Strategy for mitigating radiation to equipment in FCC-ee

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06/11/2025, CEPC2025 workshop

Introduction

- **The radiation environment is a significant concern in FCC-ee**
  - Mainly due to **synchrotron radiation → high radiation levels almost all around the ring**
  - But also (local) contributions from other sources (radiative Bhabha, Beamstrahlung, …)

Main focus of this presentation

- **Large number of radiation-sensitive equipment in machine tunnel, in particular:**
  - Cables + cable connectors, optical fibres, insulation materials, etc.
  - Electronics for vacuum system, beam instrumentation, machine protection
- **Requires a concerted effort to find technically sound (and cost-effective) solutions**
  - Compromise between **shielding** and **rad-tolerant/hard equipment**

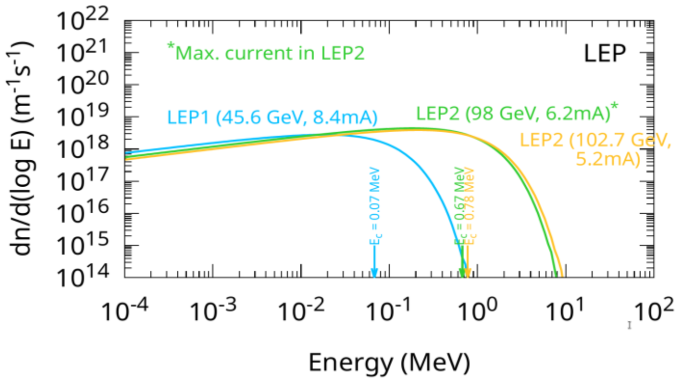
Synchrotron radiation in FCC-ee

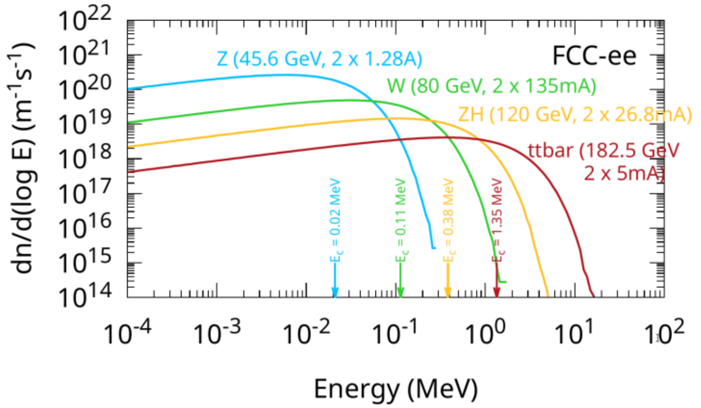
Higher photon energy = reduced shielding efficiency

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)*



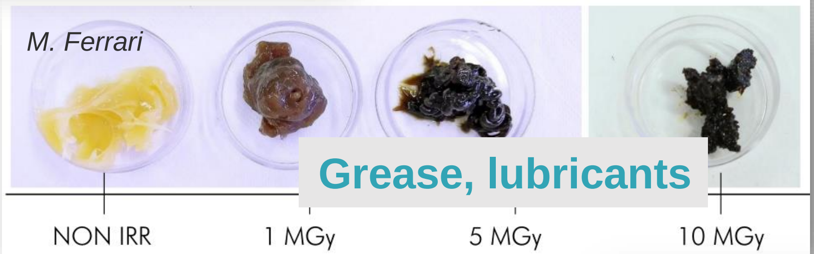


- **Power loss <u>per unit arc length</u> about two times higher in FCC-ee than in LEP2**
- **Also note that the <u>time-integrated power matters</u> for <u>cumulative radiation effects</u>:**
  - LEP was a cycling machine → beam current decayed during fills, time needed for turn-around
  - FCC-ee will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

Synchrotron radiation – main concerns for FCC-ee*

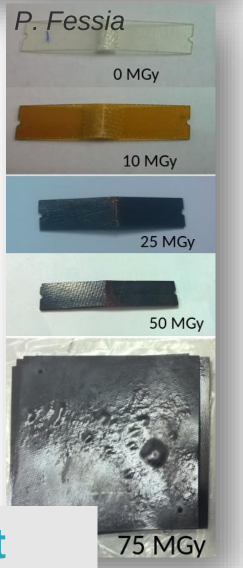
- **Heat deposition in tunnel environment**
  - Needs to be evacuated by ventilation system
- **Equipment failures due to cumulative ionizing dose**
  - Affects organic materials (magnet insulation, cable insulation, optical fibers, seals, lubricants etc.) → can limit equipment lifetime
- **Single event effects (stochastic) and cumulative effects in electronics (ionizing dose and non-ionizing dose)**
  - Destructive or non-destructive (soft errors) SEEs → can affects machine performance (premature beam aborts, machine downtime)
  - Cumulative effects can limit electronics system lifetime
- **Radiation-induced corrosion**
  - For example: nitric oxides (radiolysis of air) + humid air → nitric acids can lead to chemical corrosion → can affect equipment lifetime

Cables, magnet insulation (LEP)



Ionizing dose [Gy]

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



Magnet insulation

Radiation background in detector, and radiation protection (environmental and personnel) are not considered here

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

I^re^ PARTIE, 2^e^ 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

...A RECHERCHE NUCLÉAIRE
...OR NUCLEAR RESEARCH

...RÉSULTATS D'ESSAIS
...DE RADIORÉSISTANCE

II^e^ PARTIE, 2^e^ édition :
...astiques, matériaux composites

CERN, 1211 Geneva 23, Switzerland

30-03

GENEVA
1998

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

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.

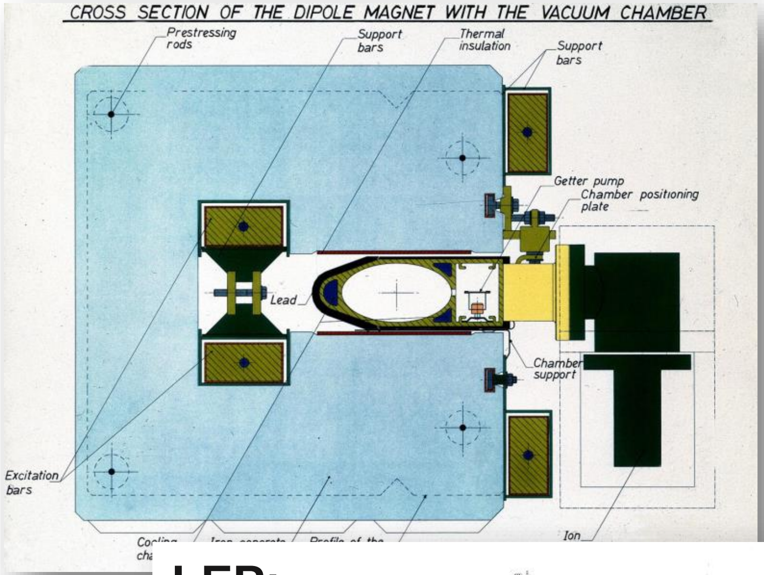
At the decommissioning in 2001, some control cables were found severely damaged at places where absorbed doses exceeded some 300 kGy. The inner insulations of these cables were also heavily damaged; Fig. 17 shows a picture of some of these cables.

