



Strategy for mitigating radiation to equipment in FCC-ee

A. Lechner, B. Humann on behalf of the **FCC-ee Radiation and Shielding WG**

In close collaboration with various CERN groups (SY/STI, TE/VSC, TE/MSC, HSE/RP, EN/MME, EN/ACE, BE/CEM), R2E and FCC WGs (FCC-ee TIWG, FCC-ee ATDC, etc.)

Acknowledgements

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The screenshot shows a calendar interface for 'FCC-ee Radiation and Shielding meetings'. At the top left is the logo for 'FUTURE CIRCULAR COLLIDER'. Below the logo, the calendar is organized by month. The 'May 2025' section is highlighted in yellow and contains one entry: '07 May 14th FCC-ee Radiation and Shielding Meeting'. The 'April 2025' section contains one entry: '16 Apr 13th FCC-ee Radiation and Shielding Meeting'. The 'March 2025' section contains three entries: '31 Mar Discussion about neutron-induced effects in electronics', '19 Mar 12th FCC-ee Radiation and Shielding Meeting', and '07 Mar Discussion about technical SR shielding design'. The 'November 2024' section contains two entries: '27 Nov 11th FCC-ee Radiation and Shielding Meeting' and '22 Nov Discussion about SR photon stopper placement'. A search bar is visible at the top right of the calendar interface.

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

Let me know in case you would like to receive the meeting invitations!

Introduction

- **Radiation to equipment is a significant concern for FCC-ee**
 - Mainly due to synchrotron radiation
 - But also (sometimes localized) contributions from beam losses
- **Shielding is essential for reducing the radiation exposure of FCC-ee equipment**
 - The goal is to reduce the need of expensive rad-hard components
 - Developed first arc shielding concepts for the Feasibility Study (FS) phase → promising reduction of radiation levels
- **Key points for the pre-TDR phase:**
 - Converge on the **required target dose levels** for the tunnel
 - Extend shielding studies **from arcs to insertion regions** (many radiation sources)
 - Develop shielding concepts into **robust technical design** (first prototyping)

Radiation – main concerns for FCC-ee*

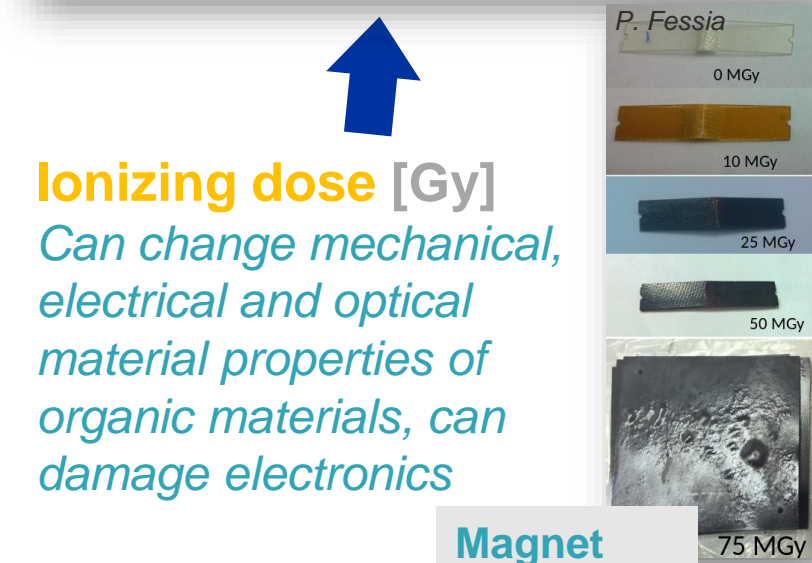
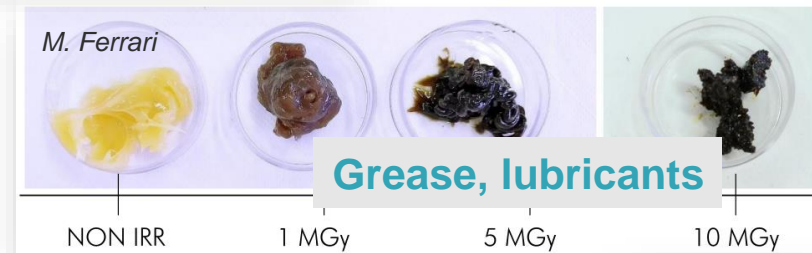
- **Heat deposition in tunnel environment**
 - Needs to be evacuated by ventilation system
- **Equipment failures due to cumulative ionizing dose**
 - Affects organic materials (magnet insulation, cable insulation, optical fibers, seals, lubricants etc.) → can limit equipment lifetime
- **Single event effects (stochastic) and cumulative effects in electronics (ionizing dose and non-ionizing dose)**
 - Destructive or non-destructive (soft errors) SEEs → can affect 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)

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



Cables (SPS)



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

Shielding concepts presented in FSR

Established first estimates of required arc shielding material and costs

Arcs → *priority in FS phase due to highest radiation levels (SR) and largest impact in terms of feasibility & costs*

- First **shielding concept** for **collider dipoles**
- Proposal of **electronics bunker** near quadrupoles
- Thicker booster dipole yokes

Insertion regions → *first radiation assessment for experimental insertions show that radiation levels are significant, technical insertions still to be studied*

- Shielding not yet defined, but can re-use/adapt shielding concepts from the arcs
- Will require custom shielding solutions for certain locations

Dipole shielding

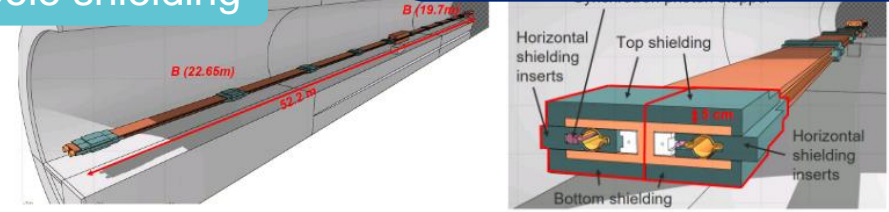


Fig. 1.41: Preliminary conceptual radiation shielding design for the collider dipoles in the FCC-ee arcs. The left figure shows a model of a representative FODO cell for ZH and $t\bar{t}$ operation, whereas the right figure presents a more detailed view of the shielding elements on the dipoles. The shielding envelope

Electronics bunker near quads

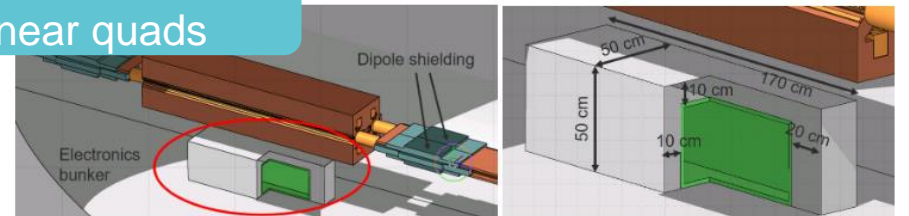


Fig. 3.22: Possible electronics bunker (red circle) near the lattice quadrupoles in the FCC-ee arcs. In this very first design, the bunker is assumed to be made of concrete (gray walls) and borated polyethylene (green sheets on the inside). The dimensions shown have to be revised once the number and size of the

