

# RADIATION PROTECTION STUDIES FOR THE FCCee

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FCC Week 2025, Vienna

# Introduction and objectives

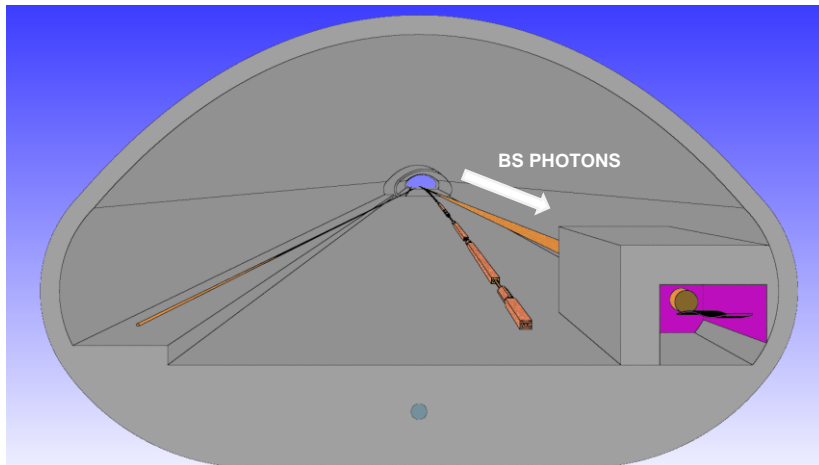
- ❑ Radiation protection studies ensure that the proposed FCC-ee design meets safety objectives and constraints for personnel and the environment.
- ❑ **The presentation focuses on three priority topics for the pre-TDR phase**, which could significantly impact system integration and civil engineering:
  - **The Beamstrahlung dump** for its impact on integration, maintenance, and radioactive waste production, with **an overview of key radiation protection aspects to be developed** in future phases.
  - **The Betatron collimation system** (at PF) **for its implications for access control** that may require modifications in integration **and civil engineering** during the pre-TDR phase.
  - **The Injector complex** to set the RP design objectives, **highlighting areas needing further development in later stages**.

# Beamstrahlung dump

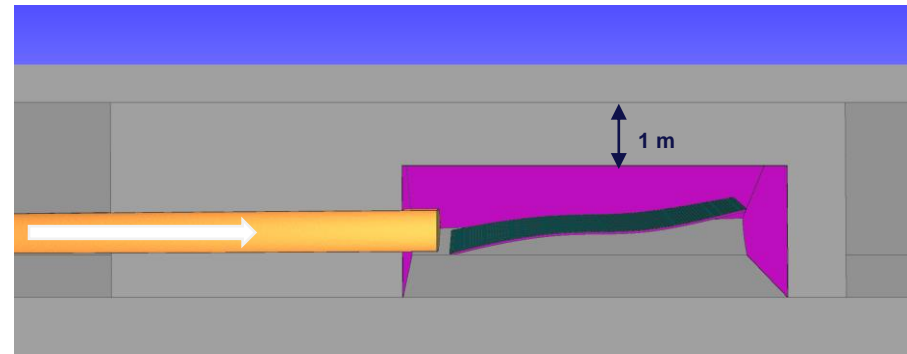
\*See also: "Status of the Beamstrahlung Dump Design" – Silvio Candido (this afternoon)

## FLUKA model

- ❑ Single sloped BS dump design: 3 cm thick SS support and 1.6 cm thick layer of liquid lead (**pure lead + impurities**). The SS steel vessel is 2 cm thick, and it is filled with inert gas (**Argon**).
- ❑ A preliminary design of concrete shielding is included in the geometry: **1 m thick in all directions** and extending upstream around the vacuum chamber to mitigate backscattering.



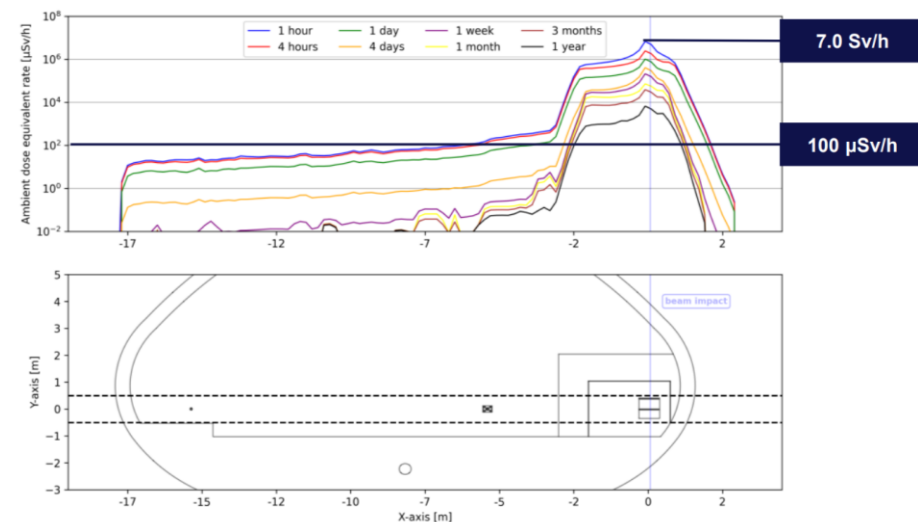
Pure lead - 11.36 g/cm <sup>3</sup>	
Mass fractions	
Ag	3.0E-06
As	9.0E-06
Bi	4.0E-06
Cd	1.0E-06
Cu	1.0E-06
Fe	1.0E-07
Pb	9.9E-01
Sb	5.1E-05
Sn	1.0E-06
Zn	2.0E-06



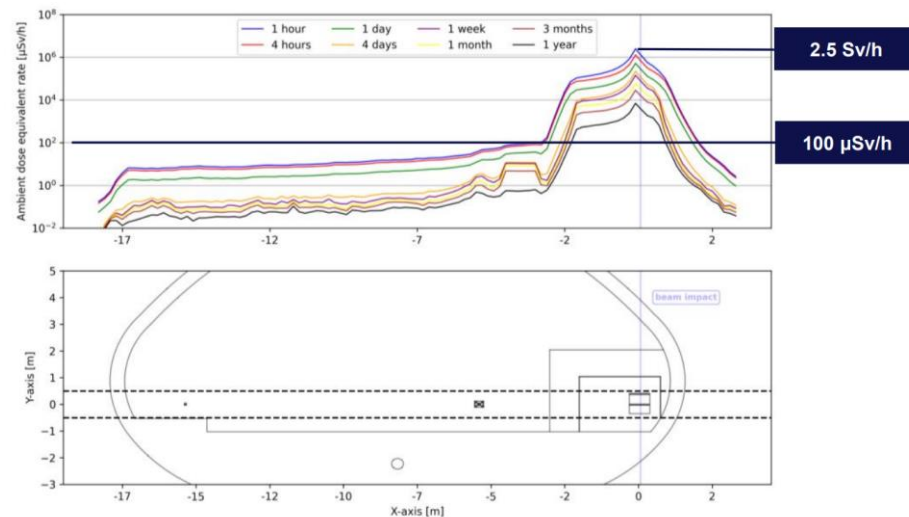
**Acknowledgement Alessandro Frasca and SY/STI**

# Results – Residual dose rate

Irradiation profile: 185 days of operation (Z pole)



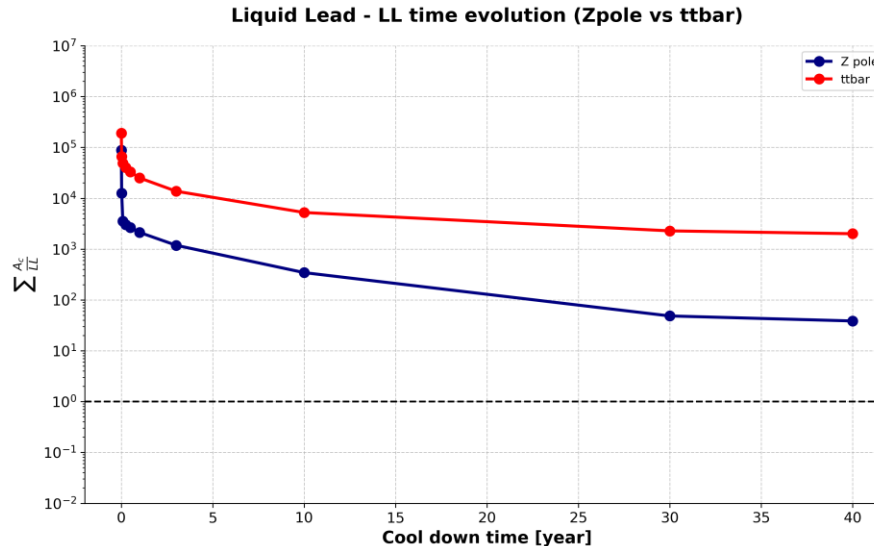
Irradiation profile: 185 days of operation (ttbar)



- ❑ The main sources of residual radiation are the surrounding materials, rather than the liquid lead itself.
  - ❑ **The residual dose rate from ttbar operation will be lower than at the Z pole:  $10 \mu\text{Sv/h}$  vs  $60 \mu\text{Sv/h}$  outside the shielding after 185 days of operation and 1 hour of cool-down time, at  $\sim 10 \text{ m}$  distance where the transport zone/passage is located.**
- The dump zone still offers space for potential shielding/cavern extensions to reach the **target dose rate to  $1 - 10 \mu\text{Sv/h}$**  in possible passage areas.

