FCC

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

Context & Motivation

Main objectives of the radiological studies for FCCee:

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ARC SECTION

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

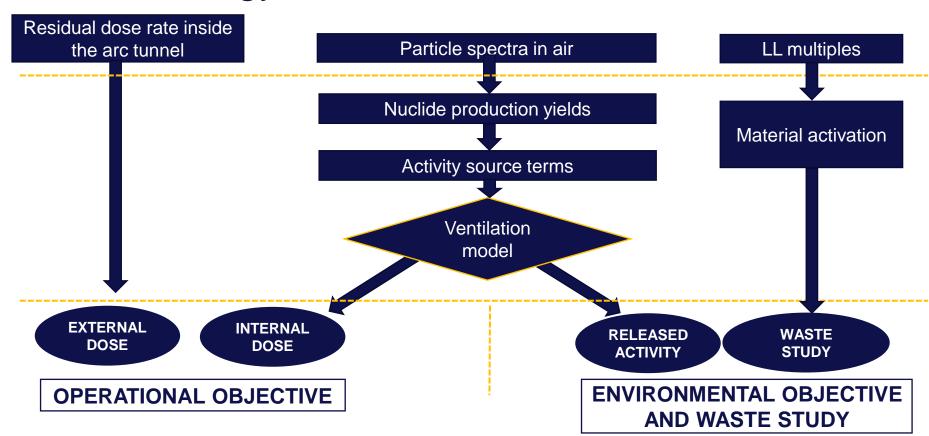
Assure FCCee design compatibility with environmental constraints, in terms of released activity through air and fluids and solid radioactive waste.

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

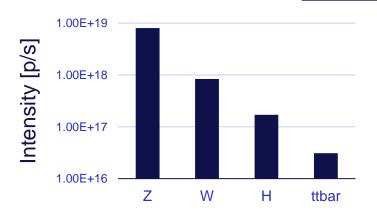
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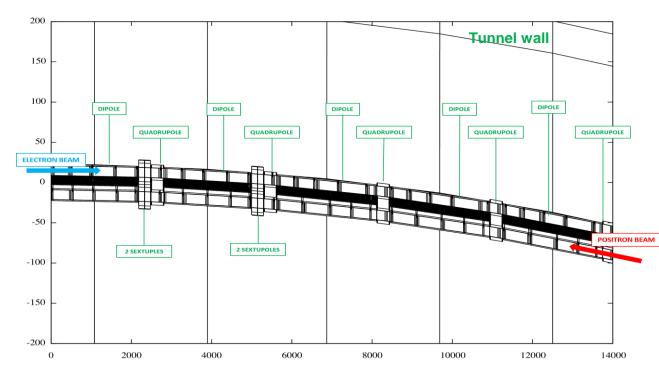






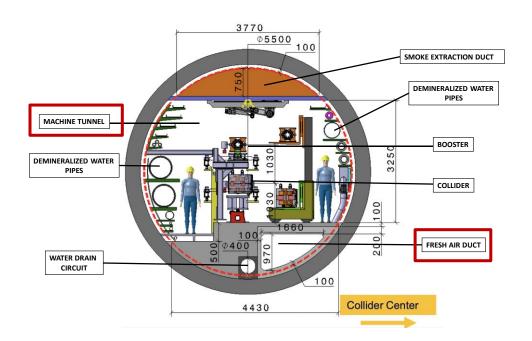
Simulation geometry

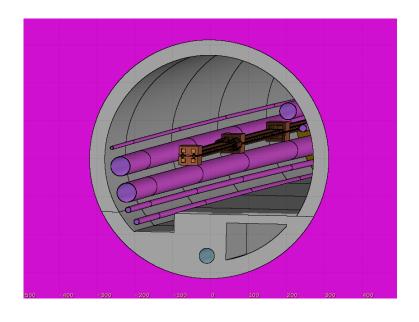
- □ Representative periodic arc cell of 140 m
- ☐ The cell is composed by
 - 5 dipoles
 - 5 quadrupoles
 - 4 sextupoles
 - 25 photon absorber per beam (23 in dipoles and 2 in quadrupoles)
- ☐ The Booster ring is not included.





Simulation geometry

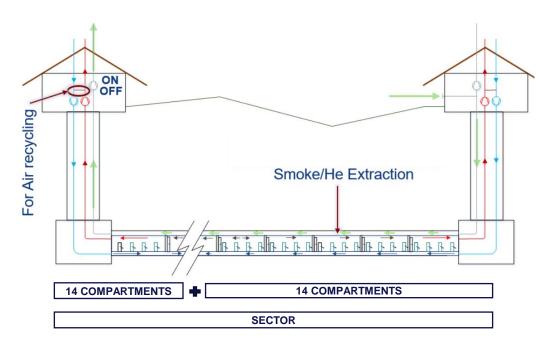






Ventilation system – Transversal layout

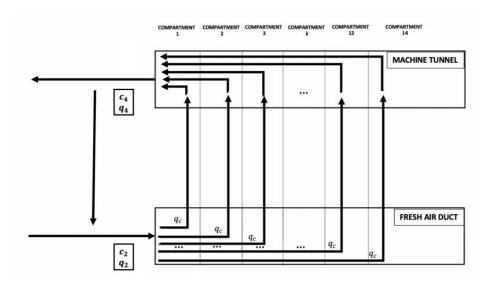
- Each sector of the FCC tunnel consists of 28 compartments, each 400m long.
- ☐ Two ventilation systems are present in each sector, serving 14 compartments each
- □ Air recycling is employed to optimise air conditioning during beam operation and beam stop. The proportion of recycled air varies seasonally,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





Ventilation system – Transversal layout

- □ 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 m3/h)
 - Laminar flux
 - Constant activity source term along the sector.



