Radiological safety aspects of the design of the RNB facilities

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for EURISOL Task#5 Safety & Radioprotection:

GANIL, France, FZJ, Germany, LMU, Germany, CERN, EU
CEA, France, NIPNE, Romania, FI, Lithuania, Univ. Warsaw, Poland

Goal & Strategy

Radiation safety issues

⇒ **the strategy used for the design of RNB facilities**

EURISOL-DS project (illustration) –early stage

Problems addressed:

✓ **Legislation framework** sets-up safety requirements protection of the environment, public and staff

✓ **Radioactive sources identification and estimation** deciding the radiation safety features

✓ **Safety design objectives:**
(*Protection of workers, public & environment)*

Goal & Strategy

1. Operation phase :

- **Protection against radiations** => **optimum shielding configuration**
- **Containment of radioactive materials**=> **risk analysis >** equipments are adequate to minimize risk of radioactive material dispersion.
- **Compatibility with the environment**=> **impact of the radioactive releases**

Radiological studies: Characterization of the prompt radiation field for normal and accident conditions
Safety studies: Classification of the events & Risk assessment
Environmental studies: Characterization of the specific site & impact assessment

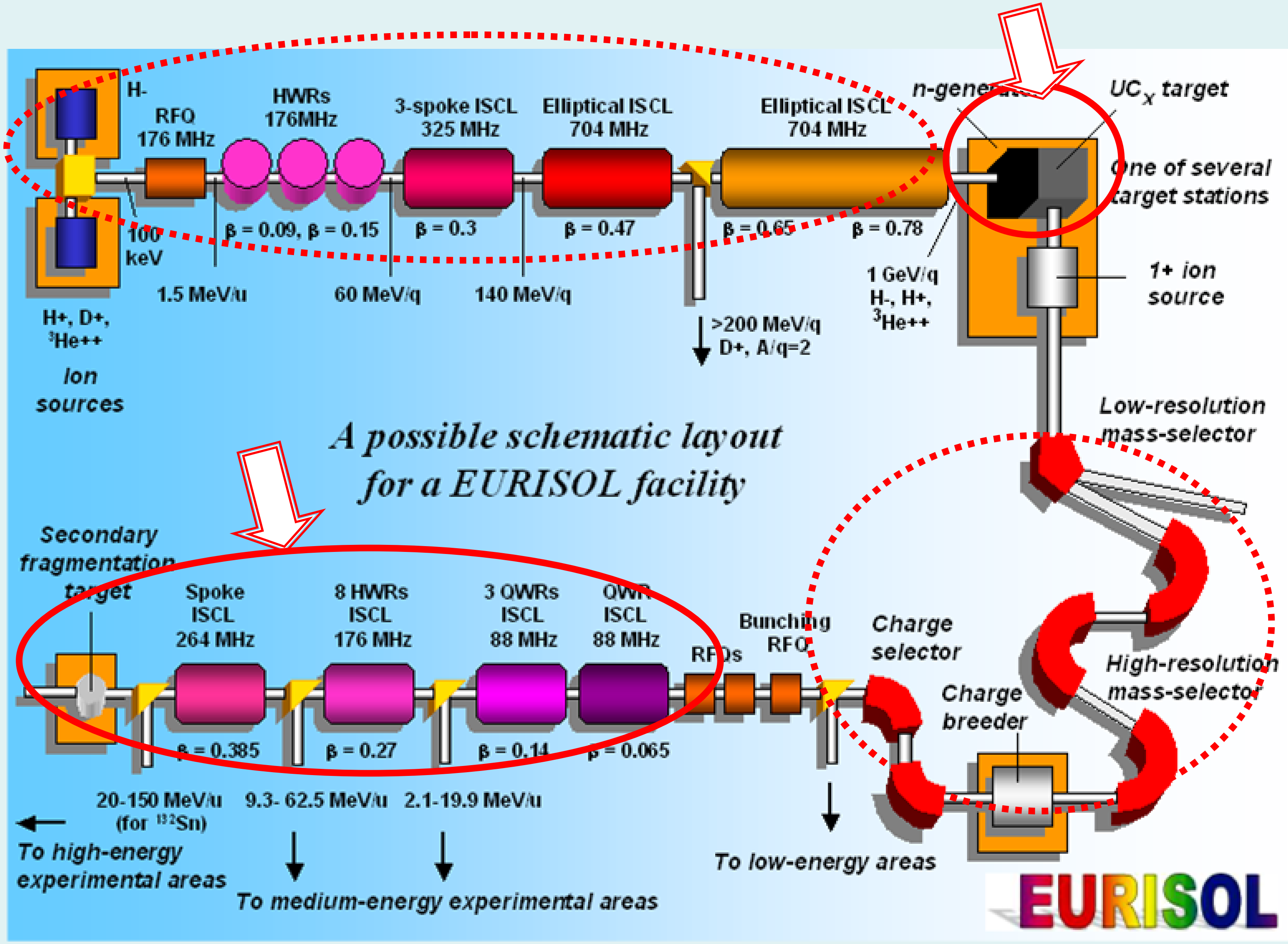
2. Post -operational phase:

- **Protection against radiations** => **measures to limit the exposure & working procedures**
  during maintenance and interventions
  machine will be **dismantled and decommissioned**
  waste transportation/disposal

- **Compatibility with the environment**=> **impact of the radioactive releases**
  >decommissioning & waste transportation/disposal

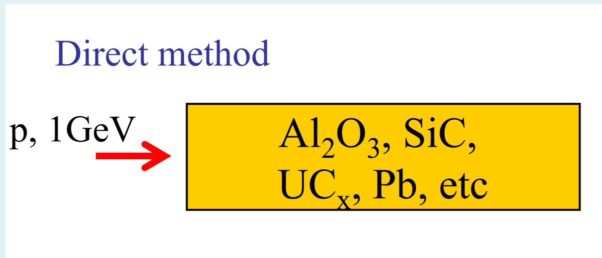
Radiological studies: assessment of the residual radiation field => specifications on the exposure of the personnel
Environmental studies: Characterization of the specific site & impact assessment

EURISOL conceptual lay-out

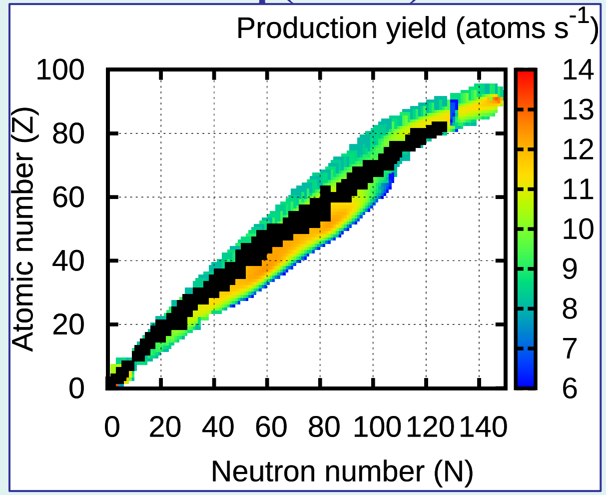


Two ways to produce RIBs:

- Direct:
  high energy spallation
  100 kW

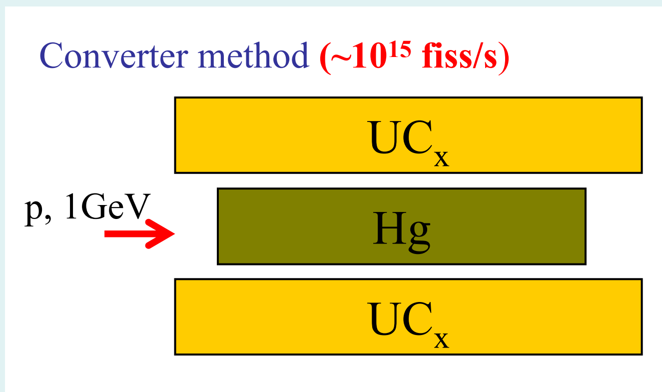


^{238}U + p(1GeV)

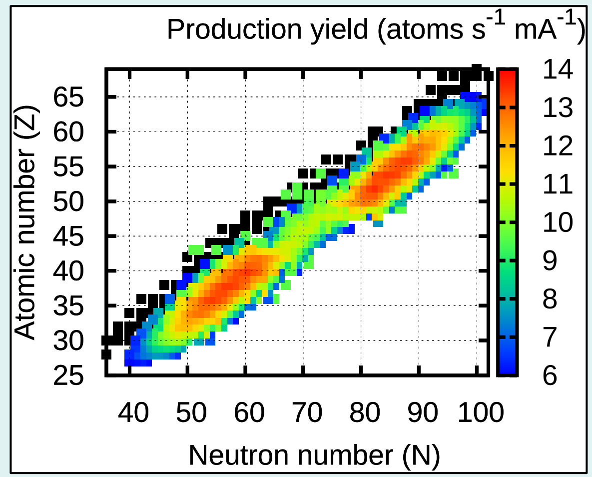


Direct target: R=1.8cm, L=40cm

\- Converter:
  neutron fission
  4MW



^{235}U + n(~ 100 keV)



Fission target(30kW)
(R_{ext}=1.75cm, R_{int}=0.4cm,H=20cm)

Legislation framework:

- ❑ JUSTIFICATION
- ❑ LIMITATION
- ❑ OPTIMISATION

Design limits for occupied areas/ ICRP 60

	H*(10) [μSv h^{-1}]	Total_H*(10) [mSv y^{-1}]
Public areas:	0.1	1
inside fence	1	
Controlled areas	10	20 / 2000 h
Full beam loss:	Total_H*(10) ≤ 50 μSv	

CERN guidelines:

H*(10) [mSv h^{-1}]	Maintenance constraints
>0.1	Planification and optimisation of all work
>2	+ limited intervention time & remote handling
>20	Remote handling essential

Radioactive sources identification & estimation

Design guidelines & previous experience => **Basic estimates**

Few exemples:

Equipement	primary	Energy	Intensity (pps)	Losses (pps)	Specific sources
Linac	p	1GeV	$(1\text{-}4)*6*10^{15}$	$6*10^{12}$/E[MeV] m^{-1}	-Few hot spots -Neutron backscatter
Linac#1 (L=209m)	^{132}Sn	(0.6 – 150) $MeVu^{-1}$	$6*10^{12}$	$(6*10^{7} - 6*10^{8})m^{-1}$	No spots specification
Linac#2 (L=156m)	^{132}Sn	(0.6 – 150) $MeVu^{-1}$	$6*10^{12} - 2.5*10^{12}$	$(6*10^{7} - 6*10^{8})m^{-1}$ $\sim 4*10^{12}$ (stripper zone)	No spots specification

Radioactive sources estimation

• Prompt radiation

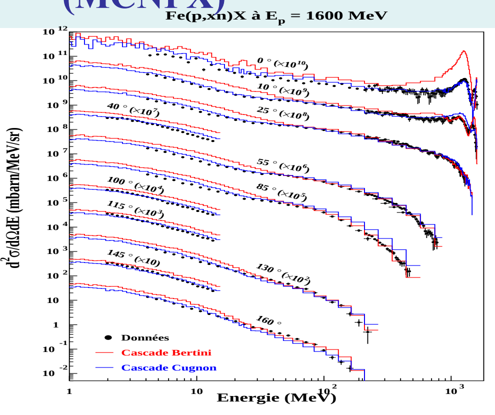
PHITS, FLUKA, MCNPX-HI

Mixed Φ & Conversion factors->H*(10)

Benchmarks related to prompt radiation

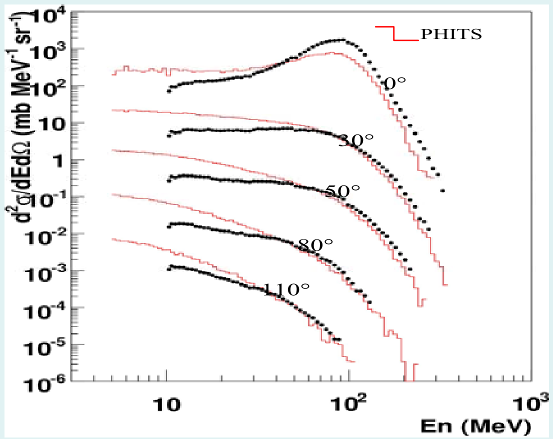
p(1.6 GeV) + Fe → neutrons

(MCNPX)

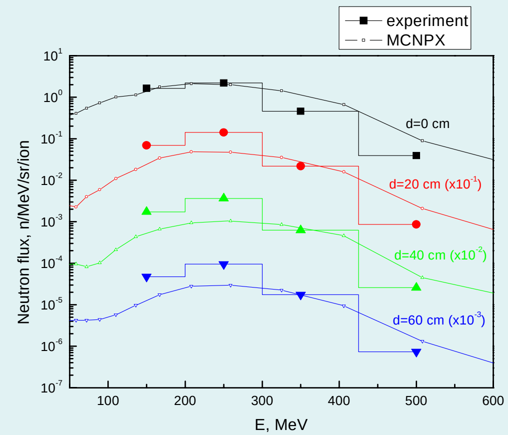


Ar(95MeV/u)+Cu → neutrons

PHITS



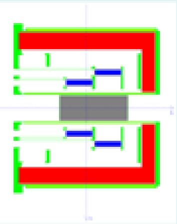
Neutron penetration in concrete shield MCNPX



Radioactive sources estimation

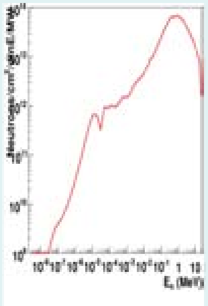
- **Residual radiation:**

Geometry and materials description

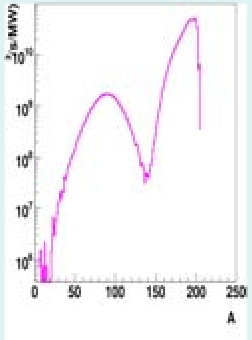


PHITS/ MCNPX

Neutron flux in ith cell



Residues in ith cell



DCHAIN-SP-2001/ CINDER

Irradiation Scheme

5000h irradiation at 4MW
40 years & duty factor 0.7

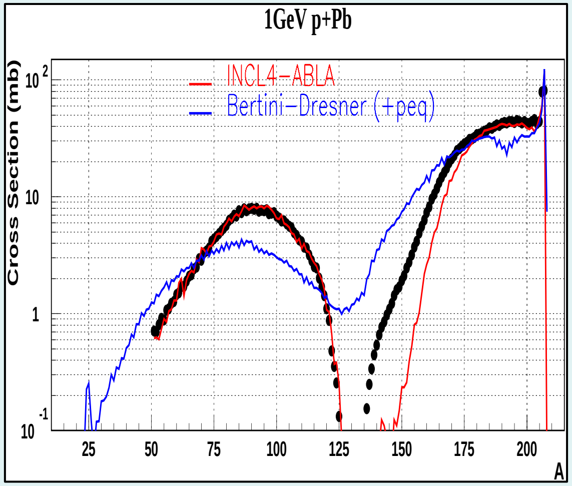
Activation products & Photon sources

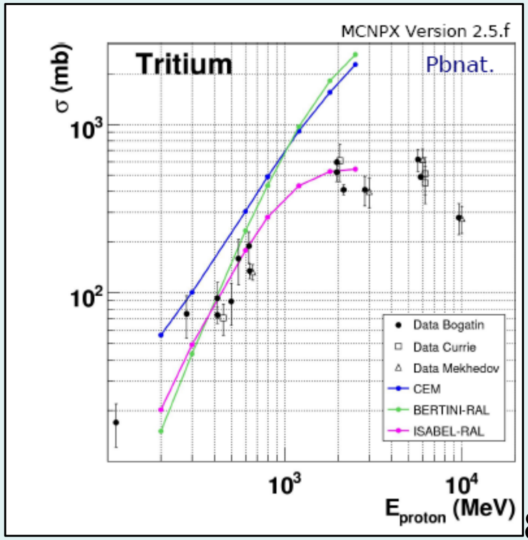
MCNPX

H*(10)

