

# RADIOLOGICAL STUDIES FOR THE FCCee ARC SECTIONS

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# Context & Motivation

## Main objectives of the radiological studies for FCCee:

1. **Operational objective:** Assure that FCCee design is optimised with respect to radiation protection criteria
2. **Environmental objective:** Provide input to the environmental impact study

❑ Presented today: Radiological studies for the FCCee arc sections

❑ Further topics not covered here, but planned:

- Beam dumps (main & beamstrahlung)
- Straight sections (experiments, collimation, RF)
- Injector facilities

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### ARC SECTION

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#### OPERATIONAL OBJECTIVE

Assess the ambient dose equivalent rates in case of access, in order to evaluate the impact on operation and maintenance of the facility.

EXTERNAL  
DOSE

INTERNAL  
DOSE

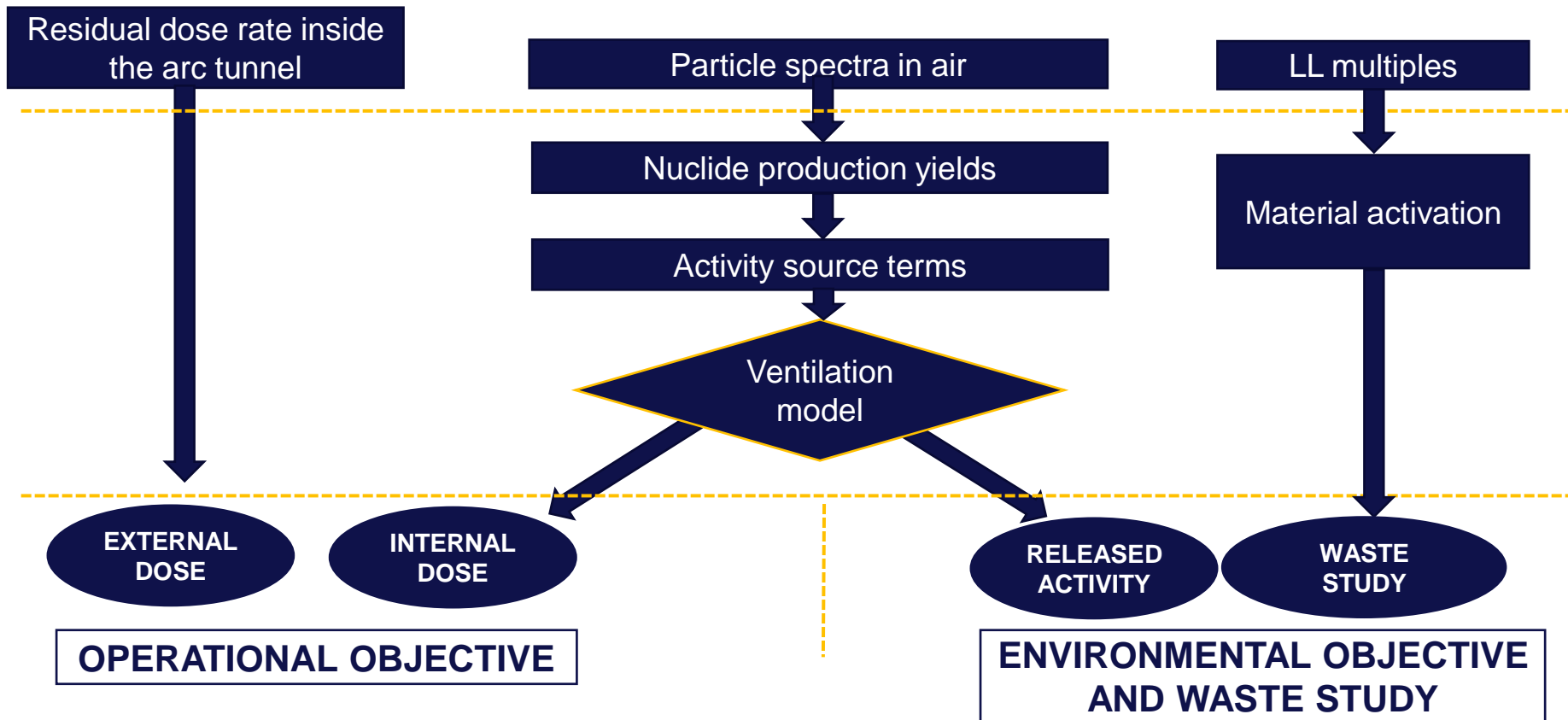
#### ENVIRONMENTAL OBJECTIVE

Assure FCCee design compatibility with environmental constraints, in terms of released activity through air and fluids and solid radioactive waste.

RELEASED  
ACTIVITY

WASTE  
STUDY

# Methodology flowchart



# Radiation sources in the arc

## BEAM - GAS INTERACTION

These interactions happen when beam particles collide with residual gas inside the beam pipe, causing stray radiation to spread in the surrounding environment.

## SYNCHROTRON RADIATION

Synchrotron radiation is emitted tangentially by charged particles moving along a curved trajectory. It consists of photons whose spectrum is broadband from the microwave to higher spectral regions.

## CRITICAL PARAMETERS

### BEAM INTENSITY



The beam intensity affects the interaction rate

### BEAM ENERGY



$$\Delta E = \frac{e^2}{3 * \epsilon_0 * (m_0 * c^2)^4} * \frac{E^4}{\rho}$$

Particle energy

Energy losses for synchrotron radiation

# Radiation sources in the arc

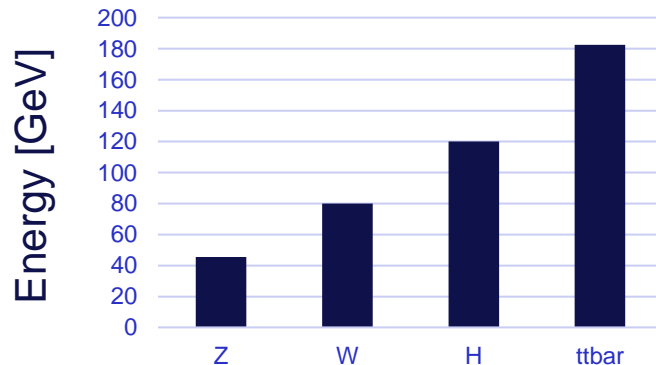
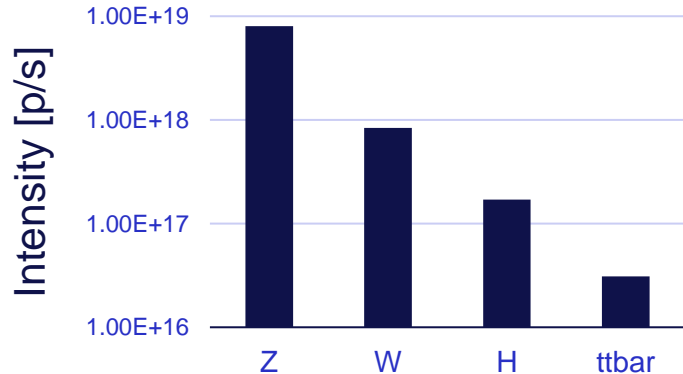
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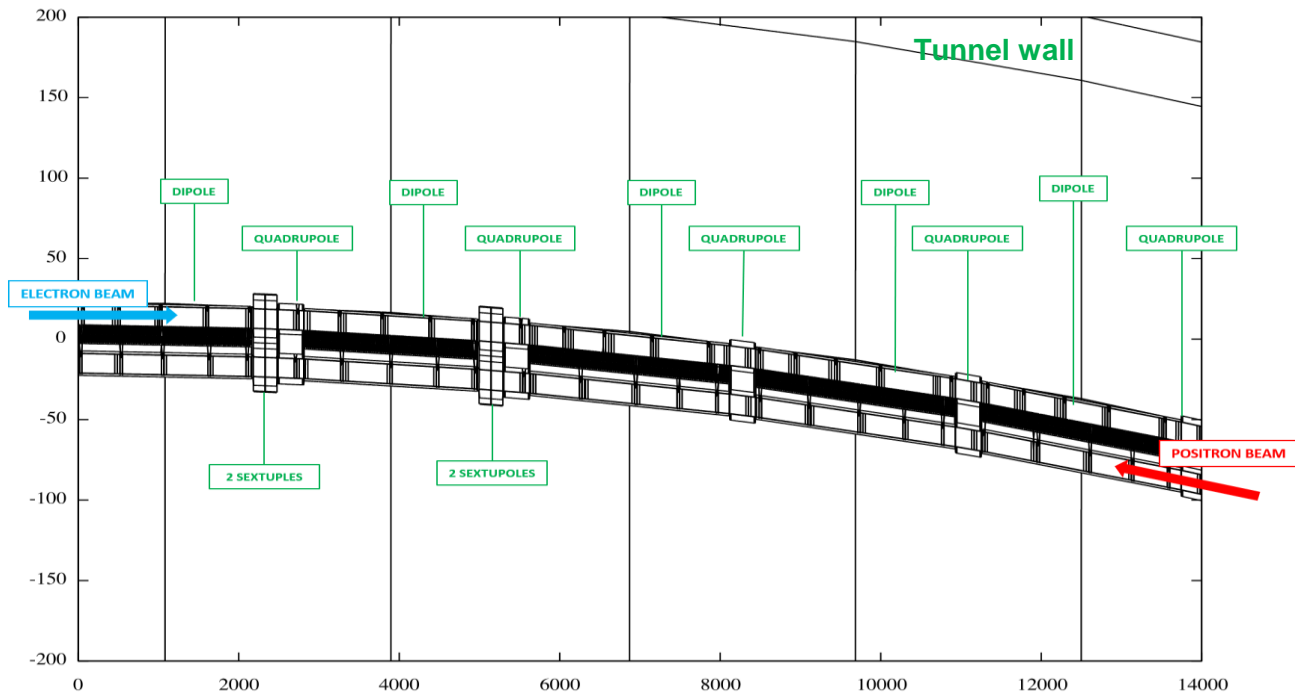
# Simulation geometry

□ Representative periodic arc cell of 140 m

□ The cell is composed by

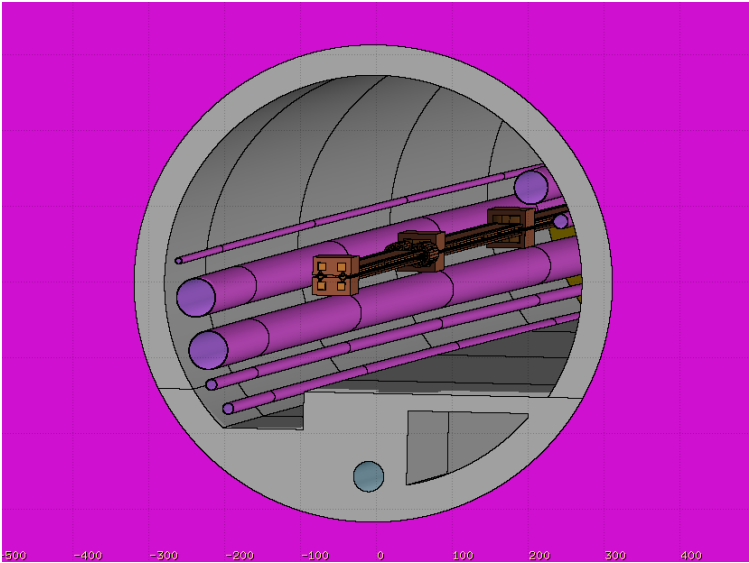
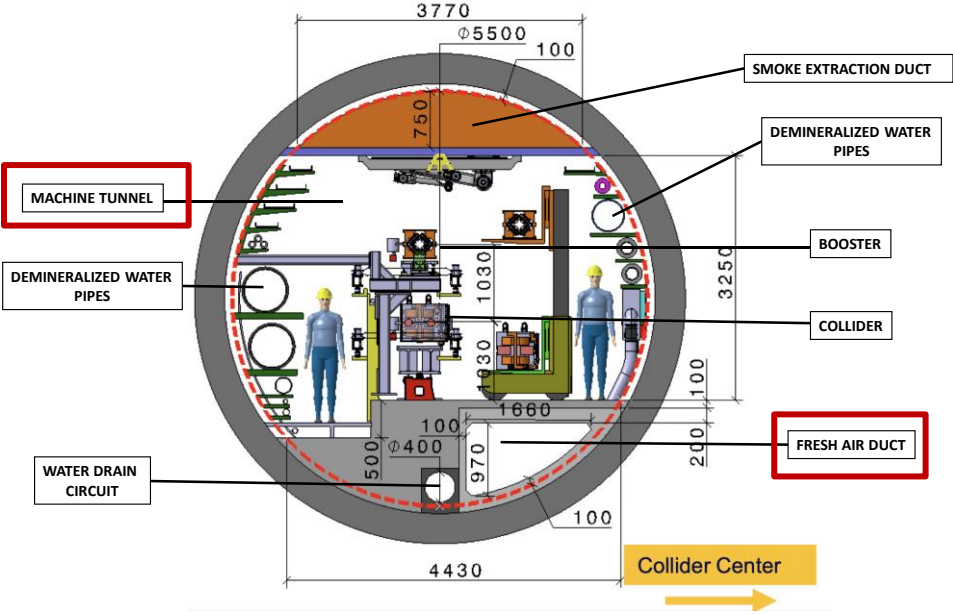
- 5 dipoles
- 5 quadrupoles
- 4 sextupoles
- 25 photon absorber per beam (23 in dipoles and 2 in quadrupoles)

□ The Booster ring is not included.



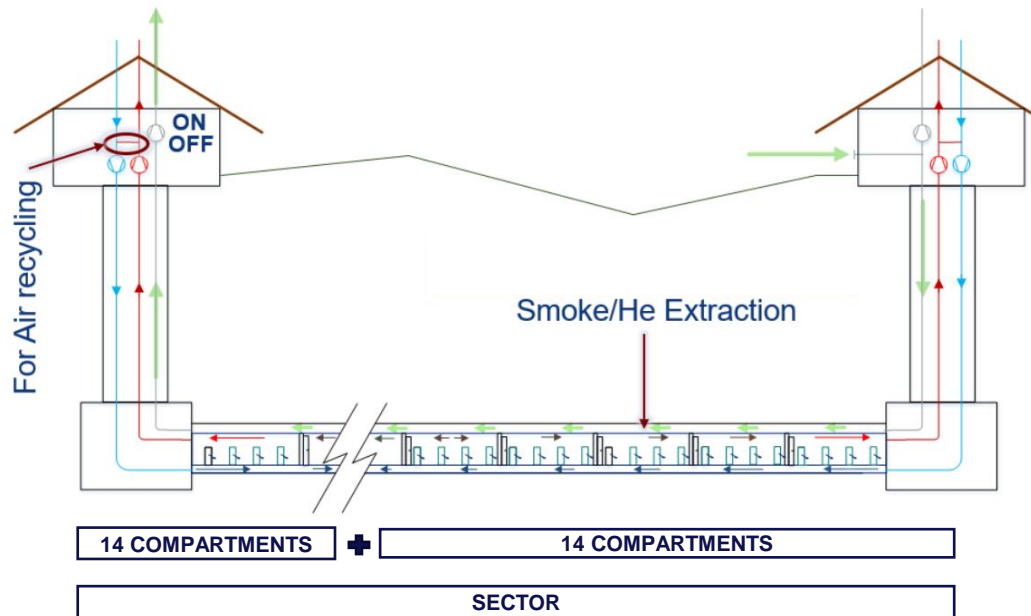
Acknowledgment B. Humann and SY/STI for providing the accelerator model

# Simulation geometry



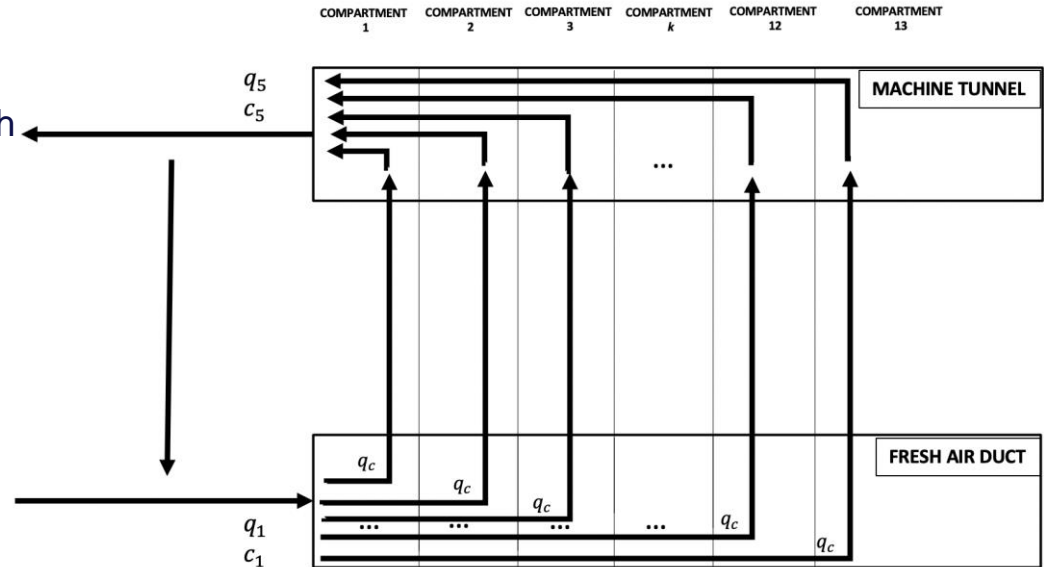
# Ventilation system

- ❑ Each sector of the FCC tunnel consists of **28 compartments**, each 400m long.
- ❑ **Two ventilation systems are present in each sector**, serving 14 compartments each
- ❑ **Air recycling** is employed to optimise air conditioning during beam operation and beam stop. The proportion of recycled air varies seasonally, ranging from 100% in summer to 40-80% in winter, with variable recycling in autumn/spring.



# Ventilation system model

- ❑ A **ventilation model** (based on mass conservation equations) is used to describe the activity concentration of each nuclide as a function of time inside each compartments.
- ❑ **The assumptions** include:
  - No gradients in radionuclide concentrations
  - Constant flow rate (27'000 m<sup>3</sup>/h)
  - Laminar flux
  - Constant activity source term along the sector.

