SPES 2010 International Workshop

*Legnaro National Laboratory*

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# RADIATION PROTECTION ASPECTS OF SPES PROJECT - PHASE ALPHA

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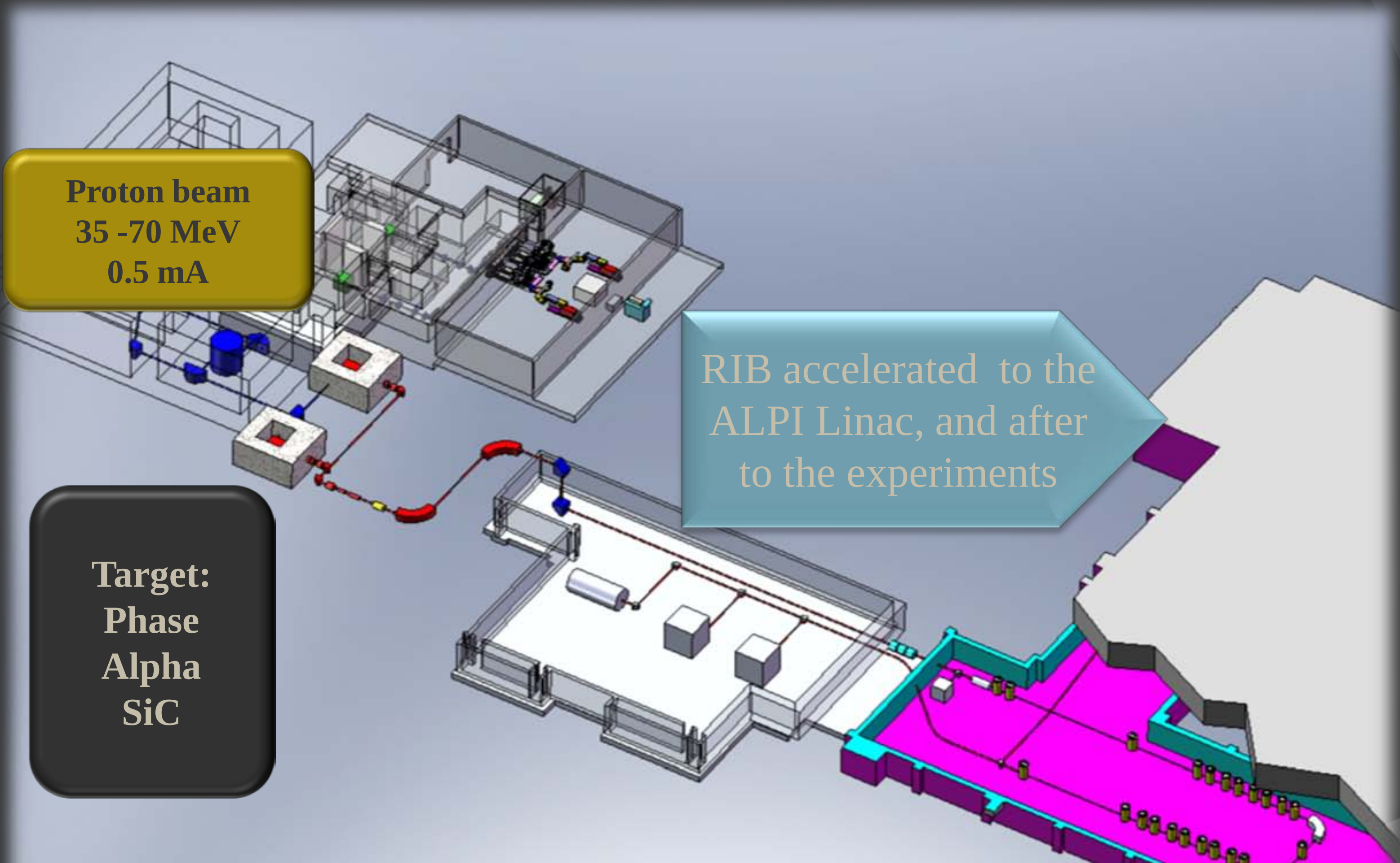
# Outlook

- Introduction
- Radioprotection Objectives – Shielding
- Activation and Dose rate calculations
- Scenario of an accident in Alpha Fase (SiC)
- Dismantling considerations

# The SPES Project




**All the radiation protection aspects have been evaluated using the FLUKA Monte Carlo code.**

# Radioprotection Objectives

- Project dose constraints:
  - max. 5 μSv/h for controlled classified areas
  - 0.3 μSv/h for non classified areas
  - 2000 hours/year working load rate of operation

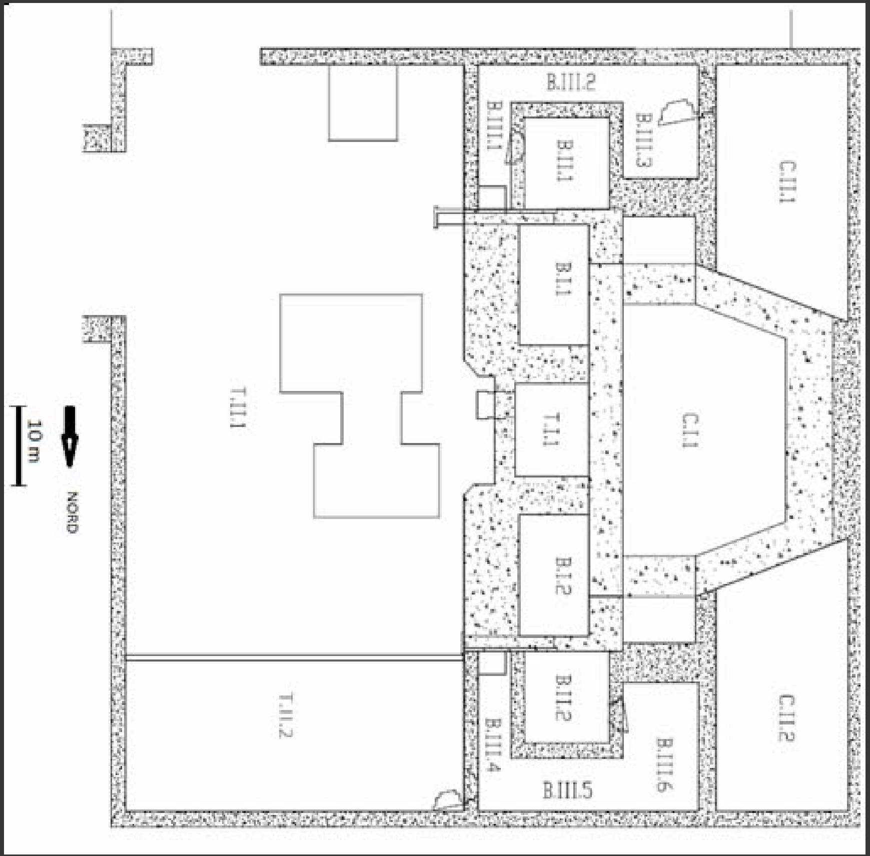
- Verify that the proposed shields thickness suit the project’s needs, considering irradiation conditions and areas destination of use

