÉSISTANCE

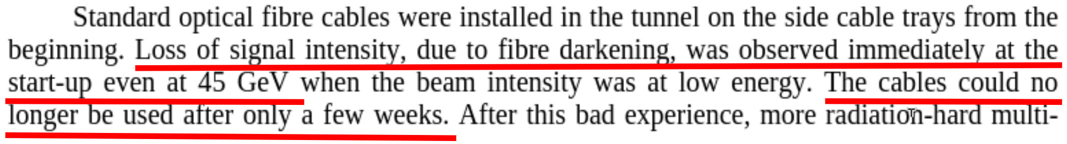
IIe PARTIE, 2e édition :
astiques, matériaux composites

CERN, 1211 Geneva 23, Switzerland

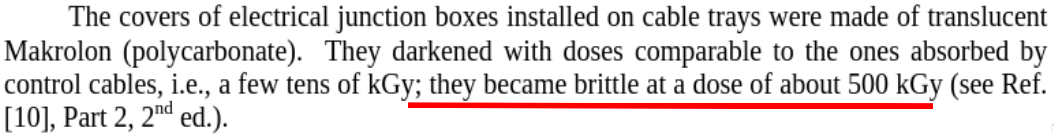
30-03

GENEVA
1998

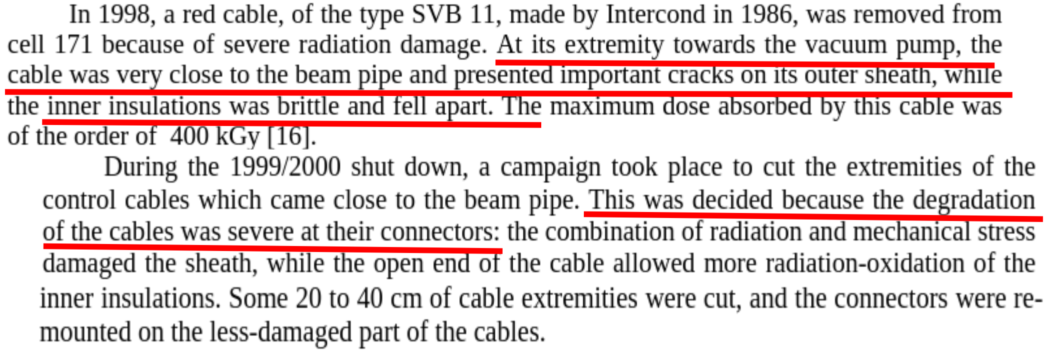
Optical fibers [1]:


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]:

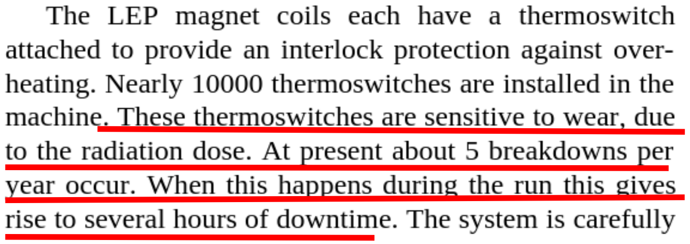

The covers of electrical junction boxes installed on cable trays were made of translucent Makrolon (polycarbonate). They darkened with doses comparable to the ones absorbed by control cables, i.e., a few tens of kGy; they became brittle at a dose of about 500 kGy (see Ref. [10], Part 2, 2nd ed.).

Cables and cable connectors [1]:

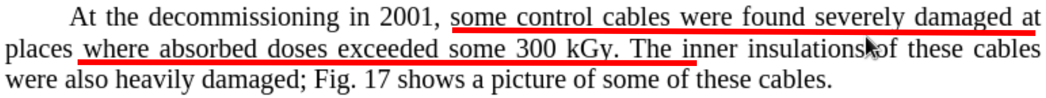

In 1998, a red cable, of the type SVB 11, made by Intercond in 1986, was removed from cell 171 because of severe radiation damage. At its extremity towards the vacuum pump, the cable was very close to the beam pipe and presented important cracks on its outer sheath, while the inner insulations was brittle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

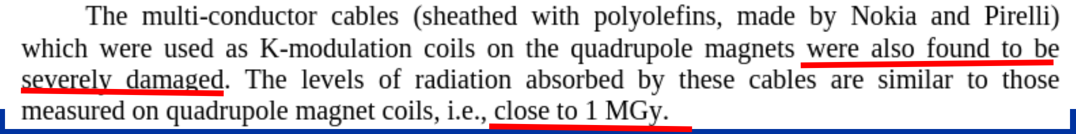
During the 1999/2000 shut down, a campaign took place to cut the extremities of the control cables which came close to the beam pipe. This was decided because the degradation of the cables was severe at their connectors: the combination of radiation and mechanical stress damaged the sheath, while the 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.

