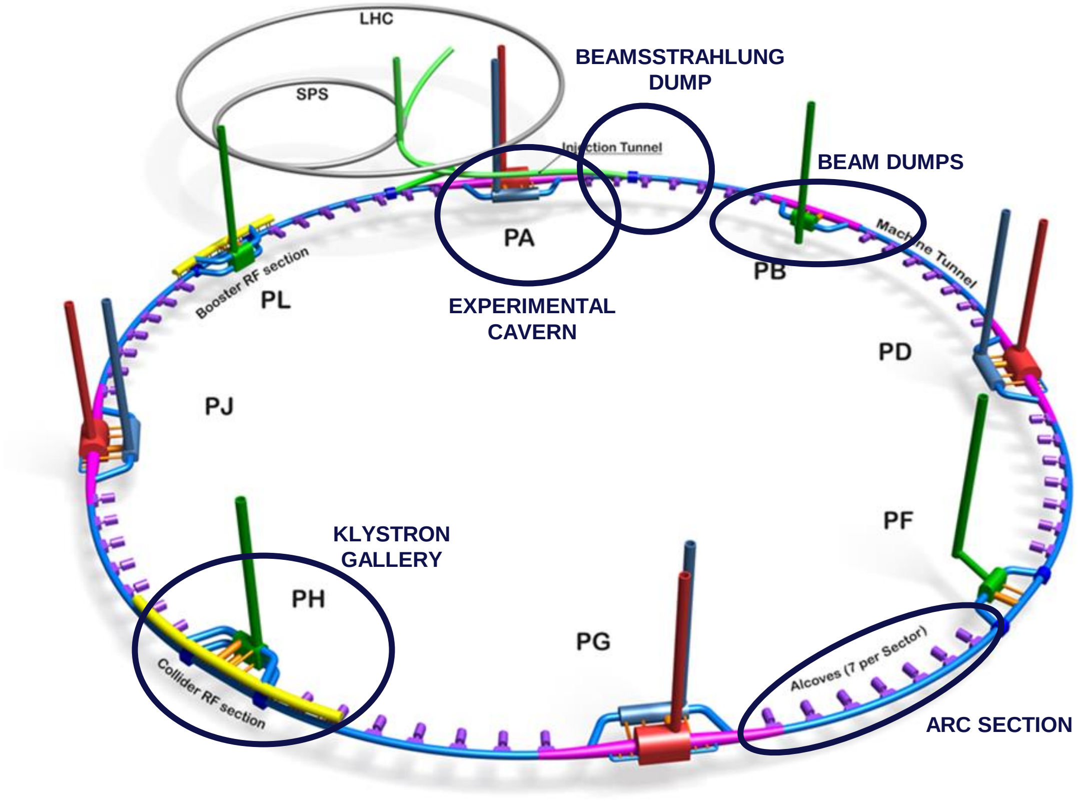
RADIOLOGICAL STUDIES FOR FCCee

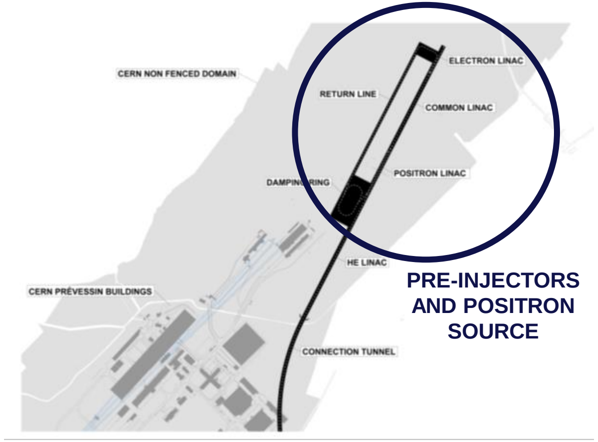
Giacomo Lavezzari, Markus Widorski, Pavol Vojtyla, Yousef Husein - CERN HSE-RP

FCC Week 2024, San Francisco

EDMS 3061156

Introduction





Radiological hazards overview

1. Prompt radiation levels in accessible areas:

- Experimental cavern <-> Service cavern
- Experimental cavern <-> Surface building
- RF straight section <-> Klystron galleries
- Injector complex <-> Surface/klystron building
- Accelerator tunnel <-> RF straight section
- Accelerator tunnel <-> Service cavern

2. Residual radiation levels :

- Arcs
- Main beam dumps
- Beamstrahlung dumps
- Positron source
- Collimators
- Injector complex
- Experiments

3. Activation:

- Rock/earth layer
- Tunnel infrastructure (cables, pipes, ducts..)
- Accelerator materials:
  - Arc
  - Collimation systems
  - Dispersion suppressors
  - Masks/collimators
- Equipment inside alcoves
- Water (arc)
- Air :
  - Arc
  - Beam dumps
  - Beamstrahlung dumps
  - RF section
  - Experiments
  - Injector complex
- Cryogenics

Radiological hazards overview

1. Prompt radiation levels in accessible areas:

- Experimental cavern <-> Service cavern
- Experimental cavern <-> Surface building
- RF straight section <-> Klystron galleries
- Injector complex <-> Surface/klystron building
- Accelerator tunnel <-> RF straight section
- Accelerator tunnel <-> Service cavern

2. Residual radiation levels :

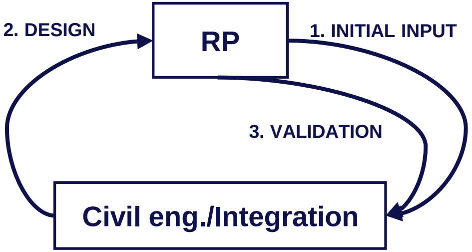
- Arcs
- Main beam dumps
- Beamstrahlung dumps
- Positron source
- Collimators
- Injector complex
- Experiments

3. Activation:

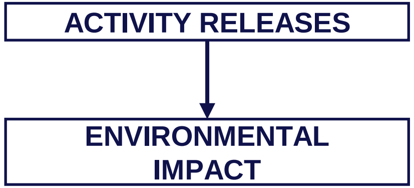
- Rock/earth layer
- Tunnel infrastructure (cables, pipes, ducts..)
- Accelerator materials:
  - Arc
  - Collimation systems
  - Dispersion suppressors
  - Masks/collimators
- Equipment inside alcoves
- Water (arc)
- Air:
  - Arc
  - Beam dumps
  - Beamstrahlung dumps
  - RF section
  - Experiments
  - Injector complex
- Cryogenics

Operational objective

(Area accessibility, layout/design for FCCee and FCChh)



Environmental objective



Tasks planned out within the feasibility study
Tasks scheduled for after the feasibility study

Radiological hazards overview

1. Prompt radiation levels in accessible areas:

- Experimental cavern <-> Service cavern
- Experimental cavern <-> Surface building
- RF straight section <-> Klystron galleries
- Injector complex <-> Surface/klystron building
- Accelerator tunnel <-> RF straight section
- Accelerator tunnel <-> Service cavern

2. Residual radiation levels :

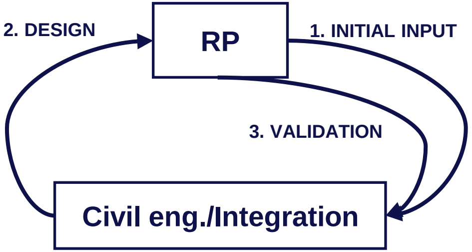
- Arcs
- Main beam dumps
- Beamstrahlung dumps
- Positron source
- Collimators
- Injector complex
- Experiments

3. Activation:

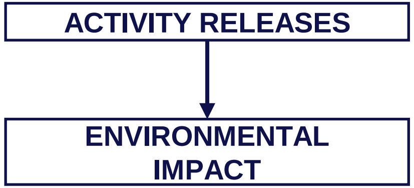
- Rock/earth layer
- Tunnel infrastructure (cables, pipes, ducts..)
- Accelerator materials:
  - Arc
  - Collimation systems
  - Dispersion suppressors
  - Masks/collimators
- Equipment inside alcoves
- Water (arc)
- Air:
  - Arc
  - Beam dumps
  - Beamstrahlung dumps
  - RF section
  - Experiments
  - Injector complex
- Cryogenics

Operational objective

(Area accessibility, layout/design for FCCee and FCChh)



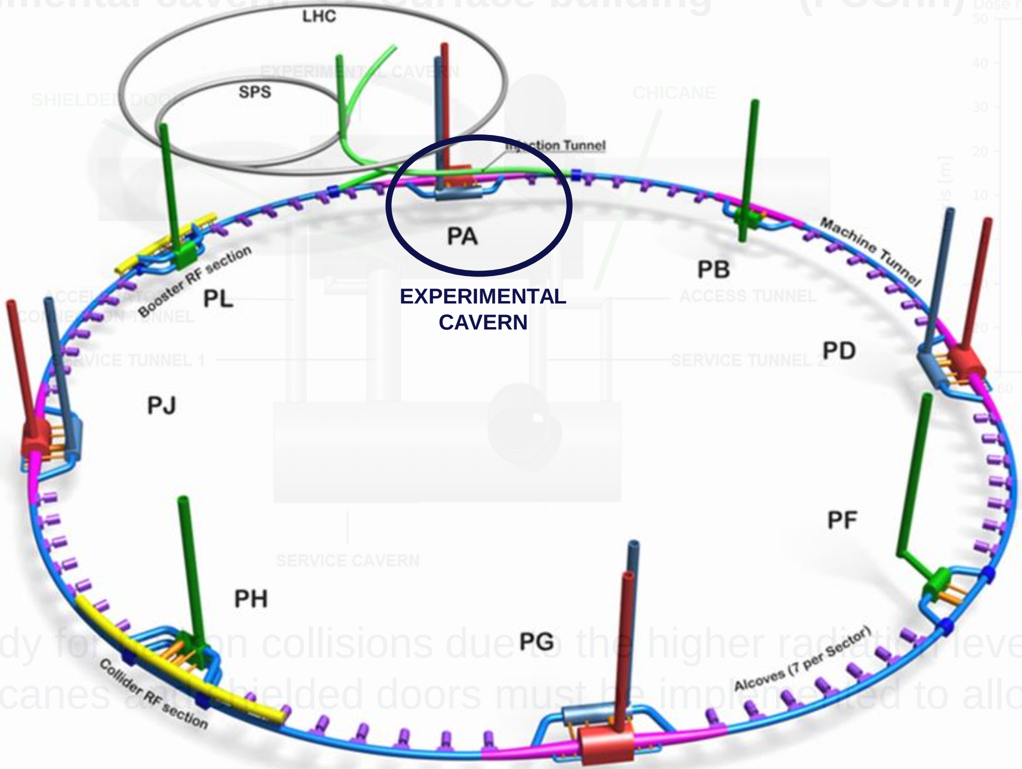
Environmental objective

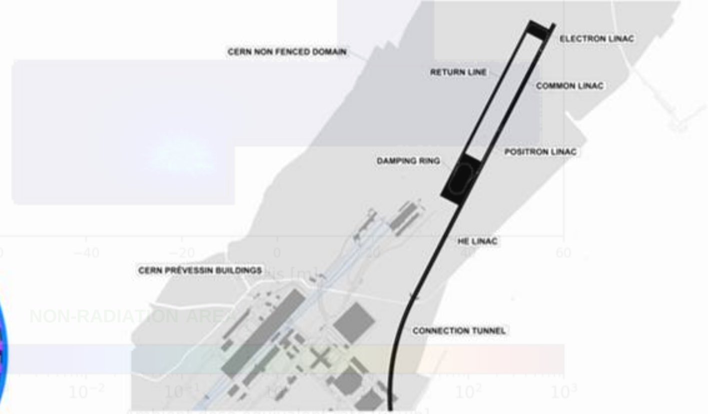


Prompt radiation studies

Prompt radiation levels in accessible areas

Experimental cavern <-> Surface building (FCChh)



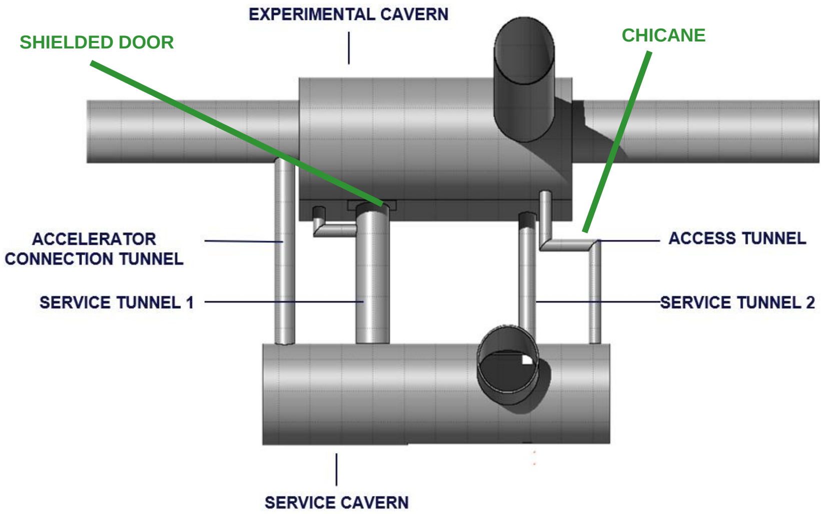


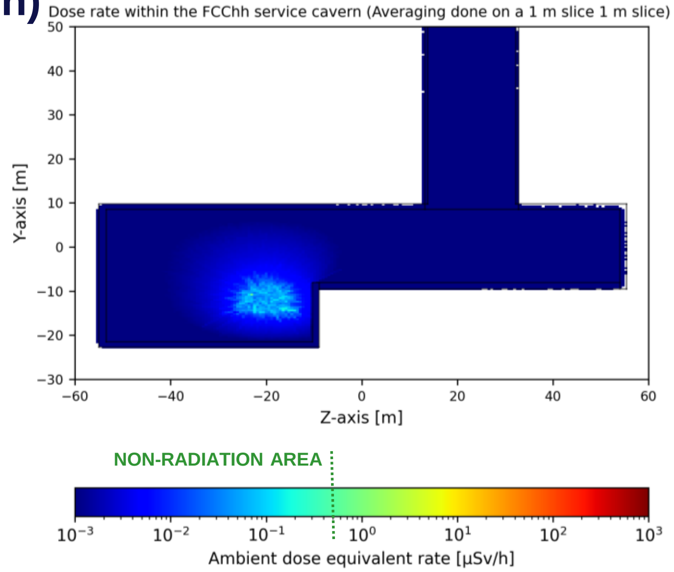
- Study for [illegible] collisions due to the higher radiation levels compared to e^-e^+.
- Chicanes and shielded doors must be implemented to allow access to the service cavern.