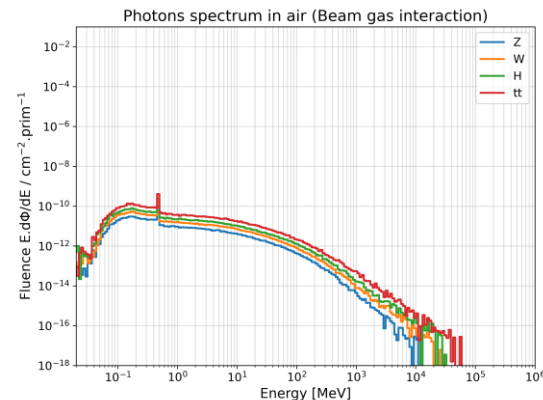
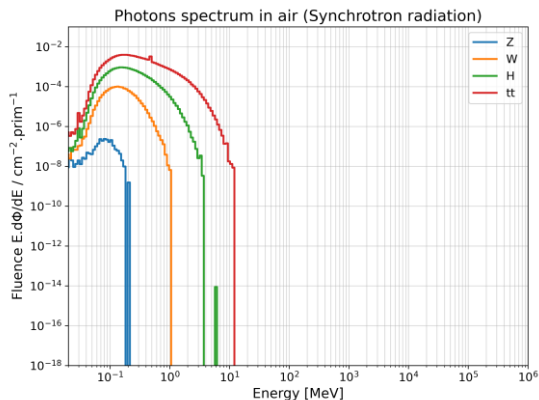


# PARTICLE SPECTRA

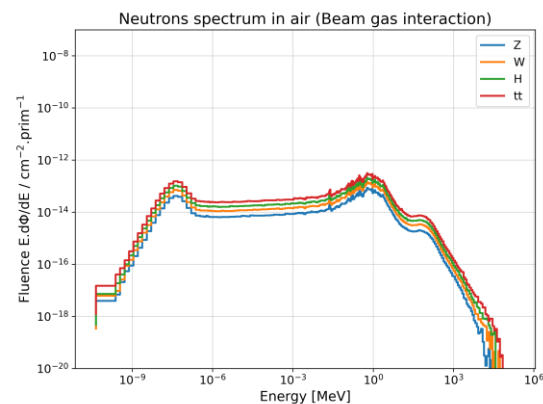
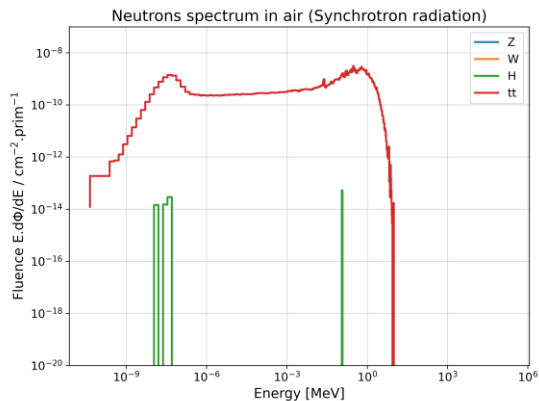
## SYNCHROTRON RADIATION

## BEAM-GAS INTERACTIONS

### PHOTONS



### NEUTRONS

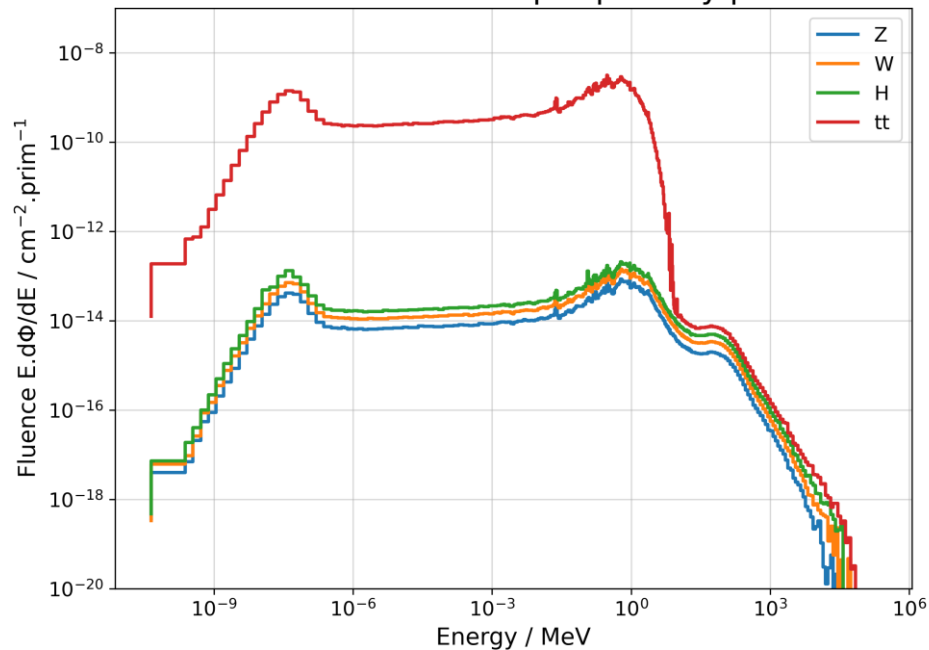


1

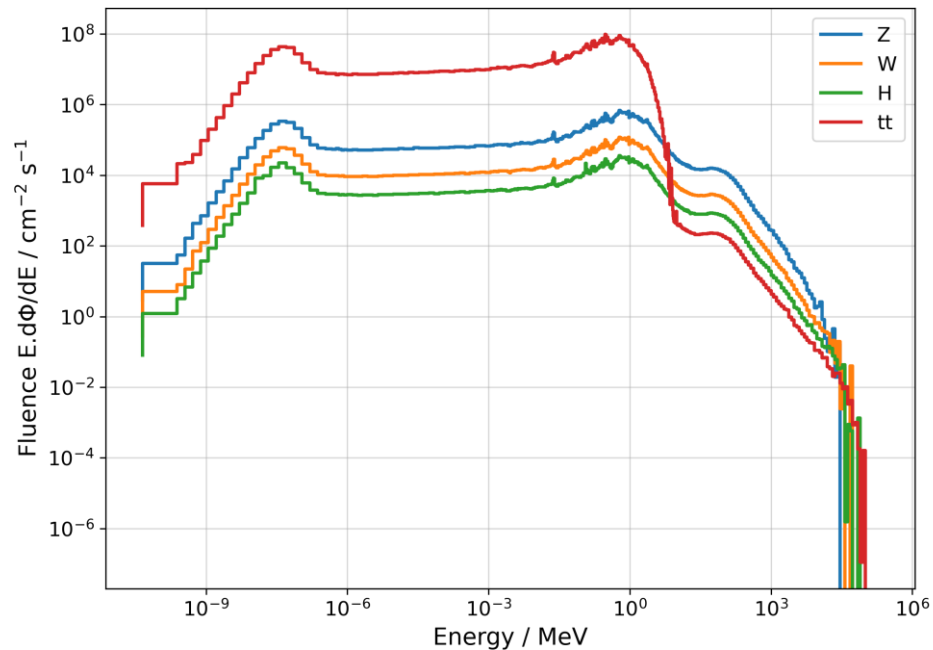
# PARTICLE SPECTRA

## SYNCHROTRON RADIATION + BEAM GAS INTERACTION

Neutron fluence in air per primary particle



Neutron fluence rate in air for nominal beam intensities

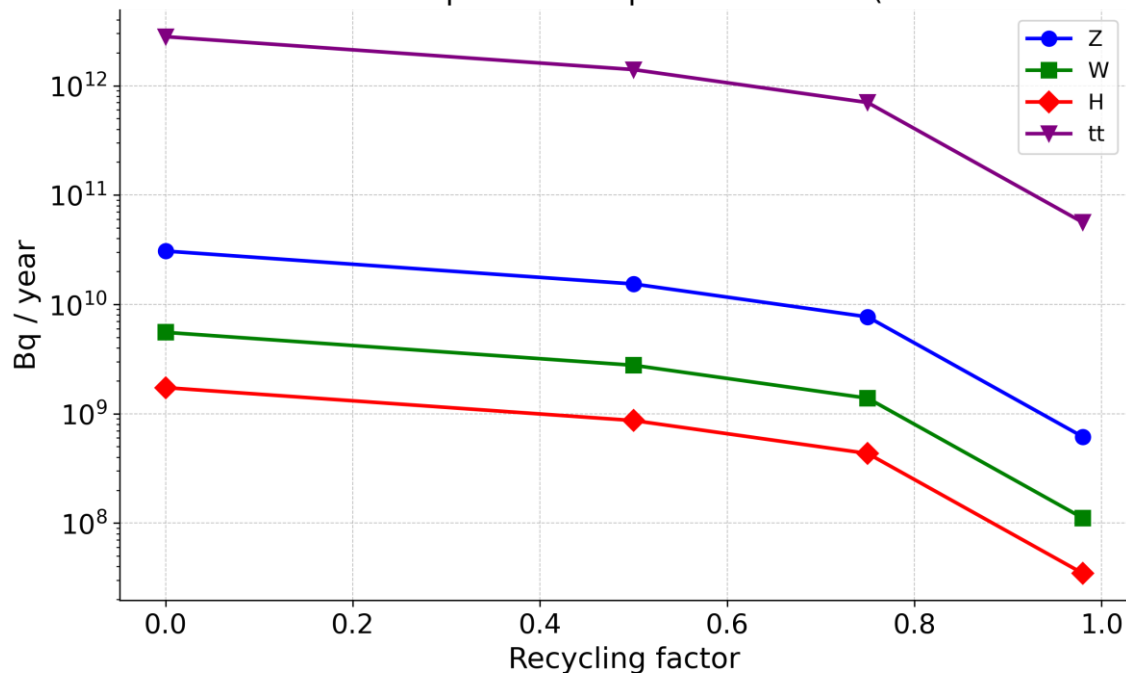


## 1 RESULTS:

## RELEASED ACTIVITY

- ❑ Strong dependence on recycling factor
- ❑ **Results consistent with neutron spectra:** the plot of  $\overline{tt}$  significantly deviates from the other three due to the higher contribution induced by the higher energetic synchrotron radiation
- ❑ In practice: Aerosol filter will reduce isotopes attached to aerosols, but isotopes in gaseous form will be released

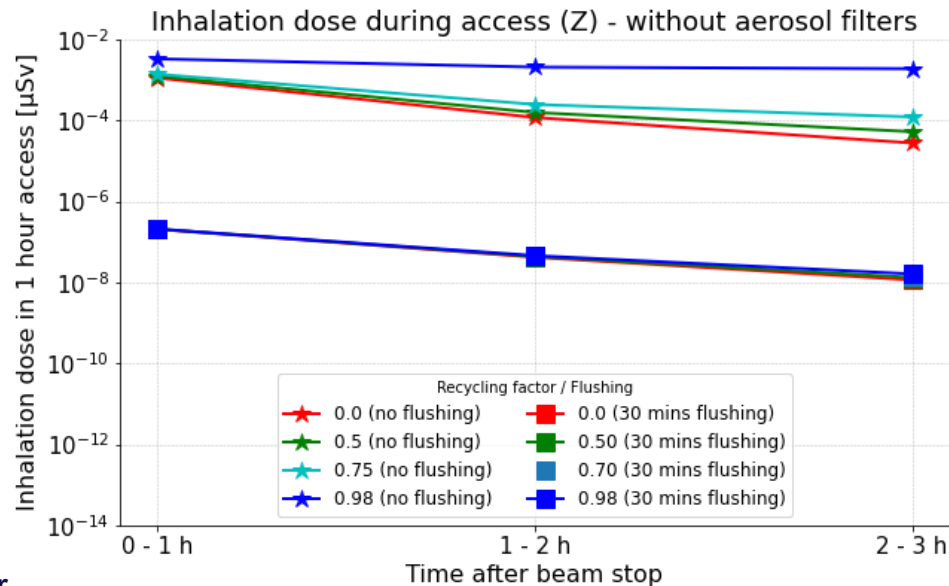
Annual release of activities per release point in the arc (without aerosol filters)



*Contribution to the annual release of activities from each release point in the arc (without aerosol filters)*

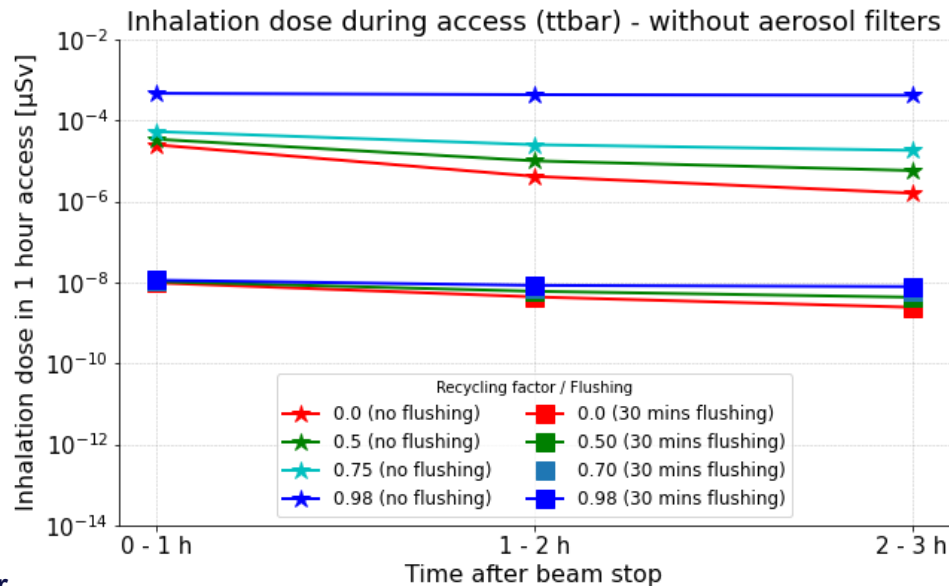
# 1 RESULTS: INHALATION DOSE

- The graphs depict the inhalation dose for one hour of access at different times after the beam stop, considering different recycling rates (represented by different colors in the graph) and two distinct flushing scenarios:
  - Absence of flushing (represented by star markers)
  - 30 minutes of flushing at a rate of 50'000 m<sup>3</sup>/h (represented by square markers)
- The inhalation dose always remains below 1  $\mu\text{Sv}$  for one hour of stay (**guideline value**) for both Z and t $\bar{b}$ ar. Similar results for W and H.

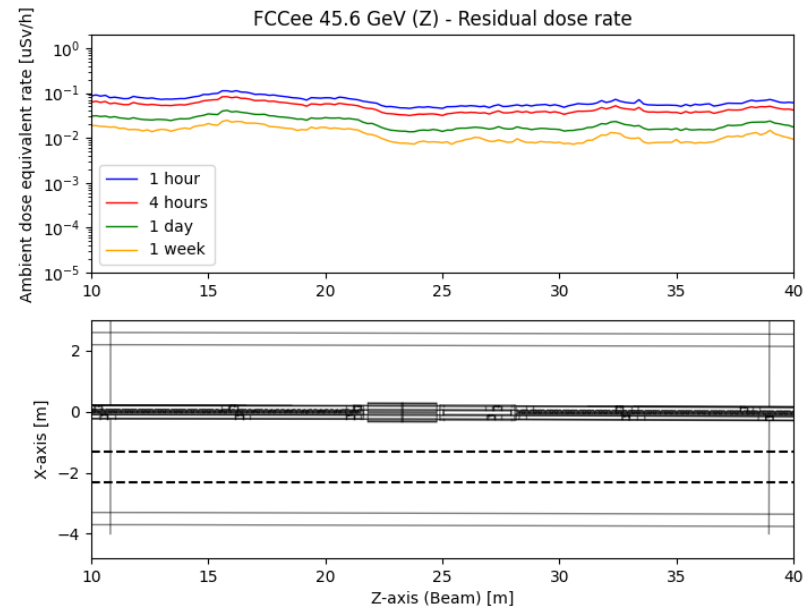
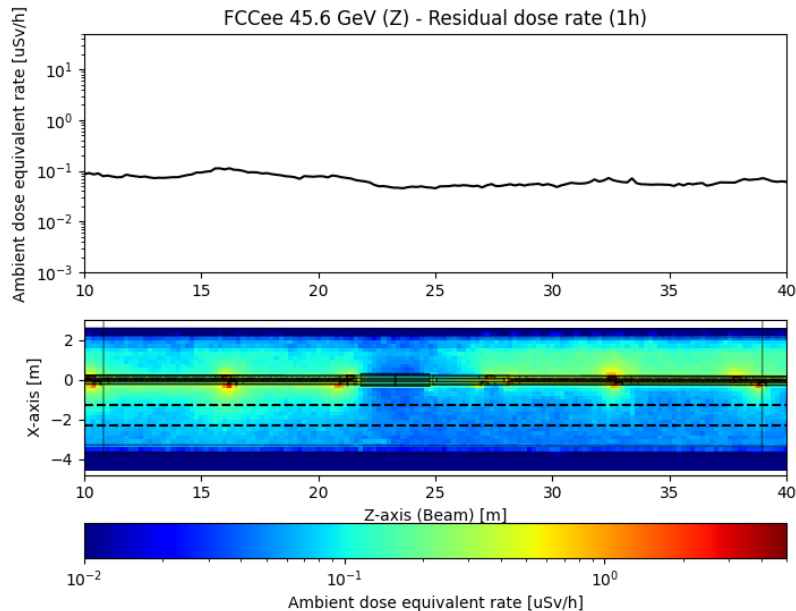


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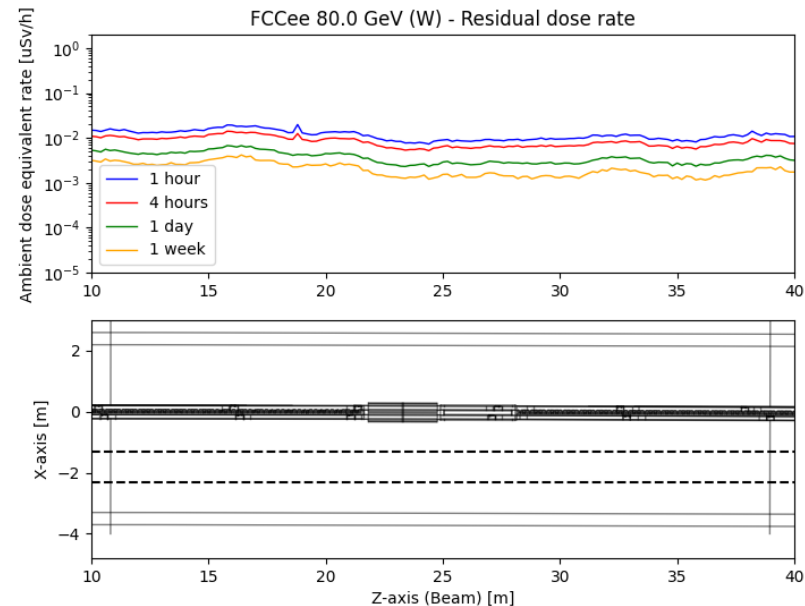
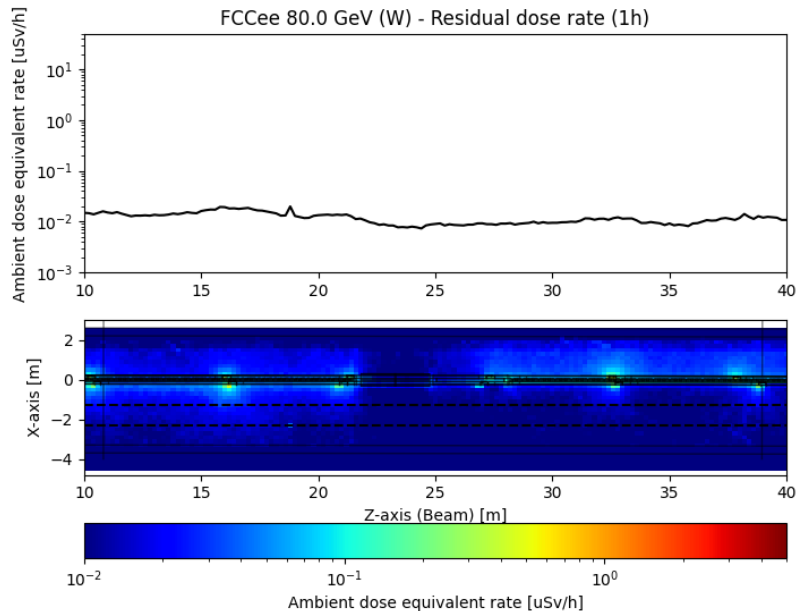