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


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.

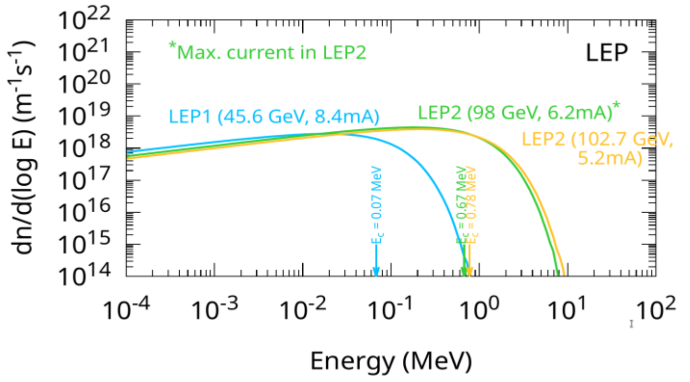
LEP vs FCC-ee arcs: SR power

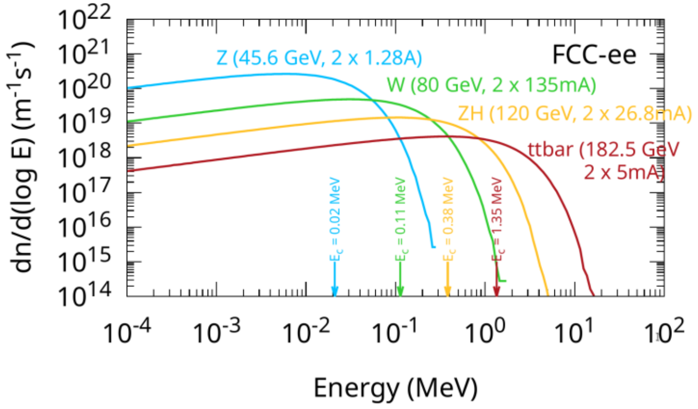
Energy loss per turn $U_0 \rightarrow E^4/\rho$ **Critical energy $E_c \rightarrow E^3/\rho$**

	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			
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**			
Crit. energy E_c	0.7-0.8 MeV	0.02 MeV	0.1 MeV	**0.4 MeV**	**1.35 MeV**

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

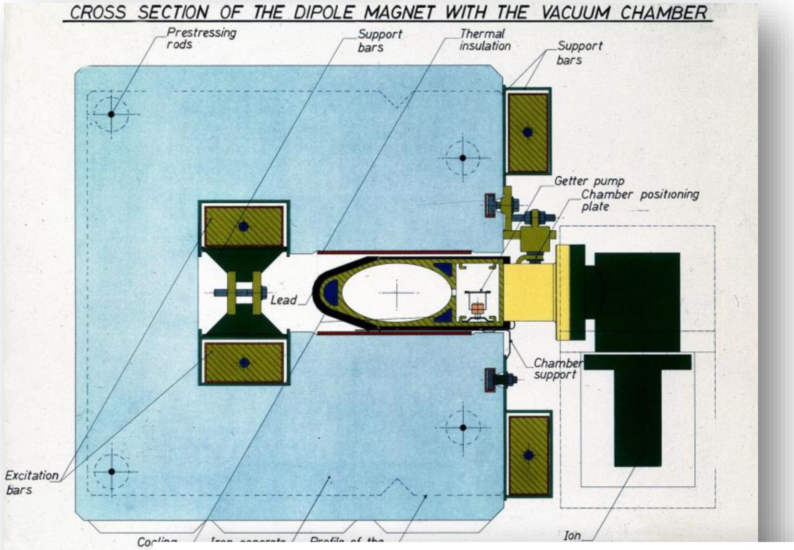
Higher photon energy = reduced shielding efficiency