Thicker booster dipole yokes

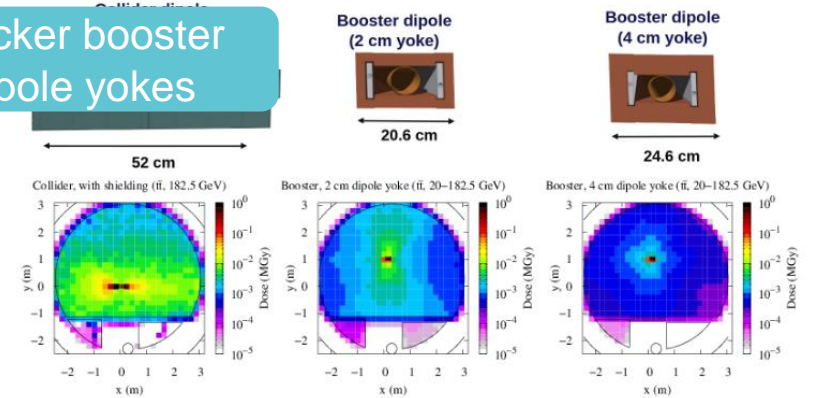
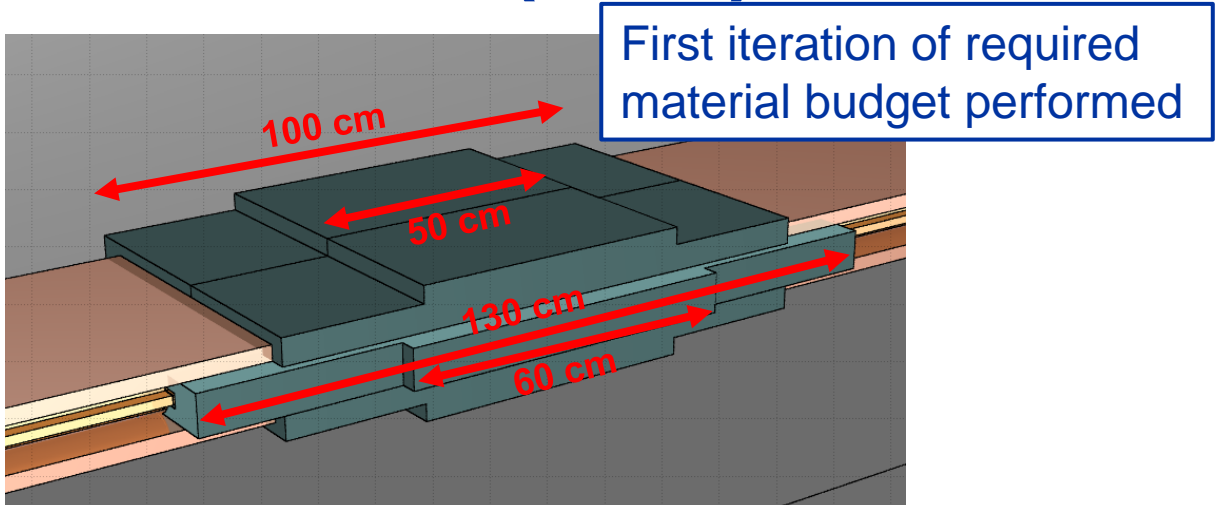
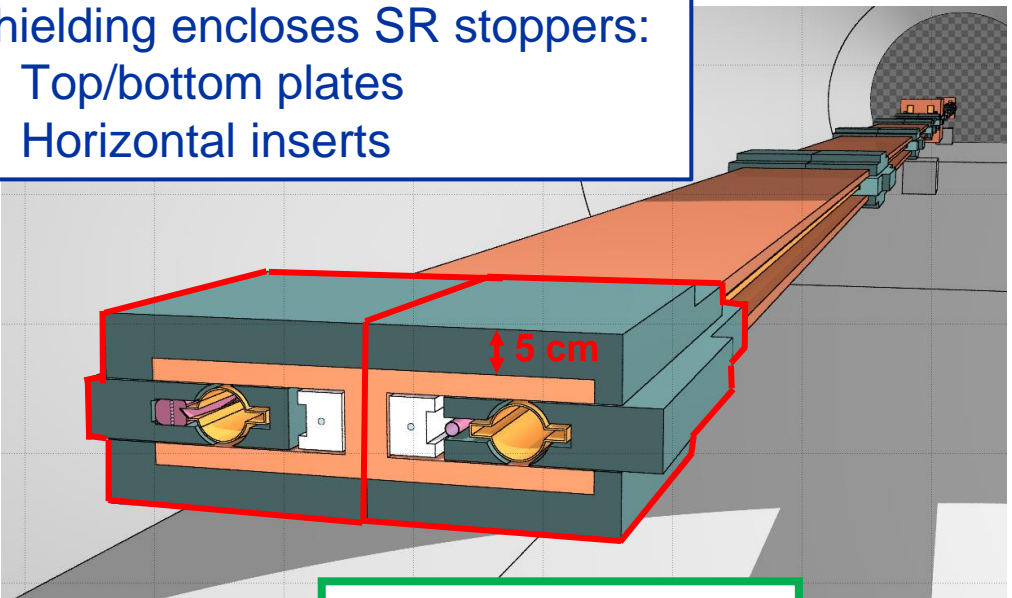


Fig. 4.13: Annual ionising dose in the arc tunnel during $t\bar{t}$ operation, showing separately the contribu-

Dipole shielding concept for the arcs (FSR)

Shielding encloses SR stoppers:

- Top/bottom plates
- Horizontal inserts



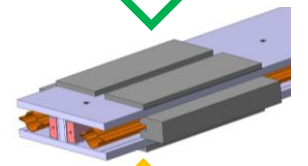
- Baseline material: Pb94Sb6 (10.88 g/cm³)
- W-alloys (17-19 g/cm³) discarded for cost reasons

Criteria for material selection and design:

Shielding efficiency (prefer high density)

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

Raw material costs and material availability



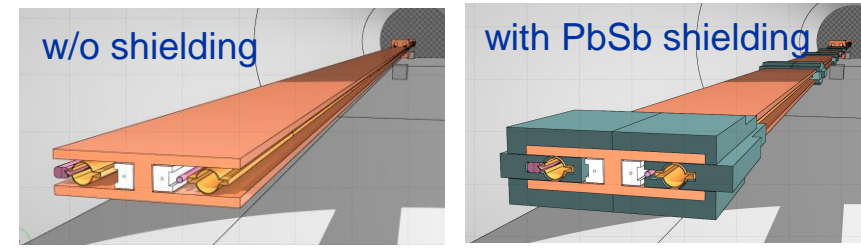
RP considerations and radioactive waste production (impurities matter)

Shielding material for full ring (arcs)

Shielding weight per stopper	400 kg
Photon stoppers per 20 m dipole	10 (5 per beam)
# dipoles	2840
Total weight	11360 tons

SR power deposition (FSR)

Relative power deposition, with and without radiation shielding:



Photons: 10 keV transport cut

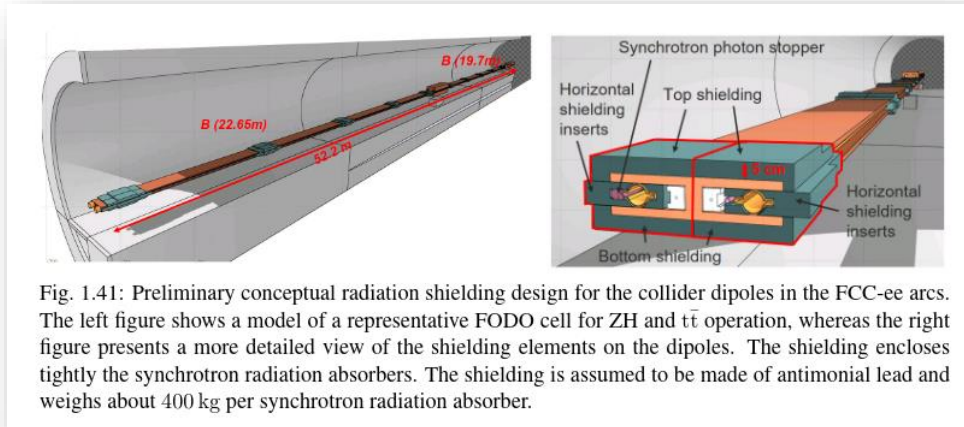
Rad. shielding:	Z (45.6 GeV)		WW (80 GeV)		ZH (120 GeV)		ttbar (182.5 GeV)	
	w/o	with	w/o	with	w/o	with	w/o	with
Photon stoppers	98.1%		82.8%		69.9%	69.7%	68.3%	68.1%
Radiation shielding	N/A	To be calculated	N/A	To be calculated	N/A	19.1%	N/A	20.4%
Vacuum chambers	1.8%		8.2%		9.0%	8.9%	8.1%	8.0%
Dipoles	0.1%		7.8%		16.7%	2.3%	17.4%	3.5%
Quadrupoles	<0.001%		<0.01%		<0.02%	<0.01%	<0.1%	<0.02%
Sextupoles	<0.001%		<0.01%		<0.02%	<0.01%	<0.1%	<0.02%
Environment*	0.01%		1.2%		4.3%	<0.01%	6.1%	<0.03%

*Air, tunnel walls, and surrounding molasse

The shielding reduces:

- Power leakage to tunnel environment (was significant for WW, ZH, ttbar)
- Power to dipole yokes which are not actively cooled → heat would have been partially dissipated in air

Key follow-up actions for collider dipole shielding in pre-TDR phase



Confirm required shielding efficiency:

- **Review the target radiation levels** for the tunnel (considering distributed systems like cables, optical fibres, etc.)
- Derive radiation level specs for equipment and infrastructure

FSR shielding concept meets presently assumed goals!

Develop shielding concept into technical design

- Converge on photon stopper + shielding **placement along the dipoles**; review supporting concept
- Converge on the main **conceptual features** of photon stoppers and shielding (volume and topology)
- Confirm shielding material choice, progress on **mechanical shielding design** and **integration**

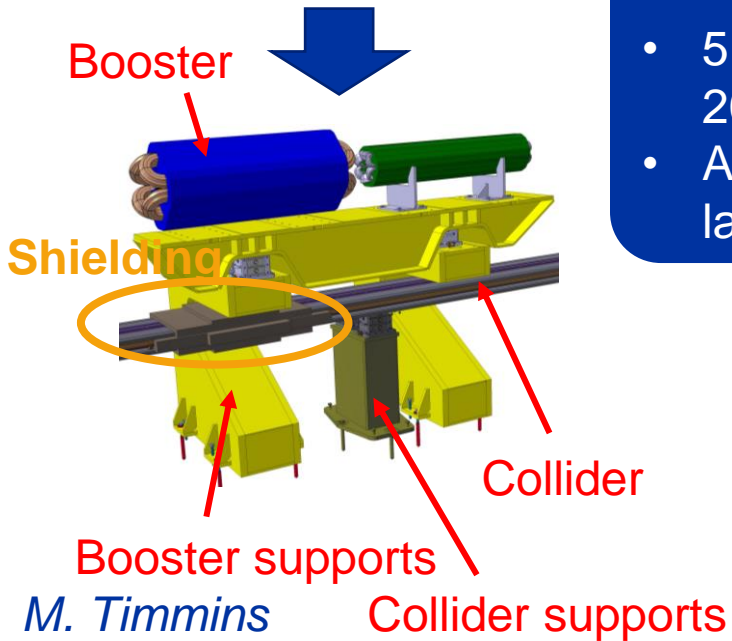


Robust design and prototyping essential
(→20k+ shielding units!)

