T.A.C. meeting

LNL 23/1/2014

Workpackage SAFETY AND RADIATION PROTECTION

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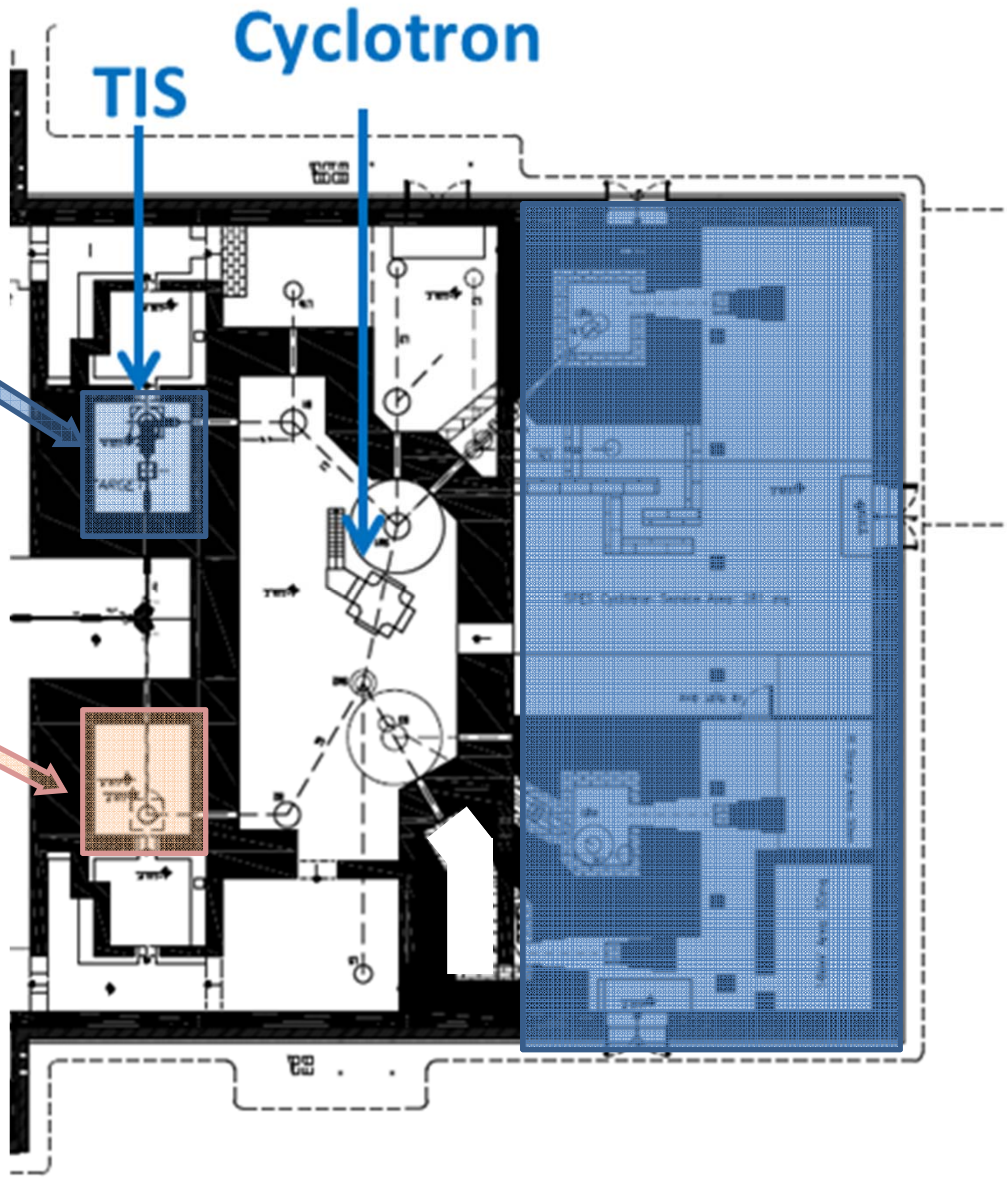
Radiation Protection items

1. Spes α: work done and existing licensing
   - Shielding
   - Activation (cyclotron-beam line, air, soil, water, concrete)
   - Radioactive release in case of accident
2. Spes β: ongoing calculations
   - RIB extraction and transport
   - Activity build up on selected elements
   - Radioactive gas exhausted
   - Irradiated targets temporary storage
   - Risk analysis
3. Spes γ: ongoing calculations

Spes α: licensing - prescriptions

- Conventional (non fissile) targets, SiC and LaC, can be used with maximum proton current 200 μA in bunker 1
- Graphite and other medium-high Z targets can be used with maximum proton current 500 μA in bunker 2
- UCx target at this stage can be used exclusively to test the transport line to the existing linac, with proton current 5 μA and energy 40 MeV (maximum test period allowed: 18 months)



Spes α: Project constraints

Compliance with the following constraints must be guaranteed:

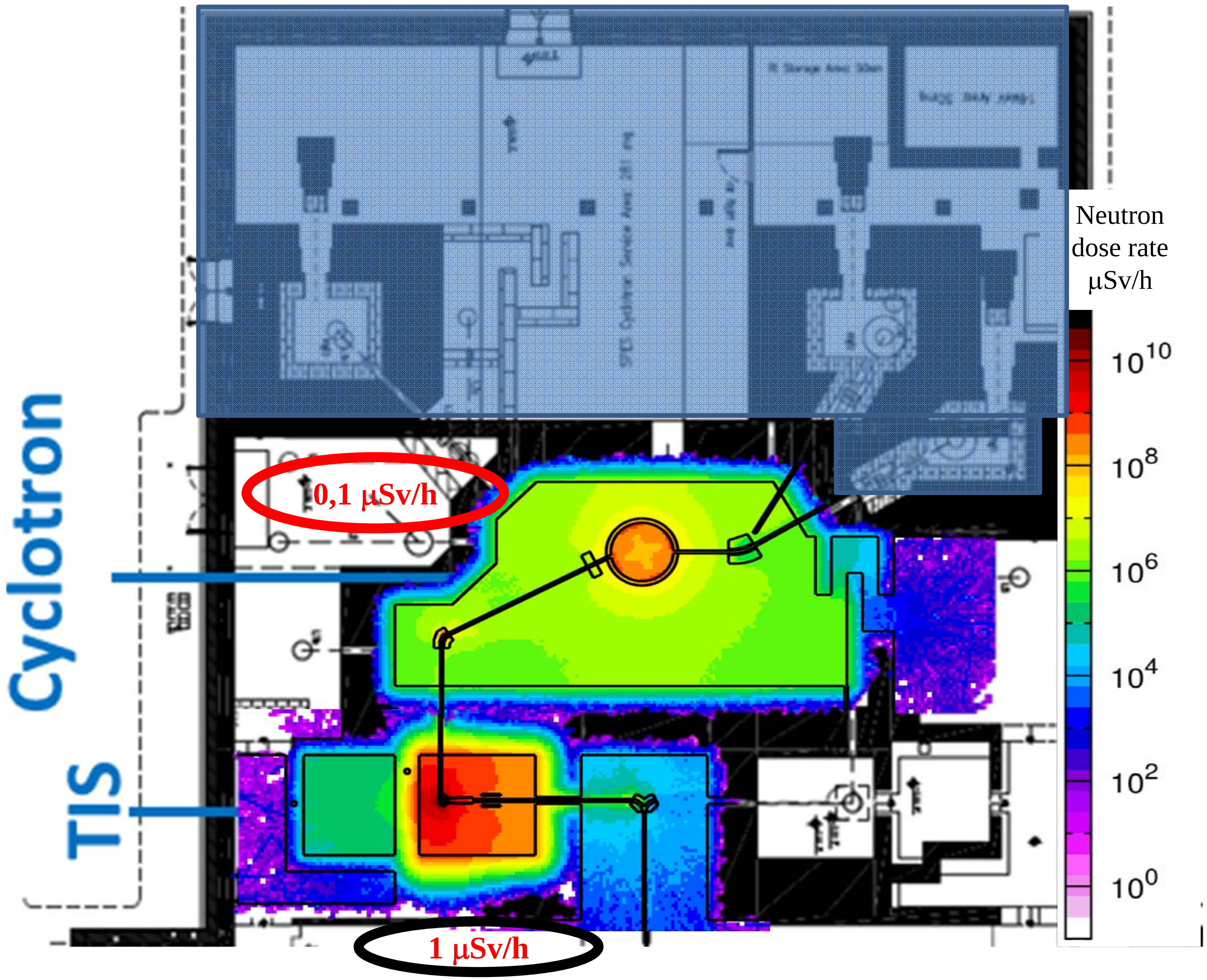
- 5 μSv/h in controlled areas
- 0.3 μSv/h in areas for non exposed personnel
- 1000 hours/year exposed classified personnel allowed to stay in controlled areas
- 2000 hours/year cyclotron working time

Spes α: existing licensing and shielding

Dose rate constraints are achieved with adequate shielding design. The optimum thickness has been evaluated with numerical simulations, using as source term:

- For the irradiation bunker shielding: UC_x target with proton current of 300 μA and energy 70 MeV
- For the cyclotron vault shielding: proton current losses of 5% in acceleration (30-70 MeV) and 0,6% on the magnet bending the beam on target