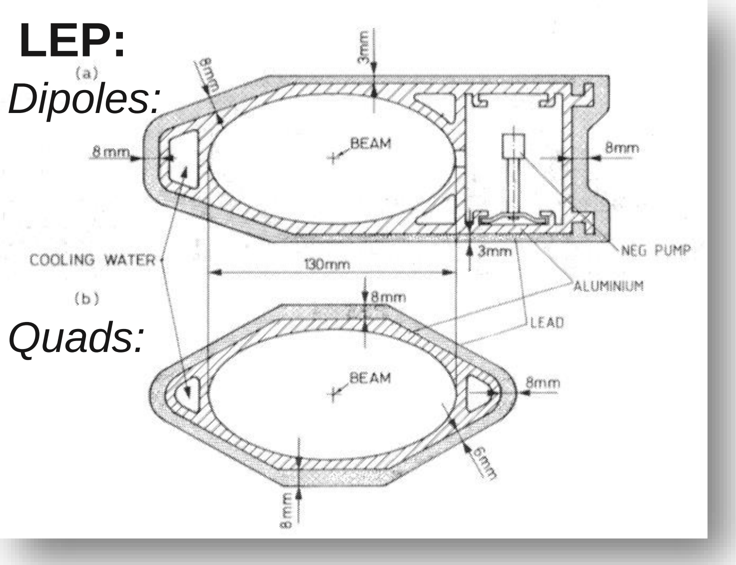




- **Power loss <u>per unit arc length</u> about two times higher in FCC-ee than in LEP2**
- **Also note that the <u>time-integrated power matters</u> for <u>cumulative radiation effects</u>:**
  - LEP was a cycling machine → beam current decayed during fills, time needed for turn-around
  - FCC-ee will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

LEP vs FCC-ee arcs: intercepting SR photons





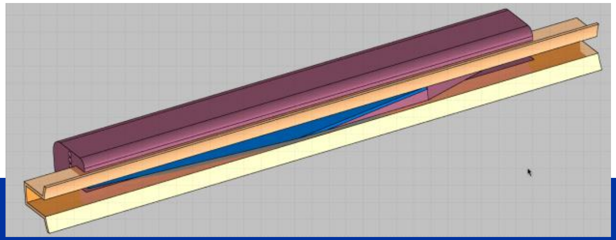
LEP:

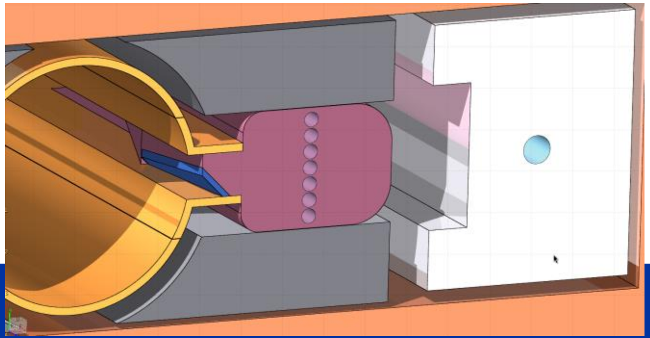
- SR photons impacted directly on water-cooled Al vacuum chambers
- A **continuous Pb shielding** (**3-8 mm**) was cladded on the chambers to reduce the radiation leakage

FCC-ee:

Designed by TE/VSC

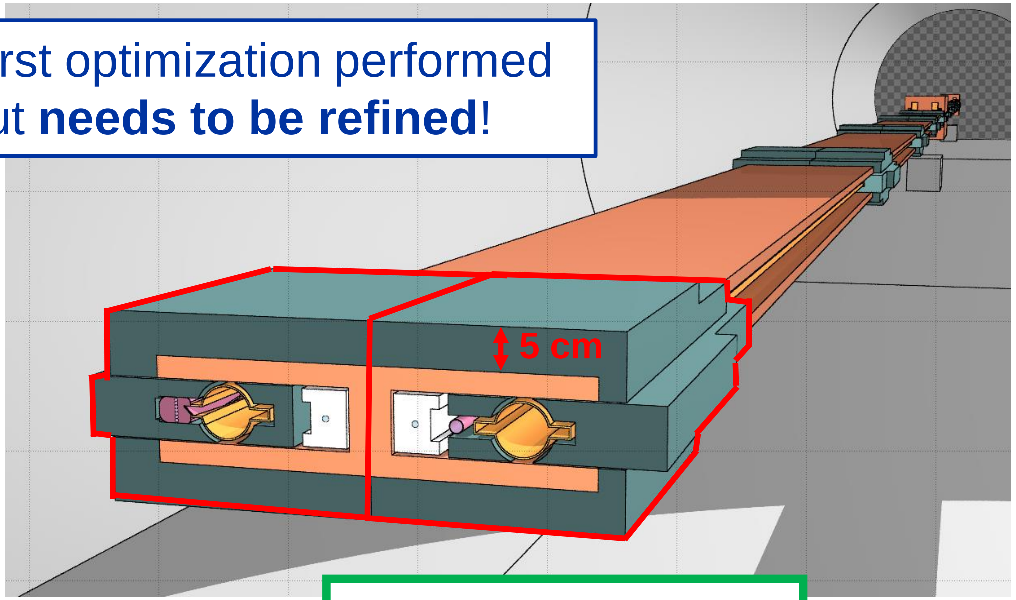
- **Discrete photon stoppers** made of **copper-alloy (CuCrZr)** intercept the primary SR fan (stopper length: about 30 cm)
- Placed in the winglets of the Cu vacuum chamber of dipoles (typical distance between stoppers: 4-5 meters), shadowing also the SSS
- The radiation leakage from the photon stoppers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