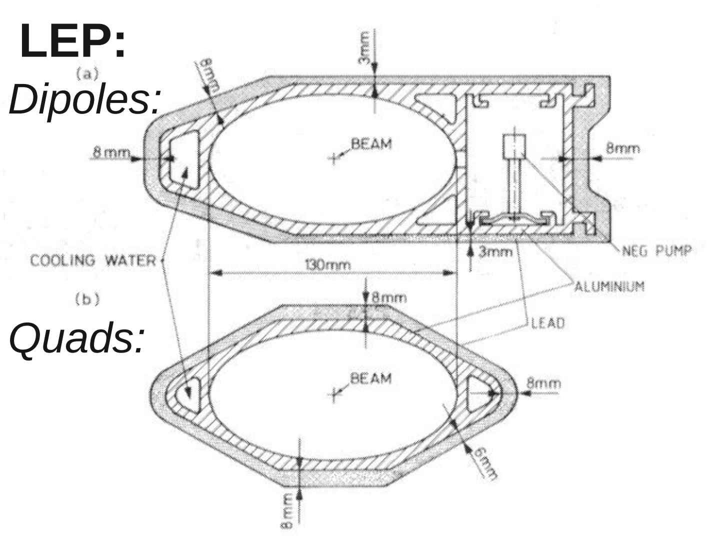
The multi-conductor cables (sheathed with polyolefins, made by Nokia and Pirelli) which were used as K-modulation coils on the quadrupole magnets were also found to be severely damaged. The levels of radiation absorbed by these cables are similar to those measured on quadrupole magnet coils, i.e., close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

LEP vs FCC-ee arcs: intercepting SR photons





LEP:

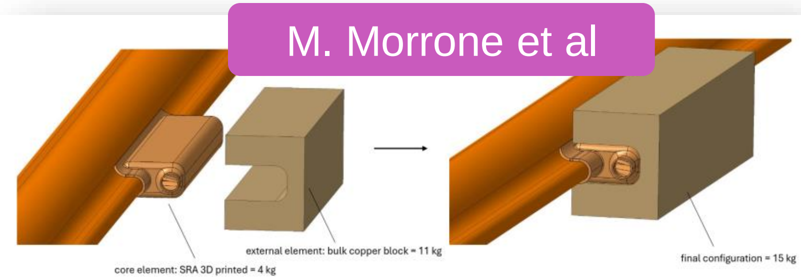
- SR photons impacted directly on water-cooled Al vacuum chambers
- A **continuous Pb shielding** (**3-8 mm**) was cladded on the chambers to reduce the radiation leakage

FCC-ee:

- **Discrete photon stoppers** made of **copper-alloy (CuCrZr)** intercept the primary SR fan (stopper length: about 35 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!!**

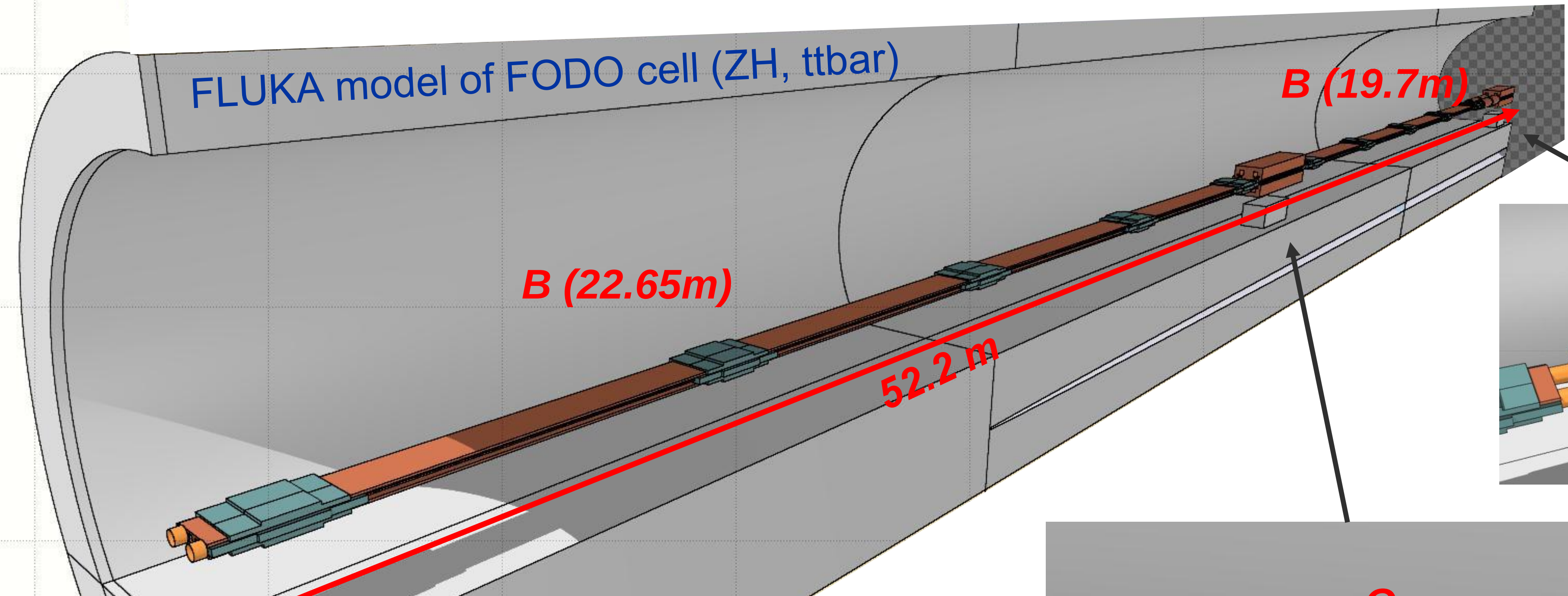
Photon stoppers designed by CERN vacuum group (TE/VSC)

M. Morrone et al



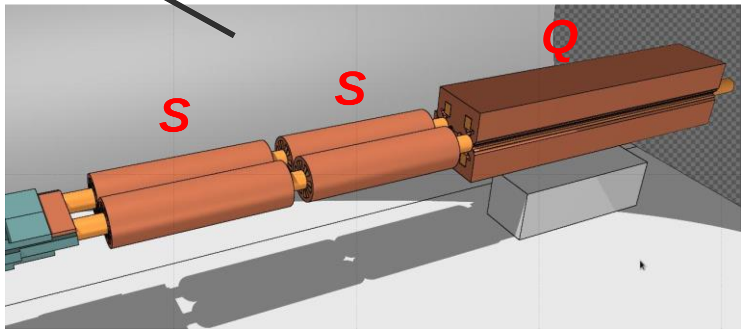
Model for radiation studies

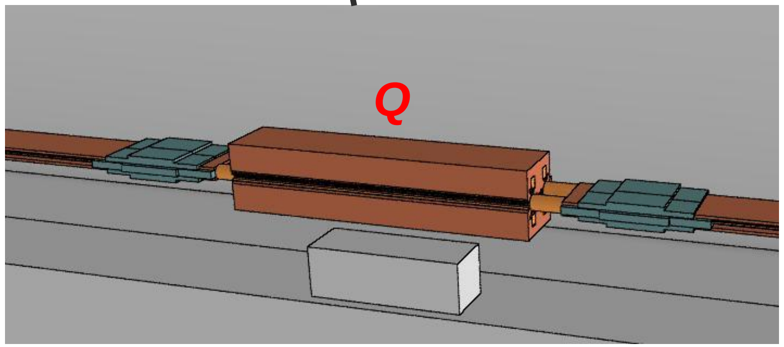
*Studied one type of FODO cell (ZH/ttbar) of **GHC** lattice (B-Q-B-S-S-Q), results can be somewhat different for other cells*