Spes α: layout and shielding results

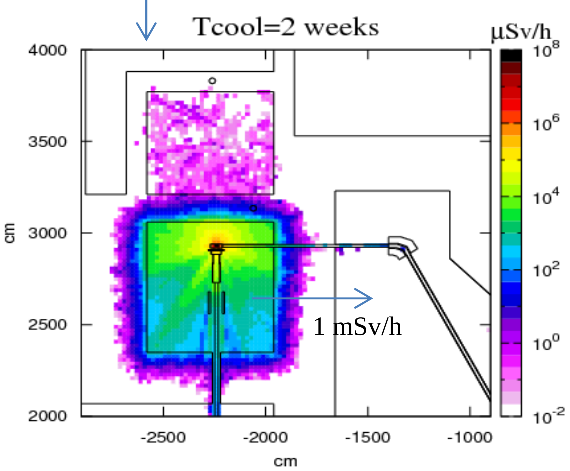


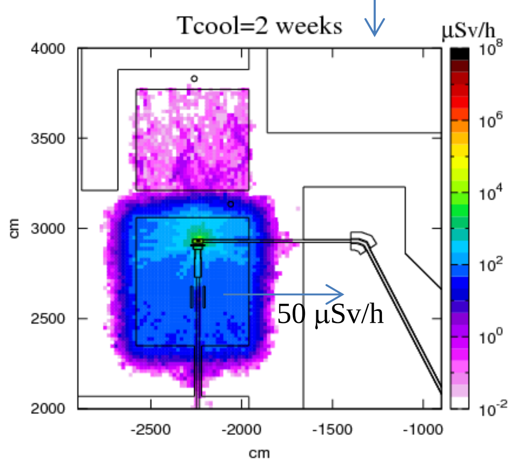
Spes α: activation

p on UCx, 40 MeV, 200 μA - 5x10^13 Bq produced at EOB

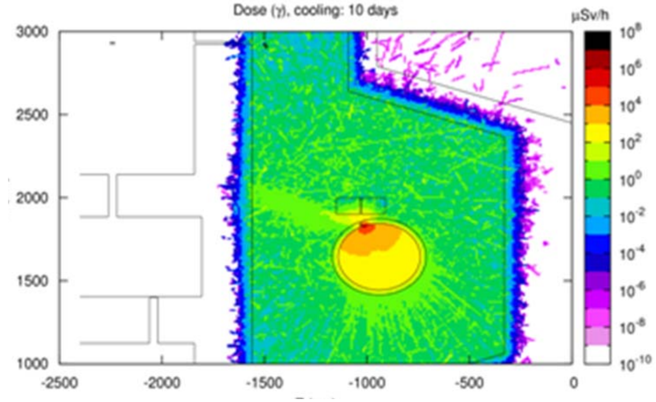
Target present

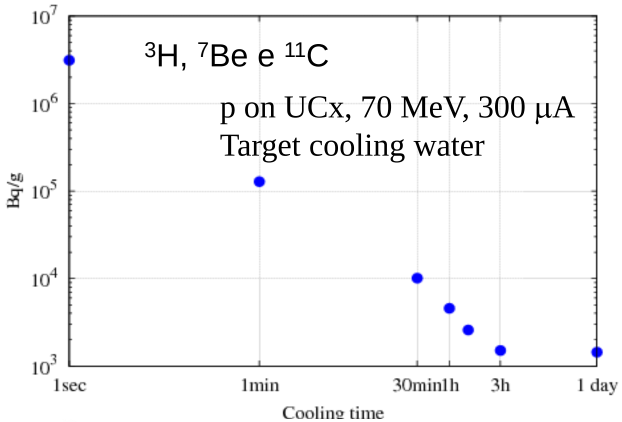
Target absent

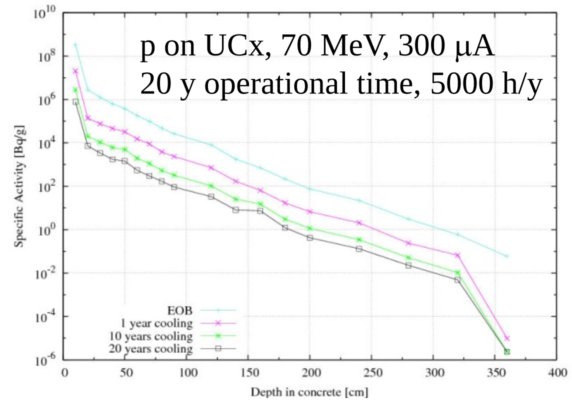




proton current losses of 5% in acceleration







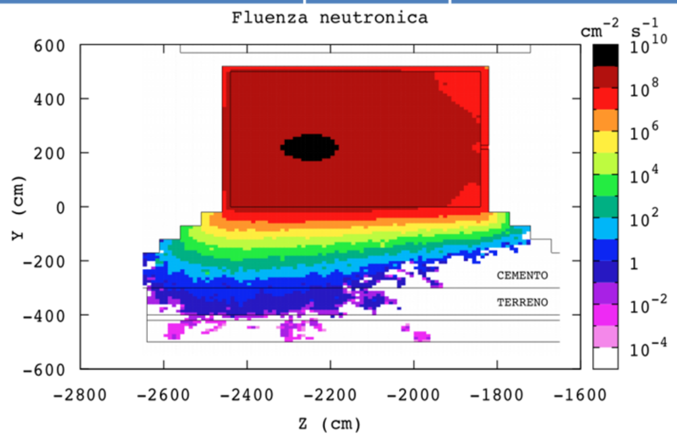
Nuclide	$T_{1/2}$	A_S	A_{eq}	RA	RA_{cooled} (20 min)	RA_{year}
		Bq/g		Bq/g per sec	Bq/g	Bq/y
^{3}H	12,33 y	6,6 10^{3}	0,2	1,2 10^{-5}	1,2 10^{-5}	7,8 10^{7}
^{7}Be	53,29 d	3,6 10^{3}	11,8	5,5 10^{-4}	5,5 10^{-4}	3,6 10^{9}
^{10}Be	1.51 10^{6} y	2,3 10^{2}	7,2 10^{-8}	-	-	-
^{11}C	20.39 m	1,5 10^{4}	1,4 10^{4}	0,6	0,3	3,9 10^{12}
^{14}C	5730 y	6,6 10^{6}	0,5	2,5 10^{-5}	2,5 10^{-5}	1,6 10^{8}
^{13}N	9,965 m	1,0 10^{4}	1,0 10^{4}	0,5	1,1 10^{-1}	3,2 10^{12}
^{15}O	122,24 s	4,8 10^{3}	4,8 10^{3}	0,2	2,5 10^{-4}	1,3 10^{12}
^{35}S	87,51 d	9,2	1,8 10^{-2}	8,5 10^{-7}	8,5 10^{-7}	5,5 10^{6}
^{41}Ar	109,34 m	1,4 10^{4}	9,6 10^{3}	0,4	0,4	2,6 10^{12}
TOT		6,6 10^{6}	4,3 10^{4}	2,0	**0,8**	1,1 10^{13}

p on UCx, 40 MeV, 200 μA

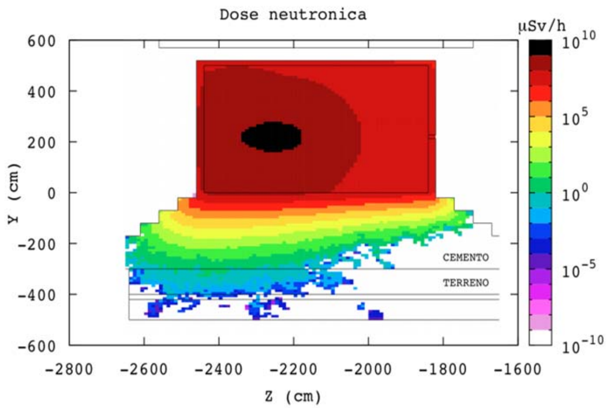
Spes α: soil activation

Soil composition

Element	**Partial density**	**% Contenent**
Ossigeno	0.79	**39.5%**
Silicio	0.32	**16.0%**
Calcio	0.63	**31.4%**
Alluminio	0.09	**4.8%**
Ferro	0.03	**1.6%**
Magnesio	0.09	**4.5%**
Potassio	0.02	**1.0%**
Sodio	0.01	**0.7%**
Mn, Ti, P, Sr, Cr, Zn, Ni, V, Ba, Cu, S, *Co*, *Cs*, Eu	**0.01**	**0.5%**



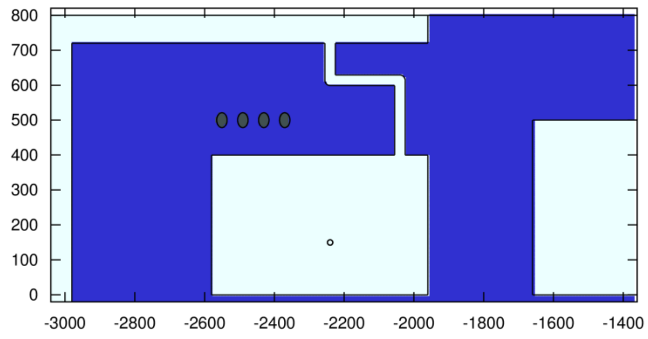
p on SiC 70 MeV,
300 μA, 1y of irradiation

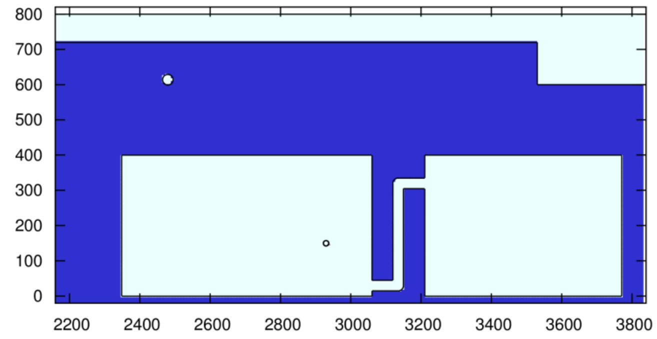


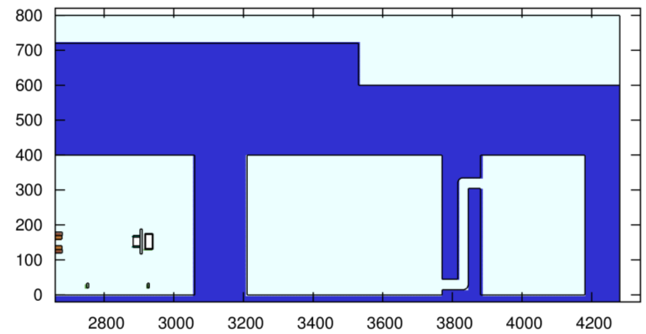
Nuclide	**$T_{1/2}$**	**Activity after 6 months (Bq)**	**Activity after 1 year (Bq)**
^{134}Cs	2.0648 y	1.9	**3.5**
^{55}Fe	2.73 y	1.1	**2.2**
^{54}Mn	312.12 d	2.4	**3.9**
^{45}Ca	162.61 d	1.7	**2.5**
^{41}Ca	$1.03\ 10^5$ y	$2.1\ 10^{-4}$	**$4.2\ 10^{-4}$**
^{40}K	$1.277\ 10^9$ y	$8.4\ 10^{-9}$	**$1.7\ 10^{-8}$**
^{39}Ar	269 y	$5.8\ 10^{-3}$	**$1.2\ 10^{-2}$**
^{38}K	7.636 m	12.9	**12.9**
^{37}Ar	35.04 d	14.6	**15.0**
^{36}Cl	$3.01\ 10^5$ y	$8.5\ 10^{-6}$	**$1.7\ 10^{-5}$**
^{28}Al	2.2414 m	22.8	**22.8**
^{26}Al	7.4E+5 y	$4.0\ 10^{-6}$	**$8.0\ 10^{-6}$**
^{24}Na	14.9590 h	2.7	**2.7**
^{15}o	122.24 s	12.9	**12.9**
^{11}C	20.39 m	12.9	**12.9**
^{3}H	12.33 y	0.4	**0.7**
TOT		**86.3**	**92.0**

Sample weight $2.5\mathrm{x}10^5$ g

Spes α: ventilation system







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 1 Bq/g at the exhaust and no storage time is needed
- 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