PARTICLE SPECTRA

SYNCHROTRON RADIATION

Photons spectrum in air (Synchrotron radiation)

10^{-2} 10- 10^{-16}

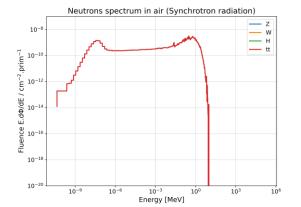
10-1

100

101

NEUTRONS

PHOTONS



10²

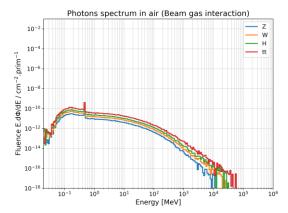
Energy [MeV]

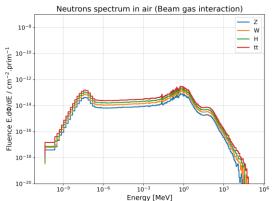
10³

104

105

BEAM-GAS INTERACTIONS



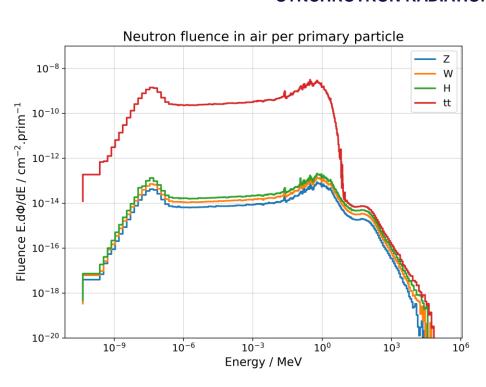


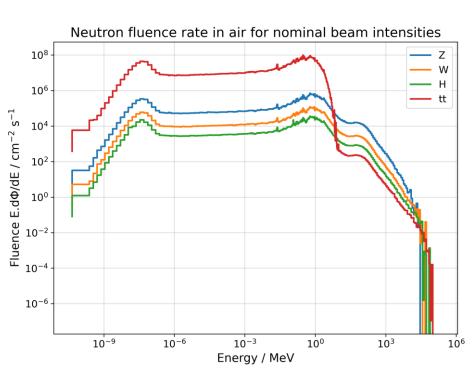


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PARTICLE SPECTRA

SYNCHROTRON RADIATION + BEAM GAS INTERACTION

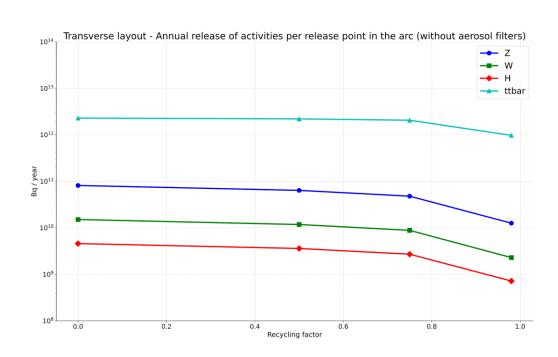






RELEASED ACTIVITY

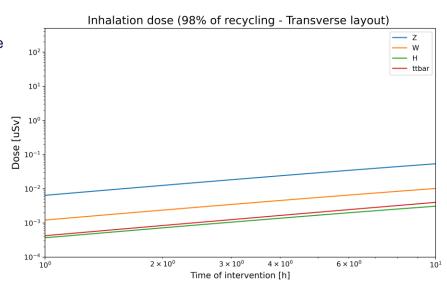
- **Annual activity release** per release point from two half-sectors during the four operation modes (Z, W, H and ttbar) for 4 different recycling factors, considering 180 days of annual operation with a complete flushing conducted after every 30 days of operation. The values are calculated taking into account the dynamics of the transverse ventilation system. The emissions account for releases occurring during the running period plus 6 flushing cycles, excluding any filtering of aerosol-bound nuclides.
- Results consistent with neutron spectra: the plot of ttbar significantly deviates from the other three due to the higher contribution induced by the higher energetic synchrotron radiation.





INHALATION DOSE

- The graphs illustrate the inhalation dose within the machine tunnel as a function of intervention time (in logarithmic scale), after an irradiation period of 185 days at 98% of recycling for all the four operation modes of FCCee, without considering any flushing.
- Air filtration systems within the recycling units have not been accounted for in this study, making the results conservative.
- The inhalation dose remains consistently below the guideline value of 1 μ Sv for 1 hour of access for all operation modes.
- Ar-41 is the primary contributor to the activity concentration in the air during ttbar. Despite the overall activity concentration being orders of magnitude higher than in previous operation modes, the contribution of Ar-41 to the inhalation dose is zero because it is a noble gas. This is the reason why the inhalation dose during ttbar is lower than in the previous operation modes.

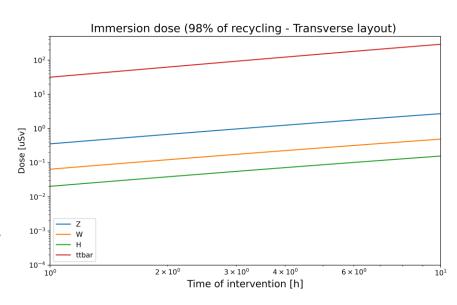




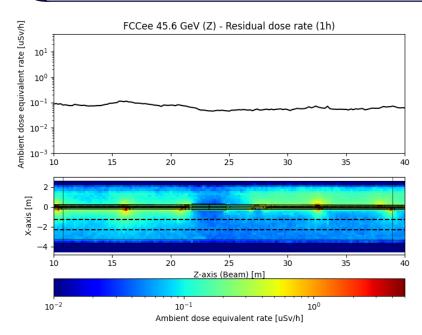
RESULTS: IMMERSION DOSE

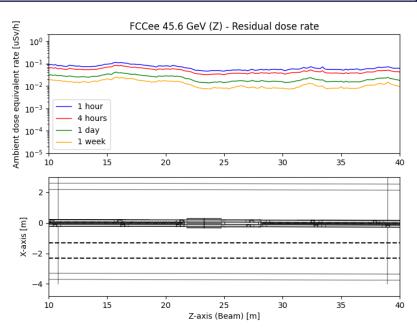
- The graphs illustrate the immersion dose within the machine tunnel as a function of intervention time (in logarithmic scale), after an irradiation period of 185 days at 98% of recycling for all the four operation modes of FCCee, without considering any flushing.
- In ttbar mode, the immersion dose reaches higher values.