Benchmarks related to induced activity

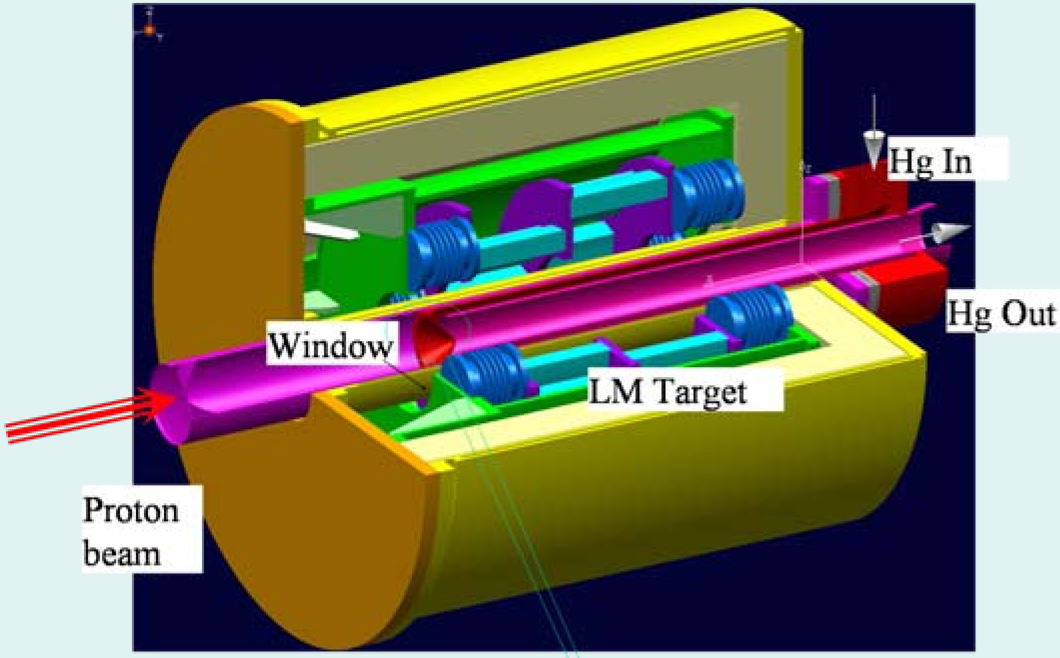
Production of Residual Nuclei

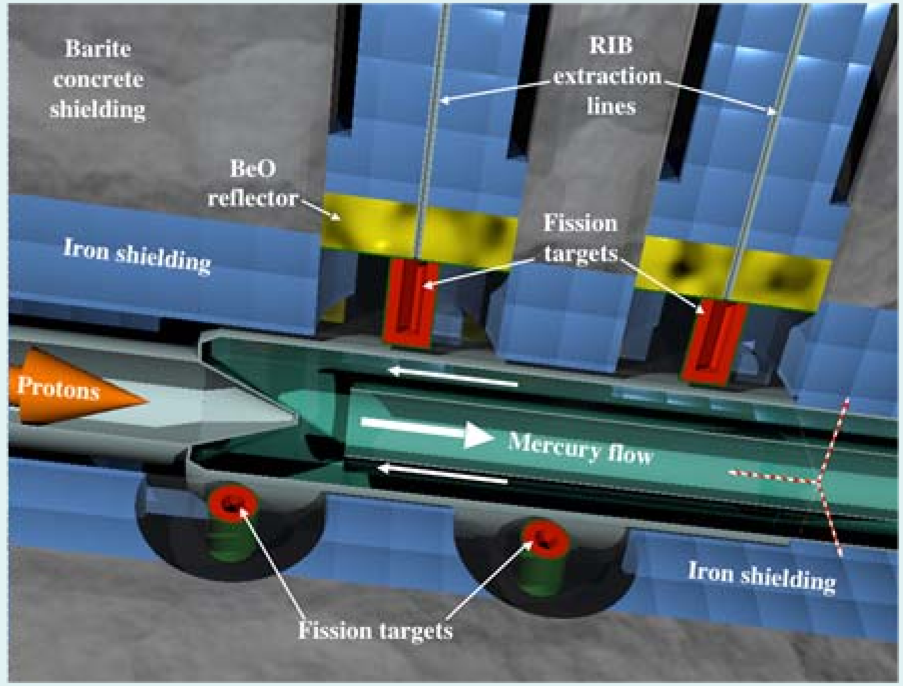




Estimation of radiation levels: MMW target assembly

Hg converter and secondary fission targets





First version of design =>

MAFF-like configuration =>

BULK SHIELDING

NEUTRON STREAMING

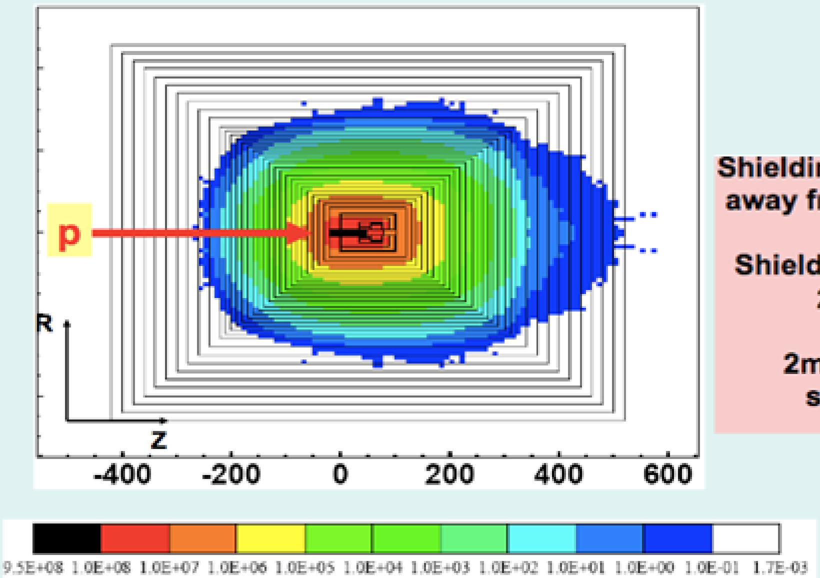
Biasing methods

Monte Carlo & generic studies -> choices of materials & shielding effect

Estimation of radiation levels: MMW target assembly

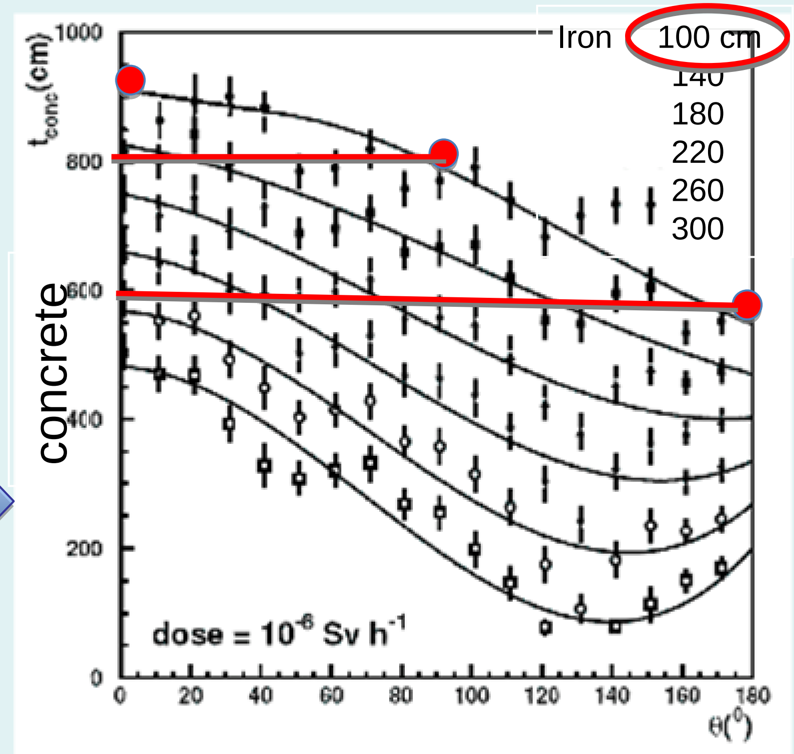
- **Prompt radiation: BULK SHIELDING**

FLUKA (CERN)



Shielding starts 20cm away from the target

Shielding materials
2m iron
+
2m concrete shielding



+

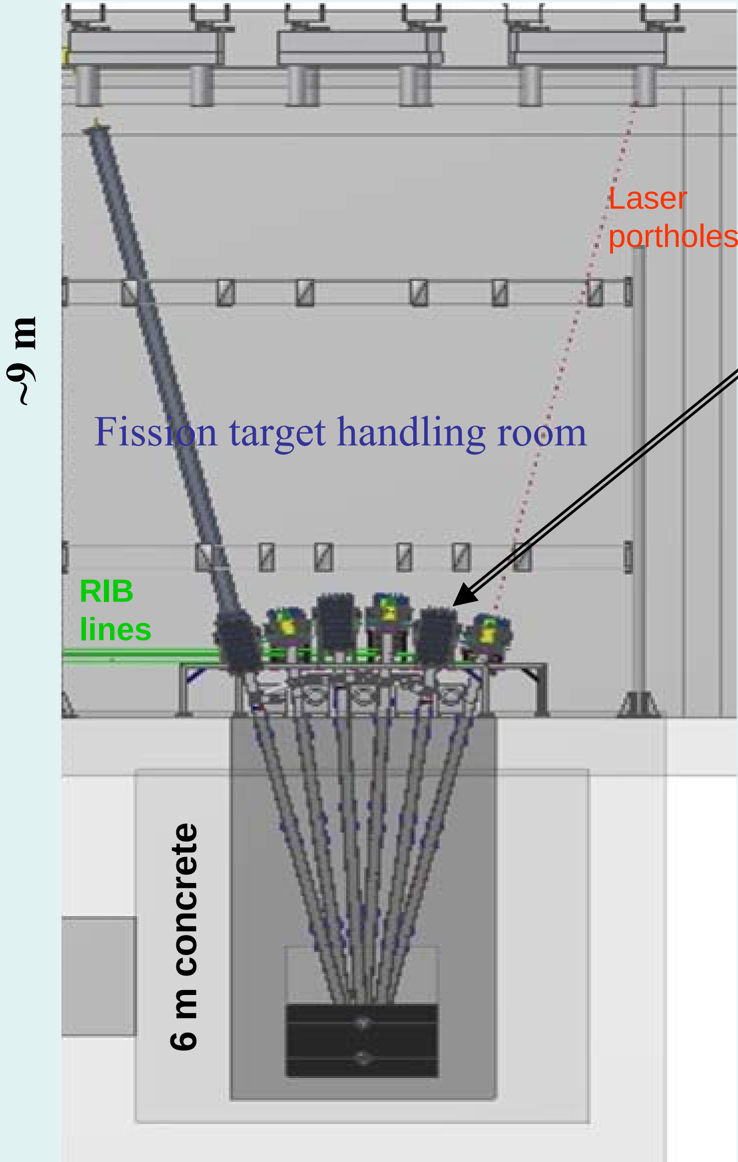
$H(\theta,d,R) = H_0(\theta)\exp\{-\Sigma_i d_i / \lambda_i(\theta)\}/R^2$

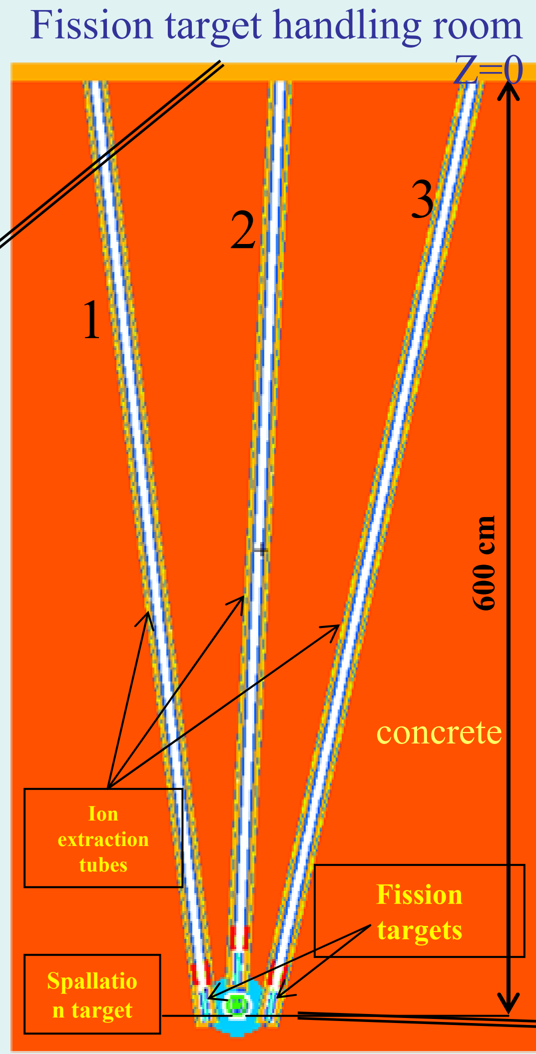
Attenuation formula

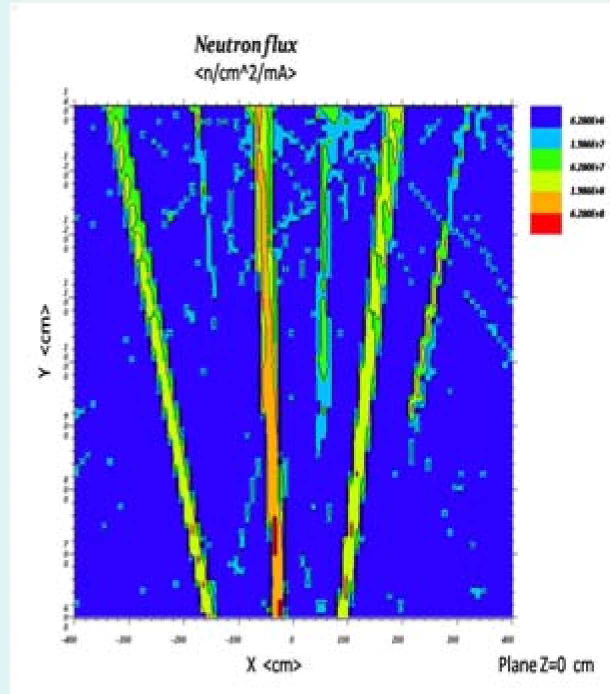
- 1 m of iron
- For $\theta = 0$, 90, 180°
  → 9.0, 8.0 & 6 m of concrete