## 2 RESULTS: RESIDUAL DOSE RATE



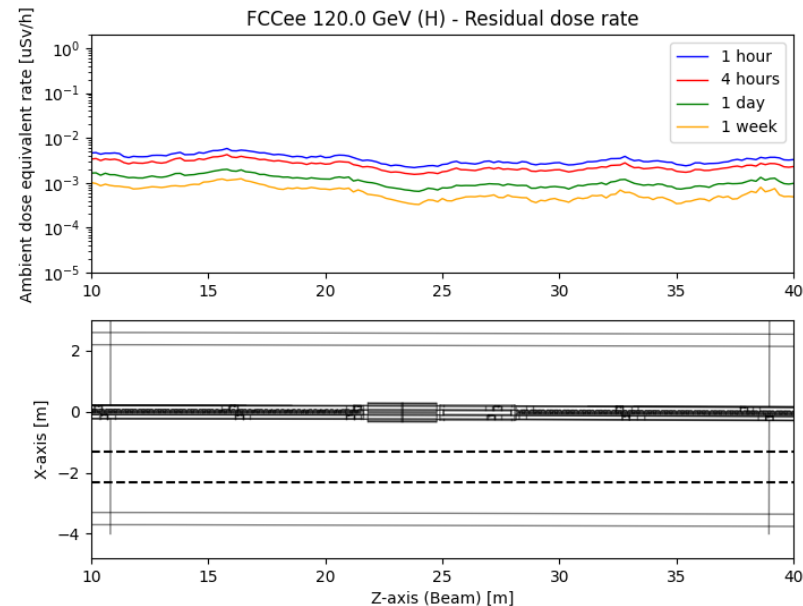
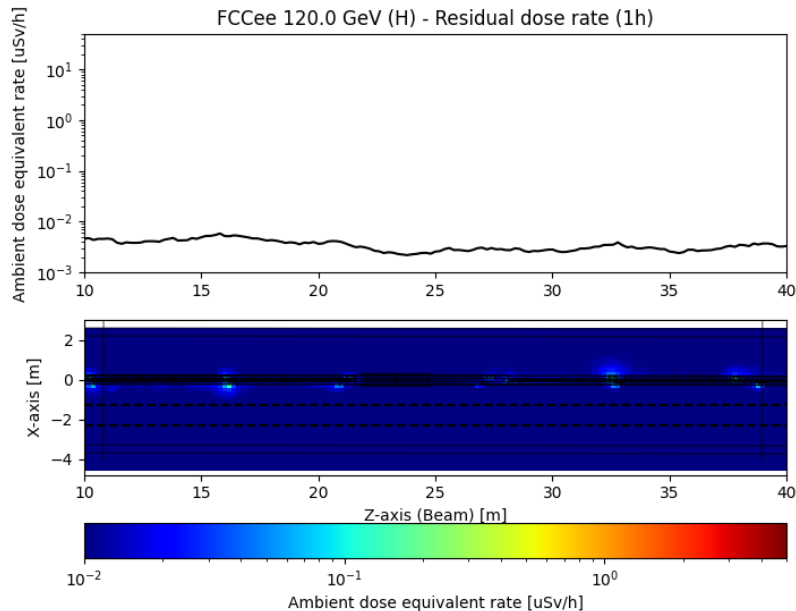
- ❑ The graphs at the top depict the 1D profile of the mean values along z, calculated within the volume enclosed by the dashed lines. This volume represents the most probable occupied space during access, typically at a distance of 1-2 meters from the beam line.
- ❑ The irradiation profile considers all the years of the operation mode, taking into account the winter shutdowns

## 2 RESULTS: RESIDUAL DOSE RATE



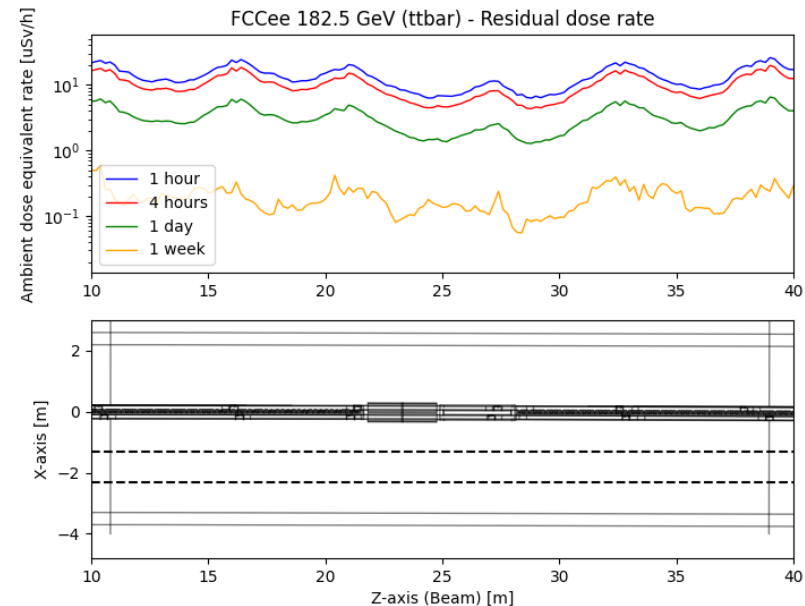
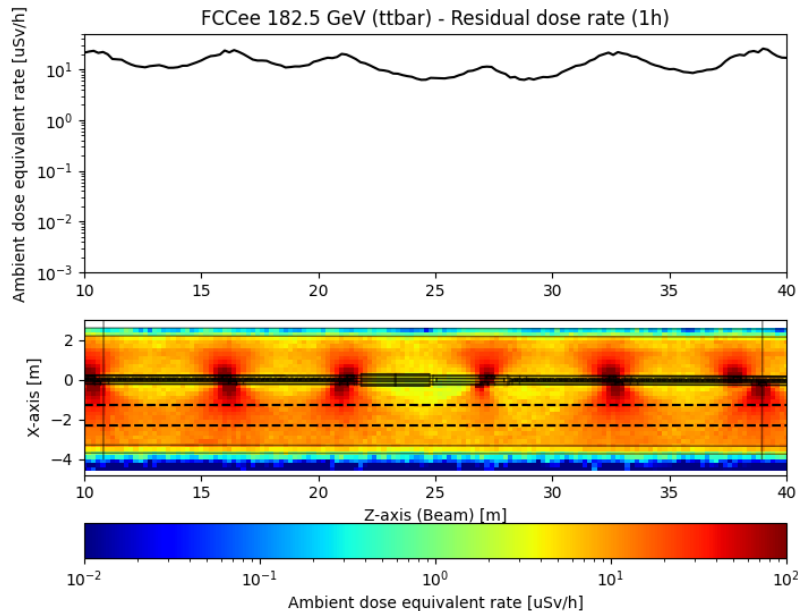
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### 3 RESULTS: WASTE STUDY

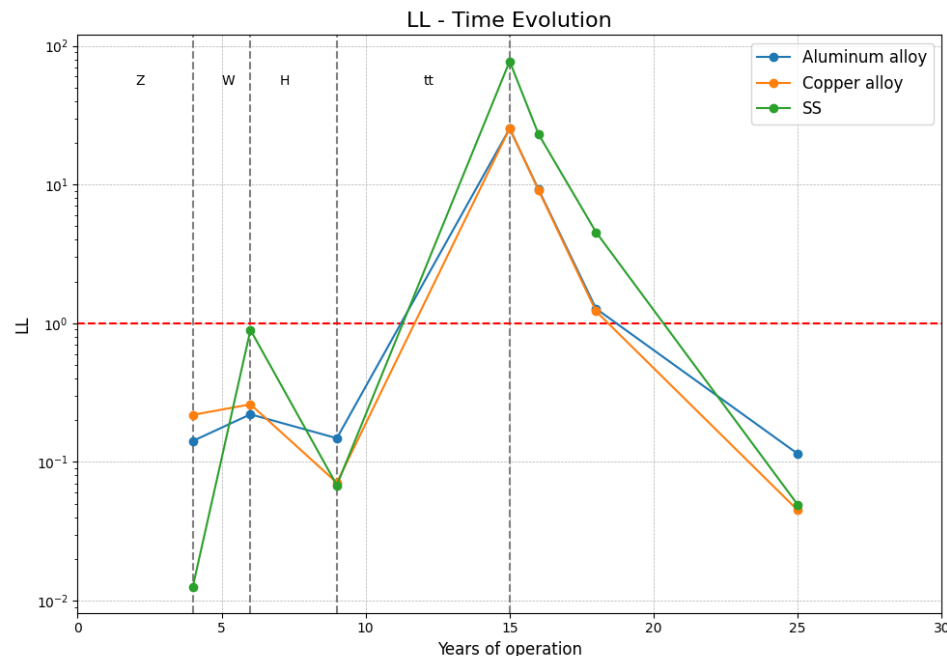
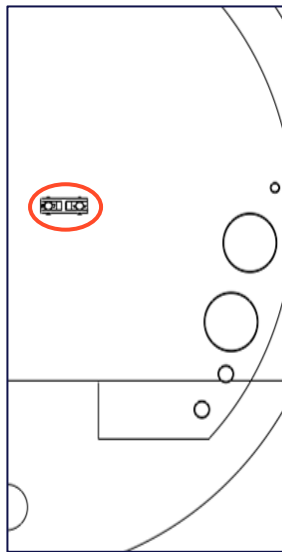
#### EXEMPLARY ANALYSIS FOR THE MOST COMMON MATERIALS: ALUMINIUM, COPPER AND STAINLESS STEEL

For radioactive material containing a mixture of radionuclides of artificial origin, the following sum rule must be fulfilled to possibly remove it from any further regulatory control:

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

Where  $a_i$  is the specific activity of the  $i$ th radionuclide of artificial origin in the material,  $LL_i$  is the respective clearance limit and  $n$  is the number of identified radionuclides.

- ❑ When LL is below 1, the material can be generally released from regulatory control.



Activation is above clearance limit for accelerator components after ttbar operation

### 3 RESULTS:

## WASTE STUDY

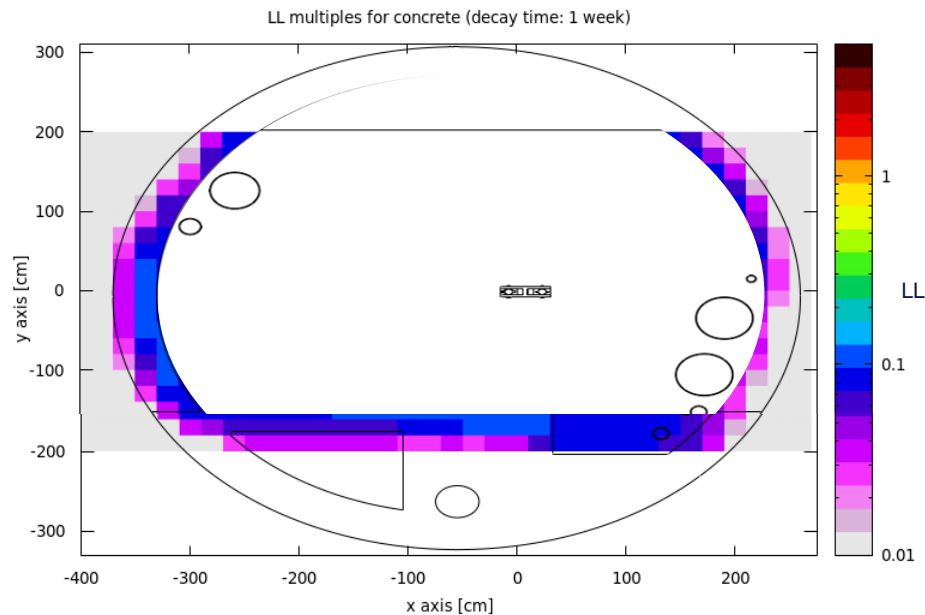
### ANALYSIS OF CONCRETE ACTIVATION

For radioactive material containing a mixture of radionuclides of artificial origin, the following sum rule must be fulfilled to possibly remove it from any further regulatory control:

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

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- ❑ When LL is below 1, the material can be generally released from regulatory control.



Irradiation profile ( $\bar{t}$ ): full operation period / 1 week of cooling time

Activation is below clearance limit for the concrete structures of the tunnel.

# Radiological studies for the FCCee arc sections

## CONCLUSIONS

### 1 OPERATIONAL OBJECTIVE

#### ☐ External dose:

- Residual ambient dose equivalent rates (after 1 hour at 1-2 m distance from the beamline):
  - Z: values between 0.1  $\mu\text{Sv/h}$  and 1  $\mu\text{Sv/h}$
  - W, H: values below 0.1  $\mu\text{Sv/h}$
  - ttbar: relevant residual dose rates after short decay times: from 10 to 20  $\mu\text{Sv/h}$ . **Impact on interventions to be considered.**

} **no intervention constraints**

#### ☐ Internal dose:

- Inhalation dose (Z, W, H, ttbar): values **below the guideline value of 1  $\mu\text{Sv}$  for 1 hour** of access after the beam stop without flushing. 30 minutes of flushing at 100'000  $\text{m}^3/\text{h}$  are sufficient to reduce the inhalation dose by further two orders of magnitude.

# Radiological studies for the FCCee arc sections

## CONCLUSIONS

2

### ENVIRONMENTAL OBJECTIVE

#### ☐ Released activity via ventilation system:

- Strong dependence on the recycling factor
- Major contributions to activity from short-lived emitters: Ar-41, C-11, N-13
- ttbar can reach  $10^6$  MBq/year per release point without aerosol filters
- For Z, W, H, the release varies from  $10^2$  to  $10^5$  MBq/year per release point without aerosol filters.

#### ☐ Released activity via water circuits:

- Not addressed here → water circuit model required

#### ☐ Materials activation:

- No relevant activation of tunnel walls and soil.
- Accelerator materials: **critical activation only during ttbar**. Below clearance limits after ~4-5 years after ttbar operation.
- There is an uncertainty on the evolution of the current legislative limits until FCCee goes into operation

# Acknowledgment

- ❑ **B. Humann** (SY-STI-BMI) for providing the accelerator model.
- ❑ **F. Valchkova-Georgieva** (EN-ACE) for providing the cross section layout.
- ❑ **D. Calzolari** (SY-STI-BMI) for his assistance in clarifying certain technical aspects of the beam-gas interaction simulations.
- ❑ **I. Martin Melero** (EN-CV-PJ) for providing the ventilation parameters.

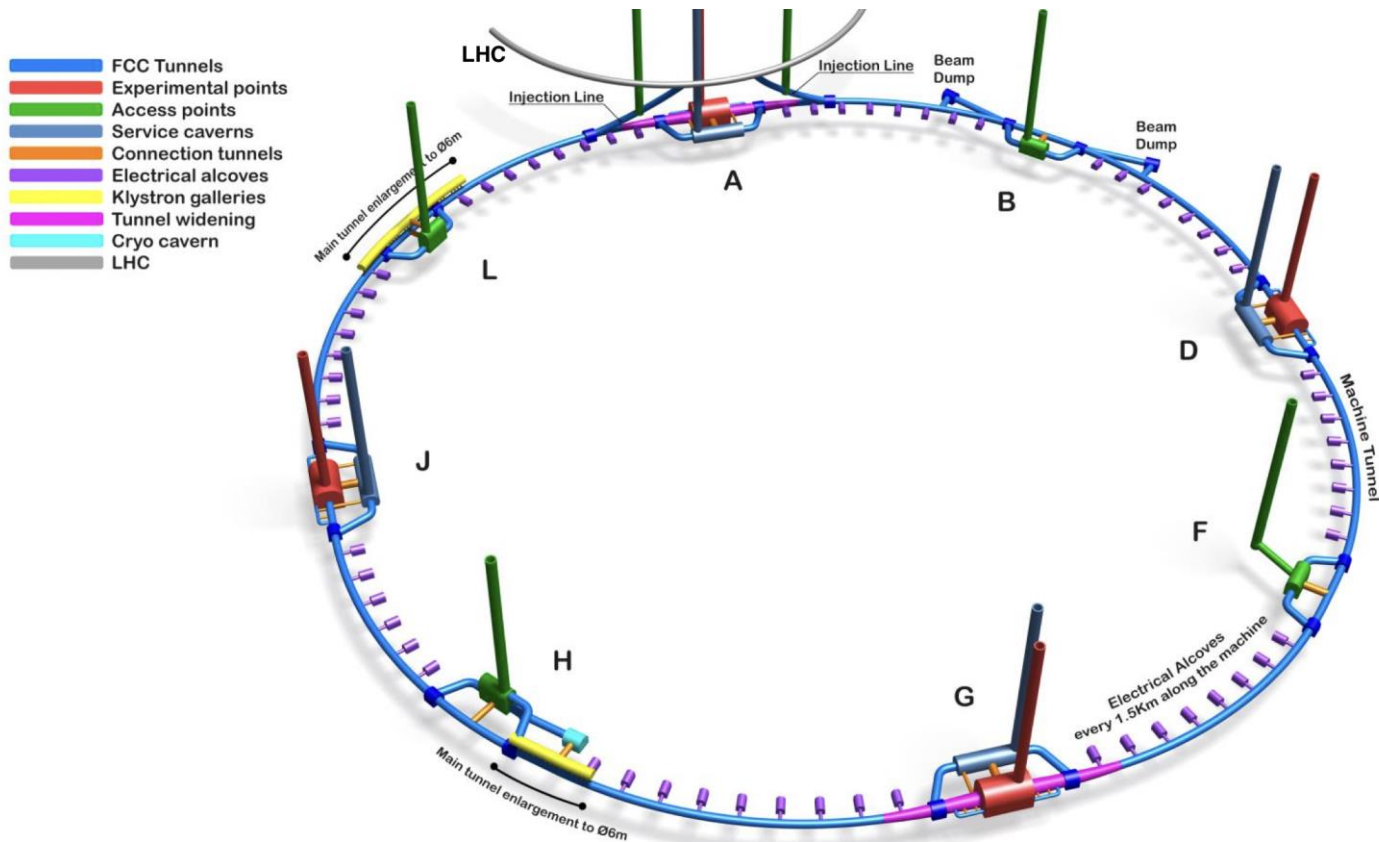


THANK YOU FOR YOUR  
ATTENTION!



# BACK UP SLIDES

# FCCee layout



# Context & Motivation

## Main objectives of the radiological studies for FCCee:

1. **Operational objective:** Assure that FCC design is optimised with respect to radiation protection criteria
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### FCCee OPERATION MODES



# Beam parameters and irradiation profile

Table 1: FCCee beam parameters used in the simulations.