Converging on photon stopper + shielding layout

Implications of stopper + shielding placement:

- It might be necessary to adapt the mechanical design of the dipole and its supporting scheme **due to the shielding weight** (4 tons/20 m)
- Influences **overall integration** of collider and booster supports



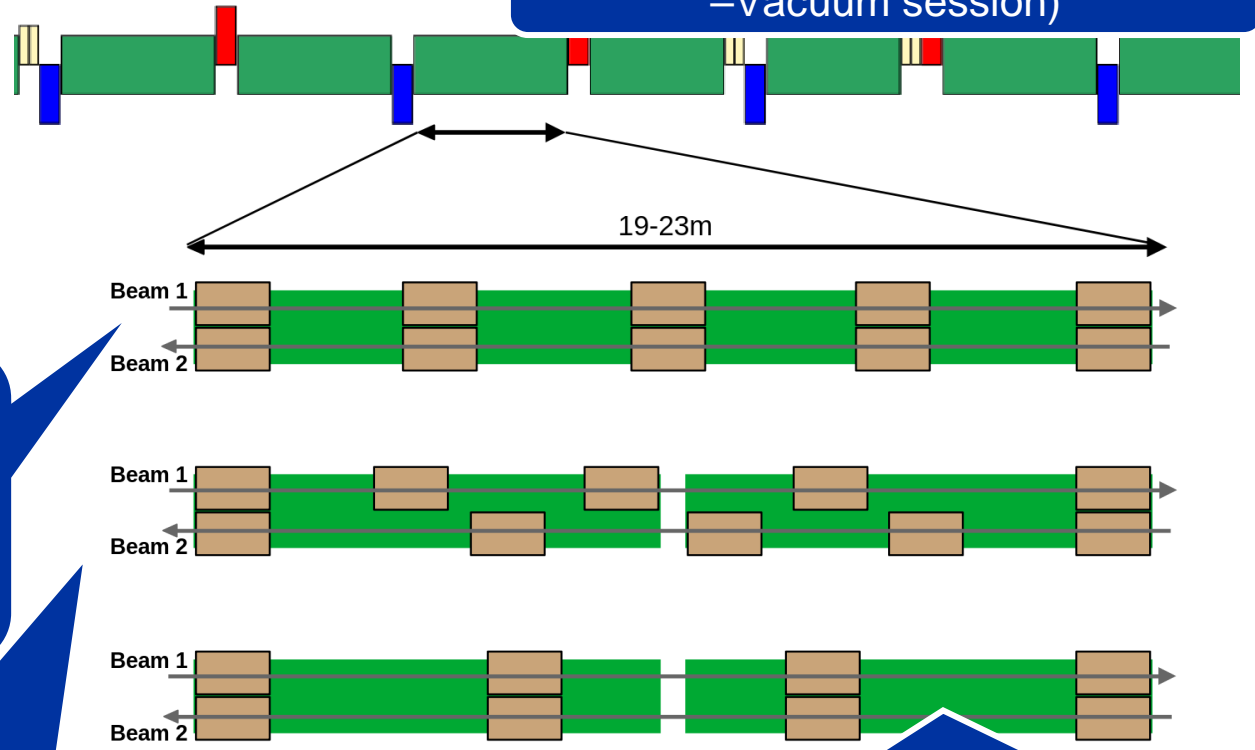
FSR:

- 5 stoppers per beam per 20 m dipole
- Assumed symmetric layout along 20 m dipole

- Need to consider that 20 m dipoles are split
- With 5 stoppers per beam this would require an asymmetric layout

- **Can we reduce the number of stoppers per beam from 5 to 4 per beam?**
- Would require important changes: stoppers closer to beam, longer stoppers
- Feasibility being studied by TE/VSC

See talk of M. Ady (Acc Tech Design - Vacuum session)

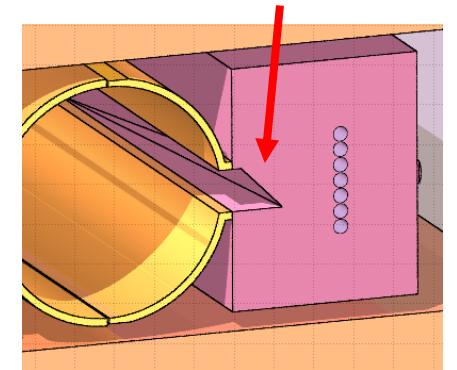
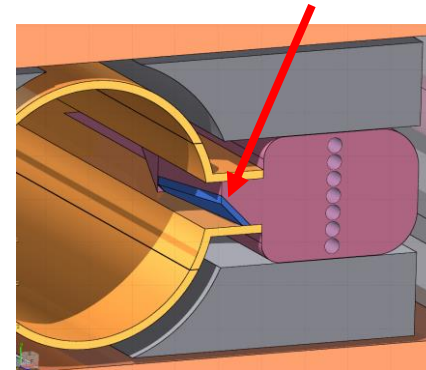


Enhancing absorption efficiency of photon stoppers

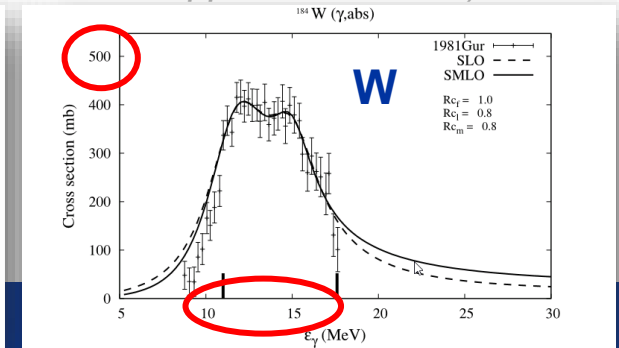
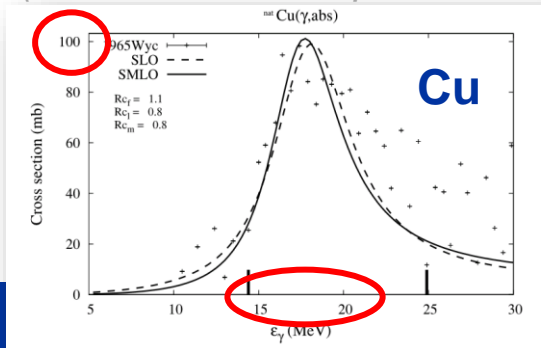
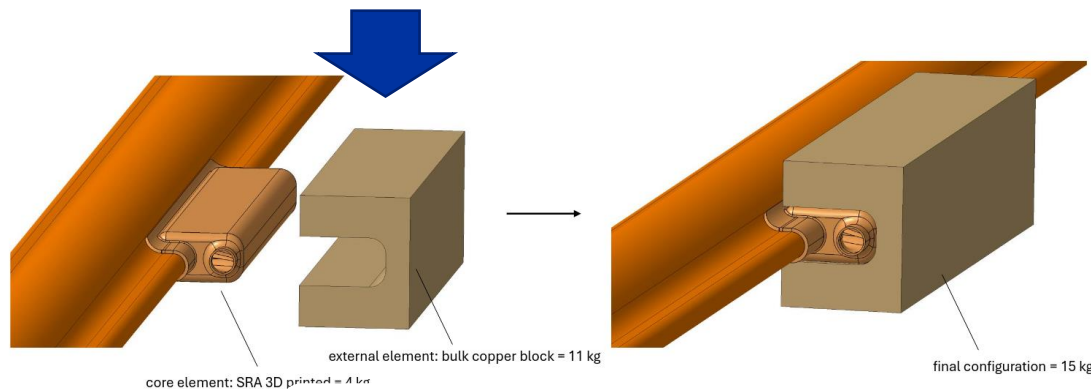
Relative power absorptions by photon stoppers (SR at ttbar):

- It is highly desirable to **increase the power absorption** of the present (FSR) CuCrZr photon stoppers (→ simpler shielding design)
- Inner tungsten surface** would help but already **discarded** before FSR
 - >10 times higher neutron flux
 - Engineering challenges
- Larger Cu bulk volume** is a possible option → technical feasibility/integration to be studied

FSR version (CuCrZr) – 4 kg	FSR version (CuCrZr) but with inner W surface – 4 kg	Enlarged photon stopper (CuCrZr + Cu bulk) – 15 kg
68.1%	76.4%	80.7%