Nuclide	**$T_{1/2}$**	**Radioactive release (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	$6.8\ 10^{6}$	

Spes α: ventilation system

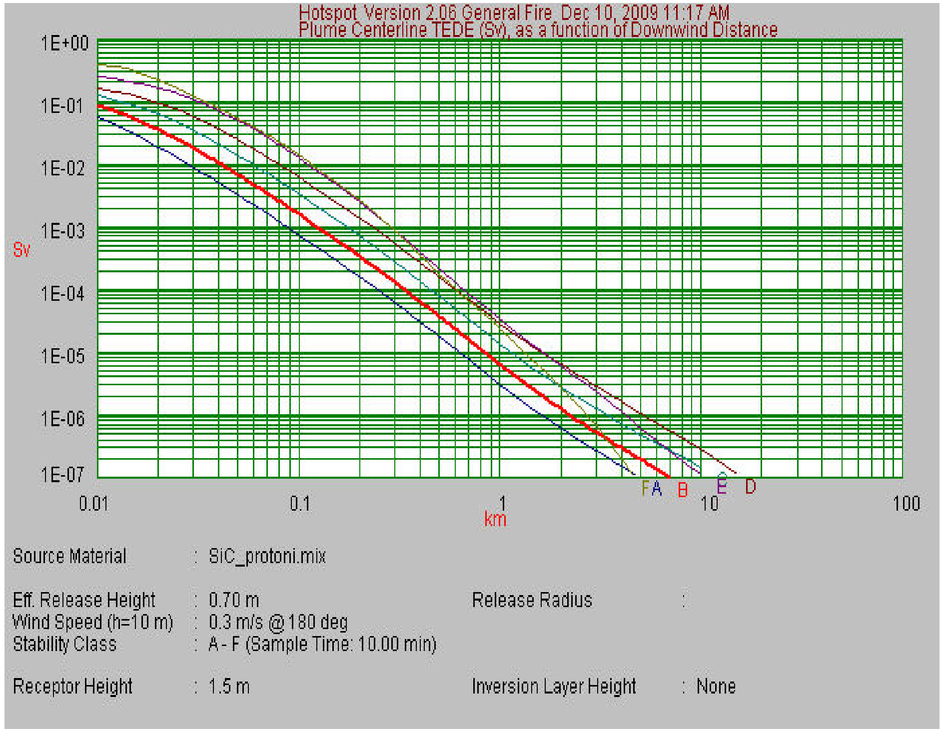
UC$_x$ target

- 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)
- For H^+ at 40 MeV and 200 μA, a decay time of 20 min is long enough to keep the concentration lower than 1 Bq/g (less than 2 hours for 70 MeV and 300 μA, annual activity released 7 x10^{14} Bq)
- In the worst irradiation case, 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 definitely not relevant from a radiological point of view.

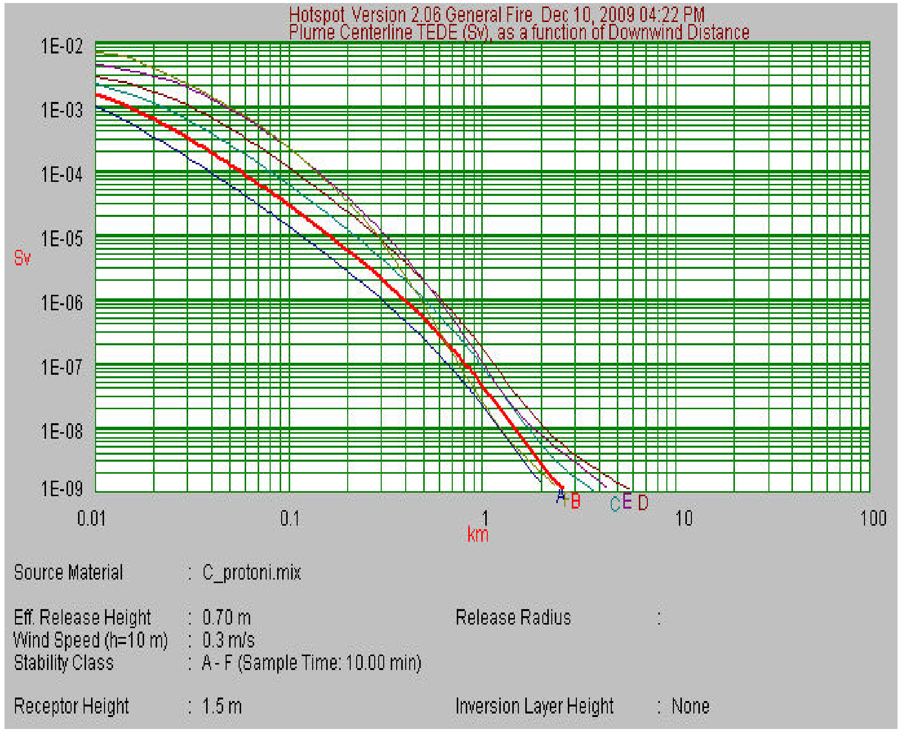
Nuclide	**$T_{1/2}$**	**Radioactive release (Bq/y)**	**TEDE (Sv/y)**
^{3}H	12.33 y	1.8 10^{9}	3 10^{-6}
^{14}C	5730 y	2.7 10^{8}	
^{35}S	87.51 d	7.7 10^{8}	

Spes α: Radioactive release in case of accident

Protons on SiC, 70 MeV, 200 μA



Protons on C, 70 MeV, 500 μA



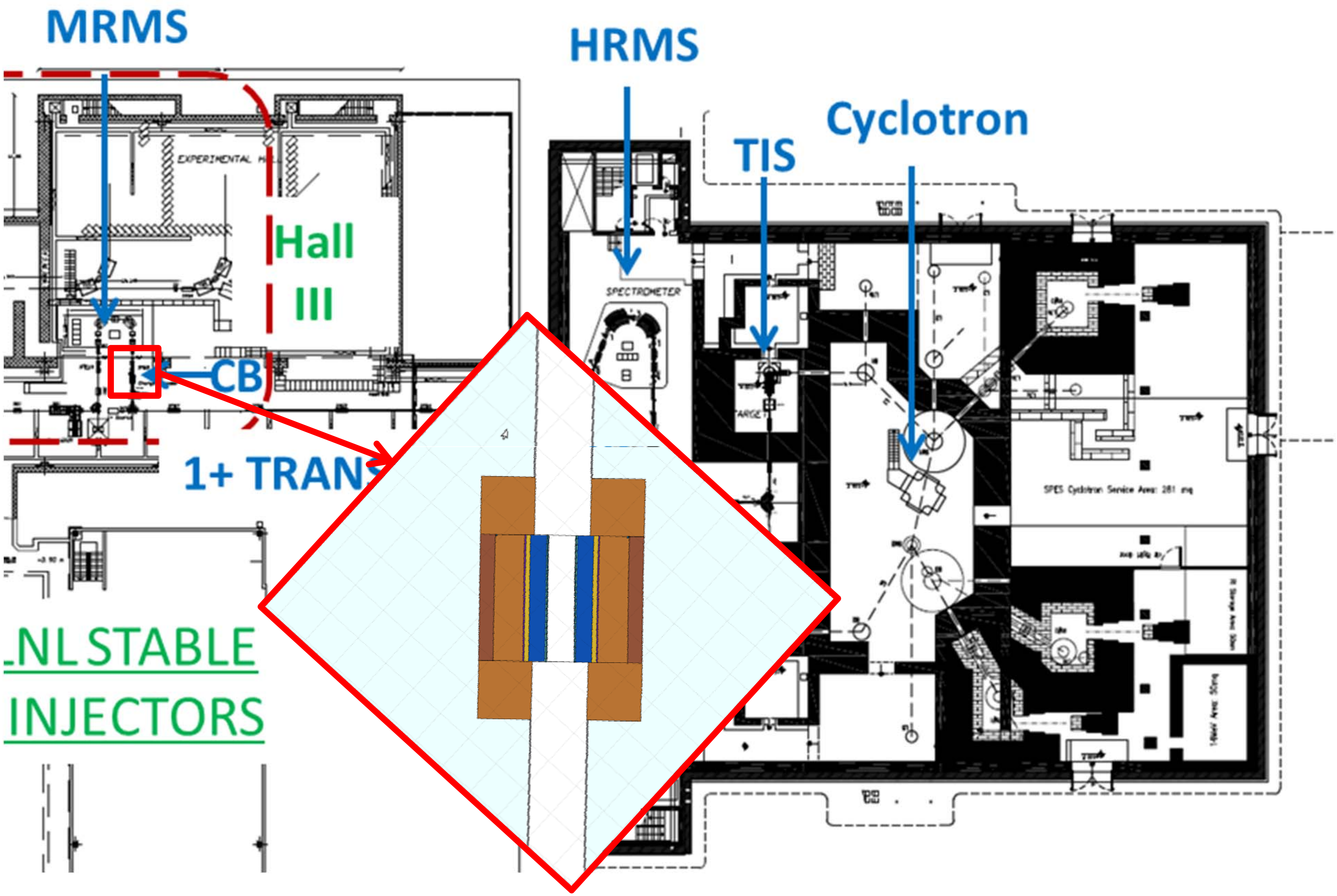
1 mSv/y and 10 μSv/y are obtained for distances greater than 300 m ad 3 km from the point of emission

1 mSv/y and 10 μSv/y are obtained for distances significantly minor than in the case of SiC

Spes β: RIB extraction and transport

- The beam of interest for physics will be extracted from the target and transported to the re-accelerating Linac
- Depending on the performances of various elements (ionization sources, Wien filter ...) the beam is not «pure», but it comes out together with other beams of the same mass number
- Interaction of those beams with the elements of the transport line might lead to a stack of radioactive ions, behaving like radioactive sources
- Ambient dose equivalent rates in presence of those sources, and radioactivity build up, are relevant quantities from a RP point of view.