# Results – Lead activation

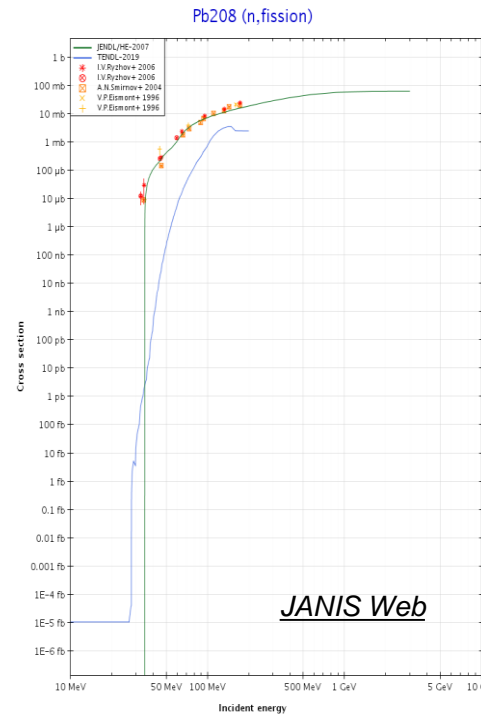
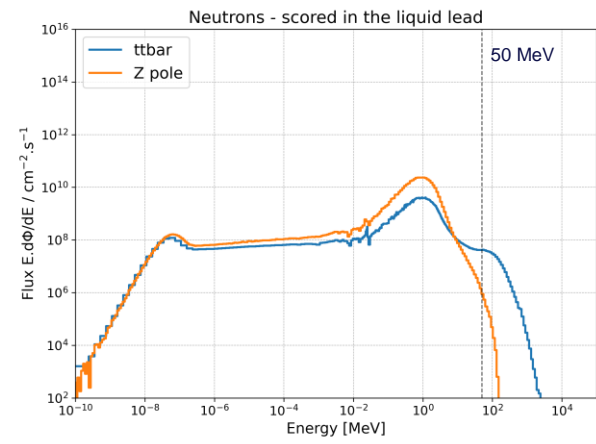
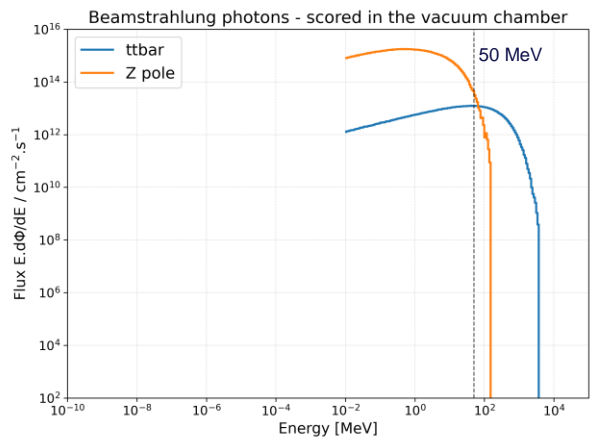
$$LL^{total} = \sum_{i=1}^n \frac{a_i}{LL_i} < 1$$



- ❑ The radionuclides in activated materials ( $a_i$ ) are compared with the CERN clearance limits ( $LL_i$ ) through the sum of their ratio ( $LL^{total}$ ). **When  $LL^{total}$  is lower than 1, the material can be considered as non-radioactive.**
- ❑ ttbar shows almost two orders of magnitude higher activity levels compared to Z-pole.  
 → Activity concentrations in the liquid lead after 5 years of ttbar operation remain above clearance limits even after 30 years of cool-down, **resulting in approximately 80 tons (10 tons x 8 dumps) of lead to be classified as FA-MA (faible et moyenne activité) radioactive waste.**

# Results – Lead activation

- Beamstrahlung intensity at the Z pole is 170 times higher compared to ttbar, but the ratio decreases significantly for the photon flux above 10 MeV and 50 MeV.
- Despite lower beam intensity, spallation and radioactivity production increases in ttbar mode due to the rising fission cross-section for Pb-208 above ~50 MeV (similar for other Pb isotopes).



	Z pole	ttbar	Ratio [Zpole/ttbar]
Beamstrahlung photons intensity	1.3E+18 p/s	7.6E+15 p/s	171
Beamstrahlung photons flux above ~photonuc. threshold (E > 10 MeV)	5.6E+16 p/s	4.1E+15 p/s	14
Beamstrahlung photons flux above ~spallation threshold (E > 50 MeV)	1.2E+15 p/s	2.2E+15 p/s	0.6

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# Conclusions and future perspectives

- ❑ **A dedicated cavern for the beamstrahlung dump system is recommended** to guarantee containment and provide for safety, incorporating engineering solutions to facilitate maintenance: **remote intervention methods are necessary due to high residual dose rates.**
  - ❑ **The liquid lead reservoir and piping will require appropriate shielding.**
  - ❑ Other topics to follow up on during the design phase:
    - The main radionuclides in the dump originate from lead, not its impurities. **Additional impurities from steel corrosion are unlikely at the operating temperature (~400°C).**
    - **Po-210 outgassing may occur due to bismuth impurities**, but a gas purification circuit is planned.
  - ❑ According to current agreements, **long-lived, medium-active waste (FA-MA) must be disposed of by Switzerland** (~ a few hundred kCHF/m<sup>3</sup> x 10-20 m<sup>3</sup>).
  - ❑ Radiological studies will be compared with those of other design alternatives, such as gas-cooled graphite.
- **A 1:1 cold test facility will be extremely helpful in identifying the challenges related to maintenance and testing systems that are important for safety.**

**Pre-TDR: Allocate resources based on the engineering design planning.**

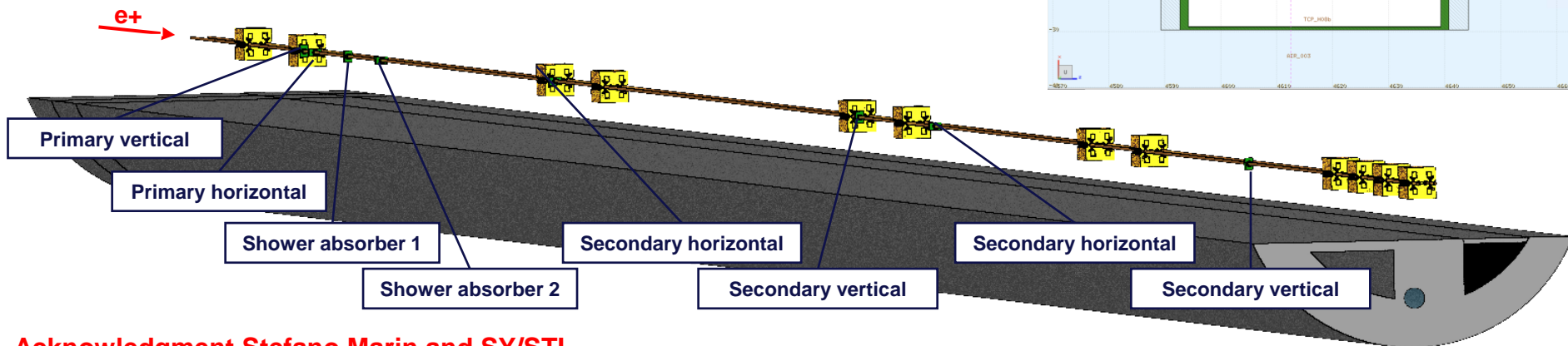
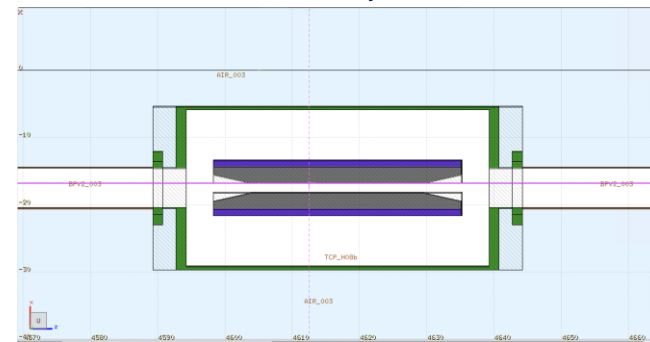
# Betatron collimation system