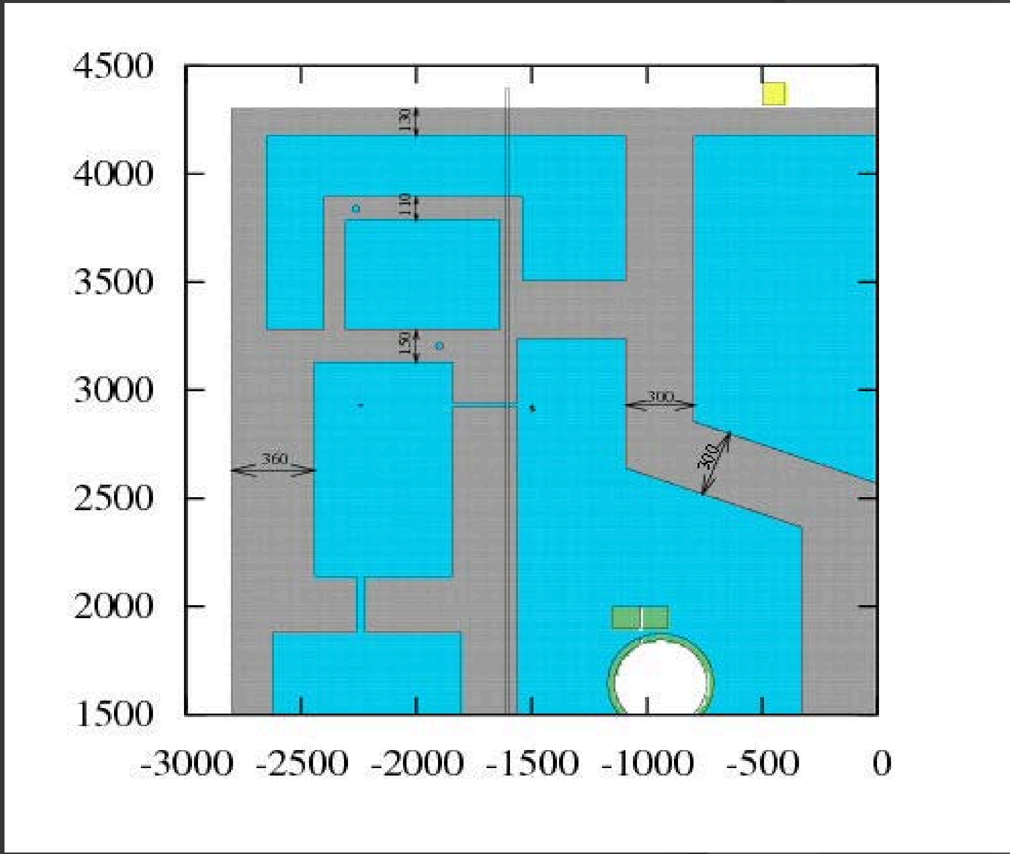
- In order to assure safety in each phase of the project, the RP requirements have been set on the outcome of the irradiation of the uranium target with a proton beam of 70 MeV energy and 300 μA current.

# Shielding Aspects: target site

- The shielding walls will be made of concrete. 360 cm in the forward-proton beam direction are enough to meet RP constraints outside of the wall in case of conventional targets irradiation.
- The thickness must be increased at least to 400 cm for the $UC_x$ target.
- The ceiling and the floor will both be 300 cm thick.

# Shielding Aspects: target site

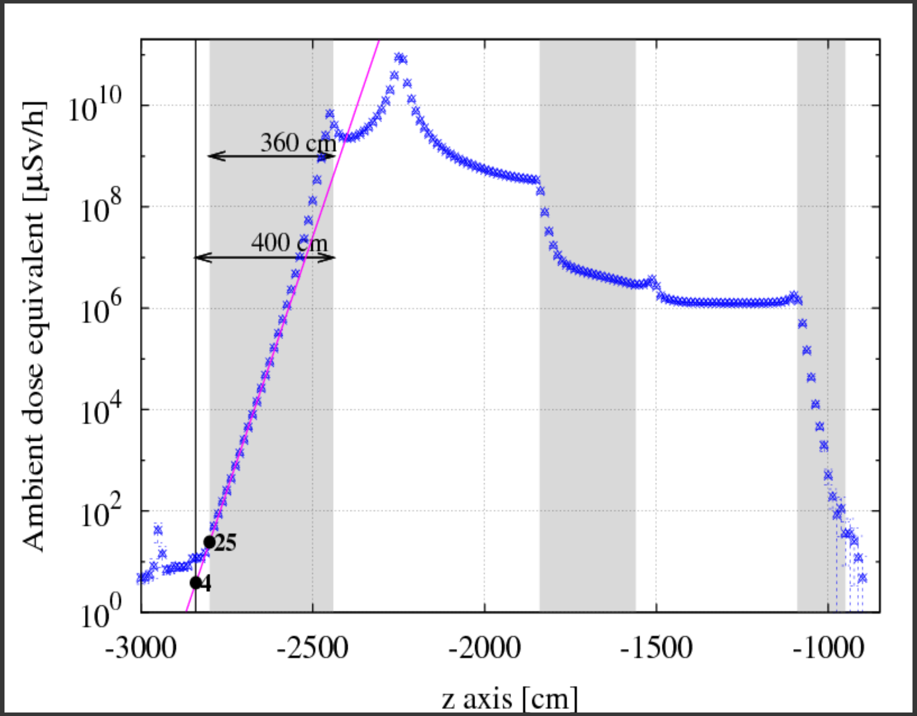


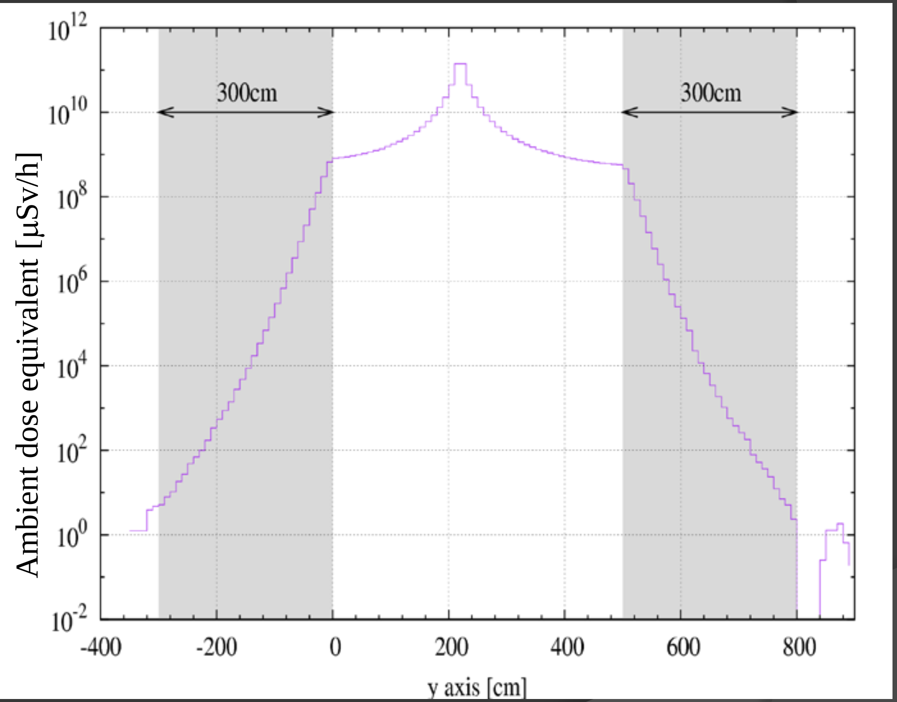



# Shielding Aspects: target site

Horizontal neutron dose rate distribution with extrapolation of the dose rate in the beam direction.

