The nELBE neutron beamline at HZDR: overview and shielding calculations

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Outline

- The Transmutation Research at HZDR: MYRRHA and nELBE
- A quick look at the measurement program at nELBE
- An overview of the first (2007-2011) nELBE neutron beamline and of the new beamline and experimental room
- Monte Carlo studies for the nELBE upgrade: radiation field characterization
- Shielding calculations
- Signal/background optimization
- Some considerations about activation

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Motivation for the transmutation research (I)

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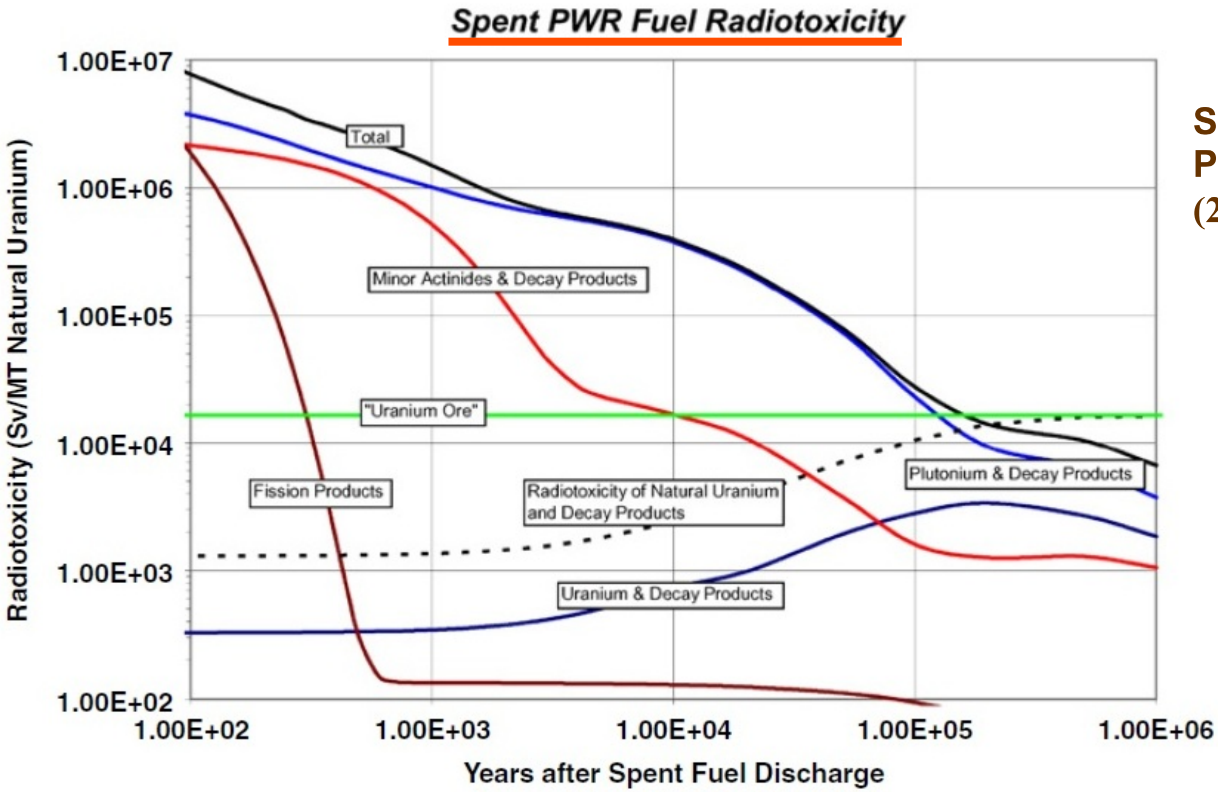

Source: Salvatores, Palmiotti, Progress in Part. And Nucl. Phys. 66 (2011)

From the IAEA FR13 Conference (March 2013, Paris):

-USA produces ~2000 MT spent fuel per year;

- estimated inventory by the end of 2012: 70000 MT spent fuel

U	Pu	Minor Actinides	Long-lived Fission Products	Short-lived Fission Products	Stable Isotopes
955.4 kg	8.5 kg	0.5 kg ^{237}Np 0.6 kg Am 0.02 kg Cm	0.2 kg ^{129}I 0.8 kg ^{99}Tc 0.7 kg ^{93}Zr 0.3 kg ^{135}Cs	1.0 kg ^{137}Cs 0.7 kg ^{90}Sr	10.1 kg Lanthanides 21.8 kg other

Motivation for the transmutation research (II)

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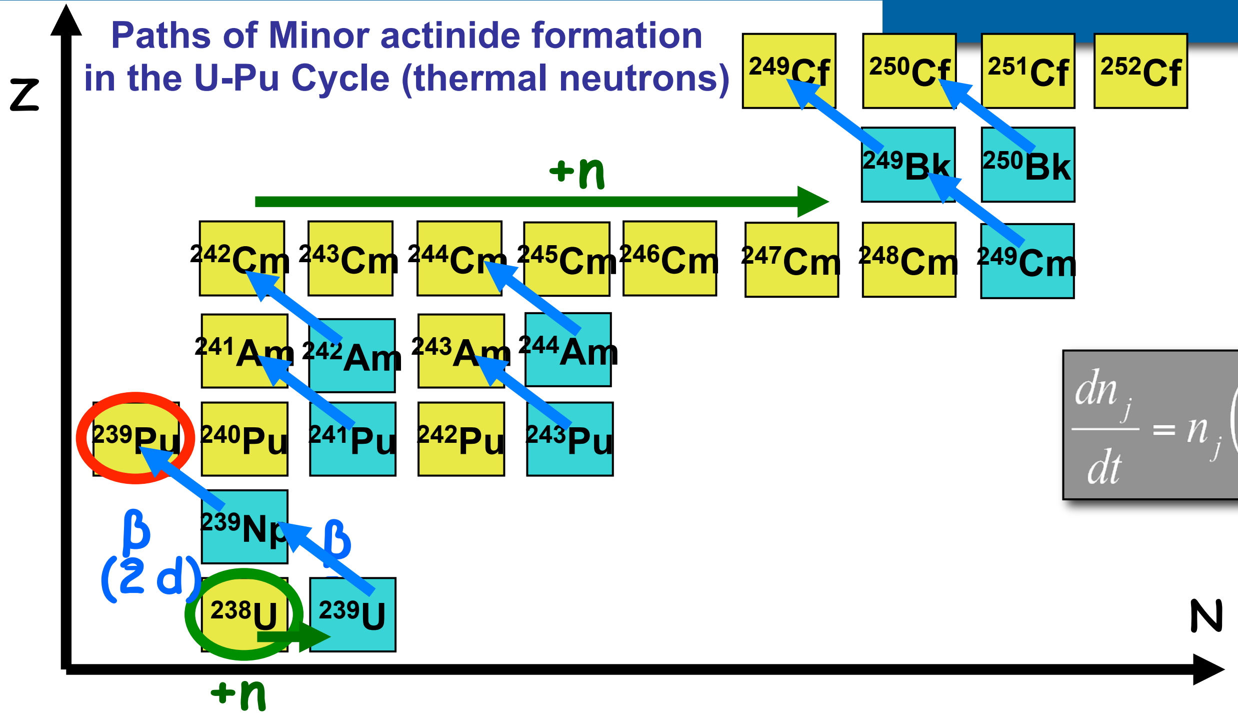


^{A}X

α – emitters
many have $T_{1/2}$~10^4a

$$\frac{dn_j}{dt} = n_j\left(-\sigma_{aj}\phi - \lambda_j\right) + \sum_K \left(\sigma_K^j \phi + \lambda_K^j\right) n_K$$

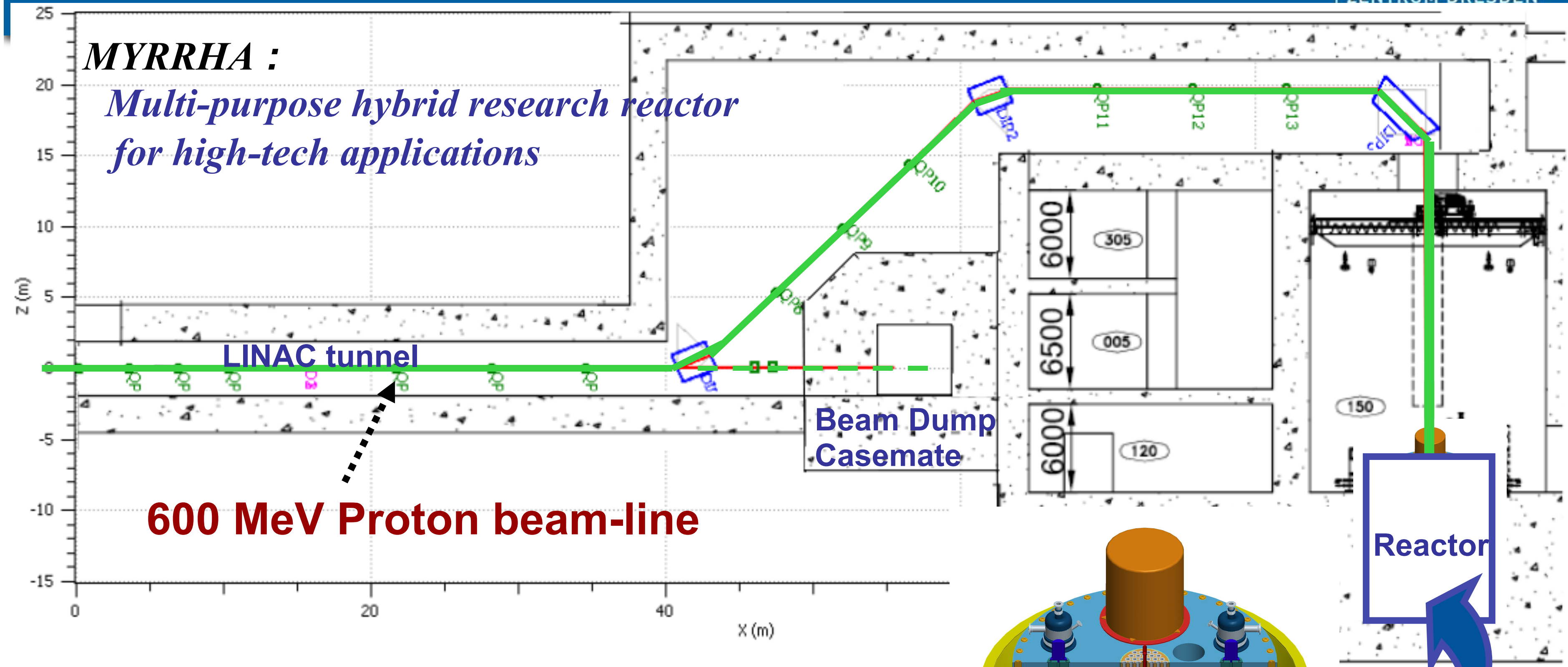
- Separated transuranic elements can be “transmuted” in shorter-lived elements in a neutron field, where fission and neutron capture processes are always in competition

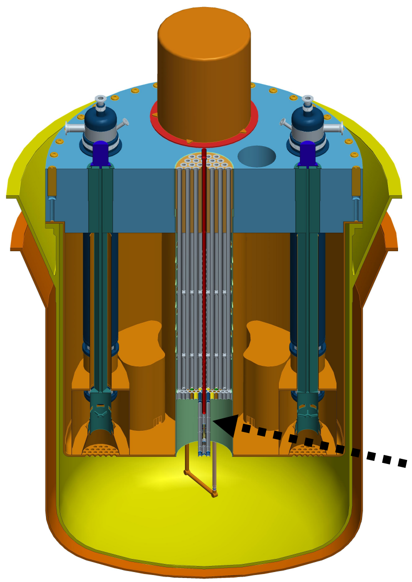
- Fast neutron spectrum appears to be the most adapted to support transmutation

Different strategies can be followed… one is **the ADS option**

Shielding calculations for MYRRHA

MYRRHA :
Multi-purpose hybrid research reactor
for high-tech applications





- ***demonstrator of the ADS concept using Lead Fast Reactor technology***
- ***European projects in support of MYRRHA (Ex. CDT-FASTEF (2009-2012), MAXSIMA, CHANDA) Established and good collaboration with ENEA and Ansaldo***

- *The **Transmutation Research** at HZDR: MYRRHA and nELBE*

- ***A quick look at the measurement program at nELBE (*)***

- ***An overview of the present nELBE neutron-line and of the new beam-line and experimental room***

- ***Monte Carlo studies for the nELBE upgrade: radiation field characterization***

- ***Shielding calculations***

- ***Signal/background optimization***

- ***Some considerations about activation***

(*) The nELBE group at HZDR:

R. Beyer, E. Birgersson, A. Ferrari, E. Grosse, R. Hannaske, A.Junghans, T. Koegler,

I. Koesterke, R. Massarczyk, A. Matič, K.-D. Schilling, R. Schwengner, G.Schramm, A. Wagner

A look at the research program at nELBE

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Table 32. Summary of Highest Priority Target Accuracies for Fast Reactors

		Energy Range	Current Accuracy (%)	Target Accuracy (%)
U238	σ_{inel}	6.07 ÷ 0.498 MeV	10 ÷ 20	2 ÷ 3
	σ_{capt}	24.8 ÷ 2.04 keV	3 ÷ 9	1.5 ÷ 2
Pu241	σ_{fiss}	1.35MeV ÷ 454 eV	8 ÷ 20	2 ÷ 3 (SFR,GFR, LFR) 5 ÷ 8 (ABTR, EFR)
Pu239	σ_{capt}	498 ÷ 2.04 keV	7 ÷ 15	4 ÷ 7
Pu240	σ_{fiss}	1.35 ÷ 0.498 MeV	6	1.5 ÷ 2
	ν	1.35 ÷ 0.498 MeV	4	1 ÷ 3
Pu242	σ_{fiss}	2.23 ÷ 0.498 MeV	19 ÷ 21	3 ÷ 5
Pu238	σ_{fiss}	1.35 ÷ 0.183 MeV	17	3 ÷ 5
Am242m	σ_{fiss}	1.35MeV ÷ 67.4keV	17	3 ÷ 4
Am241	σ_{fiss}	6.07 ÷ 2.23 MeV	12	3
Cm244	σ_{fiss}	1.35 ÷ 0.498 MeV	50	5
Cm245	σ_{fiss}	183 ÷ 67.4 keV	47	7
Fe56	σ_{inel}	2.23 ÷ 0.498 MeV	16 ÷ 25	3 ÷ 6
Na23	σ_{inel}	1.35 ÷ 0.498 MeV	28	4 ÷ 10
Pb206	σ_{inel}	2.23 ÷ 1.35 MeV	14	3
Pb207	σ_{inel}	1.35 ÷ 0.498 MeV	11	3
Si28	σ_{inel}	6.07 ÷ 1.35 MeV	14 ÷ 50	3 ÷ 6
	σ_{capt}	19.6 ÷ 6.07 MeV	53	6

Goal: Measuring fast neutron reactions with the required accuracy needed to develop Nuclear Trasmutation Facilities (structural & coolant materials)

- **Neutron Inelastic scattering (n,n ‘γ) for ^{56}Fe, Mo, Pb, Na and <u>Total neutron cross sections</u> σ_{tot} (Ta, Au, Al, C, H)**
- **<u>Fission cross sections of minor actinides</u> (radioactive targets)**
  Collaboration with n-TOF at CERN