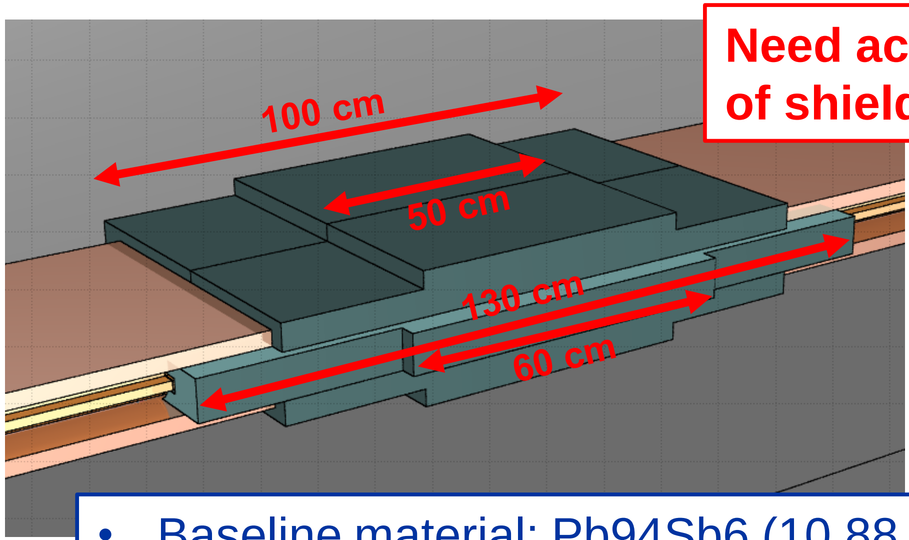


First conceptual shielding design for FCC-ee arcs

First optimization performed but **needs to be refined**!



Need active cooling of shielding!

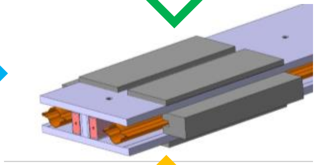


- Baseline material: Pb94Sb6 (10.88 g/cm^3)
- W-alloys (18-19 g/cm^3) discarded for cost reasons

Criteria for material selection and design:

Shielding efficiency (prefer high density)

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



Raw material costs and material availability

RP considerations and radioactive waste production (impurities matter)