\*See also: "Preliminary design of FCCee collimators" – Antonio Perillo Marcone (this afternoon)

## Simulation setup

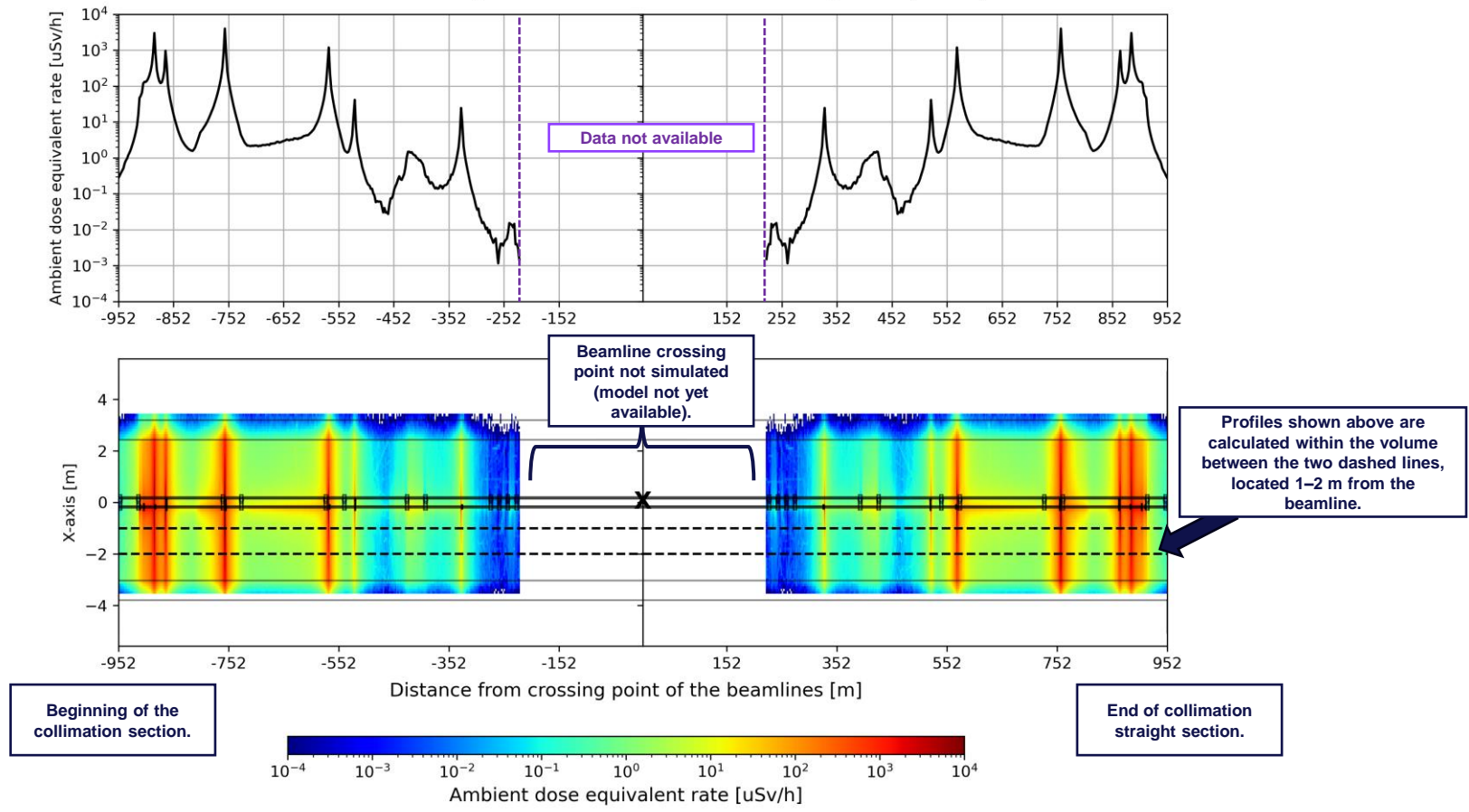
- ❑ Initial studies by SY/STI evaluated beam power losses on the collimation system made of primary and secondary collimators and shower absorbers.
- ❑ **RP assessment targeted residual radiation levels:** beam collimation systems become highly activated due to high-energy particle interactions with collimators.
- ❑ **The study focuses on Z-pole mode** because of its highest beam intensity:
  - Beam loss rate considering 30 minutes of beam lifetime.
  - Pencil beam is modelled in FLUKA, with equal impact at 1  $\mu\text{m}$  from the jaws of the primary vertical/horizontal collimators.

*Pencil beam on the Primary Horizontal Collimator*

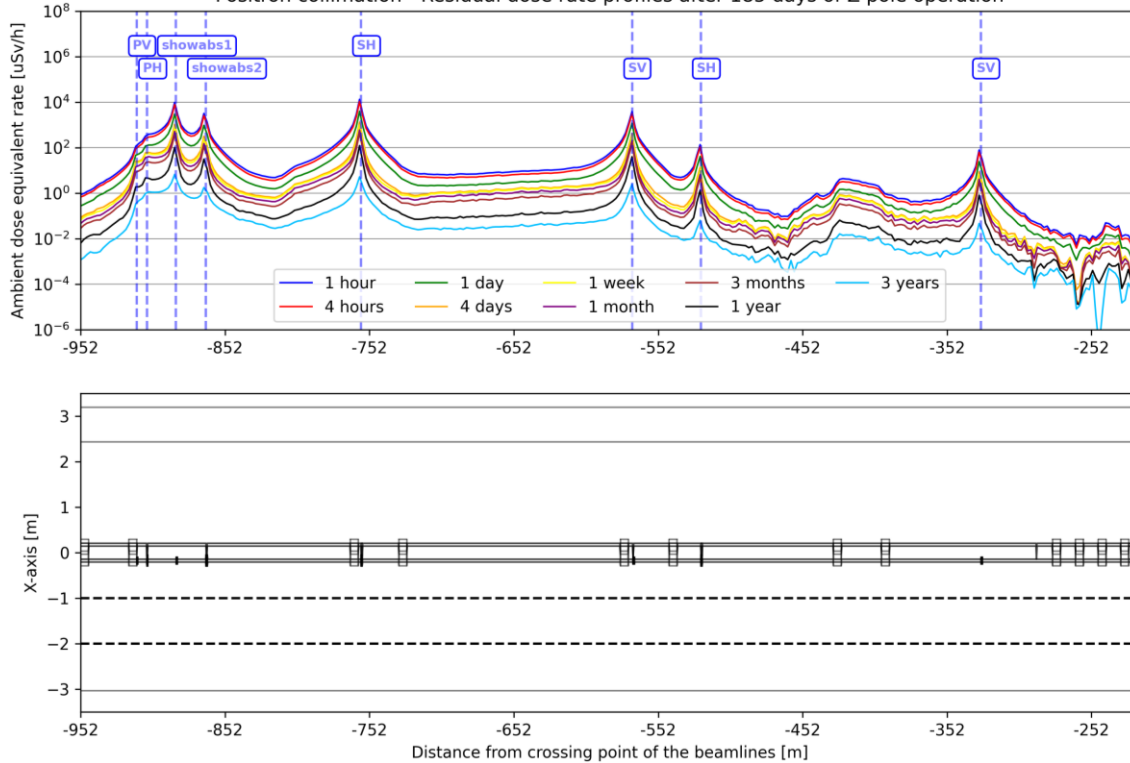


**Acknowledgment Stefano Marin and SY/STI**

### Betatron collimation - 1 day of cool down time after 185 days of Z pole operation



Positron collimation - Residual dose rate profiles after 185 days of Z pole operation



Cool-down time / after 185 days of Z pole operation	Residual Dose rate at the first secondary horizontal collimator (SH) (z = -758 m) - Passage at 1.5m distance -
1 hour	13.3 mSv/h
4 hours	10 mSv/h
1 day	4.2 mSv/h
4 days	1.3 mSv/h
1 week	1.0 mSv/h
1 month	0.7 mSv/h
3 month	0.5 mSv/h
1 year	0.3 mSv/h
3 years	0.005 mSv/h

- ❑ The profiles show very extended peaks (dozens of meters) in front of the masks and collimators.
- ❑ The values of residual dose rate are high even for longer cool down times.