The design shall ensure access to the service cavern during beam operation in FCCee+hh.

Prompt radiation levels in accessible areas

Experimental cavern <-> Surface building (FCChh)



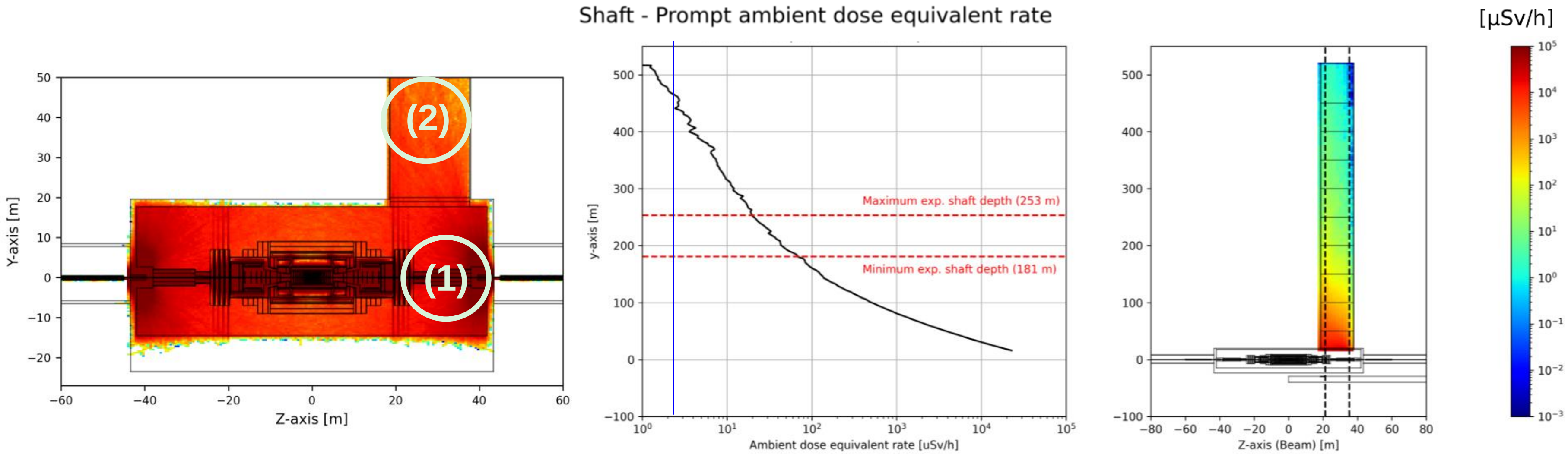


- Study for hadron collisions due to the higher radiation levels compared to e^-e^+.
- Chicanes and shielded doors must be implemented to allow access to the service cavern.

<u>The design shall ensure access to the service cavern during beam operation in FCCee+hh.</u>

Prompt radiation levels in accessible areas

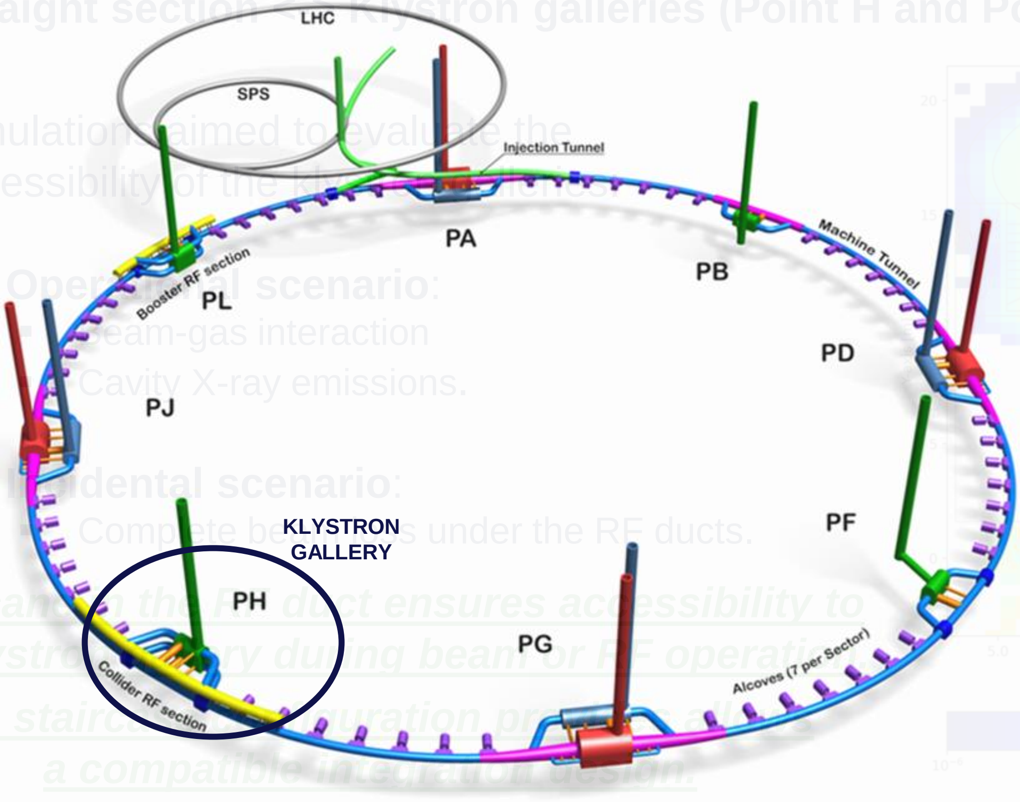
Experimental cavern <-> Surface building (FCChh)

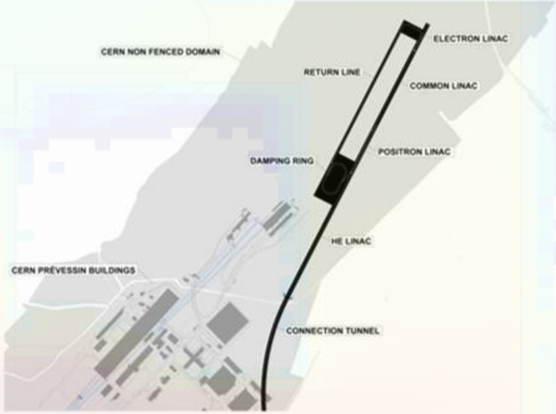


➢ Prompt radiation from the experimental cavern can reach the surface via the shaft.

(1) Shielding to be improved at the machine-detector-interface
(2) Installation of 1m concrete shielding at the top of the shaft

Prompt radiation levels in accessible areas

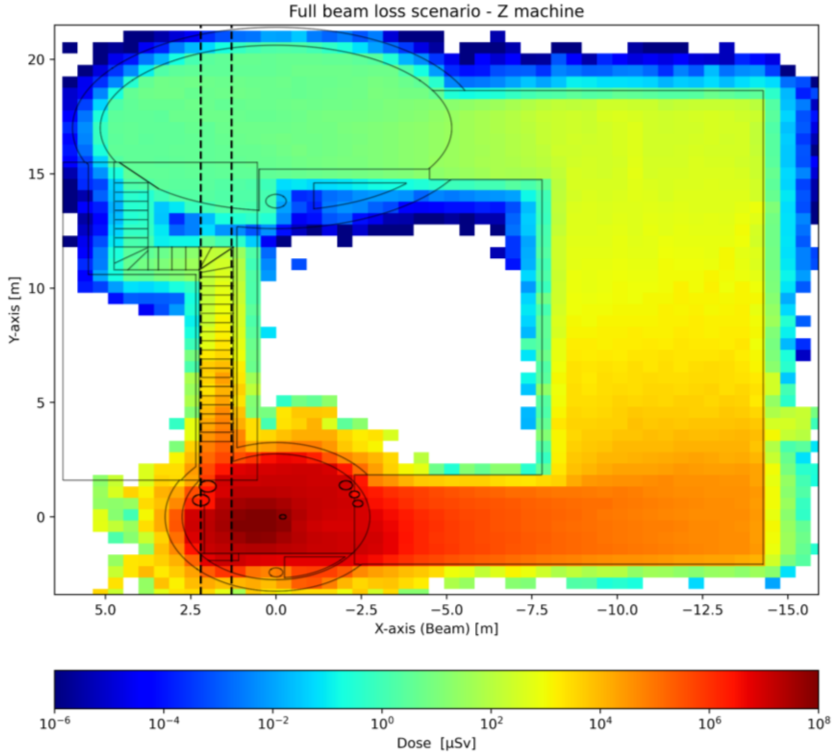




Prompt radiation levels in accessible areas

RF straight section <-> Klystron galleries (Point H and Point L)

- Simulations aimed to evaluate the accessibility of the klystron galleries:
  - **Operational scenario**:
    - Beam-gas interaction
    - Cavity X-ray emissions.
  - **Incidental scenario**:
    - Complete beam loss under the RF ducts.

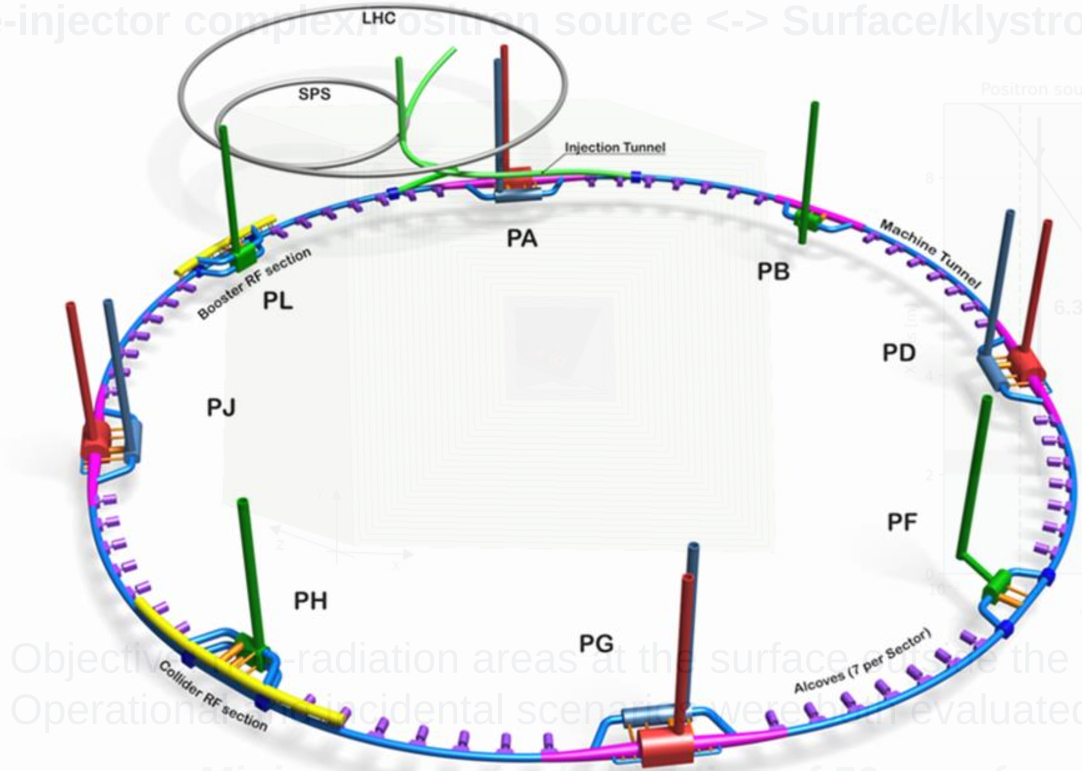


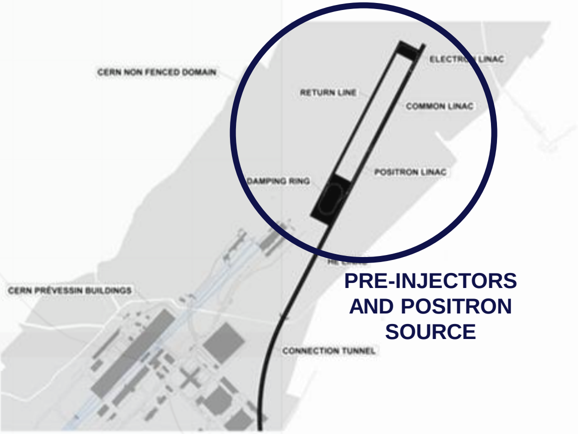
A chicane in the RF duct ensures accessibility to the klystron gallery during beam or RF operation.