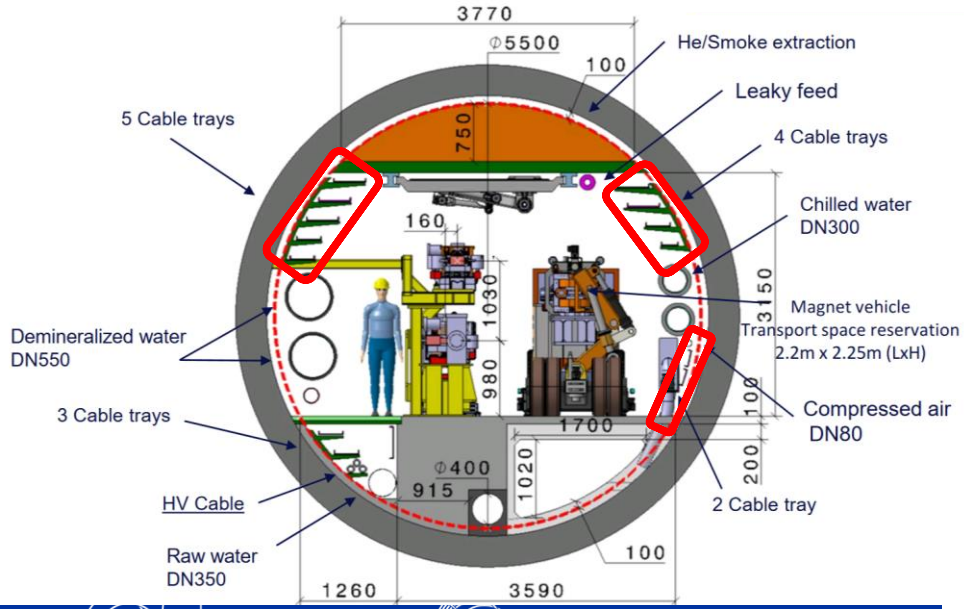
Shielding material for full ring (arcs)	
Shielding weight per stopper	400 kg
Photon stoppers per 20 dipole	10
# dipoles	2580
Total weight	10320 tons

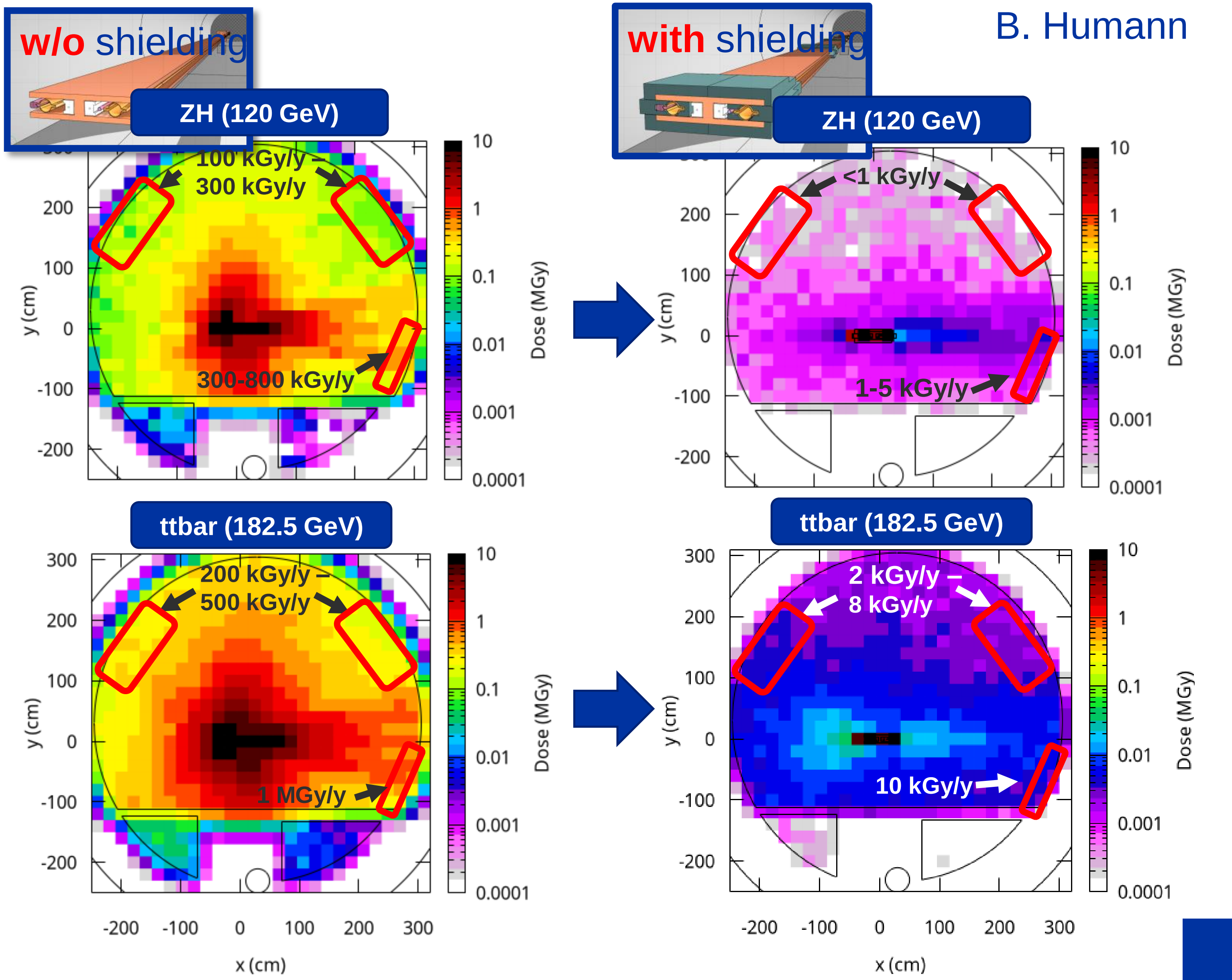
Assumption: **185 days/year** with **75%** efficiency