# Conclusions and future perspectives

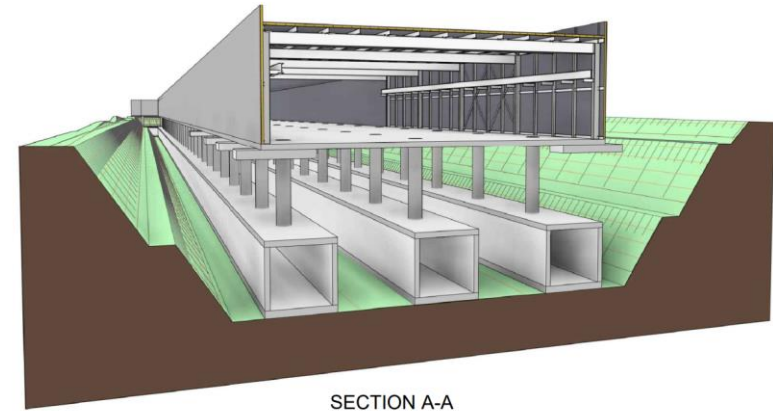
- ❑ The residual dose rates in the collimation insertion are high (**10 mSv h<sup>-1</sup> after 4-hour cool down time and 0.3 mSv h<sup>-1</sup> after 1-year-cool down time**) that affect interventions during the operation phase and the following installation phases.
- ❑ **Potential mitigation measures:**
  1. **Remote or hybrid interventions** in the collimation insertion section.
  2. **Bypass tunnels for the collimation insertion.** The exact position and length of the bypass will depend on the final collimator positions.
  3. **Separate air and water management** from the arc to control and reduce releases to the environment (via bypass tunnel or underfloor air duct and water supplies).
  4. **Restrict/limit access to arc from PF.**
  5. **Local shielding solutions** to be studied.
- ❑ Considering further optimization of design parameters, bypass tunnels solutions, and hybrid maintenance (personnel + robots), 1 day is a realistic cool-down time for access to be considered in the availability study.

NB: The residual dose rate scales linearly with beam lifetime. Therefore, to achieve a significant improvement in values, an increase in beam lifetime by several orders of magnitude would be required, which seems currently unrealistic.

# Injector complex

# Radiation protection studies

- ❑ The injector complex includes 3 LINACs, one positron production target, one damping ring, and the transfer line to the Booster.
- ❑ Preliminary studies have concluded the following:
  - A **minimum shielding** of 50 cm of concrete and 6 meters of soil is required laterally to the machine tunnels and adjacent accessible areas for a radiological separation.
  - A **concrete chicane** of 1-2 meters is needed at each waveguide duct within the LINACs.
  - The **waveguide duct diameter** should not exceed 50 cm, with an optimal diameter of 30 cm.
  - **The positron production target exhibits high residual dose rates** (~3 mSv/h) near the target after one hour of cool-down, following one year of beam operation.
    - **appropriate shielding and remote handling are mandatory.**



# Future perspectives

- ❑ The priority of conducting radiological protection studies comes from the **radiological relevance of this facility, since it is located on the surface** and close to the CERN fence. **This implies potential environmental impact and optimisation requirements.**
- ❑ **A detailed roadmap for the development of the injector complex is required** as it will be the first part to operated.
- ❑ The facility comprises multiple machines with radiologically relevant components (positron production target, dumps, ...)
- ❑ **Topics to be addressed to validate RP aspects** and optimise the design of systems and CE infrastructure:
  - **Radiation safety concept:**
    - **Shielding:** further refinement of beam loss conditions and adequate CE layout
    - **Personnel protection system:** access zoning / beam stoppers / other safety elements → impact on CE layout
  - **Relevant beam loss locations** → Shielding requirements
    - Positron production target
    - Beam dumps (e- linac, e+ linac, DR, HE linac)
  - **Cooling and ventilation concept** (particular focus on recycling to reduce releases of short-lived emitters from the positron production target sector)

# Overall conclusions

- ❑ **RP priorities for the pre-TDR phase were established, emphasizing the need to create a roadmap in particular for the development of the injector complex and BS dump.**
- ❑ **Remote maintenance can significantly reduce access wait times, impacting RP, safety, and availability. There is strong interest in integrating these systems into high-activation areas** such as collimation and the beamstrahlung dump.
- ❑ Further design iterations and studies of the collimation insertion required: **discussion and decision on the mitigation measures to be adopted at PF.**
- ❑ The conceptual and technical design of several systems need to be further developed to allow the study of their radiological relevance and impact. We rely on the provision of input from the accelerator design and technology groups to progress in the radiation protection studies.



THANK YOU FOR YOUR  
ATTENTION!



BACK UP SLIDES

# Other RP topics during preTDR

## ❑ Experiment – PD, PG, PJ, Experiment/Injection to Booster – PA

- *Connection tunnel (Service cavern  $\leftrightarrow$  Accelerator tunnel)*: junction cavern shielding/chicane design must be optimised and validated by RP.
- *Shielding of SR, SR collimation system and masks at IR*: R&D continues with STI through the Radiation Working Group.
- *Injection to Booster at PA*: Expected beam losses at injection and mitigation measures to assess RP impact.

## ❑ Collimation – PF

- *Access tunnel (Service cavern  $\leftrightarrow$  Accelerator tunnel)*: The diameter, length and shape of the access tunnel must comply with RP constraints.
- *Bypass tunnel*: Definition and decision on the integration
- *Ventilation and cooling*: Conceptual design, integration and operation

## ❑ Beam dumps, Injection to Collider – PB

- *Beam dumps*: dump design and shielding to be optimised and validated, operating parameters for the beam dump.
- *Injection to Collider*: Expected beam losses at injection and mitigation measures to assess RP impact.

## ❑ RF collider and booster – PH, PL

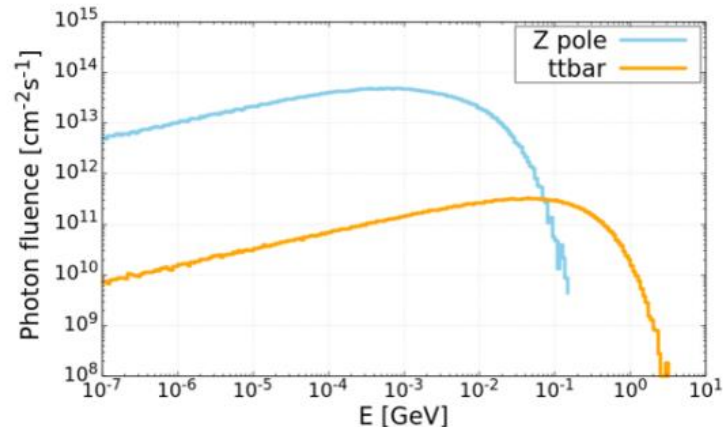
- *Staircases between Klystron galleries and tunnel*: Validate the proposed design
- *Access tunnel (Service cavern  $\leftrightarrow$  Accelerator tunnel)*: The diameter, length and shape of the access tunnel must comply with RP constraints.
- *EM separator and DC septa*: Radiological impact assessment

# Beamstrahlung dump

# Simulation settings – Z pole & ttbar

- ❑ **Radiation source:** BS photons
  - Photons sampled from distributions generated with BBREM and GUINEA-PIG++ by A. Ciarma.
  
- ❑ **Physics and Transport:**
  - **Photonuclear reaction** activated (PHOTONUC card).
  - **Biasing:** photons mean free path for inelastic interactions multiplied by a factor 0.001 (LAM-BIAS card).
  - **Energy thresholds:** energy thresholds for electron and photon production/transport set to 100 keV.
  
- ❑ **Scoring:** Residual ambient dose equivalent (AMB74):
  - **Irradiation profile:** 185 days of operation.
  - **Cool-down times:** from 1 hour to 1 year.