Spes β: RIB extraction and transport



Spes β: RIB extraction and transport, some cases

The beam of physical interest is **Sn-132**. When extracted with a Laser Ion Source, it comes out with just one contaminant beam, Cs-132

Element	Z	N	nA	$T_{1/2}$
Sn	50	82	1.759	39.7 sec
Cs	55	77	1.073	6.48 days
Ba	56	76	0.009	Stable
La	57	75	0.000	4.8 h

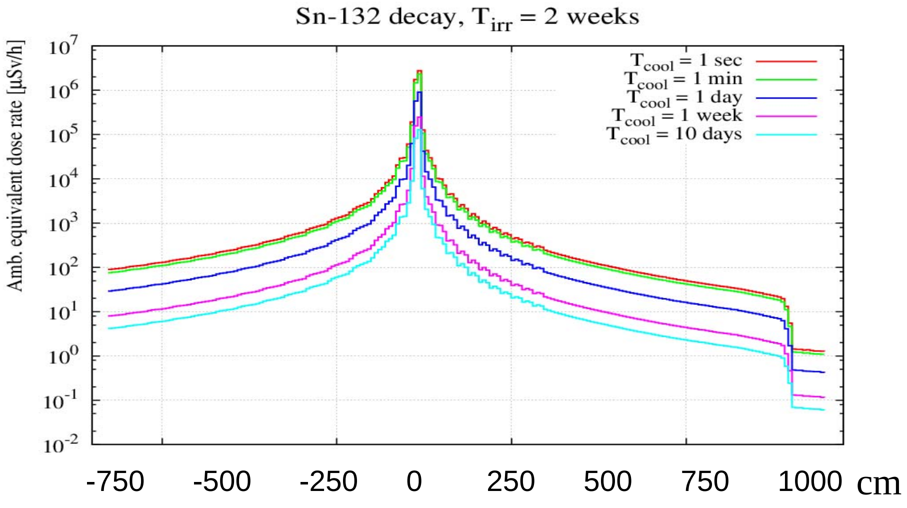
Sn-132 decay chain

$^{132}Sn \xrightarrow[\beta^-]{39.7s} {}^{132}Sb \xrightarrow[\beta^-]{2.8m} {}^{132}Te \xrightarrow[\beta^-]{3.2d} {}^{132}I \xrightarrow[\beta^-]{2.3h} {}^{132}Xe$

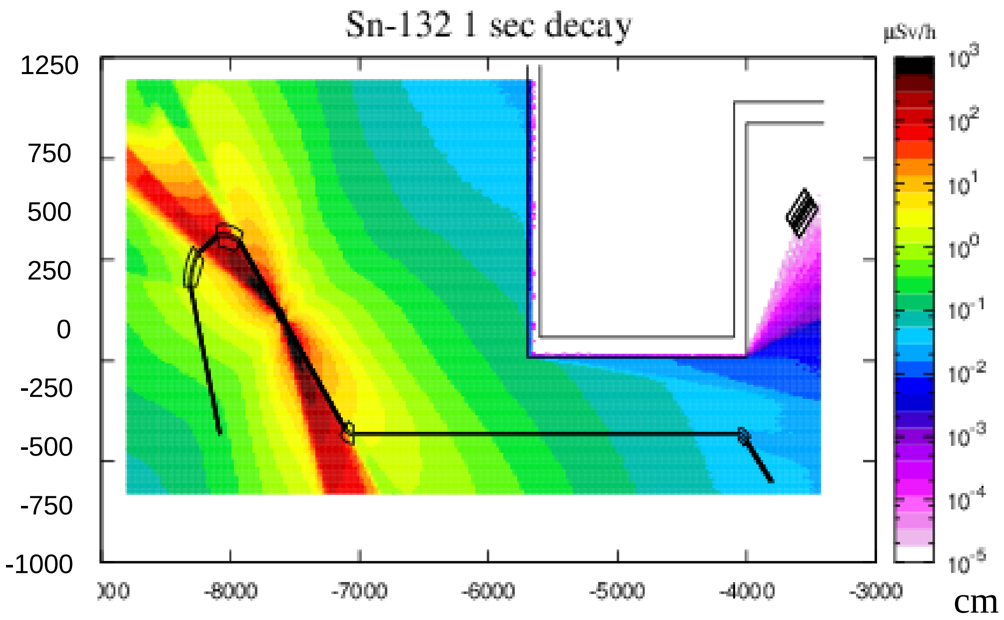
Cs-132 decay chain

$^{132}Cs \xrightarrow[\beta^-]{6.5d} {}^{132}Xe$

Spes β: RIB extraction and transport, some cases



The deposition of the beam on the element causes a problem in case personnel intervention is needed in vicinity of the Charge Breeder.



10 days after the end of the beam extraction the total dose rate (Sn+Cs) is in the order of 10 µSv/h at few meters from the element.

Spes β: RIB extraction and transport, some cases

The beam of physical interest is **I-135**. When extracted with a Plasma Ion Source, it comes out with many contaminant beams (listed in table)

Element	Z	N	nA	$T_{1/2}$
Sb	51	84	1.130	1.7sec
Te	52	83	2.794	18.6sec
I	53	82	6.378	6.61hour
Xe	54	81	4.632	9.1hour
Cs	55	80	3.841	$2 \cdot 10^6$years
La	57	78	0.575	19hours
Ce	58	77	0.080	18hours
Pr	59	76	0.005	25min

$$^{135}Sb \xrightarrow[\beta^-]{1.7s} {}^{135}Te \xrightarrow[\beta^-]{18.6s} {}^{135}I \xrightarrow[\beta^-]{6.6h} {}^{135}Xe \xrightarrow[\beta^-]{9.1h} {}^{135}Cs \xrightarrow[\beta^-]{2\ 10^6 y} {}^{135}Ba$$

$$^{135}Pr \xrightarrow[\beta^+]{23.3m} {}^{135}Ce \xrightarrow[\beta^+]{17.7h} {}^{135}La \xrightarrow[\beta^+]{19.5h} {}^{135}Ba$$

Spes β: RIB extraction and transport, some cases

The beam of physical interest is **I-135**. When extracted with a Plasma Ion Source, it comes out with many contaminant beams (listed in table)

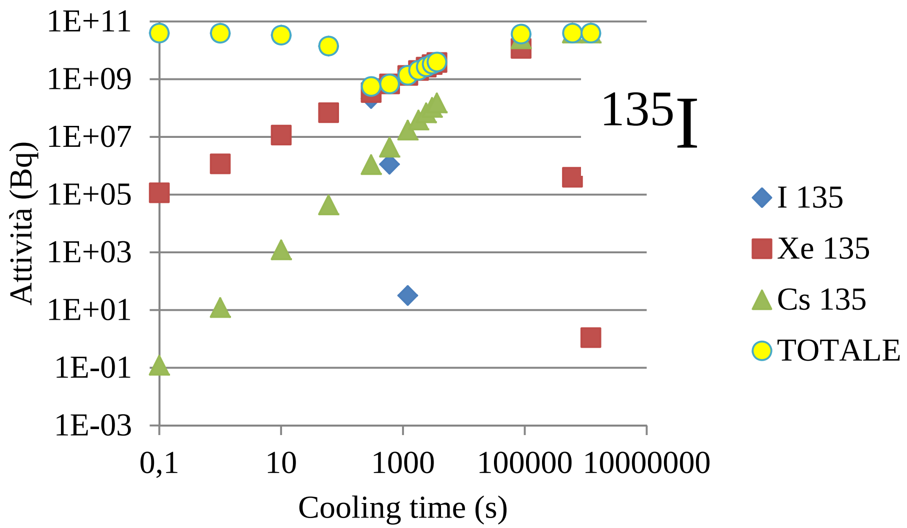
In case each of these beams hits an element of the transport line it generates a radioactive ion source of about 3 Ci (the number can be scaled to the amount of current interacting), due to Cs-135 ($T_{1/2}$= millions of years)

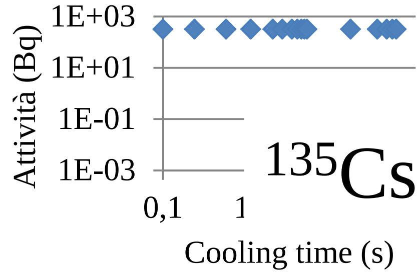
$$^{135}\mathrm{Sb} \xrightarrow[\beta^-]{1.7s} {}^{135}\mathrm{Te} \xrightarrow[\beta^-]{18.6s} {}^{135}\mathrm{I} \xrightarrow[\beta^-]{6.6h} {}^{135}\mathrm{Xe} \xrightarrow[\beta^-]{9.1h} {}^{135}\mathrm{Cs} \xrightarrow[\beta^-]{2\ 10^6 y}$$

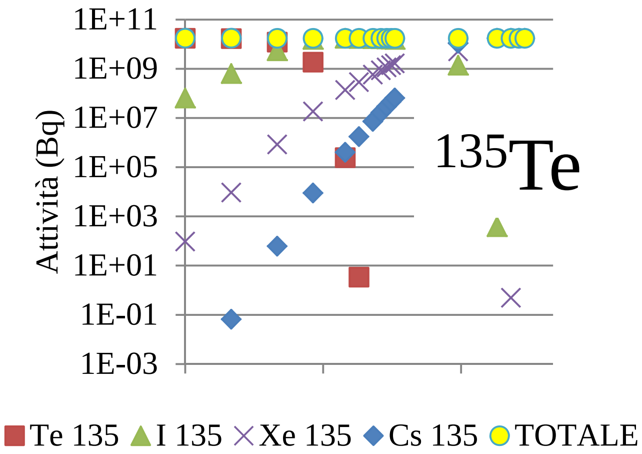
$$^{135}\mathrm{Ba}$$

$$^{135}\mathrm{Pr} \xrightarrow[\beta^+]{23.3m} {}^{135}\mathrm{Ce} \xrightarrow[\beta^+]{17.7h} {}^{135}\mathrm{La} \xrightarrow[\beta^+]{19.5h} {}^{135}\mathrm{Ba}$$

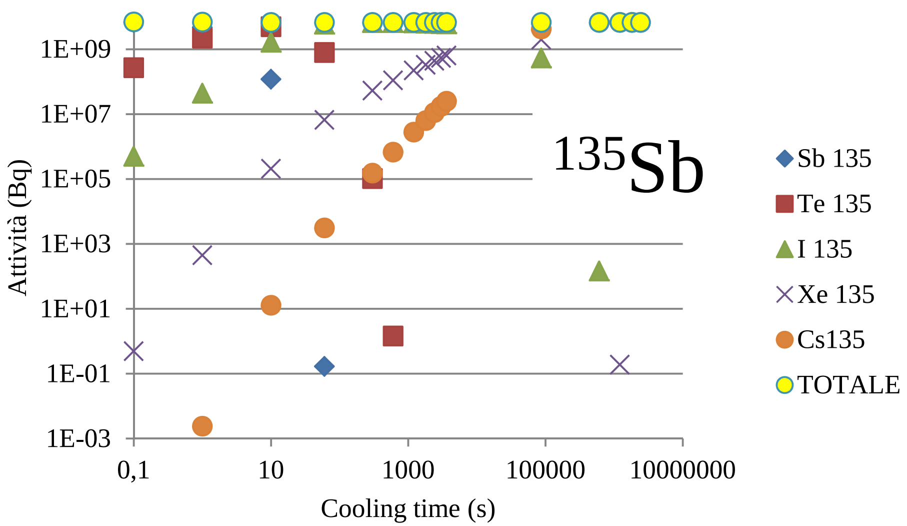
Spes β: RIB extraction and transport, some cases