The staircase configuration provides allows a compatible integration design.

Prompt radiation levels in accessible areas

Pre-injector complex/positron source <-> Surface/klystron building



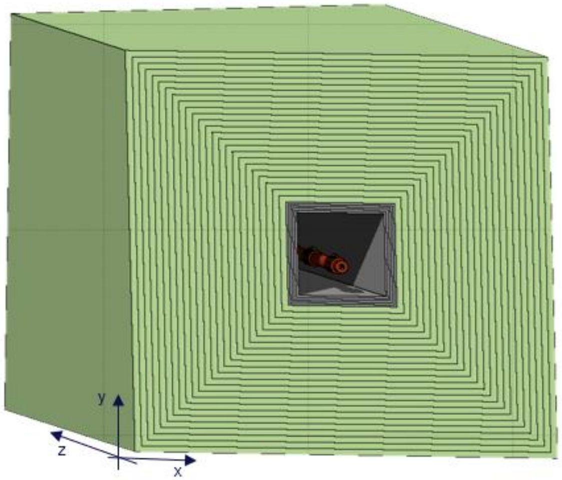


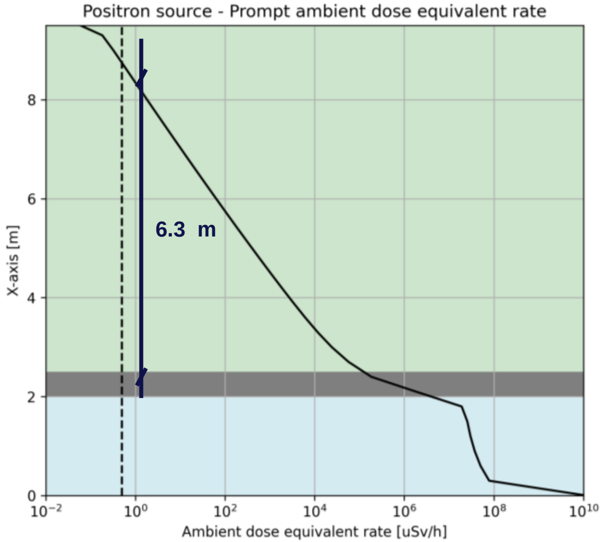
- Objective … -radiation areas at the surface outside the accelerator installation.
- Operational … incidental scenarios were both evaluated.

Minimum required shielding of 50 cm of concrete and 6.3 m of soil

Prompt radiation levels in accessible areas

Pre-injector complex/Positron source <-> Surface/klystron building



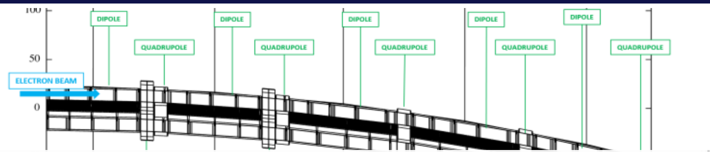


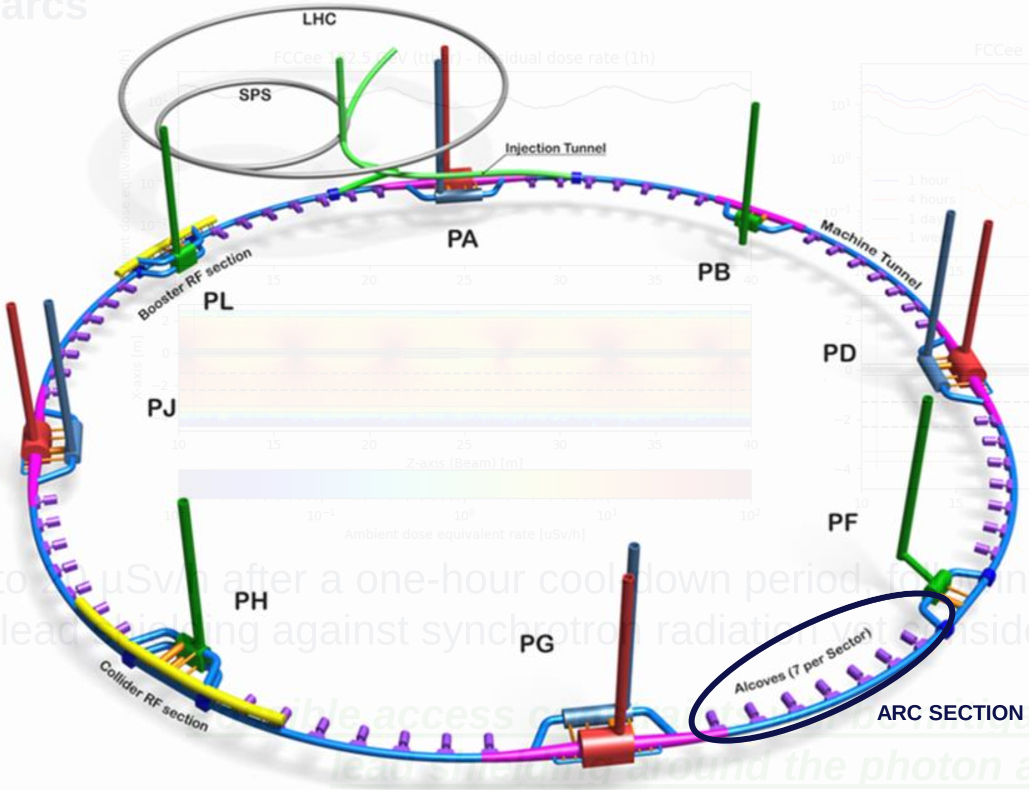
- Objective: non-radiation areas at the surface outside the accelerator installation.
- Operational and incidental scenarios were both evaluated.

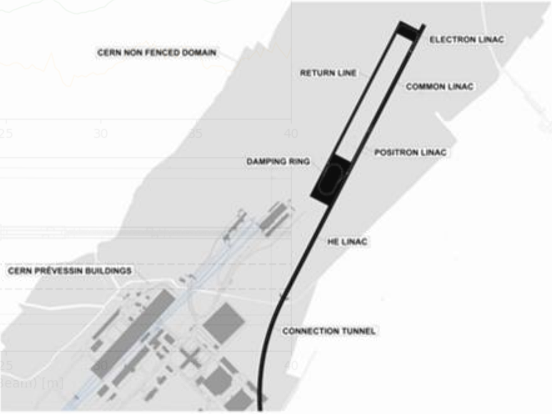
Minimum required shielding of 50 cm of concrete and 6.3 m of soil

Residual radiation studies

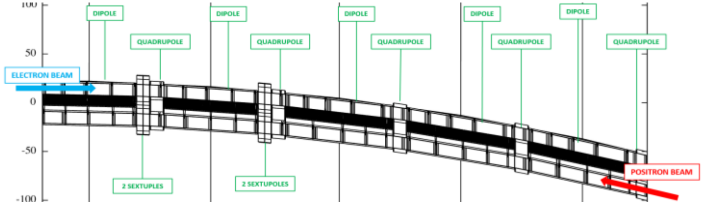
Residual dose rate



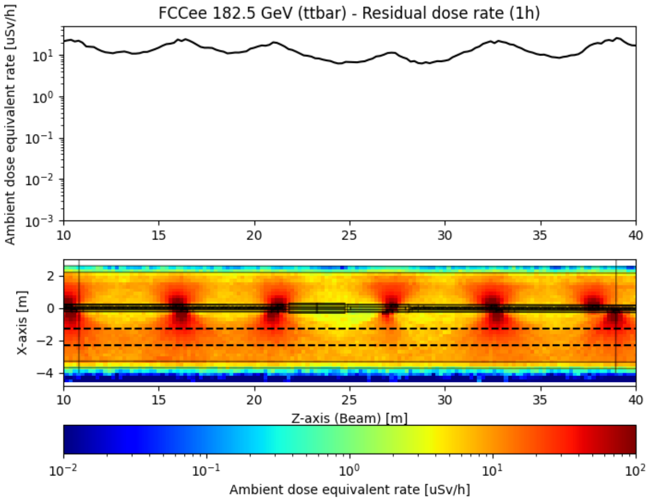


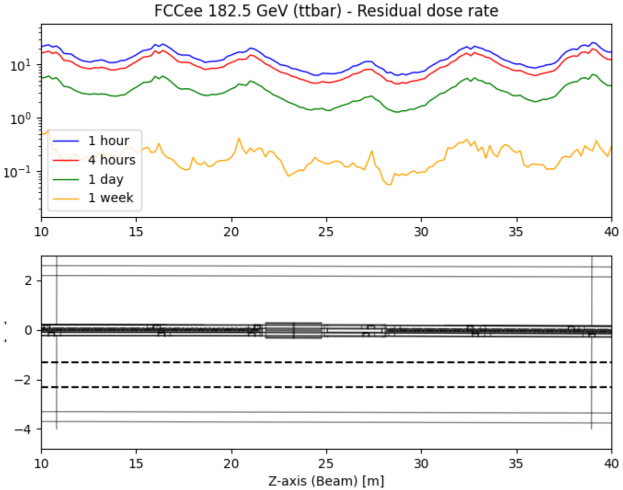


Residual dose rate



In the arcs





- 10 to 20 µSv/h after a one-hour cool-down period, following one year of ttbar operation .
- No lead shielding against synchrotron radiation yet considered in this version.

Possible access constraints will be mitigated by additional lead shielding around the photon absorbers.

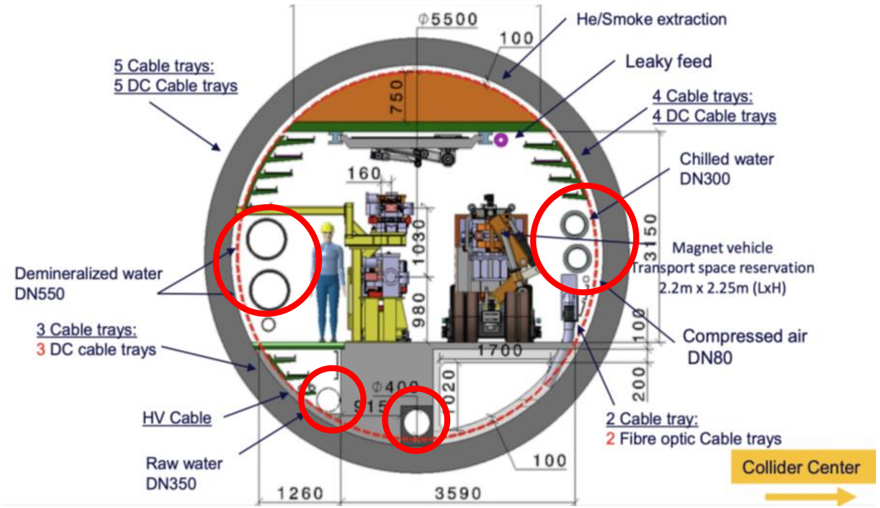
Activation studies

Air activation *(Preliminary radiological environmental impact assessment for FCCee)*

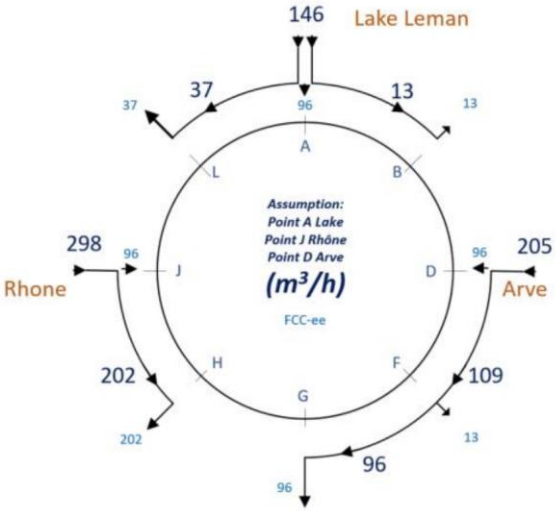
- **Quantity**: Annual effective dose to the Representative Person from the public.
- **Input**: Activity releases through air from the FCCee arc in ttbar operation (highest releases, no recycling, no filtration).
- **Expected annual effective doses for a generic exposure configuration:**
  - 2.3 TBq/y of ^{41}Ar: **0.1 µSv/y**
  - 60 kBq/y of ^{32}P: 5.8×10^{-6} µSv/y
- 0.1 µSv/y is 100 times below the threshold value of 10 µSv/y, below which further optimization is not required.