Beamstrahlung spectrum used as source in the study



FLUKA studies for the FCC-ee MD, A. Frasca, FCC Week 2024

# Simulation settings

## □ Normalization:

*BS photons intensity = N° of beamstrahlung photons per particle crossing \* N° of bunches \* Bunch population \* Revolution frequency*

FLUKA simulation source term samples from particle distributions generated with GUINEA-PIG++ based on the 2022 optics version (v22). Therefore, the normalization factor is computed using the machine parameters of 2022.

	Z pole	ttbar	Ratio [Zpole/ttbar]
N° of beamstrahlung photons per particle crossing	1.62E-01	2.43E-01	
N° of bunches	1.00E+04	3.60E+01	
Bunch population	2.43E+11	2.64E+11	
Revolution frequency	3.29E+03 s-1	3.29E+03 s-1	
Beamstrahlung photons intensity	1.30E+18 p/s	7.60E+15 p/s	<b>171.05</b>
Beamstrahlung photons intensity above <i>~photonuc. threshold</i> (E > 10 MeV)	5.64E+16 p/s	4.07E+15 p/s	<b>13.85</b>
Intensity Ratio (Above 10 MeV / All Energies)	4.34%	53.54 %	
Beamstrahlung photons intensity above <i>~spallation threshold</i> (E > 50 MeV)	1.23E+15	2.20E+15	<b>0.56</b>
Intensity Ratio (Above 50 MeV / All Energies)	<0.01 %	28.90 %	

# Simulation settings

## Lead Volume Normalization

- ❑ The total volume of lead used in the dump is estimated to approximately 10 tons, but only a fraction is exposed to the BS at a given time. A mass flow rate of about 300 kg/s must be maintained.

- ❑ Liquid lead on the slope is calculated as:

$$m_{slope} = \rho_{lead} * V_{on-slope} = 10.68 [g/cm^3] * 5.62e4 [cm^3] * 1e-3 [kg/g] = 562 [kg]$$

→ corresponding to 6% of the total **10 t** of lead designated for the circuit.

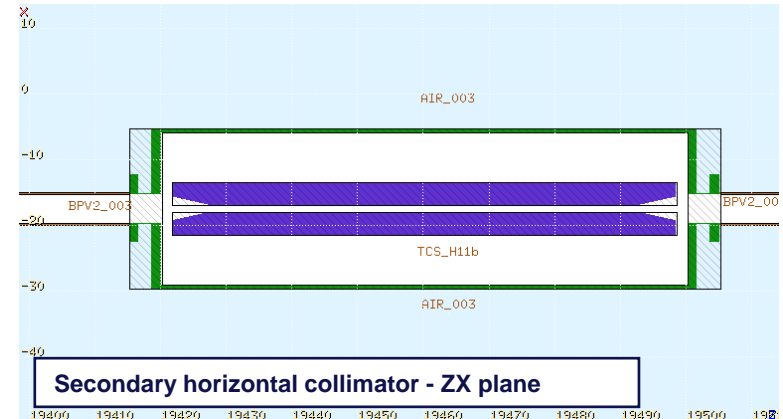
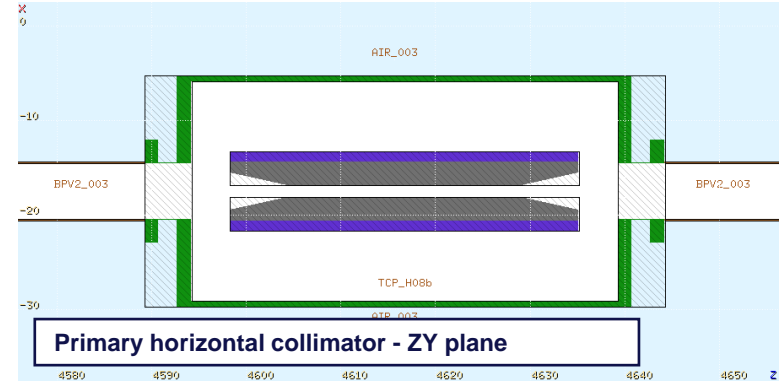
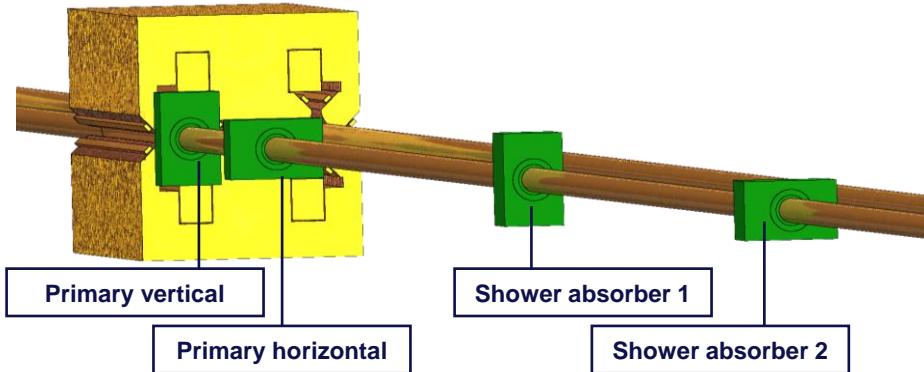
- ❑ In the simplified static simulation case, the generated activity will be contained in the lead slope. The residual dose rate generated from the liquid lead layer is therefore overestimated, while in fact the activity will be distributed in the full 10 t lead mass. Because of the high self-absorption in lead, and the main contribution coming from the activated support and shielding elements, this is an acceptable simplification at this stage of the study.
- ❑ The activity concentration and deduced LL quantity reported here are normalized over the total mass of 10 tons of liquid lead in the circuit assuming a full and homogenous mixing.

# Collimation

# FLUKA geometry

## Materials:

- **Graphite** ( $\rho = 1.8 \text{ g/cm}^3$ ), for the absorber of the primary collimators.
- **TZM\*** ( $\rho = 10.22 \text{ g/cm}^3$ ), for the absorber of the secondary collimators and the frame of both primaries/secondaries.
- **SS304L** ( $\rho = 8.02 \text{ g/cm}^3$ ), for the vessel.



\*Titanium-Zirconium-Molybdenum alloy

# Simulation settings – Z pole (45.5 GeV)

## □ Radiation source:

- Pencil beam
- Equal impact on the jaws of the primary horizontal and primary vertical collimator, always centrally with 1  $\mu\text{m}$  impact parameter (SPOTBEAM / SPOTPOS cards).

## □ Physics and Transport:

- **Photonuclear reaction** activated (PHOTONUC card).
- **Biasing**: photons mean free path for inelastic interactions multiplied by a factor 0.01 (LAM-BIAS card).
- **Energy thresholds**: 100 keV for both electrons and photons for residual radiation transport, prompt cut at 3 MeV.

## □ Scoring: Residual ambient dose equivalent (AMB74):

- **Irradiation profile**: 1 year (=185 days) of operation.
- **Cool-down times**: from 1 hour to 3 years.

<b>Bunch population</b>	<b>2.16E+11</b>
<b>Bunches/beam</b>	<b>1.12E+04</b>
<b>1 - 1/e</b>	<b>0.632121</b>
<b>Beamlife time [s]</b>	<b>1800</b>
<b>Loss rate [p/s]</b>	<b>5.10E+12</b>