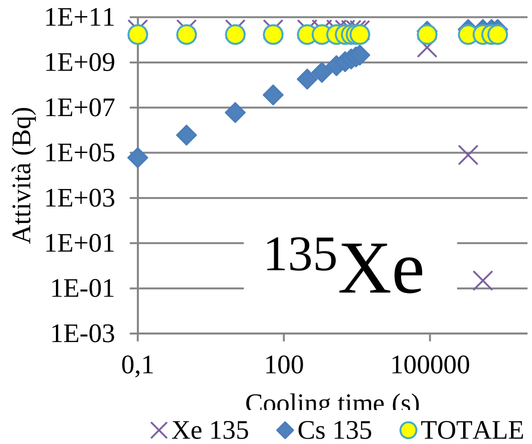






Totale: 2,5 Ci (T_{irr} 2 weeks, T_{cool} 2 weeks)

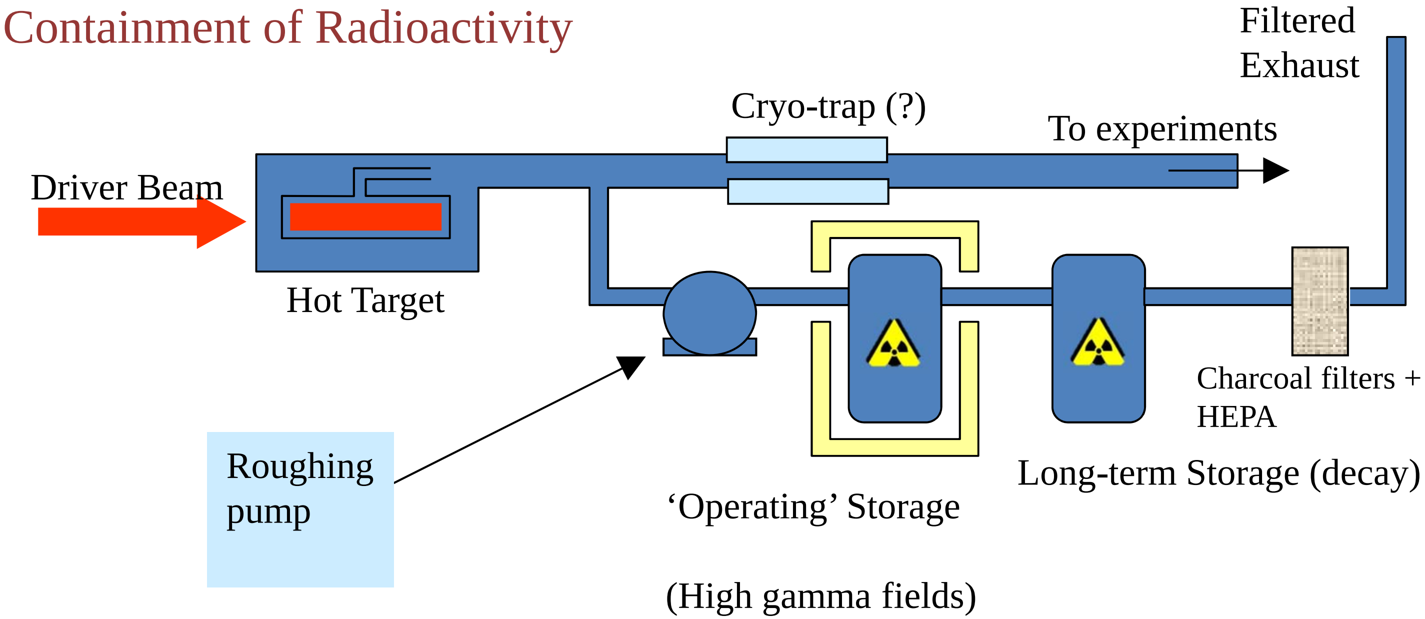




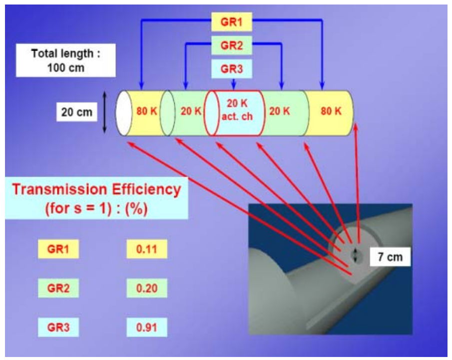
Bateman equations

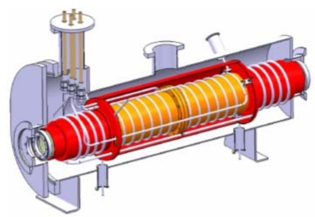
Spes β: radioactive gas exhausted

Containment of Radioactivity



- Calculations show that if the gaseous radioactive species would be stocked all together immediately after an UCx irradiation cycle (2 weeks), the dose rate outside of the tank would be as high as 200 mSv/h
- After 1 day there would be less than 10 mSv/h, and after 10 days around 1 mSv/h





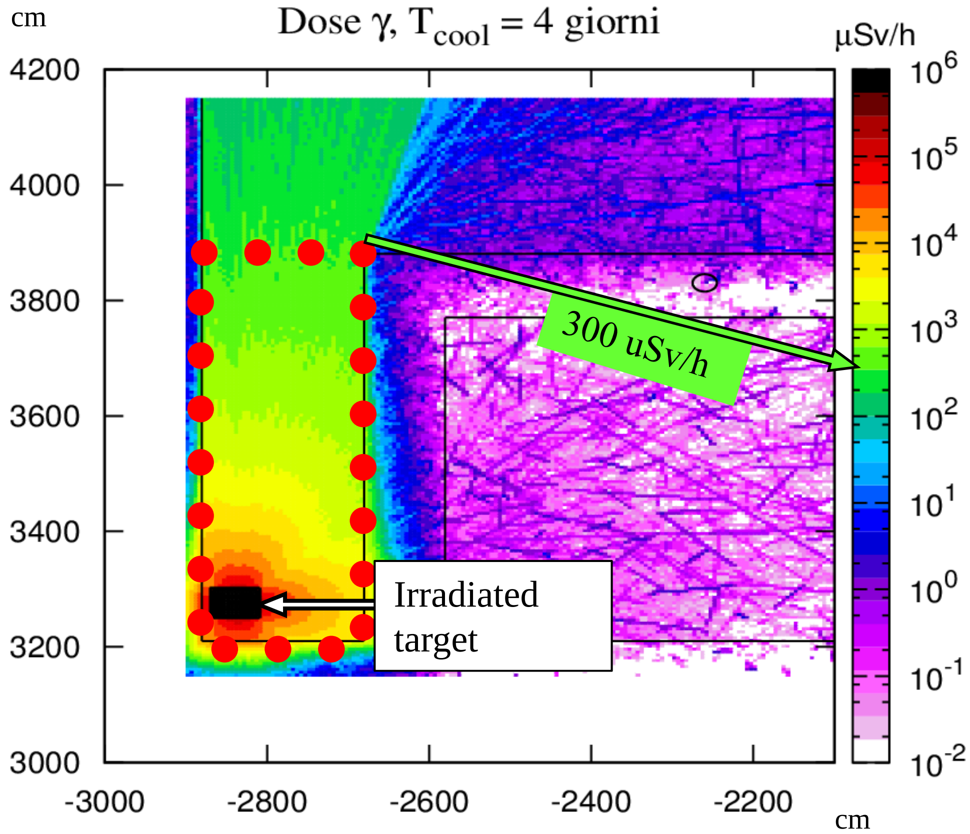
GR1 GR2 GR3

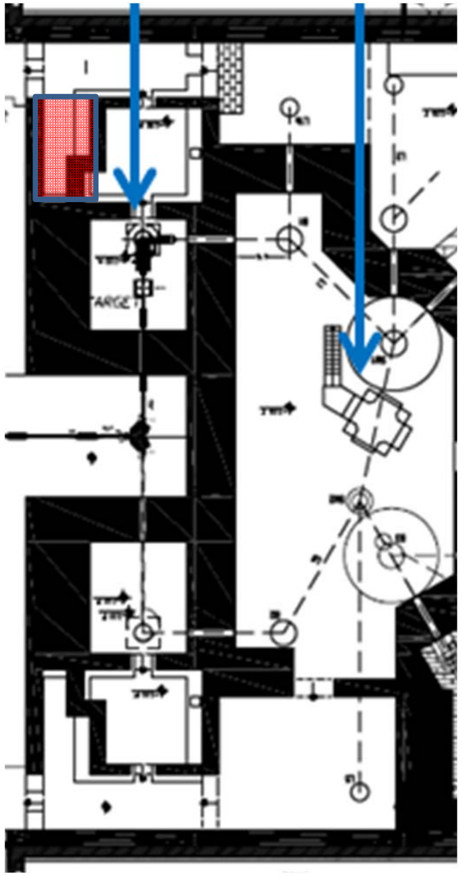
GR1	GR2	GR3
Te, Ba, Sr, Sb, In,…, H_2O	N2, O2, CO2, CO, rare gases	H_2 ; H_3

Spes β: irradiated targets storage

- The UCx target is irradiated for two weeks with a proton beam of 40 MeV energy and 200 uA current
- After few days the target is removed from the front end and placed in a lead-steel box. It is then moved close to the bunker, in a temporary storage place.
- The lead-steel box is 4 cm thick: **1 cm** Steel + **2,5 cm** Pb + **0,5 cm** Steel
- When a second irradiated target has to be stored, the first one is moved forward, so that it will partially shield the fresh one (and so on for further targets)