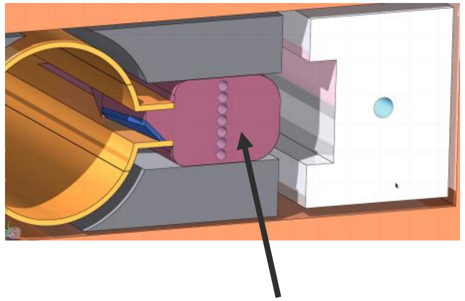


https://fluka.cern

FLUKA is a **general purpose Monte Carlo code** for the interaction and transport of photons, leptons, and hadrons







Photon stopper

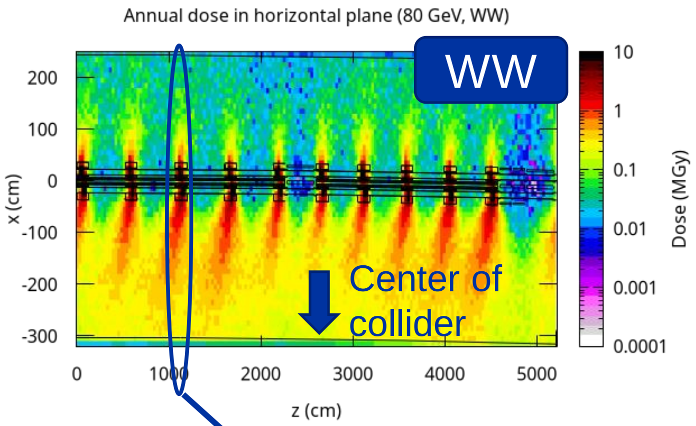
5 photon stoppers per dipole and per beam
→ 20 photon stoppers in FODO cell

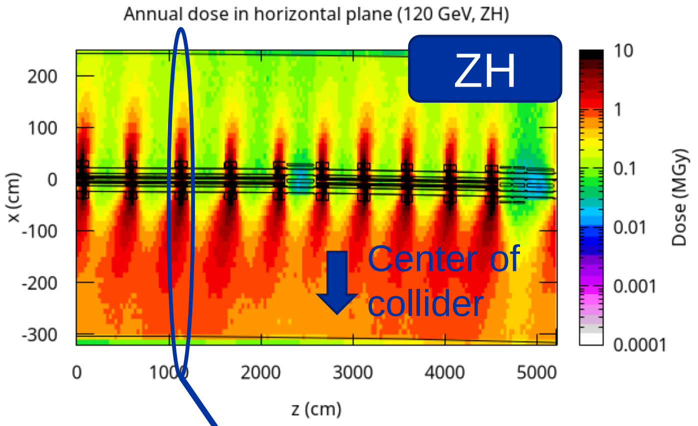
Assumption: **185 days/year** with **75% efficiency**

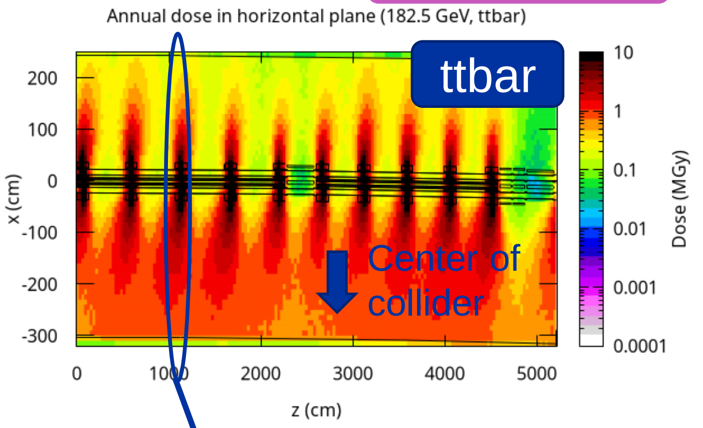
FCC-ee arcs: annual dose in tunnel w/o shielding

B. Humann

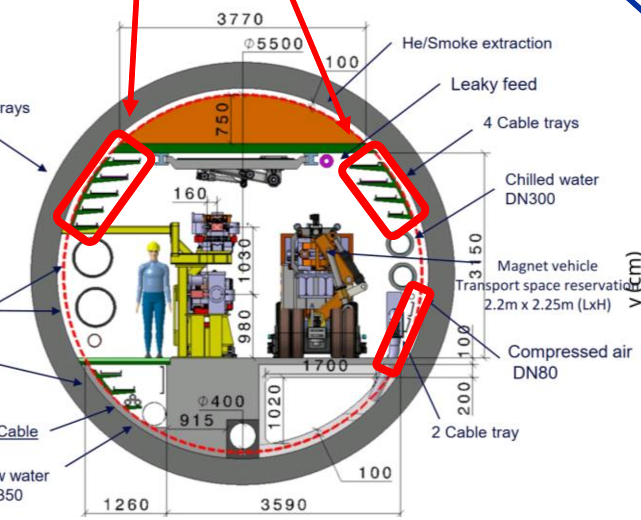
Annual dose in horizontal plane at collider height (vertically averaged over +/-50cm)