*Z pole parameters (FCC Week 2024)*

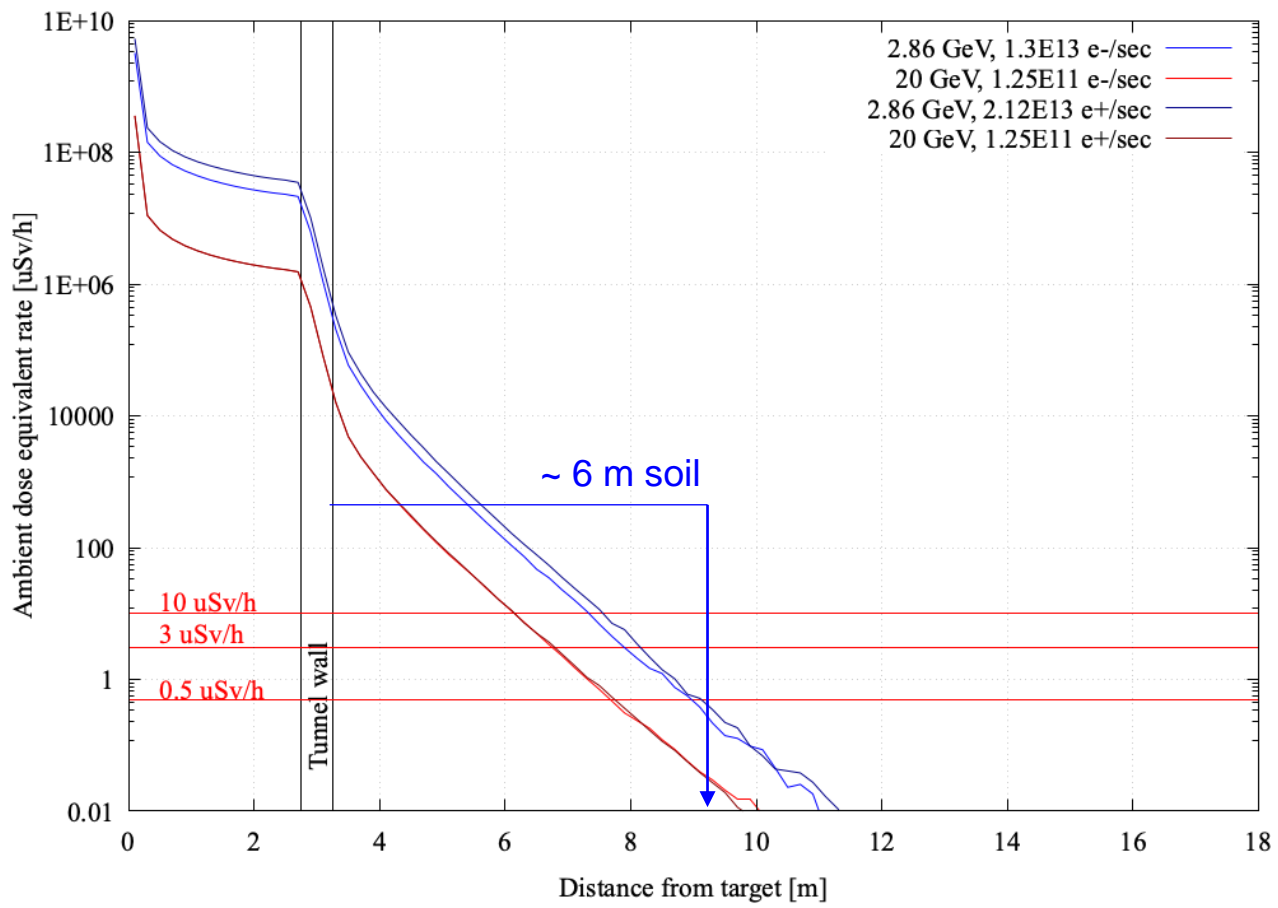
## □ Normalization factor: beam loss rate considering 30 minutes of beam lifetime\*.

$$\begin{aligned} \text{loss rate} &= (\text{bunch population} \times \text{bunches per beam} \times (1-1/e)) / (\text{beam lifetime}) \\ &= 8.50\text{E}+11 \text{ p/s} \end{aligned}$$

\* in a previous version of this document, we considered a beam lifetime of 5 min which was considered as too conservative as not sustainable by the injectors.

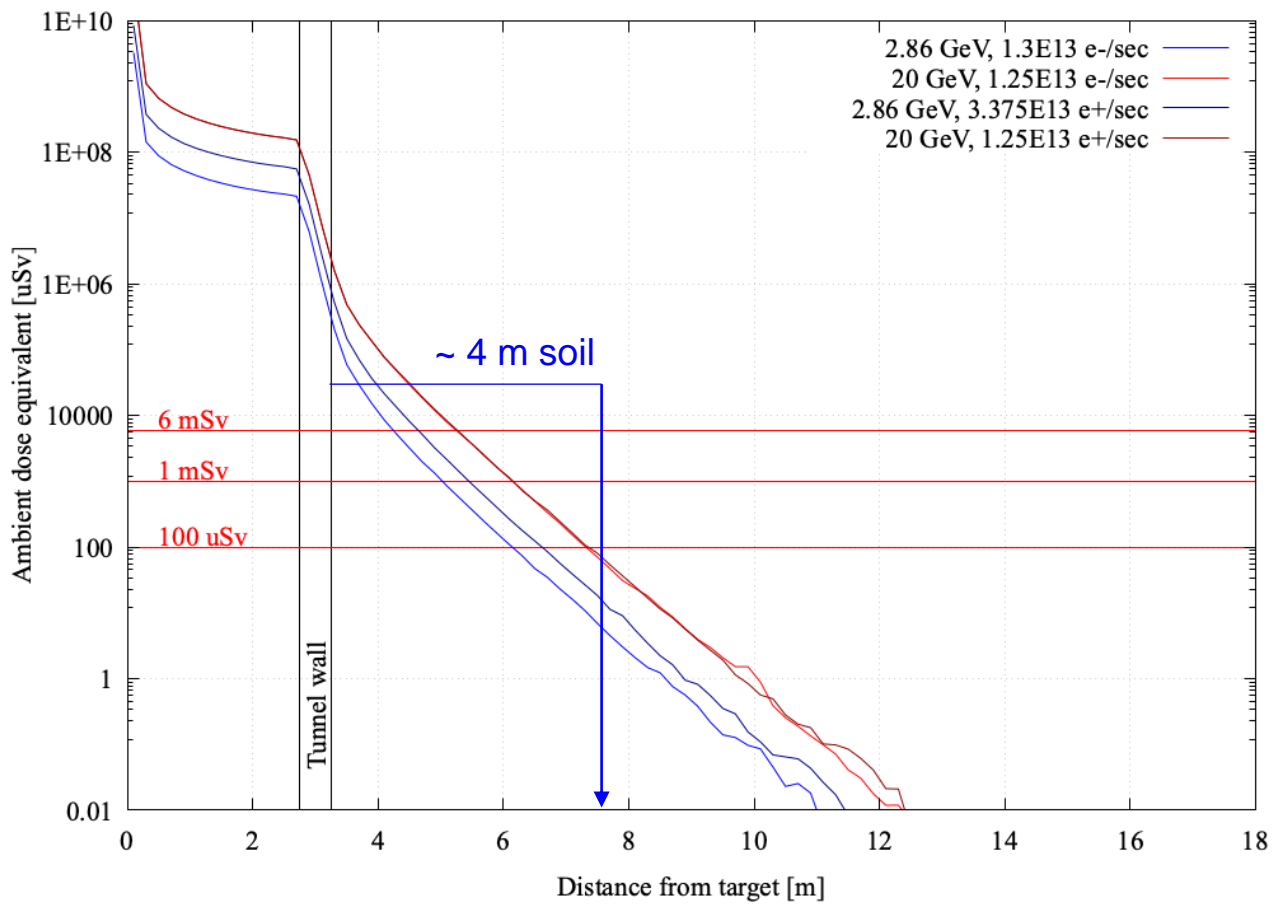
# Injector complex

FCCee injector - Ambient dose equivalent rate from prompt radiation



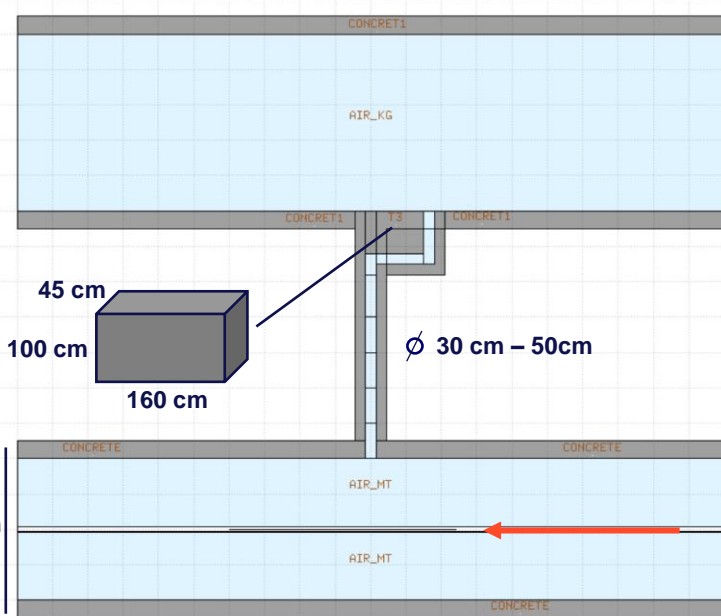
- Beam loss at projected rate and maximum energy
- Continuous beam loss
- Required shielding of 6 m for unshielded loss points in Damping Ring or Positron target
- Local shielding not considered (technical integration currently unknown)

FCCee injector - Ambient dose equivalent in 1 hour from prompt radiation



- Full beam loss at maximum beam intensity and maximum energy
- Conservative (improbable) loss duration of 1 hour
- Required shielding thickness remains below what is needed for assumed permanent loss conditions
- Doses would remain < 100  $\mu\text{Sv}$  in such a scenario

# Simulation settings and geometry



Beam loss is simulated by having the beam impact a very thin copper target (1 mm of diameter).