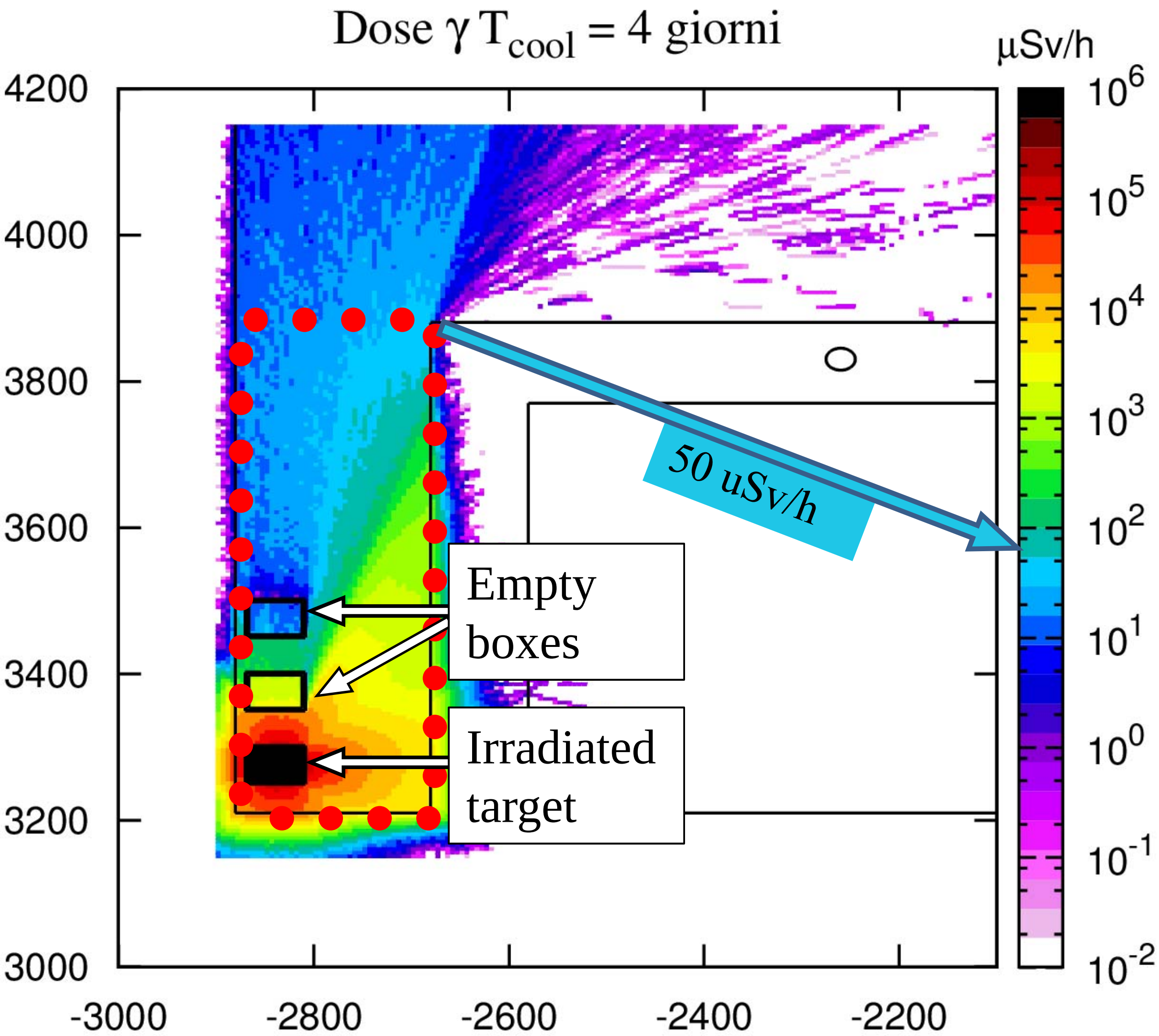
Spes β: irradiated targets storage





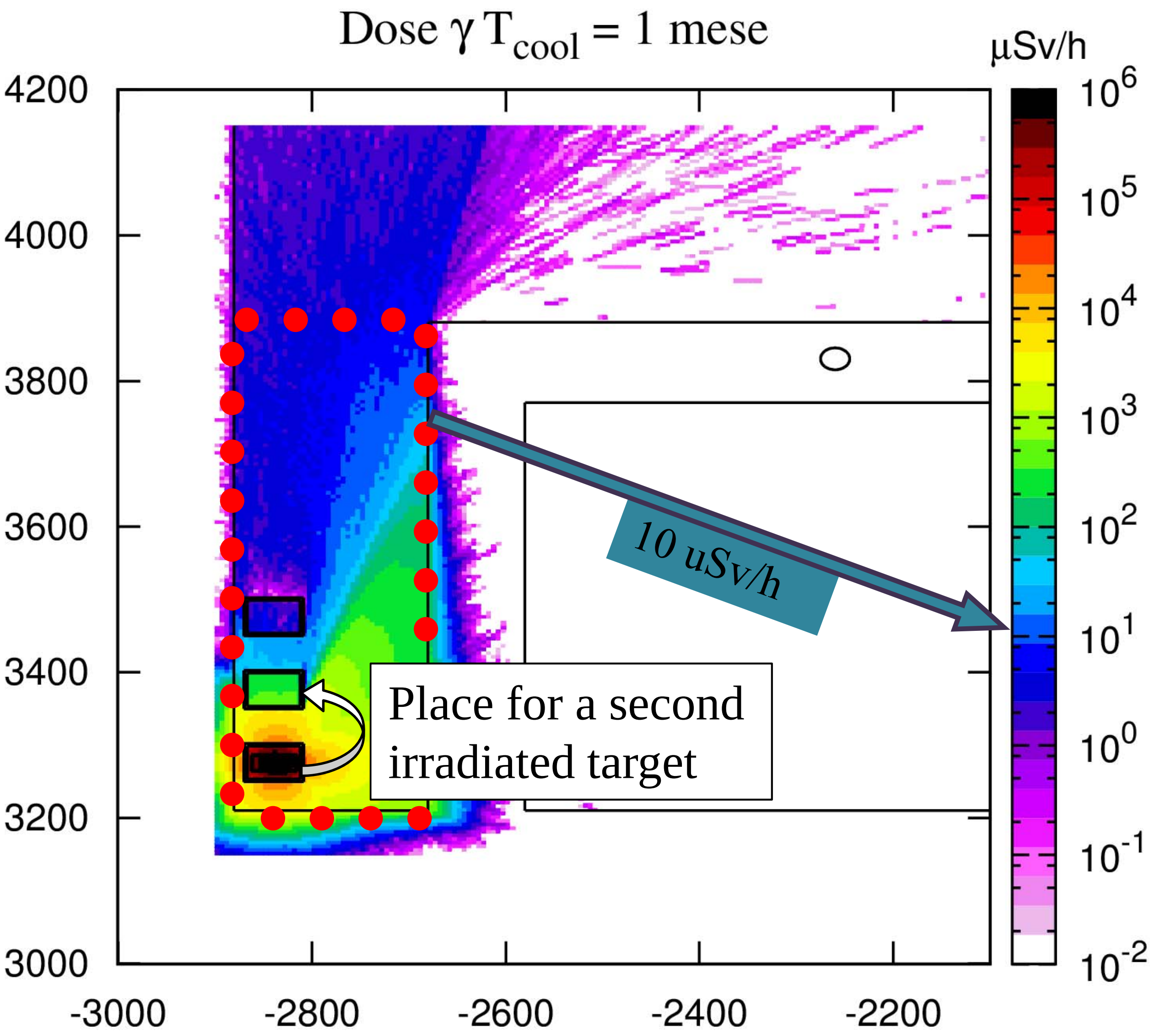
If unshielded, at the end of the storage-corridor there would be 300 μSv/h.
A concrete wall of **70 cm** at least is necessary to achieve an attenuation of 10^{-3} for the dose rate (photons of nearly 3 MeV).

Spes β: irradiated targets storage



The irradiated target is shielded by two empty boxes to reproduce the effect of various targets simoultaneously present.
At the end of the garage-corridor the dose is 50 μSv/h.
A concrete wall of **50 cm** is sufficient to achieve a reduction of 100 for the dose rate (already foreseen by the designers of the storage system)

Spes β: irradiated targets storage



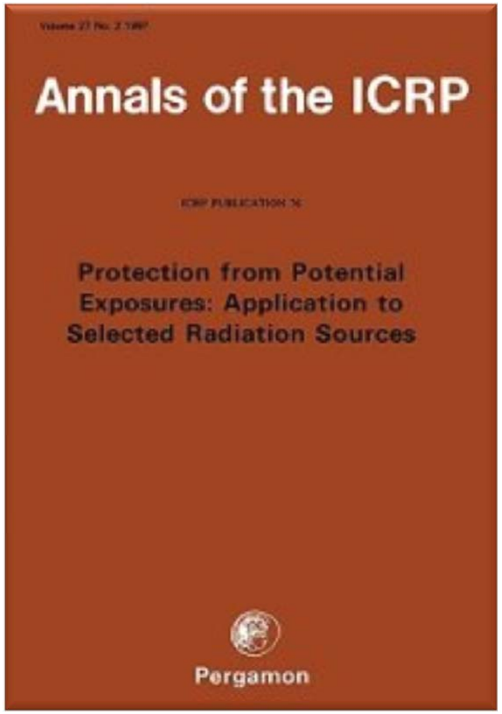
Once a new irradiated target has to be placed in the storage, the first one is moved forward.

10 uSv/h

+

50 uSv/h

Risk analysis – International references



- ICRP 76: *Protection from Potential Exposure : Application to Selected Radiation Sources*

Risk analysis for answering if a potential exposure to radiation could be acceptable or not.