 These value is comparable to the external residual dose, indicating the importance of taking into account the potential impact on the access during ttbar. Given that Ar-41 is a major contributor in ttbar, the application of filtering would not alter the situation.
- It is advisable to implement a total flushing, which takes approximately 3 hours, before entering the tunnel.



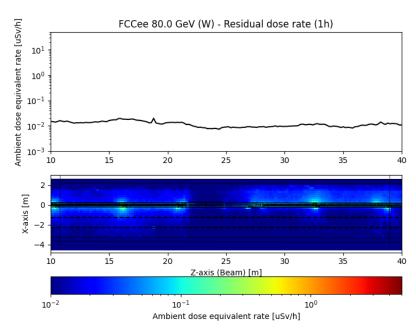


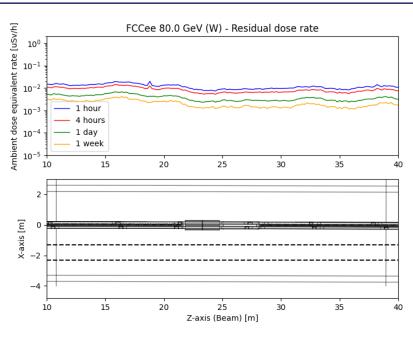




- ☐ The graphs at the top depict the 1D profile of the mean values along z, calculated within the volume enclosed by the dashed lines. This volume represents the most probable occupied space during access, typically at a distance of 1-2 meters from the beam line.
- ☐ The irradiation profile considers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



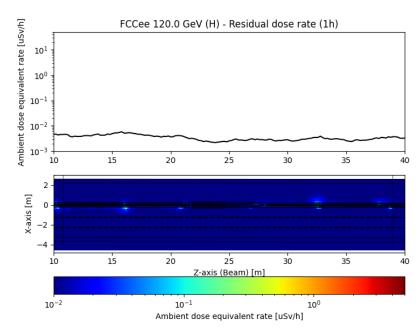


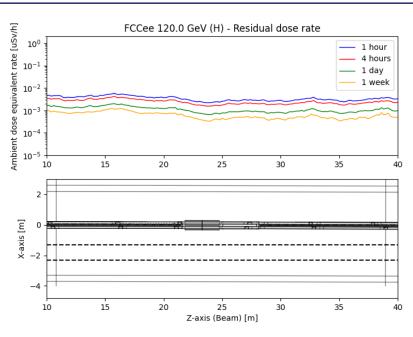


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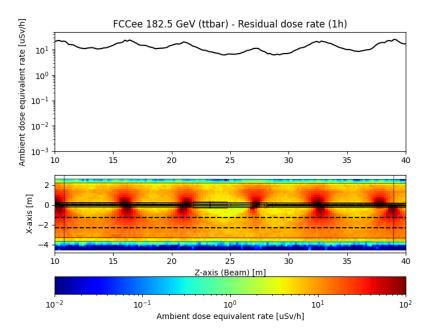
² RESULTS:

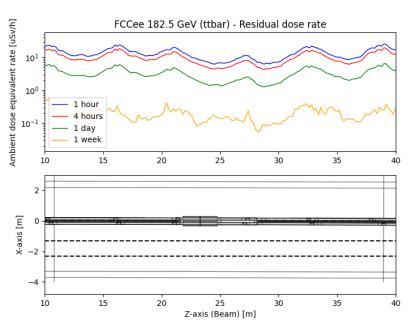




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WASTE STUDY

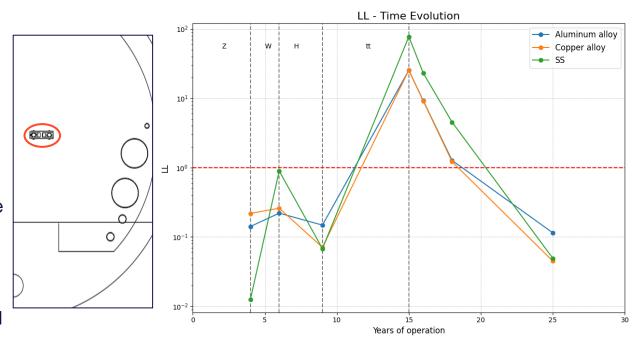
EXEMPLARY ANALYSIS FOR THE MOST COMMON MATERIALS: ALUMINIUM, COPPER AND STAINLESS STEEL

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 ith 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



WASTE STUDY

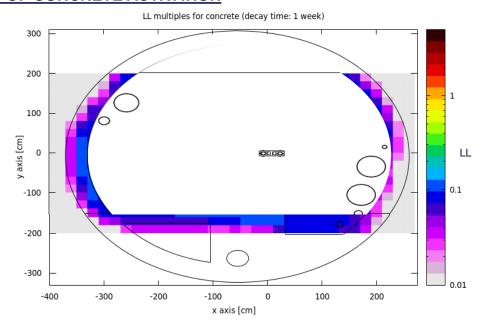
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ANALYSIS OF CONCRETE ACTIVATION



Irradiation profile (ttbar): 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

OPERATIONAL OBJECTIVE

■ External dose:

- Immersion dose: it is advisable to implement a total flushing in ttbar, which takes approximately 3 hours, before entering the tunnel.
- Residual ambient dose equivalent rates (after 1 hour at 1-2 m distance from the beamline):
 - Z: values between 0.1 μSv/h and 1 μSv/h
 no intervent
 - W, H: values below 0.1 μSv/h

- no intervention constraints
- ttbar: relevant residual dose rates after short decay times: from 10 to 20 μSv/h. **Impact on interventions to be considered**.

☐ Internal dose:

• Inhalation dose (Z, W, H, ttbar): values below the guideline value of 1 μSv for 1 hour of access after the beam stop without flushing.



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 mode could lead to emissions of 2.3E+12 Bq/year per release point, not considering any aerosol filtering, while, for Z, W, and H, the releases range from 4.6E+09 to 8.2E+10 Bq/year per release point.
- □ Released activity via water circuits:
 - Not addressed here → water circuit model required
- <u>Materials activation:</u>
 - 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.