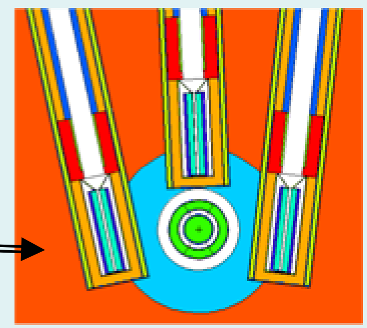
Estimation of radiation levels: MMW target assembly

- **Prompt radiation: NEUTRON STREAMING** FLUKA (CERN)



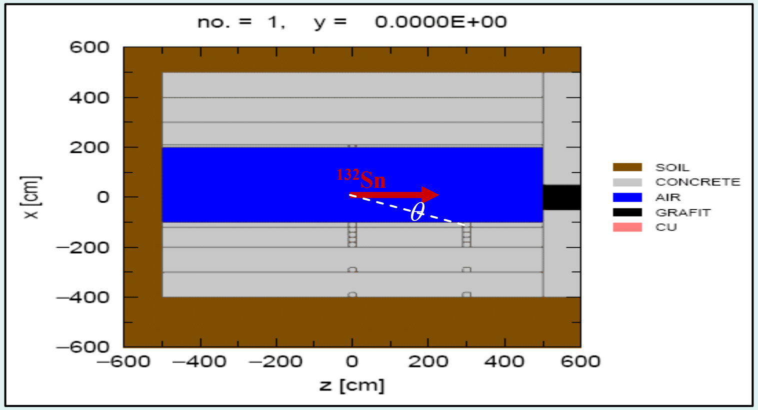




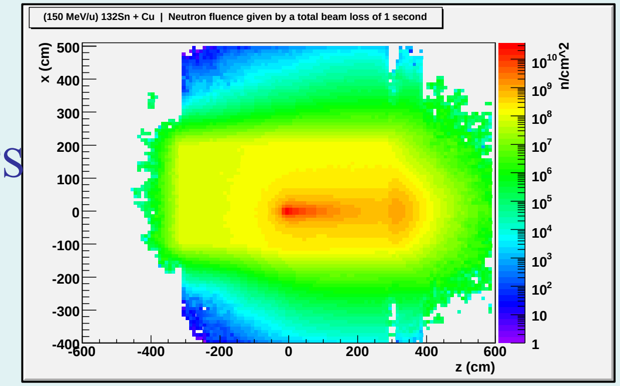


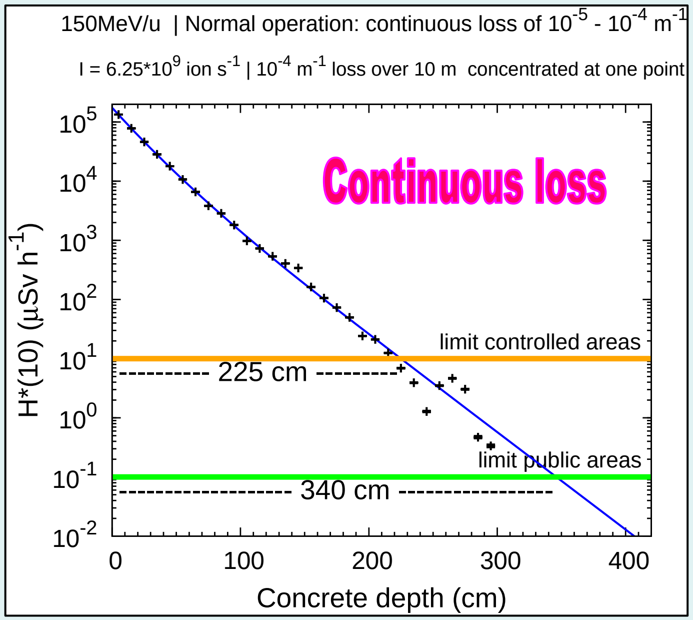
Estimation of radiation levels: Postaccelerator

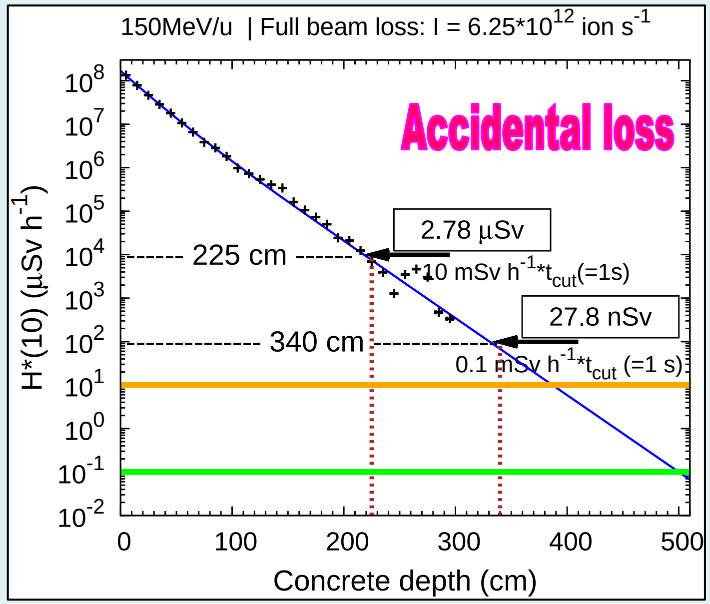
Method (CEA)



PHITS



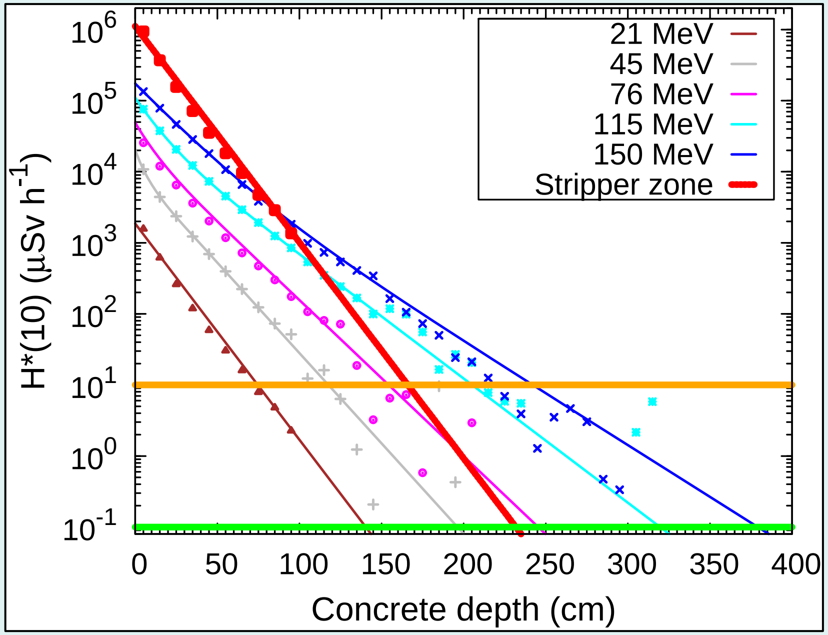




A shield designed for a continous beam loss of 10^{-4} m^{-1} (point loss of 6.25×10^{9} ion s^{-1}) during the routine operation is also adequate for an accident loss of the full beam at a localised point, providing that the linac cutoff time is less than 1s.

Estimation of radiation levels: Postaccelerator

neutrons

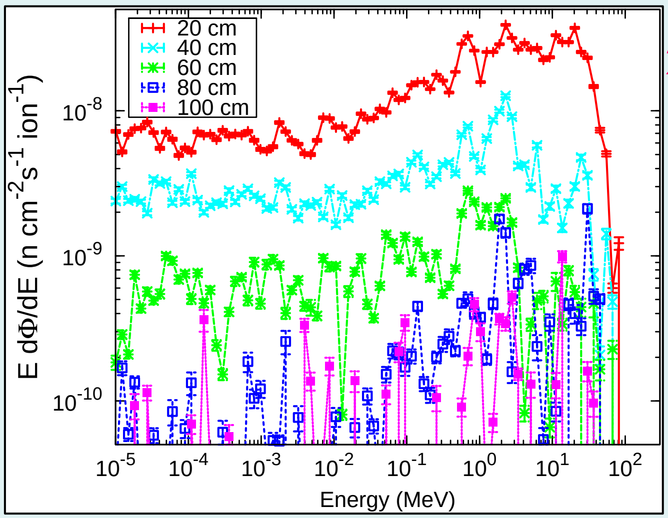


$$H^*(E_p, d/\lambda) = \frac{H_1(E_p)}{r^2} \exp\left[-\frac{d}{\lambda_1}\right] + \frac{H_2(E_p)}{r^2} \exp\left[-\frac{d}{\lambda_2}\right]$$

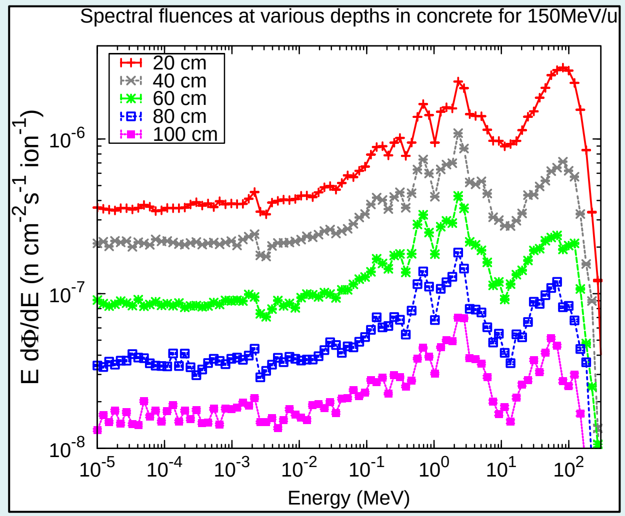
!!

* Agosteo S, Nakamura T , at al. NIM/B 217, 2004

E [MeV/u]	H_1 [Sv m² ion⁻¹]	λ_1 [g cm⁻²]	H_2 [Sv m² ion⁻¹]	λ_2 [g cm⁻²]
150	2.00E-10	38.78	7.98E-11	62.00
115	1.13E-10	23.50	6.14E-11	57.32
76	6.18E-11	21.36	1.27E-11	53.20
45.5	1.69E-11	12.19	1.55E-11	40.52
21.3	-	-	2.00E-12	33.57



21MeV/u **150MeV/u**



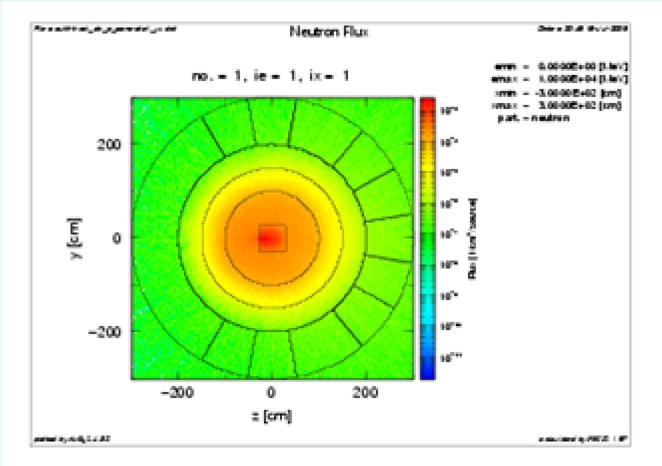
Estimation of radiation levels: Postaccelerator

Other species & secondaries

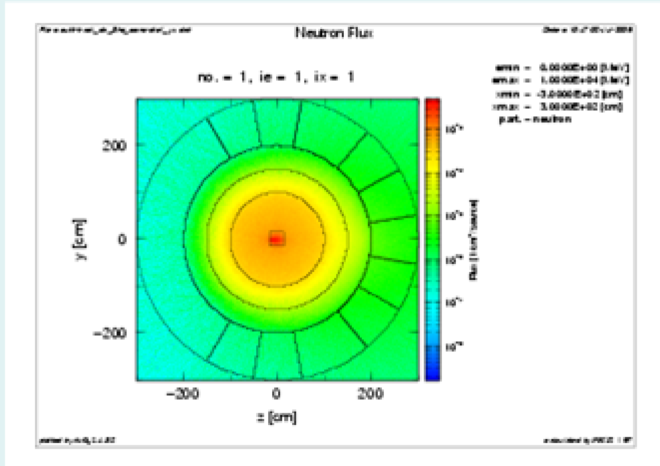
Beam direction →

Beam on stopping Cu targe

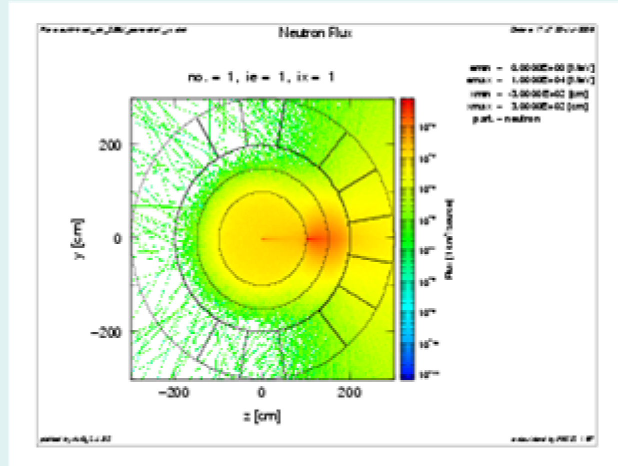
Ronningen & Remec, 2005



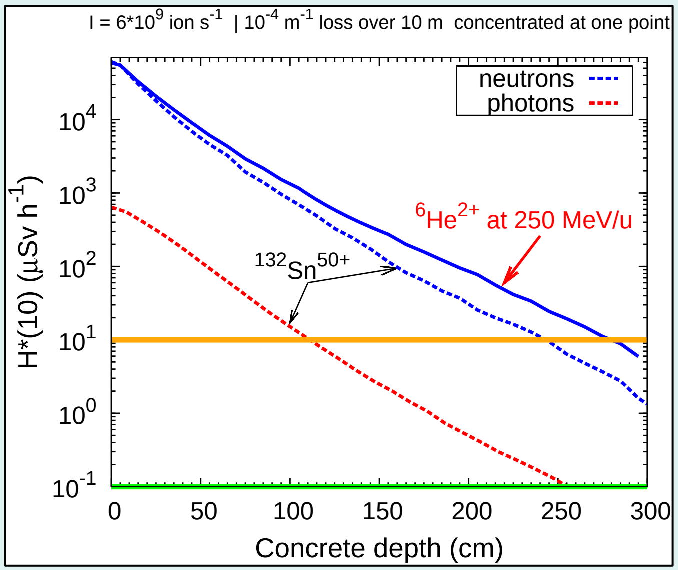
proton : 1 GeV



He-3 : 777 MeV/u



U-238 : 400 MeV/u



Photon H*(10) < 3% Total H*(10)