Mode	Beam Energy	Current	Years of operation
Z	45.6 GeV	1280 mA (8.0e18 p/s)	4
W	80.0 GeV	135 mA (8.4e17 p/s)	2
H	120.0 GeV	26.7 mA (1.7e17 p/s)	3
ttbar	182.5 GeV	5.4 mA (3.1e16 p/s)	5

Between consecutive operating years, a winter closure period is considered, according to *F. Zimmermann, A. Apollonio et al.,. FCC-ee Operation Model, Availability & Performance.*

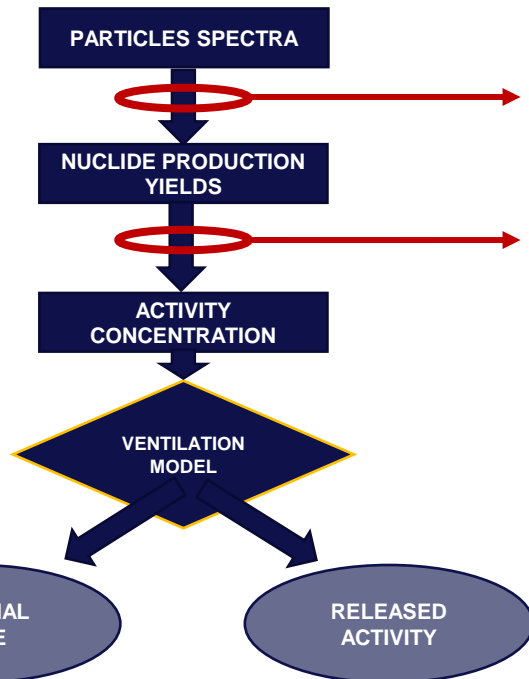


## VENTILATION MODEL

# Radiological studies for the FCCee arc sections

1

## FROM SPECTRA TO ACTIVITY CONCENTRATION



Particle's spectra computed in air were folded by using Actiwiz3

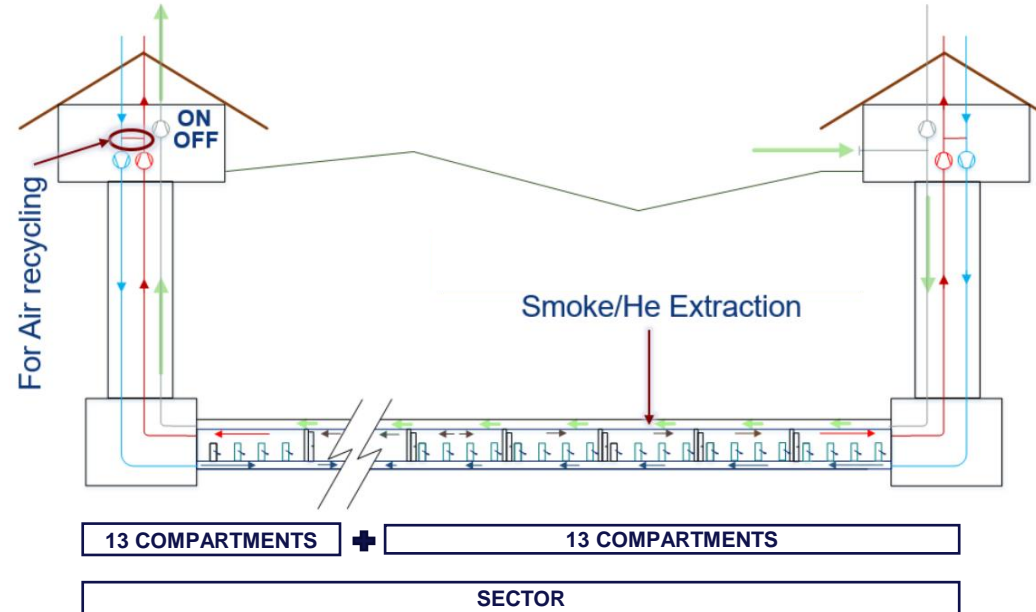
Activity source terms  $S_j^i$  [Bq h<sup>-1</sup>] for radionuclide  $i$  inside a region  $j$  is obtained through the following equation:

$$S_j^i = N_j^i * I * \rho_{air} * V_j * \lambda_f^i * 1e6$$

- $N_j^i$  : nuclide production yield (of  $i$  in  $j$ )
- $I$  : beam intensity
- $\rho_{air}$  : air density
- $V_j$  : volume of the region  $j$
- $\lambda_f^i$  : physical decay constant of the radionuclide  $i$

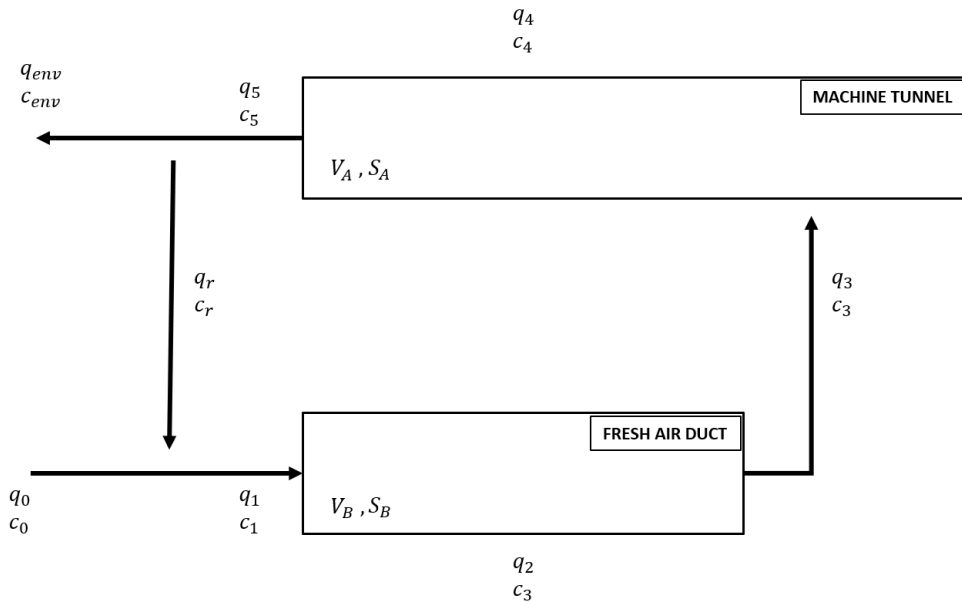
# Ventilation system

- ❑ Each sector of the FCC tunnel consists of 26 compartments, each 440m long. Two ventilation system are placed at opposite ends of the sector tunnel, **resulting in 13 compartments served by a single ventilation system.**
- ❑ The fresh air is conducted within the fresh air duct and consecutively injected in the machine tunnel; thereafter the air flow reaches the outlet part and is partly recycled and partly released in the environment.



# Ventilation system model

- A ventilation model is implemented with the purpose of describing the activity concentration function  $c_i(t)$  of a generic radionuclide  $i$  along the time variable  $t$ , in accordance with the working dynamics of the ventilation system. The nuclide generation terms are represented by a constant activity source terms and its decay process is modeled using a conventional exponential decay model, which takes into account both the physical decay and the decrease caused by the air renewal; this twofold impact is accounted by the effective decay constant  $\lambda_{ij}$ .
- A specific airborne radioactivity model was constructed as a two-box model, with the purpose of describing the ventilation dynamics inside a single compartment.



# Ventilation system model

## Time domain

$$\left\{ \begin{array}{l} c_1^i(t) = f * c_5^i(t) \\ c_2^{i'}(t) = \lambda_B^i * c_1^i(t) - \lambda_B^i * c_2^i(t) + \frac{S_B^i}{V_B} \\ c_3^i(t) = c_2^i(t) * e^{-\lambda_f * t_{2,3}} \\ c_4^{i'}(t) = \lambda_A^i * c_3^i(t) - \lambda_A^i * c_4^i(t) + \frac{S_A^i}{V_A} \\ c_5^i(t) = c_4^i(t) * e^{-\lambda_f * t_{4,5}} \\ c_{env}^i(t) = c_5^i(t) * e^{-\lambda_f * t_d} \end{array} \right.$$

- $c_1(t)$  the activity concentration at the entrance of the fresh duct tunnel [ $\frac{Bq}{m^3}$ ]
- $c_2(t)$  the activity concentration inside the fresh air duct [ $\frac{Bq}{m^3}$ ]
- $c_3(t)$  the activity concentration injected from the fresh air duct into the machine tunnel [ $\frac{Bq}{m^3}$ ]
- $c_4(t)$  the activity concentration inside the machine tunnel [ $\frac{Bq}{m^3}$ ]
- $c_5(t)$  the activity concentration at the exit of the machine machine tunnel [ $\frac{Bq}{m^3}$ ]
- $f$  the fraction of recycled air
- $t_{2,3}$  the transit time in the fresh air duct (one compartment)
- $t_{4,5}$  the transit time in machine tunnel (one compartment)
- $S_A$  the generation/source term [ $\frac{Bq}{s}$ ] in the machine tunnel (one compartment)
- $S_B$  the generation/source term [ $\frac{Bq}{s}$ ] in the fresh air duct (one compartment)
- $\lambda_f^i$  is the physical decay constant [ $s^{-1}$ ] of the radionuclide
- $\lambda_A^i$  is the effective decay constant in [ $s^{-1}$ ] in the machine tunnel compartment volume, i.e.

$$\lambda_A^i = \lambda_f^i + n_A \quad (5)$$

where  $n$  is equal to the air changes per hours [ $s^{-1}$ ] (also called ventilation constant) in a proper volume; given the flow rate  $q$  [ $\frac{m^3}{s}$ ]:

$$n_A = \frac{q}{V_A} \quad (6)$$

- $\lambda_B$  is the effective decay constant in [ $s^{-1}$ ] in a fresh air duct compartment, computed with the Equation 5 and 6, using the volume of the fresh air duct ( $V_B$ ).

# Ventilation system model

Time domain

$$\left\{ \begin{array}{l} c_1^i(t) = f * c_5^i(t) \\ c_2^{i'}(t) = \lambda_B^i * c_1^i(t) - \lambda_B^i * c_2^i(t) + \frac{S_B^i}{V_B} \\ c_3^i(t) = c_2^i(t) * e^{-\lambda_f * t_{2,3}} \\ c_4^{i'}(t) = \lambda_A^i * c_3^i(t) - \lambda_A^i * c_4^i(t) + \frac{S_A^i}{V_A} \\ c_5^i(t) = c_4^i(t) * e^{-\lambda_f * t_{4,5}} \\ c_{env}^i(t) = c_5^i(t) * e^{-\lambda_f * t_d} \end{array} \right.$$

Frequency domain

$$\left\{ \begin{array}{l} Y_1^i(s) = f * Y_5^i(s) \\ s * Y_2^i(s) = \lambda_B^i * Y_1^i(s) - \lambda_B^i * Y_2^i(s) + \frac{S_B^i}{V_B} * \frac{1}{s} \\ s * Y_3^i(s) = Y_2^i(s) * e^{-\lambda_f * t_{2,3}} \\ s * Y_4^i(s) = \lambda_A^i * Y_3^i(s) - \lambda_A^i * Y_4^i(s) + \frac{S_A^i}{V_A} * \frac{1}{s} \\ Y_5^i(s) = Y_4^i(s) * e^{-\lambda_f * t_{4,5}} \\ Y_{env}^i(s) = Y_5^i(s) * e^{-\lambda_f * t_d} \end{array} \right.$$

# Ventilation system model

## 7.1.4 Beam operation scenario

The representative solutions of the ventilation conditions during beam operation is computed assuming all the initial activity concentrations equal to zero, and two no-null source terms, i.e.  $S_A$  and  $S_B \neq 0$ . The activity concentration in time for a generic radionuclide  $i$  is described by Equation 8. The index  $\omega$  refers to the beam operation scenario.

$$c_{4,\omega}(t) = \left[ \frac{W}{R * T} \right] + \left[ \left( \frac{Q * R + W}{R * (R - T)} \right) * e^{R * t} \right] + \left[ \left( \frac{Q * T + W}{T * (T - R)} \right) * e^{T * t} \right] \quad (8)$$

where

- $Q = \frac{S_A^i}{V_A}$
- $W = \left( \frac{S_B^i}{V_A} * \lambda_B^i \right) + \left( \frac{S_B^i}{V_B} * \lambda_A^i * e^{-\lambda_j^i * t_{2,3}} \right)$
- $R, T = \frac{-(\lambda_A^i + \lambda_B^i) \pm \sqrt{\Delta}}{2}$  with  $\Delta = (\lambda_A^i + \lambda_B^i)^2 - 4 * [(\lambda_A^i * \lambda_B^i) - (f * \lambda_A^i * \lambda_B^i * e^{-\lambda_j^i * (t_{2,3} + t_{4,5})})]$

## 7.1.5 Beam stop scenario

The representative solutions of the ventilation conditions during beam stop is computed assuming all the initial activity concentrations equal to the saturation values, and two null source terms, i.e.  $S_A$  and  $S_B = 0$ . The activity concentration in time for a generic radionuclide  $i$  is described by Equation 11. The index  $\delta$  refers to the beam stop scenario.

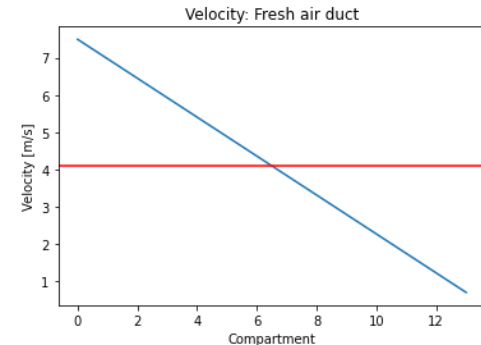
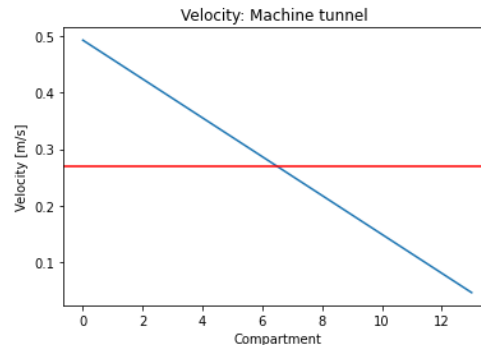
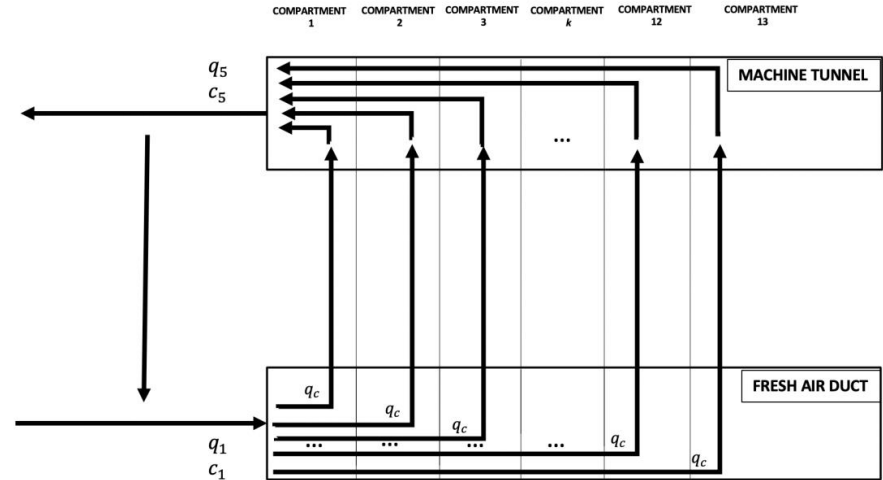
$$c_{4,\delta}^i(t) = \left[ \left( \frac{Q * R + W}{R * (R - T)} \right) * e^{R * t} \right] + \left[ \left( \frac{Q * T + W}{T * (T - R)} \right) * e^{T * t} \right] \quad (11)$$

where

- $Q = c_4^{i,sat}$
- $W = (\lambda_B * c_4^{i,sat}) + (\lambda_A^i * c_2^{i,sat} * e^{-\lambda_f * t_{2,3}})$
- $R, T = \frac{-(\lambda_A^i + \lambda_B^i) \pm \sqrt{\Delta}}{2}$  with  $\Delta = (\lambda_A^i + \lambda_B^i)^2 - 4 * [(\lambda_A^i * \lambda_B^i) - (f * \lambda_A^i * \lambda_B^i * e^{-\lambda_j^i * (t_{2,3} + t_{4,5})})]$

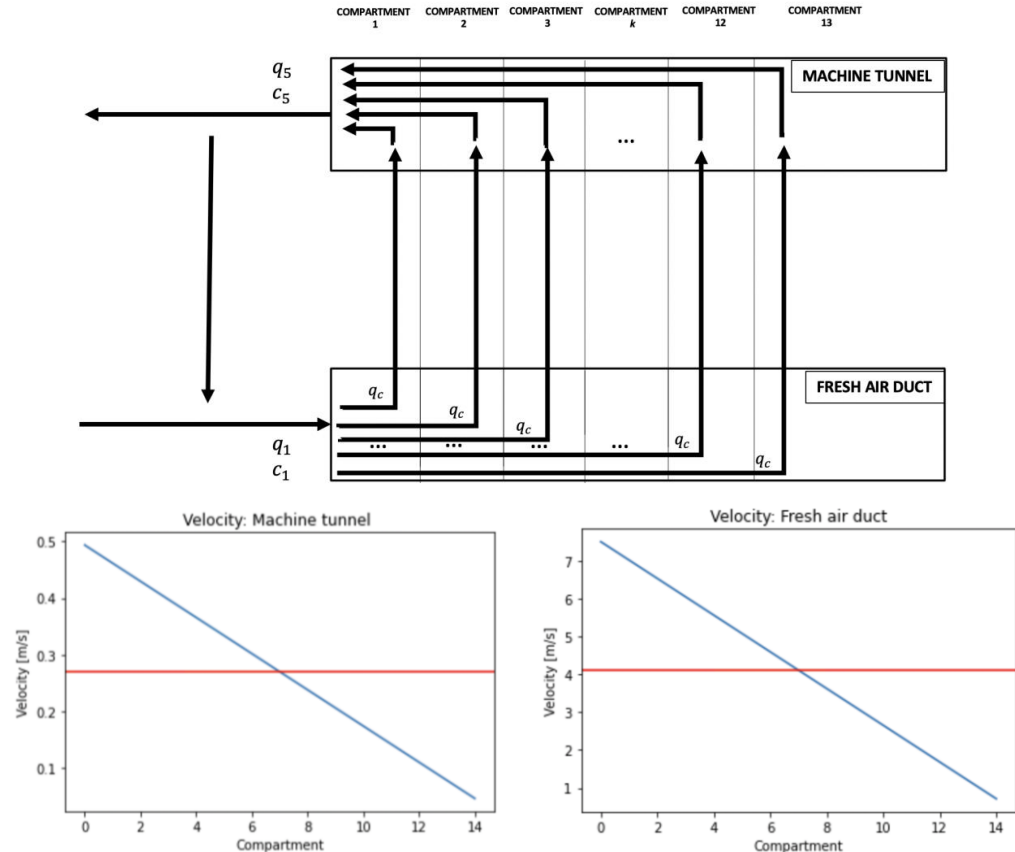
# Ventilation system model

- Since the whole flow rate is progressively injected into the machine tunnel, the initial flow rate is split into 14 'sub-flows' (one for each compartment).
- For instance, the first subflow will enter the fresh air duct, run one compartment length, and be injected at the end of the machine tunnel's first compartment; the  $k$ -subflow ( $k = 1, \dots, 13$ ) will enter the fresh air duct, run  $k$ -compartment length, and be injected at the end of the machine tunnel's  $k$ -compartment; and so on...



# Ventilation system model

- Hence, the airborne radioactivity functions are applied to each subflow, accounting for different pass-through times in the fresh air duct and machine tunnel, as well as different activity source terms, because the nuclides production is higher the longer the sub-flow pipe is (i.e. larger volume activated).
- To be noted that as each compartment causes a loss of air in the flow rate, the velocity decreases and this reduction in velocity leads to longer passage and exposition times (so  $t_{12}$  and  $t_{45}$  will not be constants).