## Geometry

- The waveguides have a diameter of 16 cm. To account for additional clearance, we are considering two duct diameter options: 30 cm and 50 cm.
- The chicane is oriented in the direction opposite to that of the beam but could alternatively be oriented perpendicular to the beam direction.

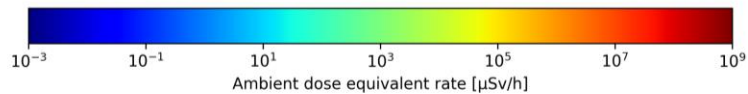
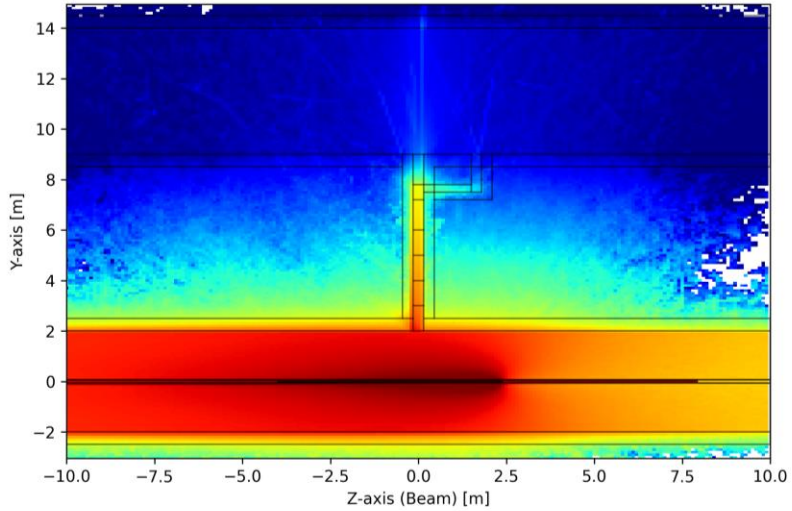
## Beam loss terms (EDMS 3134156 v.1)

Location	Energy	Loss terms in nominal operation [p/s]	Loss fraction in nominal operation (1-Transmission)	Full loss in accidental scenario [p/s]
e- Linac	2.86 GeV	6.88E+11	0.05	1.38E+13
e+ Linac	2.86 GeV	6.75E+12	0.20	3.38E+13
HE Linac (e-)	20 GeV	1.25E+11	0.01	1.25E+13

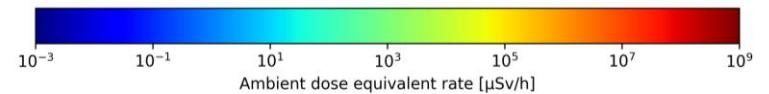
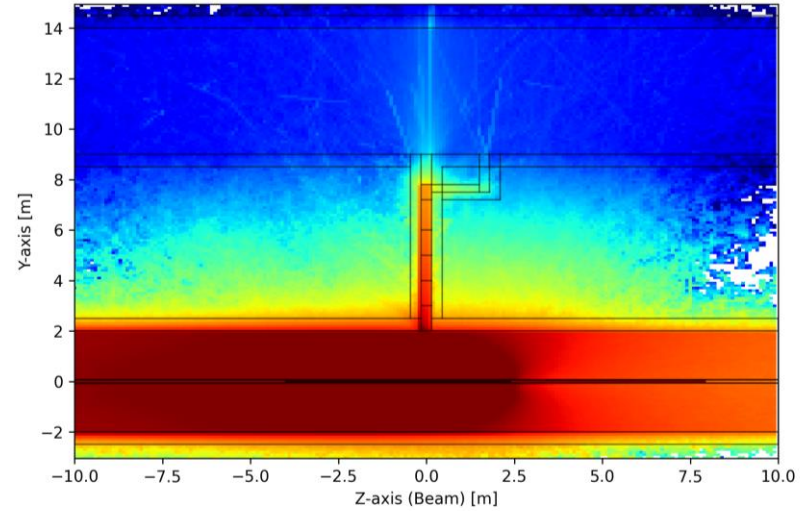
- Simulations were performed for the HE and e<sup>+/-</sup> LINACs, since they have the highest beam energy and loss term, respectively.

# e- LINAC (30 cm of diameter)

5% beam loss in e- LINAC - 30cm diameter waveguide ducts

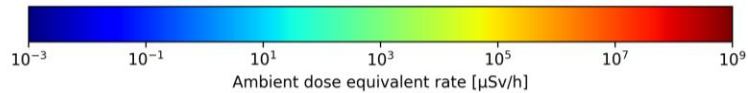
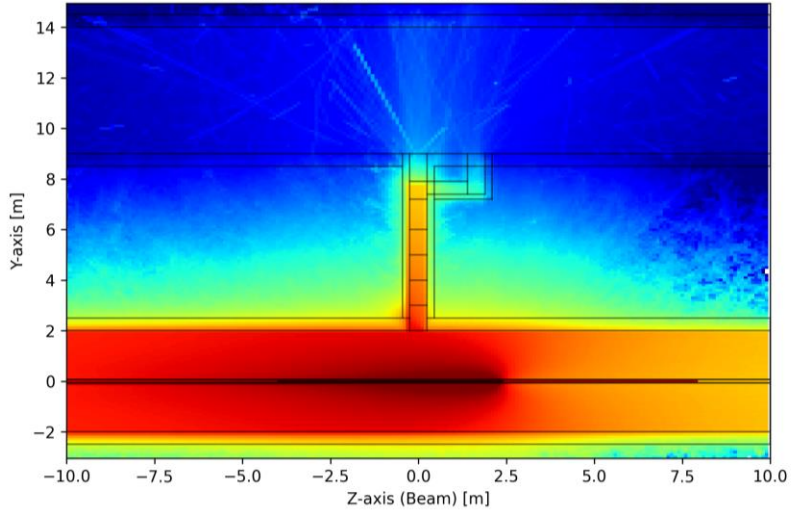


Full beam loss in e- LINAC - 30cm diameter waveguide ducts

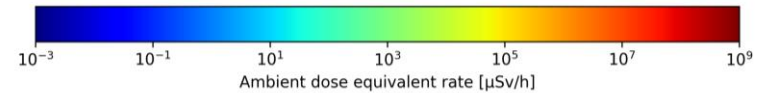
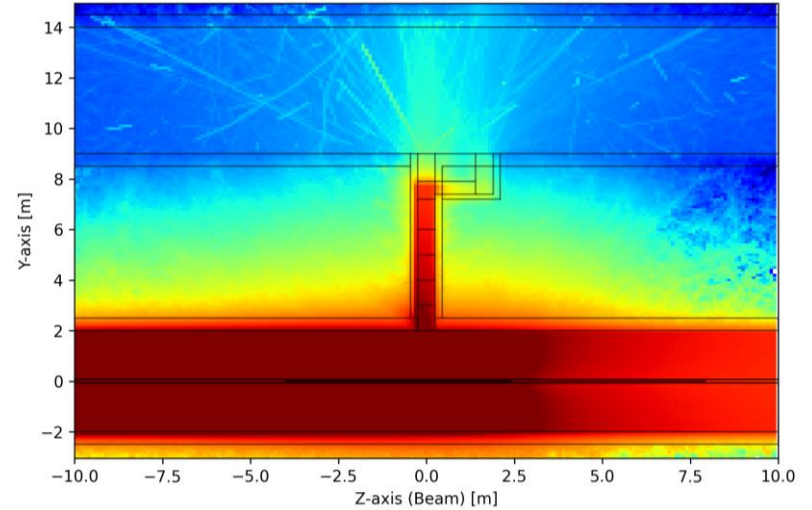