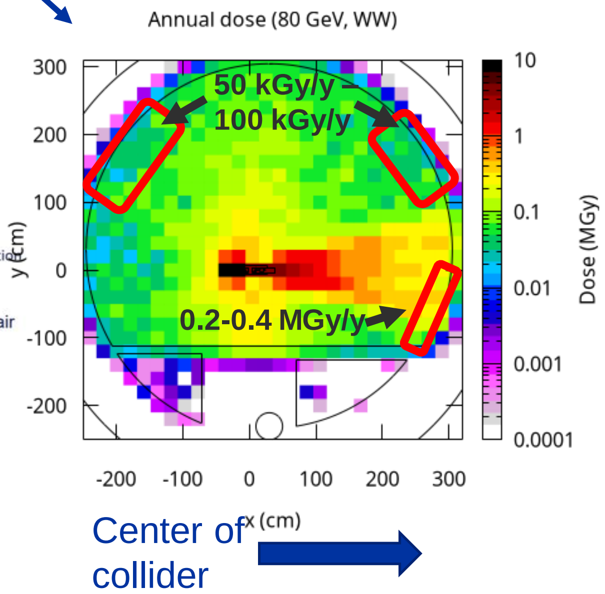


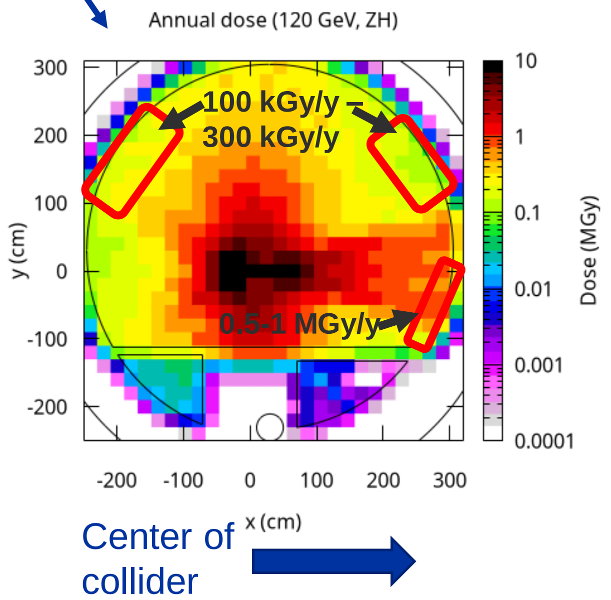


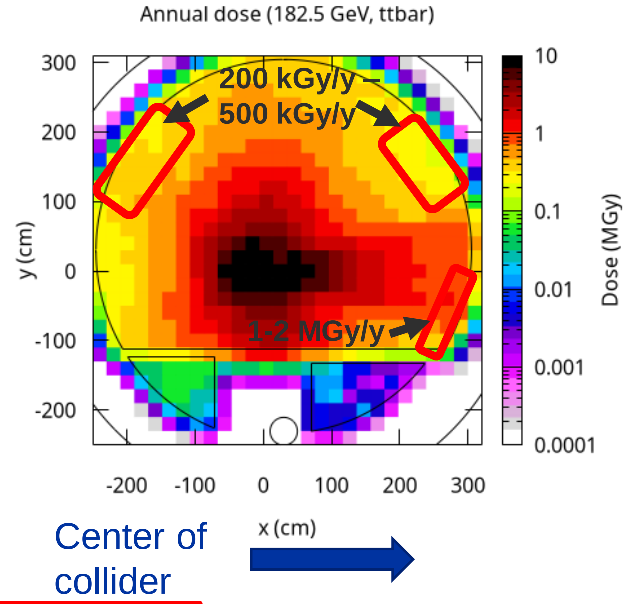


Cable trays









Shielding is essential for reducing the dose levels

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

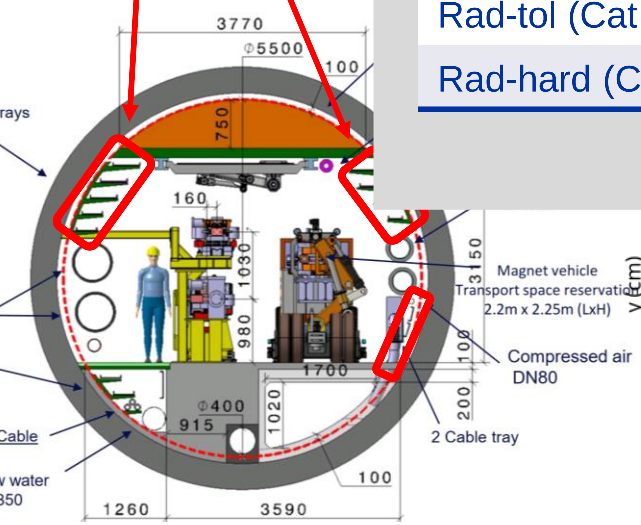
FCC-ee arcs: annual dose in tunnel w/o shielding

B. Humann

Annual dose in horizontal plane (80 GeV, WW)

Annual dose in horizontal plane at collider height (vertically averaged over +/-50cm)

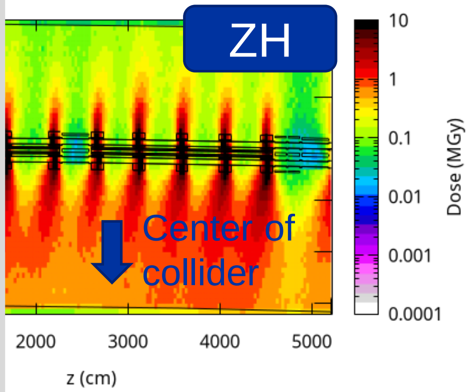
Cable trays

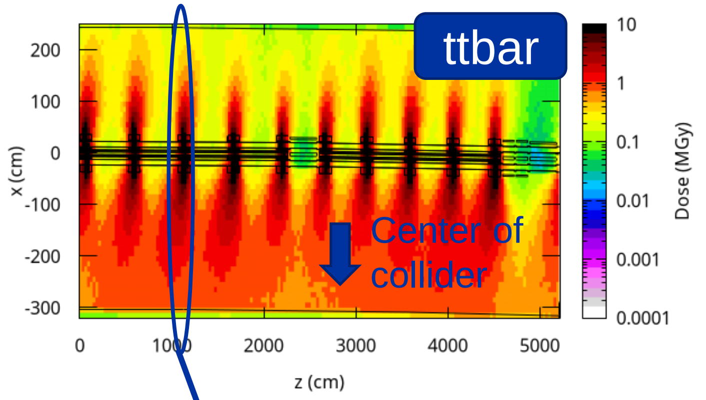


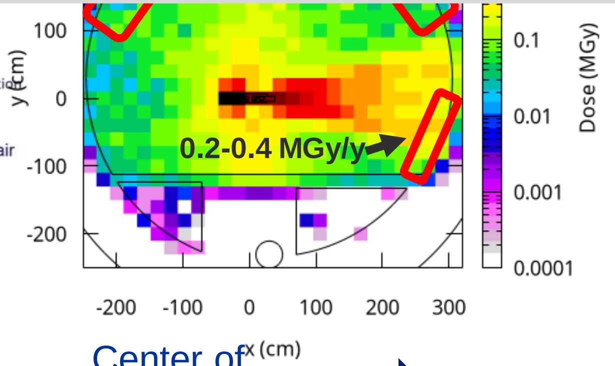
For comparison: present CERN cable categories for HL-LHC:

Cables (HL-LHC categories)	Operational lifetime limit
Standard (Cat 1)	100 kGy
Rad-tol (Cat 2)	700 kGy
Rad-hard (Cat 3)	2 MGy