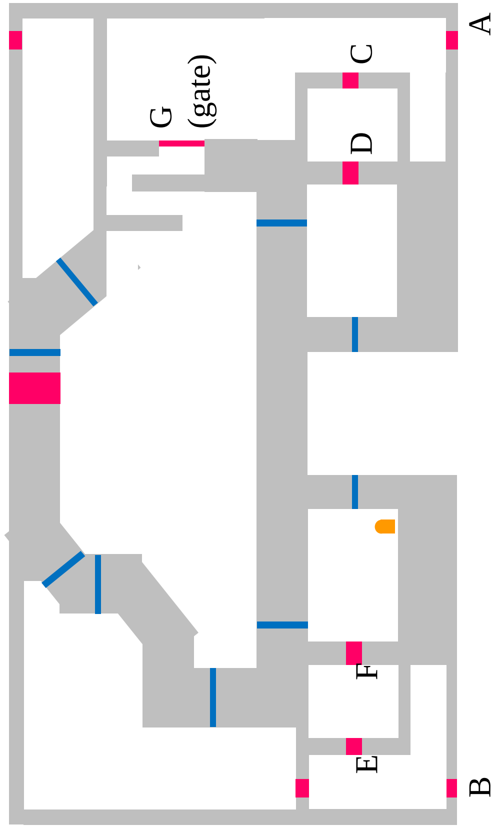
- Principle: *defence in depth*

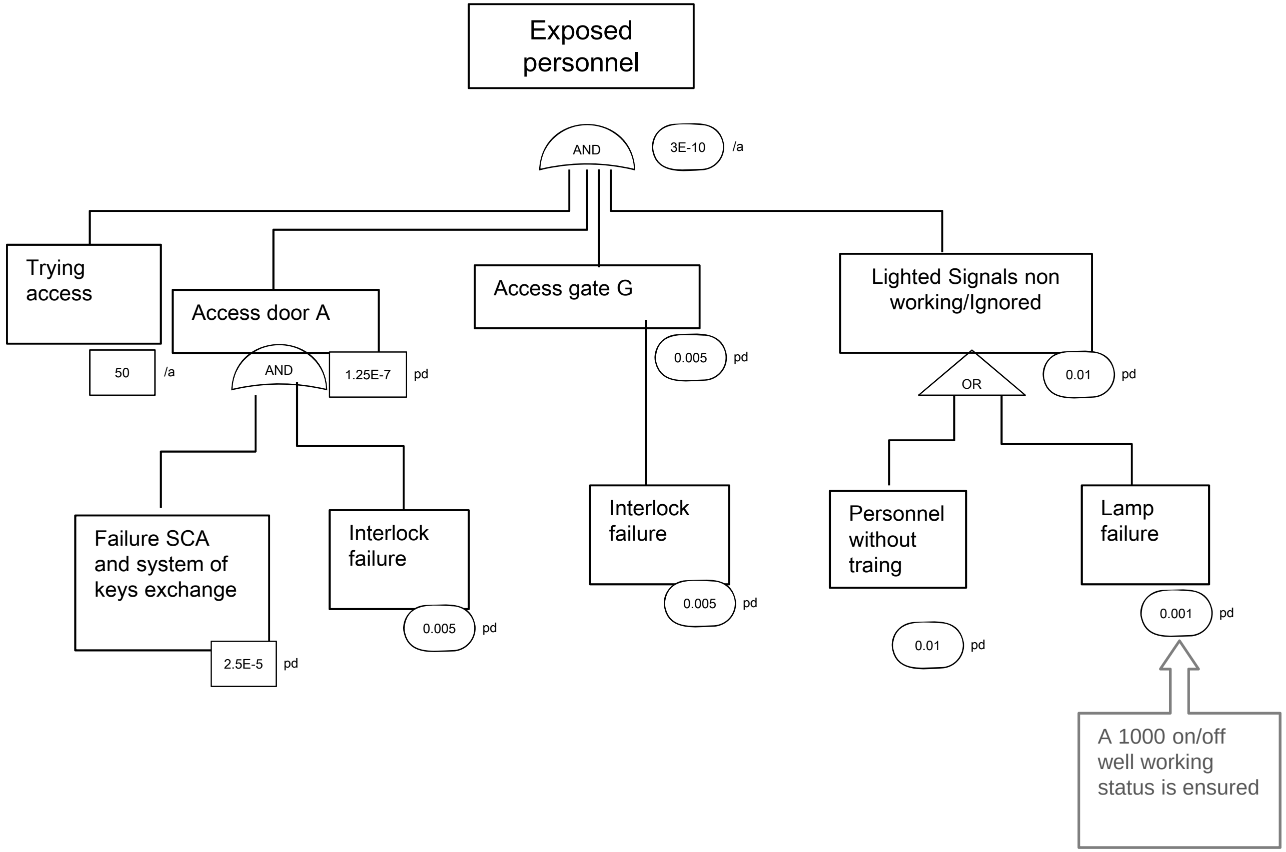
1) Design aimed to minimize the risk
2) Risk reduction using safety devices (interlocks)
3) Alarm devices (radiation alarms)
4) Procedures and training of personnel
5) Residual risk identification at the stage of reviewing the facility

Redudance and diversification

Risk analysis examples 1

Entrance in the cyclotron area when cyclotron is operating: Fault Tree Analysis

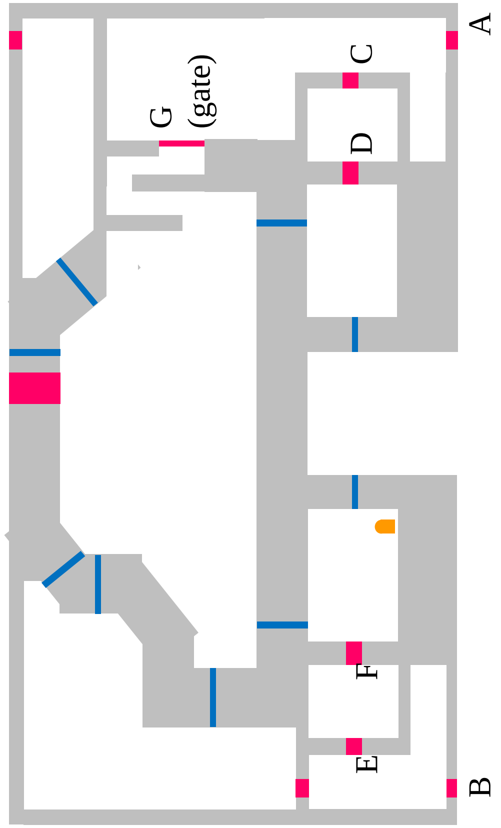


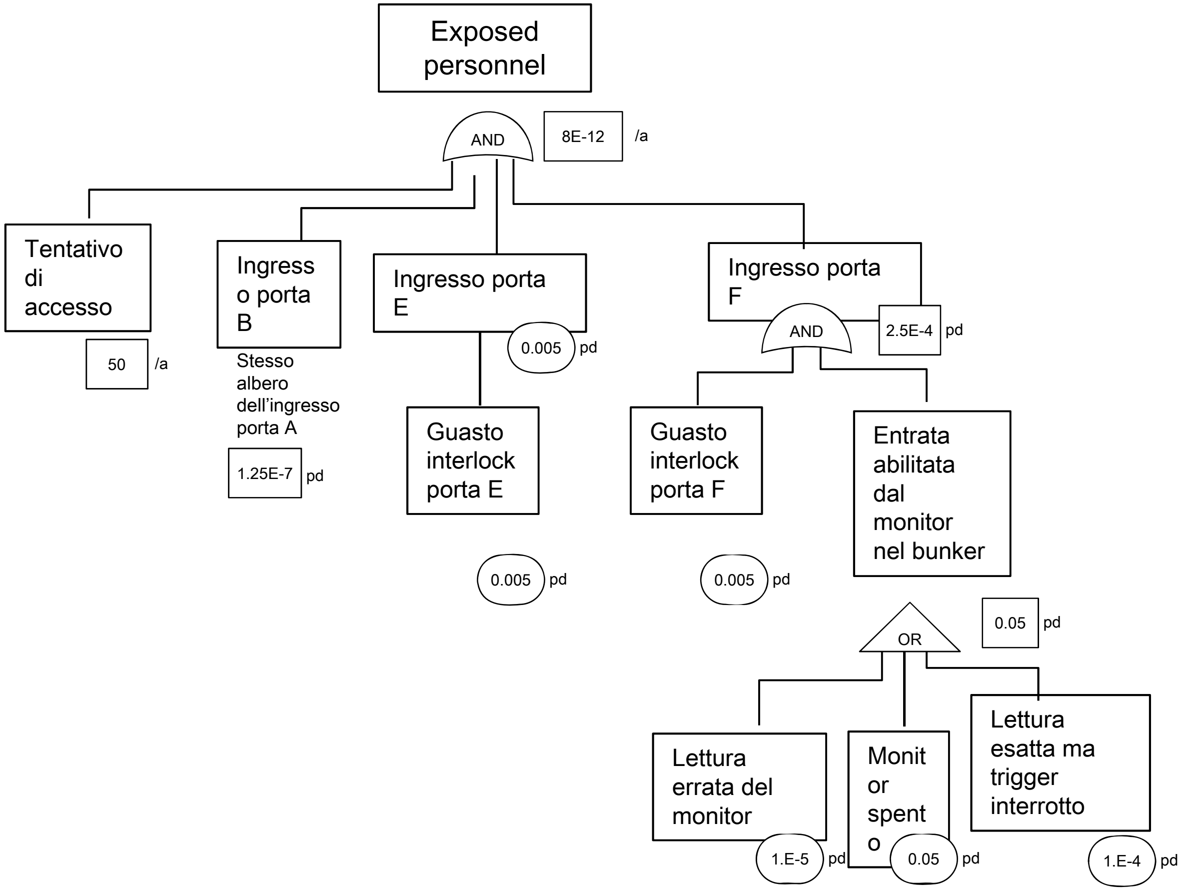


For multiple interlocks data relative to entrance (A-G-…) had to be mltiplied with 0.005.

Risk analysis examples **2**

Entrance in the bunker area when the beam is on target: Fault Tree Analysis



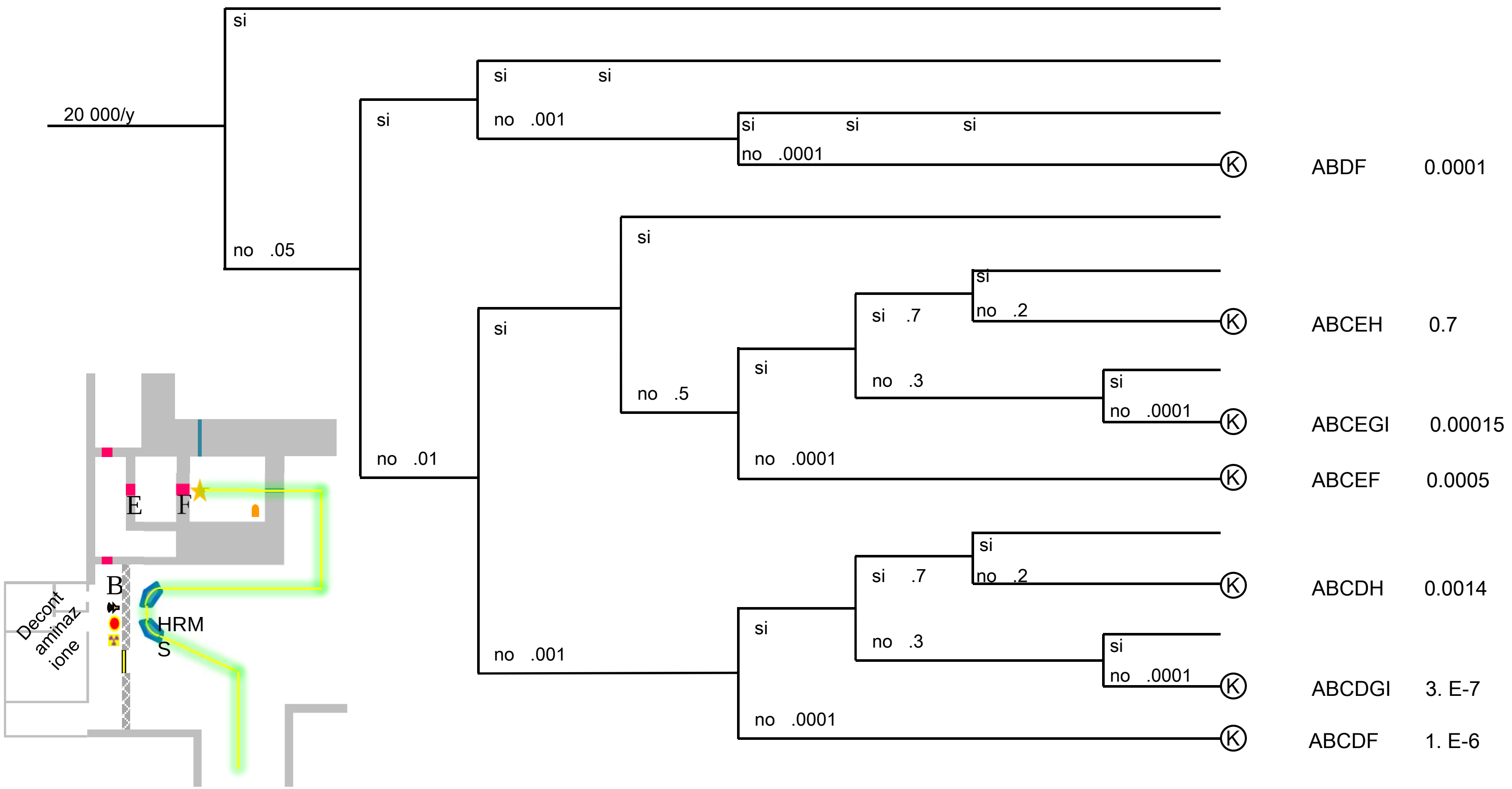


Risk analysis examples **3**

Entrance in the RIB'S area when the beam running: Event Tree Analysis)