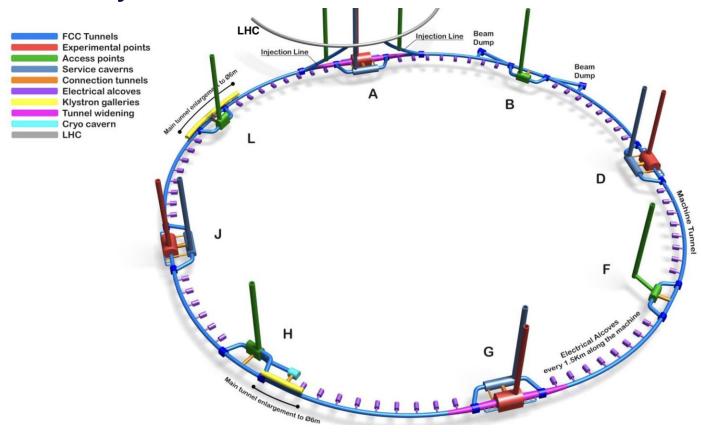




BACK UP SLIDES



FCCee layout





Context & Motivation

Main objectives of the radiological studies for FCCee:

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4 years 2 years 3 years 5 years Z WW ZH 45.6 GeV 1280 mA 80 GeV 135 mA 120 GeV 26.7 mA 182.5 GeV 5 mA



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
Н	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.

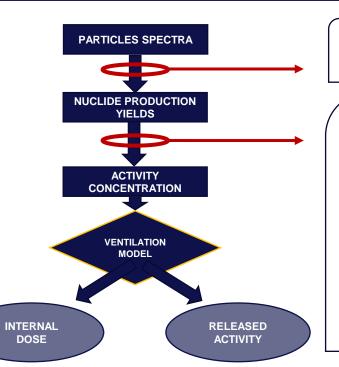


VENTILATION MODEL



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-1] for radionuclide i inside a region j is obtained through the following equation:

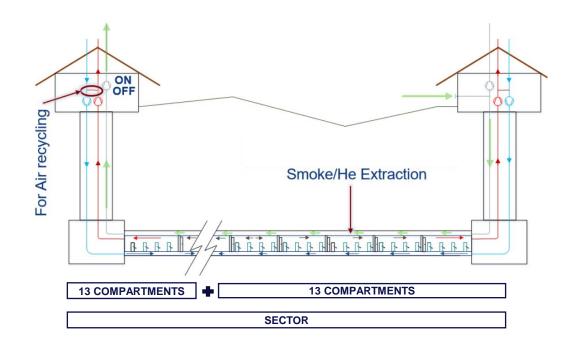
$$S_j^i = N_j^i * I * \rho_{air} * V_j * \lambda_f^i * 1e6$$

- N_i^i : nuclide production yield (of i in j)
- I : beam intensity
- ρ_{air} : air density
- V_i : volume of the region j
- λ_f^i : physical decay constant of the radionuclide i



Ventilation system

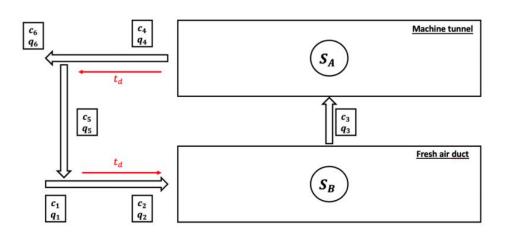
- Each sector of the FCC tunnel consists of 26 compartments, each 440m long. Two ventilation system are placed at opposite ends of the sector tunnel, resulting in 13 compartments served by a single ventilation system.
- ☐ The fresh air is conducted within the fresh air duct and consecutively injected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





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 λ_{ii}

A specific airborne radioactivity model was constructed as a two-box model, with the purpose of describing the ventilation dynamics inside a single compartment.





Time domain

$$\begin{cases} c_1^i(t) = 0 \\ c_2^i(t) = f * c_5^i(t) * e^{-\lambda_p * t_d} \\ \\ \frac{c_3^i(t)}{dt} = \lambda_B^i * c_2^i(t) - \lambda_B^i * c_3^i(t) + \frac{S_B^i}{V_B} \\ \\ \frac{c_4^i(t)}{dt} = \lambda_A^i * c_3^i(t) - \lambda_A^i * c_4^i(t) + \frac{S_A^i}{V_A} \\ \\ c_5^i(t) = c_6^i(t) = c_4^i(t) * e^{-\lambda_p * t_d} \end{cases}$$

These equations describe the activity concentration of a single nuclide while the total activity concentration is determined as the sum of all nuclide contributions.

The terms of the equations are the following:

- c₁(t) the activity concentration at the entrance of the air inlet, before the reinjection of recycled air fraction [\(\frac{B_3}{B_3}\)] (equal to 0).
- c₂(t) the activity concentration before entering the fresh air duct, after injection of the recycled air [^{Bq}/_{im3}].
- c₃(t) the activity concentration at the exit of the fresh air duct, and at the entrance of the machine tunnel [\(\frac{Bq}{m^3}\)].
- c₄(t) the activity concentration at the exit of the machine tunnel [^{Bq}/_{m³}].
- $c_5(t)$ the activity concentration in the recycled air $\left[\frac{Bq}{m^3}\right]$
- c₆(t) the activity concentration of the air injected in the environment [^{Bq}/_{m³}].
- f the fraction of recycled air.
- S_A the generation/source term $\left[\frac{Bq}{s}\right]$ in the machine tunnel (in a single compartment).
- S_B the generation/source term $\left[\frac{Bq}{s}\right]$ in the fresh air duct (in a single compartment).
- λ_p^i is the physical decay constant $[s^{-1}]$ of the nuclide i.
- λⁱ_A is the effective decay constant [s⁻¹] in the machine tunnel volume (in a single compartment), i.e.

$$\lambda_A^i = \lambda_{nh}^i + n_A \tag{5}$$

where n is equal to the air changes per unit time $[s^{-1}]$ (also called ventilation constant) in a proper volume :

$$n_A = \frac{q}{V_A} \tag{6}$$

given the flow rate $q\left[\frac{m^3}{s}\right]$.