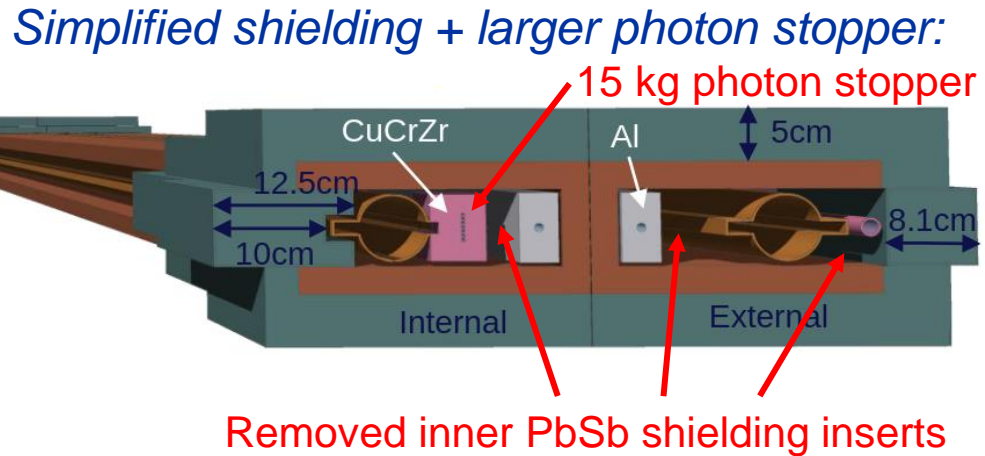
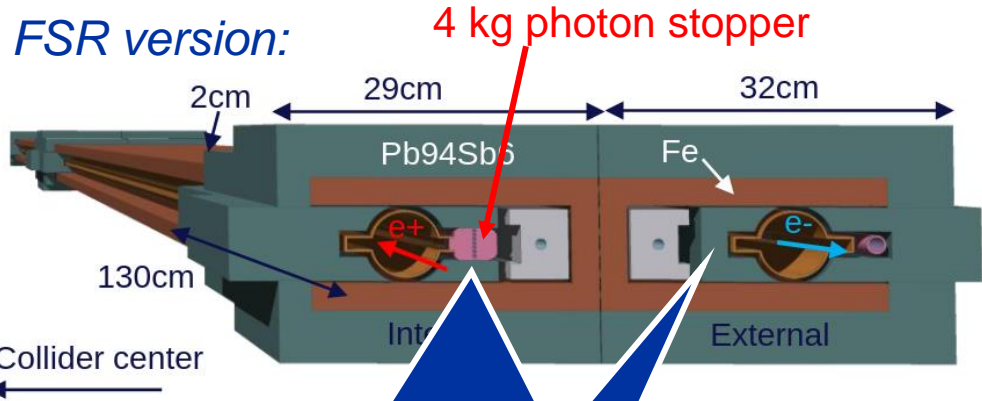
Figures below: photo-nuclear cross sections → neutron production (IAEA handbook on photo-nuclear data for applications, 2020).



See talk of M. Morrone (Acc Tech Design – Vacuum session)

Simplifying the shielding concept

See talk of B. Humann (Tech Infrastructure – Integration session)



Integration of inner shielding components very challenging (tight space constraints)

- Aiming to **simplify FSR shielding topology** to facilitate tech design
- First studies ongoing, **but expect more iterations** in the next months
- Closely linked to possible photon stopper design iteration

	ttbar (182.5 GeV)	
Rad. shielding:	FSR	Simplified
Photon stoppers	68.1%	80.7%
Radiation shielding	20.4%	3.7%
Vacuum chambers	8.0%	5.2%
Dipoles	3.5%	10.1%
Quadrupoles	<0.02%	<0.02%
Sextupoles	<0.02%	<0.02%
Environment*	<0.03%	<0.05%

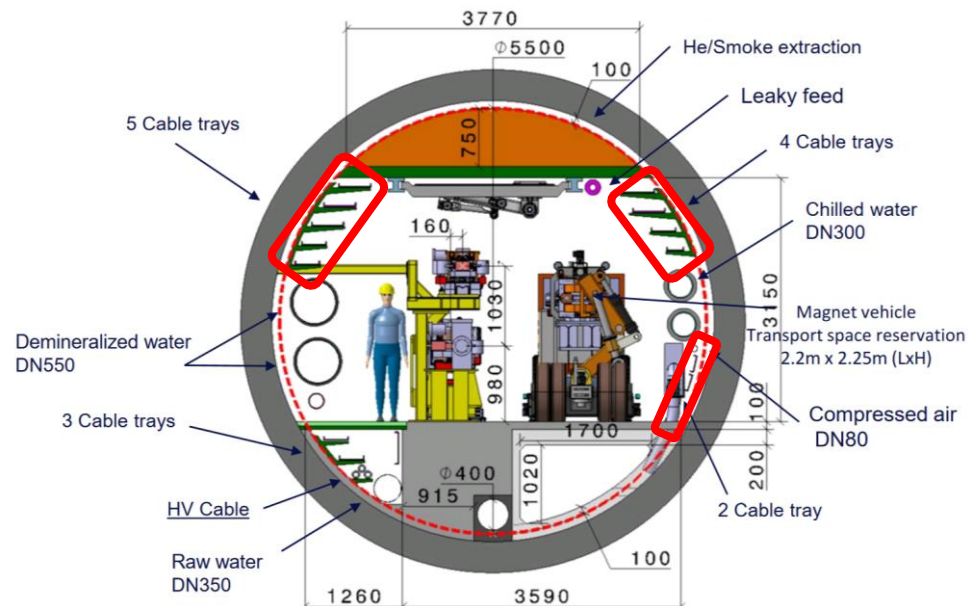
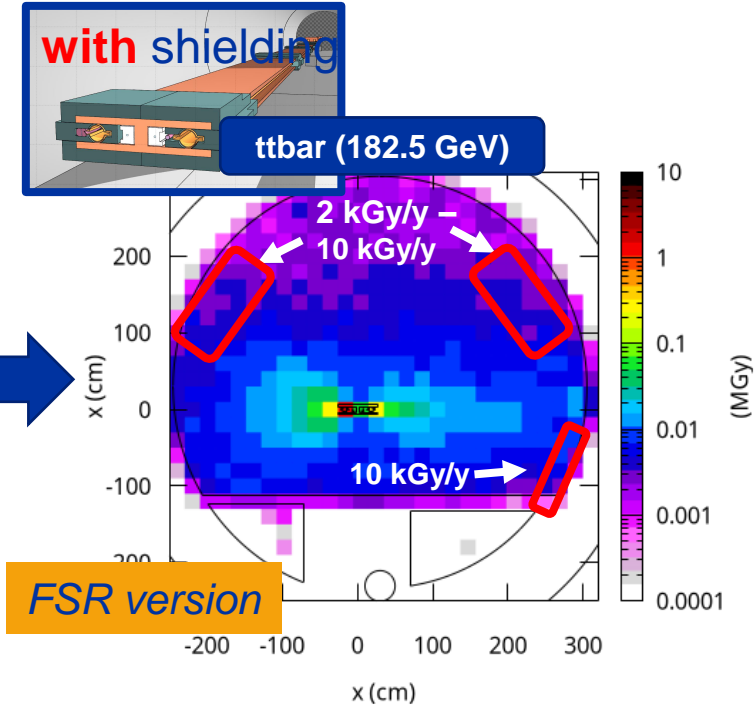
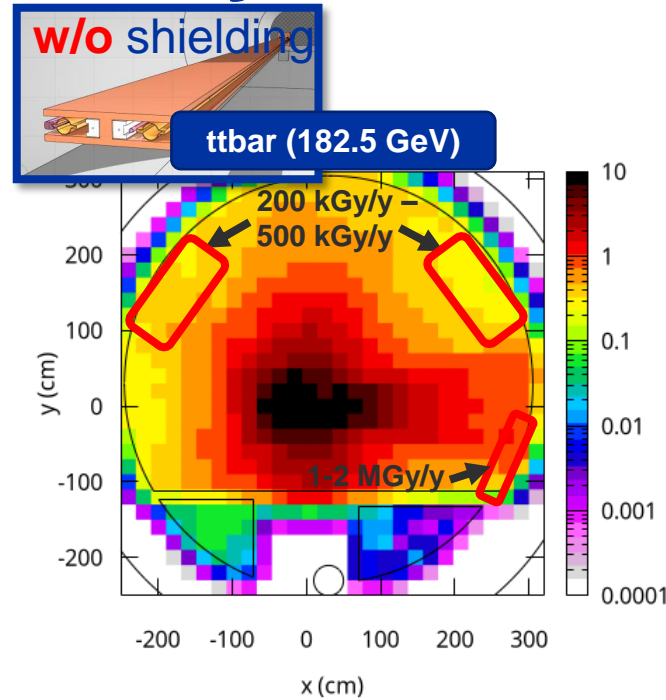
To be followed up!

Evacuate heat from yoke through shielding?