Vertical neutron dose rate distribution from the floor (negative y axis) to the ceiling (positive y axis) through target.



# Shielding Aspects: cyclotron vault

- The source term in the cyclotron shielding evaluation has been the current lost during acceleration and extraction: 15% (about 112 μA) with energy varying between 30 and 70 MeV.

- On the bending dipole it has been considered that 0.6% (about 3 μA) is lost.

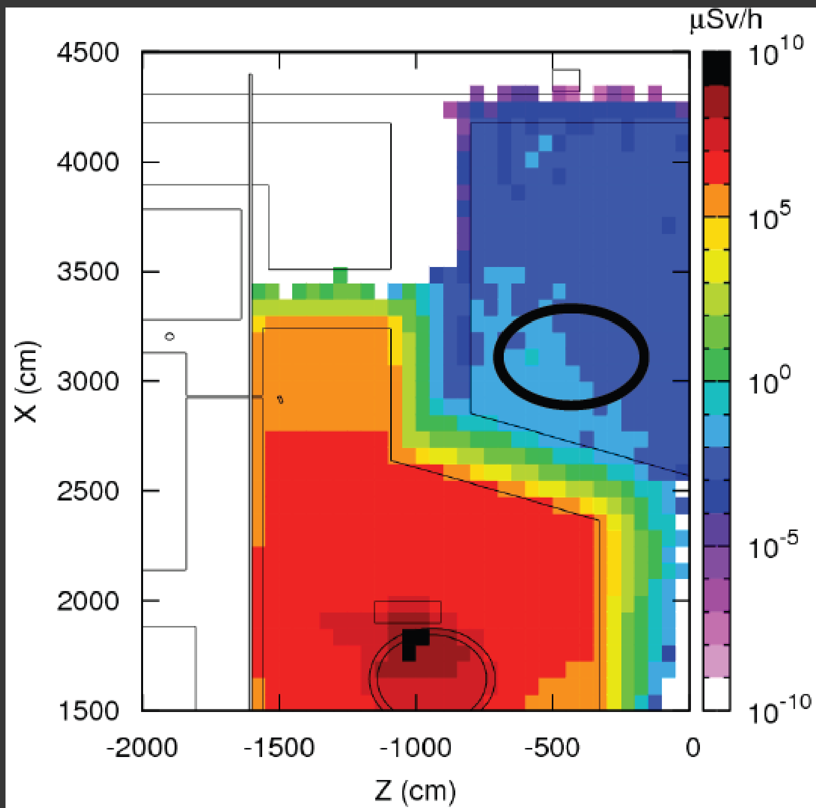
- The contribute of the secondary particles backscattered by the target can be neglected.

# Shielding Aspects: cyclotron vault

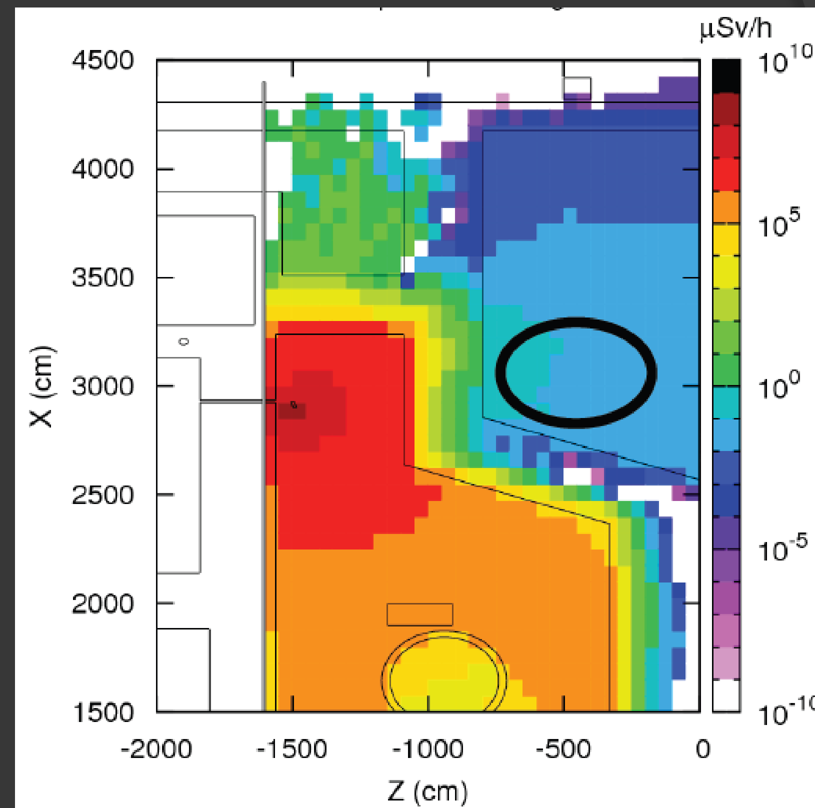
| Beam losses | Energy [MeV] | % | of 750 $\mu$A |
|---|---|---|---|
| In the cyclotron | 30 | 3% | 22.5 $\mu$A |
| | 40 | 3% | 22.5 $\mu$A |
| | 50 | 1.5% | 11.25 $\mu$A |
| | 60 | 1.5% | 11.25 $\mu$A |
| | 70 | 6% | 45 $\mu$A |
| Dipoles | 0.3% | 0.6% | 3 $\mu$A (1 tgt) - 4.5 $\mu$A (2 tgt) |
| Quadrupoles | | 15 $\mu$A (1 tgt) - 22.5 $\mu$A (2 tgt) | |
| Beam lines | | 1.5 $\mu$A (1 tgt) – 2.25 $\mu$A (2 tgt) | |