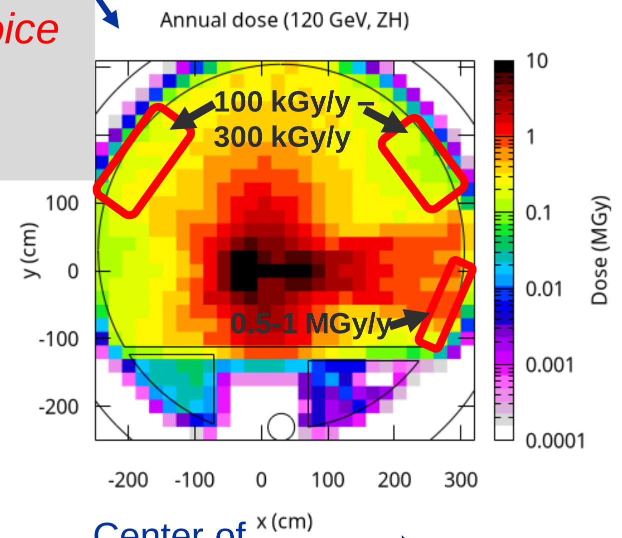
Significantly higher cost, less choice



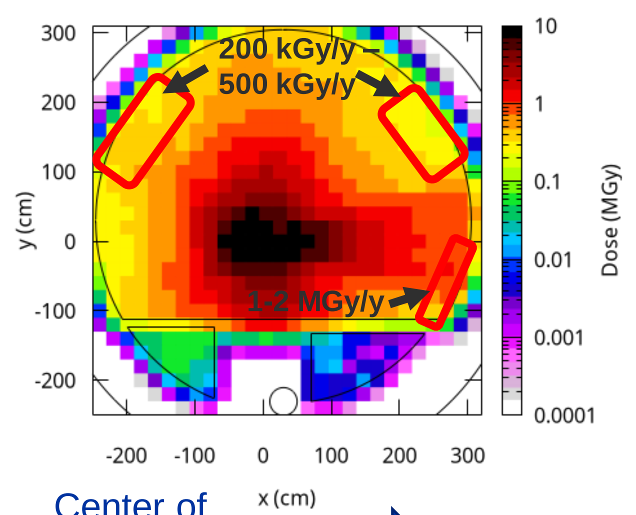




Center of collider



Center of collider



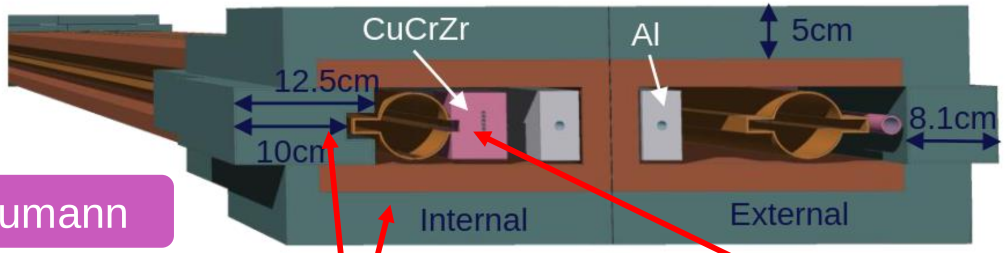
Center of collider

Shielding is essential for reducing the dose levels

First dipole shielding concept for FCC-ee arcs

- **SR photon stoppers** in dipoles ***enclosed by* top/bottom shielding plates** and **horizontal shielding inserts**

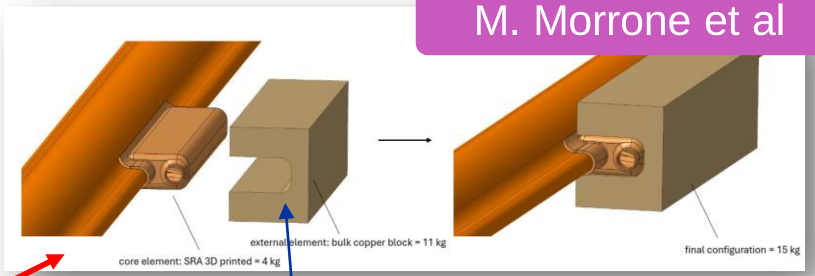
B. Humann



Shielding

Photon stopper

M. Morrone et al



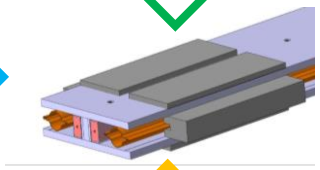
Cu sleeve to enhance absorption

- Baseline material: **PbSb-alloy** (~11 g/cm^3)
- W-alloys (18-19 g/cm^3) discarded for cost reasons
- Technical points to be addressed in pre-TDR phase (until 2027): mechanical shielding design, shielding integration and cooling, supports, assembly procedures, ….

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)

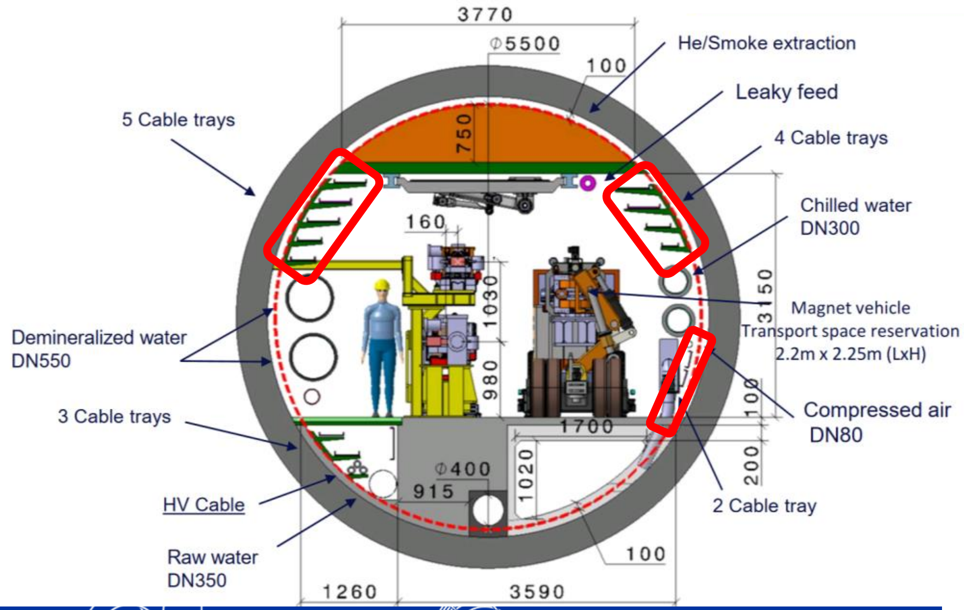
Shielding material for full ring (arcs)	
Shielding weight per stopper	400 kg
Photon stoppers per 20 dipole	10
# dipoles	2840
Total weight	11360 tons