 λi_B is the effective decay constant in [s⁻¹] in a fresh air duct compartment, computed with the Equation 12 and 13, using the volume of the fresh air duct (V_B).



Time domain

$$\begin{cases} c_1^i(t) = 0 \\ c_2^i(t) = f * c_5^i(t) * e^{-\lambda_p * t_d} \end{cases}$$

$$\begin{cases} \frac{c_3^i(t)}{dt} = \lambda_B^i * c_2^i(t) - \lambda_B^i * c_3^i(t) + \frac{S_B^i}{V_B} \\ \frac{c_4^i(t)}{dt} = \lambda_A^i * c_3^i(t) - \lambda_A^i * c_4^i(t) + \frac{S_A^i}{V_A} \\ c_5^i(t) = c_6^i(t) = c_4^i(t) * e^{-\lambda_p * t_d} \end{cases}$$

Frequency domain

$$\begin{cases} Y_1^i(s) = 0 \\ Y_2^i(s) = f * Y_5^i(s) * e^{-\lambda_p * t_d} \\ \\ s * Y_3^i(s) = \lambda_B^i * Y_2^i(s) - \lambda_B^i * Y_3^i(s) + \frac{S_B^i}{V_B} * \frac{1}{s} \\ \\ s * Y_4^i(s) = \lambda_A^i * Y_3^i(s) - \lambda_A^i * Y_4^i(s) + \frac{S_A^i}{V_A} * \frac{1}{s} \\ \\ Y_5^i(s) = Y_6^i(s) = Y_4^i(s) * e^{-\lambda_p * t_d} \end{cases}$$



7.3.2 Beam operation scenario - Transverse layout

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. $S_A \neq 0$ and $S_B \neq 0$. The activity concentration as a function of time for a generic nuclide i is described by Equation 8. The index ω refers to the beam operation scenario.

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

where

•
$$Q = \frac{S_A^i}{V_A}$$

•
$$W = \left(\frac{S_A^i}{V_A} * \lambda_B^i\right) + \left(\frac{S_B^i}{V_B} * \lambda_A^i\right)$$

$$\bullet \ \ R,T=\frac{-(\lambda_A^i+\lambda_B^i)\pm\sqrt{\Delta}}{2} \text{ with } \Delta=(\lambda_A^i+\lambda_B^i)^2-4*[(\lambda_A^i*\lambda_B^i)-(f*e^{-2\lambda_{ph}^it_d}*\lambda_A^i*\lambda_B^i)]$$

Equation 8 results in a sum of exponential terms, with R and T inherently being negative due to mathematical construction. From Equation 8 one can compute the saturation value for a generic nuclide *i* inside the machine tunnel:

$$c_4^{i,sat} = \lim_{t \to +\infty} c_{4,\omega}^i(t) = \frac{W}{R * T}$$
 (9)

7.3.3 Beam stop scenario - Transverse layout

The representative solutions of the ventilation conditions during beam stop is computed starting from the actual activity concentrations at the moment of the beam stop $(c^{i,start})$, and by considering two null source terms, i.e. $S_A=0$ and $S_B=0$. The activity concentration in time for a generic nuclide i is described by Equation 10. The index δ refers to the beam stop scenario.

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

$$(10)$$

where

•
$$Q = c_4^{i,start}$$

•
$$W = (\lambda_B * c_4^{i,start}) + (\lambda_A^i * c_3^{i,start})$$

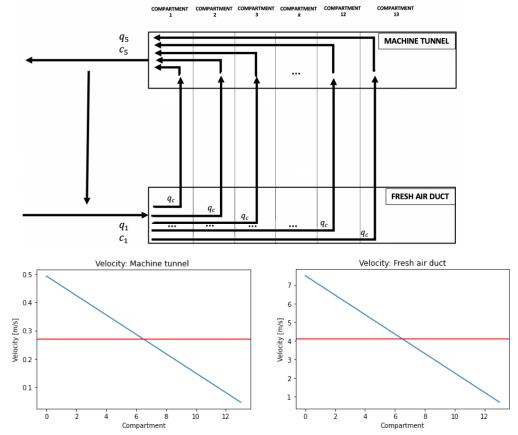
$$\bullet \ \ R,T=\frac{-(\lambda_A^i+\lambda_B^i)\pm\sqrt{\Delta}}{2} \text{ with } \Delta=(\lambda_A^i+\lambda_B^i)^2-4*[(\lambda_A^i*\lambda_B^i)-(f*e^{-2\lambda_{ph}^it_d}*\lambda_A^i*\lambda_B^i)]$$

Here, too, R and T are inherently negative because of the mathematical construction.



Ventilation system model

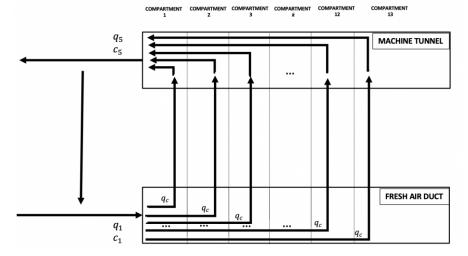
- ☐ Since the whole flow rate is progressively injected into the machine tunnel, the initial flow rate is split into 14 'sub-flows' (one for each compartment).
- □ For instance, the first subflow will enter the fresh air duct, run one compartment length, and be injected at the end of the machine tunnel's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

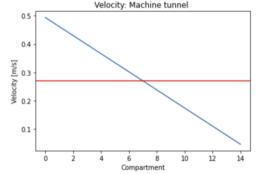


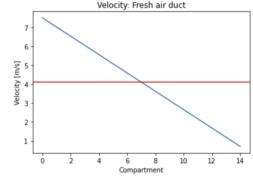


Ventilation system model

- 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 t₁₂ and t₄₅ will not be constants).