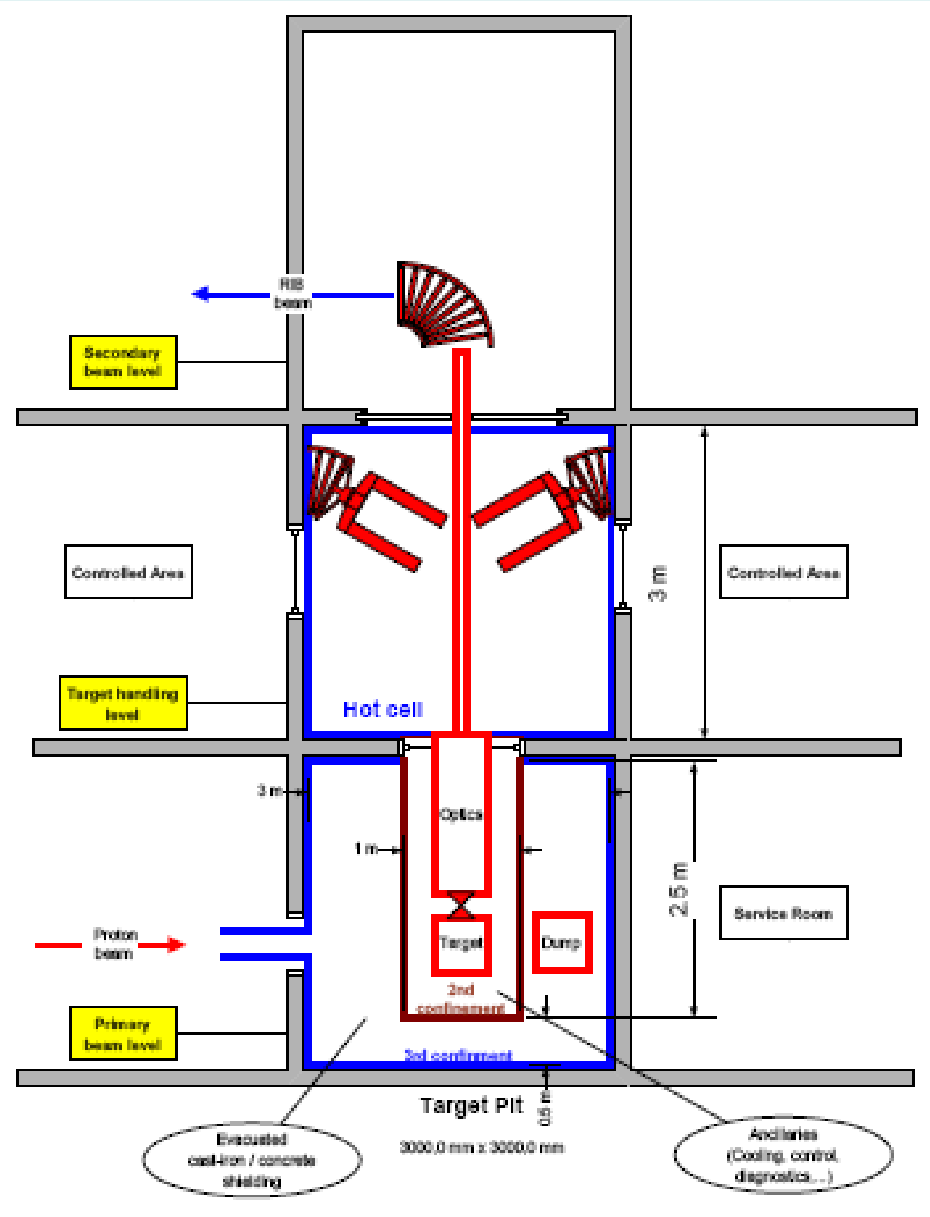
3 m of concrete: **!!**

$$\frac{\textbf{Neutron H*(10) for } ^{6}\textbf{He (250MeV/u)}}{\textbf{Neutron H*(10) for } ^{132}\textbf{Sn (150MeV/u)}} \sim 5$$

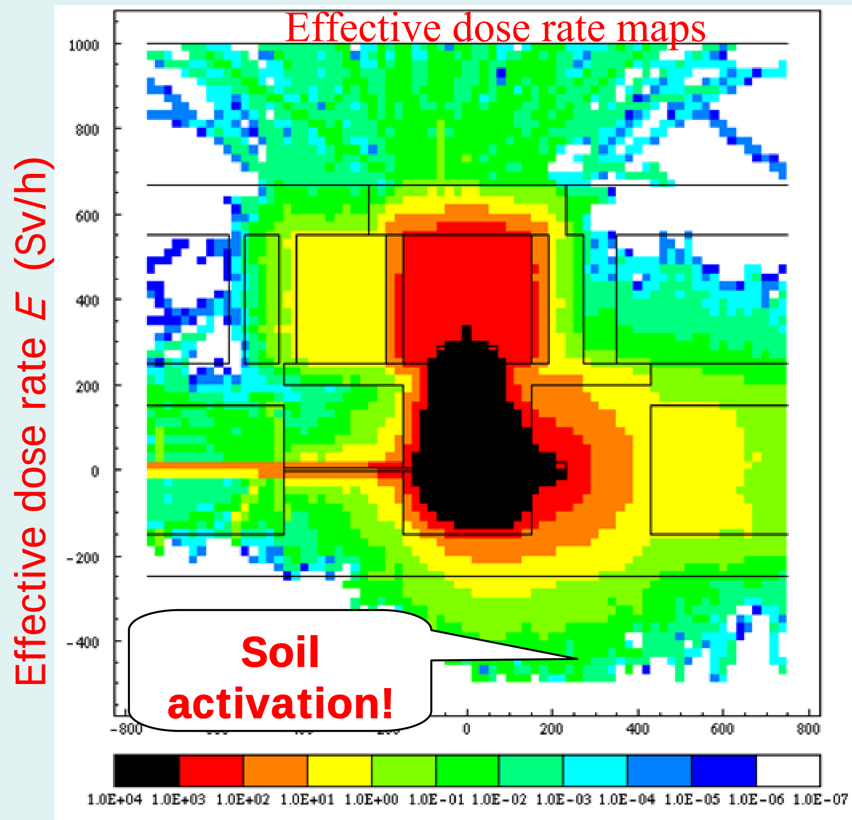
Safety operation domain: energy range and beam intensities.

OPERATION: shielding configuration

Conceptual design of 100kW target station (CERN)

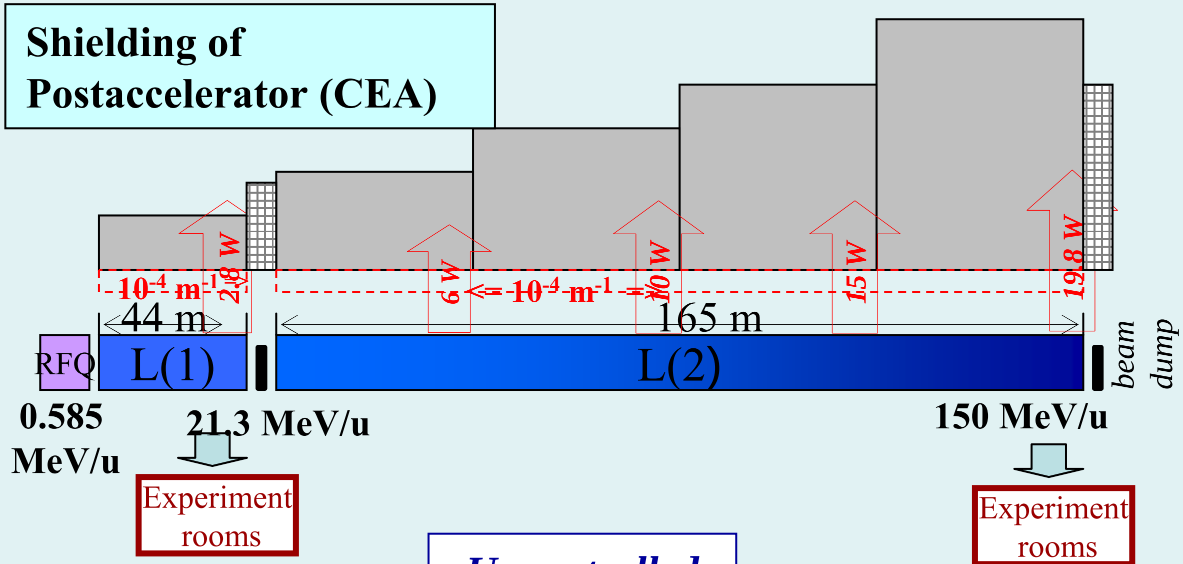


- Underground target position
- Front-end retracts vertically
- Hot-cell for target exchange
- Separator in 3rd level
- Neighboring hot-cell accessible during run



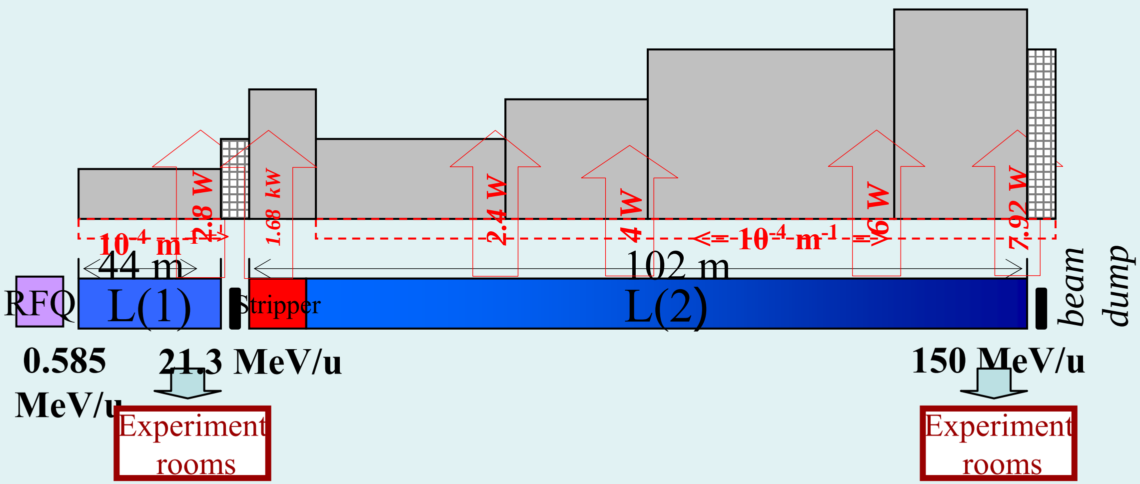
OPERATION: shielding configuration

Shielding of Postaccelerator (CEA)



Staff	Energy [MeV]	21.3	45.5	76	115	150
	Length [m]	44	40	40	40	45
	Thickness (cm)	70	130	175	210	225
	V_{staff} (m^3)	338.05* → 4732.7 for a tunnel surface of 3 m x 4m				
Public	Thickness (cm)	140	195	245	320	380
	V_{public} (m^3)	536.6* → 7512.4 for a tunnel surface of 3m x 4m				

Uncontrolled beam loss of 10^{-4} m^{-1}



	Energy [MeV]	21.3	Stripper	45.5	76	115	150
	Length (m)	44	10	31	21	33	17
Staff	Thickness (cm)	70	160	110	150	180	200
	V_{staff} (m^3)	*205.8** → 2881.2 for a tunnel surface of 3 m x 4 m					
Public	Thickness (cm)	140	235	185	230	295	325
	V_{public} (m^3)	*343.4** → 4120.2 for a tunnel surface of 3 m x 4 m					

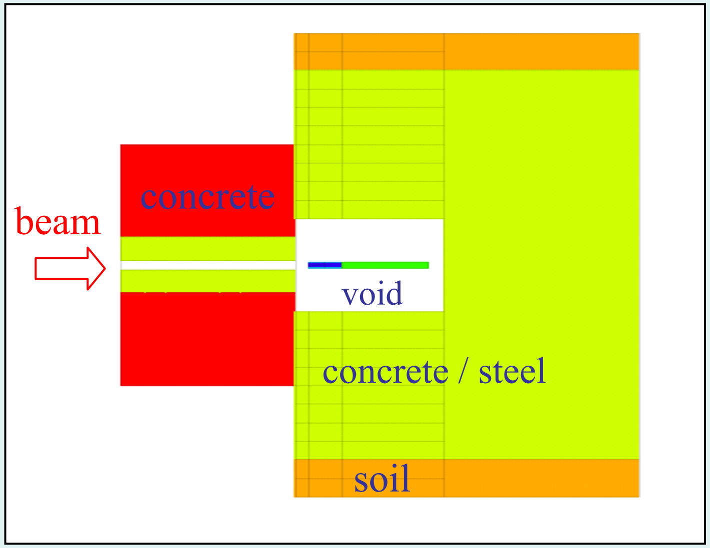
OPERATION: shielding configuration

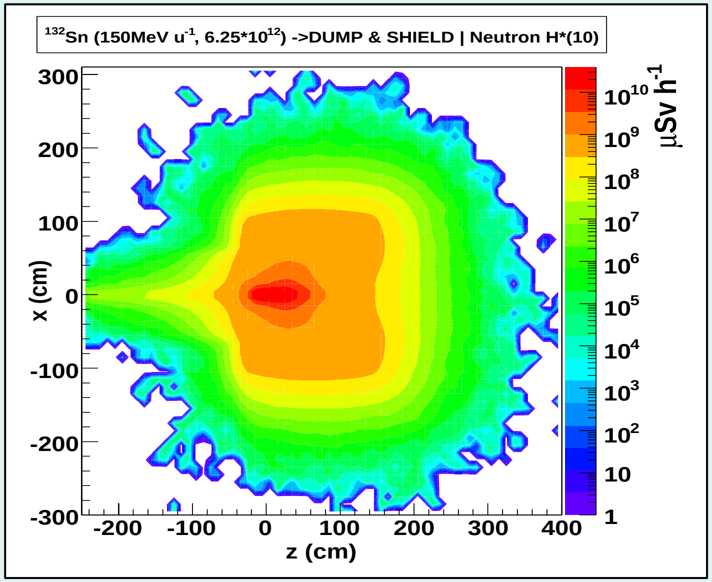
Beam Dump cavity: thickness of lateral wall (CEA)

$^{132}Sn^{25+}$

Beam power = 19.8 kW (150 MeV/u)

Beam size σ = 2 mm





material	H_1 [Sv m^2]	λ_1 [g cm^{-2}]	H_2 [Sv m^2]	λ_2 [g cm^{-2}]	SHIELD [cm]	
					Staff	Public
concrete	1.747E+03	23.7	1.338E+02	**60.36**	*364*	*480*
steel	-	-	5.000E+04	**112.14**	*254*	*320*

OPERATION: containment of volatile radioactivity

Dispersion of radioactivity: from MAFF

P. Thirolf et al.
(LMU)

EURISOL → 10 higher!