No relevant environmental impact expected from air releases from FCCee arcs.

Water activation



RAW WATER SUPPLY

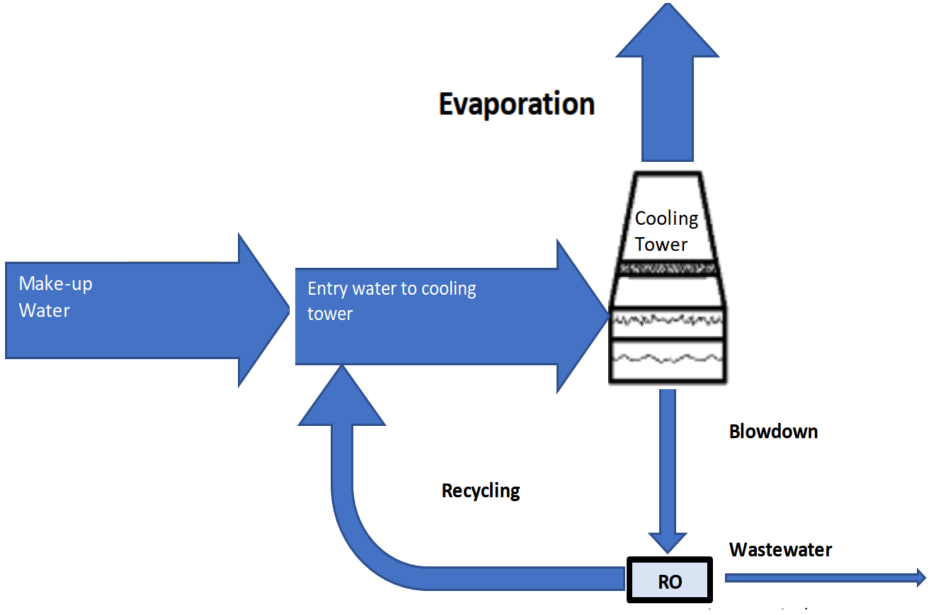


- Four water circuits pass through the arcs:
  - **Demineralized water & Chilled water**
    closed circuits; potential activation
  - **Drain water & Raw water**
    open circuits; low activation as the pipes are placed under the floor

- **Raw water** provided at points PA, PD, and PJ and transported to the surface of all other locations via the arc tunnel for use by surface facilities.

Water activation

- **The raw water** is used as makeup water.
- **Objective**:
  - Determine the amount of activity released into the environment per year through evaporation.
- **Conservative assumptions:**
  - All nuclides released via water vapour.
  - Activation considered as if the pipe was not under the floor but next to the line (such as the demineralized water circuit)



<u>Activity releases by raw water evaporation would be significantly lower than those from air activation in the arc.</u>

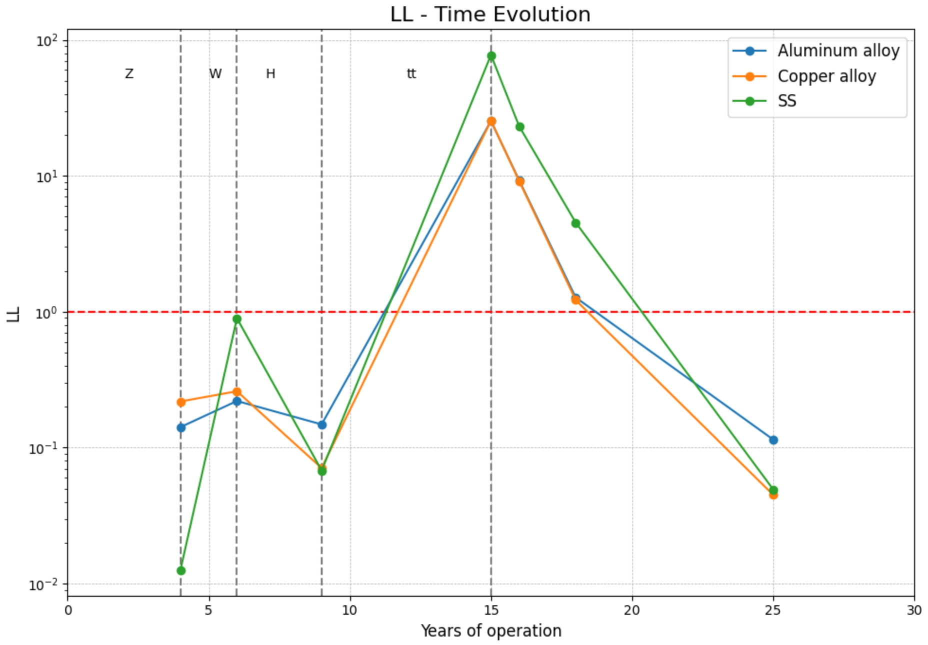
Accelerator material activation

High volume accelerator materials

- Excessive costs for elimination for the high-volume components, when activation is above limits.

- Preliminary studies indicate potentially relevant activation during ttbar operation (from synchrotron radiation).

- Further detailed studies in progress on:
  - CuCrZr (used for the photon absorber)
  - CuOFE (vacuum chamber material),
  - Lead shielding (for photon absorbers) of different material quality.



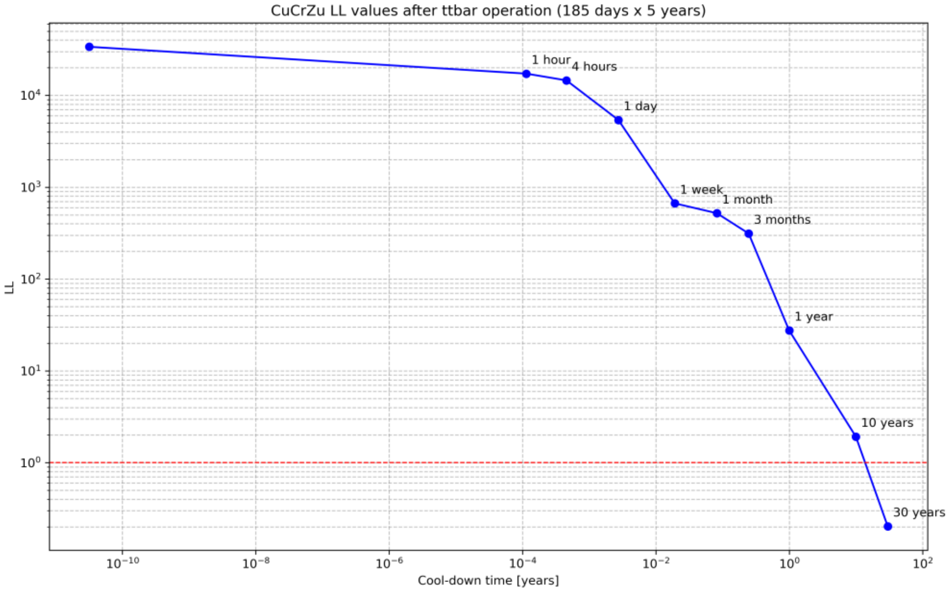
Accelerator material activation

High volume accelerator materials

- Excessive costs for elimination for the high-volume components,
  when activation is above limits.

- Preliminary studies indicate potentially relevant activation during ttbar operation (from synchrotron radiation).

- Further detailed studies in progress on:
  - CuCrZr (used for the photon absorber)
  - CuOFE (vacuum chamber material),
  - Lead shielding (for photon absorbers) of different material quality.



Select materials that can be considered as non-radioactive after a "short" decay time.

Conclusions

1

FCCee Scenarios

FCChh Scenarios

Provide input to the civil engineering and integration teams

Validation and optimisation of proposed design

2

Preliminary environmental study (releases by air from the FCCee arc)

Integrate further sources of air activation (dumps, straight sections, caverns)

3

High-volume material activation study for the FCCee life time

Material selection

Radioactive waste production assessment

THANK YOU FOR YOUR ATTENTION !

BACK UP SLIDES

Dose (rate) limits and reference levels

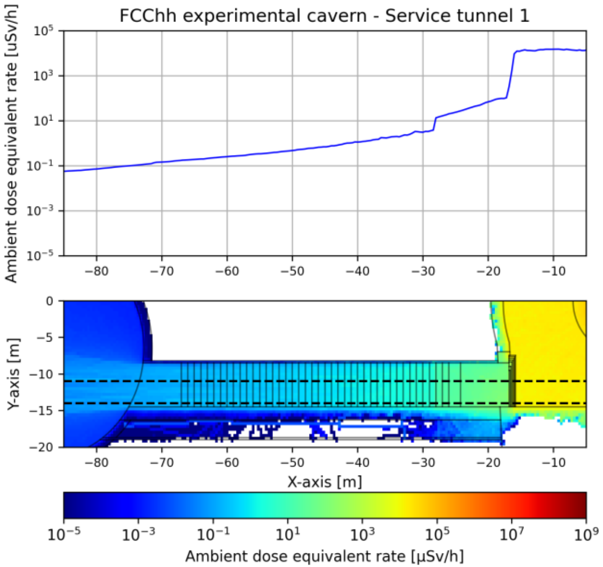
Location	On site					
Population	Non-classified workers	Radiation workers				-
Area classification	Non-designated	Supervised	Simple	Limited Stay	High Radiation	Exclusion Zone
Effective dose from direct radiation, air and water (total), nominal operation	100 µSv/a [1] (1 mSv/a [1])	6 mSv [1] in 12 months	20 mSv [1] in 12 months	20 mSv [1] in 12 months	20 mSv [1] in 12 months	20 mSv
Effective dose per incident event (event probability < 0.01 per year)	100 µSv [1] (1d mSv/a)	6 mSv [1]	6 mSv (20 mSv [1])	6 mSv (20 mSv [1])	6 mSv (20 mSv [1])	20 mSv
Effective dose from airborne radioactivity (inhalation/immersion)	1 mSv/a [2] (or 0.05 CA)	1 µSv in 1 h 3 µSv in 1 h	1 µSv in 1 h 10 µSv in 1 h	1 µSv in 1 h 10 µSv in 1 h	1 µSv in 1 h 10 µSv in 1 h	-
Ambient dose equivalent rate, nominal operation, permanent stay area	0.5 µSv/h [3] (1 mSv/a [1])	3 µSv/h [3] (6 mSv/a [1])	10 µSv/h [3] (20 mSv/a [1])	-	-	10 µSv/h
Ambient dose, nominal operation, equivalent rate low occupancy area	2.5 µSv/h [3]	15 µSv/h [3]	50 µSv/h [3]	2 mSv/h [3]	100 mSv/h [3]	50 µSv/h
Intervention related maximum individual personal dose equivalent	-	2 mSv (per intervention) 3 mSv (per shutdown)	-	-	-	-
Area related upper limit for surface contamination	< 1 CS	< 1 CS	< 1 CS	< 1 CS	< 1 CS	-

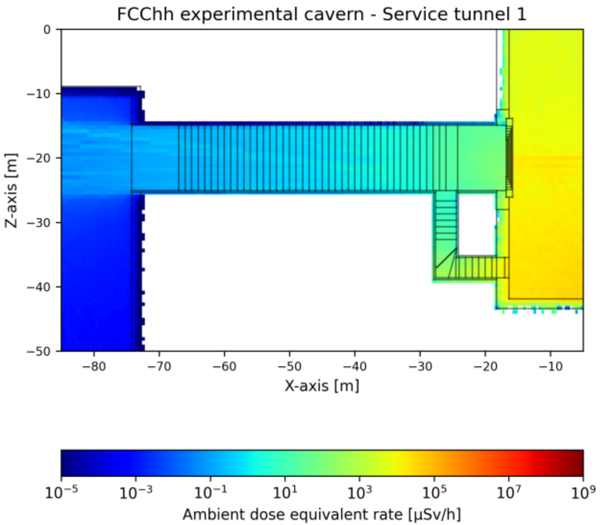
Dose (rate) limits and reference levels

Location	Off-site	On-site	
Population	General public (8670 h/a)	Public visit (1h)	Prof. visit (8h)
Area classification	Non-designated	-	-
Effective dose from direct radiation, air and water (total), nominal operation	10 μSv/a [1] (300 μSv/a [1])	10 μSv [4]	100 μSv [4]
Effective dose per incident event (event probability $<$ 0.01 per year)	1 mSv	10 μSv [4]	100 μSv [4]
Effective dose from airborne radioactivity (inhalation and immersion)	-	-	-
Ambient dose equivalent rate nominal operation, permanent stay area	-	-	-
Ambient dose equivalent rate, nominal operation, low occupancy area	- -	2.5 μSv/h [3]	2.5b μSv/h [3]
Intervention related maximum individual personal dose equivalent	-	-	-
Area related upper limit for surface contamination	- -	$<$ 1 CS	$<$ 1 CS