Ventilation system

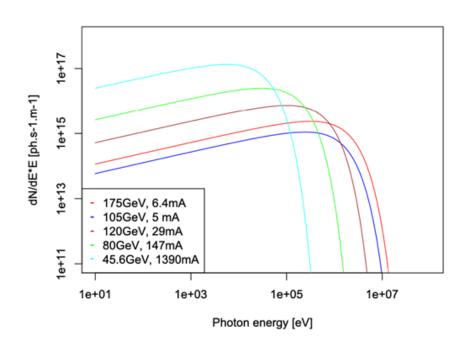
Parameter	Variable	Value	
Number of compartment per sector	num_c	28	-
Compartment length	1	400 m	
Mass flow rate	m	27000 $\frac{m^3}{h}$	
Compartment cross section (machine tunnel)	A_A	$15.2 \ m^2$	
Compartment cross section (fresh air duct)	A_B	$1 m^2$	
Volume of the machine tunnel per compartment	V_B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

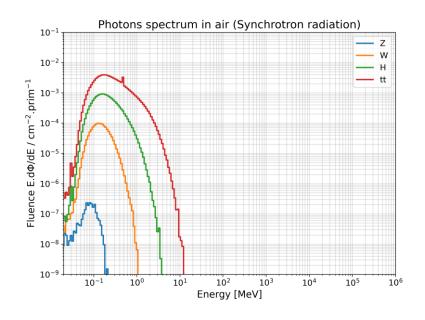


PARTICLE SPECTRA



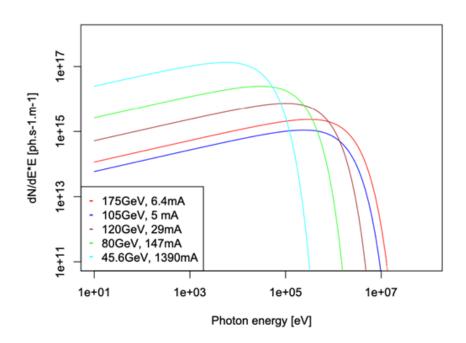
Synchrotron radiation - Spectra







Synchrotron radiation - Spectra



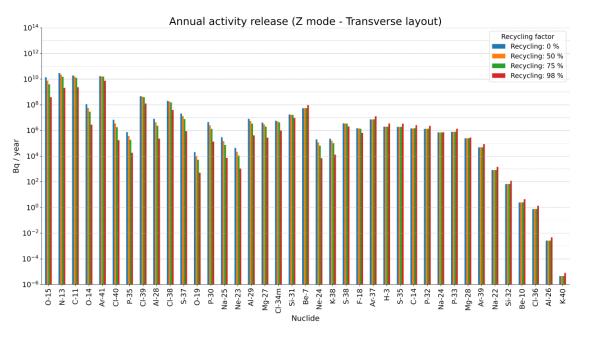
E [GeV]	I [mA]	E _c [keV]	Flux [ph/sec]	~ Fraction > 7 MeV	Flux > 7 MeV [ph/sec]
182.5	5.4	1254	8.0e+20	3.8e-03	3.0e+18
175	6.4	1105	9.0e+20	1.8e-03	1.6e+18
120	29	356	2.8e+21	3.0e-09	8.4e+12
105 (LEP)	5	849	4.2e+20	2.6e-04	1.1e+17
80	147	106	9.5e+21	1.7e-29	1.6e-07
45.6	1390	20	5.1e+22	4.7e-156	2.4e-133



ANNUAL ACTIVITY RELEASES



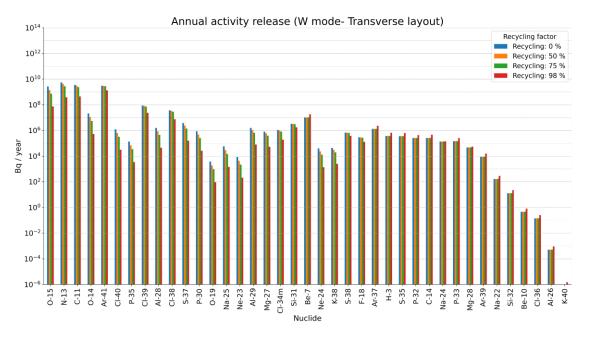
Annual activity release – Z mode



Annual activity release per isotope and per release point from two half-sectors during Z mode for 4 different recycling factors, considering 180 days of annual operation with a complete flushing conducted after every 30 days of operation. The values are calculated taking into account the dynamics of the transverse ventilation system. The emissions account for releases occurring during the running period plus 6 flushing cycles, excluding any filtering of aerosol-bound nuclides.



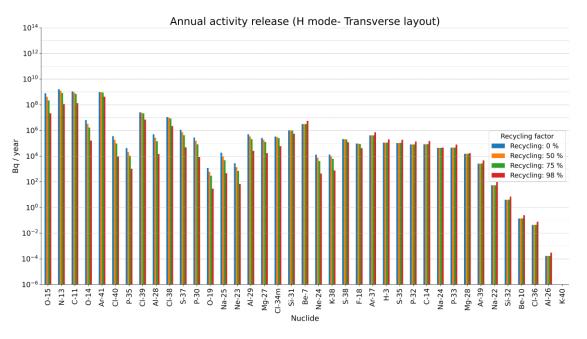
Annual activity release – W mode



Annual activity release per isotope and per release point from two half-sectors during W mode for 4 different recycling factors, considering 180 days of annual operation with a complete flushing conducted after every 30 days of operation. The values are calculated taking into account the dynamics of the transverse ventilation system. The emissions account for releases occurring during the running period plus 6 flushing cycles, excluding any filtering of aerosol-bound nuclides.



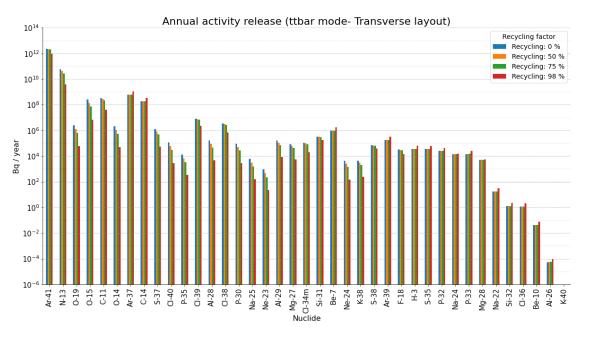
Annual activity release – H mode



Annual activity release per isotope and per release point from two half-sectors during H mode for 4 different recycling factors, considering 180 days of annual operation with a complete flushing conducted after every 30 days of operation. The values are calculated taking into account the dynamics of the transverse ventilation system. The emissions account for releases occurring during the running period plus 6 flushing cycles, excluding any filtering of aerosol-bound nuclides.