Dose in distance of 1m after 1 day decay time:

10^{14} fission/sec
^{235}U ion source
~ 10 kCi 'open' source

→ Beam tube
$3 \cdot 10^8$ μSv/h
non-volatile
activity

~68% non volatile

~2% ions

~30% atoms/gases

slit aperture of
pre-separator
(m=95, 140: 97%)
~ $5 \cdot 10^6$ μSv/h

slit aperture of
high-resolution
separator
~ 10^4 μSv/h

slits/targets of
beam line
~ 3.10^3 μSv/h

decay on the
cryopump

regeneration

~ 0.02%

outer beam tube
~ 300 μSv/h

exhaust
storage tanks

Capability of Cryotrap

3 cryotraps prototypes tested:

Retention capability (vs. pressure behind cryotrap)

'carry over': fraction of leaking gas load transported across cryotrap

Cryotrap works within (simulated) expectations → 99.98% of volatile radioactivity can be localized!

OPERATION:Containment | Risk register

derived from the CERN-AB risk register elaborated by P. Bonnal (05/05/2003)

- The methodology used

1	Insignificant	< 1 day of loss of physics, or < 0.5% of EURISOL annual budget, or No environmental consequence
2	Moderate	1 day < < 1 week of loss of physics, or Management level, or 0.5 < < 4% of EURISOL annual budget, or Injury, no loss of working day
3	Major	3 < < 5 weeks of loss of physics, or Executive board level, or Additional budget, or Injury, loss of working day
5	Catastrophic	~1 year of loss of physics, or EURISOL future jeopardized, or Loss of life

- The file format

EURISOL-DS RISK REGISTER

Equipment			Operational phase and Risk			RP [mSv/h] and intervention		Risk assessment **before** mitigation			Mitigation of Risk	Risk assessment **after** mitigation		
Owner	**Name and location**	**Acronym - Number**	**Action type**	**desccription of failure**	**Description of associated risk**	**Dose rate**	**Job duration**	**Probability**	**Impact**	**Score**	**Comments - Needed actions**	**Probability**	**Impact**	**Score**

1 **Rare**, i.e. less than once in 25 years ; probability less than 0.1
2 **Possible**, i.e. one time in 5 to 10 years ; probability between 0.2 and 0.5
3 **Likely**, i.e. one time in 2 to 5 years ; probability 0.6
4 **Frequent**, i.e. about once a year ; probability 0.9

Risk score calculated as follow: **RS** = **P** × **I** (updated via cell A1 click)
RS ∈ [1,2] **low**; **RS** ∈ [3,8] **medium**; **RS** ∈ [9,20] **high**

Main risks for the Hg converter

EURISOL-DS RISK REGISTER

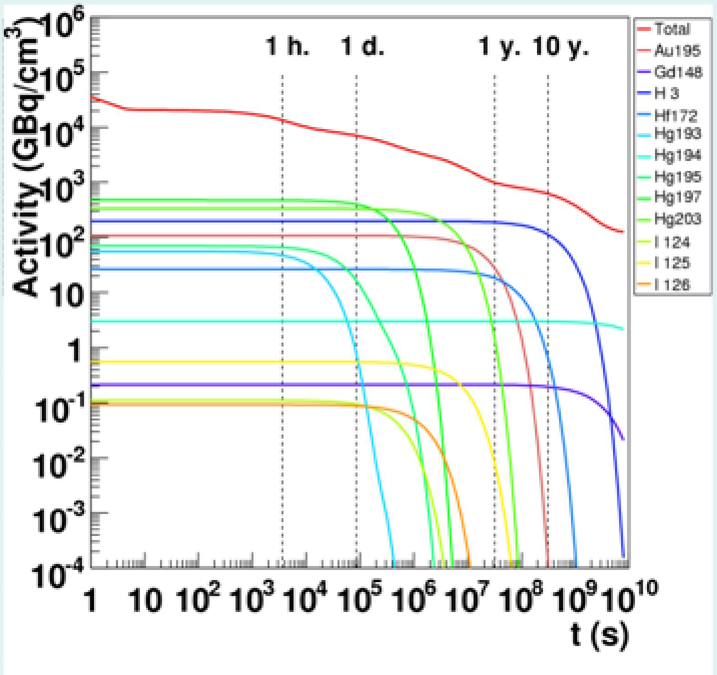
Equipment			Operational phase and Risk			RP [mSv/h] and intervention		Risk assessment **before** mitigation			Mitigation of Risk	Risk assessment **after** mitigation		
Owner	Name and location	Acronym - Number	Action type	desccription of failure	Description of associated risk	Dose rate	Job duration	Probability	Impact	Score	Comments - Needed actions	Probability	Impact	Score
T2	CGS target vessel	???	Operation	Rupture of the vanes	Loss of Hg flow, flow blockage and cavitation			2	2	4	Instrumentation to control Hg flowrates	2	1	2
					Explosion by Hg boiling			1	5	5	Containement of Hg (safety hull)	1	1	1
					Overheating of the window			3	3	9	Instrumentation to control Window temperature	3	1	3
					Partial melting of the window			1	5	5	Containement of Hg (safety hull)	1	1	1

Main risks for the Fission target

EURISOL-DS RISK REGISTER

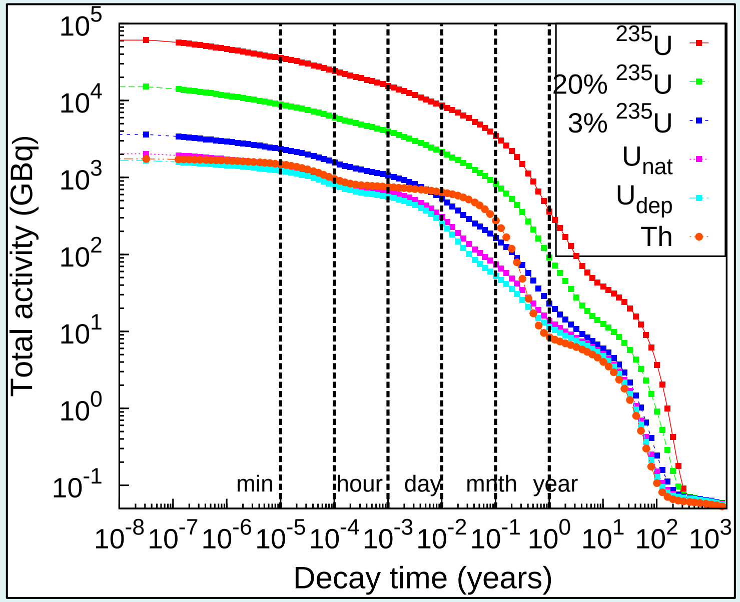
Equipment			Operational phase and Risk			RP [mSv/h] and intervention		Risk assessment **before** mitigation			Mitigation of Risk	Risk assessment **after** mitigation		
Owner	Name and location	Acronym - Number	Action type	desccription of failure	Description of associated risk	Dose rate	Job duration	Probability	Impact	Score	Comments - Needed actions	Probability	Impact	Score
T4	UC target/running	RU-T-06	operation	firing target	stop of operation, target is lost, removal of target and replace with a new one, clean the pit region. The pit and beam line are highly contaminated.	1PBq	2000	2	5	10	avoid oxygen contamination, redondancy of safety valves. Neutral atmosphere during removal may be foreseen	1	5	5

POST-OPERATION: Activation of targets



Hg

MMW target



UCx

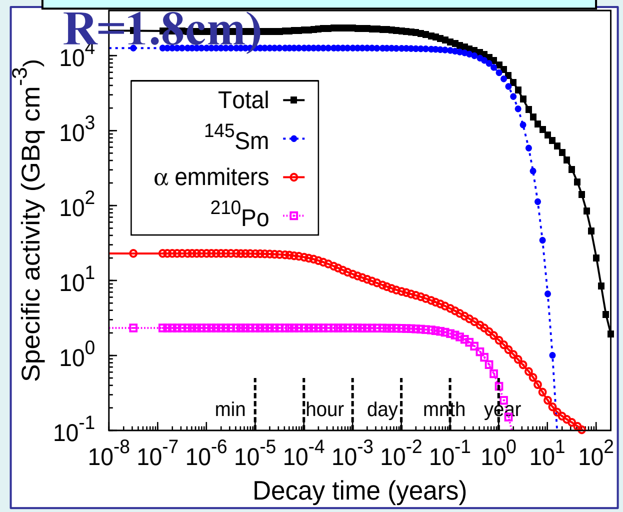
^{235}U:

7% halogens

10% rare gases

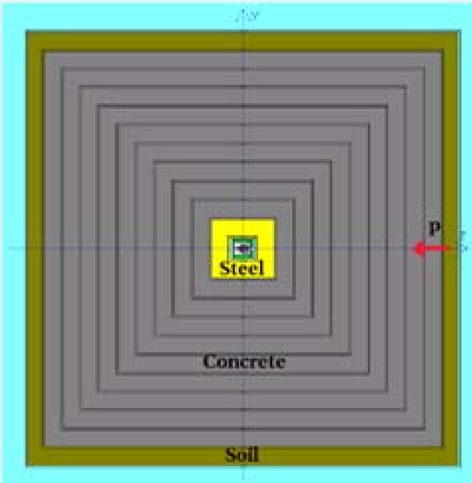
1% actinides

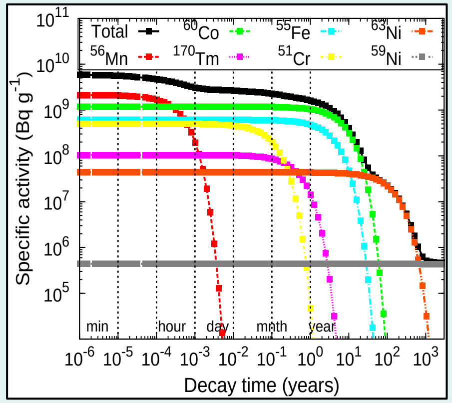
Direct target | CEM2k UCx(L=40cm, R=1.8cm)



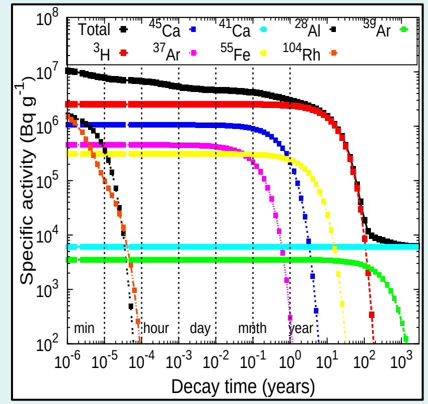
Hg		1 year after irradiation			10 years after irradiation		
		ISABEL-ABLA	CEM2k	INCL4-ABLA	ISABEL-ABLA	CEM2k	INCL4-ABLA
Total activity	Half life	9.810^{2}	$2.8\ 10^{3}$	$4.1\ 10^{2}$	$6.1\ 10^{2}$	$1.6\ 10^{3}$	$2.0\ 10^{2}$
^{195}Au	186.1 d	$2.8\ 10^{1}$	2.410^{1}	$2.6\ 10^{1}$	$2.1\ 10^{-4}$	$1.8\ 10^{-4}$	$2.0\ 10^{-4}$
^{148}Gd	**74.6 y**	**2.110^{-1}**	**$7.4\ 10^{-1}$**	**$1.1\ 10^{-1}$**	**$2.0\ 10^{-1}$**	**$6.8\ 10^{-1}$**	**$9.7\ 10^{-2}$**
^{3}H	12.32 y	$1.9\ 10^{2}$	$2.3\ 10^{3}$	$3.9\ 10^{1}$	$1.1\ 10^{2}$	$1.4\ 10^{3}$	$2.3\ 10^{1}$
^{172}Hf	1.87 y	$1.8\ 10^{2}$	$2.3\ 10^{2}$	$1.7\ 10^{2}$	$6.5\ 10^{-1}$	$8.3\ 10^{-1}$	$6.1\ 10^{-1}$
^{194}Hg	444 y	3.0	$1.2\ 10^{1}$	2.6	3.0	$1.2\ 10^{1}$	2.5