Based on the NEA high priority request list
and on the OECD Working Party on Evaluation Co-operation, subgroup 26

http://www.nea.fr/html/science/wpec/volume26/volume26.pdf

ELBE: Electron Linear accelerator with high Brilliance and low Emittance

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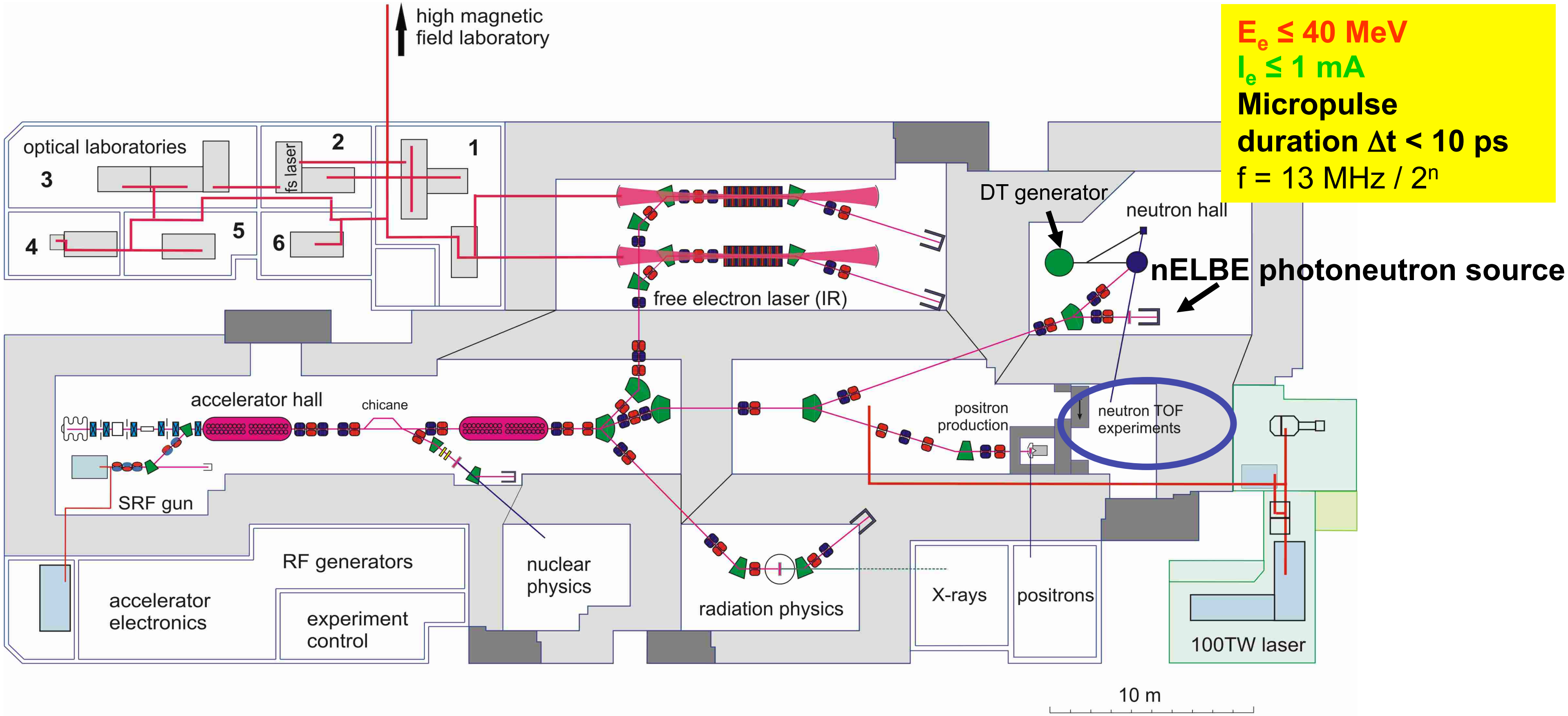
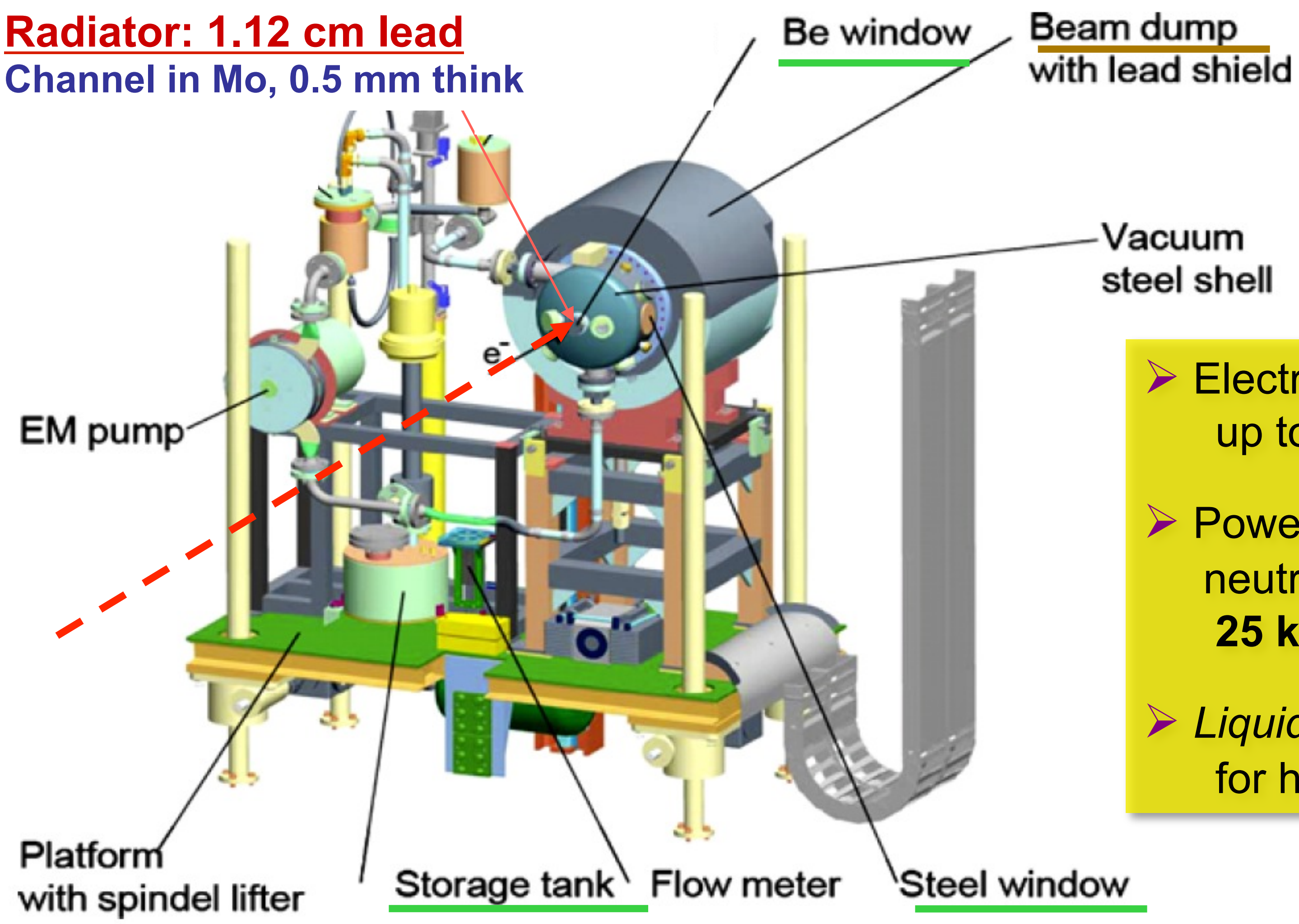


$E_e \leq 40$ MeV
$I_e \leq 1$ mA
Micropulse duration $\Delta t < 10$ ps
$f = 13\ \text{MHz} / 2^n$

1: Diagnostic station, IR-imaging and biological IR experiment
2: Femtosecond laser, THz-spectroscopy, IR pump-probe experiment
3: Time-resolved semiconductor spectroscopy, THz-spectroscopy
4: FTIR, biological IR experiment
5: Near-field and pump-probe IR experiment
6: Radiochemistry and sum frequency generation experiment, photothermal deflection spectroscopy

The nELBE photo-neutron target



- Electron beam power up to **40 kW**
- Power density in the neutron radiator up to **25 kW/cm^3**
- *Liquid lead circuit* for heat transport

The old experimental halls (2007-2011)

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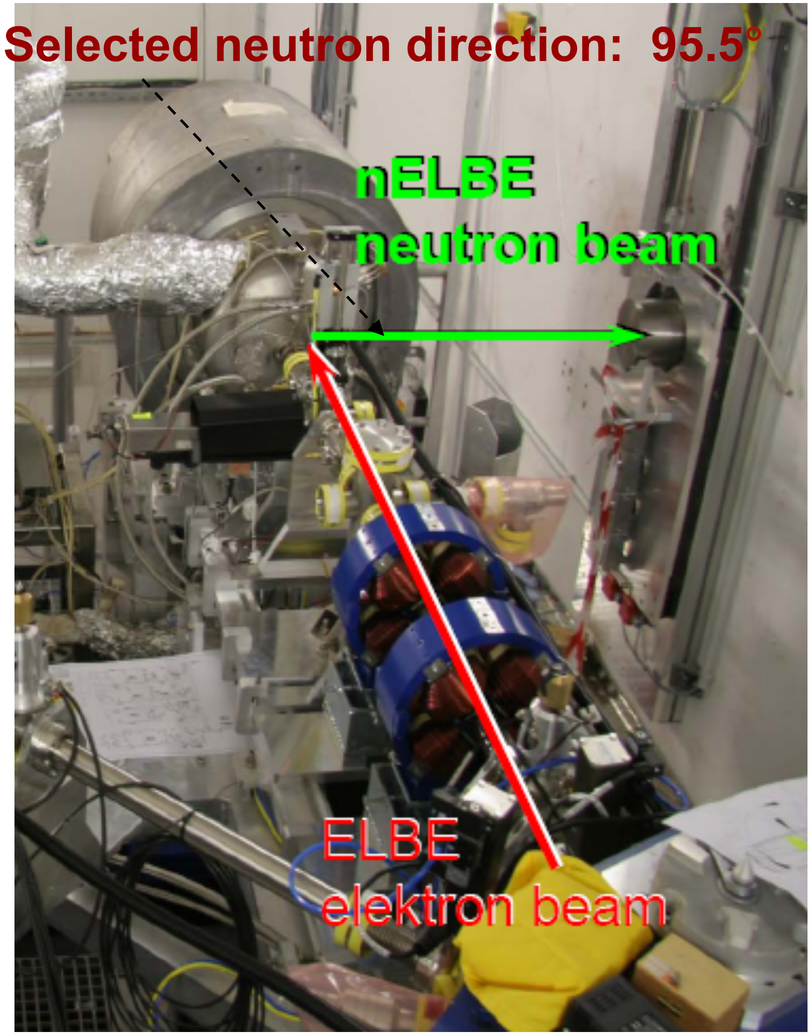
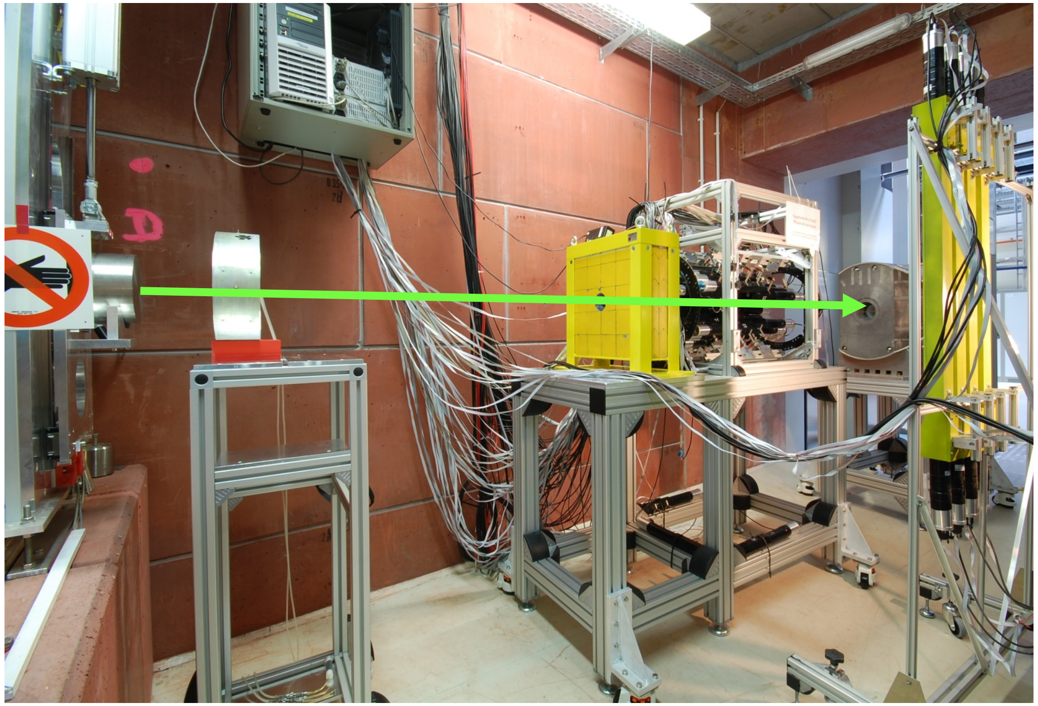
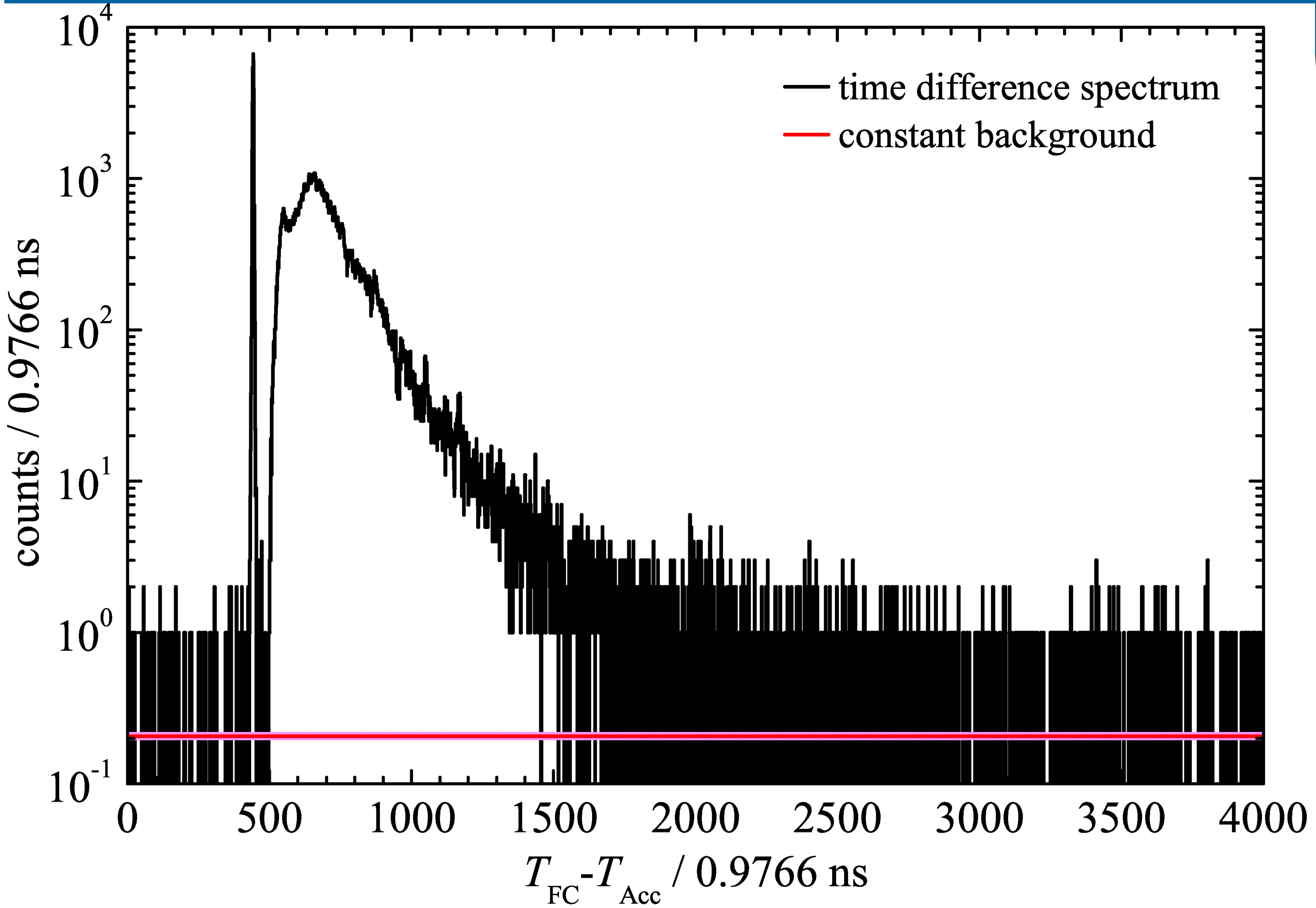
Photo-neutron source



Experimental room



The nELBE TOF spectrum



^{235}U fission chamber H19 from PTB.