# HE LINAC (50 cm of diameter)

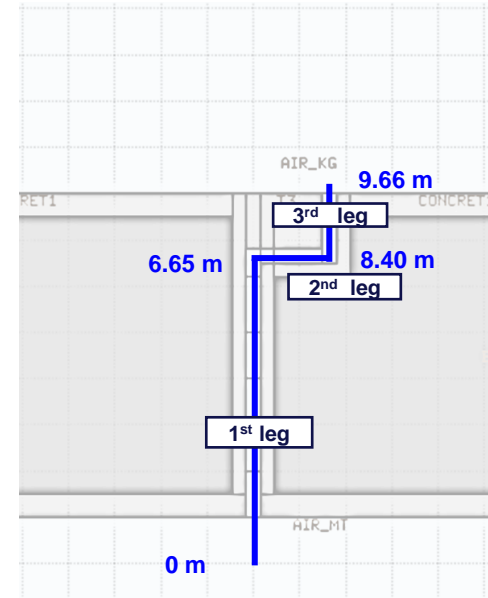
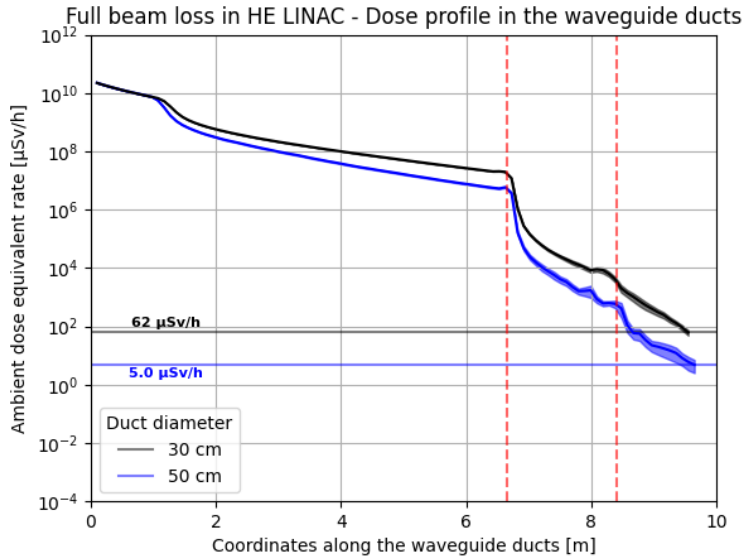
1% beam loss in HE LINAC - 50cm diameter waveguide ducts



Full beam loss in HE LINAC - 50cm diameter waveguide ducts



# Dose rate profile – HE LINAC



**Positron source**

# FLUKA simulation

□ **Electron beam energy: 6 GeV**

□ The output of the simulations are:

➤ **Prompt ambient dose equivalent rate:** to dimension the thickness of the soil layer.

- Normalization factor = 2 bunches \* 200 Hz \* 1.30E10 e-/bunch = 5.20E12 e-/s

➤ **Residual ambient dose equivalent rate:** to study design choices, maintenance scenarios and shielding needs:

- Irradiation profile: To date the exact operation mode is not known; hence simplified operational model is used for the irradiation profile.

- Intensity = 2 bunches \* 200 Hz \* 1.30E10 e-/bunch \* **0.5** = 2.60E12 e-/s
- Period = 185 days/year \* **0.84** = 155.4 days/year

➤ **Particle spectra:** for future study on air activation:

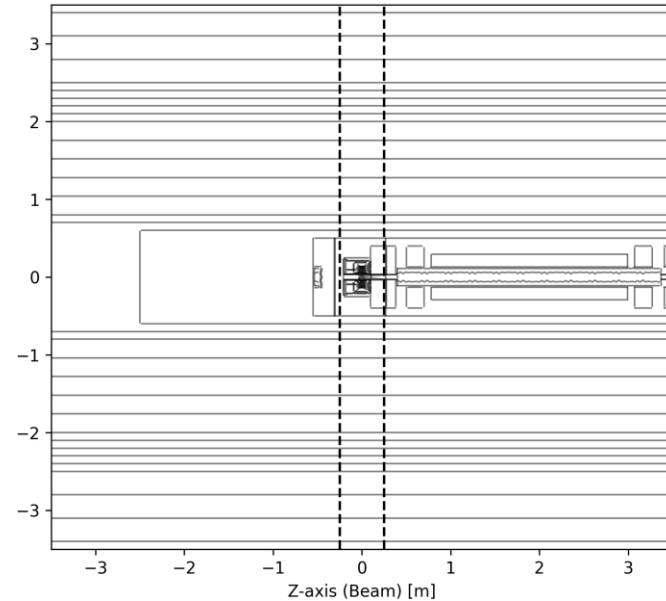
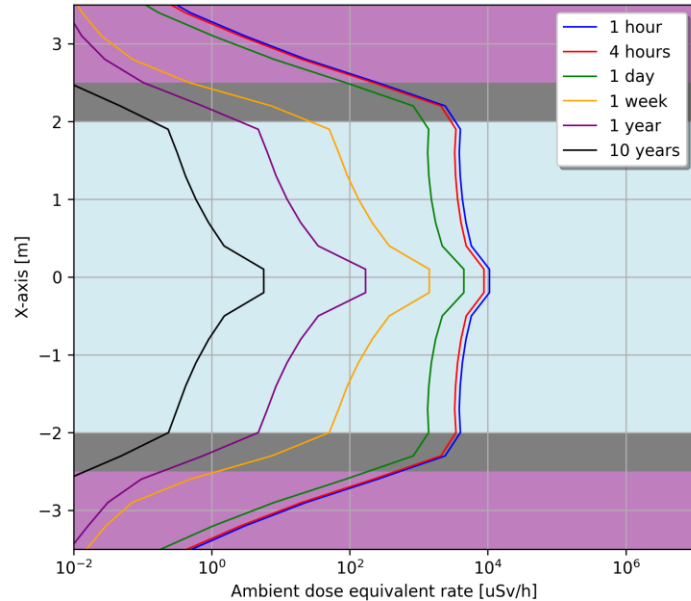
- Neutrons
- Protons
- Pions +/-
- Photons

- **0.5** as only half of the operational time is used to produce positrons

- **0.84** is the duty factor of the machine

*\* Overall injection strategy for FCC-ee, S. Ogur et al.*

# Results – Residual radiation around the target



- ❑ The graphs at the top depict the 1D profile of the dose rate values along x, calculated within the volume enclosed by the dashed lines.
- ❑ The irradiation profile considers one year of operation, taking into account the duty factor of the machine.

# Conclusions

## **Soil layer thickness**

- ❑ The prompt dose rates through the shielding indicate that a minimum of 6.3 m of soil is required after 50 centimeters of concrete to allow a permanently accessible area outside of the shielding during operation, maintaining a dose rate lower than  $0.5 \mu\text{Sv/h}$ . This is a comparable thickness to the value determined in a prior generic study for the pre-injector complex. Considering the actual operation time on the target, the criteria of  $< 1 \text{ mSv/year}$  is fulfilled at the same time.

## ***Residual dose rate following the beam stop***

- ❑ The residual dose rates are significantly high at  $\sim 3 \text{ mSv/h}$  in the vicinity of the target after one hour of cool-down, considering one year of beam operation. This imposes constraints on access and maintenance, even after longer cool-down periods.
- ❑ **Remote handling and shielding must be considered according to intervention and maintenance requirements.** Intervention scenarios need to be defined, and dose reduction must be studied and integrated into the design.

# **Dose (rate) limits and reference levels**



## COMMENTS

<sup>1</sup> Considering all potential sources that could contribute

<sup>2</sup> 1  $\mu\text{Sv}$  in 1 hour is equivalent to 2  $\text{mSv/a}$  for 2000 hours of stay or  $0.1^b \times \text{CA}$

<sup>3</sup> Permanent stay: 2000 hours per year, Low occupancy area: 400 hours per year

<sup>4</sup> Exclusion Zones shall be generally avoided to be considered in a design of a facility; values only given for reference.

- Effective dose comprises internal and external exposure
- Ambient and personal dose equivalent comprises only external exposure
  
- The table shall be understood as an overview of design target values for different aspects of an RP study. Depending on the study scope and relevance, not all scenario related quantities may need to be evaluated.

## REFERENCES

<sup>a</sup> General Safety Instruction GSI-SH-001, Visits on the CERN site, EDMS 1137263 v.3

<sup>b</sup> RGE section 9 / S3-GSI1, Area Classification, EDMS 810149 v.1

<sup>c</sup> Ordonnance sur la radioprotection (ORaP), 814.501, du 26 avril 2017 (Etat le 1er janvier 2022)

<sup>d</sup> Safety Code F Radiation Protection, EDMS 335729



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