Experimental cavern

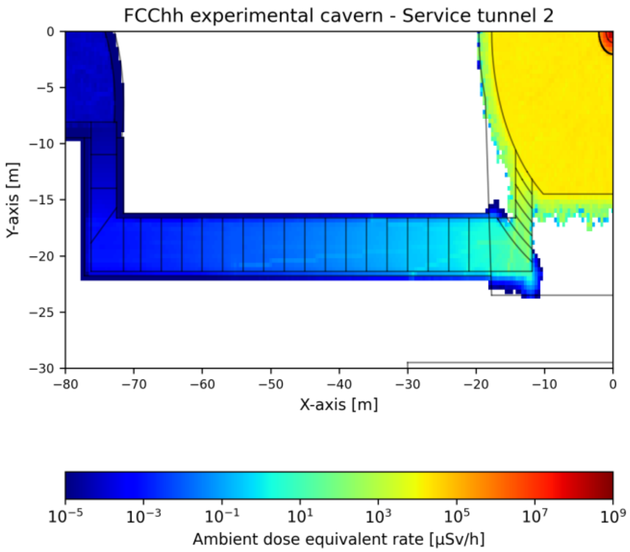
Ambient dose equivalent rate scoring in the *service tunnel 1*





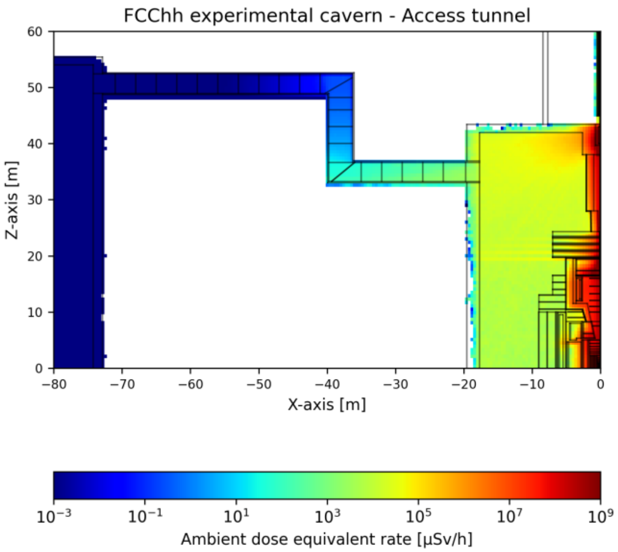
- The results depicted in the left plot illustrate **the ambient dose equivalent rate** resulting from pp collision, and at the top depicts the 1D profile of the mean values along x-axis, calculated within the volume enclosed by the dashed lines, which is the most likely occupied space during access: from the floor at a height of 3 m, and along the z-axis deviating 3 meter from the center of the tunnel.
- The plot on the right depicts the ambient dose equivalent rate for the same scenario, but plotted on the z-x plane.
- The results indicate that 1 meter of shielded doors is sufficient to ensure values lower than 0.5 µSv/h, corresponding to the classification of a Non-Designated area.

Ambient dose equivalent rate scoring in the *service tunnel 2*



- The results shown in the plot illustrate **the ambient dose equivalent rate** resulting from pp collisions in the service tunnel n°2.

Ambient dose equivalent rate scoring in the *access tunnel*



- The results shown in the plot illustrate **the ambient dose equivalent rate** resulting from pp collisions in the access tunnel, passing through a three-legged chicane of 20 meters, 20 meters, and 30 meters respectively.

Klystron gallery

❑ Operational scenario (Z and ttbar)

- The estimated dose rate within the klystron gallery, without the chicane in the waveguide duct, lead to values exceeding the upper threshold for a Supervised Radiation area. In this scenario, implementing a chicane would effectively attenuate the photon fluence, resulting in a substantial reduction in the dose rate by 5-6 orders of magnitude.

❑ Incidental scenario (Z and ttbar)

- In both operational modes, if a full beam loss incident occurs without utilizing the chicane, the ambient dose within the klystron gallery remains below the annual dose limit for a Supervised Area, which is 6 mSv.

- This situation imposes no significant constraints or limitations in terms of radiation protection. However, implementing the chicane would lead to less doses, meeting the requirements even for a Non-designated area.

Operation mode	Dose rate in the klystron gallery with chicane	Dose rate in the klystron gallery without chicane
Z machine	< 1 nSv/h	70 μSv/h
ttbar machine	< 1 nSv/h	300 μSv/h

Incidental scenario (full beam loss)

Operation mode	Dose in the klystron gallery with chicane	Dose in the klystron gallery without chicane
Z machine	10 μSv	2 mSv
ttbar machine	0.2 μSv	50 μSv

Radiological classification limits

Classification	Ambient dose equivalent rate limit for permanent occupancy	Annual dose limit
Non-designated area	**0.5 μSv/h**	**1 mSv**
Supervised area	**15 μSv/h**	**6 mSv**
Simple controlled area	**50 μSv/h**	**20 mSv**

We conclude:

- **The primary source of uncertainty in this study is systematic** because X-ray emissions from the RF cavities primarily depend X-ray production source (energy distribution and locations, absolute dose rates) and the geometry and materials of the cavity, which were approximated based on the cryomodules used in LHC and measurements done on those. These results were used (energy/absolute dose rate) to normalise the simulation results.
- The use of the Klystron gallery during FCChh operation still must be defined, and if it shall remain accessible, the radiological conditions must be compliant for radiation sources present in the FCChh.
- While this systematic uncertainty allows for a margin of improvement, given the current state of the project and the conservative input parameters, **it would be cautious to integrate the duct chicane into the project's design to achieve the radiological standards required for the access of the klystron gallery, both for FCCee and FCChh.**

Operation mode	Dose rate in the klystron gallery with chicane	Dose rate in the klystron gallery without chicane
Z machine	< 1 nSv/h	70 μSv/h
ttbar machine	< 1 nSv/h	300 μSv/h

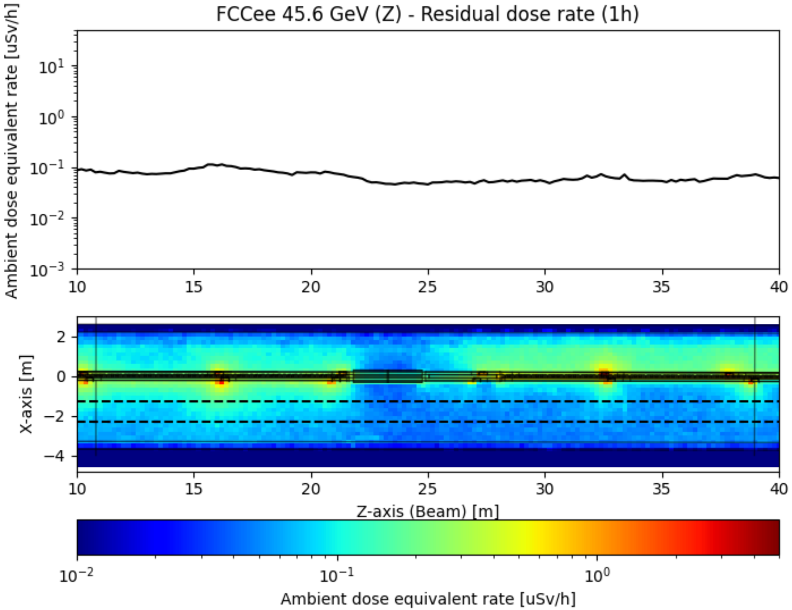
Incidental scenario (full beam loss)

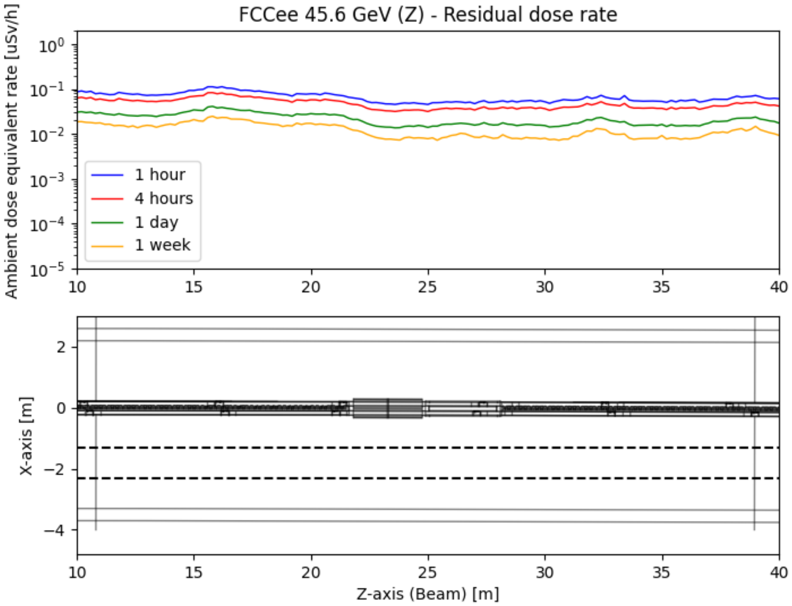
Operation mode	Dose in the klystron gallery with chicane	Dose in the klystron gallery without chicane
Z machine	10 μSv	2 mSv
ttbar machine	0.2 μSv	50 μSv

Radiological classification limits

Classification	Ambient dose equivalent rate limit for permanent occupancy	Annual dose limit
Non-designated area	**0.5 μSv/h**	**1 mSv**
Supervised area	**15 μSv/h**	**6 mSv**
Simple controlled area	**50 μSv/h**	**20 mSv**

Arc

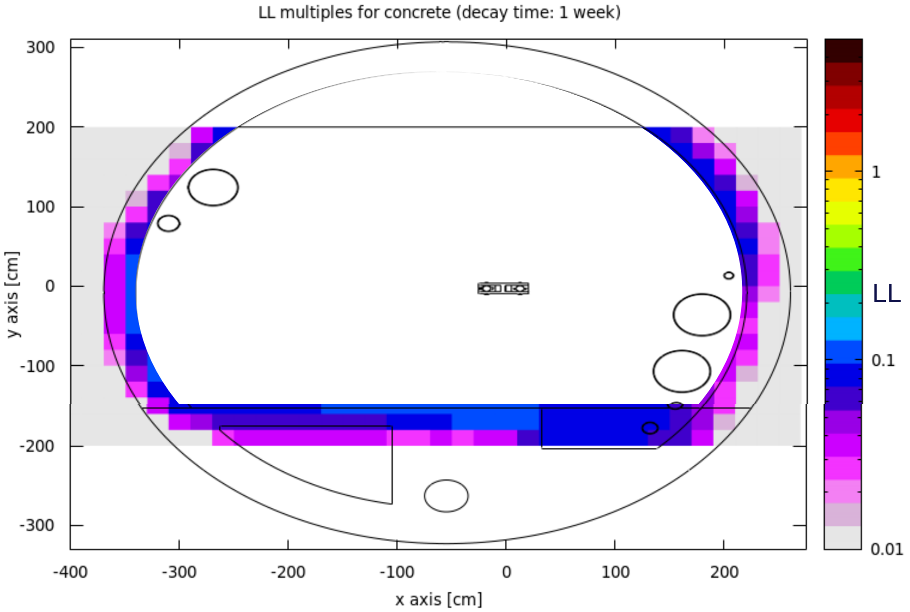




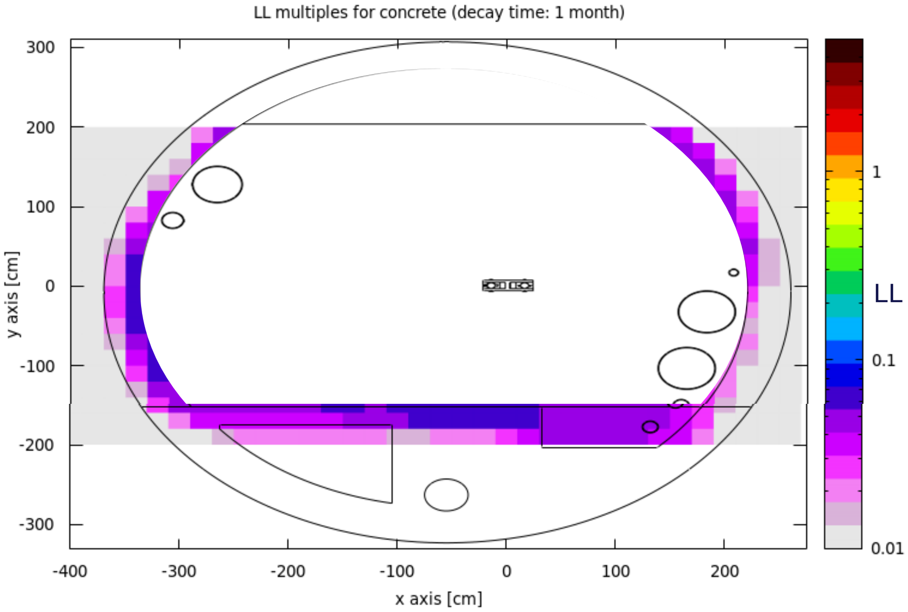
- The graphs at the top depict the 1D profile of the mean values along z, calculated within the volume enclosed by the dashed lines. This volume represents the most probable occupied space during access, typically at a distance of 1-2 meters from the beam line.
- The irradiation profile considers all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