Time resolution from peak width = 3.8 ns FWHM

The nELBE neutron spectrum

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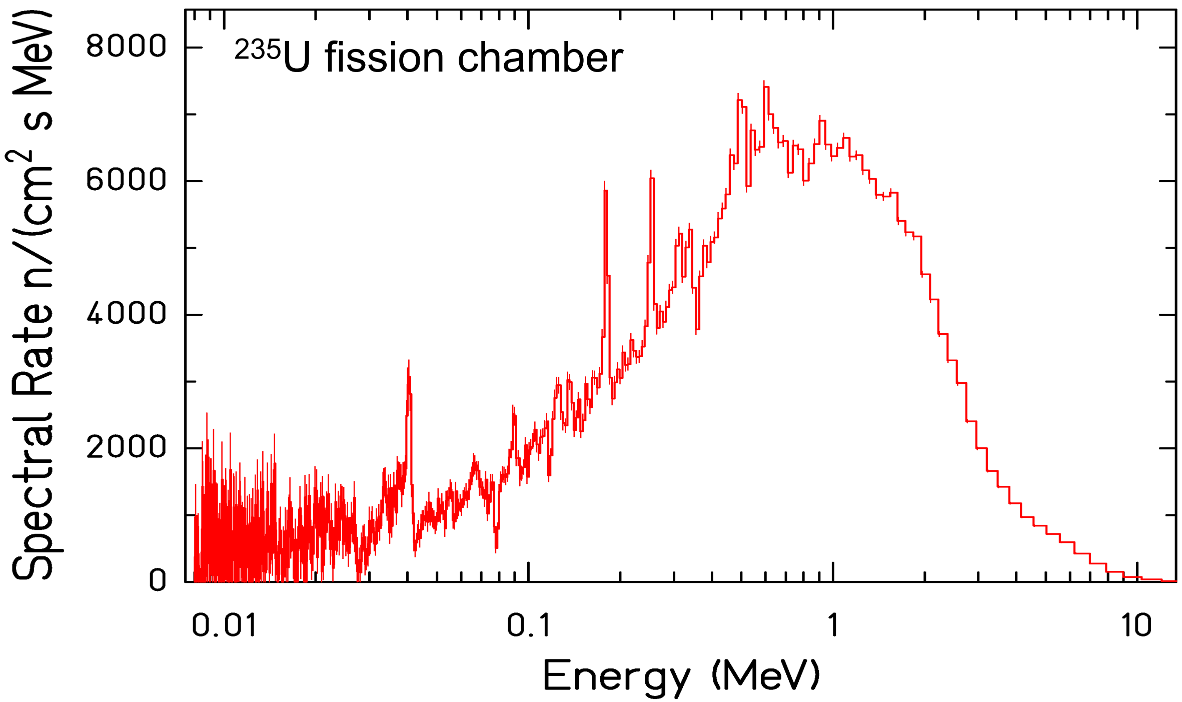
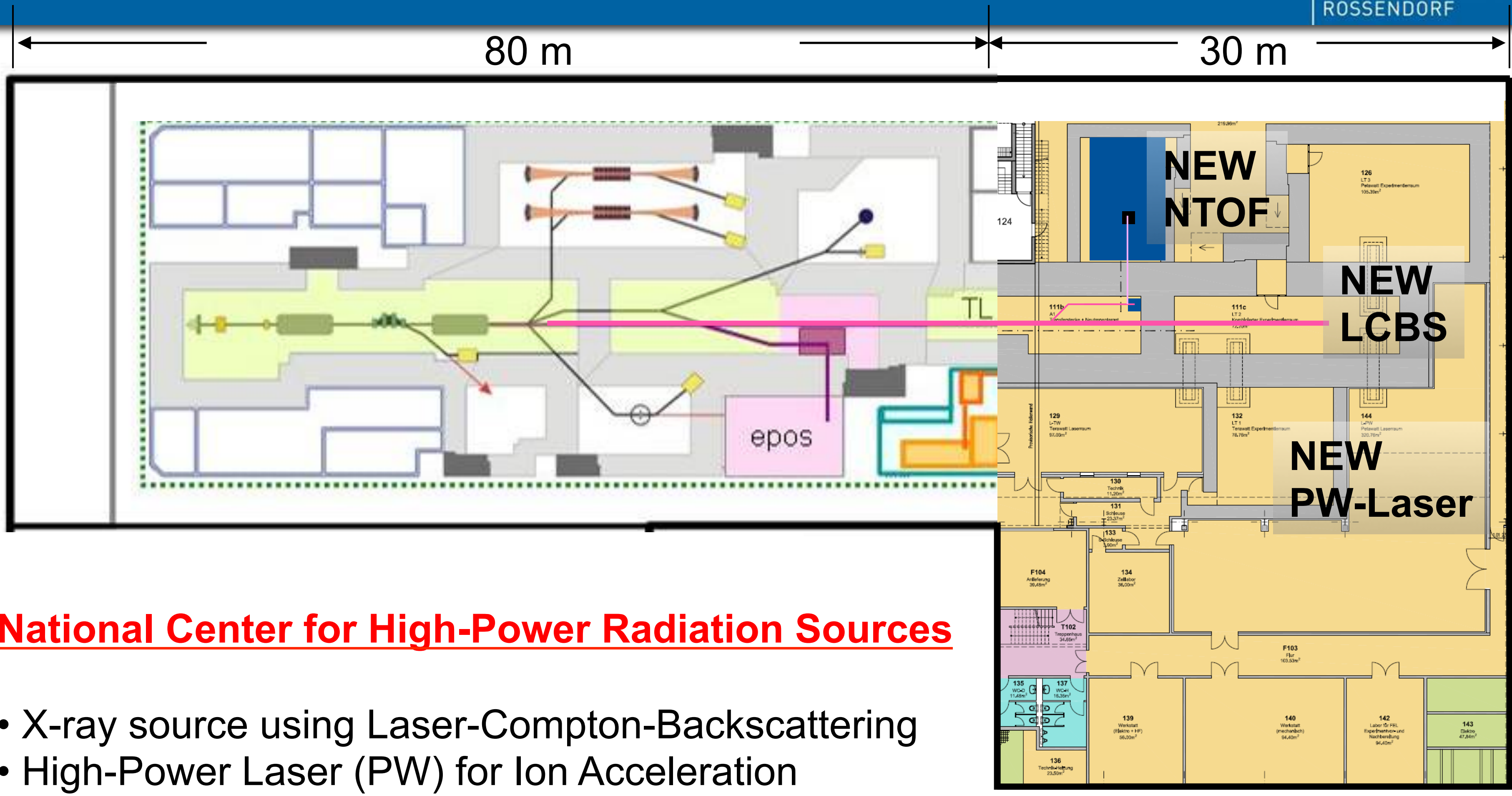


Measurement time : 49.4 h **I_{e-} = 15 µA**, **E_{e-} = 31 MeV**
Flight path 618 cm total uncertainty 3.5%
Absorption dips : 78,117, 355, 528, 722, 820 keV ^{208}Pb scattering resonances
Emission peaks: 40,89,179, 254, 314, 605 keV near threshold photoneutron emission
In ^{208}Pb (strong capture resonances of ^{207}Pb)
R. Beyer et al. submitted to NIM A (2012)

Extension of the ELBE facility



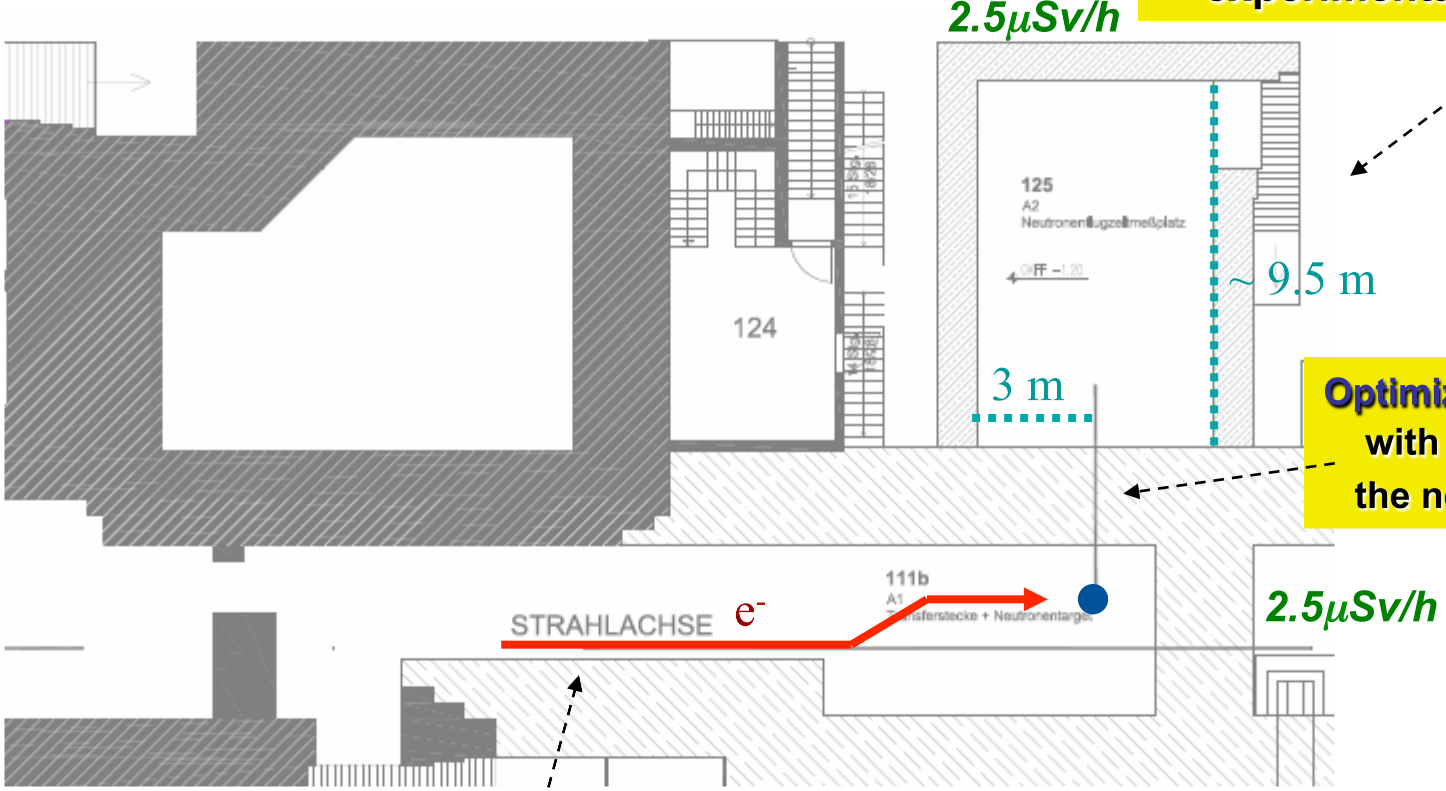
National Center for High-Power Radiation Sources

- X-ray source using Laser-Compton-Backscattering
- High-Power Laser (PW) for Ion Acceleration
- New Neutron Time-of-Flight Facility for Transmutation Studies

nELBE is a partner in the EURATOM FP7 ERINDA and (from 2013) CHANDA projects
Transnational access is supported. External users are very welcome

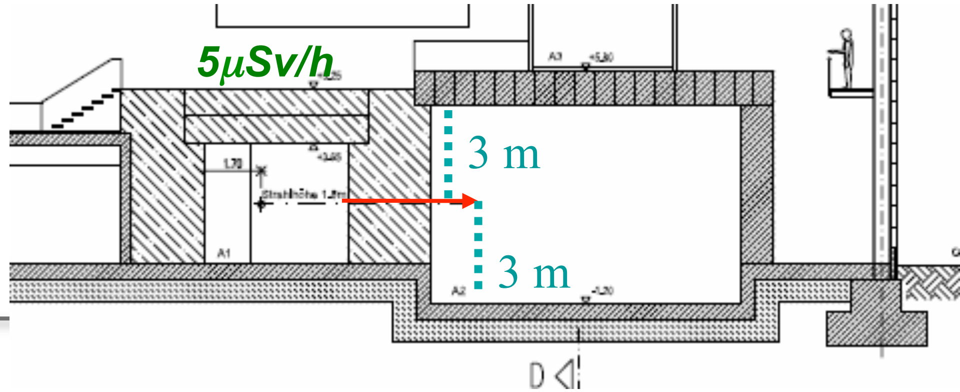
The new neutron experimental room

Larger dimensions and better experimental conditions



Optimized neutron beam-line with respect to the neutron/photon ratio

Enhanced energy of the electron beam (up to 50 MeV)



Liquid-lead photo-neutron source

Time-of-flight hall
6 m x 6 m x 9 m

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Strength of the improved source

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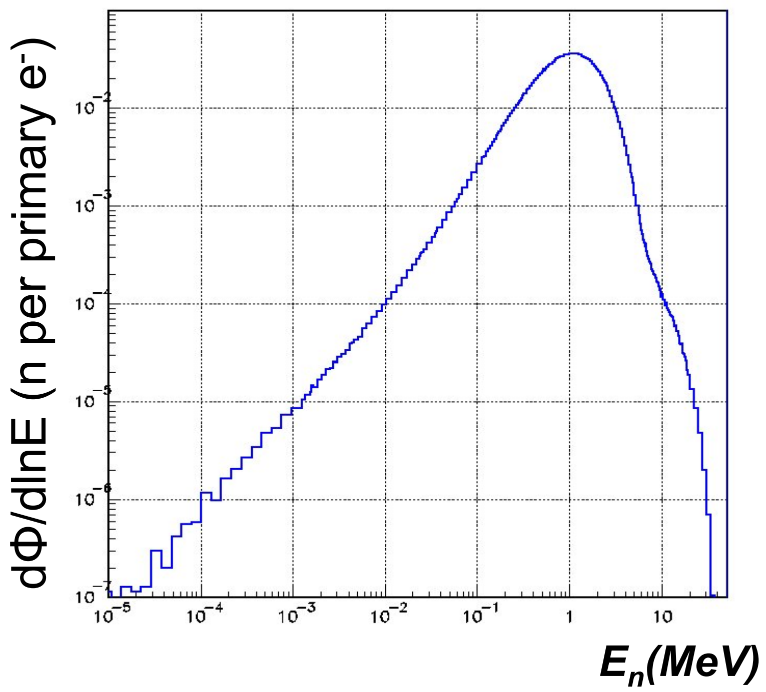
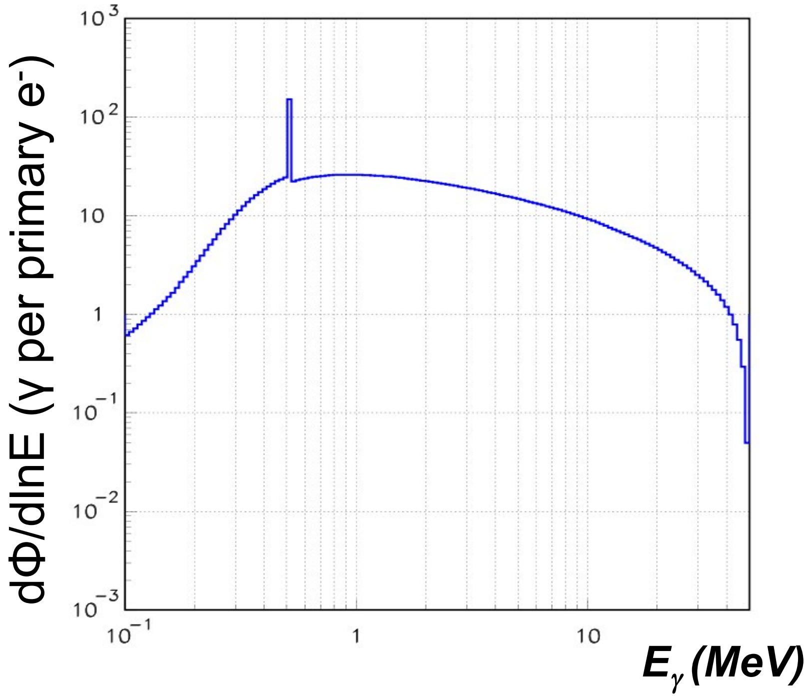
Neutron and photon total yields at E_{e^-} = 50 MeV (FLUKA Simulation)





n_{yield} (tot) = 5.67 10^{-3} n/e-

γ_{yield}(tot)= 6.68 γ/e

At the entrance of the collimator:

n_{yield} = 4.34 10^{-8} n per cm² per primary e-

A deeper look at the photoproduction simulation

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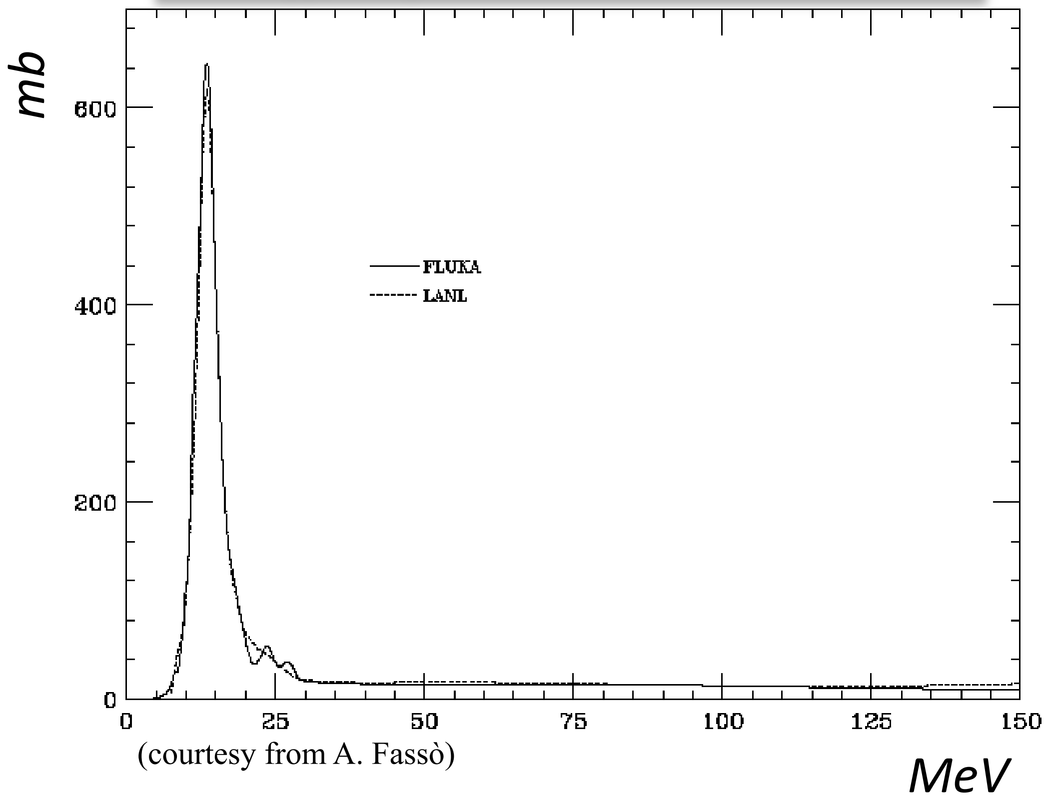
Comparison of the total cross sections in FLUKA and in the MCNP code