# Shielding Aspects: cyclotron vault

Dose rate due to the current lost in the cyclotron




Dose rate due to the current lost on the dipole

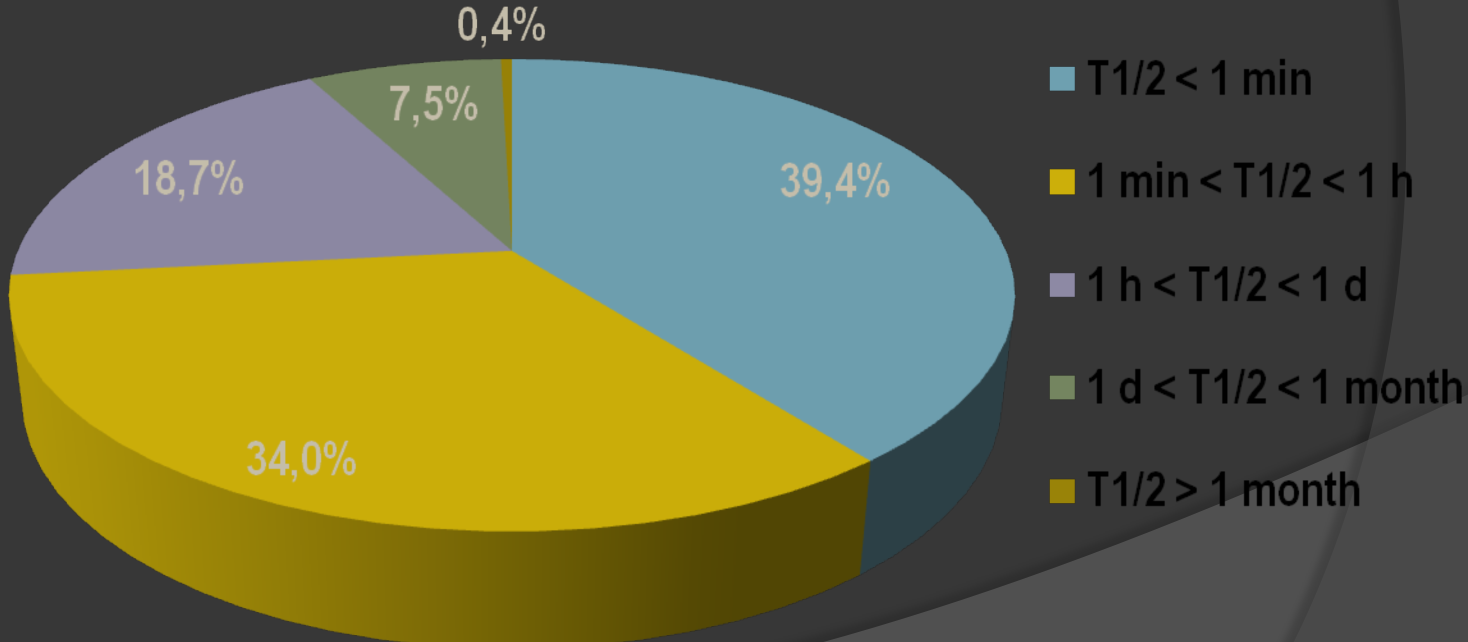



300 cm thick side walls, allow for a dose rate less than 1 µSv/h outside.

# Target Activation

- The emission of γ radiation following the activation of materials in the target hall and in the cyclotron vault, arises the problem of timed and controlled access.

- In the target, after 14 days of irradiation **$10^{14}$ Bq** are produced

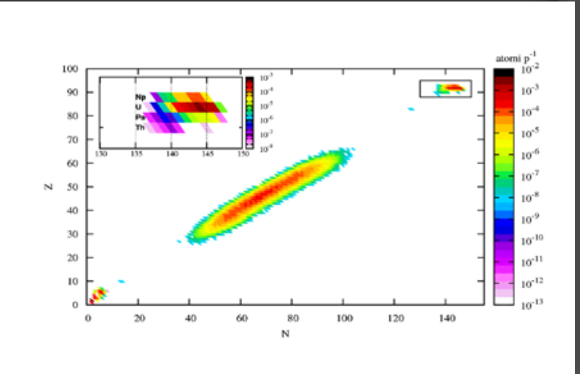


## Radionuclides production on SiC

| Nuclide | $T_{1/2}$ | Abbondanza isotopica | Attività dopo due settimane di irraggiamento | | Attività dopo 1 giorno di raffreddamento |
|---|---|---|---|---|---|
| | | *(nuclei prodotti/protone)* | *(Bq)* | *(Bq/g)* | *(Bq/g)* |
| $^{31}$Si | 157.3 m | $4.7\ 10^{-8}$ | $6.7\ 10^{7}$ | $1.5\ 10^{5}$ | $2.6\ 10^{2}$ |
| $^{30}$P | 2.5 m | $6.8\ 10^{-5}$ | $8.6\ 10^{10}$ | $1.9\ 10^{8}$ | - |
| $^{29}$Al | 6.6 m | $4.0\ 10^{-5}$ | $5.2\ 10^{10}$ | $1.2\ 10^{8}$ | - |
| $^{28}$Mg | 20.9 h | $5.4\ 10^{-7}$ | $5.2\ 10^{8}$ | $1.2\ 10^{6}$ | $5.3\ 10^{5}$ |
| $^{28}$Al | 2.2 m | $3.7\ 10^{-4}$ | $4.8\ 10^{11}$ | $1.1\ 10^{9}$ | $5.3\ 10^{5}$ |
| $^{27}$Mg | 9.5 m | $7.8\ 10^{-6}$ | $1.0\ 10^{10}$ | $2.3\ 10^{7}$ | - |
| $^{26}$Al | $7.4\ 10^{5}$ y | $4.7\ 10^{-3}$ | $1.1\ 10^{5}$ | $2.4\ 10^{2}$ | $2.4\ 10^{2}$ |
| $^{24}$Na | 15 h | $4.1\ 10^{-5}$ | $5.1\ 10^{10}$ | $1.1\ 10^{8}$ | $3.8\ 10^{7}$ |
| $^{22}$Na | 2.6 y | $6.2\ 10^{-4}$ | $7.9\ 10^{9}$ | $1.8\ 10^{7}$ | $1.8\ 10^{7}$ |
| $^{18}$F | 110 m | $6.1\ 10^{-5}$ | $7.8\ 10^{10}$ | $1.7\ 10^{8}$ | $2.0\ 10^{4}$ |
| $^{15}$O | 122.24 s | | $2.9\ 10^{10}$ | $6.6\ 10^{7}$ | - |
| $^{14}$C | 5730 y | $1.7\ 10^{-6}$ | $1.0\ 10^{4}$ | 22.4 | 22.4 |
| $^{13}$N | 10 m | $1.4\ 10^{-5}$ | $1.8\ 10^{10}$ | $4.0\ 10^{7}$ | - |
| $^{11}$C | 20.4 m | $3.8\ 10^{-3}$ | $4.8\ 10^{12}$ | $1.1\ 10^{10}$ | - |
| $^{7}$Be | 53.3 d | $1.1\ 10^{-3}$ | $2.3\ 10^{11}$ | $5.1\ 10^{8}$ | $5.1\ 10^{8}$ |
| $^{3}$H | 12.3 y | $5.6\ 10^{-4}$ | $1.5\ 10^{9}$ | $3.4\ 10^{6}$ | $3.4\ 10^{6}$ |