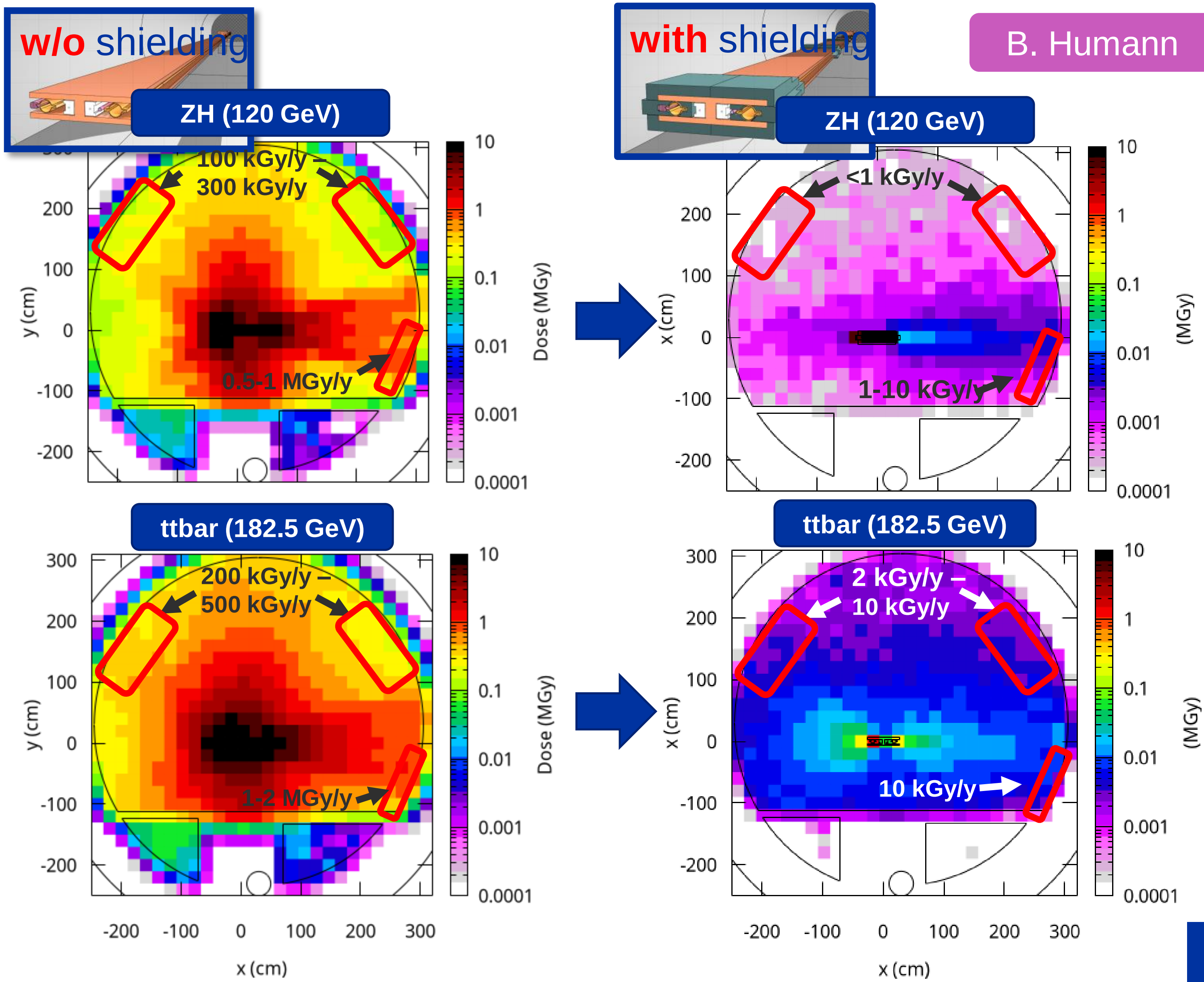
Assumption: **185 days/year** with **75%** efficiency

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)





SR emission from the booster arc dipoles

B. Humann

- Even @ttbar, the average **SR power from booster** is still **O(500) times lower** than from collider
- No photon stoppers or shielding foreseen, but O-shaped dipole yokes help in shielding the photons
- Based on simplified simulation model (dipoles only), suggested thicker booster dipole (2cm → 4cm) to reduce radiation leakage to tunnel

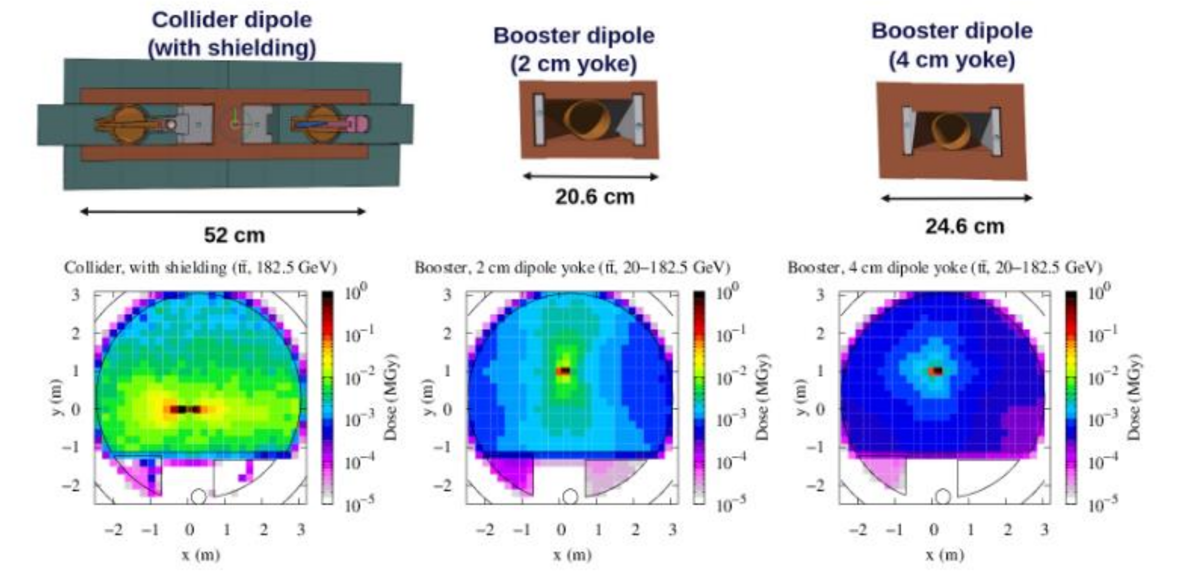


Fig. 4.13: Annual ionising dose in the arc tunnel during $t\bar{t}$ operation, showing separately the contributions of the collider (left) and the booster (middle: with a 2 cm-thick yoke, right: with a 4 cm-thick yoke).

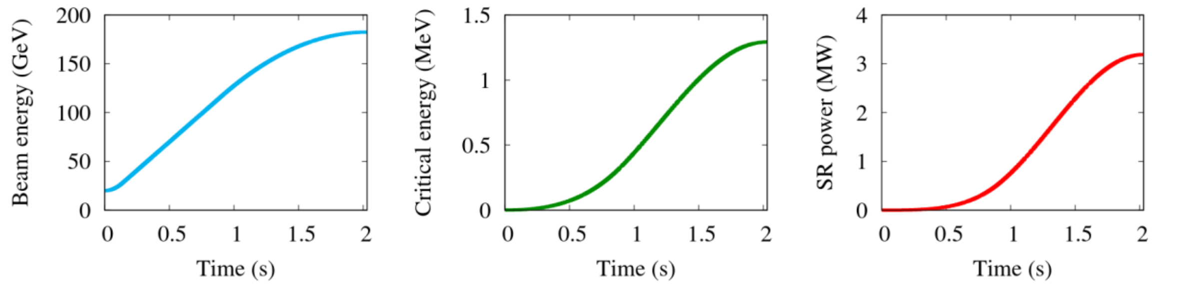


Figure 1: Time evolution of the beam energy (top), critical energy of the synchrotron photon spectrum (center) and emitted synchrotron radiation power (bottom) for a booster ramp from 20 GeV to 182.5 GeV ($t\bar{t}$ operation). The flat bottom and flat top plateaus are not shown.