An important difference:

- **MCNP** works with differential cross sections, for each reaction channel

- **FLUKA** uses the total cross sections to determine where the interaction occurs, then proceeds with the models (PEANUT[pre-equilibrium], evaporation and Fermi break-up)

$^{208}Pb(\gamma, tot)$ - **FLUKA and LANL**



(courtesy from A. Fassò)

FLUKA vs MCNP

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Calculation of the total yields (Source Strength)

Electron Energy (MeV)	Neutron Yield (n/e^-) FLUKA	Neutron Source Strength at the radiator (n/s) MCNP (*)	FLUKA
20	$1.205\ 10^{-3}$	$7.9\ 10^{12}$	$7.52\ 10^{12}$
30	$3.108\ 10^{-3}$	$1.9\ 10^{13}$	$1.94\ 10^{13}$
40	$4.51\ 10^{-3}$	$2.7\ 10^{13}$	$2.81\ 10^{13}$
50	$5.67\ 10^{-3}$		$3.54\ 10^{13}$

Hyp: 1 mA current → $6.24\ 10^{15}\ e^-/s$

(*) nELBE published results:
Ann. of Nucl. En. 34 (2007) 36-50

FLUKA statistical accuracy: < 1%

➡ ***MCNP and FLUKA agree at the level of few percent in the yield calculation***

An additional check: the comparison with the Swanson evaluations

Swanson (SLAC-PUB-2042, 1978)
calculated the neutron yields from semiinfinite slabs of materials by folding the measured photoneutron cross sections with the numerical integration of the photon track length distributions (derived from the analytical theory of the showers)

⬇

$9.3 \cdot 10^{10}\ Z^{(0.73 \pm 0.05)}$ neutrons s^{-1} kW^{-1}

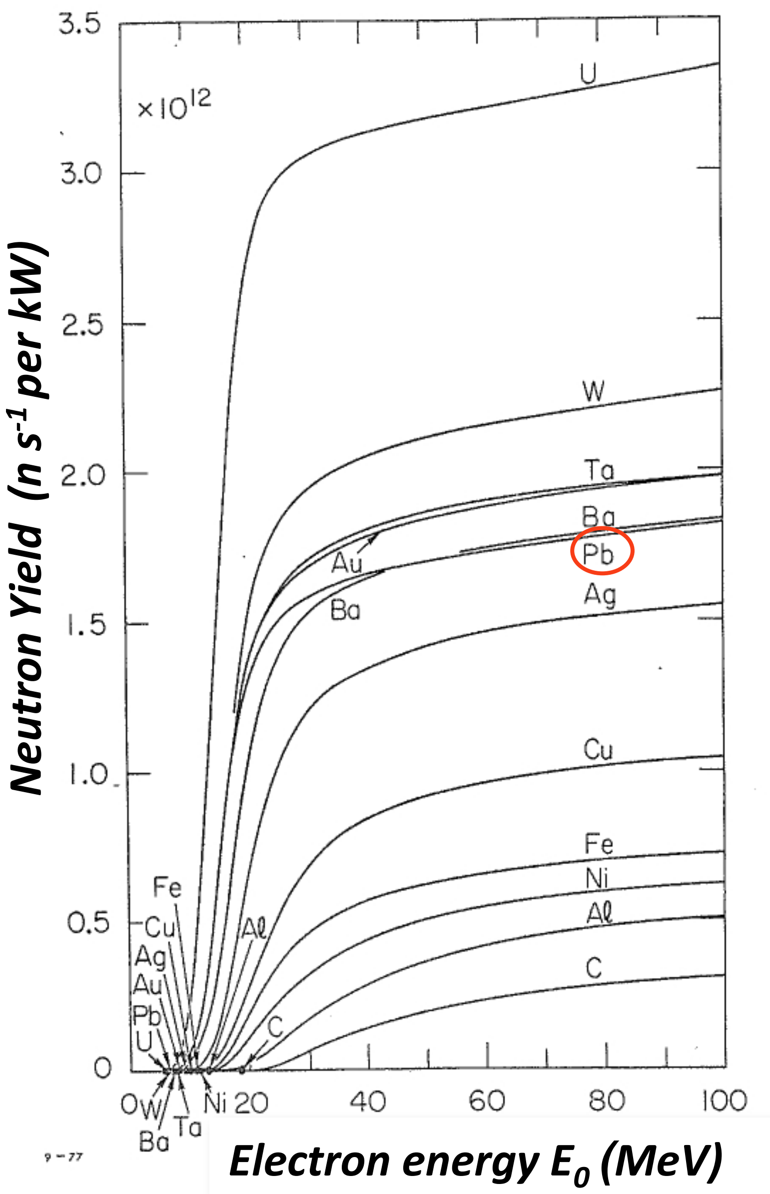
The formula gives, for the asymptote of the curve of the lead: $2.32 \cdot 10^{12}$ n s^{-1} kW^{-1}

This value is valid for semiinfinite slabs and at high energies: we have to correct in real cases.

By correcting for the energy (for ex. @ 30 MeV) and for the finite dimensions of the slab ($2X_0$ in our case) we get:

$1.92\ 10^{13}$ n s^{-1} @1 mA and @30 MeV

in perfect agreement with both MCNP and FLUKA



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Steps of the radiation protection calculations

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1. Complete description of geometry and materials of the photo-neutron target, the Al-Lead beam dump, the Lead/Poly-Bor collimator, the walls and the final Lead/Poly-Bor Dump

2. To compute all the dose rates in the photo-neutron source hall:

   → We start from the photoproduction process, to have in each point the mixed field given by the neutron (isotrope) source + the Bremsstrahlung spectrum

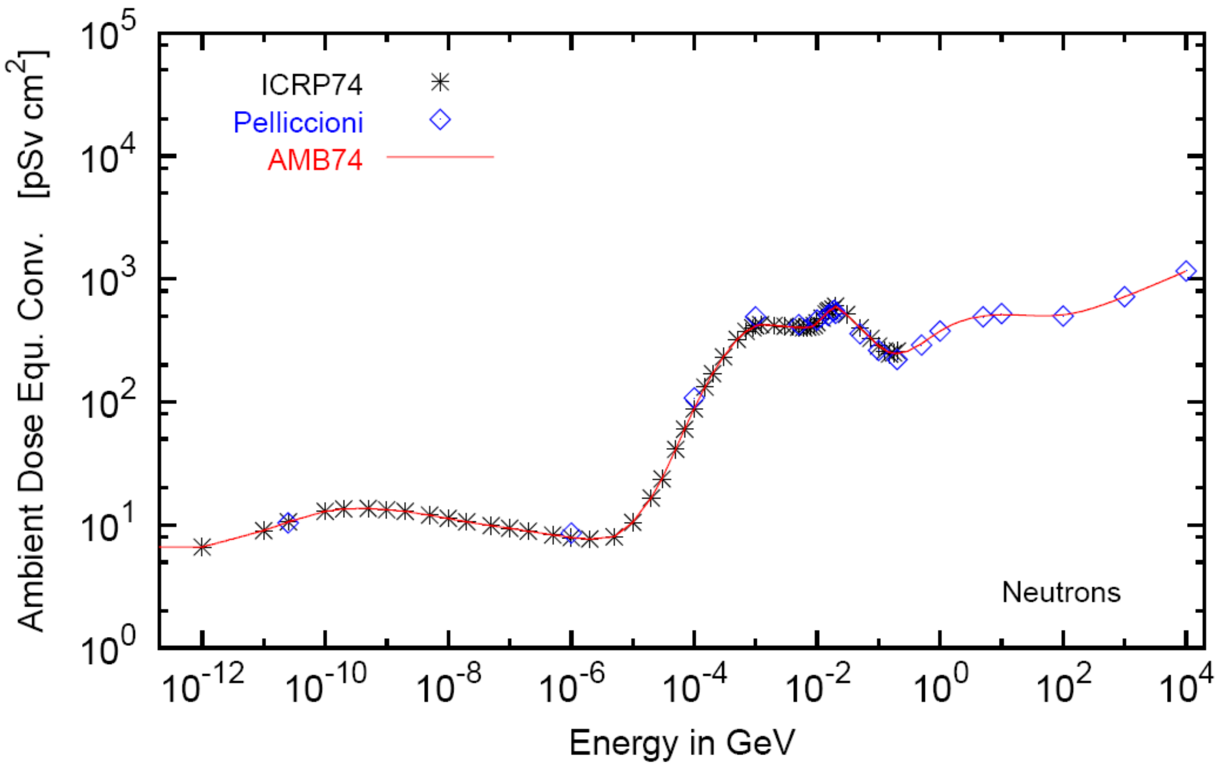
3. To compute all the dose rates in the nELBE experimental room:

   → We use as source term the secondary neutron and photon spectra, calculated in the direction of the collimator

Fluence - H(10) conversion coefficients in FLUKA*

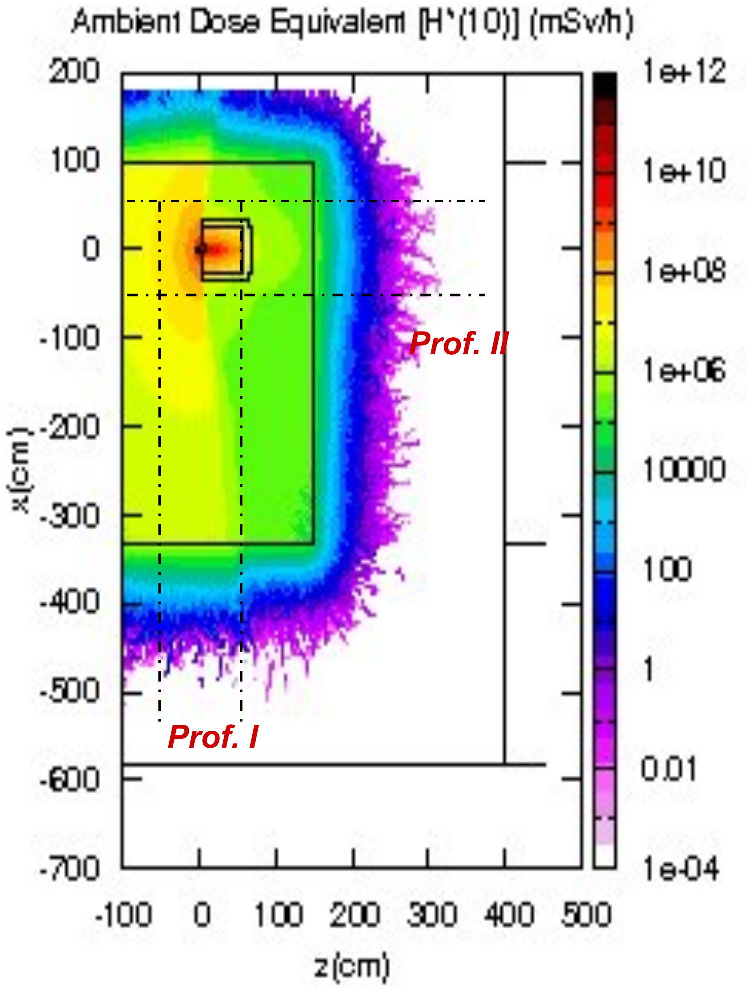
Conversion coefficients from fluence to ambient dose equivalent are based on ICRP74 values and values calculated by M.Pelliccioni. They are implemented for protons, neutrons, charged pions, muons, photons, electrons (conversion coefficients for other particles are approximated by these).

In the card: AMB74 is the default choice for dose equivalent calculation



Dose profiles
through the walls of the photo-neutron hall

Horizontal section through the neutron hall



Definition of the volumes for the calculation:

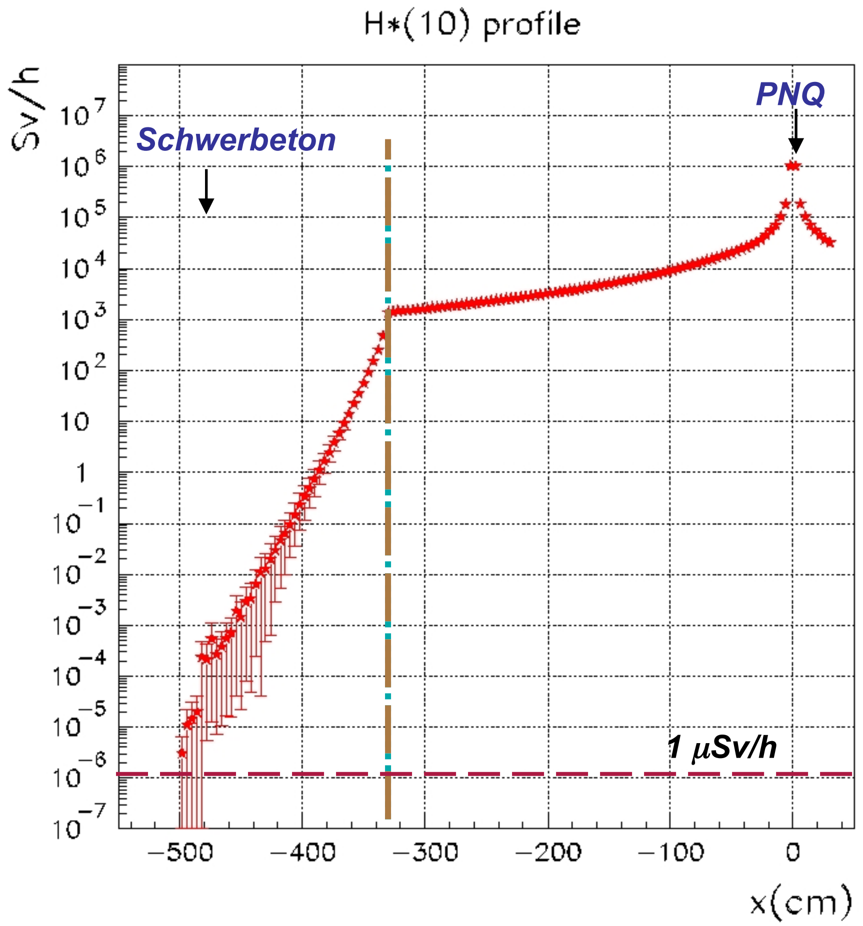
Profile I (wall opposite to the neutron beamline)

a column along x, large:
(-50 cm, 50 cm) in z
(-50 cm, 50 cm) in y

Profile II (wall behind the beam dump)