Post-OPERATION: MMW target shielding





Stainless steel



Concrete

Activity map at 100days

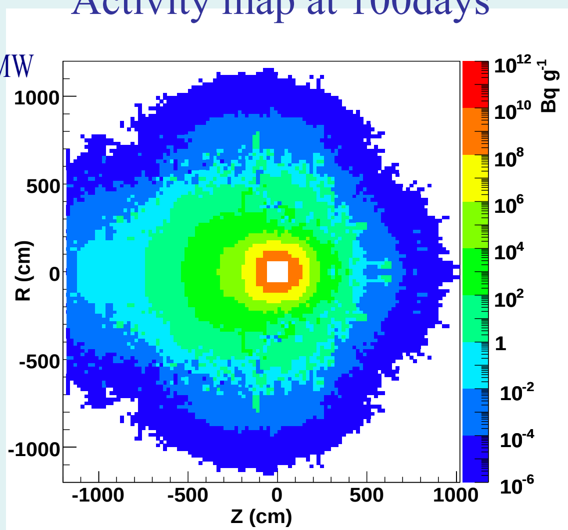
40 years irradiation at 2.28 MW

1 MBq/g < A < 1GBq/g

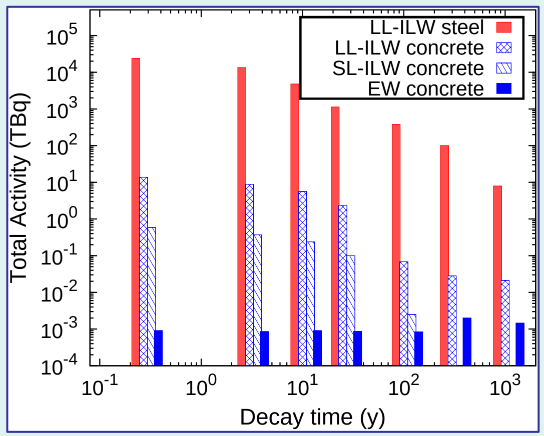
1 kBq/g < A < 1MBq/g

1 Bq/g < A < 1kBq/g

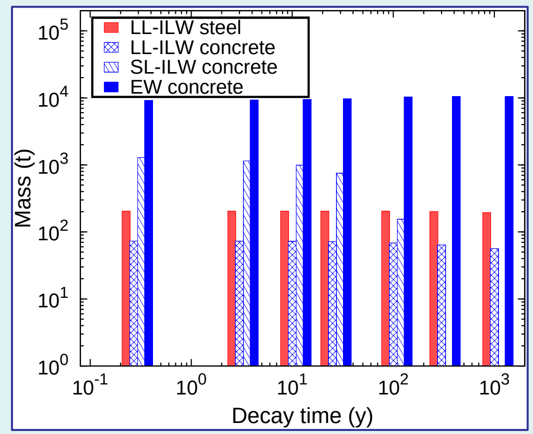
A < 1Bq/g



Waste categories

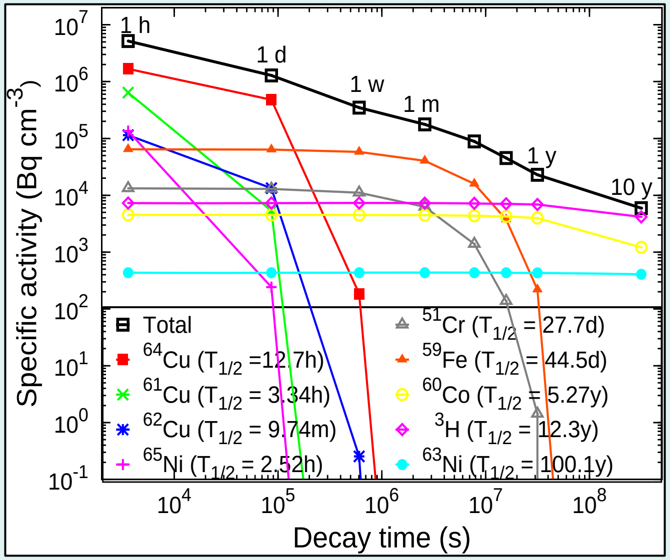


Activities



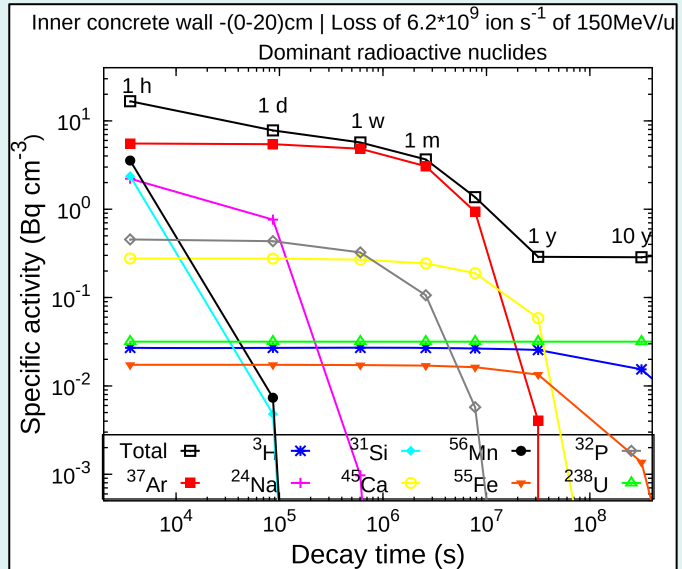
Mases

POST-OPERATION: Postaccelerator tunnel



Activation of Cu structure (150 MeV/u)

Contribution of the wall is **not significant**



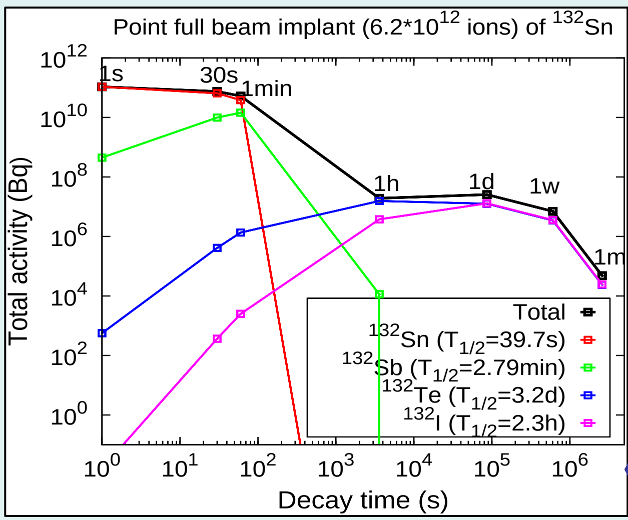
Activation of concrete (150 MeV/u)

Air activation using PHITS (evaluated cross sections)

$^{14,15}O, ^{13}N$ |^{41}Ar 0.35Bq cm^{-3}

Activity vs Discharge limit

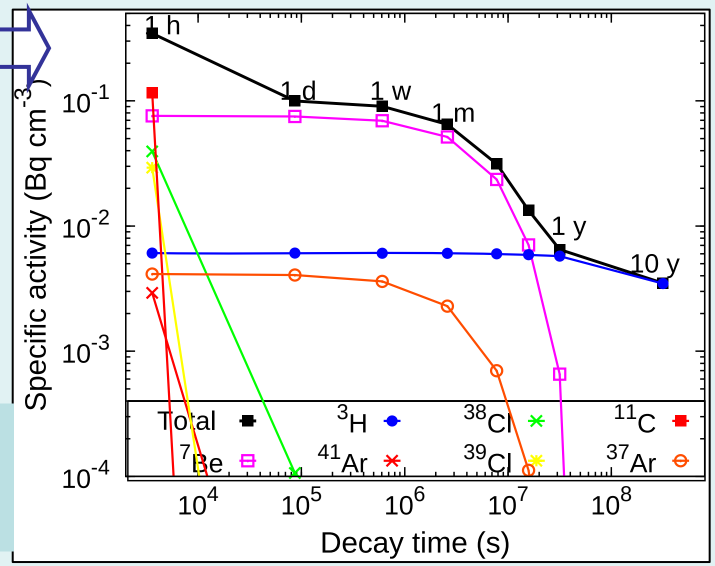
Inhalation dose received by workers intervening in tunnel



Total activity due to implantation

10^{11} Bq ^{132}Sn implantation

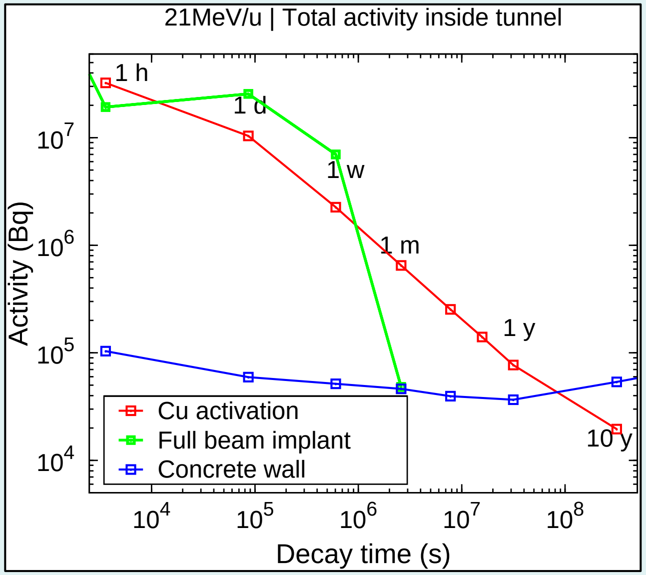
^{132}I accumulation after 1h

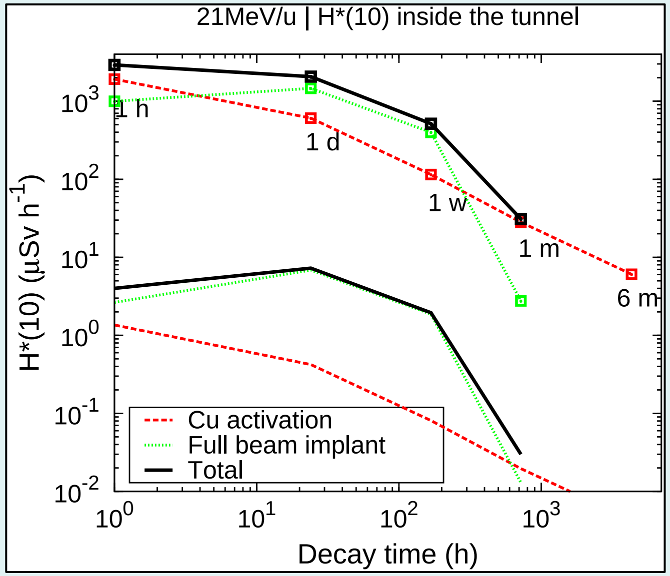


Air activation (150 MeV/u)

POST-OPERATION: Postaccelerator tunnel

21MeV/u





Residual field:

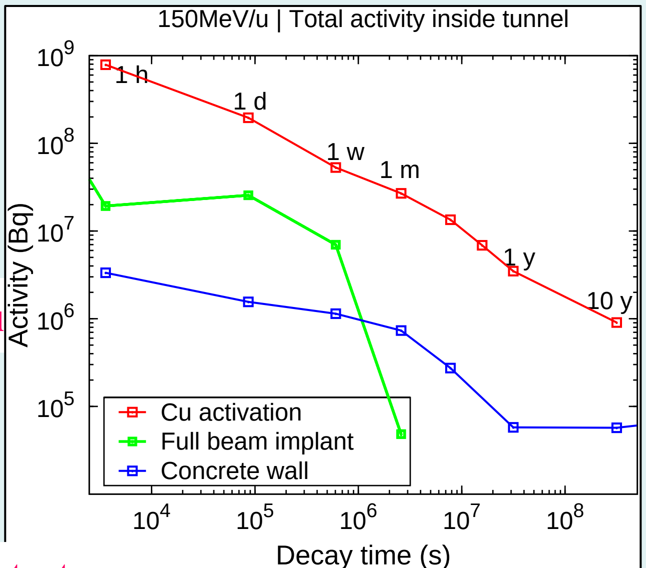
-high energy zone

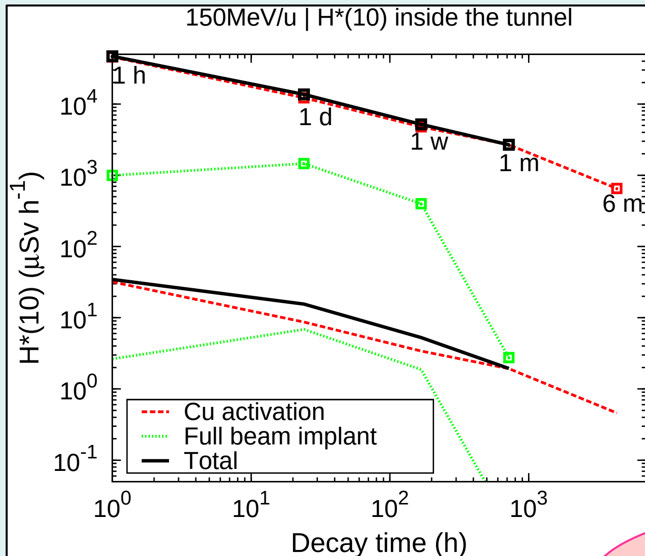
copper structure activation

-low energy zone

ion implantation

150MeV/u





In the high energy zone continuous accessibility after ~ week cooling time or occupancy factor of minimum 570 hours/year => 20 mSv y^{-1}

Maintenance operations to be planed

Points -> contact

Lines -> 1m distance

Total activity

H*(10)

Impact of radiactive releases: Source term

POSTACCELERATOR

Specific activity [Bq cm^{-3}] in first 100 cm of soil/groundwater surrounding the concrete wall after 40 y of continous irradiation

Isotope	$T_{1/2}$	Soil	Groundwater
^{3}H	***12.33y***	***$3.149*10^{-5}$***	***$3.299*10^{-6}$***
^{7}Be	53.12d	$3.662*10^{-6}$	$3.662*10^{-7}$
^{22}Na	***2.6y***	***$7.782*10^{-6}$***	***$7.784*10^{-7}$***
^{24}Na	14.96h	$7.551*10^{-6}$	$7.583*10^{-7}$
^{32}P	14.26d	$1.047*10^{-8}$	$9.584*10^{-9}$
^{35}S	87.32d	$2.262*10^{-23}$	4.938*10-9
^{45}Ca	162.61d	$8.111*10^{-6}$	$7.800*10^{-7}$
^{46}Sc	83.79d	$6.833*10^{-7}$	$2.540*10^{-21}$
^{54}Mn	312.3d	$2.217*10^{-7}$	$3.674*10^{-13}$
^{55}Fe	2.73y	$2.679*10^{-6}$	$4.912*10^{-12}$
^{65}Zn	244.26d	$3.867*10^{-8}$	$5.880*10^{-12}$

$5.265*10^{4}$ Bq < 10^{12} Bq --LIMIT*

$1.301*10^{4}$ Bq < 10^{5} Bq --LIMIT*

Transport of radioactive species into the ground does not represent a hazard for the population

Real evaluation to be done after the site will be chosen

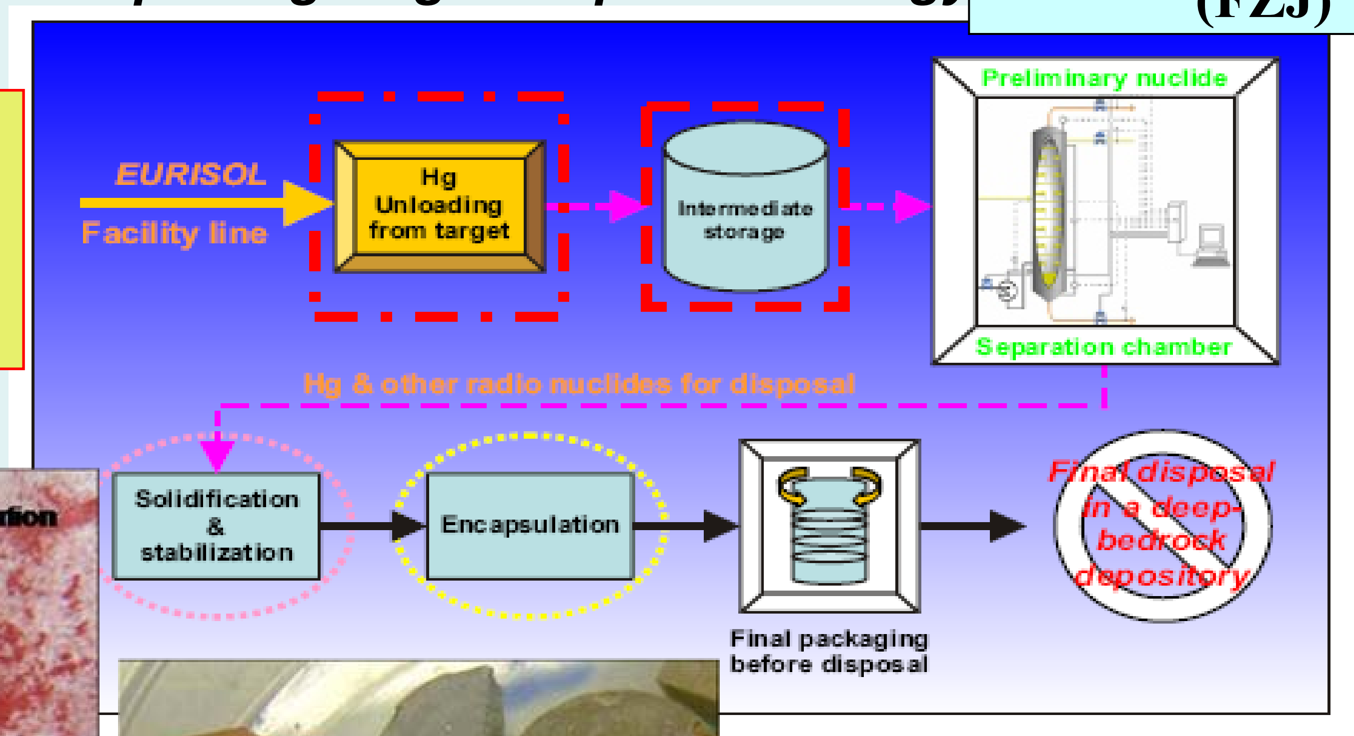
***IAEA TECDOC-1000, 1998,**
Clearance of materials resulting from the use of radionuclides in medicine, industry and research.