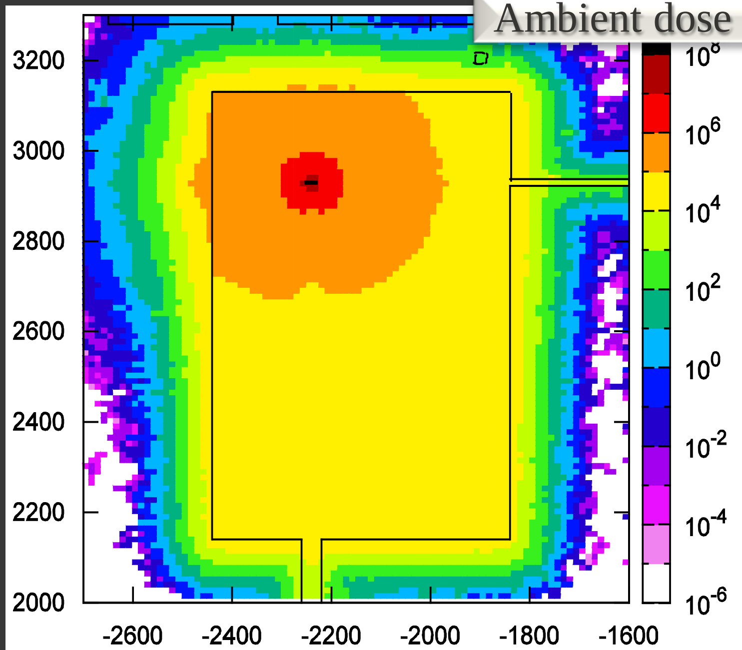
## UCx

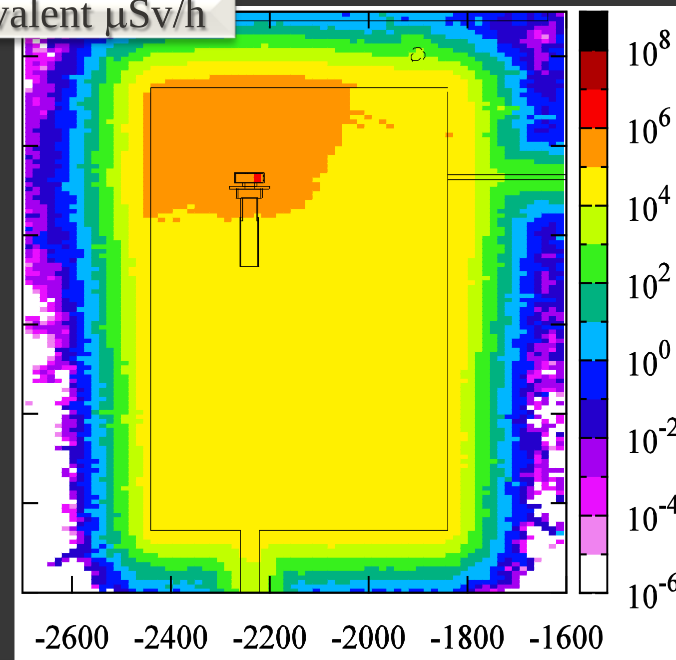
| Nuclde | $T_{1/2}$ | Abbondanza isotopica | Attività dopo due settimane di irraggiamento | | Attività dopo 1 giorno di raffreddamento |
|---|---|---|---|---|---|
| | | *(nuclei prodotti/protone)* | *(Bq)* | *(Bq/g)* | *(Bq/g)* |
| $^{230}$U | 20.8 d | $3.8\ 10^{-7}$ | $2.1\ 10^{8}$ | $7.2\ 10^{6}$ | $7.0\ 10^{6}$ |
| $^{231}$U | 4.2 d | $2.9\ 10^{-6}$ | $3.4\ 10^{9}$ | $1.2\ 10^{8}$ | 1.0 108 |
| $^{232}$U | 68.9 y | $3.8\ 10^{-5}$ | $2.3\ 10^{7}$ | $7.9\ 10^{5}$ | $7.9\ 10^{5}$ |
| $^{233}$U | $1.592\ 10^{5}$ y | $1.5\ 10^{-4}$ | $3.7\ 10^{4}$ | $1.3\ 10^{3}$ | $1.3\ 10^{3}$ |
| $^{234}$U | $2.455\ 10^{5}$ y | $2.7\ 10^{-4}$ | $4.7\ 10^{4}$ | $1.6\ 10^{3}$ | $1.6\ 10^{3}$ |
| $^{235}$U | $7.038\ 10^{8}$ y | $3.7\ 10^{-4}$ | 20.6 | 0.7 | 0.7 |
| $^{236}$U | $2.342\ 10^{7}$ y | $5.5\ 10^{-4}$ | $9.3\ 10^{2}$ | 32.5 | 32.6 |
| $^{237}$U | 6.75 d | $4.1\ 10^{-4}$ | $4.6\ 10^{11}$ | $1.6\ 10^{10}$ | $1.4\ 10^{10}$ |
| $^{238}$U | $4.468\ 10^{9}$ y | $4.3\ 10^{-4}$ | 3.7 | 0.1 | 0.1 |
| $^{239}$U | 23.45 m | $8.1\ 10^{-6}$ | $1.2\ 10^{10}$ | $4.3\ 10^{8}$ | - |
| $^{236}$Pu | 2.858 y | - | $3.4\ 10^{8}$ | $1.2\ 10^{7}$ | $1.2\ 10^{7}$ |
| $^{238}$Pu | 87.7 y | - | $1.3\ 10^{7}$ | $4.7\ 10^{5}$ | $5.1\ 10^{5}$ |
| $^{239}$Pu | 24110 y | - | $1.0\ 10^{4}$ | $3.6\ 10^{2}$ | $3.8\ 10^{2}$ |