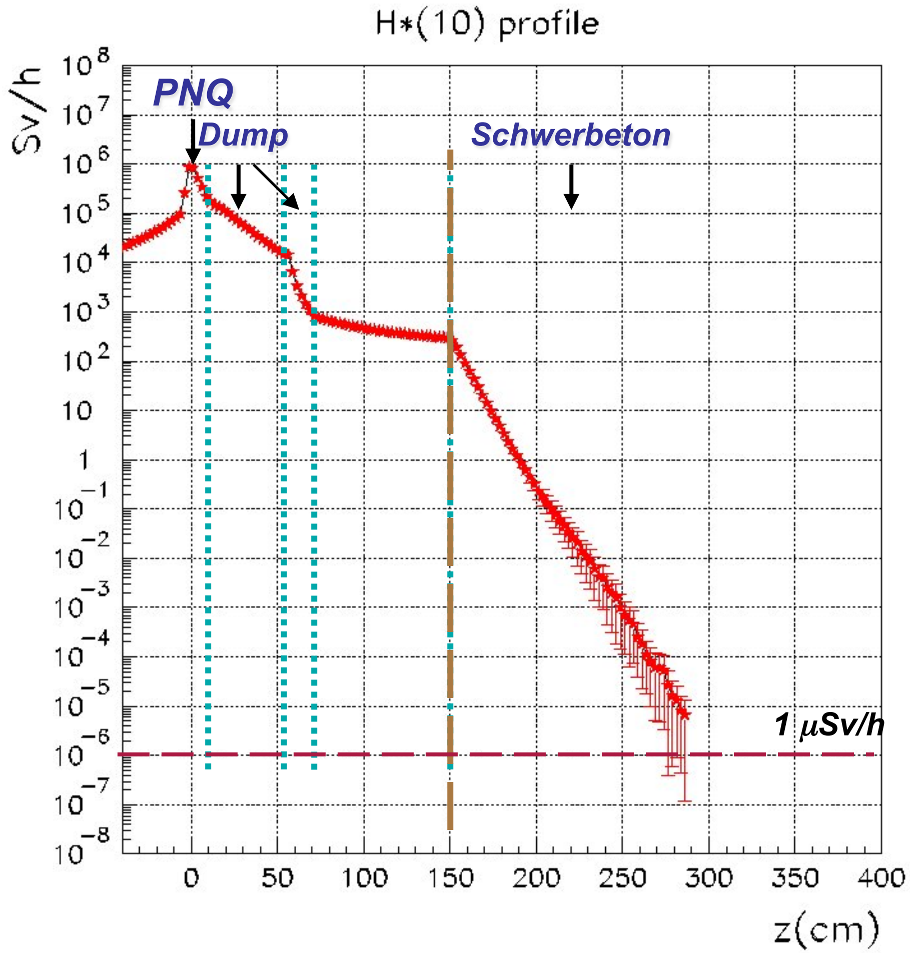
a column along z, large:
(-50 cm, 50 cm) in x
(-50 cm, 50 cm) in y

Profile I.
Wall opposite to the neutron beamline



Extrapolation: **1 μSv/h** at ~ -525 cm
(after 200 cm in the heavy concrete)

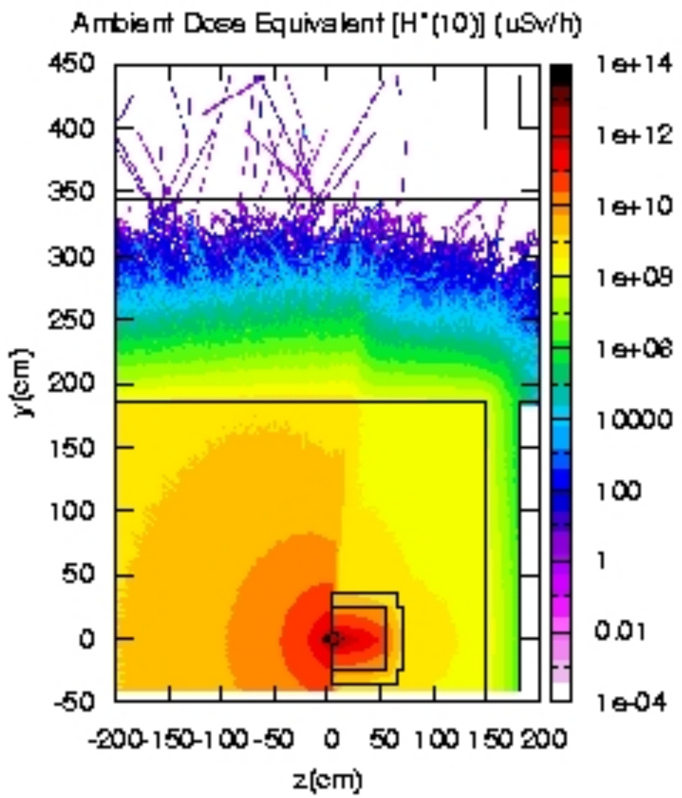
Profile II.
Wall behind the PNQ

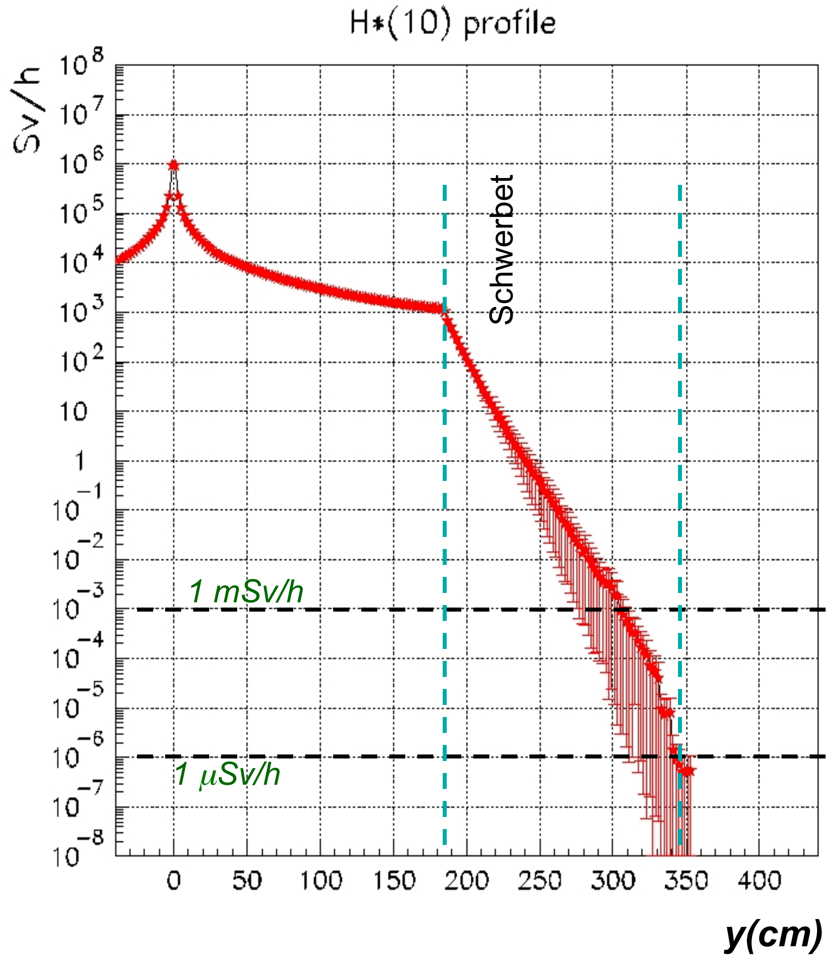


Extrapolation: **1 μSv/h** at ~300 cm
(after 150 cm in the heavy concrete)

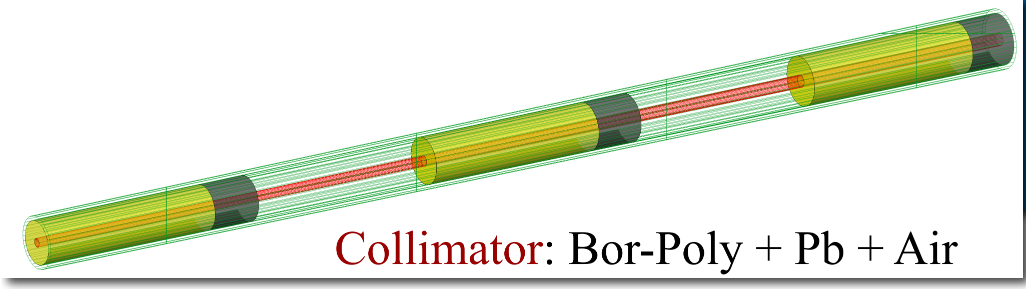
Dose profiles through the roof of the photo-neutron hall

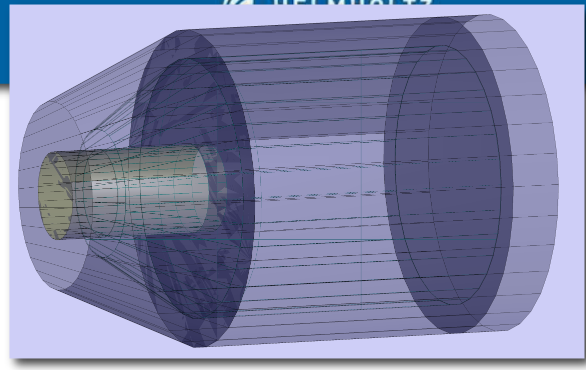
Solution: 160 cm of heavy concrete

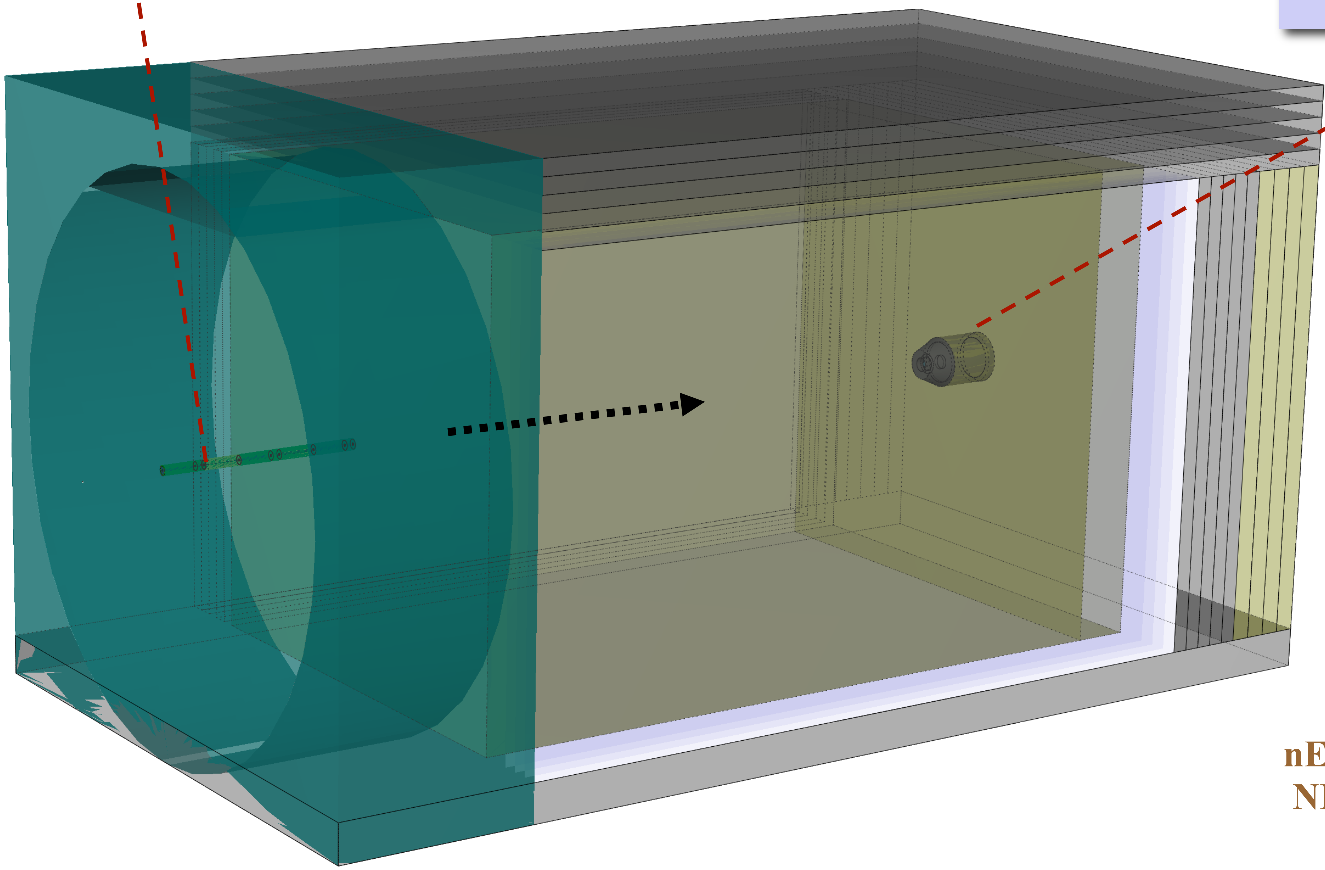




With this solution we find a dose rate of about 0.5 μSv/h at the exit of the roof.







Beam Dump:
Bor-Poly +
Lead +
Cadmium foil

nELBE published paper:
NIM A 577 (2007) 641-653

Optimization of the longitidinal shielding in the neutron experimental room

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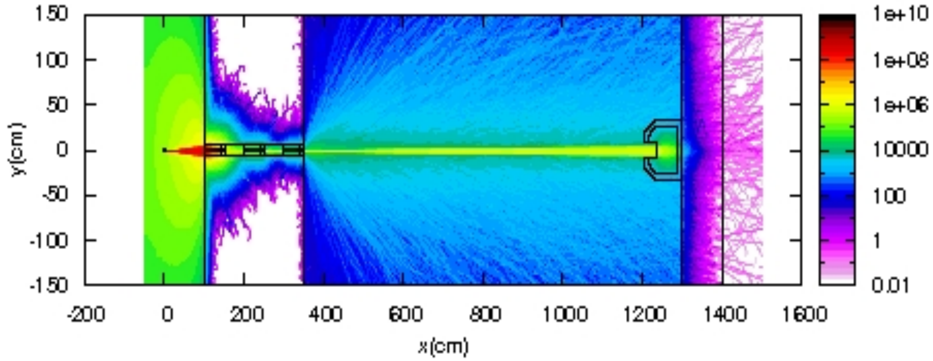
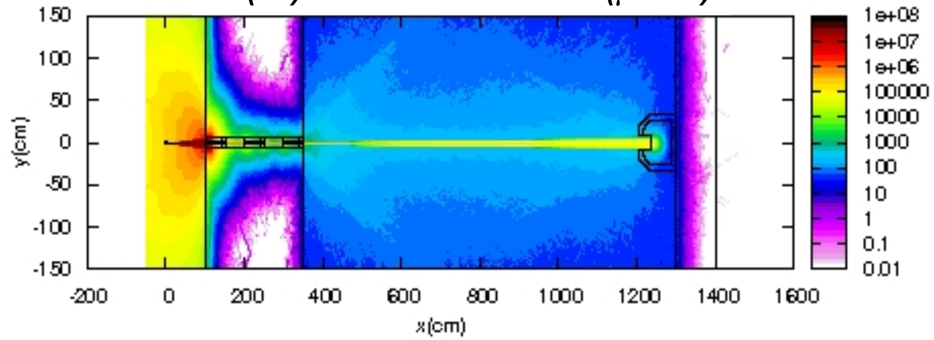
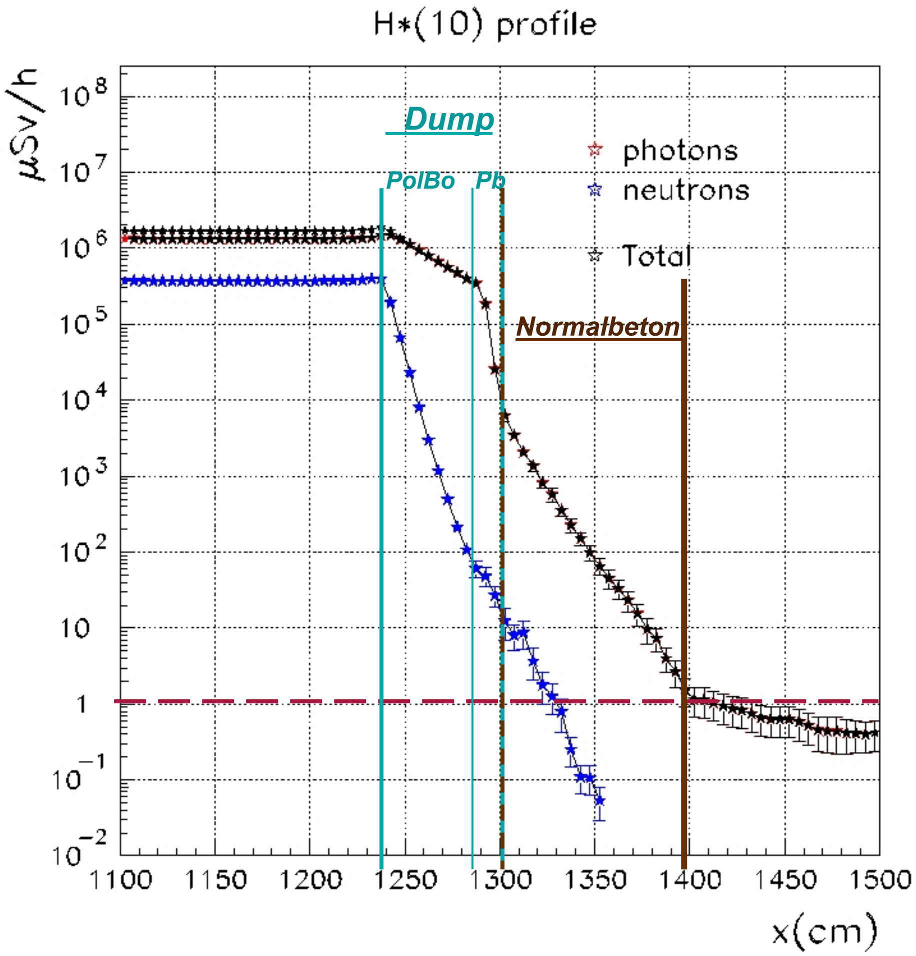
H*(10) rate from photons (μSv/h)