Annual activity release – ttbar mode



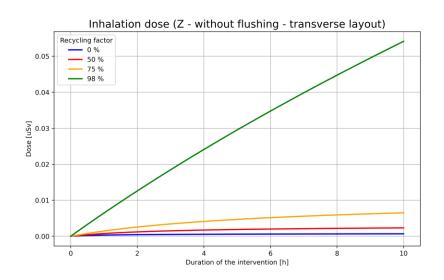
Annual activity release per isotope and per release point from two half-sectors during ttbar mode for 4 different recycling factors, considering 180 days of annual operation with a complete flushing conducted after every 30 days of operation. The values are calculated taking into account the dynamics of the transverse ventilation system. The emissions account for releases occurring during the running period plus 6 flushing cycles, excluding any filtering of aerosol-bound nuclides.

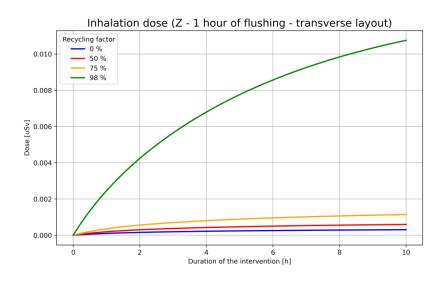


INHALATION DOSE



Inhalation dose – Z mode

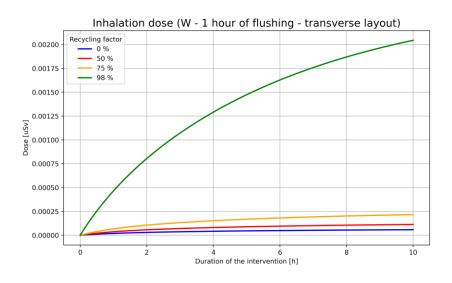






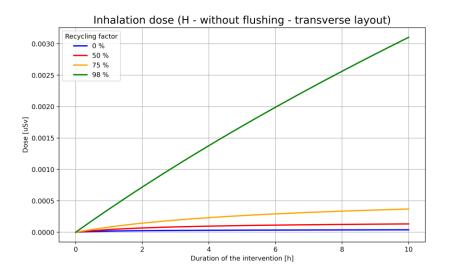
Inhalation dose – W mode

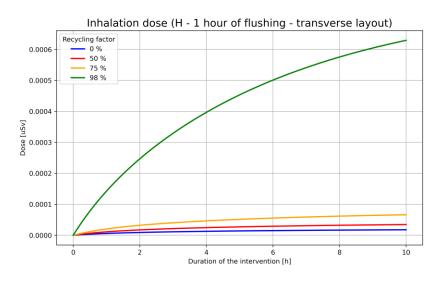






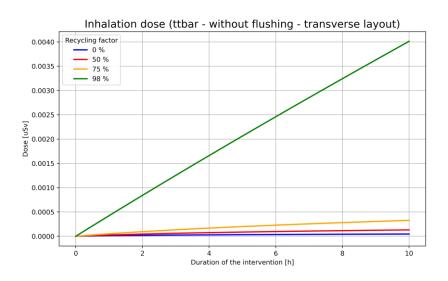
Inhalation dose – H mode

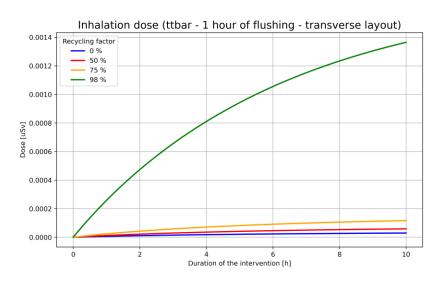






Inhalation dose – ttbar mode





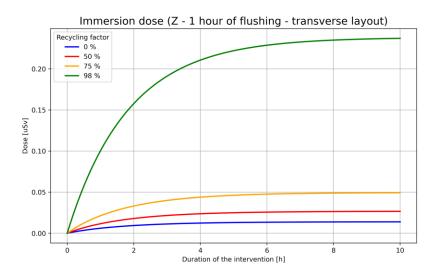


IMMERSION DOSE



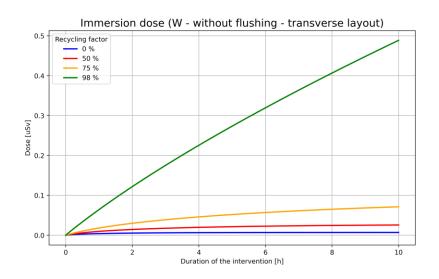
Immersion dose – Z mode

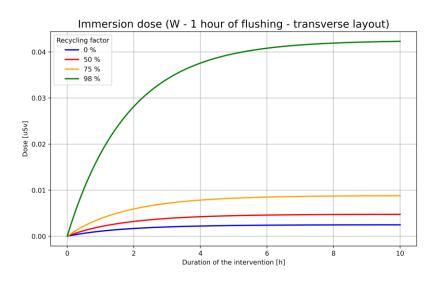






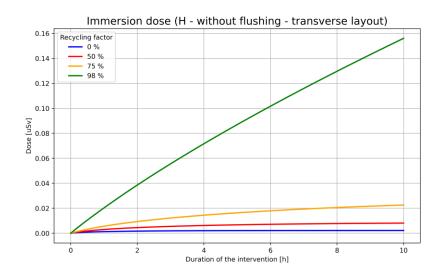