# Target and front-end activation

Ambient dose equivalent μSv/h



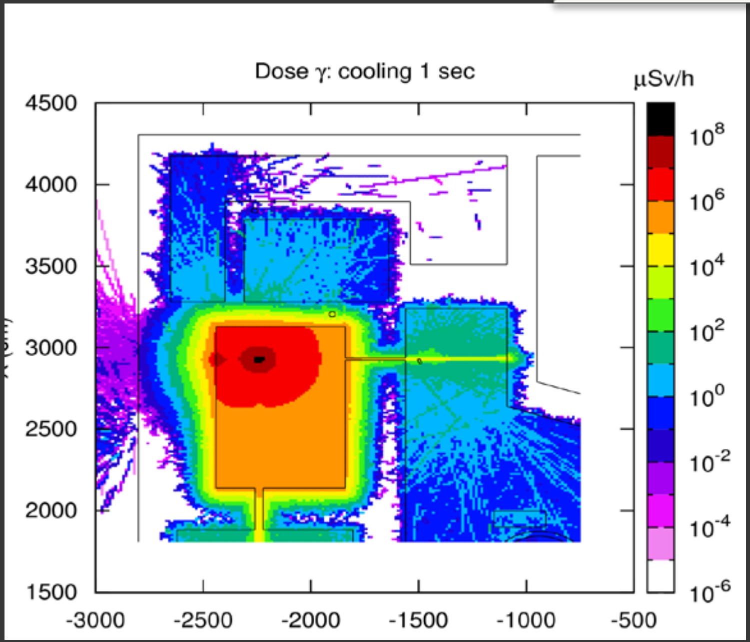

70 Mev, 300 mA, 14 days of irradiation, SiC

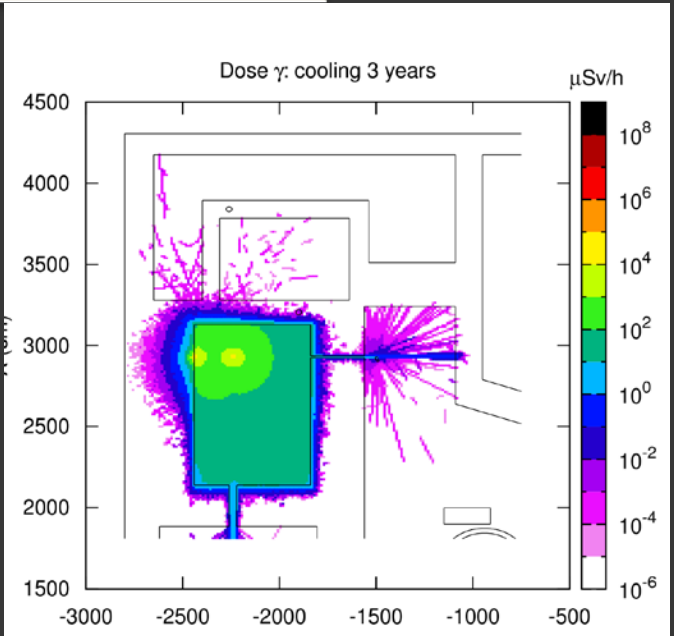
| | Residual γ dose rate: **target** | Residual γ dose rate: **front end** |
|---|---|---|
| **Cooling time** | ***Sv m²/h*** | |
| 1 second | 9.8 | 0.7 |
| 1 day | 0.5 | 0.1 |
| 10 days | 0.1 | 2.7 $10^{-3}$ |
| 1 year | **2.0 $10^{-3}$** | - |

Target must be removed to let people in

# Target activation

Ambient dose equivalent µSv/h in the presence of the tgt



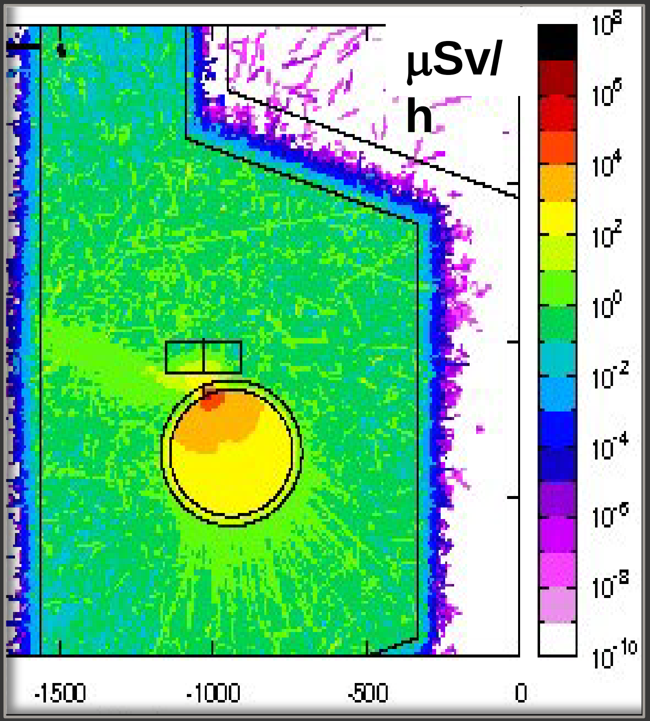




70 Mev, 300 mA, 14 days of irradiation, UCx

| Cooling Time | Gamma dose rate at 1m from the target |
|---|---|
| 1 sec | 50 Sv/h |
| 1 month | 0.1 Sv/h |
| 1 year | 2 mSv/h |
| 3 years | 1 mSv/h |

# Cyclotron Activation

- After 2 weeks of irradiation and 10 days of cooling time the dose rate inside the cyclotron vault is < 10 μSv/h
- Close to the extraction point the dose rate is around 1 mSv/h
- Controlled access is needed for maintenance intervention
- Time keeping is essential for emergency interventions

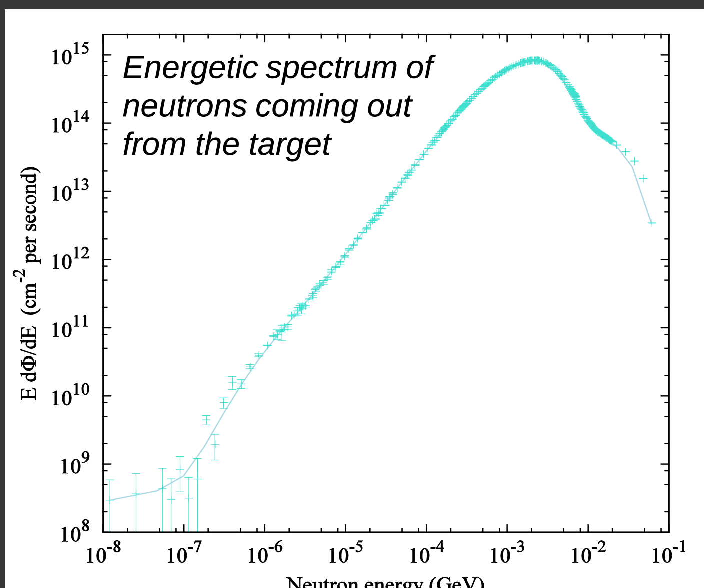


# Air activation

- For each radioisotope in air it has been calculated:
  - the production rate in the enclosed volume;
  - the activity at the extraction, considering a ventilation rate of $50 m^3/h$: this value is supposed to compensate for the leaks in the depression system ($V=300\ m^3$);
  - the dose received due to inhalation and submersion in the exhausted plume, using the recent ICRP coefficients for dose-activity conversion (by means of the Hotspot code).
- The calculation has been made considering the $UC_2$ target and the SiC target.

# Air activation

- The production rate has been obtained folding the neutron fluence with the cross sections of the main radioisotopes produced in air




| Nuclide | Half-life | Reactions | Cross-Section (mb) |
|---|---|---|---|
| $^{3}H$ | 12.3 a | $^{16}O(n,sp)^{3}H$<br>$^{14}N(n,sp)^{3}H$ | 30<br>30 |
| $^{7}Be$ | 53.3 d | $^{16}O(n,sp)^{7}Be$<br>$^{14}N(n,sp)^{7}Be$ | 10<br>10 |
| $^{11}C$ | 20.3 m | $^{16}O(n,sp)^{11}C$<br>$^{14}N(n,sp)^{11}C$ | 20<br>20 |
| $^{13}N$ | 9.97 m | $^{16}O(n,sp)^{13}N$<br>$^{14}N(n,2n)^{13}N$ | 10<br>10 |
| $^{15}O$ | 2.03 m | $^{16}O(n,2n)^{15}O$ | 40 |
| $^{41}Ar$ | 1.83 h | $^{40}Ar(n,\gamma)^{41}Ar$ | 610 |

70 MeV, 300 μA, UCx target

# Air activation: $UC_2$ target

- The annual activity released is $7\ 10^{14}$ Bq
- More than 99% of the total activity is due to nuclides with half life lower than 75 days ($^{7}$Be, $^{11}$C, $^{13}$N, $^{15}$O, $^{41}$Ar)
- Less than 2 hours “storage” time is sufficient to lower the concentration to 1 Bq/g: in this condition release to the environment is permitted without further authorization
- For nuclides with half life longer than 75 days it is shown that the total effective dose equivalent (TEDE) is less than 10 μSv/y, thus is not relevant from a radiological point of view.

| Nuclide | $T_{1/2}$ | Activity release rate Bq/y | TEDE Sv/y |
|---|---|---|---|
| $^{3}$H | 12.33 y | $1.8\ 10^{9}$ | $3\ 10^{-6}$ |
| $^{14}$C | 5730 y | $2.7\ 10^{8}$ | |
| $^{35}$S | 87.51 d | $7.7\ 10^{8}$ | |

# Air activation: SiC target

- The annual activity released is 5 $10^{12}$ Bq
- More than 99% of the total activity is due to nuclides with half life lower than 75 days ($^{7}$Be, $^{11}$C, $^{13}$N, $^{15}$O, $^{41}$Ar)
- The concentration is already 1 Bq/g at the exhaust and there would be no need of storage time (in practice the system must be designed for the worst case facility – see $UC_2$ case)
- For nuclides with half life longer than 75 days it is shown that the total effective dose equivalent (TEDE) is less than 1 μSv/y, thus is definitely not relevant from a radiological point of view.