H*(10) rate from neutrons (μSv/h)



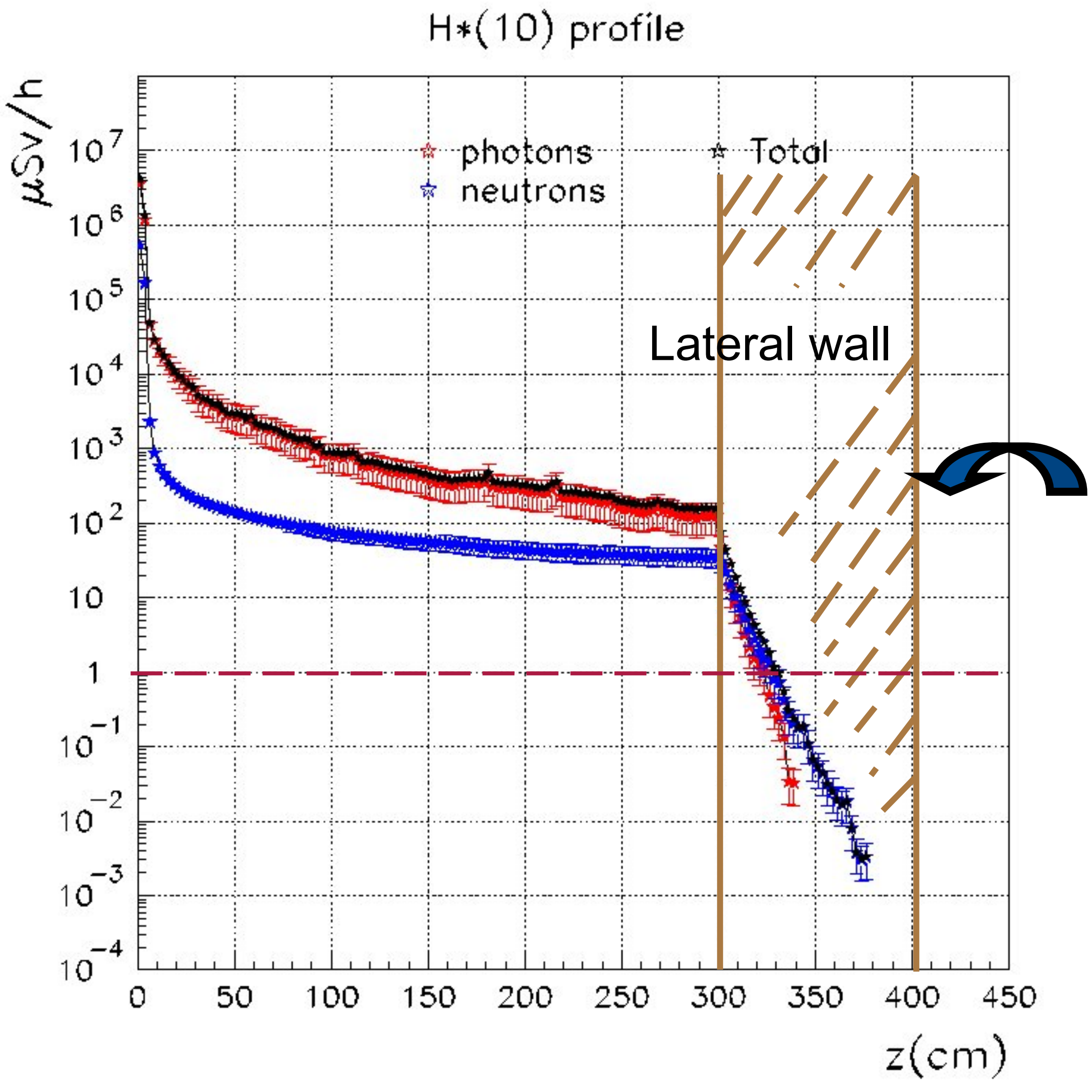
Dose profile from the mixed field



By adding **5 cm Pb** to the actual beam dump :

1.15 μSv/h ± 0.92 μSv/h at the exit of the wall (1400 cm)
0.42 μSv/h ± 0.34 μSv/h after 1 m (1500 cm)

Dose profiles through the walls of the experimental room



The H*(10) profile is calculated by averaging:

- on a quite narrow region above and below the beam level:
  (-24 cm, 24 cm) in y
- on a large region in x (covering all the lateral walls)
  and in steps of 2.5 cm in z.

The gamma component of the radiation is rapidly attenuated, faster then the neutron one.

This behaviour is different if compared with the (more critical) longitudinal radiation profiles

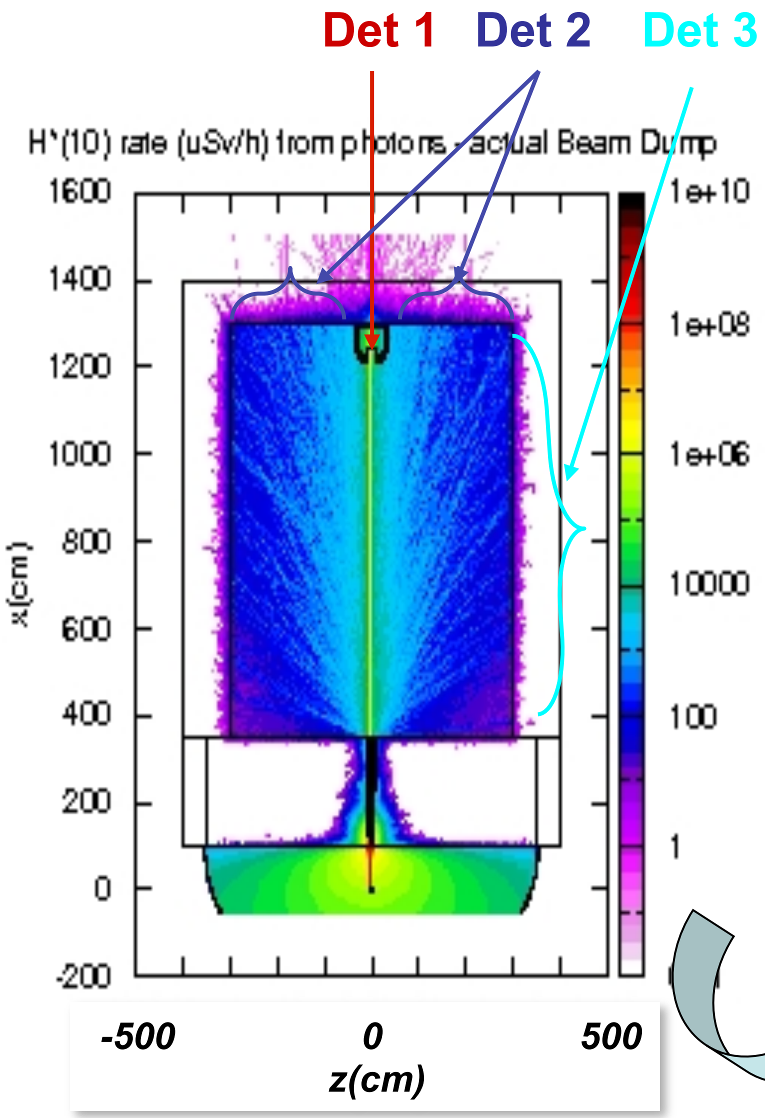
The reason is in the different energy spectrum of the photon radiation

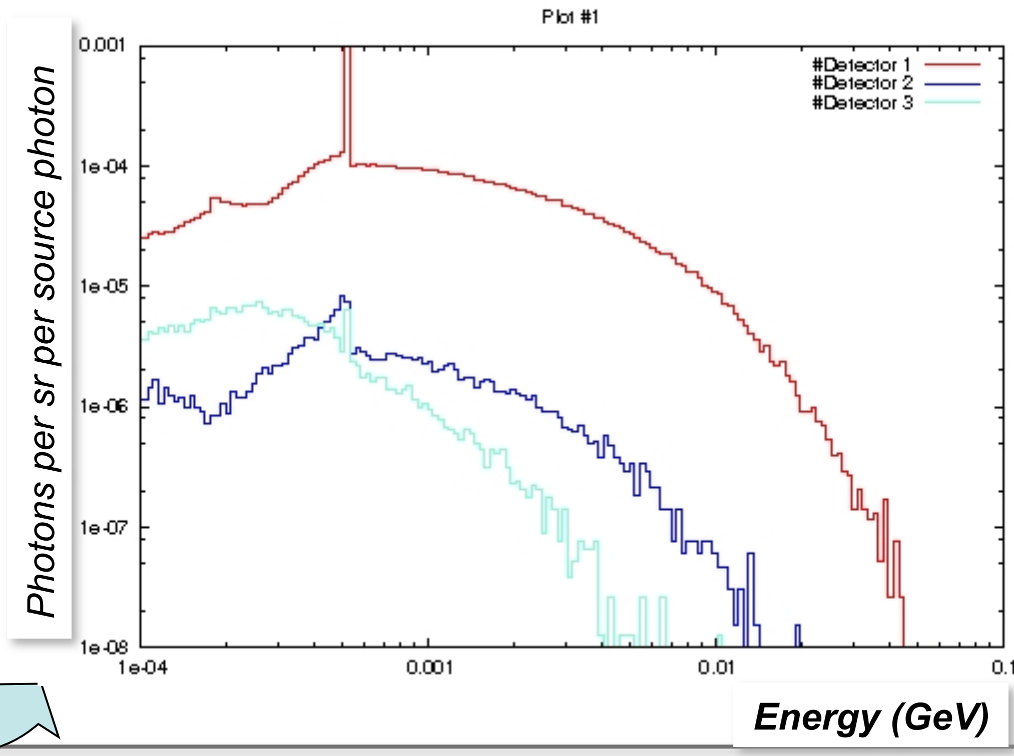
Photon energy spectra in the experimental room

The photon energy spectrum has been studied considering three different detectors:

- Det.1 at the beam dump surface;
- Det. 2 at the surface of the wall, where the beam is impinging ;
- Det. 3 at the surface of the lateral walls and of the roof.

The radiation, that reaches the roof and the lateral walls, is essentially a low energy radiation, with the higher tail until only 6-7 MeV.
The spectrum of the forward radiation is extended – as expected – until the higher energy value of the Bremsstrahlung (50 MeV).





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From shielding to physics: the neutron beam direction optimization

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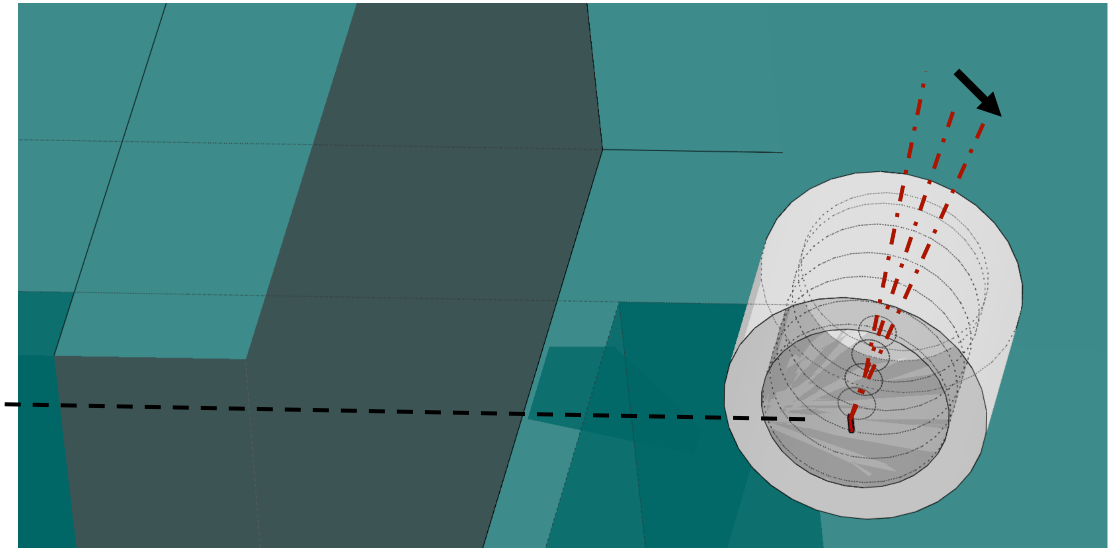
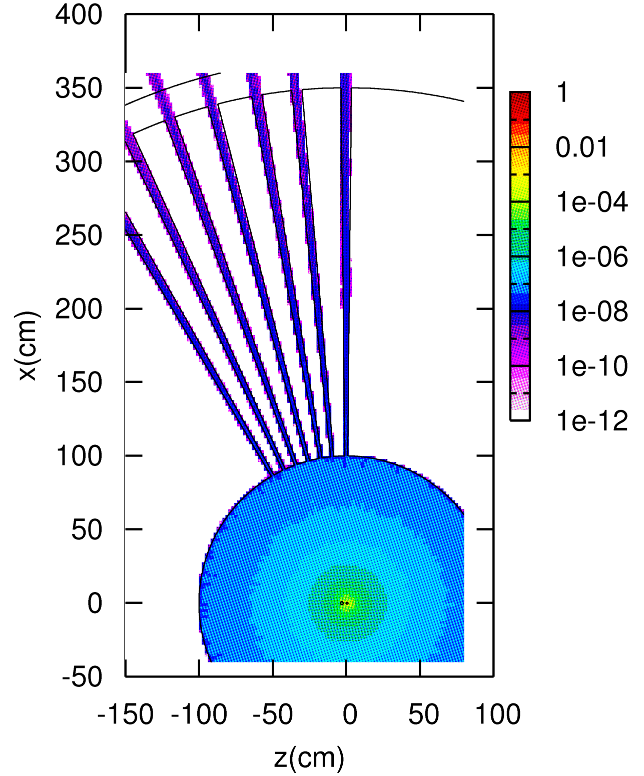
- Goal: choose a direction of the neutron beam-line
  that maximize the ratio n_{yield}/γ_{yield},
  taking into account the isotropy of the neutron
  production and the typical shape of the bremsstrahlung