Immersion dose – W mode

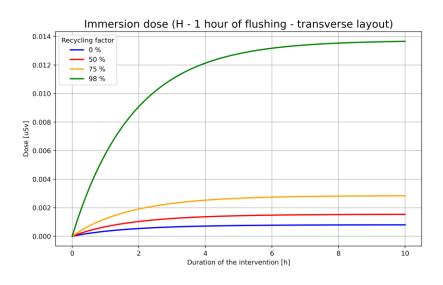






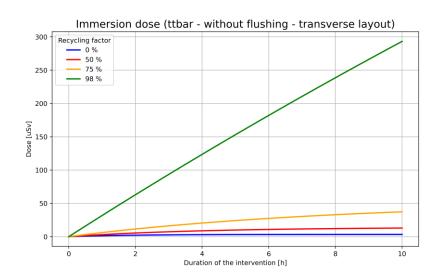
Immersion dose – H mode

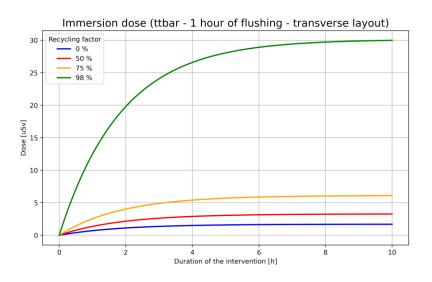






Immersion dose – ttbar mode







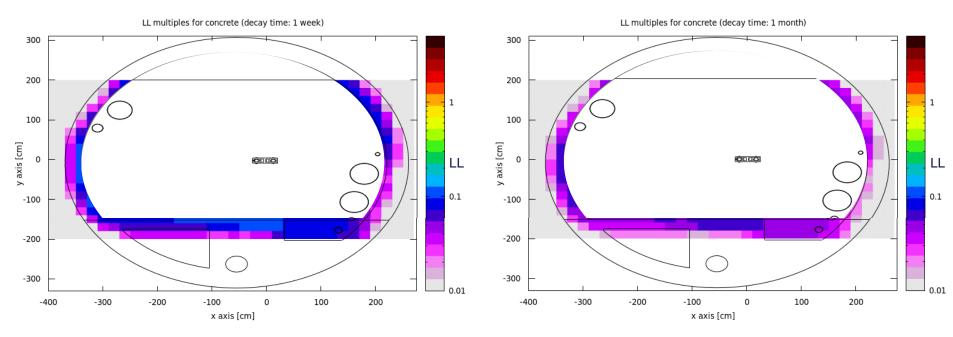
ANALYSIS OF CONCRETE ACTIVATION – ttbar

(After the full operation period)



ANALYSIS OF CONCRETE ACTIVATION – ttbar

(After the full operation period)



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

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

LL

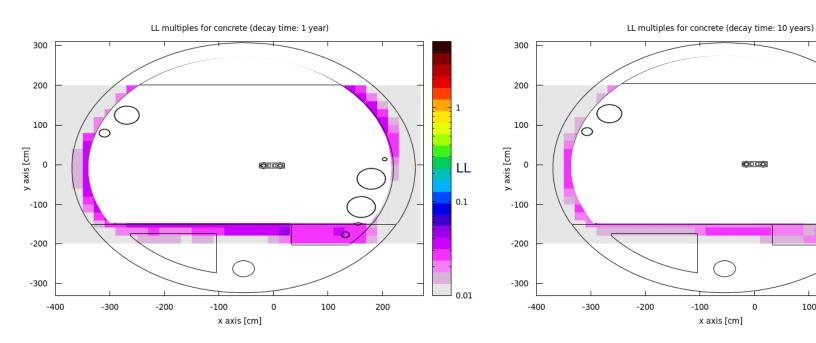
0.1

0.01



ANALYSIS OF CONCRETE ACTIVATION – ttbar

(After the full operation period)



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

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

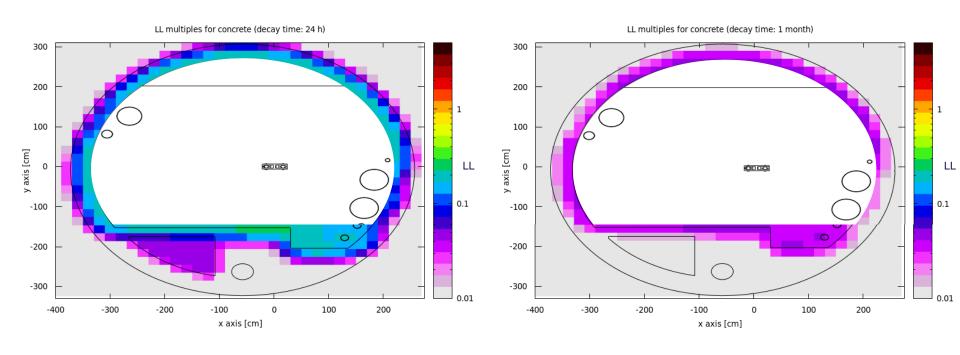
100

200



ANALYSIS OF CONCRETE ACTIVATION – ttbar

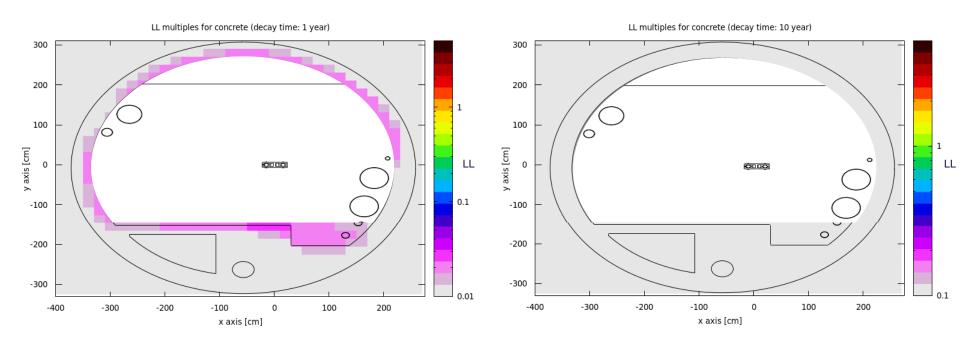
(After 1 year of operation)





ANALYSIS OF CONCRETE ACTIVATION – ttbar

(After 1 year of operation)





RESIDUAL DOSE RATES

(ttbar - 182.5 GeV, 1 year of operation)

FCC

Residual dose rate (profile XY plane) ttbar -> 1 year of operation