Impact of radiactive releases: waste disposal

Disposal of liquid Hg (FZJ)

A schematic layout for liquid Hg-target disposal strategy

Chemical stabilization of Hg as an inorganic compound, e.g. HgS, HgSe, HgO, Hg_2Cl_2, $HgCl_2$



Extrapolation from laboratory scale to "industrial" scale still to be done!

Impact of radiactive releases: Dispersion of the radioactivity

NIPNE

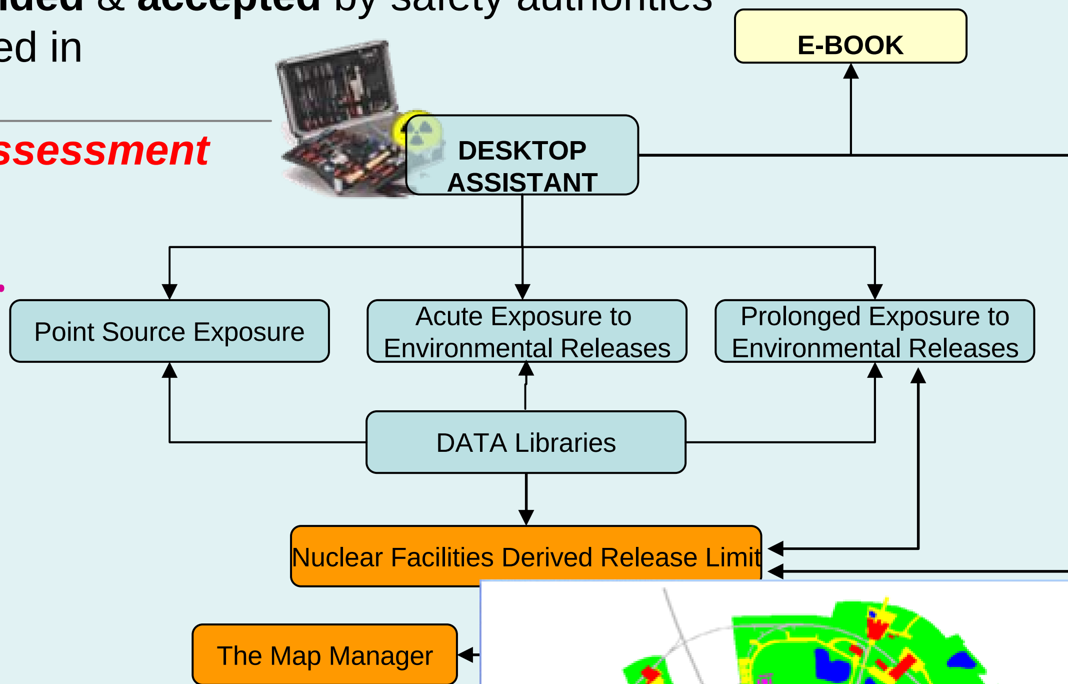
Combination of knowledge **on** Accelerator & Research Reactor based nuclear installations

→ creation of dedicated toolkit for EURISOL DS

→ Methodology **validated**, **recommended** & **accepted** by safety authorities

→**Tools**, **data** & **knowledge** to be used in

Environmental and health Impact Assessment



Toolkit operational both for normal operation and accidental situations!

Further steps:

- *Derived Intervention Levels (DIL)*
- *Exposure from underground water contamination*
- *Development of a resident GIS platform*
- *Cadastral Impact Analysis (GIS based)*
- …

Site dependent analysis to be performed!

Summary

- ❑ **Safety integration from the start hints innovative and flexible solutions in maters of safety**

- ❑ **EURISOL has similarities with high-power spallation n-sources & small research reactors**

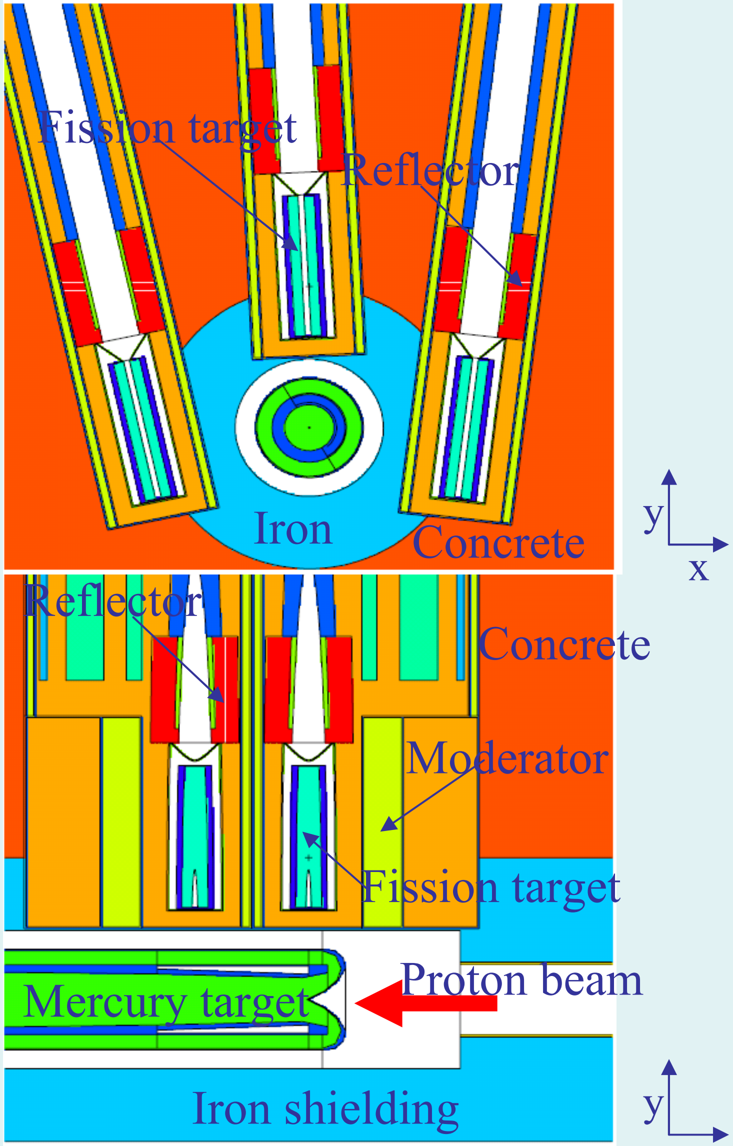
Very specific features:

- ✓**Use of pyrophoric actinide carbide targets;**
- ✓**Presence of alpha-emitters;**
- ✓**Distribution over extended buildings of intense RIBs and sources of all chemical nature**

Dedicated technical standards to be applied under utmost reliable safety rules and procedures.

Back-up

CONVERTER: Parameters / Model



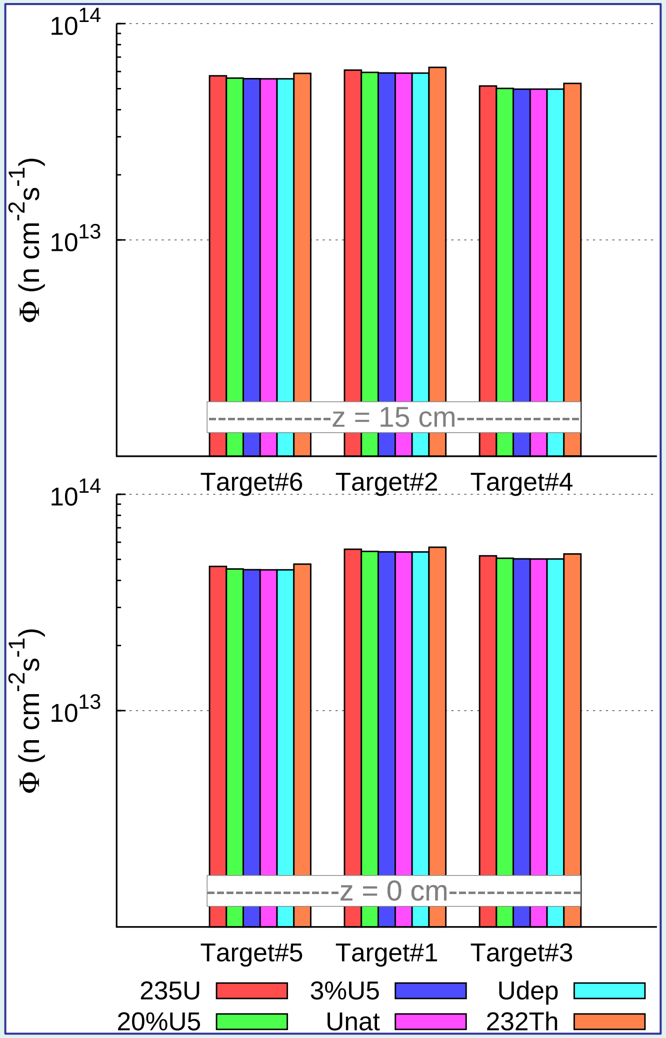
Target positions:

z = 0	T#5	T#1	T#3
z = 15	T#6	T#2	T#4
x=>	-15	0	15
y=>	-12.9	10	-12.9

- ❑ Geometry :
- ✓ Last design variant (L. Tecchio): 30kW load heat
- ✓ Volume = 181cm^3 (R_{ext}=1.75cm, R_{int}=0.4cm,H=20cm)
- ❑ Material:
- ✓ Targets: graphite + U, density=1.88 g cm^{-3}, (mass U=15g | mase rate: U/C=1/20 , MKLN)
- ✓ Moderator: H_2O, Fe (^{232}Th)
- ✓ Reflector: BeO, Fe (^{232}Th)
- ❑ Physics parameters:
- ✓ Source:
- ✓ Model:(
- ✓ T=239K

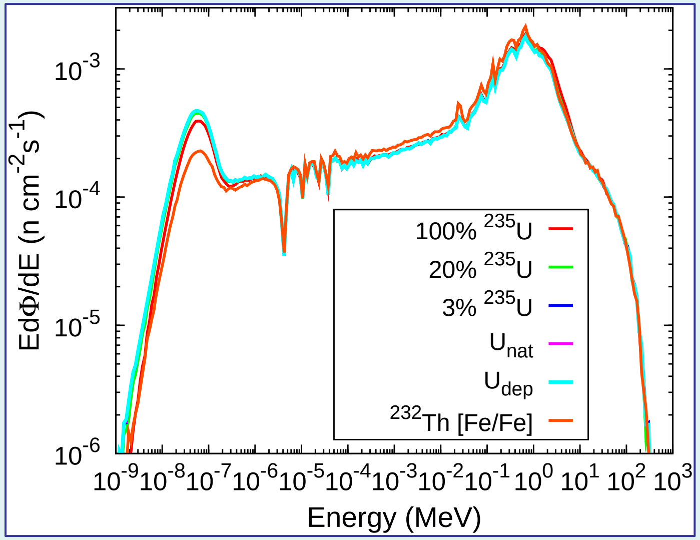
Results normalised at 1mA

CONVERTER: Results | Neutron flux



Configuration	Average z=0cm	Average z=15cm
^{235}U	5.1380E+13	5.6604E+13
20% ^{235}U	5.0084E+13	5.5219E+13
3% ^{235}U	4.9764E+13	5.4867E+13
U_{nat}	4.9707E+13	5.4811E+13
U_{dep}	4.9700E+13	5.4794E+13
^{232}Th	5.2496E+13	5.8150E+13

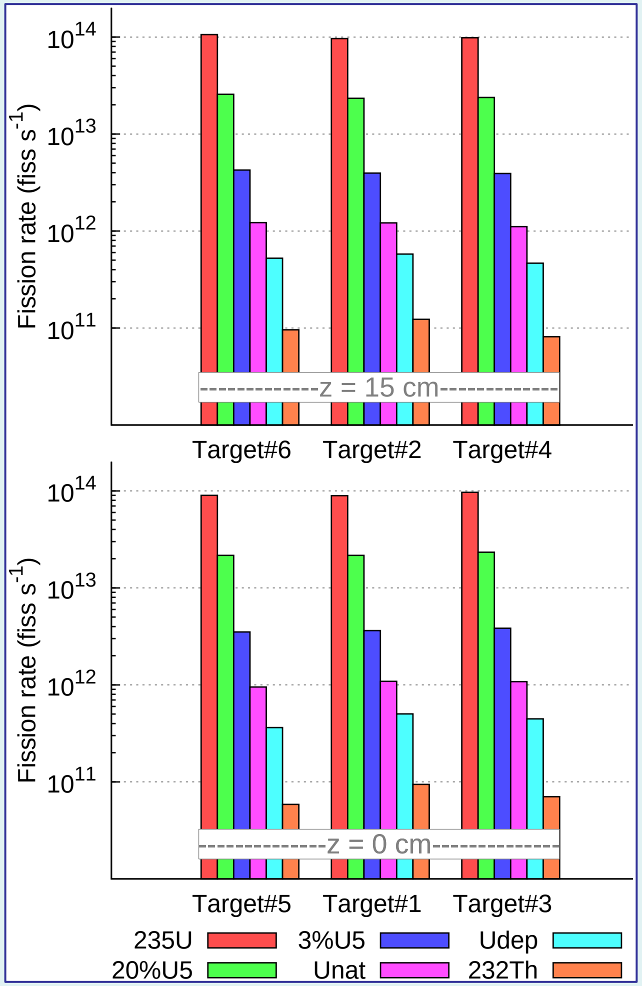
Neutron flux (n cm^{-2} s^{-1})



Neutron Flux – distribution over the targets

Neutron Flux – energy distribution (T#1)