ANALYSIS OF CONCRETE ACTIVATION – ttbar

(After the full operation period)



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

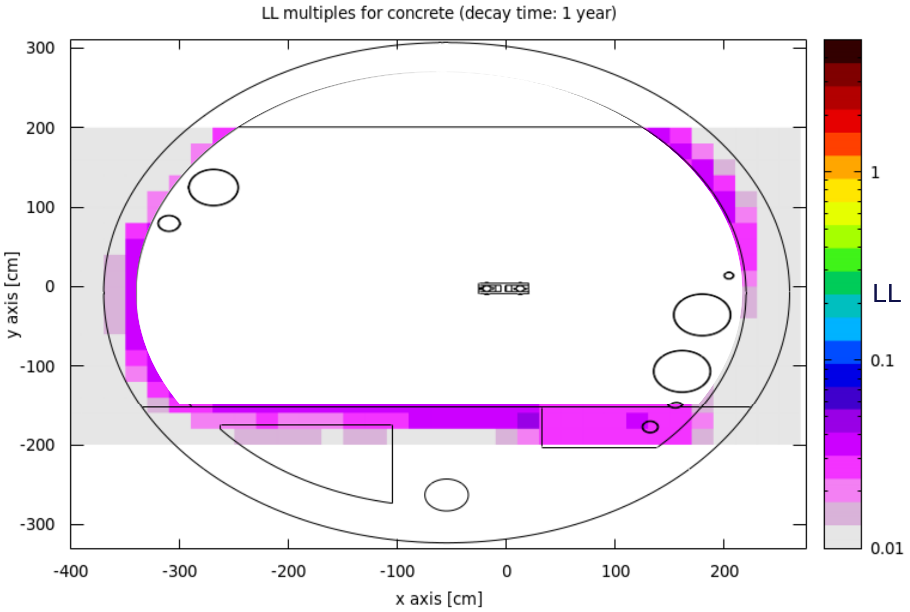


Irradiation profile (ttbar): full operation period / 1 month of cooling time

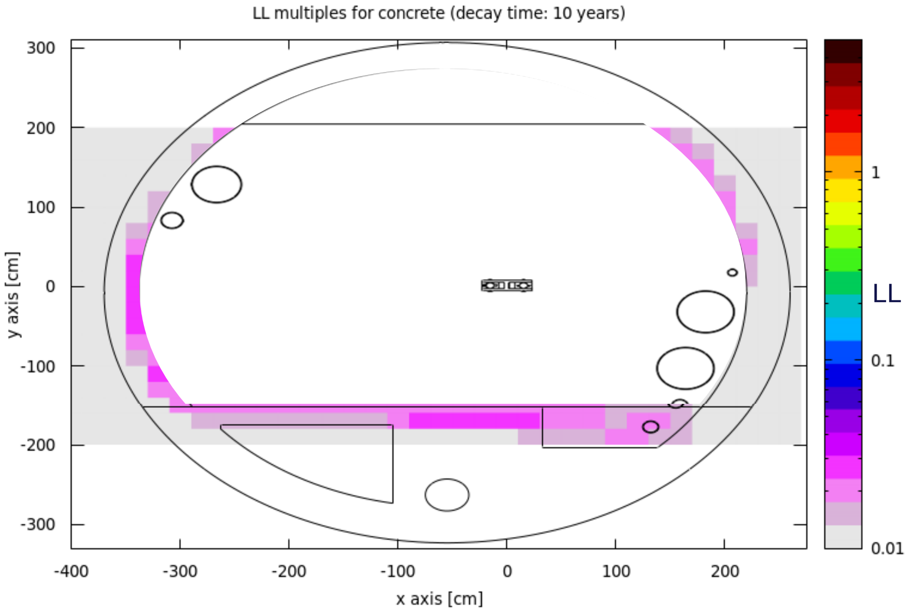
Activation is below clearance limit for the concrete structures of the tunnel.

ANALYSIS OF CONCRETE ACTIVATION – ttbar

(After the full operation period)



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

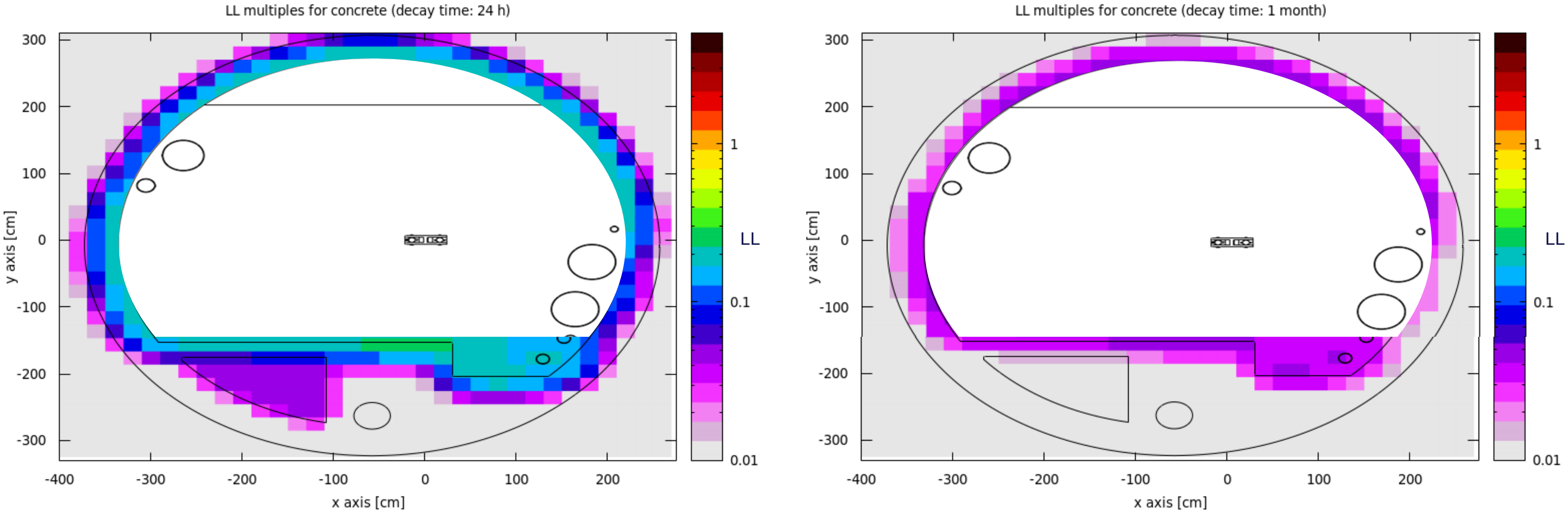


Irradiation profile (ttbar): full operation period / 10 years of cooling time

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

ANALYSIS OF CONCRETE ACTIVATION – ttbar

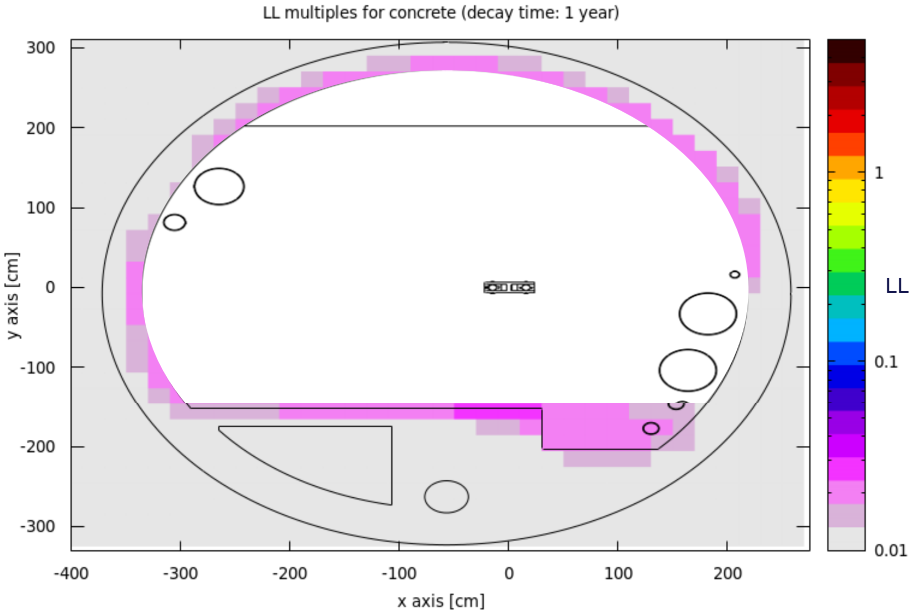
(After 1 year of operation)

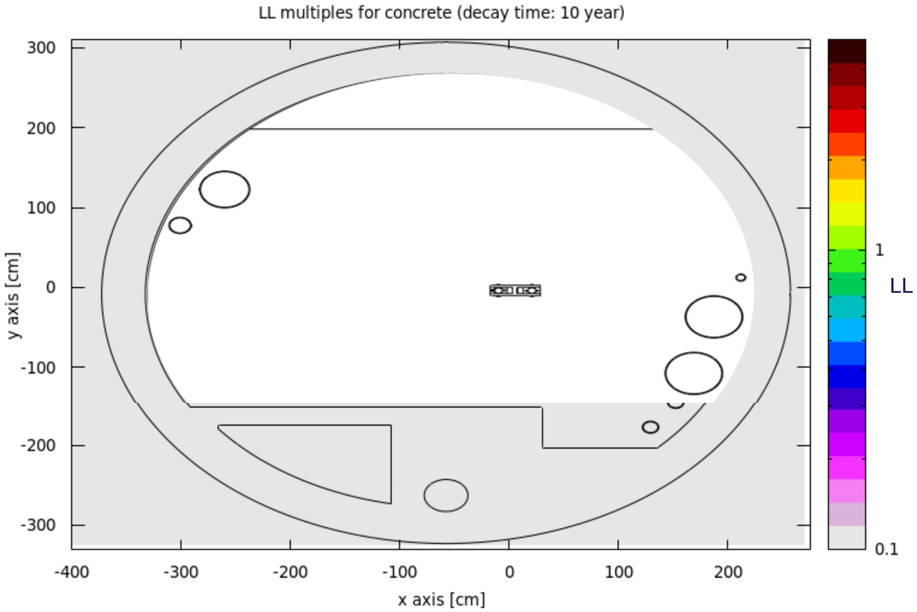


Activation is below clearance limit for the concrete structures of the tunnel.

ANALYSIS OF CONCRETE ACTIVATION – ttbar

(After 1 year of operation)