Dipole shielding efficiency: annual dose in arc tunnel

B. Humann

- Reduces dose levels in tunnel **by factor O(100)**
- **It seems feasible that most cables in cable trays receive <100 kGy in full FCC-ee era (including ttbar)**
- In vicinity of machine, rad-hard cables/cable connectors are likely still needed (qualified for MGy levels)

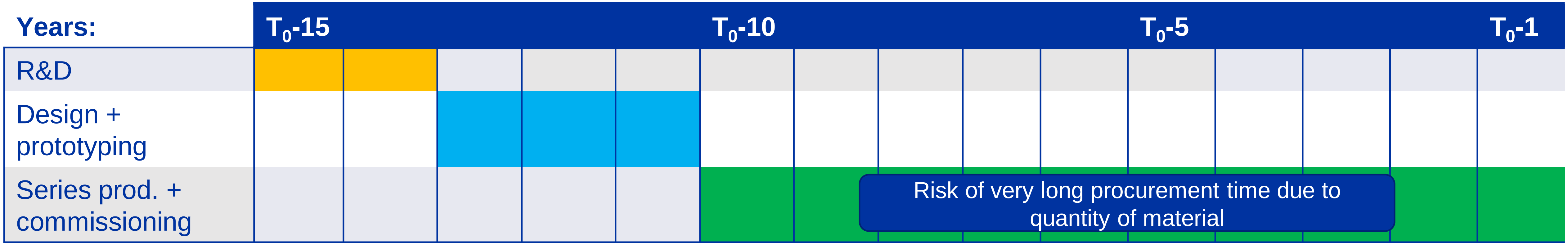




Requests and perspective for the next couple of years Assuming STI as shielding equipment owner

- Need to tackle engineering and design/cost optimisation in collaboration with VSC & MSC
- Design work to be done by STI design office and verify integration with TE teams
- Inquire cost, availability, feasibility, optimisation
- Cooling design (liaising with CV to understand impact on infrastructure)
- Production of full-scale prototypes. Test, validation of performance.
- Required material resources for next years (also in view of mock-up):
  - ➢ Design Optimisation: 250 kCHF (CDO)
  - ➢ Material : 500 kCHF for studies (estimated 200 MCHF total costs for full FCC shielding)

A. Perillo Marcone



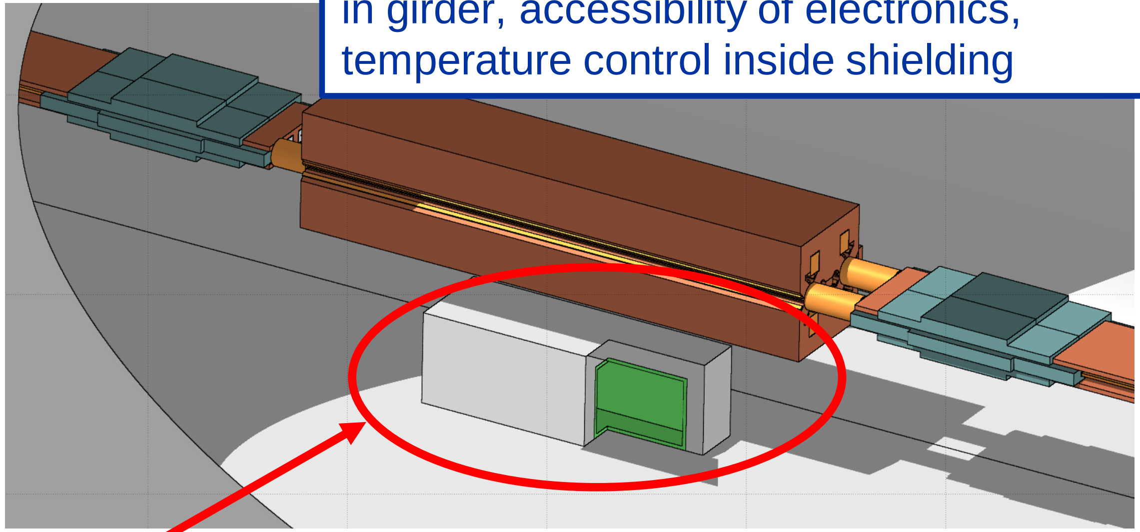
Years:	**T_0-15**					**T_0-10**					**T_0-5**				**T_0-1**
R&D	🟧	🟧													
Design + prototyping			🟦	🟦	🟦										
Series prod. + commissioning						🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