Converter: Results | Fission rates

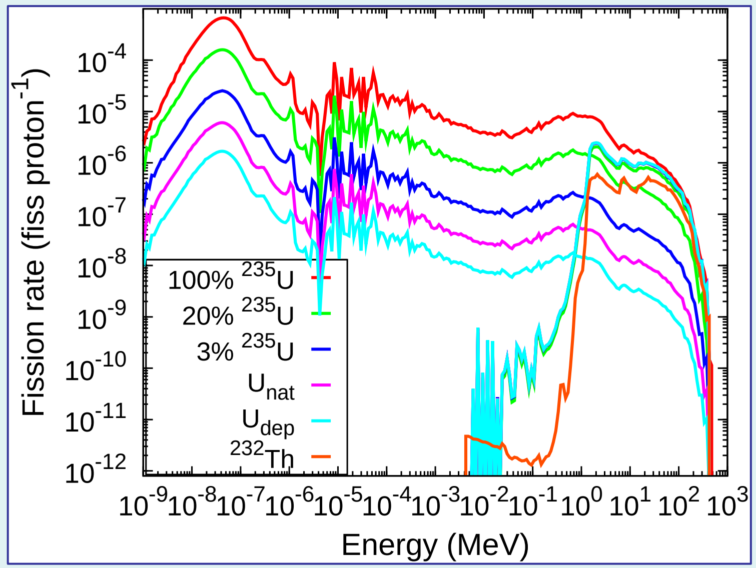


Fission Rates – distribution over the targets

Configuration	^{235}U* (fiss/s)	^{238}U (fiss/s)	Total (fiss/s)	^{235}U [%]
^{235}U	5.7689E+14		5.7689E+14	100
20% ^{235}U	1.3823E+14	1.2021E+12	1.3943E+14	99.14
3% ^{235}U	2.1712E+13	1.3931E+12	2.3106E+13	93.97
U_{nat}	5.2449E+12	1.4172E+12	6.6621E+12	78.73
U_{dep}	1.4591E+12	1.4223E+12	2.8814E+12	50.64
^{232}Th	5.2366E+11		5.2366E+11	

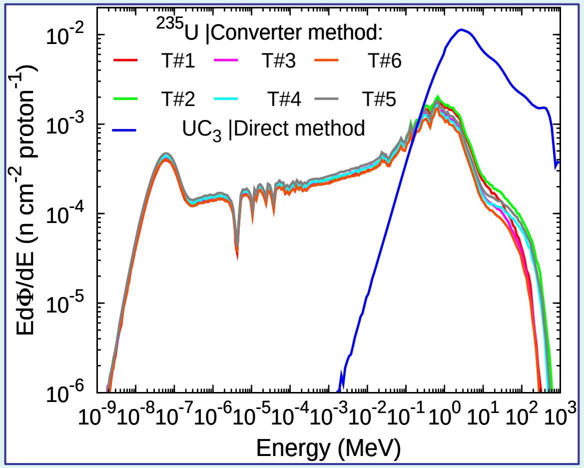
* ^{232}Th for Th case

Fission Rates – total



Fission Rates –energy distribution (T#1)

COMPARISON: Direct vs Converter methods | Flux & Fission rates

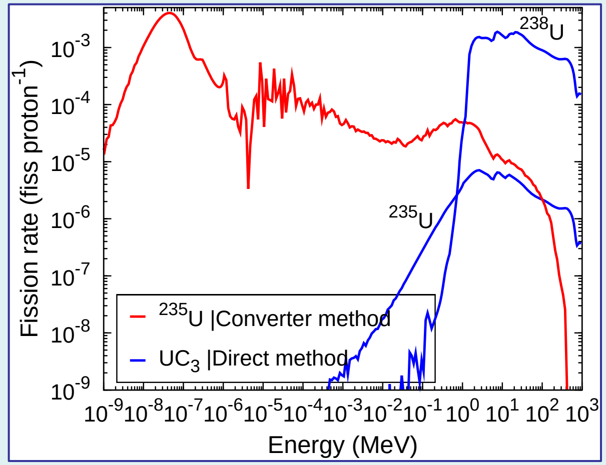


Neutron flux: fission | spallation

Neutrons vs 1GeV protons

C(^{235}U) vs D(UC_3*)

* Direct target:
R=1.8cm, L=40cm



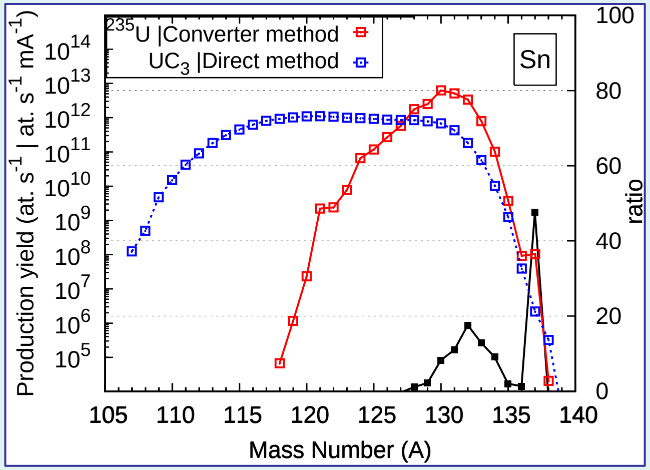
Neutron fission rate: fission | spallation

Configuration	Φ_{avg}(n cm^{-2} s^{-1}) z=0cm	Φ_{avg}(n cm^{-2} s^{-1}) z=15cm	Φ_{total} (n cm^{-2} s^{-1})
Converter (^{235}U)	5.1380E+13	5.6604E+13	
Direct (UC_3)			2.473E+13

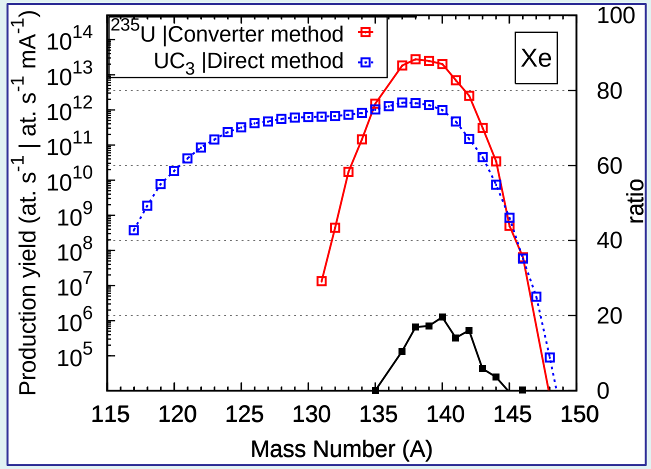
Configuration	^{235}U (fiss/s)	^{238}U (fiss/s)	Total (fiss/s)
Converter (^{235}U)	5.7689E+14		5.7689E+14
Direct (UC_3)	1.591E+11	4.0415E+13	4.0574E+13

COMPARISON: Direct vs Converter methods | Yields

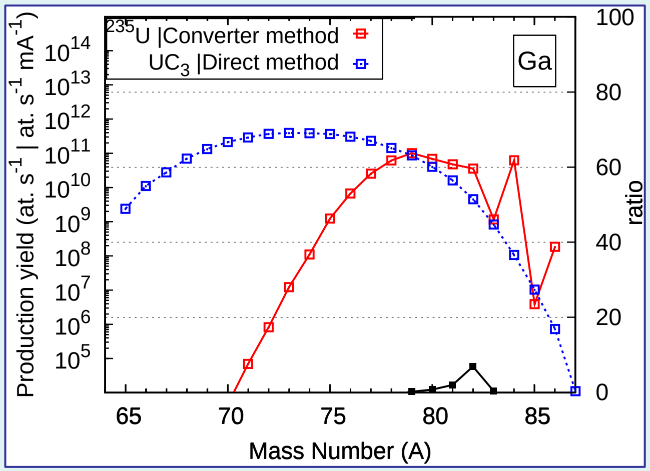
Neutrons vs 1GeV protons



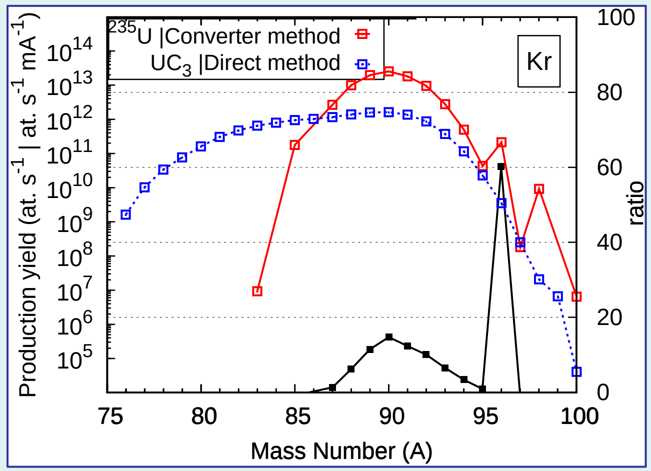
Yields – Sn: fission | spallation



Yields – Xe: fission | spallation



Yields – Ga: fission | spallation



Yields – Kr: fission | spallation

OPERATION:Containment | Risk register

Main risks for the Fission target

Major Risks:

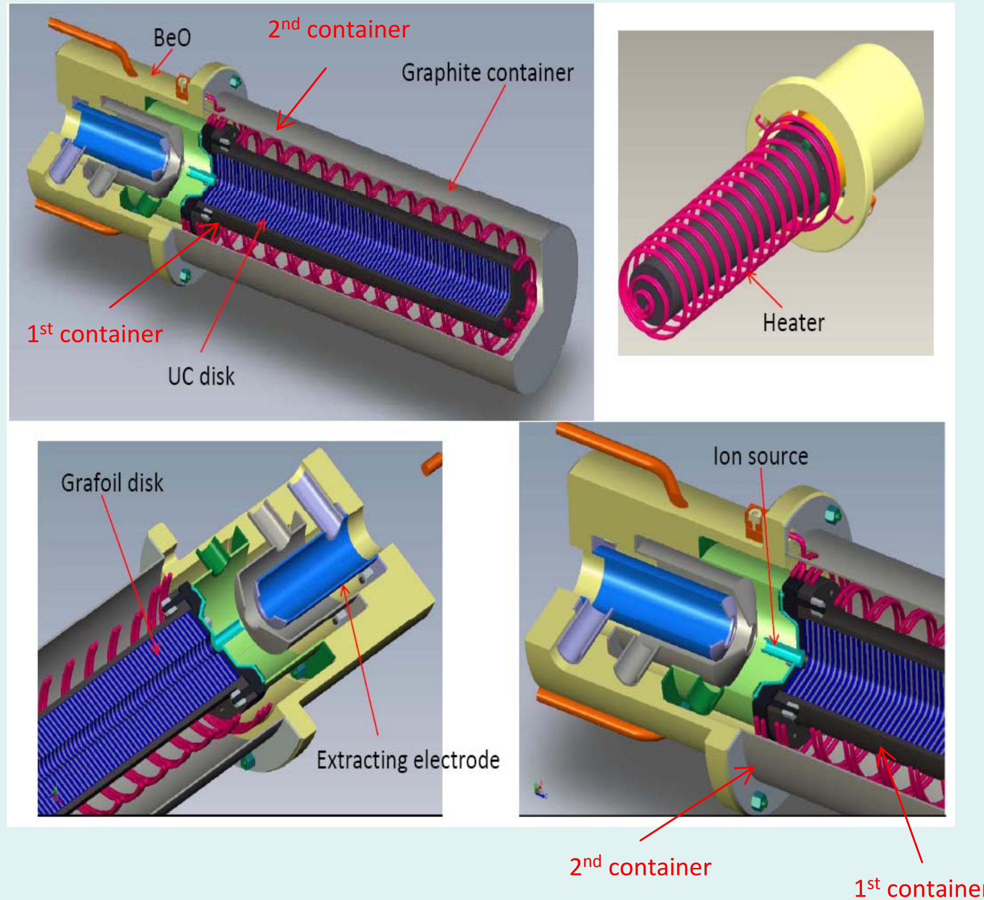
- breaking of target container
- target firing

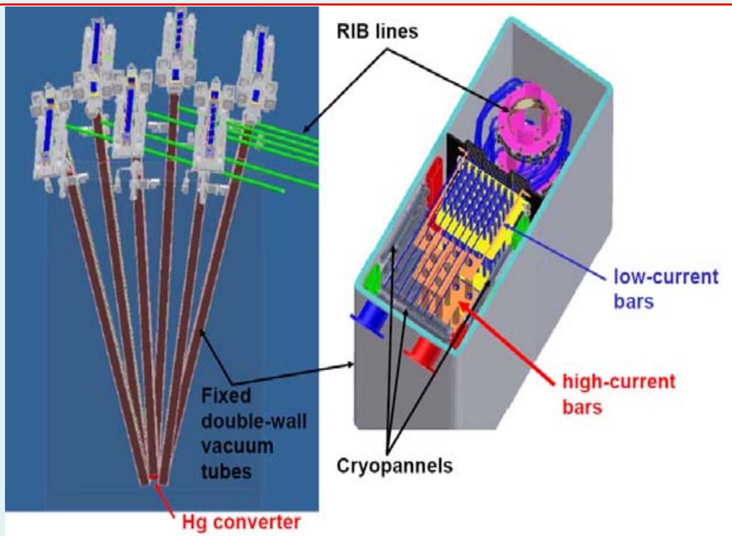
Consequences:

Dissemination of radioactivity in the environment

10^{15} fission fragments/sec per target

(~ 5 x 10^4 Ci)





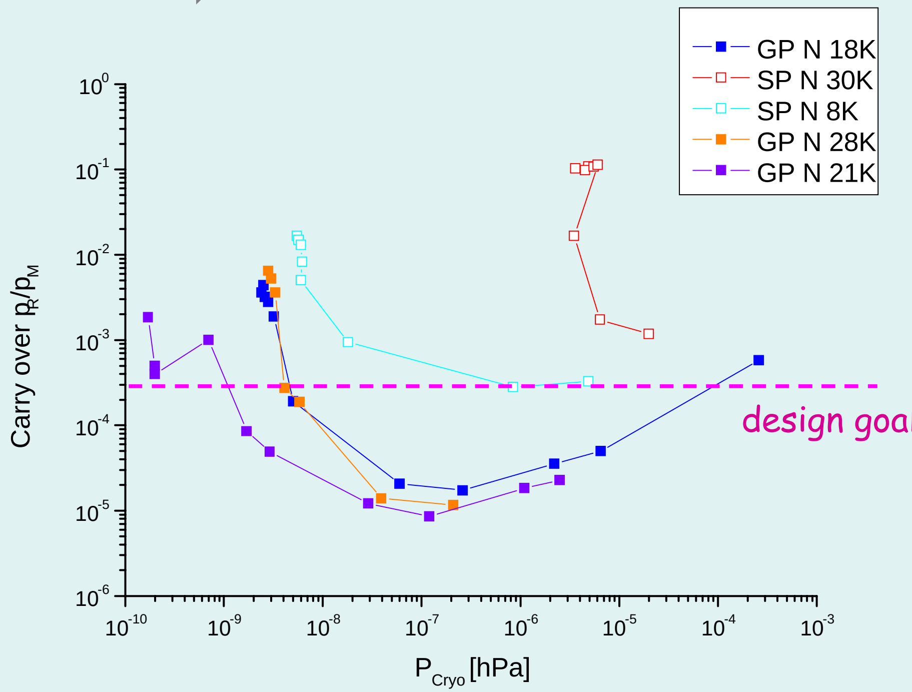
OPERATION: containment of volatile radioactivity

Capability of Cryotrap (LMU)

3 cryotraps prototypes tested: retention capability (vs. pressure behind cryotrap)

'carry over': fraction of leaking gas load transported across cryotrap

2 trap types operated at different temperatures:



Cryotrap works within (simulated) expectations → 99.98% of volatile radioactivity can be localized!