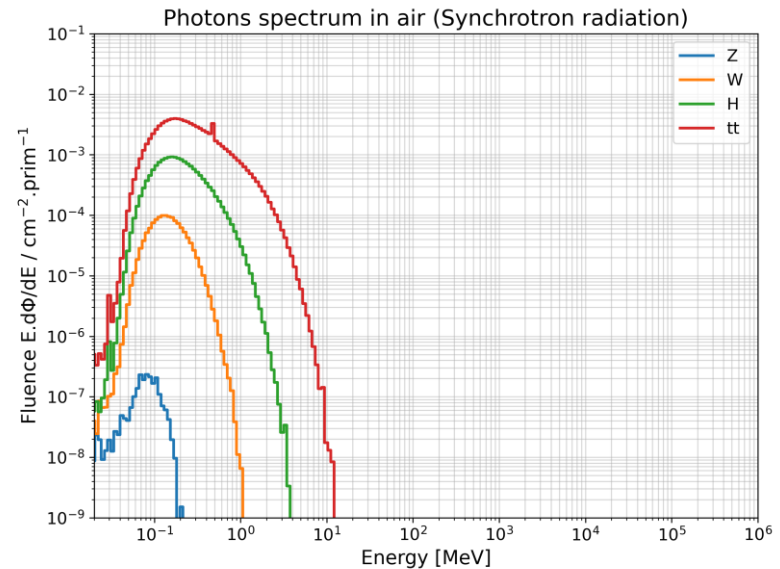
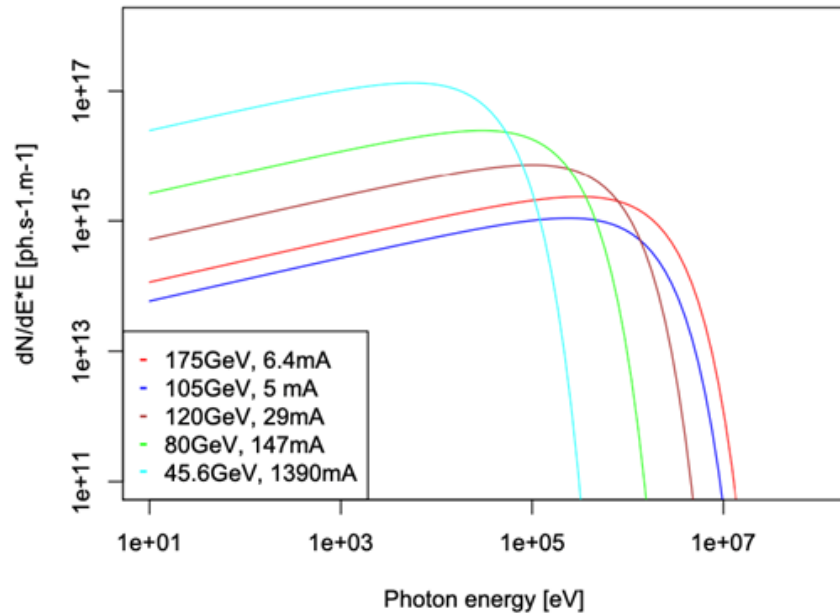
# Ventilation system

Parameter	Variable	Value	
Number of compartment per sector	$num_c$	28	-
Compartment length	$l$	400 m	
Mass flow rate	$m$	$27000 \frac{m^3}{h}$	
Compartment cross section (machine tunnel)	$A_A$	$15.2 m^2$	
Compartment cross section (fresh air duct)	$A_B$	$1 m^2$	
Volume of the machine tunnel per compartment	$V_B$	$6080 m^3$	
Volume of the fresh air duct	$V_B$	$400 m^3$	

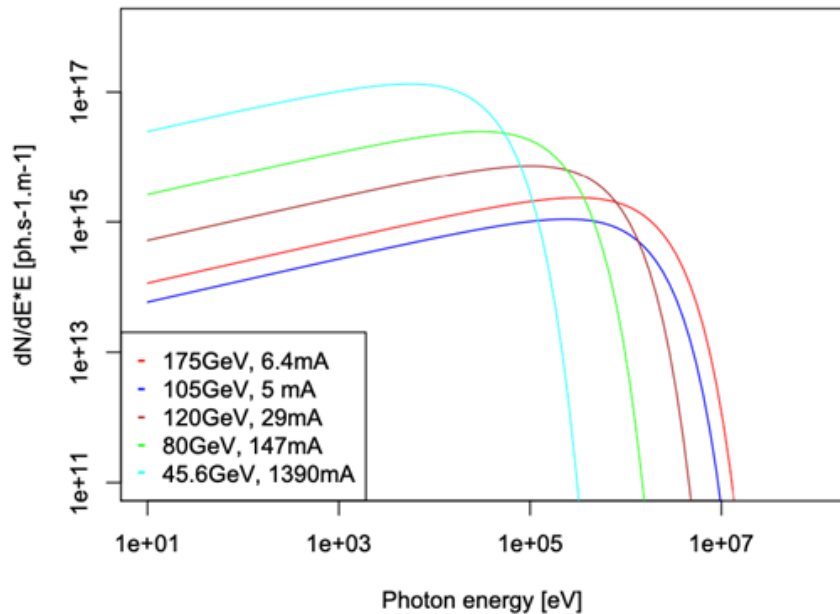


# PARTICLE SPECTRA

# Synchrotron radiation - Spectra



# Synchrotron radiation - Spectra

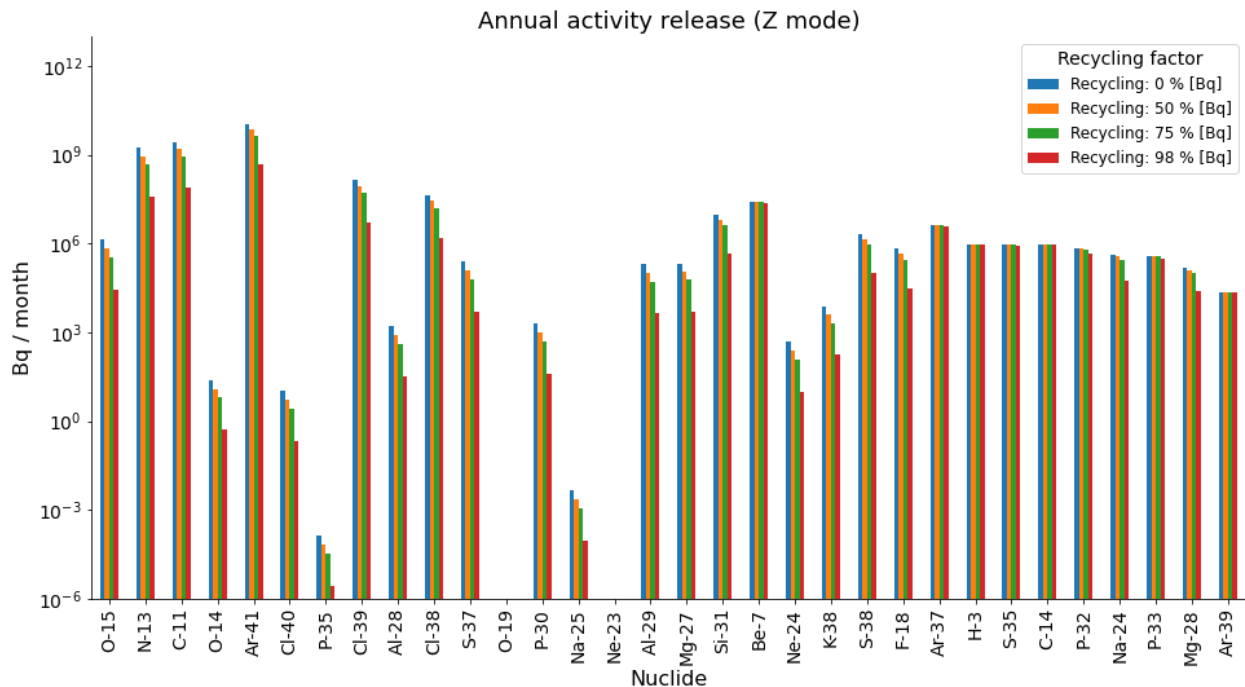


E [GeV]	I [mA]	$E_c$ [keV]	Flux [ph/sec]	~ Fraction > 7 MeV	Flux > 7 MeV [ph/sec]
182.5	5.4	1254	$8.0\text{e}+20$	$3.8\text{e}-03$	$3.0\text{e}+18$
175	6.4	1105	$9.0\text{e}+20$	$1.8\text{e}-03$	$1.6\text{e}+18$
120	29	356	$2.8\text{e}+21$	$3.0\text{e}-09$	$8.4\text{e}+12$
105 (LEP)	5	849	$4.2\text{e}+20$	$2.6\text{e}-04$	$1.1\text{e}+17$
80	147	106	$9.5\text{e}+21$	$1.7\text{e}-29$	$1.6\text{e}-07$
45.6	1390	20	$5.1\text{e}+22$	$4.7\text{e}-156$	$2.4\text{e}-133$



## ANNUAL ACTIVITY RELEASES

# Annual activity release – Z mode



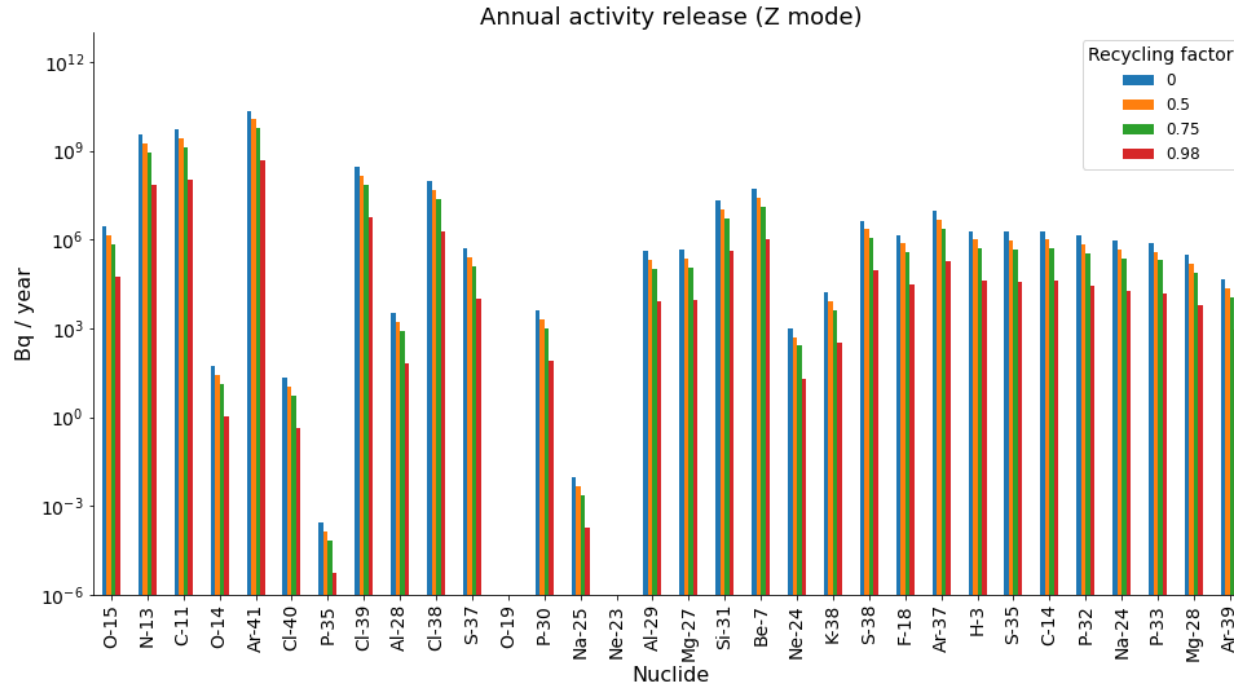
30 days of emission + total flushing

x 6

=

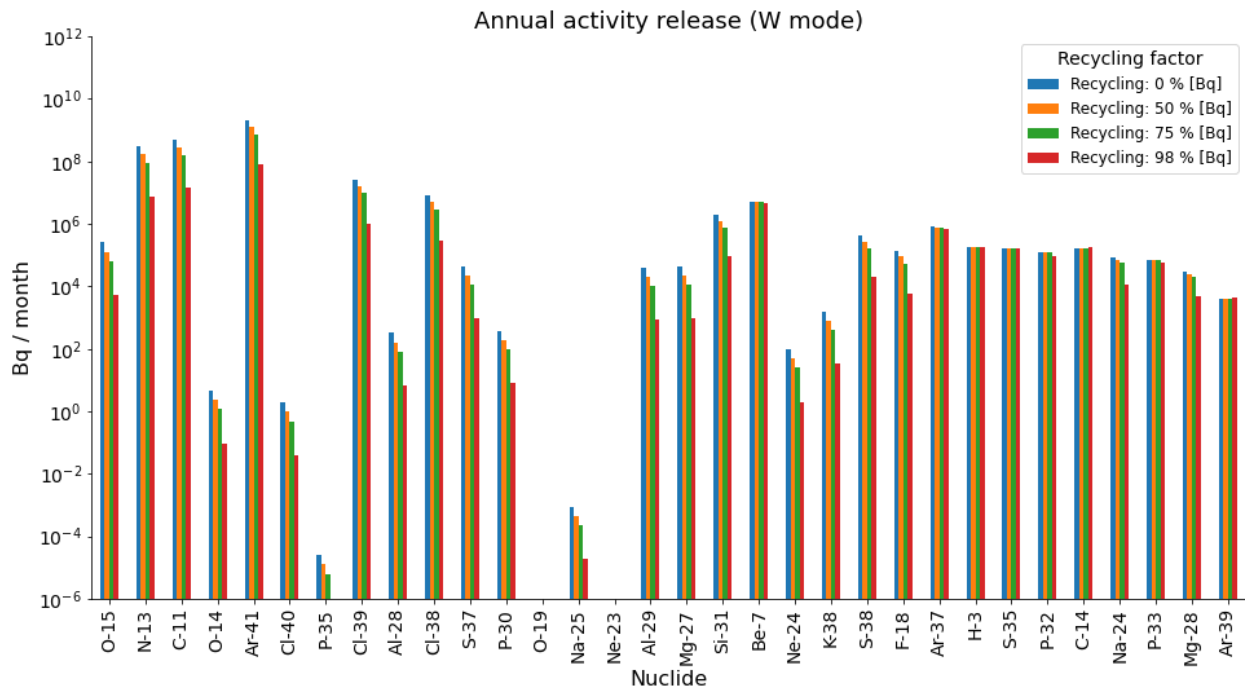
~180 days per year

## Annual activity release – Z mode



185 days of irradiation considering that all the nuclides are at the saturation level

# Annual activity release – W mode



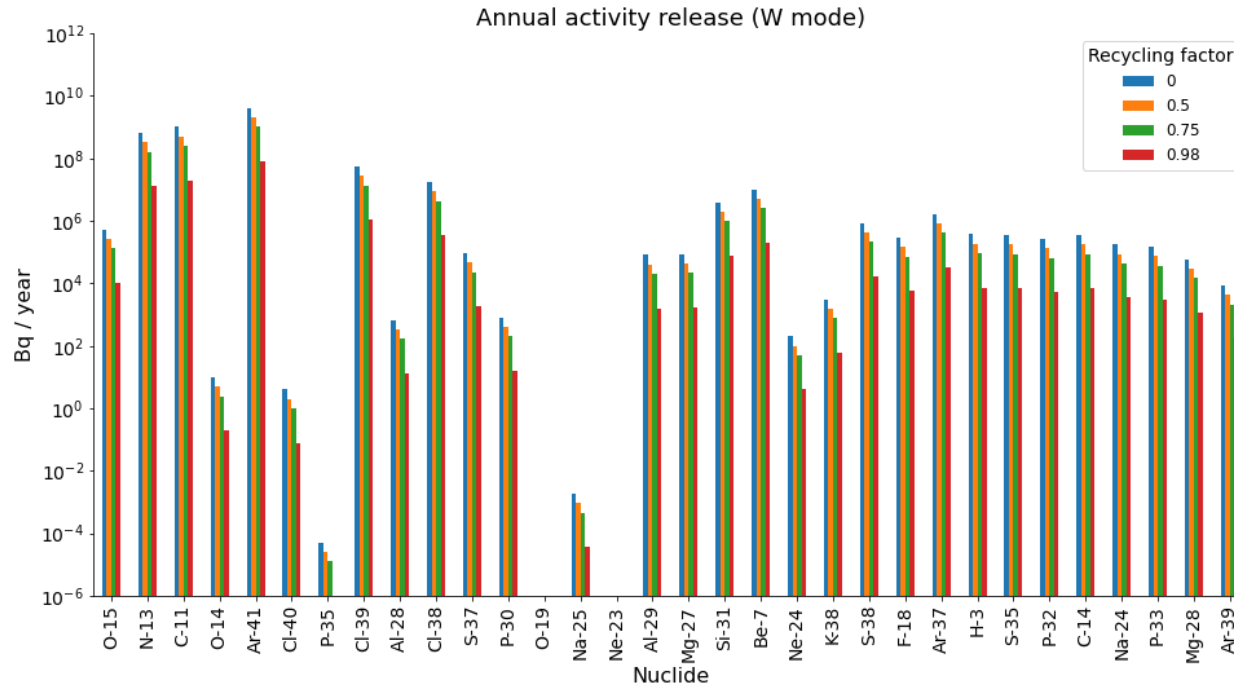
30 days of emission + total flushing

x 6

=

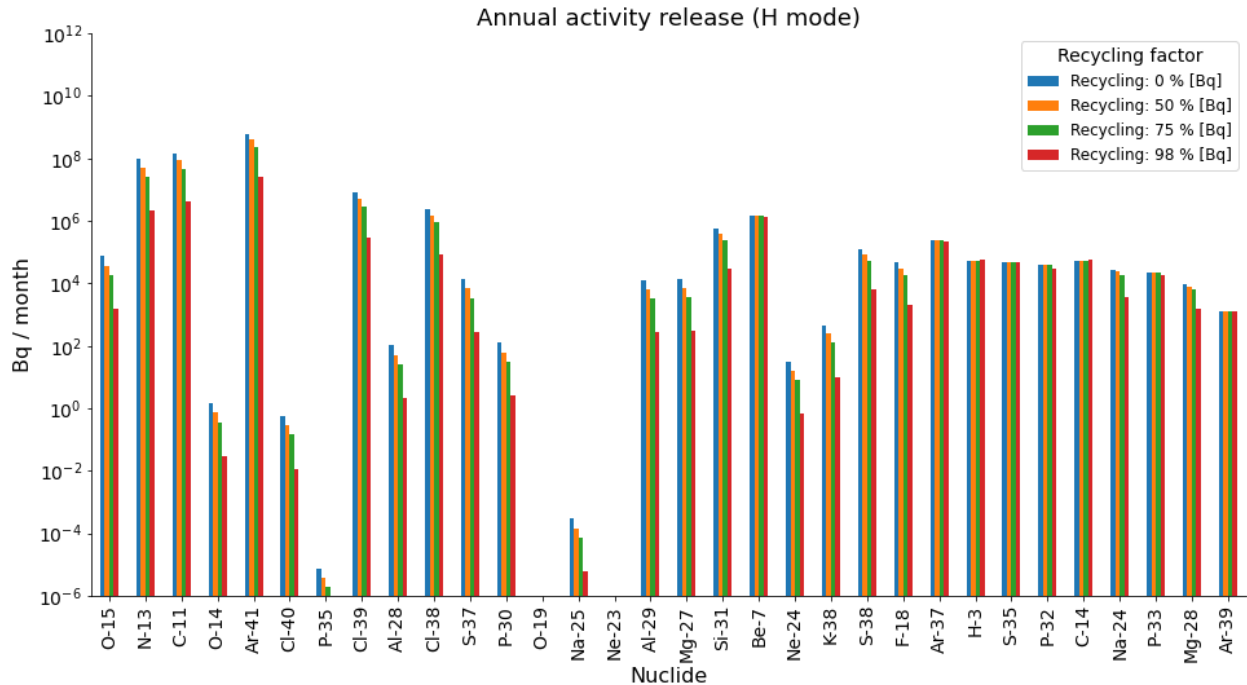
~180 days per year

## Annual activity release – W mode



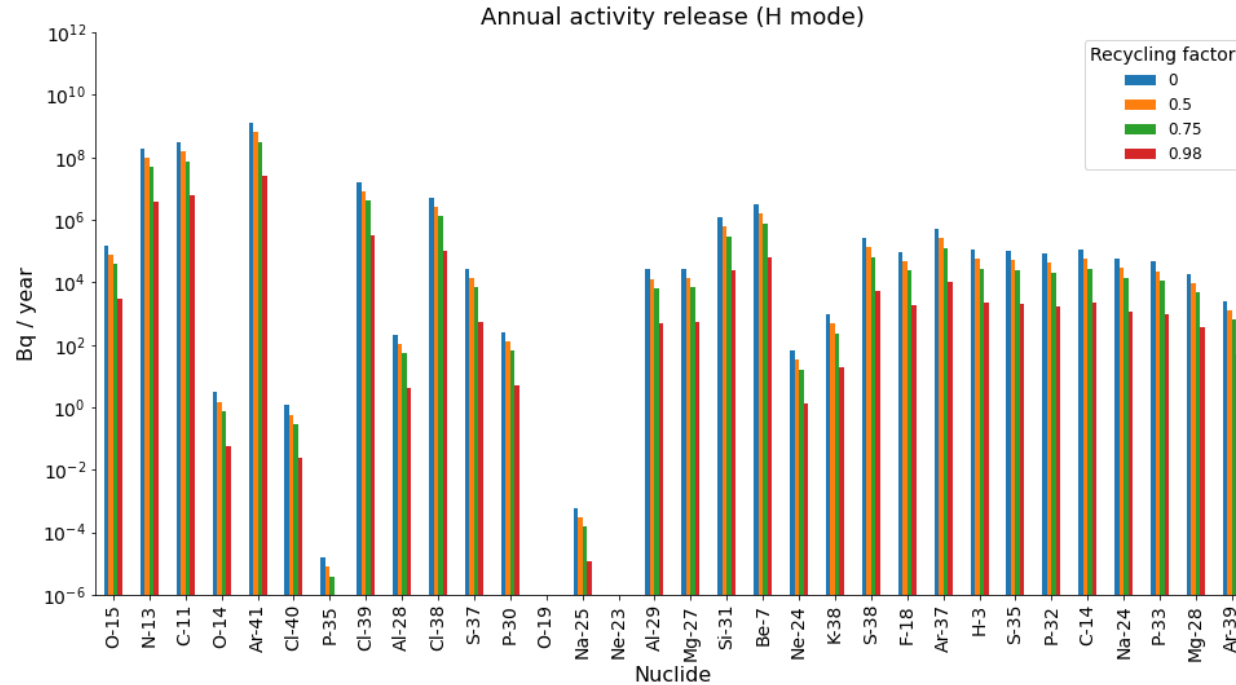
185 days of irradiation considering that all the nuclides are at the saturation level