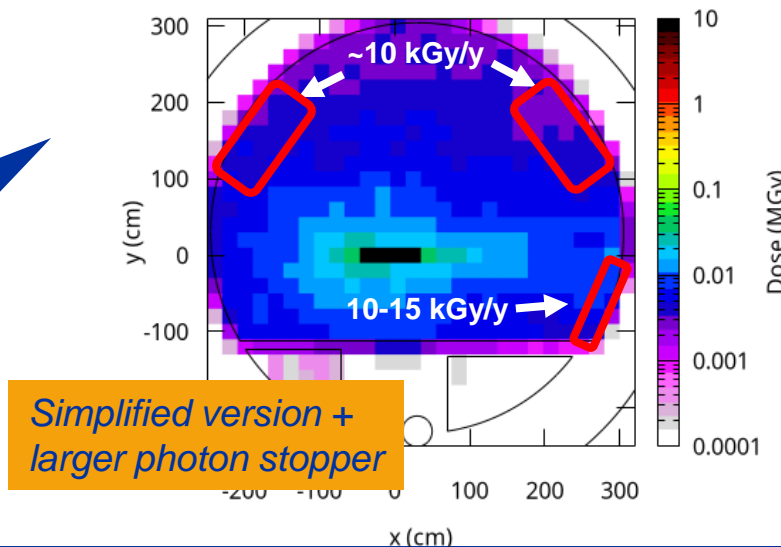
Rad leakage still quite acceptable!

Dipole shielding efficiency: annual dose in arc tunnel

- 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)



Simplified shielding + larger photon stopper results in (almost) same performance as FSR version



Revisiting target dose levels for the FCC-ee tunnel

- Sensitivity to ionizing dose depends strongly on type of equipment
 - Have to give particular attention to large distributed systems (cables, optical fibres,...)
 - These systems have to remain functional for the full FCC-ee era (including tbar)
- **For the FSR, we oriented ourselves at “classical” dose limits adopted for HL-LHC cables**
- Shall anticipate an evolution in equipment technology
 - For example, fibres instead of classical copper cables, photonics, wireless technologies
 - This means, also the radiation resistance criteria evolve → **need to consolidate target radiation levels in pre-TDR phase**

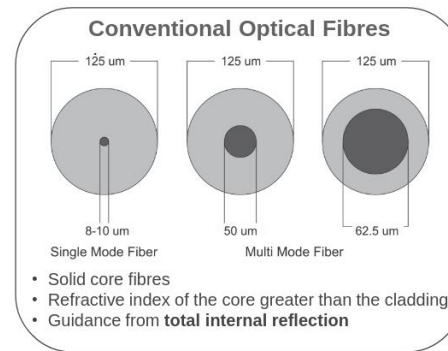
Cables*	Operational lifetime limit	To be qualified up to
Standard (Cat 1)	100 kGy	500 kGy**
Rad-tol (Cat 2)	700 kGy	3.5 MGy**
Rad-hard (Cat 3)	2 MGy	10 MGy**

Significantly higher cost, less choice

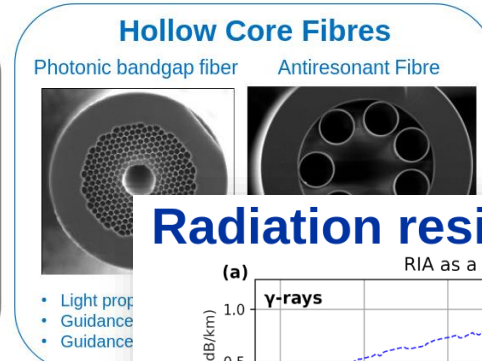
*See CERN Safety Guideline SG-FS-2-1-1 (EDMS 2669629), “Fire safety and radiation resistance requirements for cables”

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

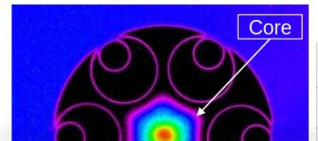
New developments Hollow Core Fibres (HCFs)



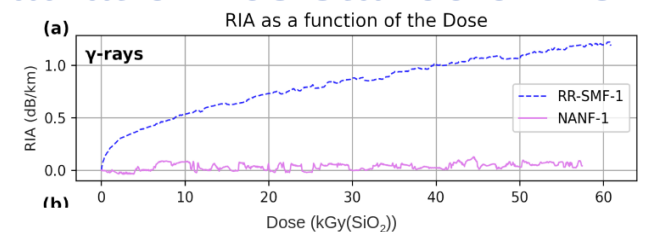
D. Ricci



Nested Antiresonant Nodeless Fibre (NANF)



Radiation resistance of HCFs

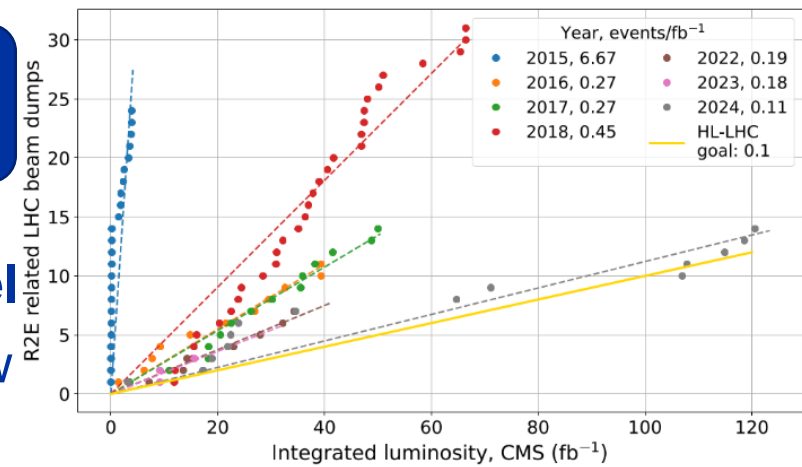


Radiation to electronics

Important
experience from
LHC operation

Some collider/booster 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-tol systems (not only for ttbar!)



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

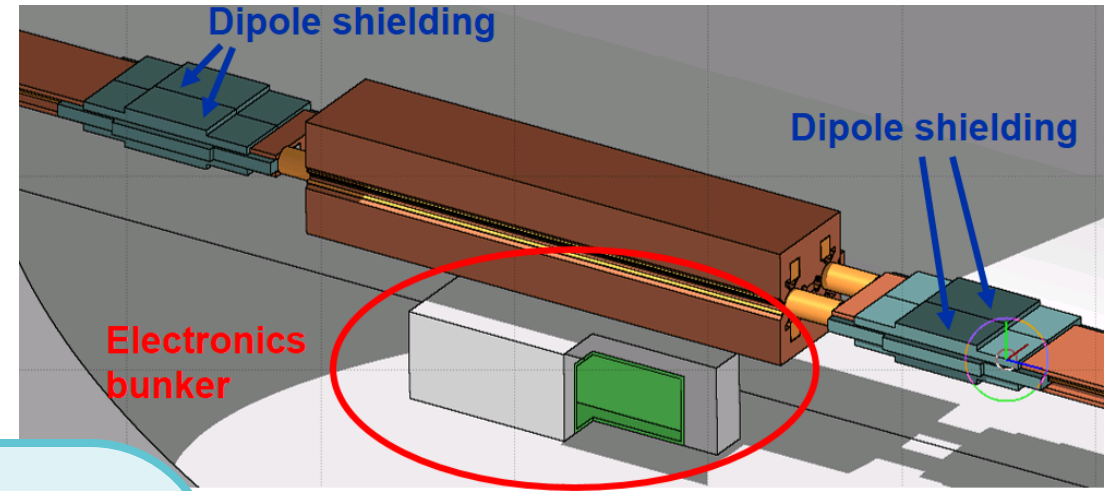
Strategy for electronics → dedicated electronics bunker?

- Technological choices for electronics are strongly linked to radiation levels
- Developing the electronics system design strategies* might require time by equipment groups
- Our assumption for the pre-TDR phase is that a bunker **is needed** and we shall proceed with the bunker design and integration

**The FCC-ee Rad&Shielding WG can study the rad environments and can advices on rad effects, but it is beyond the scope of the WG to steer the design choice for electronics*