SR power arcs (ttbar)	Totals	Per unit length
SR power **collider**	100 MW	1.3 kW/m
SR power **booster** (peak)	3 MW	0.04 kW/m
SR power **booster** (average)	0.2 MW	0.003 kW/m

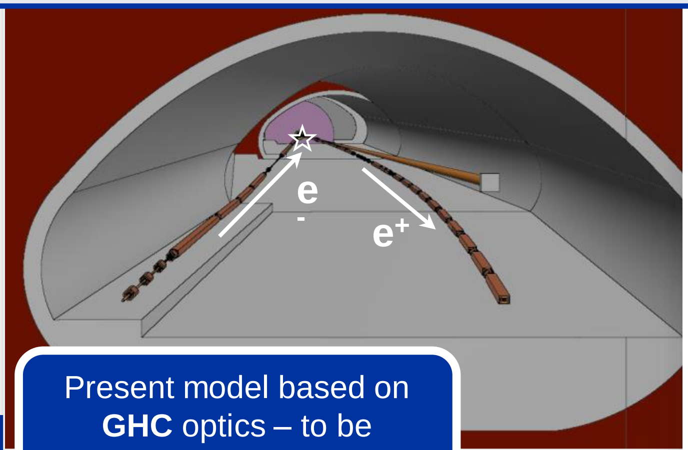
Dose levels in the FCC-ee exp insertions

A. Frasca,
G. Lerner

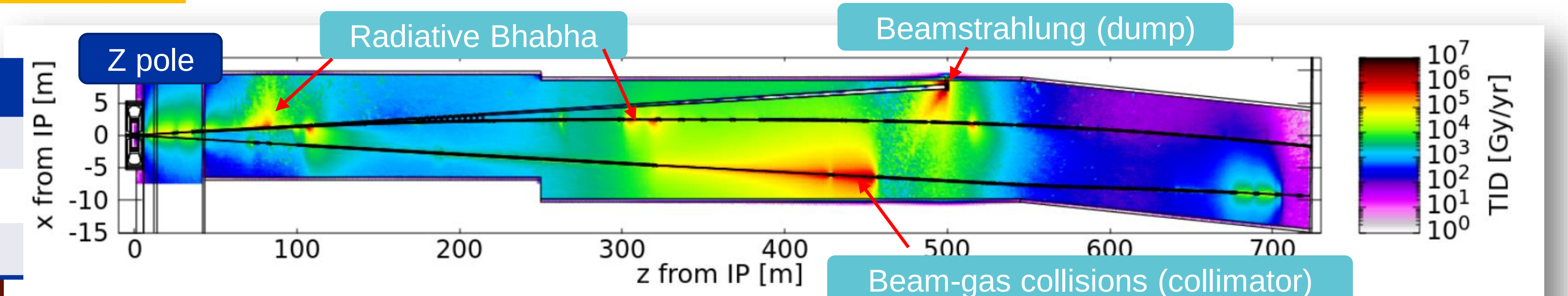
- Significant radiation levels are also expected in the experiment insertions
- Complex radiation environment with many different radiation sources (beamstrahlung, radiation Bhabha, synchrotron radiation, …) → **O(1-2 MW)** dissipated in IR
- Similar values dose values as in the arcs - **O(MGy/year)** w/o shielding (very location dependent)

➢ ***Shielding still to be developed***

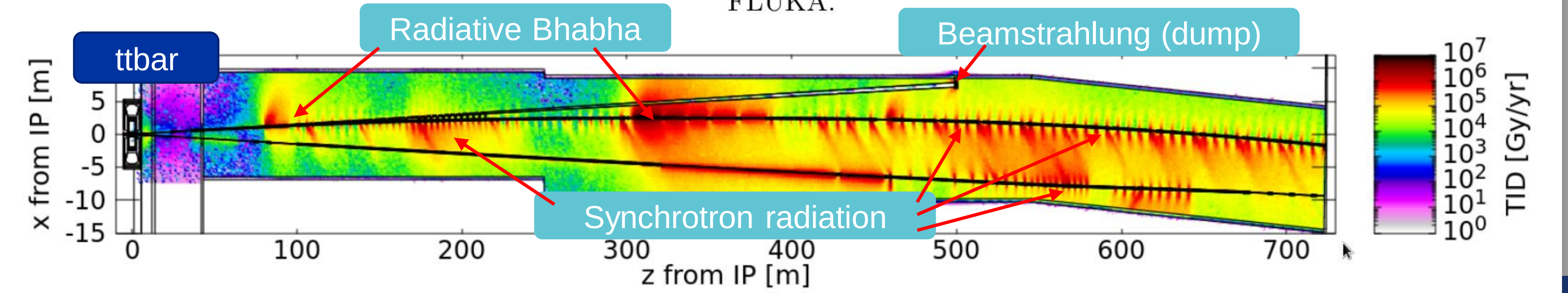
Per IR side	Z pole	ttbar
Beamstr.	O(400 kW)	O(100 kW)
SR	O(400 kW)	O(400 kW)
Rad Bhabha	Few kW	<1 kW



Present model based on **GHC** optics – to be adapted to **LCC** if chosen



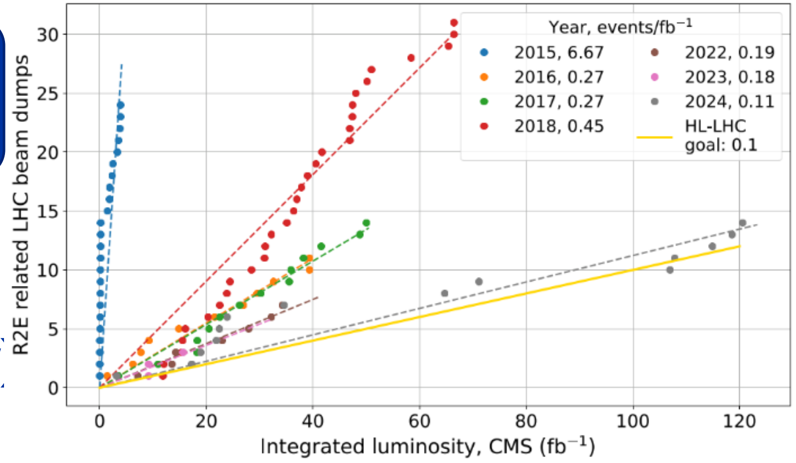
(a) Top view (average over ±20 cm in y) of annual TID from RB, BS and BG losses on collimators at Z pole as simulated with FLUKA.



(b) Top view (average over ±20 cm in y) of annual TID from RB, BS and SR at $t\bar{t}$ as simulated with FLUKA.

Radiation to electronics

Important experience from LHC operation



D. Soderstrom et Al, " Radiation Monitoring and Performance of Electronic Systems in High-Energy Accelerator Radiation Environments"

Some FCC-ee electronics needs to be located in tunnel

- Vacuum system (gauges, pumps, valves, water temperature/flow)
- Beam instrumentation (beam loss & beam position monitors)
- Others (machine protection, cooling & ventilation, …)

➢ Even with dipole shielding, **dose levels in tunnel remain significant for electronics** → still too high for commercial-off-the-shelf (COTS)-based rad-tolerant systems (not only for ttbar!)