# Annual activity release – H mode



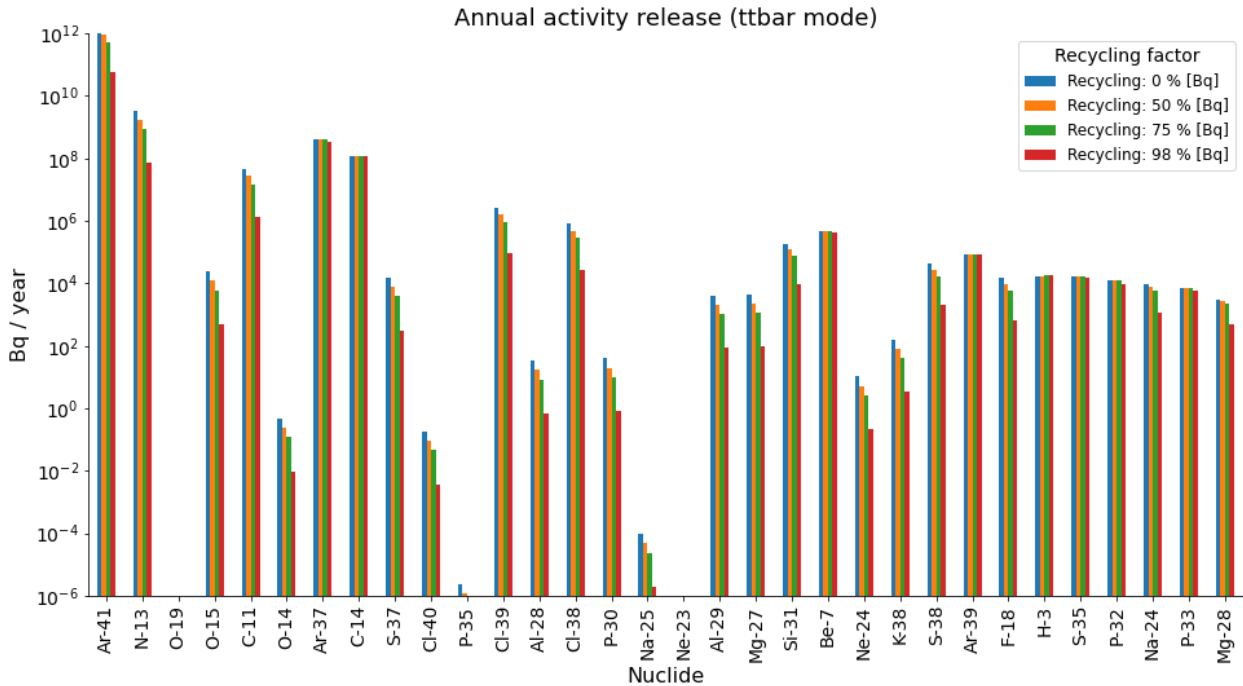
30 days of emission + total flushing x 6 = ~180 days per year

## Annual activity release – H mode



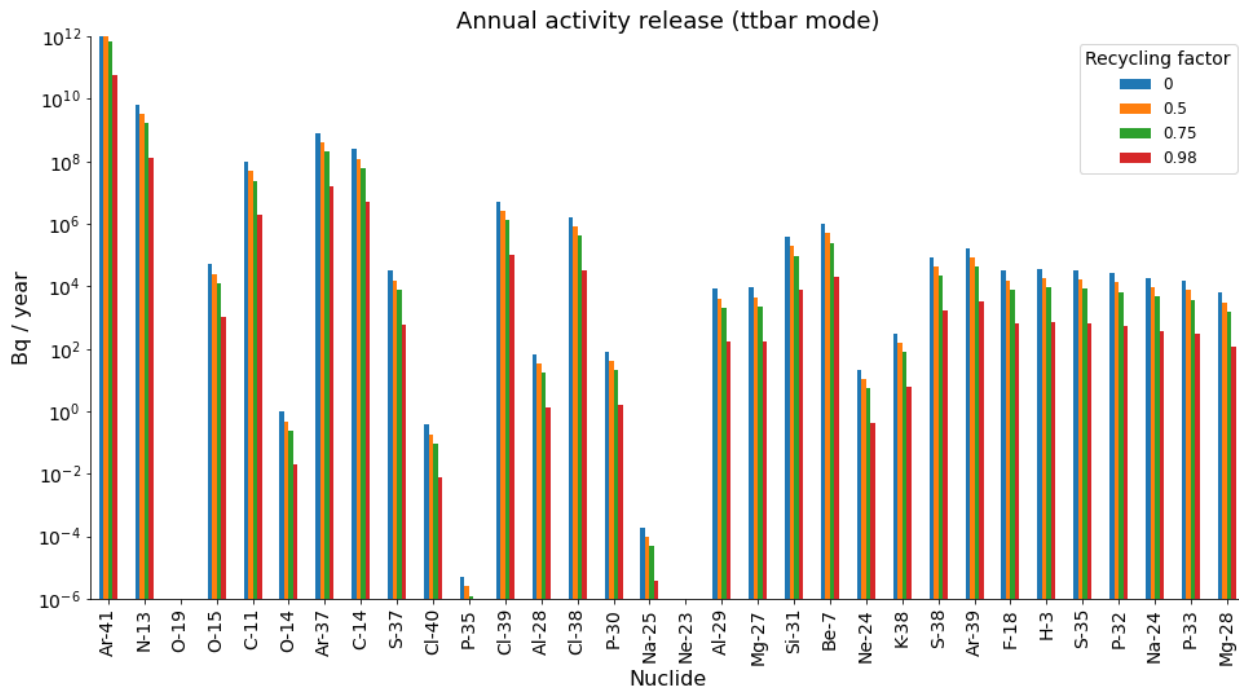
185 days of irradiation considering that all the nuclides are at the saturation level

# Annual activity release – ttbar mode

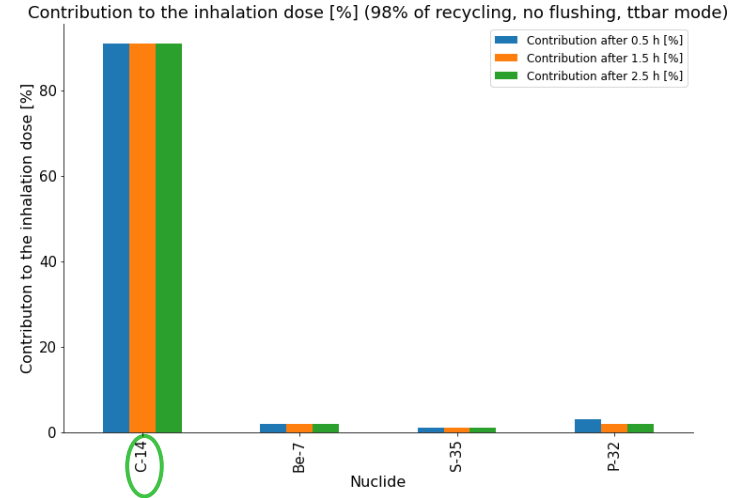
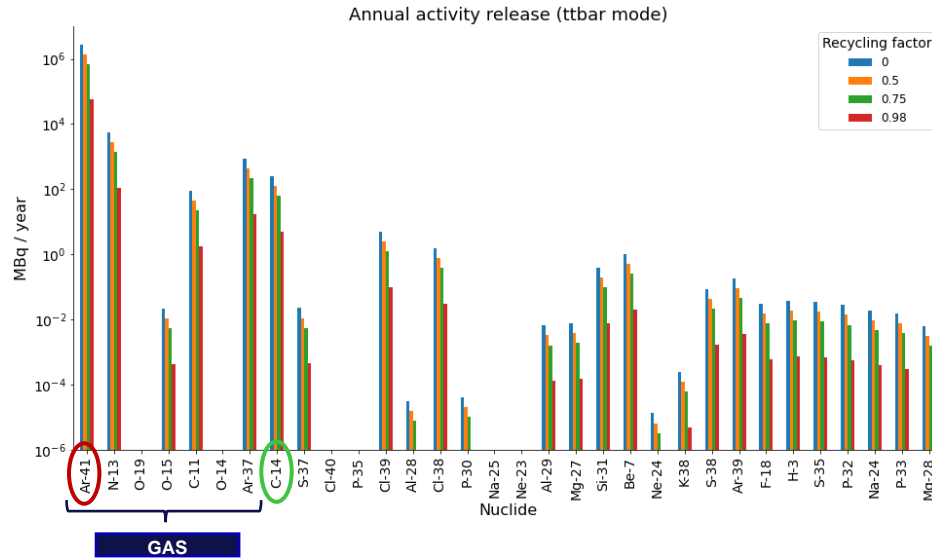


30 days of emission + total flushing      x 6      =      ~180 days per year

## Annual activity release – ttbar mode



185 days of irradiation considering that all the nuclides are at the saturation level

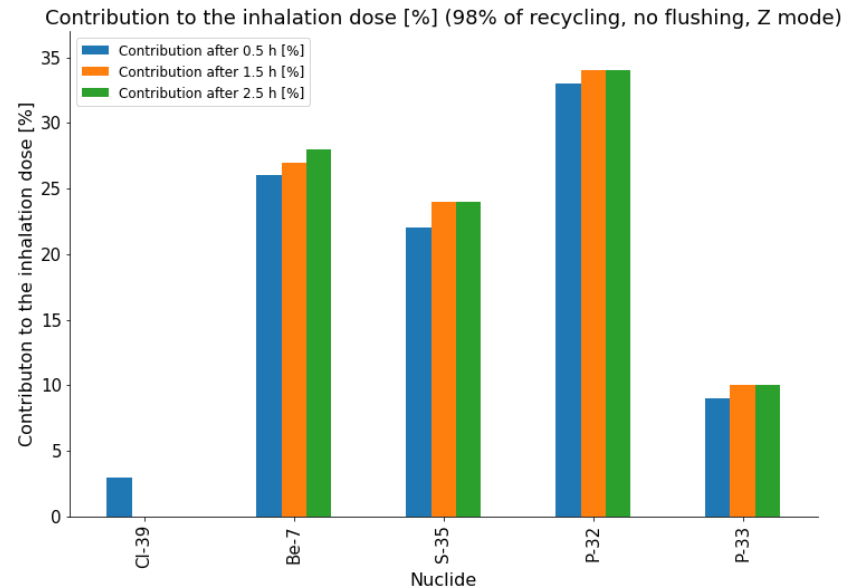
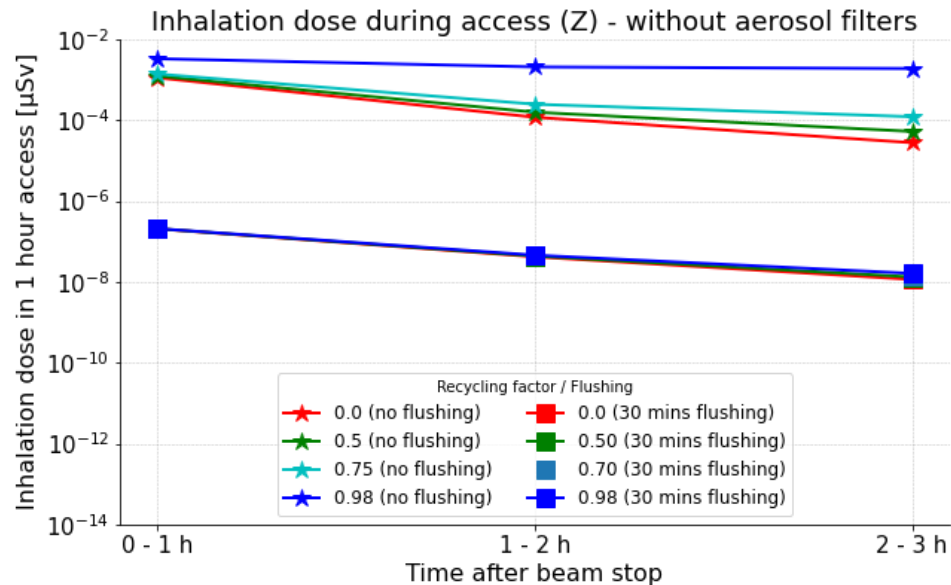


- Not all nuclides contribute equally to the inhalation dose
- Ar-41 accounts for the highest released activity, but it does not contribute to inhalation dose due to its conversion coefficient being zero. This explains the difference in terms of released activity between Z and ttbar, while still resulting in similar inhalation doses.

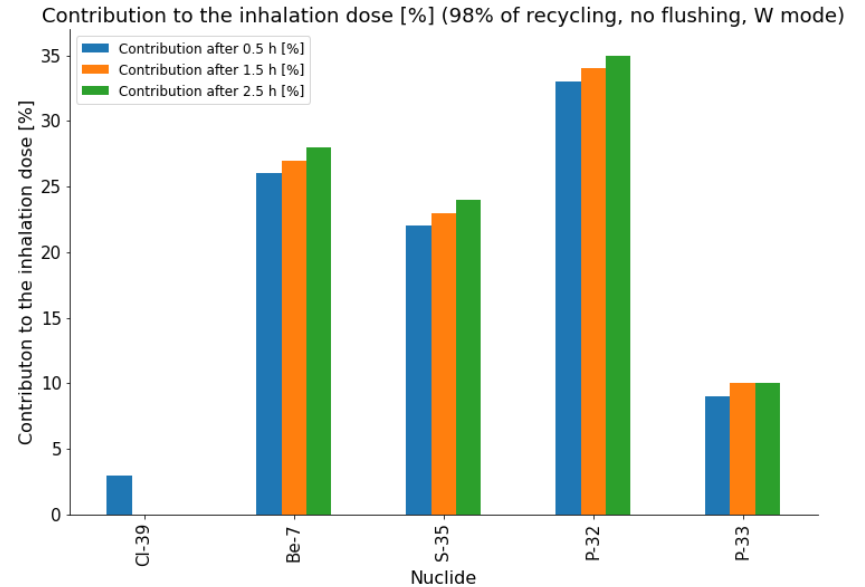
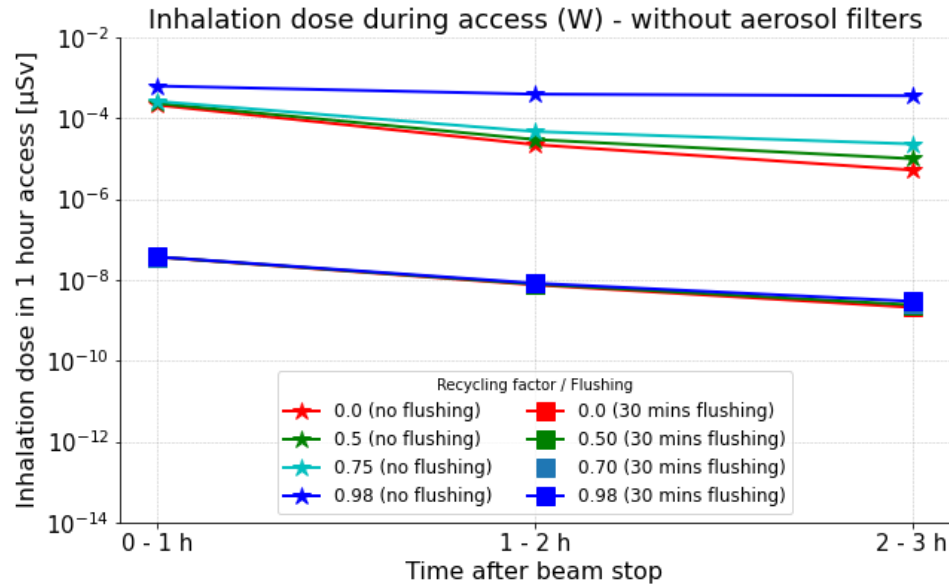