Access attempt	Beam off?	A trained worker ?	Are the allarms well working?	Allarms respected ?	Door closed?	Door closed respected?	Barrier respected?	Interlocks on the door well working?	Produced event	Coarse	Frequence of K /year
A	B	C	D	E	F	G	H	I			

Ⓚ= Man entrance in danger area



Total 0.7 times/year could happen an entrance in an area with radiation risk

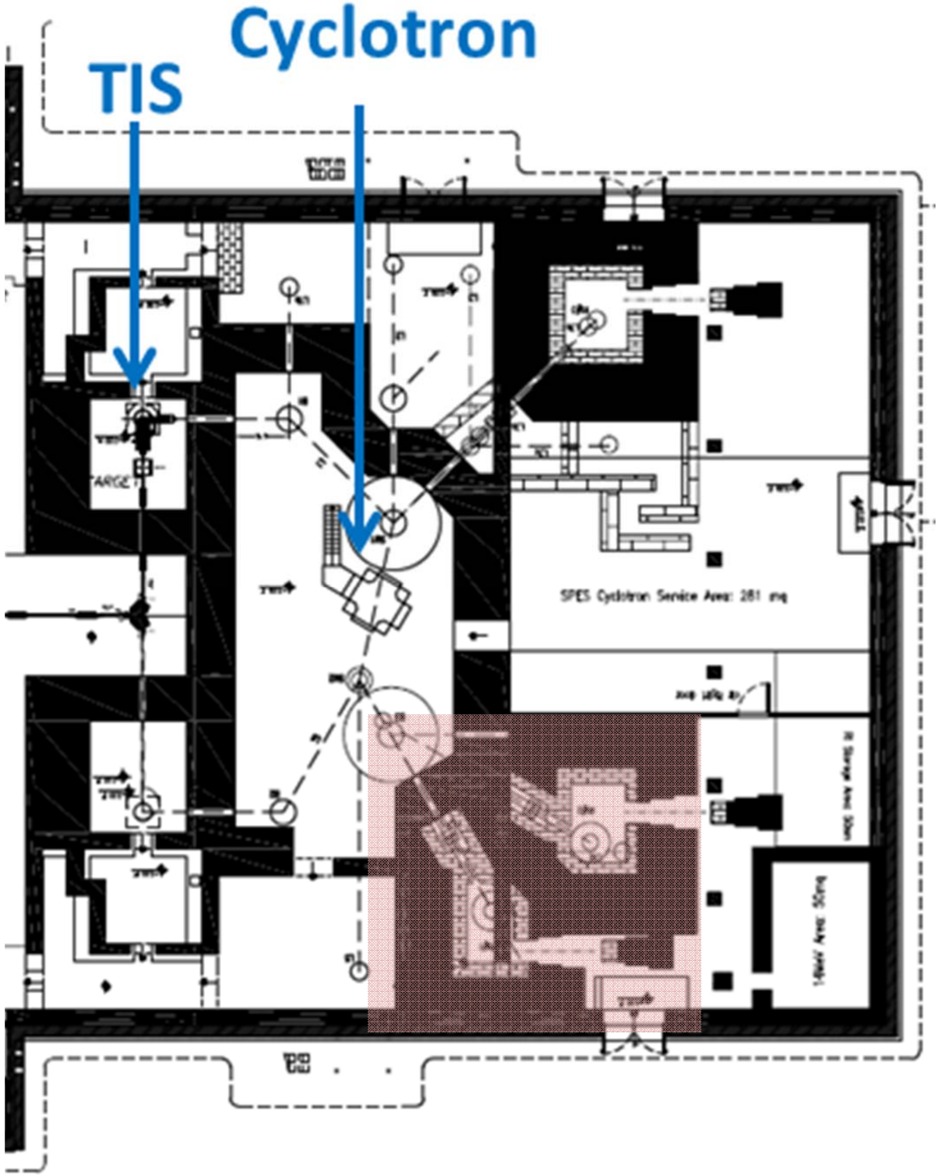
Spes γ: source term

- Among the target nuclides proposed for the production of radiopharmaceuticals, ^{85}Rb is the crucial one for the determination of the shielding thickness and the RP measures.
- Through a **(p,4n)** reaction, ^{85}Rb leads to ^{82}Sr, that decays into ^{82}Rb of medical interest
- With proton energy in the range 40-70 MeV σs of the reactions are between tens and hundreds of mb → high neutron fluxes

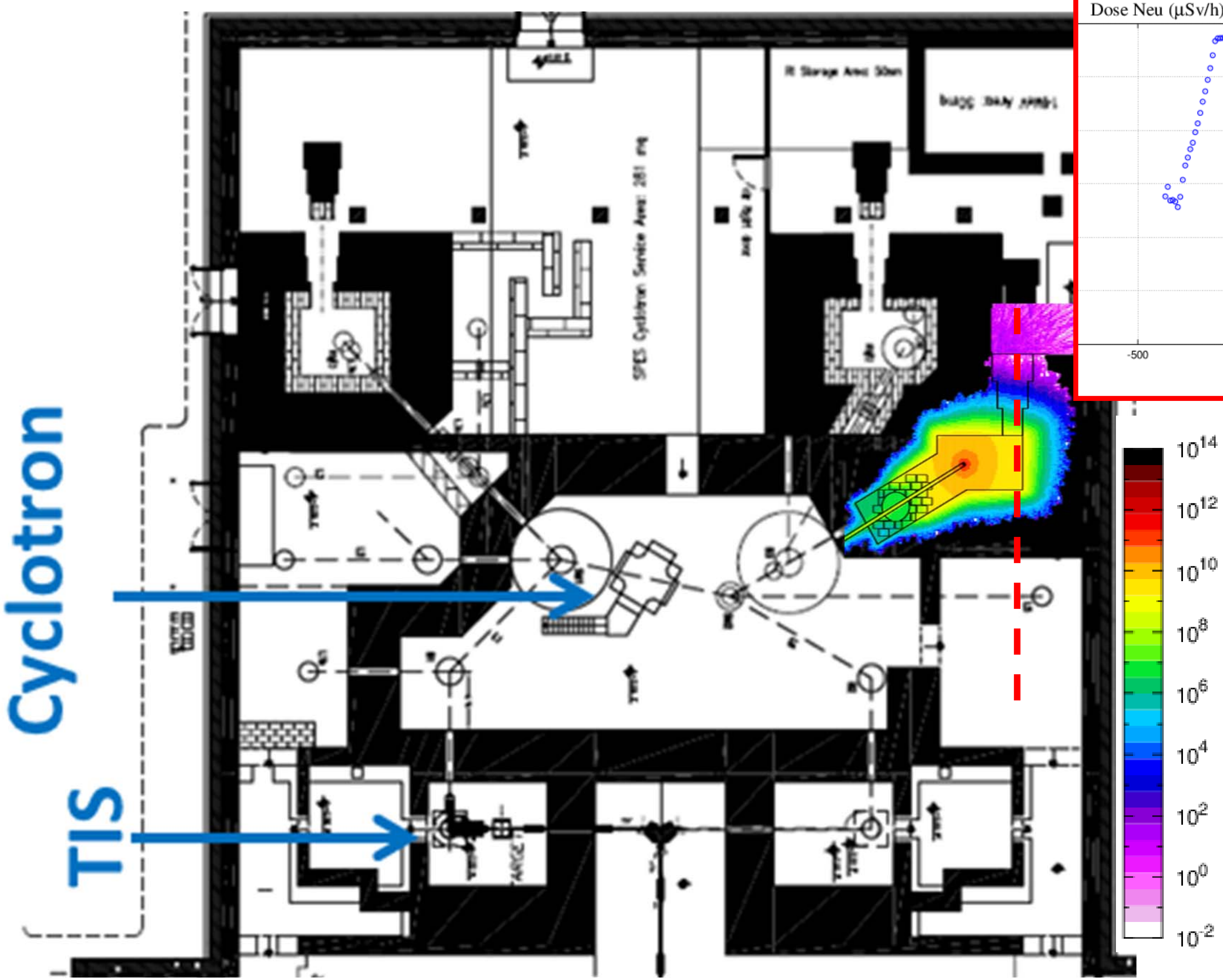
  ^{85}Rb(p,3n)^{83}Sr

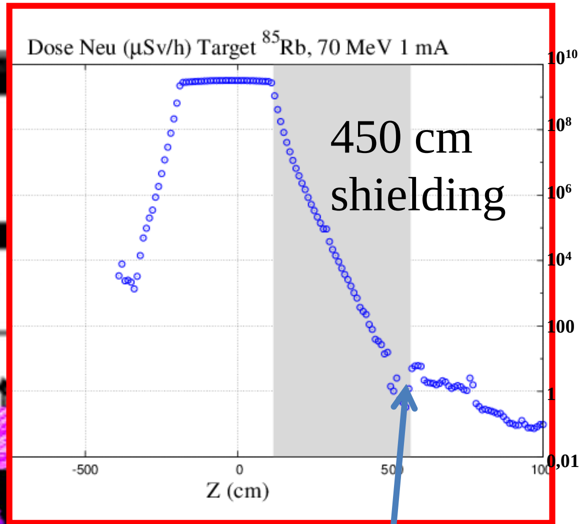
  ^{85}Rb(p,4n)^{82}Sr

  ^{85}Rb(p,5n)^{81}Sr
- Shielding have been designed considering a maximum current of 1 mA



Spes γ: shielding





10 μSv/h
Contribution from the door gaps

With doors properly sealed the dose rate outside of the shielding is less than 0,1 μSv/h

Involved in:

- Defining the Radiological Safety System for SPES-α
- Completing the SPES-β phase (evaluation of the various experimental areas, improvement of the exhausted system, accident related to the UCx source) and produce the Technical Report for licensing
- Completing the SPES-γ phase (shielding completion, target transport system, activation of the air and surroundings, maximum accident predictable, laboratory areas)