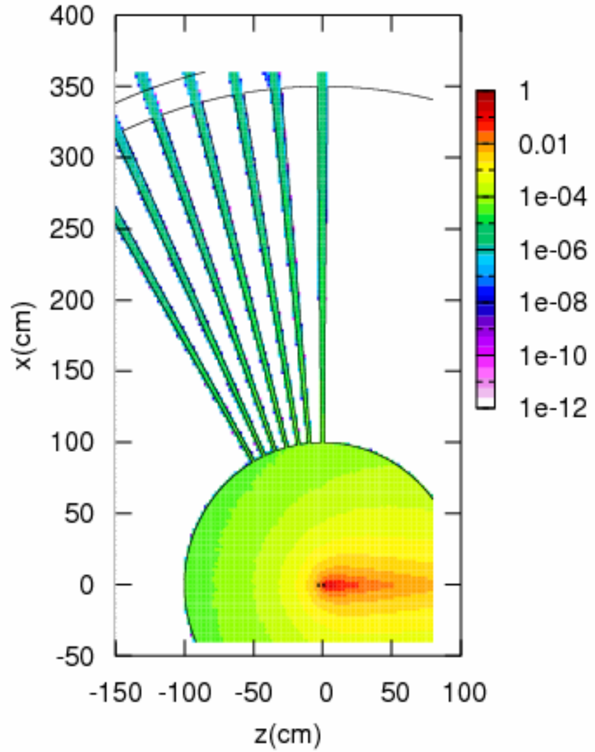
⬇

The optimized direction is implemented in the new neutron beam-line by rotating the whole photo-neutron source (liquid lead target + dump)



The case of an ideal source (no dump)



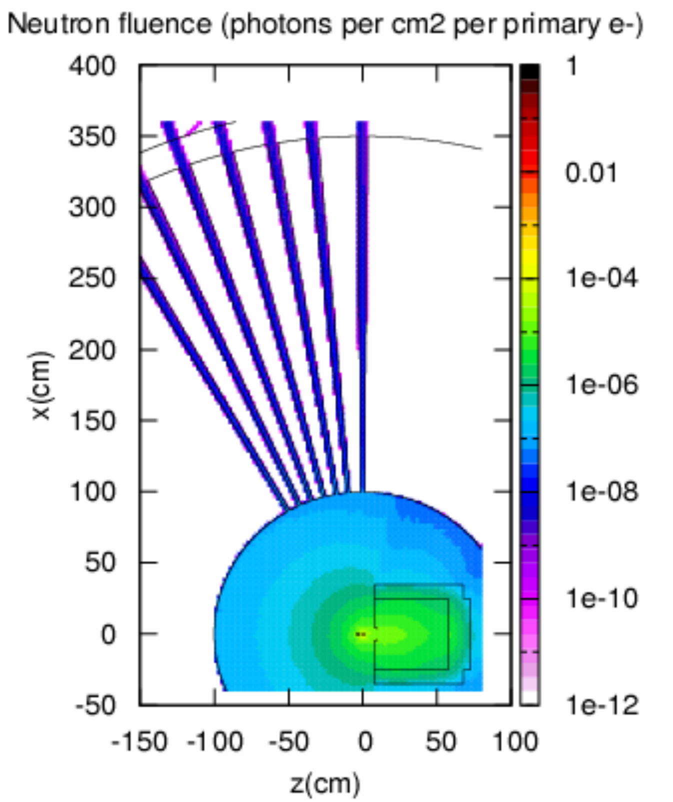


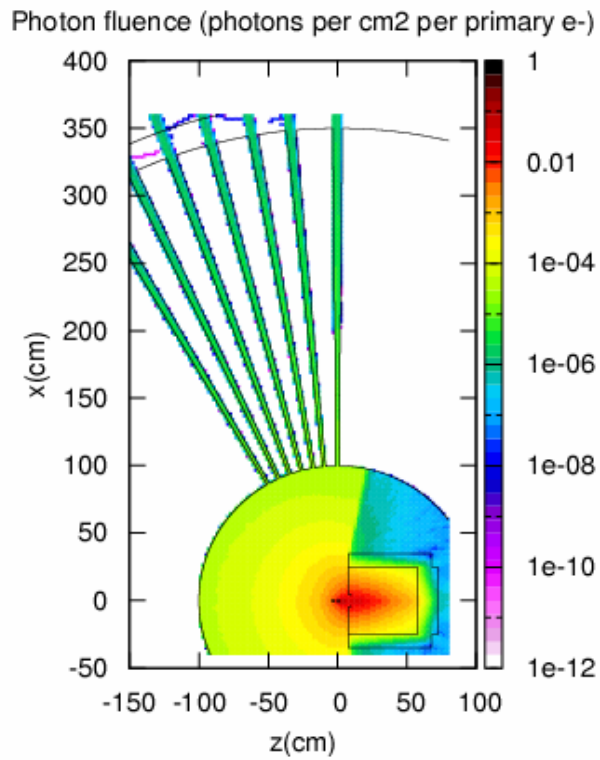
Statistical accuracy of the FLUKA fluence simulation: $\leq$ 1%

We increase the neutron/photon ratio of ~ 40 % by moving the angle from 90° to 115°

	90°	95.5°	100°	105°	110°	115°
Ratio n_{yield}/γ_{yield}	$2.20\ 10^{-3}$	$2.38\ 10^{-3}$	$2.52\ 10^{-3}$	$2.77\ 10^{-3}$	$2.88\ 10^{-3}$	$3.05\ 10^{-3}$

The real source



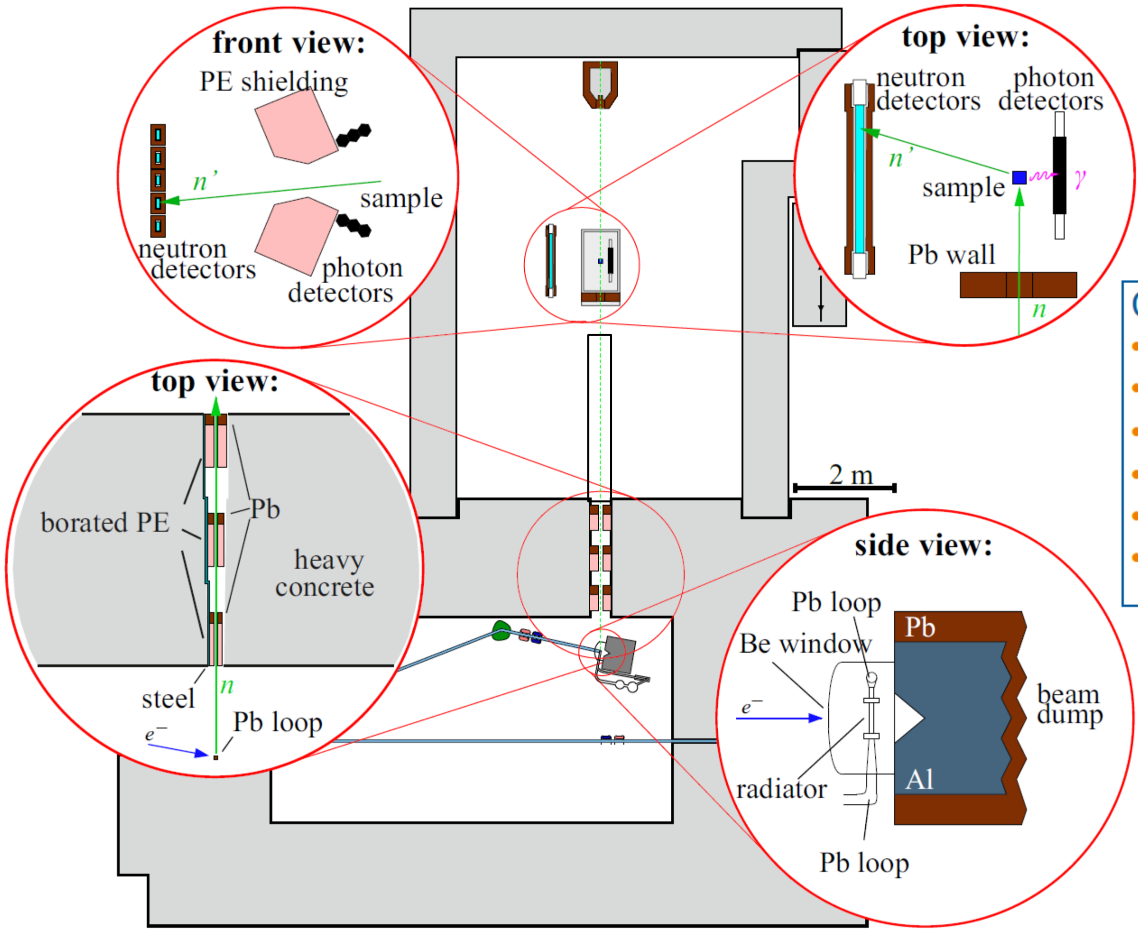


In real life we must avoid the ‘contamination’ coming from the neutrons scattered on the beam dump (or photoproduced in the dump material).

A sizeable contamination starts to be visible at 110° (around 1%). At 115° it is still at an acceptable level (around 3%)

	90°	95.5°	100°	105°	110°	115°
Ideal source n_{yield}/γ_{yield}	2.20 10^{-3}	2.38 10^{-3}	2.52 10^{-3}	2.77 10^{-3}	2.88 10^{-3}	3.05 10^{-3}
Real source n_{yield}/γ_{yield}	2.17 10^{-3}	2.39 10^{-3}	2.53 10^{-3}	2.78 10^{-3}	2.92 10^{-3}	3.14 10^{-3}

The new nELBE experimental room



Floor plan of the new nELBE neutron source and low scattering experimental hall.

Characteristic parameters:

- repetition rate: 101 or 202 kHz
- flight path: 5 - 11 m
- source strength: ca. $1.6 \cdot 10^{11}$ n/s
- intensity @ target: ca. $2.5 \cdot 10^{4}$ n/cm²s
- energy range: 10 keV - 10 MeV
- energy resolution: < 1 %

The source strength can be upgraded to **$3.5 \cdot 10^{13}$ n/s** if **E_{e-} = 50 MeV** and **I=1 mA**

Project at KAERI
T.Y. Song et al., Journal of the Korean Physical Society, Vol. 59, No. 2, (2011) 1609

- *The **Transmutation Research** at HZDR: MYRRHA and nELBE*
- *A quick look at the measurement program at nELBE*
- *An overview of the present nELBE neutron-line and of the new beam-line and experimental room*
- *Monte Carlo studies for the nELBE upgrade: radiation field characterization*
- *Shielding calculations*
- *Signal/background optimization*
- ***Some considerations about activation***

Residual radiation in FLUKA: residual dose rates and specific activity

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

✓ For an arbitrary irradiation pattern, the time evolution of the system (build-up and decay during the irradiation and cooling) is obtained <u>runtime</u> via the exact analytical solution of the **Bateman equations**:

$$\frac{dN_i}{dt} = -\sum_{j \neq i}\left[\lambda^d_{ji} + \bar{\sigma}_{ji}\bar{\varphi}\right]N_i + \sum_{j \neq i}\left[\lambda^d_{ij} + \bar{\sigma}_{ij}\bar{\varphi}\right]N_j$$ for each radionuclide in the material

where $\bar{\sigma}_{ji} = \frac{1}{\bar{\varphi}}\int \varphi(E)\sigma_{ji}(E)dE$ and $\bar{\varphi} = \int \varphi(E)dE$

The specific activity of each material at the cooling time t_{cool} is given by:

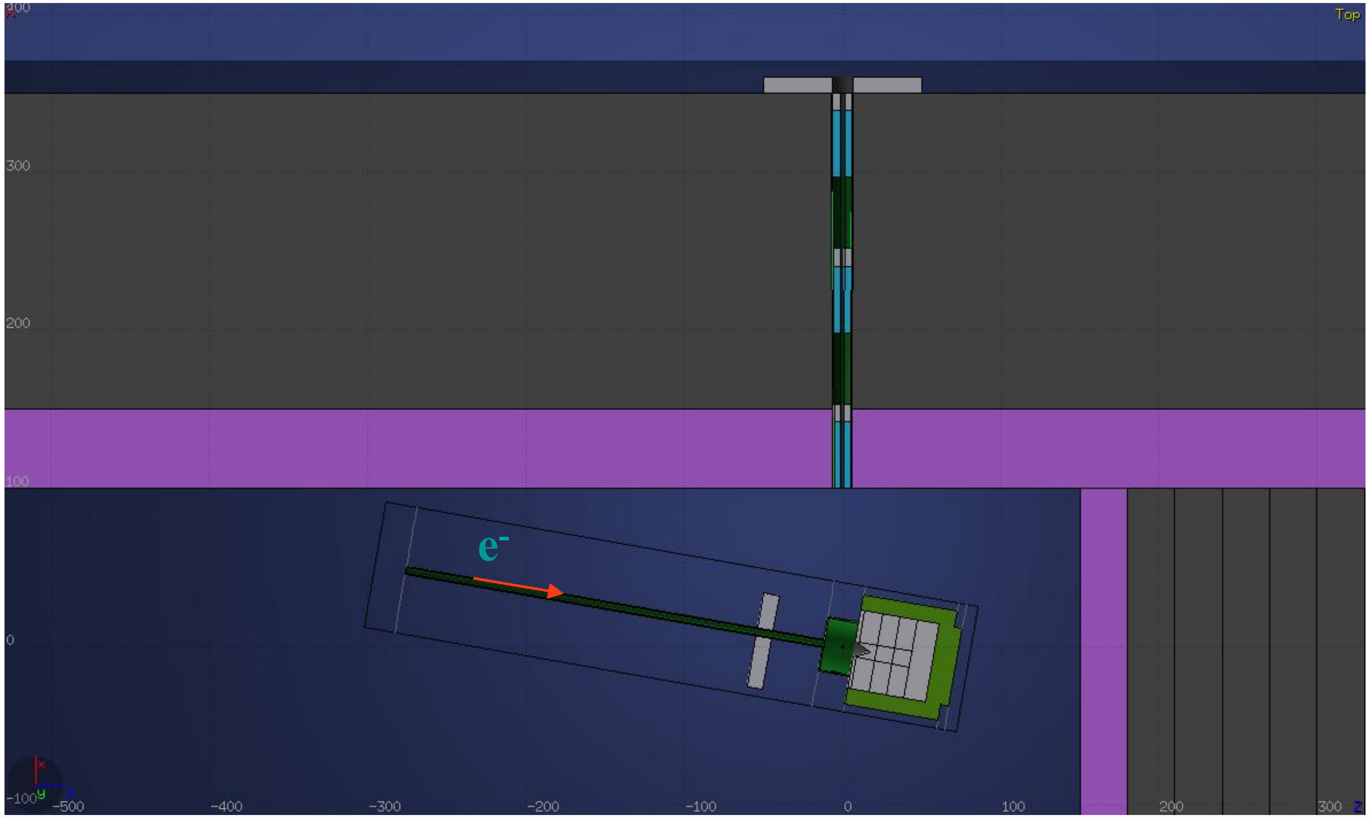
$$a(t_{cool}) = N\sigma\phi(1 - e^{-\lambda t_{irr}})e^{-\lambda t_{cool}}$$

✓ **At the same time FLUKA can perform the generation and transport of the decay radiation**

➡ **In the same run we can obtain production of the residuals, their time evolution and the residual doses due to their decays**

FLUKA model used for the activation studies

- **a detailed model of the Photo-neutron source (Liquid Lead + Molybdenum around the target)**
- **Al-Pb beam dump.** The lead of the beam dump has been realistically described as **PbSb4** alloy
- **the last 3 m of the electron beam-pipe**
- **shielding walls (the first 30-50 cm, then an infinite absorber is used) and collimator**