INHALATION DOSE

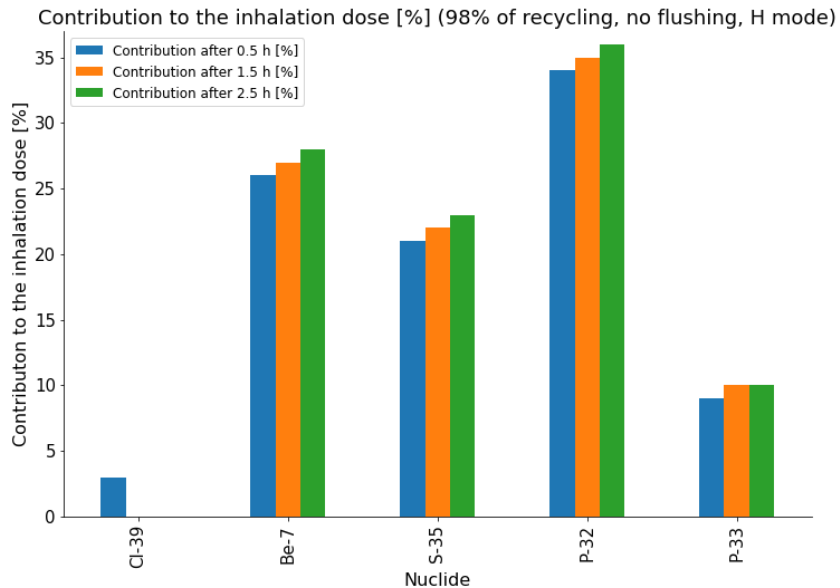
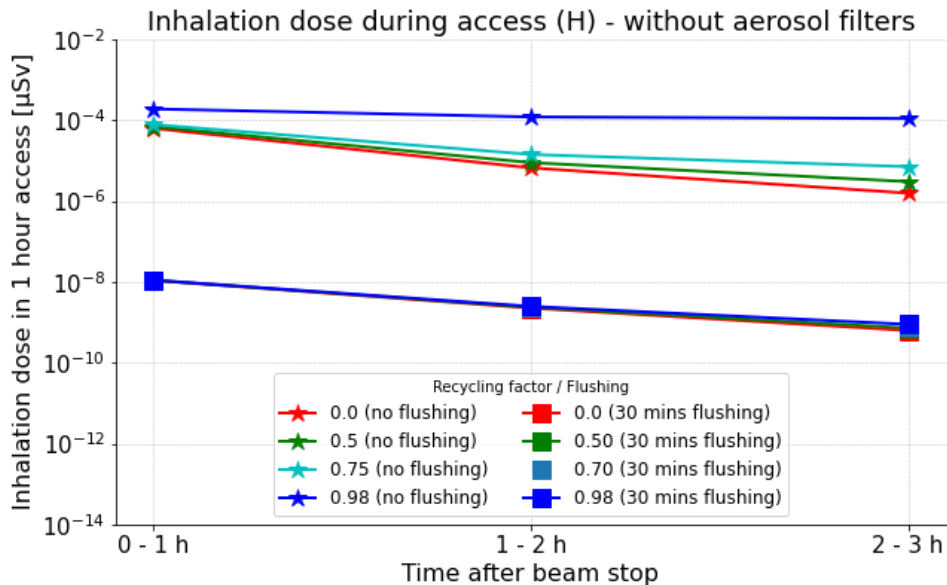
## Inhalation dose – Z mode



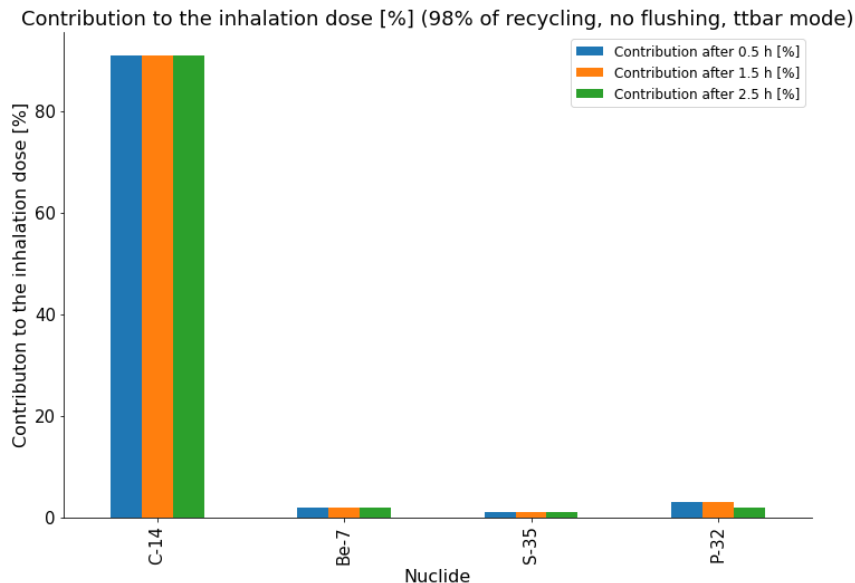
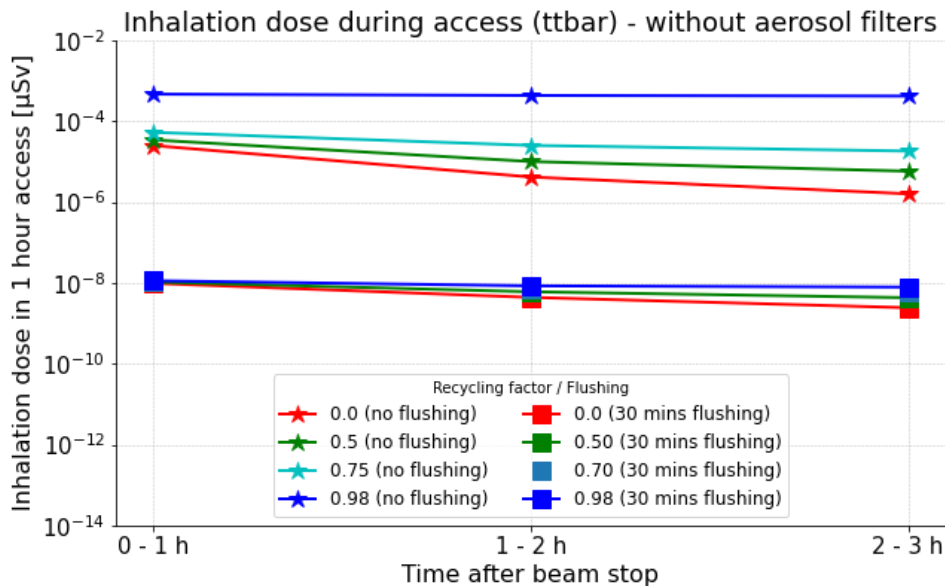
# Inhalation dose – W mode



## Inhalation dose – H mode



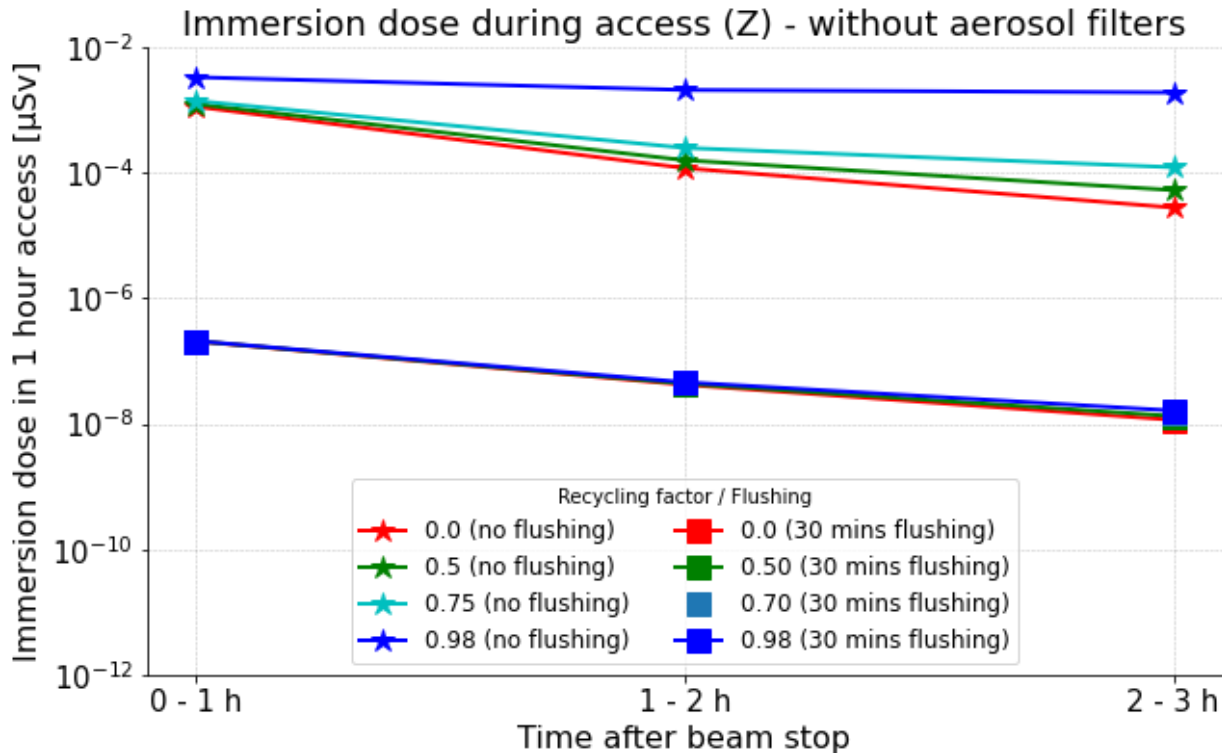
# Inhalation dose – ttbar mode



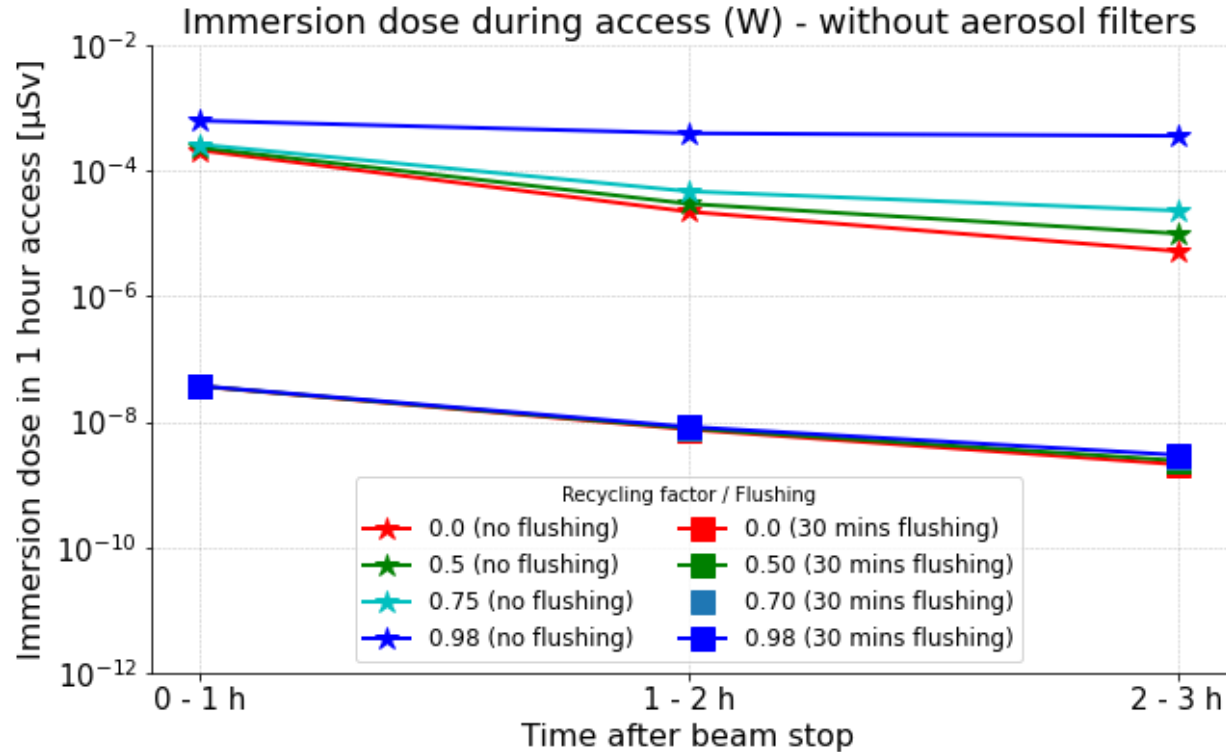


IMMERSION DOSE

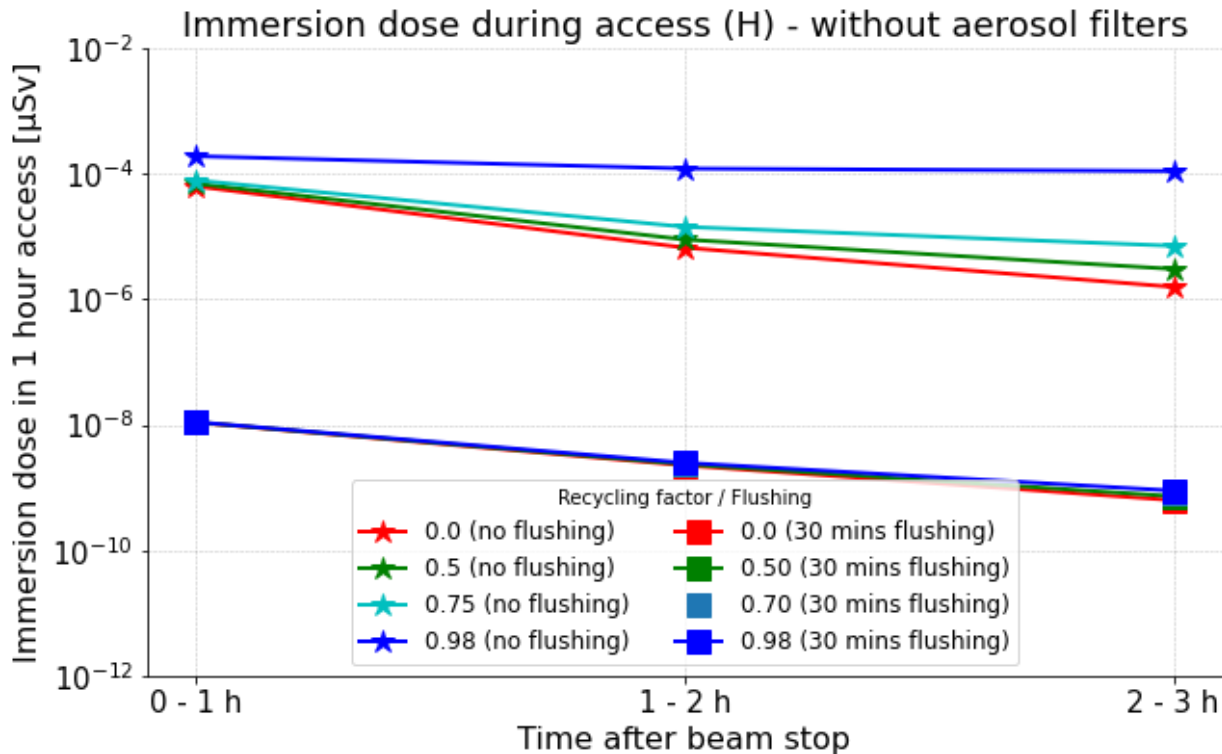
## Immersion dose – Z mode



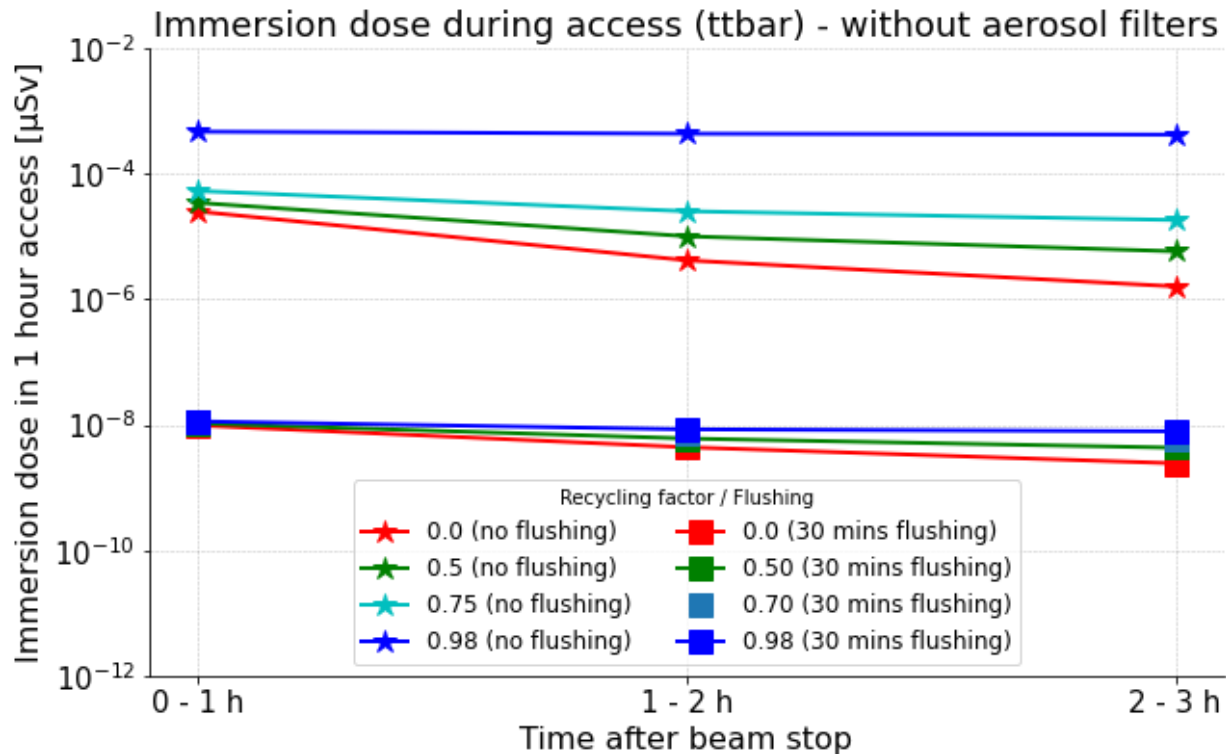
## Immersion dose – W mode

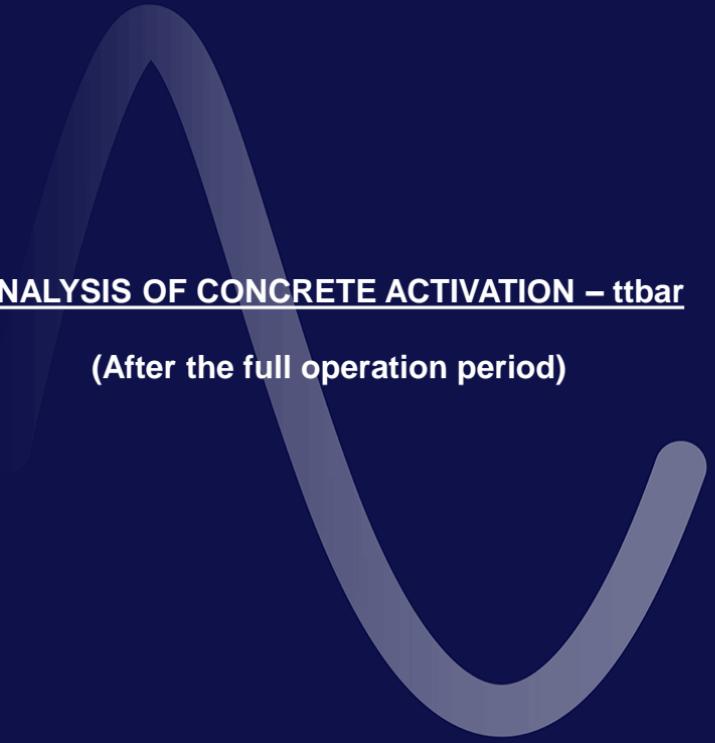


## Immersion dose – H mode



## Immersion dose – ttbar mode





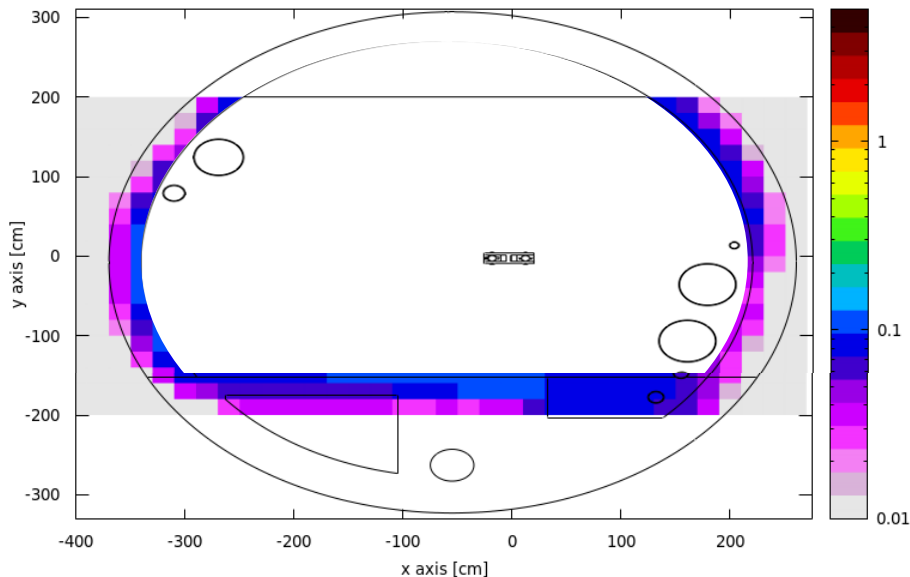
ANALYSIS OF CONCRETE ACTIVATION –  $tt_{bar}$