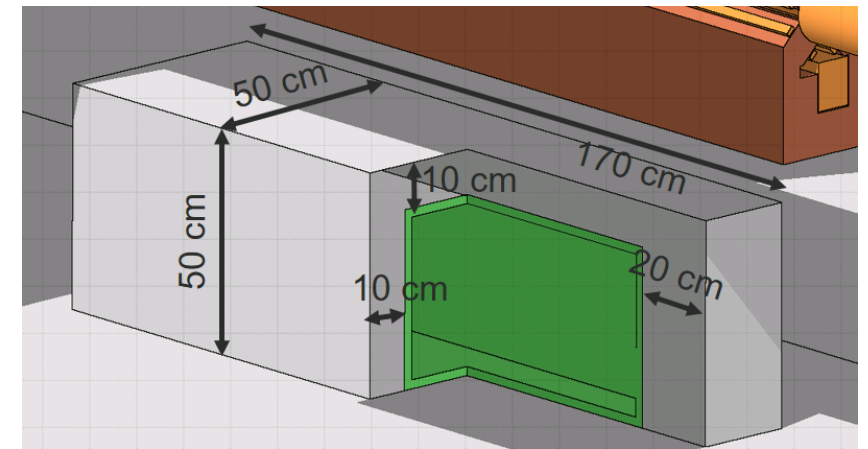
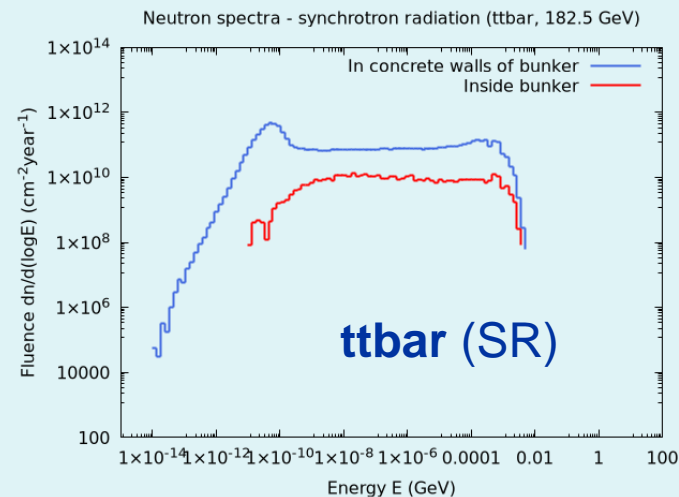
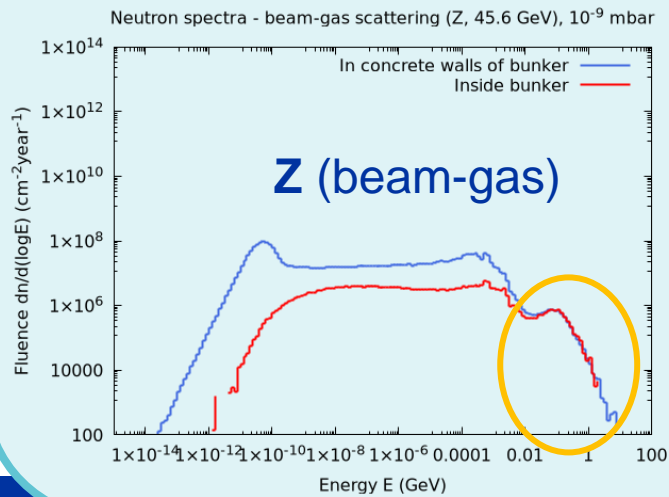
Electronics bunker concept (FSR)

- Assumed to be located **below quadrupoles**
- Concrete walls** (lateral 10 cm, front/back 20 cm) to reduce the flux of secondary electrons/photons
- Borated polyethylene** (10%) on the inside (2 cm) to moderate and capture neutrons



Radiation levels in bunker driven by:

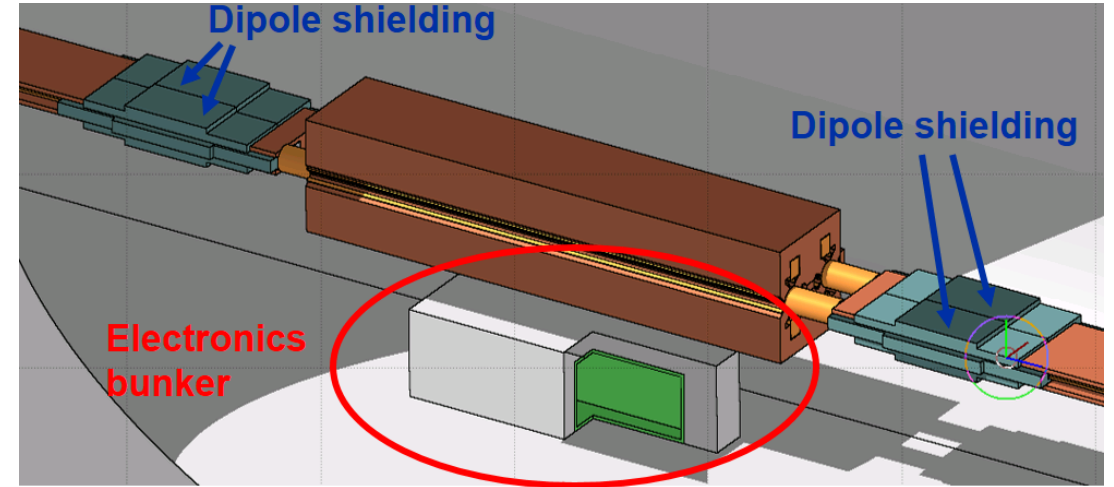
- **Z (45.6 GeV):** beam-gas scattering
- **ttbar (182.5 GeV):** synchrotron radiation



- **SR at ttbar yields higher neutron fluence** than beam-gas scattering at Z
- But beam-gas scattering gives rise to **higher-energy neutron tails**

Radiation levels inside bunker (FSR)

- 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



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

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

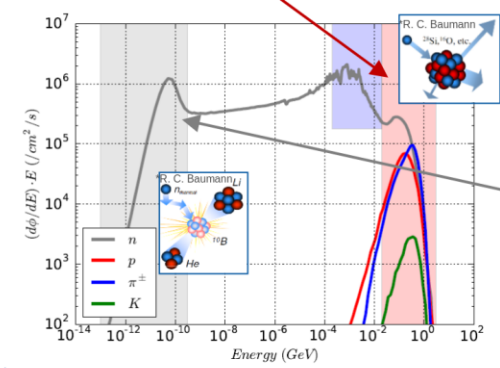
➤ Bunker primarily needed for SR at ttbar, not necessarily for beam-gas losses

Predicting Single Event Effects (SEEs) for FCC-ee

- Recent memory technologies: **large sensitivity to neutrons below 10 MeV** (concerns Single Event Upsets (SEUs) and, more generally, soft errors)
- No Single Even Latch-up (SEL) sensitivity expected for FCC-ee SR environment (threshold above ~14-20 MeV), but still to be assessed for beam-gas environment
- The Φ_{HEHeq} approximation, despite its simplicity, has shown to be efficient and robust in predicting SEE rates for LHC-type environments
- But: risk of severe SEU underestimation at FCC-ee (up a factor 75) **when using the same HEHeq approach for SR-induced neutron spectra**

High Energy Hadrons (HEH):
n, p, π , K with $E \geq 20$ MeV
Responsible for both soft and hard SEEs

HEH equivalent (HEHeq):
HEH + n between 0.2-20 MeV



$$\varphi_{HEHeq} = \int_{0.2\text{MeV}}^{20\text{MeV}} w(E) \frac{d\varphi_n(E)}{dE} dE + \int_{20\text{MeV}}^{+\infty} \frac{d\varphi_{HEH}(E)}{dE} dE$$

Intermediate energy neutrons - major concern with **scaling of technology**

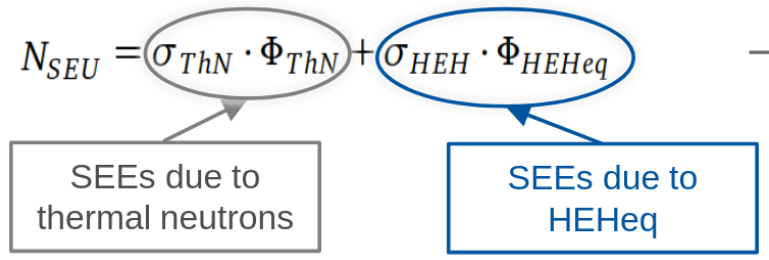
Thermal Neutrons (ThN):
n with $E \approx 25$ meV
Only soft SEEs, interacting with ^{10}B through the $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction

$$\varphi_{ThNeq} = \int \sqrt{\frac{0.025[\text{eV}]}{E[\text{eV}]}} \frac{d\varphi_n(E)}{dE} dE$$

Underestimation factors HEHeq(memory)/HEHeq(Toshiba)

Memory	FCC sync	FCC gas	RR	UJ
Toshiba	1.0	1.0	1.0	1.0
Cypress65nm	75.4	1.7	1.3	2.9
ISSI40	61.3	1.5	1.2	2.5
M2GL090 RAM	4.0	1.2	1.1	1.3
FPGA 55nm	22.1	1.2	1.1	1.5
12 nm FinFet	71.2	2.3	1.6	3.4

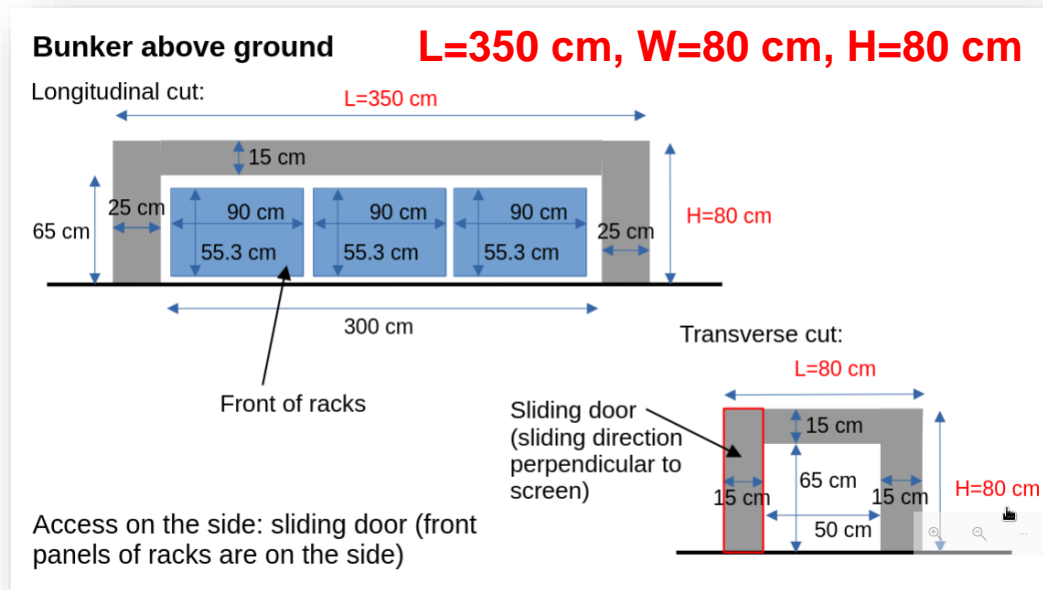
M. Checchetto, R. Garcia Alia, D. Lucsanyi