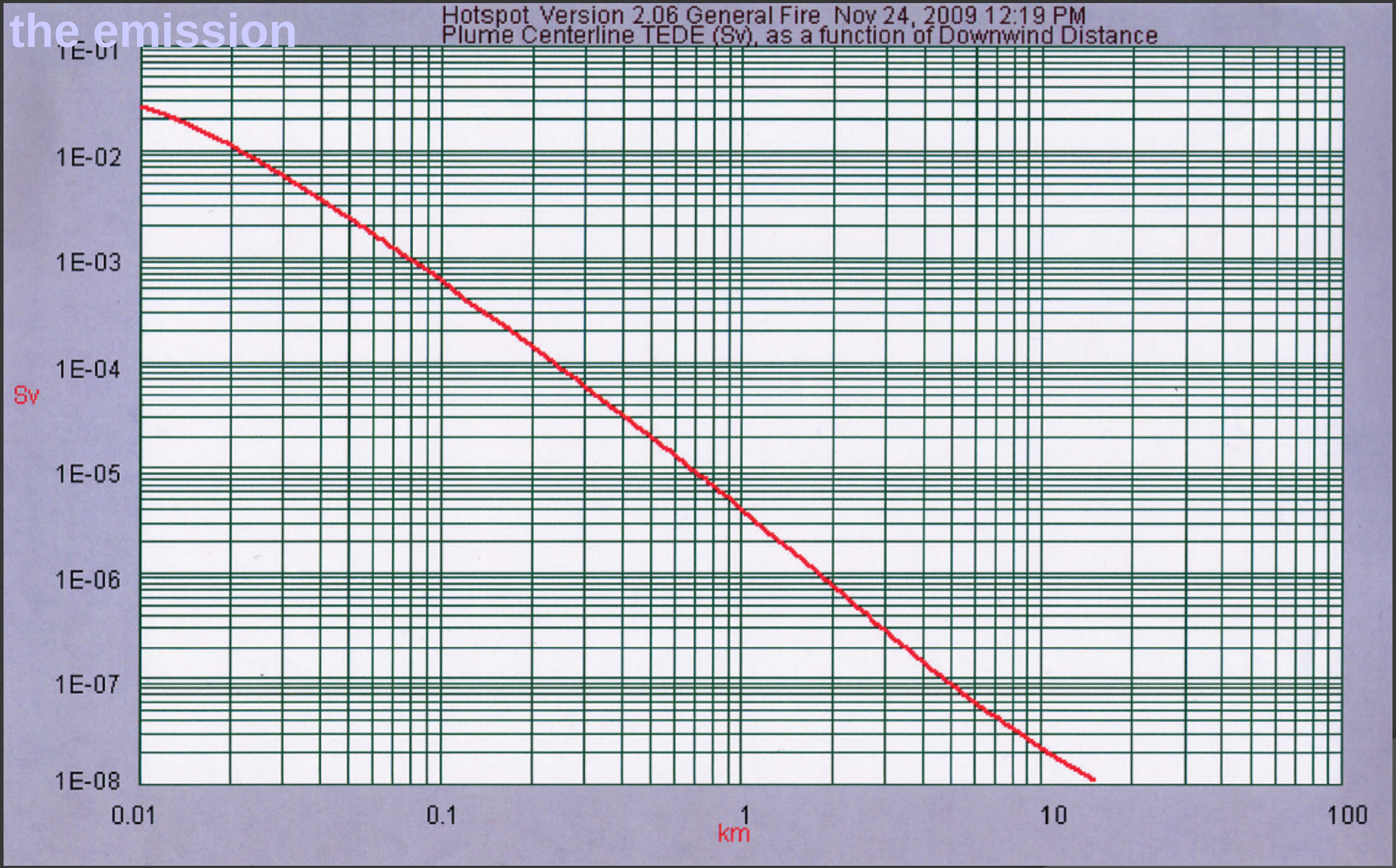
| Nuclide | $T_{1/2}$ | Activity release rate Bq/y | TEDE Sv/y |
|---|---|---|---|
| $^{3}$H | 12.33 y | 1.1 $10^{8}$ | 3 $10^{-7}$ |
| $^{14}$C | 5730 y | 4.3 $10^{7}$ | |
| $^{35}$S | 87.51 d | 6.8 $10^{6}$ | |

# Accident analysis

- The worst possible accident is the fire of the target after an irradiation cycle, with consequent release to the environment of all the produced radionuclides.
- The dose commitment and the activity distribution have been evaluated through the HotSpot code, v. 2.06
- Neglecting the very low probability of happening, this type of scenario gives an indication about the maximum danger, from the RP point of view, to the reference group of the population in the region.