(After the full operation period)

## ANALYSIS OF CONCRETE ACTIVATION – ttbar

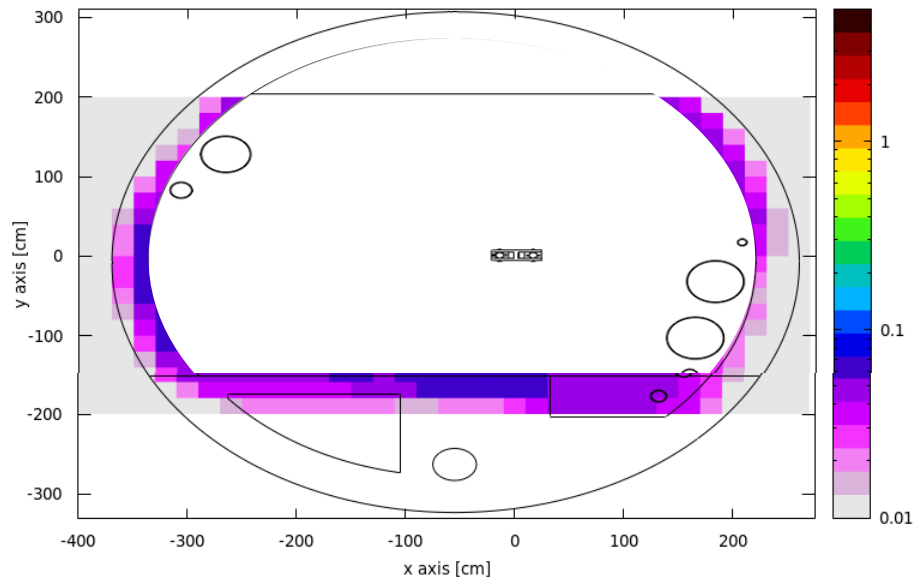
(After the full operation period)

LL multiples for concrete (decay time: 1 week)



**Irradiation profile (ttbar):** full operation period / 1 week of cooling time

LL multiples for concrete (decay time: 1 month)



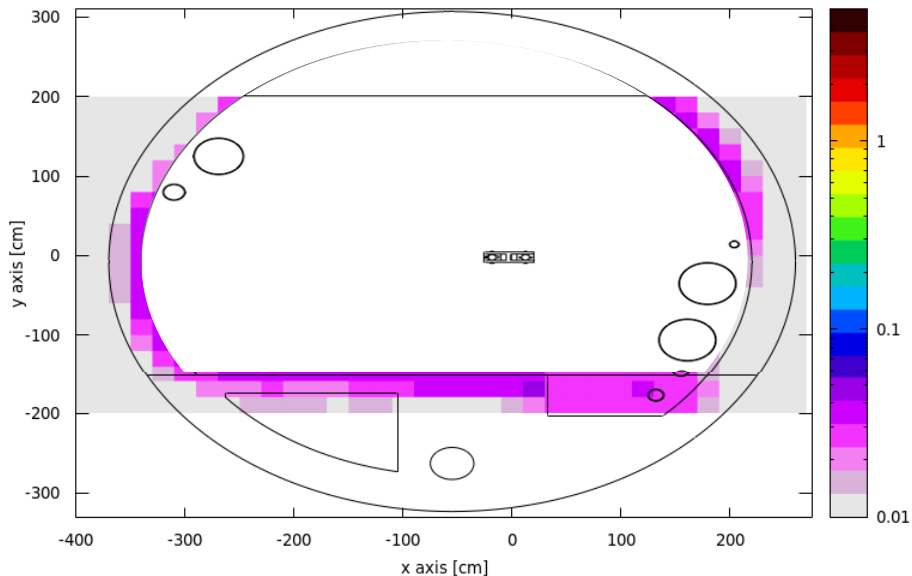
**Irradiation profile (ttbar):** full operation period / 1 month of cooling time

Activation is below clearance limit for the concrete structures of the tunnel.

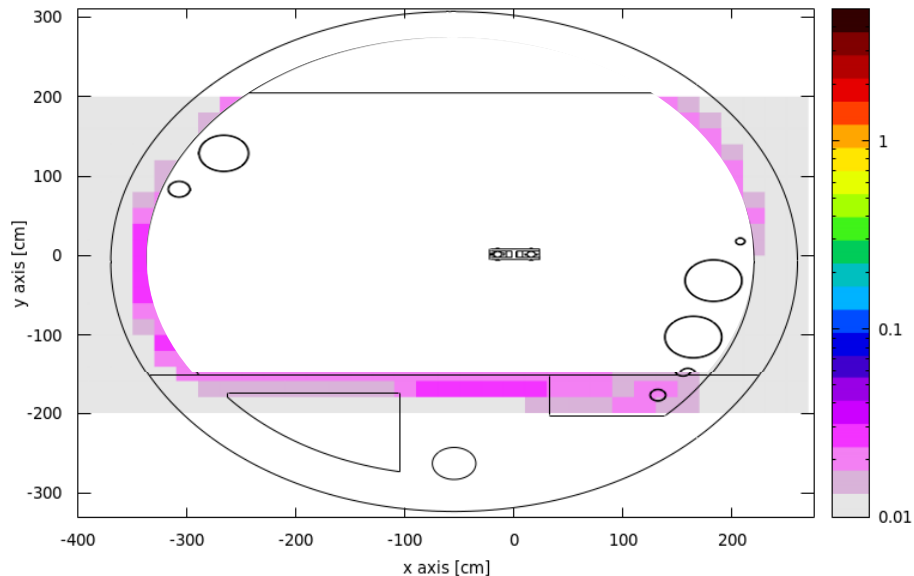
## ANALYSIS OF CONCRETE ACTIVATION – ttbar

(After the full operation period)

LL multiples for concrete (decay time: 1 year)



LL multiples for concrete (decay time: 10 years)



**Irradiation profile (ttbar):** full operation period / 1 year of cooling time

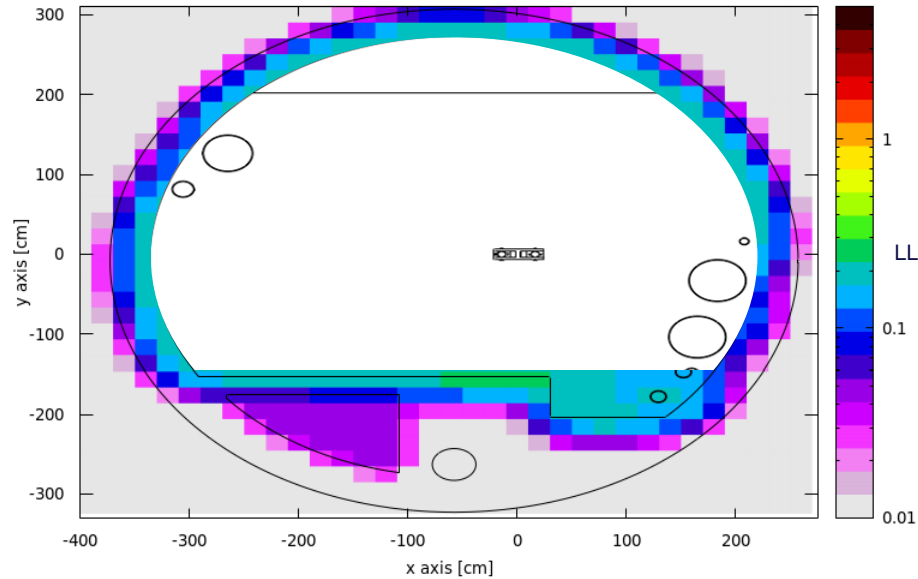
**Irradiation profile (ttbar):** full operation period / 10 years of cooling time

Activation is below clearance limit for the concrete structures of the tunnel.

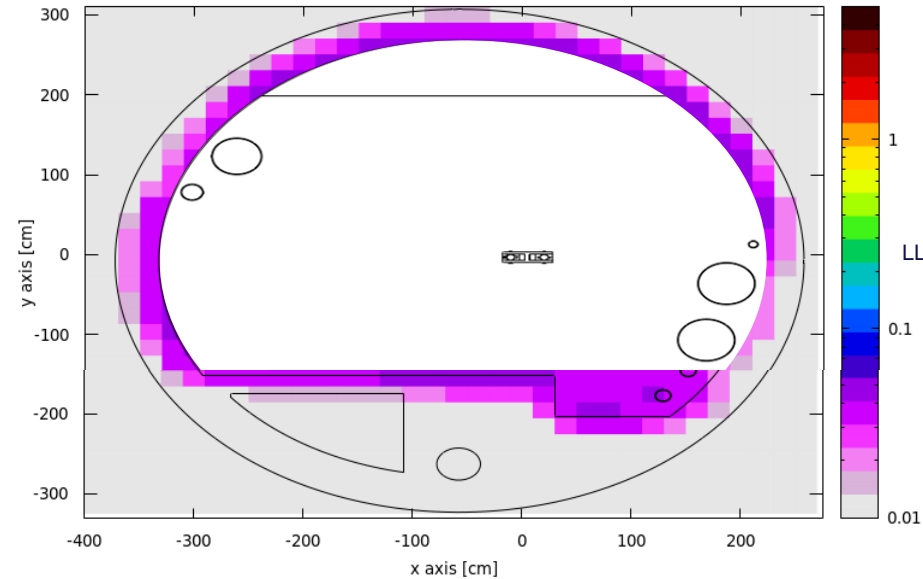
## ANALYSIS OF CONCRETE ACTIVATION – ttbar

(After 1 year of operation)

LL multiples for concrete (decay time: 24 h)



LL multiples for concrete (decay time: 1 month)

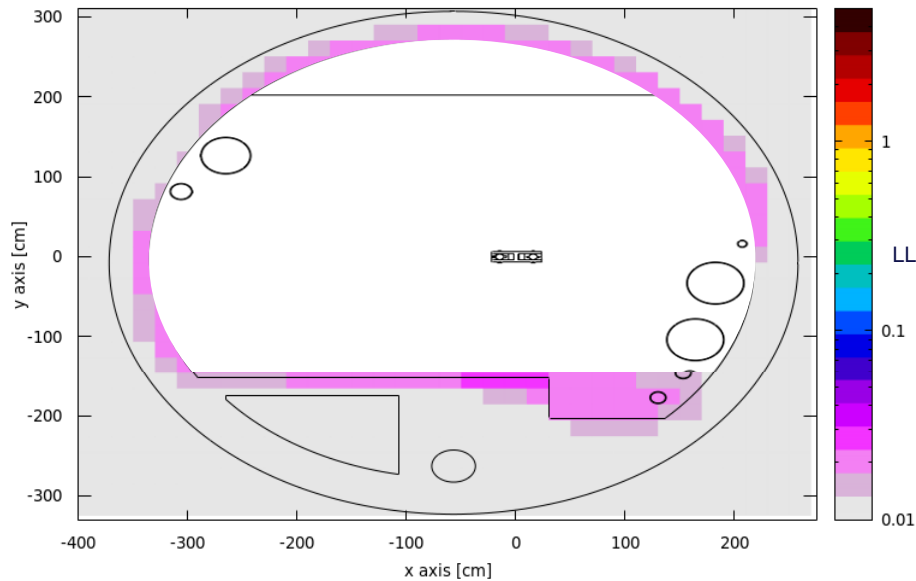


Activation is below clearance limit for the concrete structures of the tunnel.

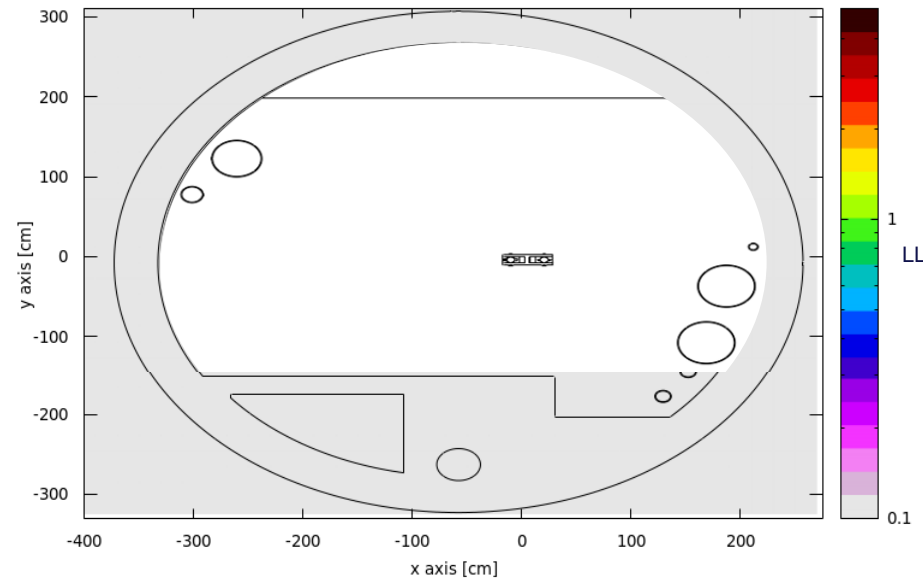
## ANALYSIS OF CONCRETE ACTIVATION – ttbar

(After 1 year of operation)

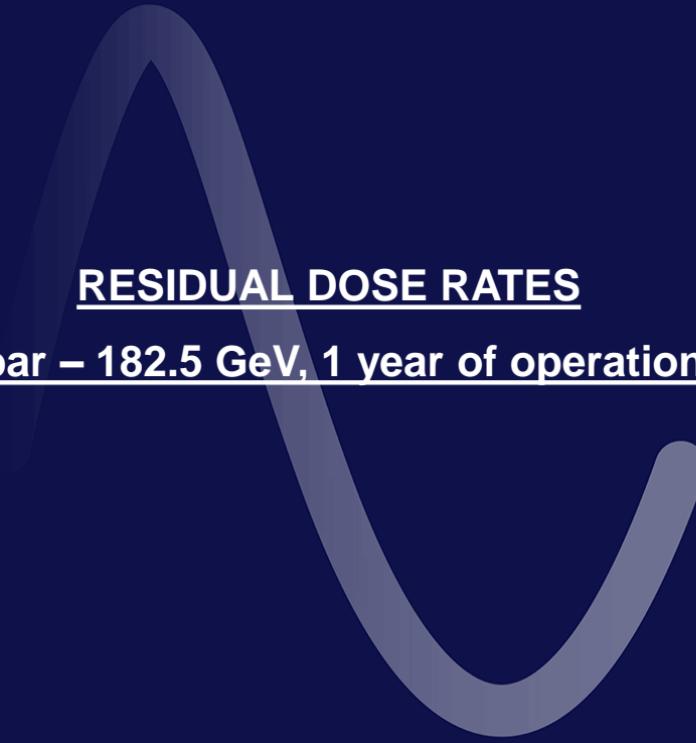
LL multiples for concrete (decay time: 1 year)



LL multiples for concrete (decay time: 10 year)



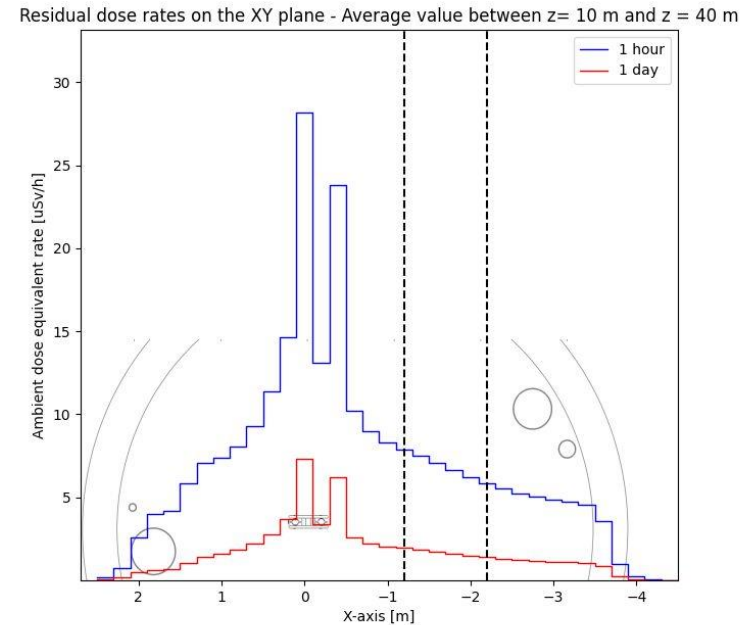
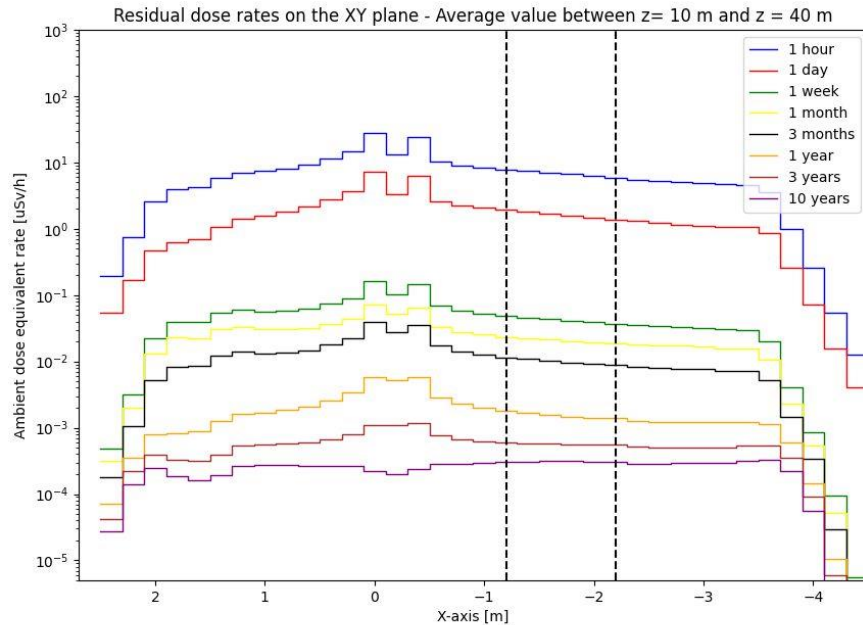
Activation is below clearance limit for the concrete structures of the tunnel.



**RESIDUAL DOSE RATES**  
**( ttbar – 182.5 GeV, 1 year of operation )**

# Residual dose rate (profile XY plane)

## ttbar -> 1 year of operation





FUTURE  
CIRCULAR  
COLLIDER