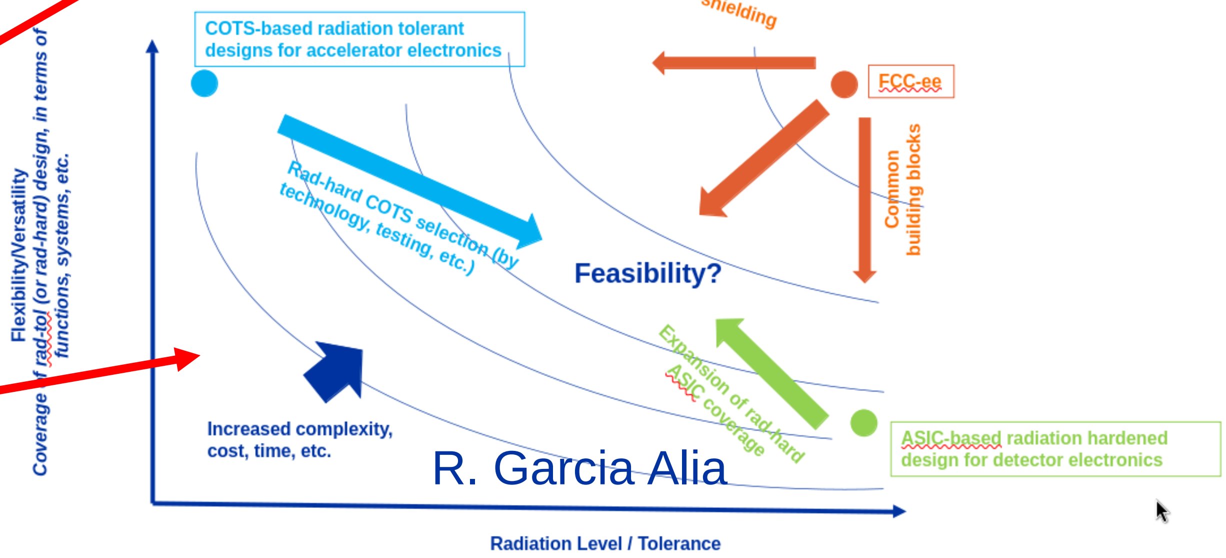
Risk of very long procurement time due to quantity of material

Radiation to electronics

Still many points to be addressed: space requirements for racks, shielding integration in girder, accessibility of electronics, temperature control inside shielding

- **Some racks (e.g. for vacuum systems, beam instrumentation) need to be located in the tunnel**
- **Radiation levels and shielding:**
  - Even with the dipole shielding, **dose levels in tunnel remain significant for electronics** (too high for COTS-based systems)
  - In addition, have to cope with a **significant neutron flux** (SEEs and displacement damage)
  - **Presently exploring the possibility of adding a local shielding for electronics below quadrupoles (e.g. concrete + borated PE) -** ***achievable rad levels inside this shielding still to be quantified!***
- **In any case, need an integral approach for FCC-ee electronics design (COTS-based design not yet excluded)**





R. Garcia Alia

Summary

*Requires close collaboration with many groups (e.g. **TE/VSC**, **TE/MSC**, **HSE/RP**, **SY/BI**, **EN/EL, EN/MME, BE/CEM, EN/ACE, …**) and relevant committees/projects in ATS sector (e.g. **R2E**, **CTTB, CARE** project)*