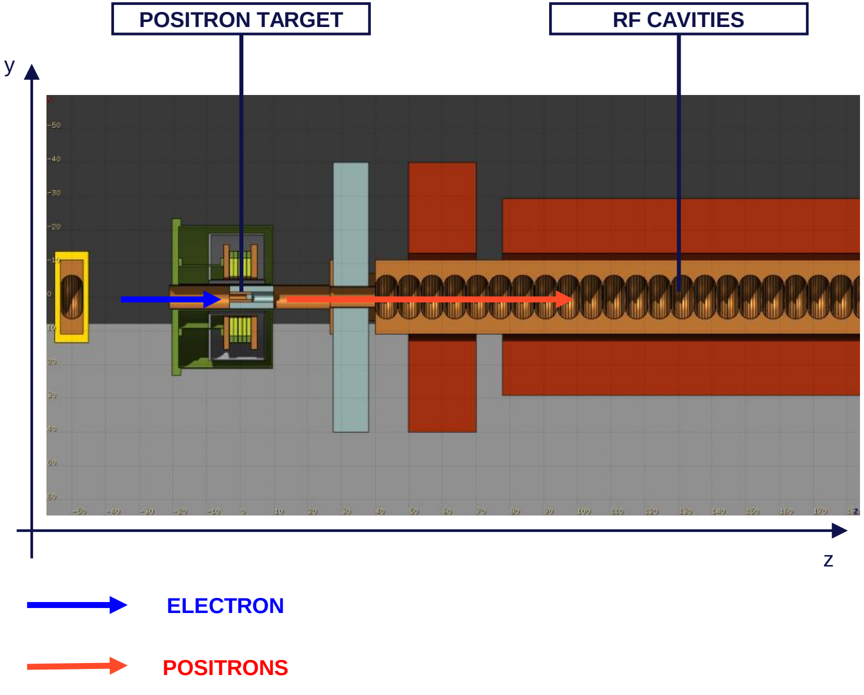


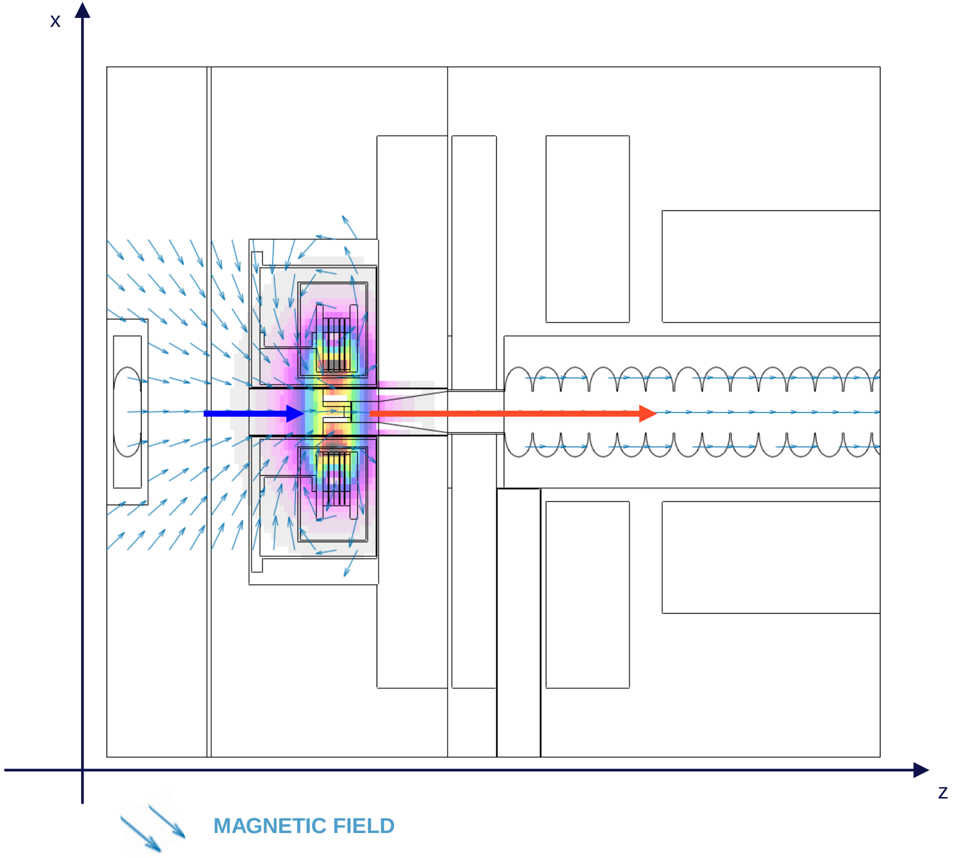


Activation is below clearance limit for the concrete structures of the tunnel.

Positron source

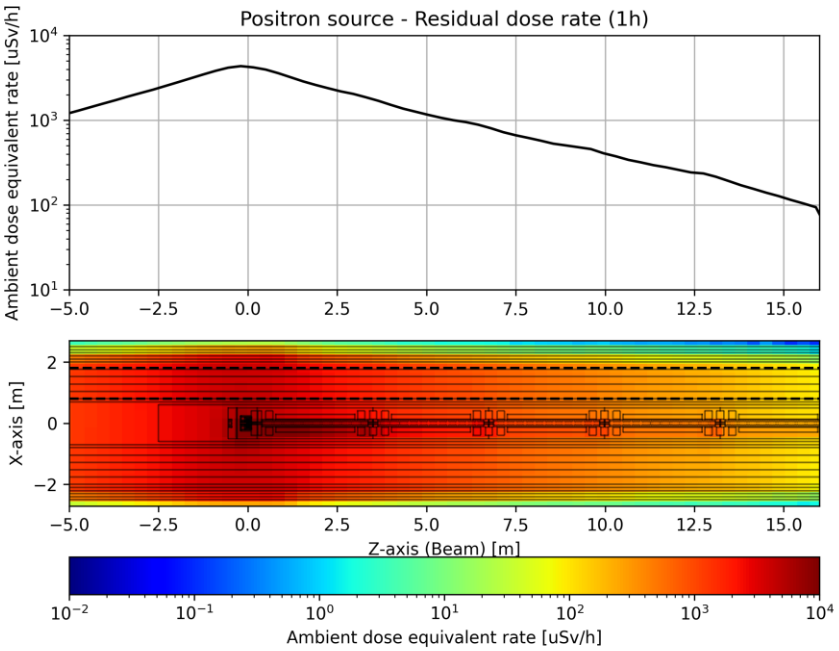
FLUKA geometry

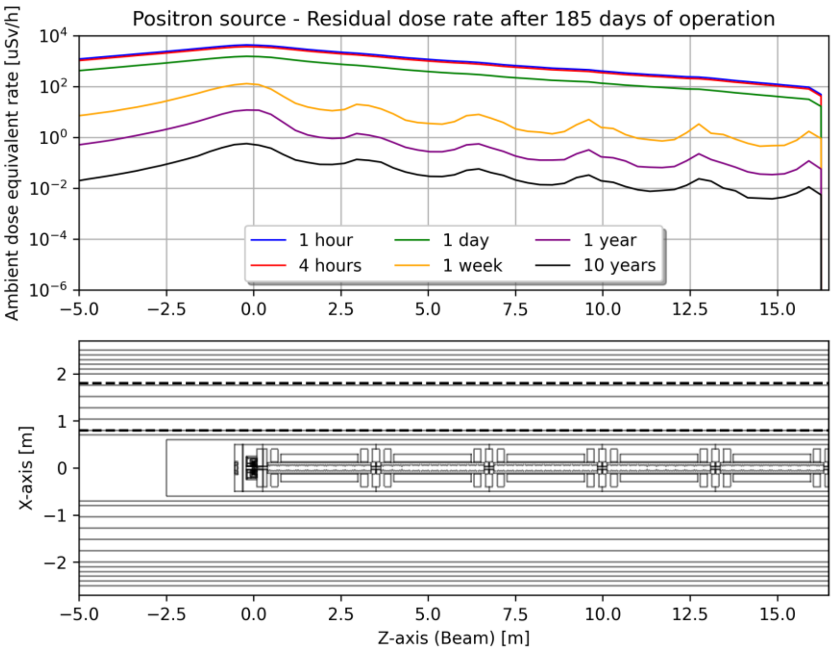




Acknowledgment B. Humann and SY/STI for providing the geometry

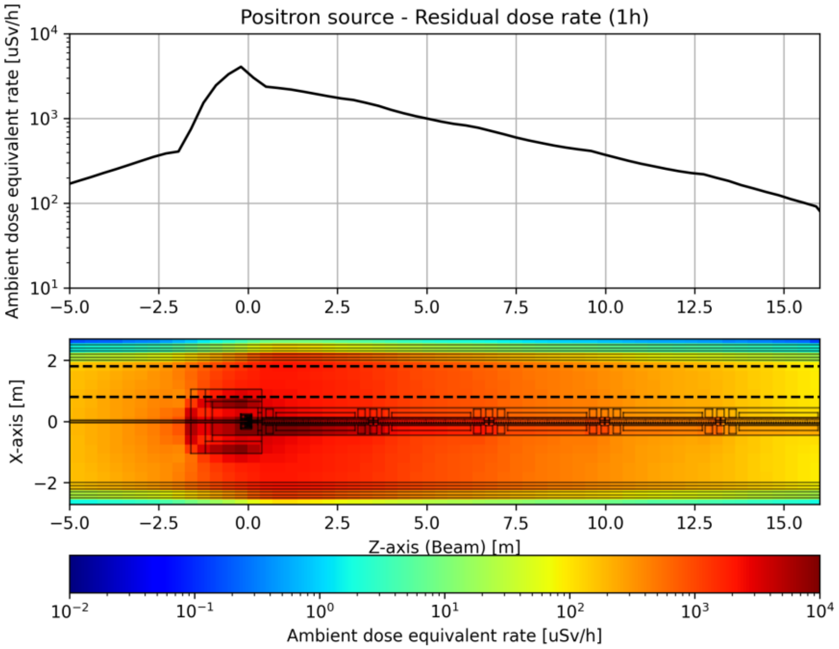
Results – Residual radiation

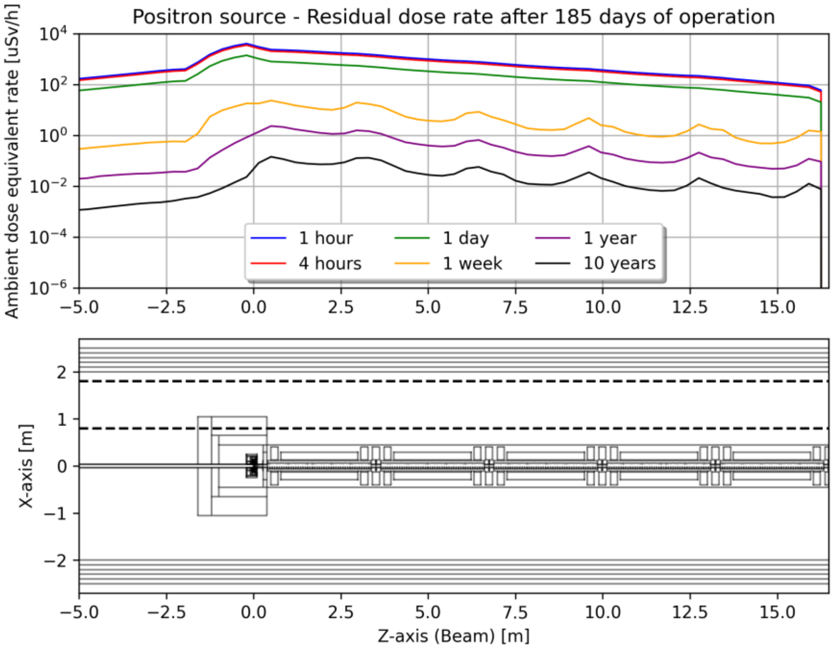




- The graphs at the top depict the 1D profile of the dose rate values along z, calculated within the volume enclosed by the dashed lines. This volume represents the most probable occupied space during access.
- The irradiation profile considers one year of operation, taking into account the duty factor of the machine.

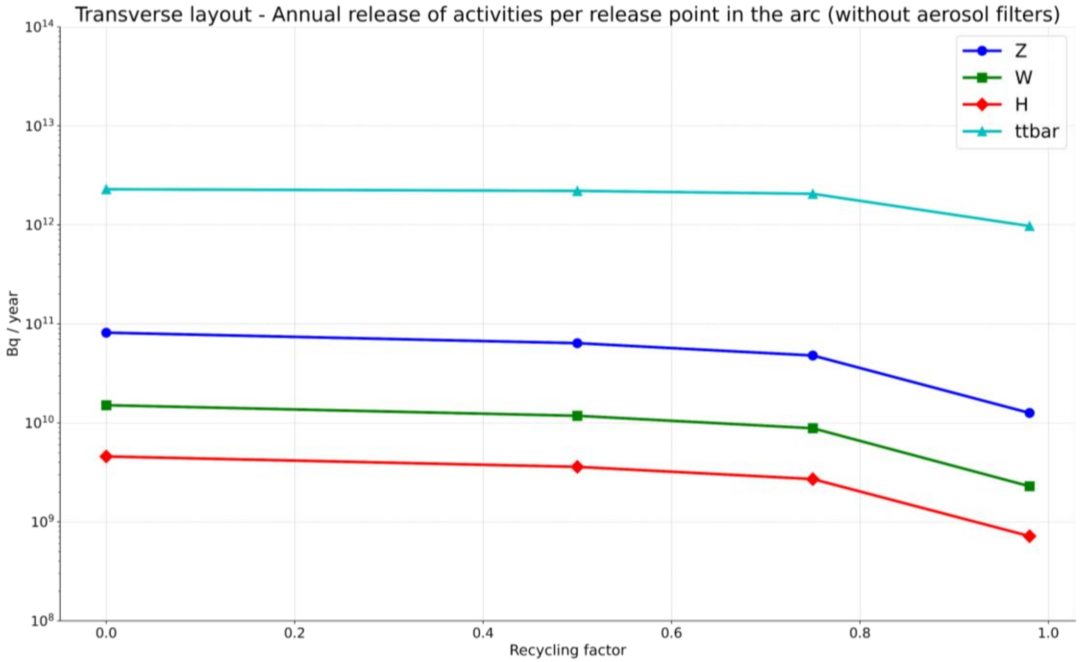
Results – Residual radiation (with shielding)





- The graphs at the top depict the 1D profile of the dose rate values along z, calculated within the volume enclosed by the dashed lines. This volume represents the most probable occupied space during access.
- The irradiation profile considers one year of operation, taking into account the duty factor of the machine.