➢ In addition, **Single Event Effects** due to **photo-neutron production** are a concern → can lead to premature beam aborts as LHC experience shows

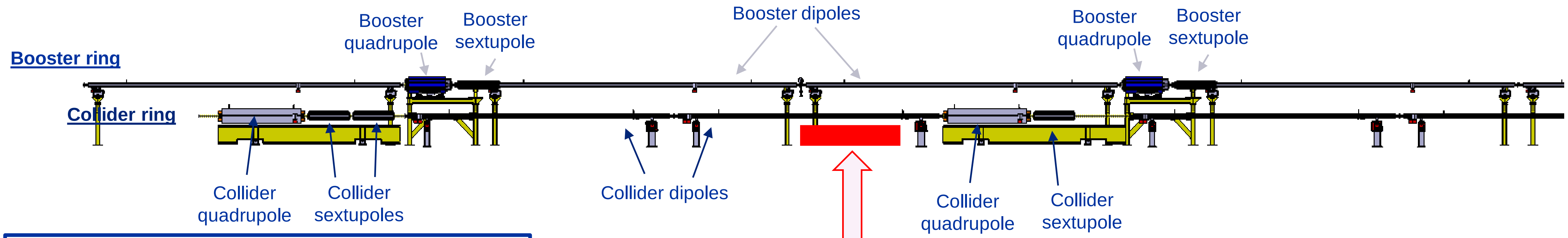
Technological choices for electronics are strongly linked to radiation levels

Strategy for FCC-ee electronics in tunnel → dedicated electronics bunkers (allow for COTS rad-tol design)

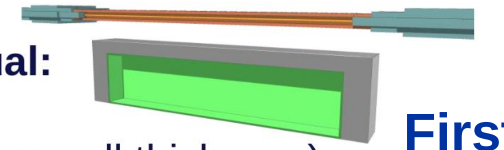
Electronics	Operational lifetime limit
Rad-tol design based on Commercial-Off-The-Shelf (COTS) components	0.5-1 kGy
Rad-hard design based on Application-Specific Integrated Circuits (ASICs)	MGy

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

Electronics bunker concept for the arcs



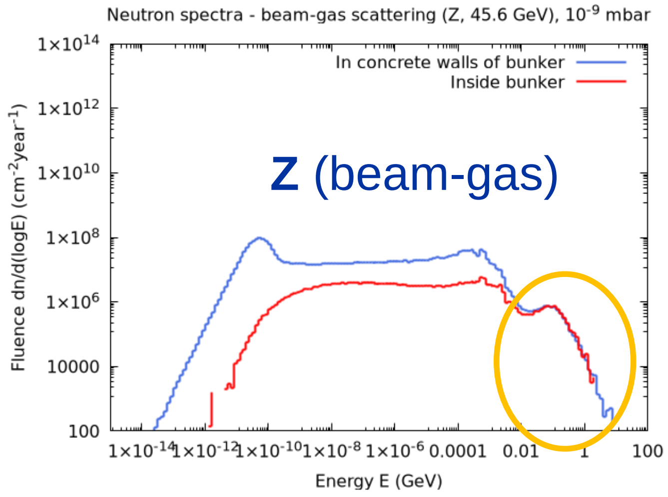
Still many points to be addressed: space requirements for racks, shielding integration, accessibility of electronics, temperature control inside bunker (cooling of electronics)

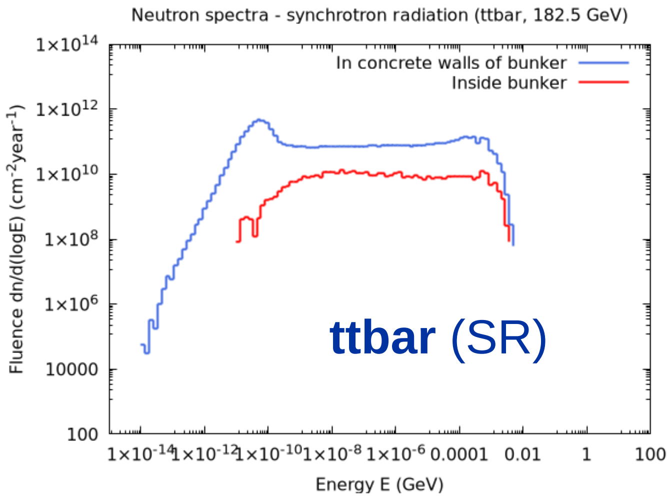


Conceptual:
below MB
(15cm/25cm wall thickness)

First concept:

- **Concrete walls** to reduce the flux of secondary electrons/photons
- **Borated polyethylene** on the inside to moderate and capture neutrons



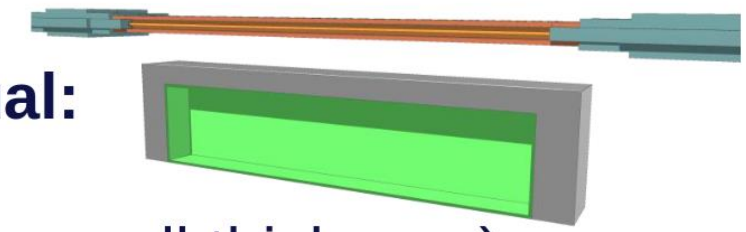


Radiation levels in bunker driven by:
- **Z pole (45.6 GeV):** beam-gas scattering
- **ttbar (182.5 GeV):** synchrotron radiation

Radiation levels in arc bunker

- Bunker yields **promising reduction of rad levels**
- Annual levels for ttbar **comparable to HL-LHC arcs** (below magnets), except somewhat higher dose
- Custom radiation tolerant electronics systems based on **COTS semiconductor devices in reach** for all beam modes

Conceptual:
below MB
(15cm/25cm wall thickness)



		FCC-ee (Z) Beam-gas scattering (outside bunker)	FCC-ee (Z) Beam-gas scattering (inside bunker)	FCC-ee (ttbar) Synchrotron radiation (outside bunker)	FCC-ee (ttbar) Synchrotron radiation (inside bunker)	HL-LHC arcs* (below magnets)
Cumulative radiation effects	TID	~1 Gy/y	<0.01 Gy/y	**few kGy/y**	<10 Gy/y	1.4 Gy/y
	$\Phi_{1MeV\ n\ Si}$	$3x10^{8}$ cm^{-2}/y	$\sim10^{7}$ cm^{-2}/y	$6x10^{\mathbf{11}}$ cm^{-2}/y	$2x10^{10}$ cm^{-2}/y	$1.6x10^{10}$ cm^{-2}/y
Single event effects	Φ_{HEHeq}	$7x10^{6}$ cm^{-2}/y	$\sim10^{6}$ cm^{-2}/y	$8x10^{8}$ cm^{-2}/y	$2x10^{7}$ cm^{-2}/y	$2.4x10^{9}$ cm^{-2}/y
	Φ_{THNeq}	$2x10^{8}$ cm^{-2}/y	$\sim10^{6}$ cm^{-2}/y	$5x10^{\mathbf{11}}$ cm^{-2}/y	$4x10^{9}$ cm^{-2}/y	$1.2x10^{10}$ cm^{-2}/y

*HL-LHC radiation level specification doc, EDMS 2302154 v.1.1, LHC-N-ES-0001.

➢ Bunker **primarily needed for SR at ttbar**, not necessarily for beam-gas losses

Conclusions

- **Radiation is a significant concern in FCC-ee – severe risk of equipment failures if not shielded properly**
- **The arc shielding concepts elaborated so far (dipole shielding + electronics bunker) provided a first basis for managing radiation in FCC-ee**
- **Need to refine the target radiation levels for machine equipment and infrastructure in the next phase (pre-TDR)**
- **Need to extend shielding design studies to experimental and technical insertion regions (many loss sources!)**
- **The technical design and integration for dipole shielding and bunker entails still many challenges**

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