- **Shielding is essential for reducing the radiation exposure of FCC-ee equipment**
  - ➢ Present results look promising, but much work still ahead
- **Key items for the pre-TDR phase:**
  - ➢ Optimize the conceptual shielding design for the arcs and
  - ➢ Continue/start with rad. & shielding studies for the exp./tech. insertions (not only SR, also beam losses)
    - Key areas are MDI regions, regions with electrostatic separators, inj/extraction regions
  - ➢ Progress on the mechanical design and integration of the dipole shielding (incl. structural considerations, cooling, tolerances, assembly procedures, …)
  - ➢ Progress on the technical design of the electronics shielding (incl. integration in girder, temperature control, …)
  - ➢ Review and consolidate **radiation level specs for equipment in the tunnel**
  - ➢ Elaborate in more detail the **associated strategies/design choices** for radiation-sensitive equipment and their components (cables, electronics, etc.)
  - ➢ Develop first ideas/concepts for a radiation monitoring system

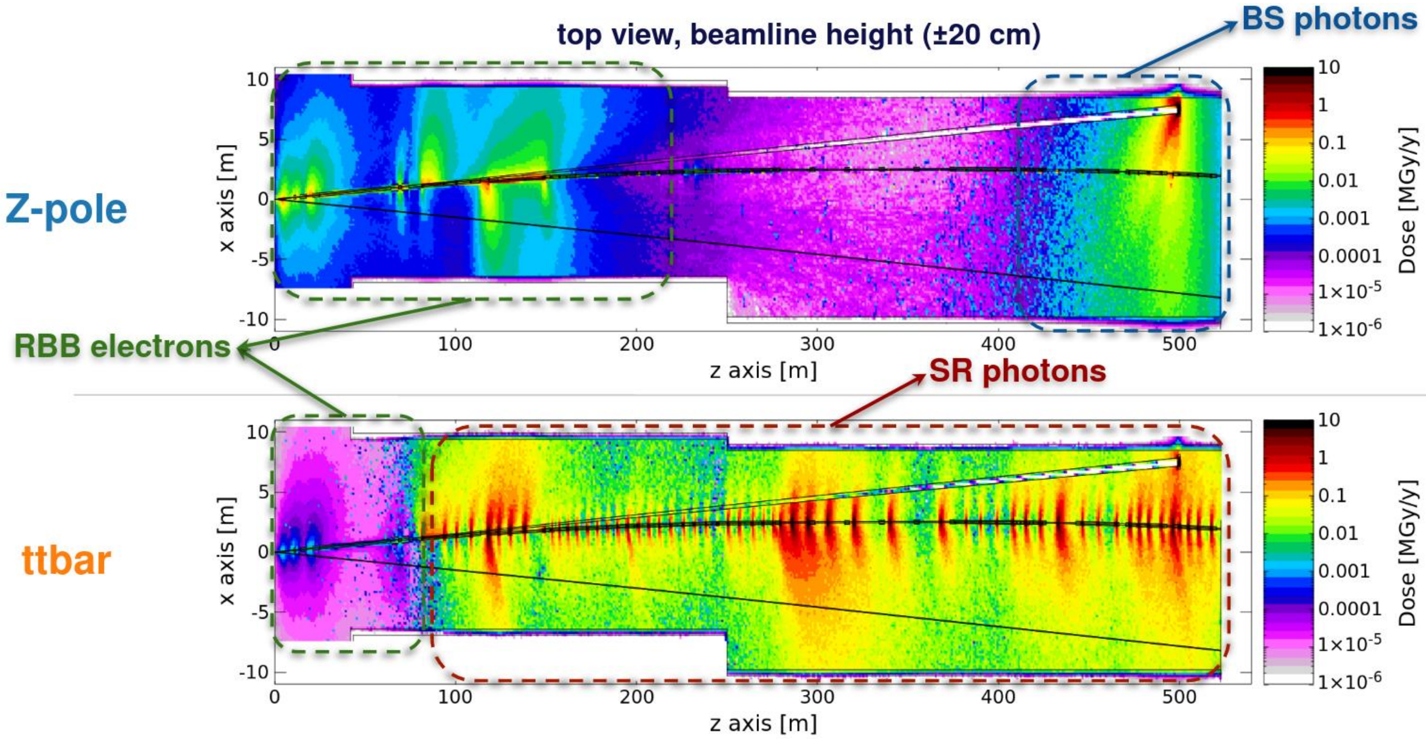
Profit from arc-cell mockup

home.cern

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