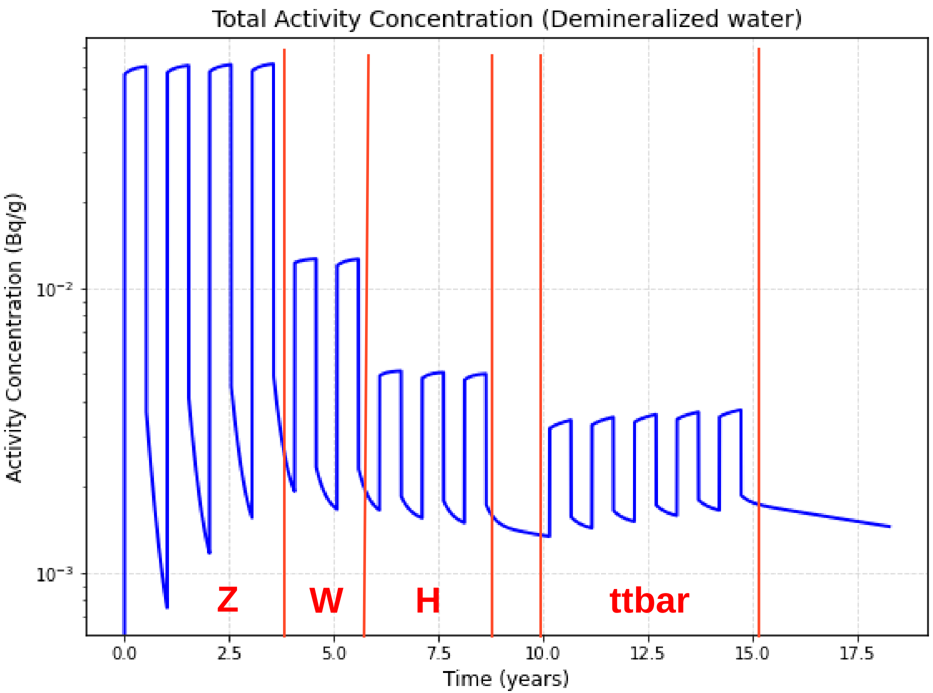
Activation study


Transverse layout - Annual release of activities per release point in the arc (without aerosol filters)
Z
W
H
ttbar
Bq / year
Recycling factor
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
0.0
0.2
0.4
0.6
0.8
1.0

Air activation *(Preliminary radiological environmental impact assessment for FCCee)*

- **Quantity:** Annual effective dose to the Representative Person from the public
- **Input:** Activity releases through air from the FCCee arc in ttbar operation (highest releases, no recycling, no filtration).
- The exact exposure configuration is not yet known
- Experience with the existing CERN facilities comprising about 250 configurations – 95 Percentiles for the two most contributing radionuclide groups:
  - Short-lived gases (^{41}Ar): 4.5E-20 Sv/Bq
  - Agriculture (^{32}P): 9.5E-17 Sv/Bq
- Expected annual effective doses:
  - 2.3 TBq/y of ^{41}Ar: 0.1 µSv/y
  - 60 kBq/y of ^{32}P: 5.8 pSv/y
- 3’000 times below the source-related dose constraint of 300 µSv/y
- 100 times below the *de minimis* dose of 10 µSv/y (justified and optimized)

No relevant environmental impact expected from air releases from FCCee arcs.

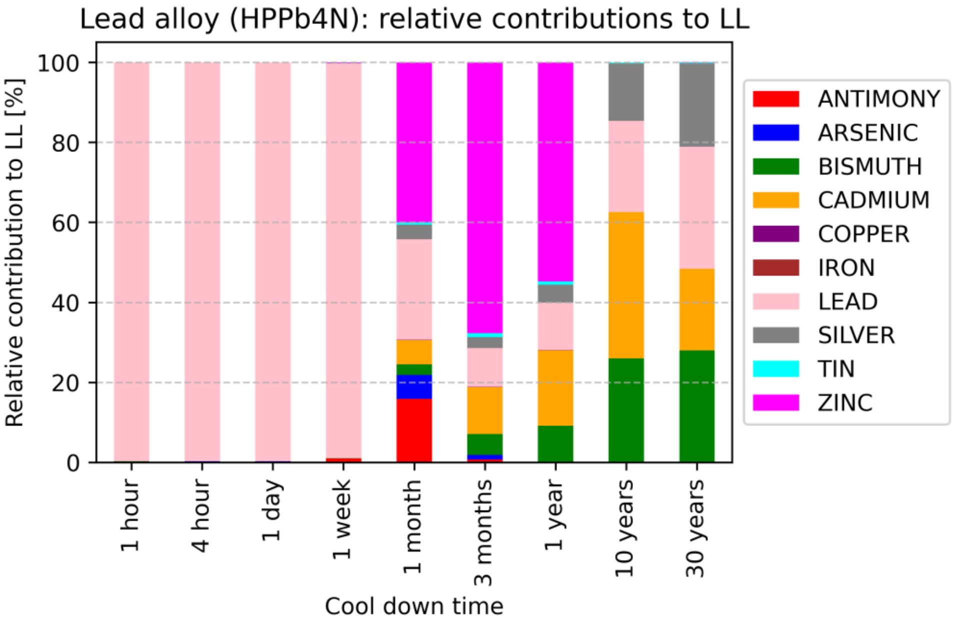

Total Activity Concentration (Demineralized water)
Activity Concentration (Bq/g)
10^{-2}
10^{-3}
Z
W
H
ttbar
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
Time (years)

Activation

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

WHEN LL IS BELOW 1, THE MATERIAL CAN BE GENERALLY RELEASED FROM REGULATORY CONTROL

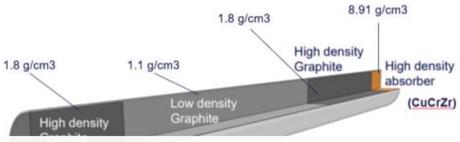
- Accelerator materials

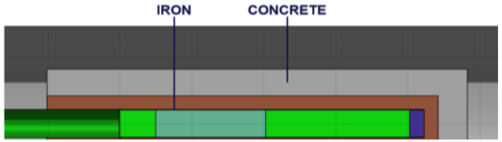


- For each material, it is essential to identify the main contributors to long-term activity and, whenever feasible, avoid them.
- In the case of lead, the primary contributors to the activation are impurities like silver, cadmium, and bismuth.

Beam dumps

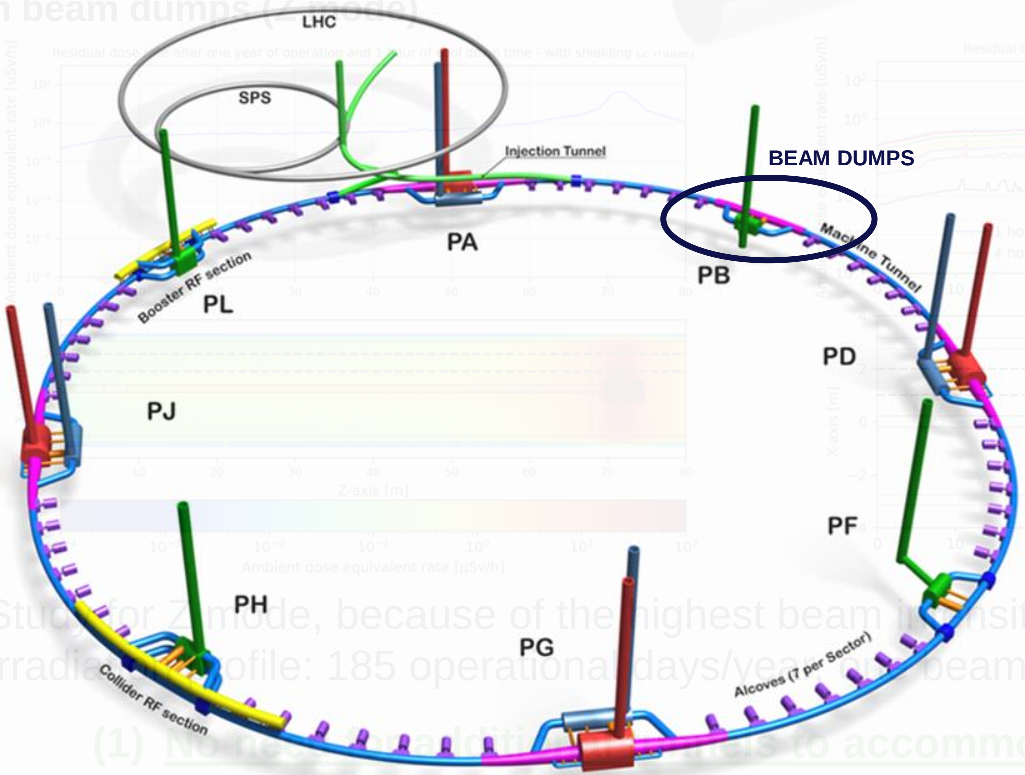
Residual dose rate

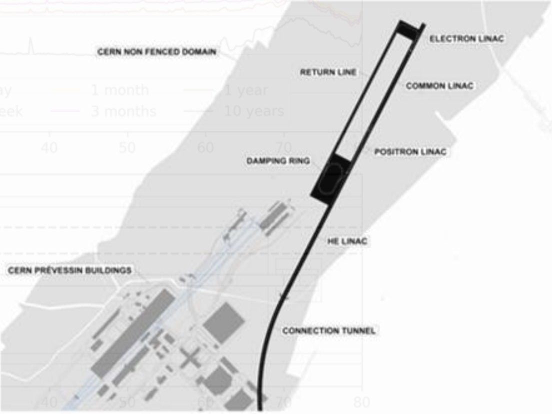




At main beam dumps (Z mode)

Dump shielding
IRON: 20 cm
CONCRETE 40 cm

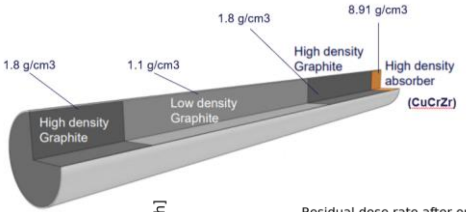


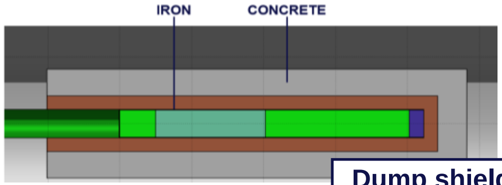


- Study for Z mode, because of the highest beam intensity.
- Irradiation profile: 185 operational days/year, one beam dump per day.

(1) No need for additional tunnels to accommodate the beam dumps
(2) Sufficient space for additional shielding in the foreseen integration design

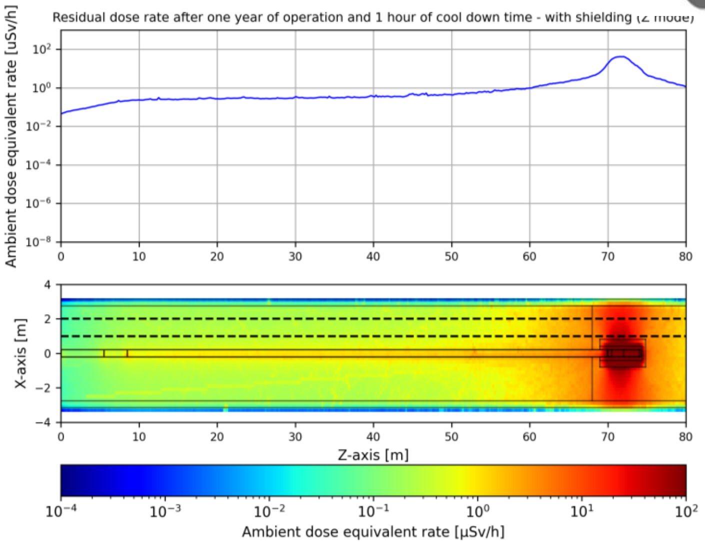
Residual dose rate

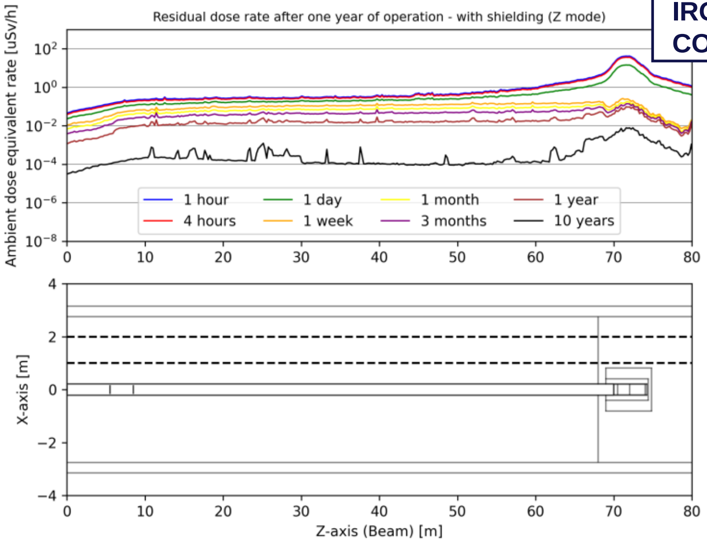




At main beam dumps (Z mode)

Dump shielding
IRON: 20 cm
CONCRETE 40 cm





- Study for Z mode, because of the highest beam intensity.
- Irradiation profile: 185 operational days/year, one beam dump per day.

(1) No need for additional tunnels to accommodate the beam dumps

(2) Sufficient space for additional shielding in the foreseen integration design

FUTURE
CIRCULAR
COLLIDER

FCC