➤ SEE assessment for FCC-ee will require significant effort and expertise (simulation and experimental approach)

Bunker size requirements

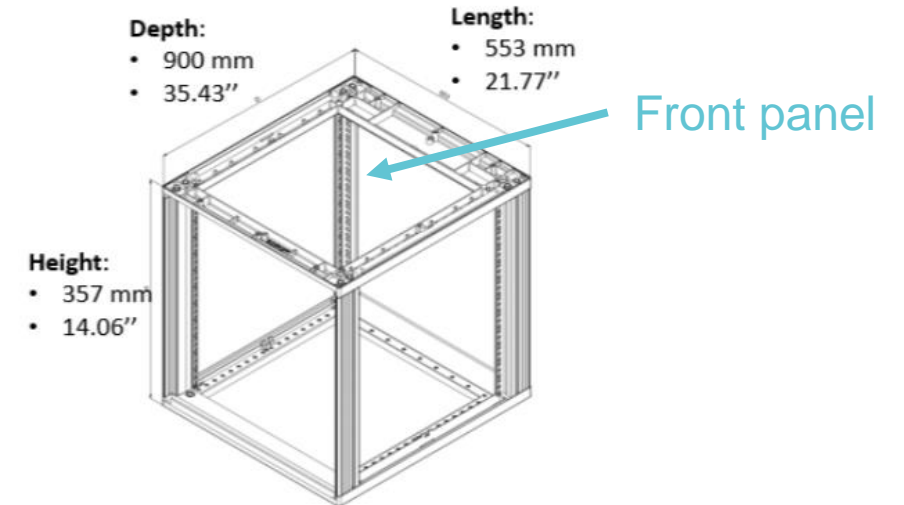
- Received first input from **vacuum** and **beam instrumentation** groups concerning the space requirements for electronics racks
- Still require feedback for other systems (machine protection, survey, cooling & ventilation, ...)



➤ Expect that bunker size will evolve in the pre-TDR phase once systems are better defined

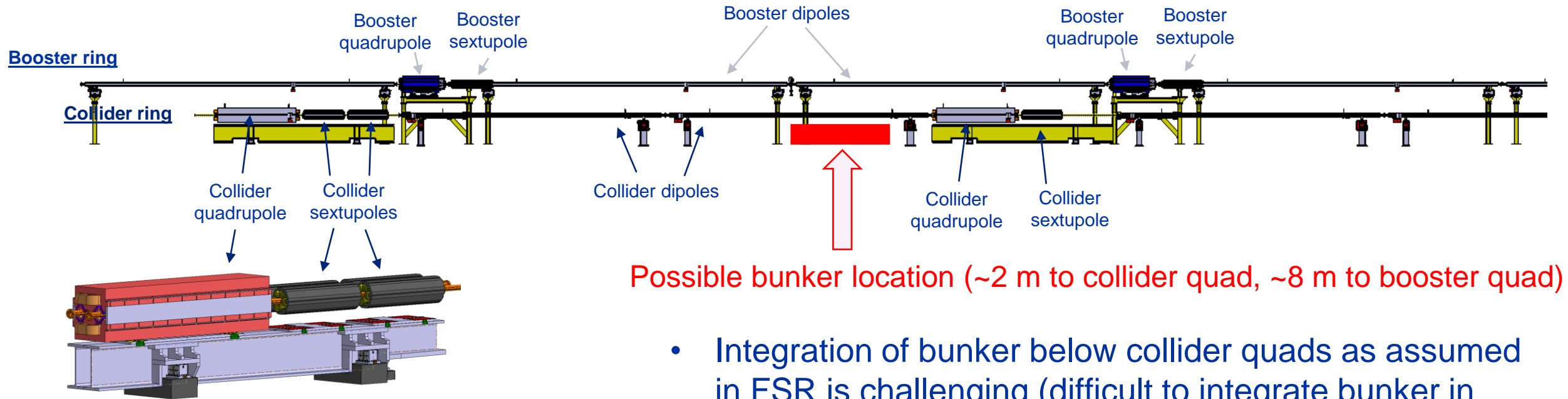
Present assumptions:

- Considered rack size suggested by SY/BI group:



- Includes some margin for cooling fans, cable routing etc.
- For the moment, assume that **three such racks are needed per collider quad**
- Need for more racks to be confirmed, depending on the requirements of other systems

Bunker integration and design considerations



Possible bunker location (~2 m to collider quad, ~8 m to booster quad)

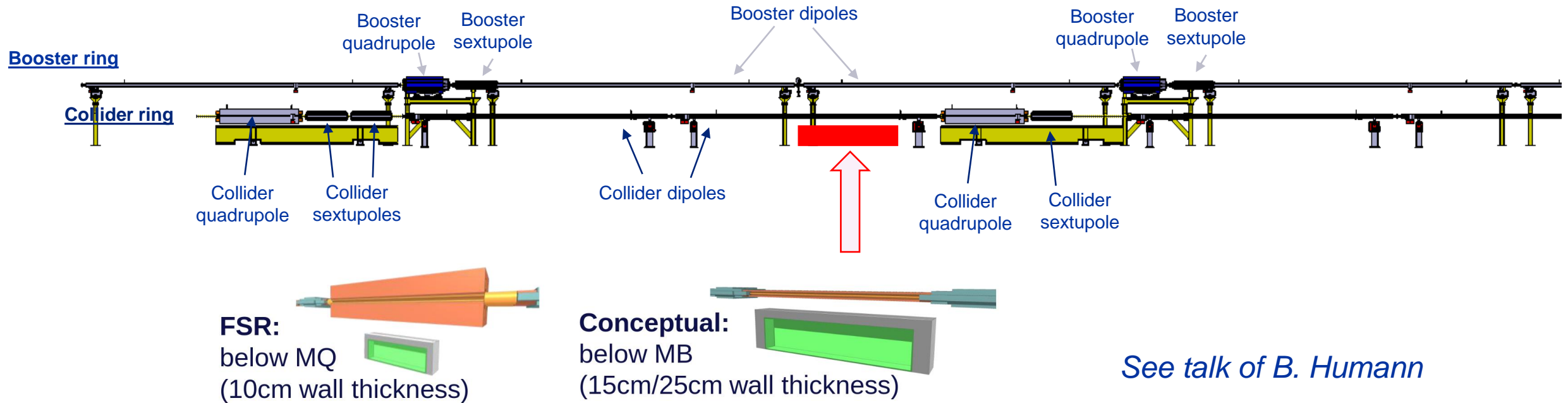
Important design considerations:

- **Accessibility:** need to enable human and fully robotic interventions (opening the bunker and exchanging cards)
- **Cable routing** from bunker to machines (collider and booster)
- **Cooling system** for bunker

- Integration of bunker below collider quads as assumed in FSR is challenging (difficult to integrate bunker in girder)
- Studying new positions → most promising is a placement **below collider dipole** next to quads (will also depend on final collider support positions)
- **Above ground bunker preferred** over trench due to accessibility reasons

➤ If the collider height is reviewed, this might have an impact on the bunker integration (if the collider is lowered)

Radiation levels at newly proposed bunker position



See talk of B. Humann

- Assumed 5 cm thicker bunker walls at new position since radiation fields are higher below dipole
- Radiation levels in bunker comparable at new position**

See talk of B. Humann (Tech Infrastructure – Integration session)

	FCC-ee (ttbar)		HL-LHC arcs*
	<u>FSR (below MQ)</u>	<u>New (below MB)</u>	(below magnets)
TID	<10 Gy/y	<10 Gy/y	1.4 Gy/y
$\Phi_{1\text{MeV n Si}}$	$2 \times 10^{10} \text{ cm}^{-2}/\text{y}$	$7 \times 10^9 \text{ cm}^{-2}/\text{y}$	$1.6 \times 10^{10} \text{ cm}^{-2}/\text{y}$
Φ_{HEHeq}	$2 \times 10^7 \text{ cm}^{-2}/\text{y}$	$1 \times 10^7 \text{ cm}^{-2}/\text{y}$	$2.4 \times 10^9 \text{ cm}^{-2}/\text{y}$
Φ_{THNeq}	$4 \times 10^9 \text{ cm}^{-2}/\text{y}$	$4 \times 10^9 \text{ cm}^{-2}/\text{y}$	$1.2 \times 10^{10} \text{ cm}^{-2}/\text{y}$