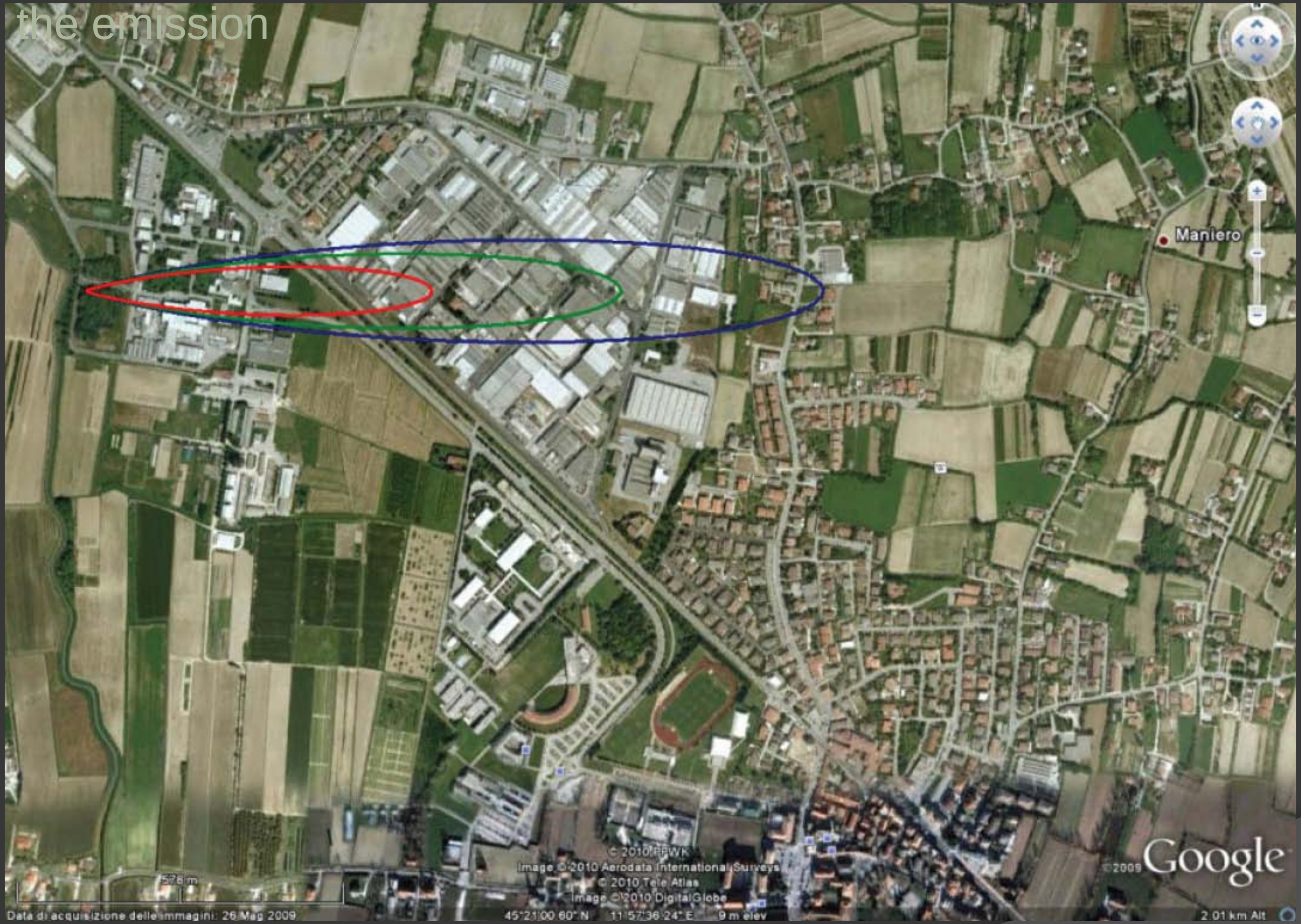
# Accident analysis of the SiC target

**Dose (Sv) to the population as a function of the distance from the emission**



# Accident analysis of SiC

Dose (Sv) to the population as a function of the distance from the emission




**Inner: 5.0 $10^{-5}$ Sv** **Middle: 2.0 $10^{-5}$ Sv** **Outer: 1.0 $10^{-5}$ Sv**

# Dismantling consideration

- Study based on the hypothesis of running the facility for 20 years at the rate of 5000 hours/year, irradiating an $UC_2$ target with a proton beam of 70 MeV energy and 300 μA current.
- Problems concerning the disposal of the activated shielding structure.
- Residual activity calculated as a function of cooling time and depth in concrete.

# Dismantling consideration

Long lived radionuclides in a sample 20 cm deep from the surface, at the end of the irradiation period (20 years).

6% of the overall activity is due to nuclides with half lives longer than 1 year.

The nuclides specified in the table are found in the concrete sample.

In the reinforcement rods some of these nuclides can be found (species produced by irradiation of iron, $^{60}$Co, $^{59}$Fe, $^{55}$Fe, $^{54}$Mn) with higher concentrations.

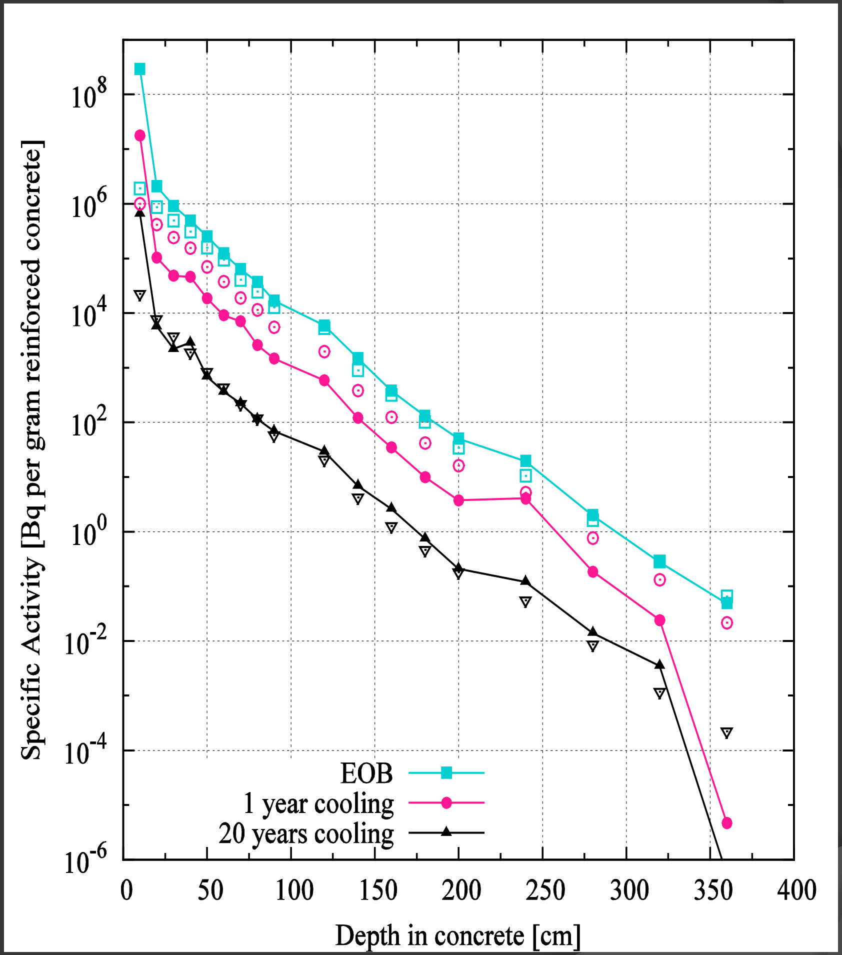
| Nuclide | Half life | Activity (Bq/g) |
|---|---|---|
| $^{152}$Eu | 13.5 y | 232.7 |
| $^{60}$Co | 5.27 y | 172.7 |
| $^{59}$Fe | 44.5 d | 137.8 |
| $^{55}$Fe | 2.73 y | 1.2 $10^4$ |
| $^{54}$Mn | 312.12 d | 1.5 $10^3$ |
| $^{45}$Ca | 162.61 d | 1.0 $10^4$ |
| $^{26}$Al | 7.4 $10^5$ y | 216.0 |
| $^{22}$Na | 2.602 y | 223.0 |
| $^{3}$H | 12.33 y | 1.4 $10^3$ |

# Dismantling considerations

Activity concentration rapidly decays as the depth increases in the first 20-30 cm.

Symbols represent the activity concentration in the rods, while lines represent the same quantity in concrete.

As a representative value, 1Bq/g is obtained after 20 years of cooling time in the outer part 185 cm thick.



THANK’S FOR YOUR ATTENTION

AND REMEMBER THAT LICENSING REQUEST IS ALREADY DELIVERED!