Shielding needs in the insertion regions

Experiment IRs:

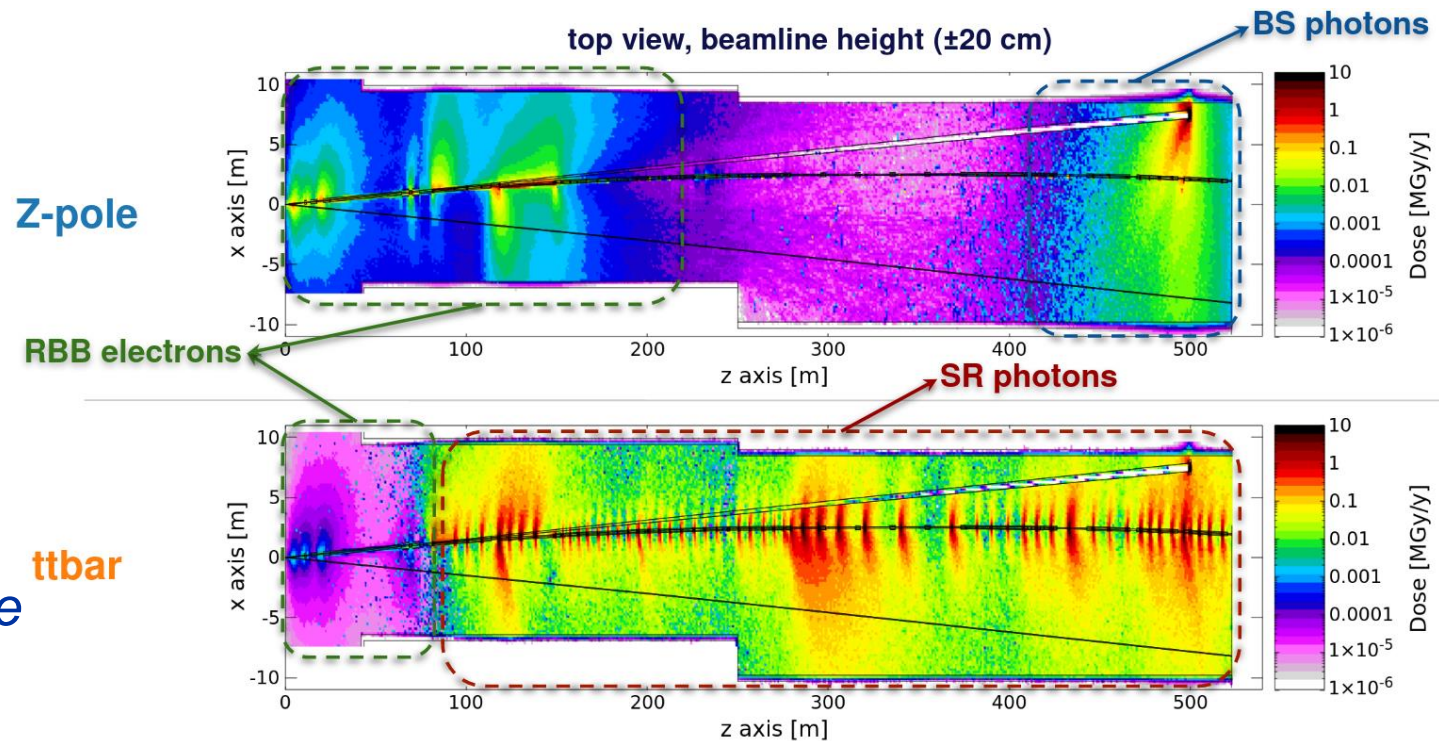
- The radiation levels are also significant in the tunnel of the experimental IRs
- Different radiation sources contribute (see figure)

Technical IRs:

- Need to study radiation fields in some key areas (injection&extraction region in PB, EM separators in PH, collimation region in PF)

➔ *Will be followed up in pre-TDR phase*

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



A. Frasca

Summary and conclusions

- **The arc shielding concepts elaborated in the FSR (dipole shielding + electronics bunker) provide a first basis for managing radiation in FCC-ee**
- **Need to refine the target radiation levels for machine equipment and infrastructure in the pre-TDR phase (→ consolidate the required shielding efficiency)**
 - Requires close collaboration with equipment groups and the relevant working groups/panels
 - Establish limits for different kind of equipment, combined with a more in-deep assessment of radiation effects expected in the FCC-ee environment (e.g. for electronics)
- **Extend shielding studies to insertion regions (many loss sources!)**
- **The technical design and integration, both for dipole shielding and bunker, entails still many challenges**
 - Requires iteration between different expert teams to arrive at a robust solution
 - Early prototyping would be important; integration in mock-up would be beneficial



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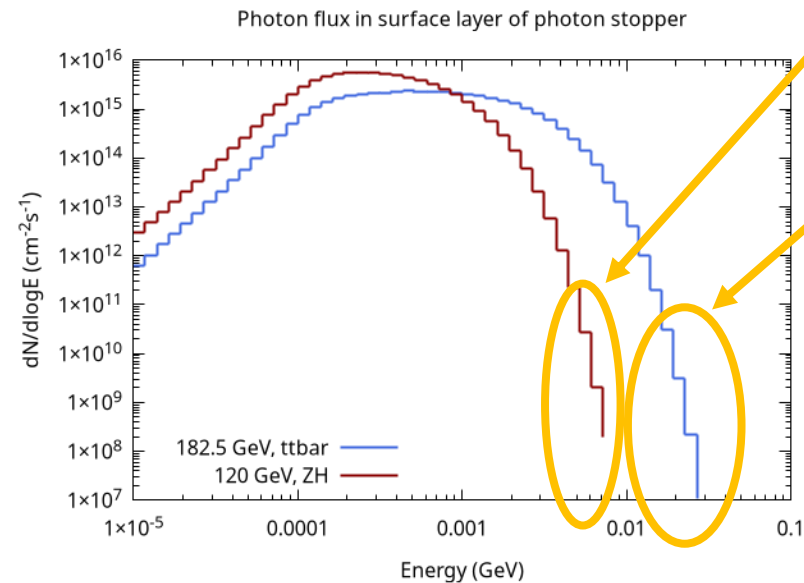
Neutron production in photo-nuclear interactions

- Some SR photons* have sufficiently high energies to produce neutrons in the regime of the Giant Dipole Resonance
- The **energy threshold** for neutron production, as well as the **energy and width of the resonance** depends on the material
- The photon stopper softens the photon spectrum → most of the neutron production takes place in the photon stoppers themselves (photon stopper material matters - CuCrZr)

	Abundance	$E_{\text{threshold}} (\gamma, n)$
Cu-63	69.17%	10.9 MeV
Cu-65	30.83%	9.9 MeV
Cr-50	4.34%	13.0 MeV
Cr-52	83.79%	12.0 MeV
Cr-53	9.50%	7.9 MeV
Cr-54	2.37%	9.7 MeV
Zr-90	51.45%	12.0 MeV
Zr-91	11.22%	7.2 MeV
Zr-92	17.15%	8.6 MeV
Zr-94	17.38%	8.2 MeV

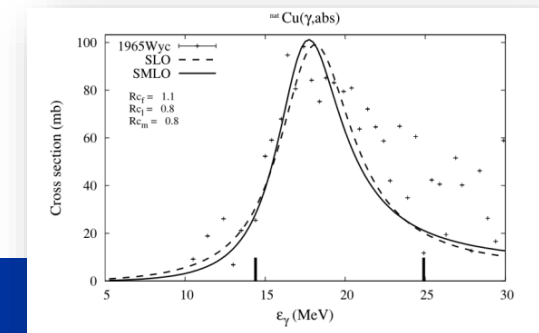
Table credit: IAEA handbook on photo-nuclear data for applications, 2020.

Isotopes of Cu, Cr, and Zr



ZH (120 GeV): SR spectrum just at the edge of reaching (n, γ) threshold in CuCrZr

ttbar (182.5 GeV): SR spectrum extends into resonance region of Cu



Radiation to electronics – relevant quantities

	Quantity	Description*	
Cumulative radiation effects	Total ionizing dose	Energy deposited through ionisation processes per unit mass	(Gy)
	Si 1 MeV neutron-equivalent fluence	Amount of Displacement Damage (DD) in Silicon, defined as the fluence of 1-MeV neutrons that produces a DD equivalent to the one of the physical particles.	(cm ⁻²)
Single event effects	High Energy Hadron (HEH) equivalent fluence	Fluence of all hadrons with energy greater than 20 MeV, plus an additional weighted contribution from intermediate energy neutrons from 0.2 MeV to 20 MeV.	(cm ⁻²)
	Thermal neutron equivalent fluence	Fluence of neutrons at thermal energies (approximately 25 meV) with weighed contribution of other energy ranges.	(cm ⁻²)

*From HL-LHC Radiation level specification document, EDMS 2302154 v.1.1, LHC-N-ES-0001.