(I) Prompt dose rate

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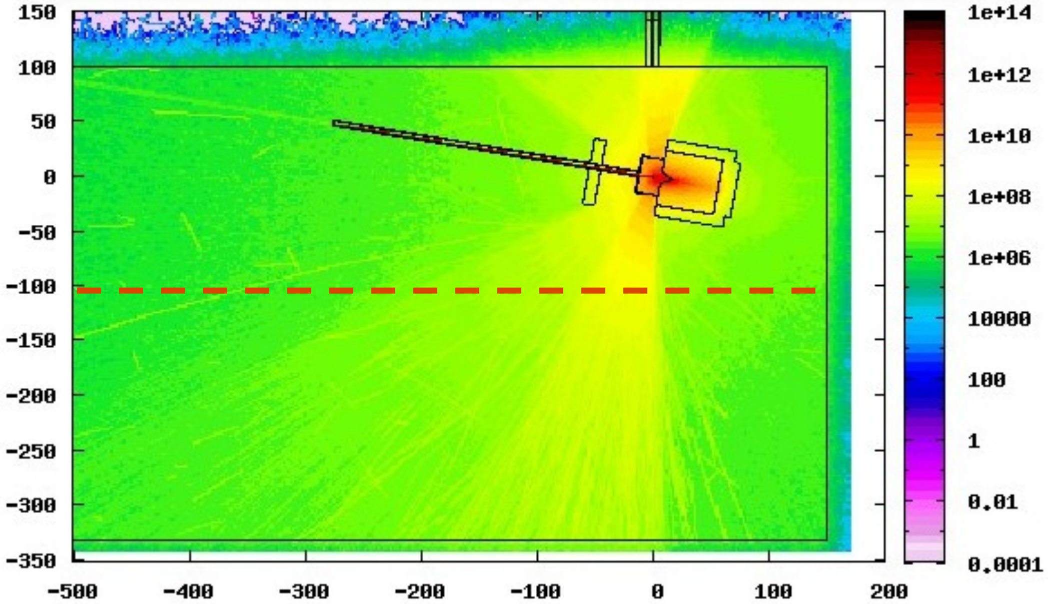
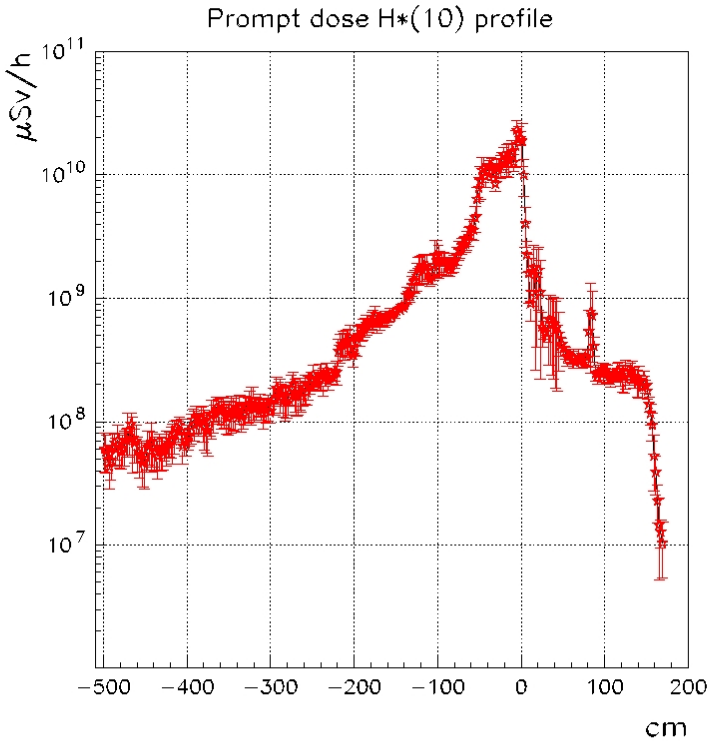
I = 15 μA

Ambient dose equivalent rate (μSv/h)



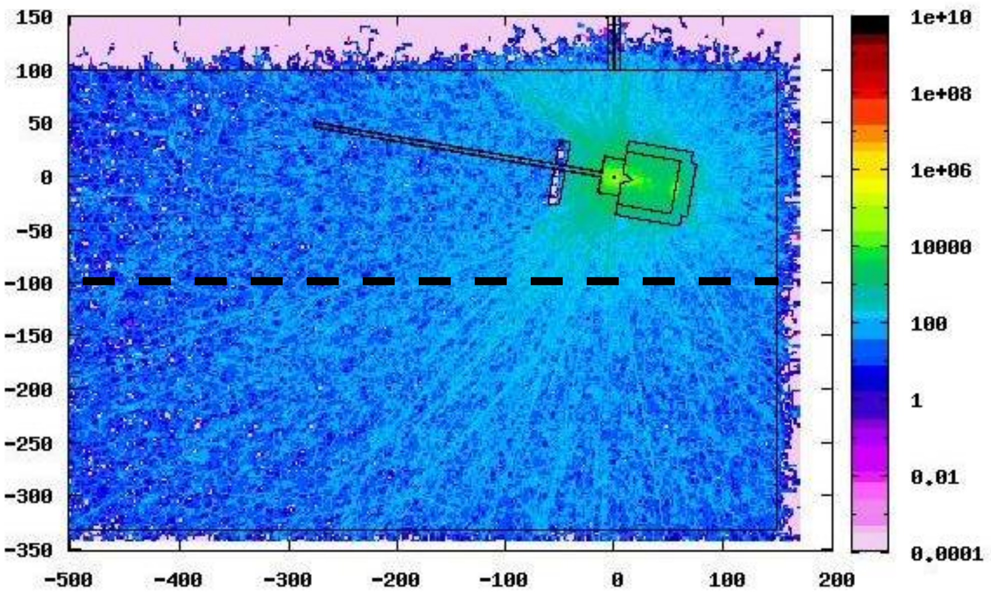


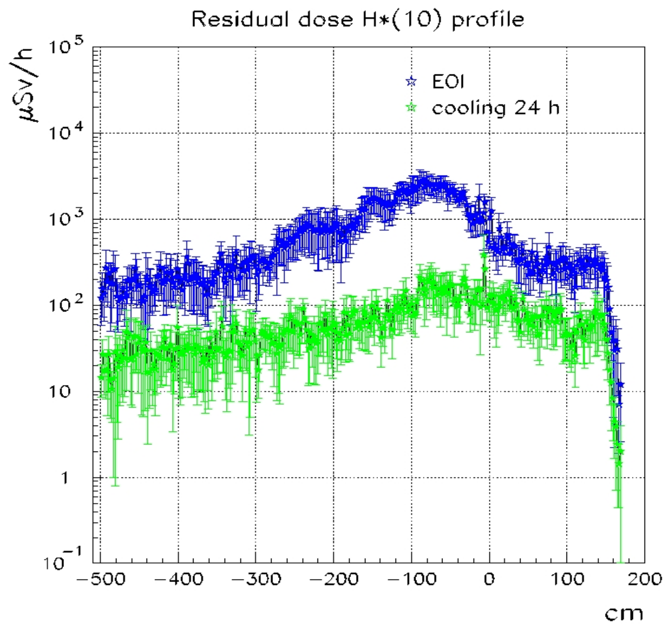
Along the axis x = -100 cm the prompt and the residual dose profiles have been evaluated

(II) Residual dose rates

Irradiation hypothesis: 6 weeks continous at 15 μA
Cooling times: end of irradiation (EOI), 24 h, 1 week

Ambient dose equivalent rate (μSv/h)



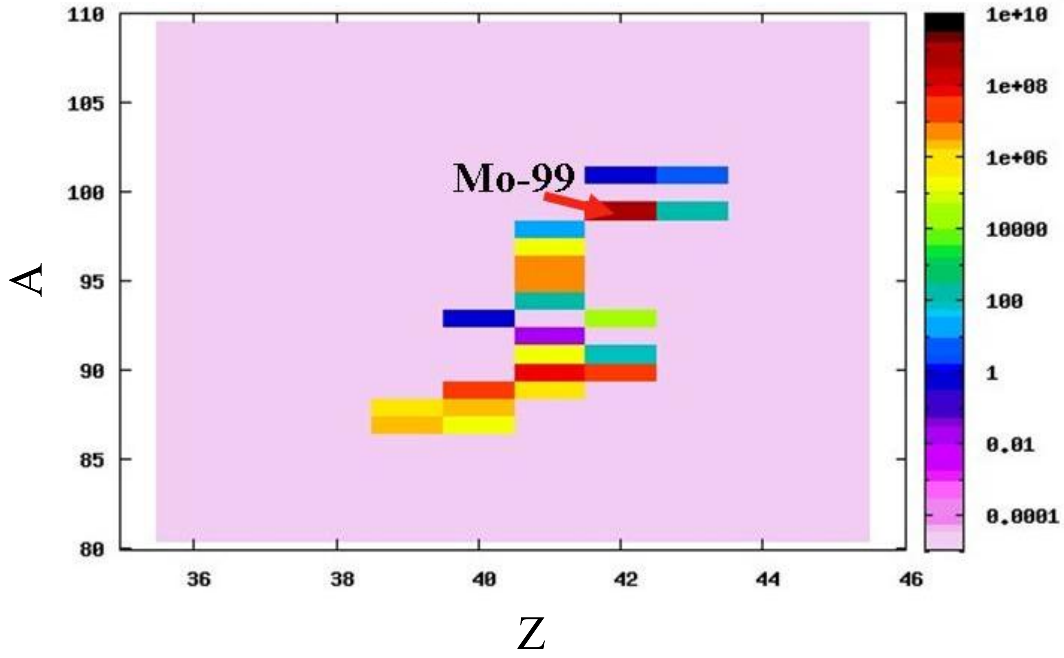


- At EOI we are dominated by radionuclides produced in the aluminum of the dump
- After 24 h the contribution of the activated Molybdenum becomes dominant, due to the presence of the ^{99}Mo ($t_{1/2}$ = 65.9 h)

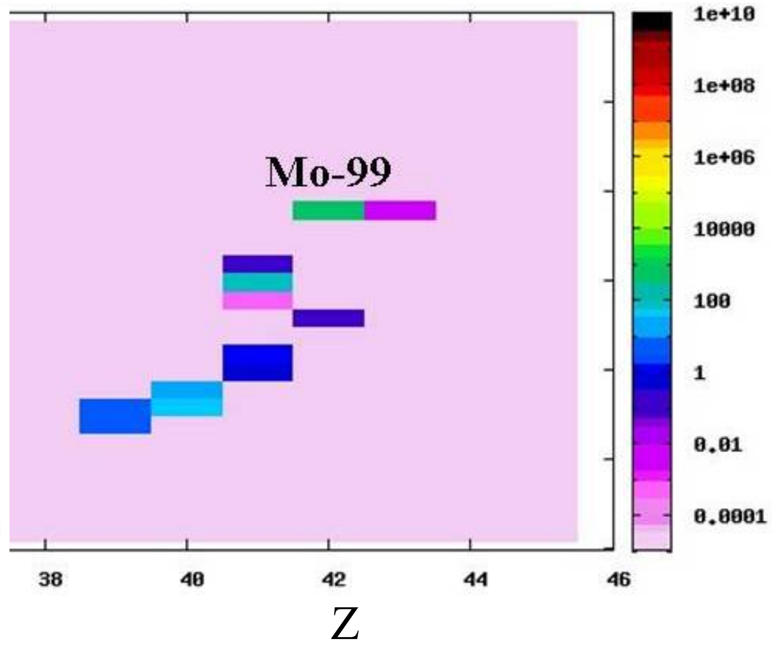
Contribution of the single radionuclides to the total specific activity in the central part of the Molybdenum tube around the liquid lead channel

Residual activity [Bq/cm3]

EOI



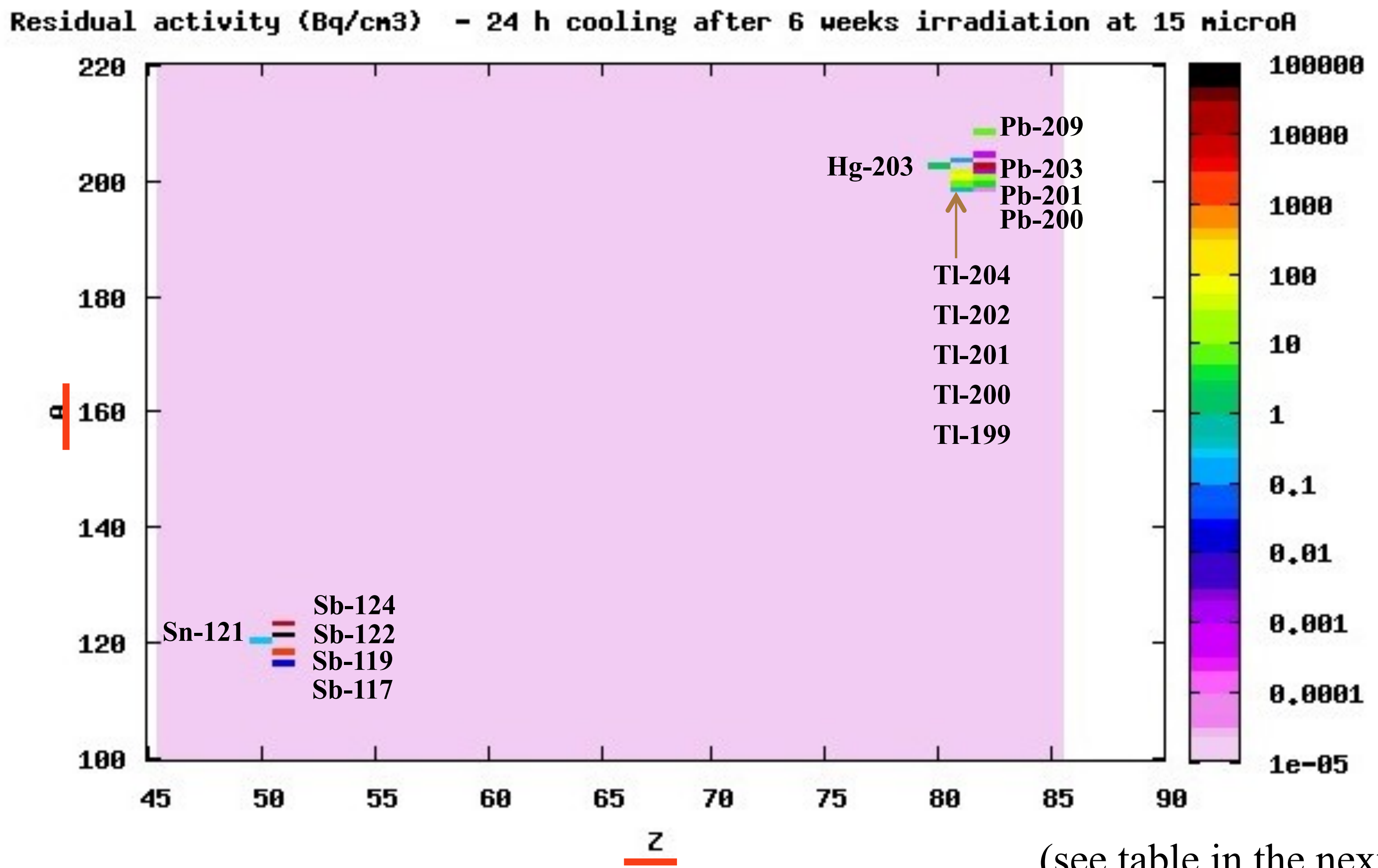
Cooling = 24 h



Radionuclide	$t_{1/2}$	Production process	Decay mode	Specific activity [Bq/cm3] after 24 h cooling
^{99}Mo	65.94 h	Thermal neutron activation	β^-	4.4 E+3

Contribution of the single radionuclides to the total specific activity in the PbSb4 alloy of the beam dump

Hypotheses: 6 weeks continous irradiation
24 h cooling time



(see table in the next slide)

Thank you for your attention!

Spares

Physics in the FLUKA code (in a glance)

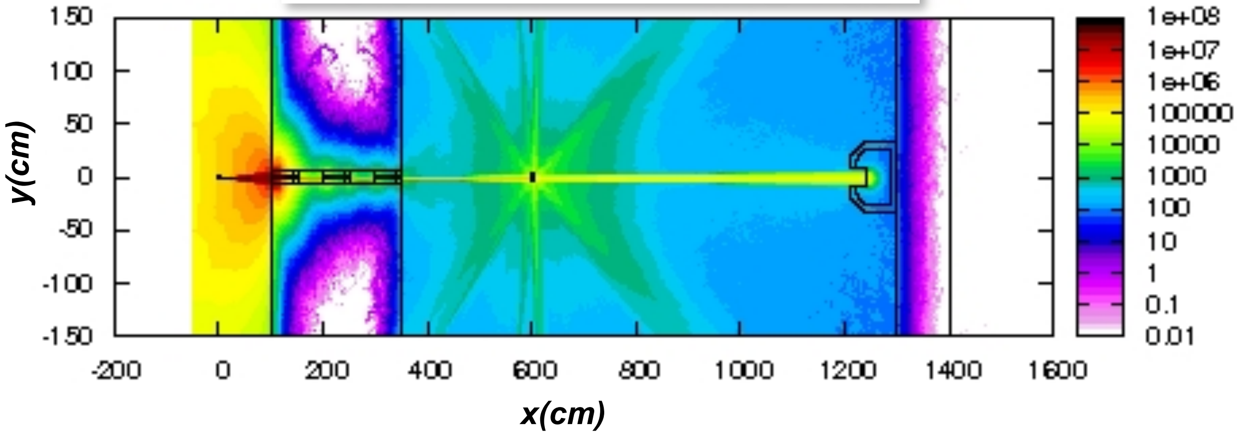
- **Nucleus –nucleus interactions** 100 MeV/n – 10^5 TeV/n
  → New Model (BME) down to 20 MeV/n
- **Electromagnetic and μ interactions** 1 keV – 10^5 TeV
- **Hadron – hadron and hadron – nucleus interactions** 0 – 10^5 TeV
- **Neutrino interactions**
- **Charged particle** transport, transport in magnetic field
- Full **neutron transport** above 20 MeV
  and **multigroup transport under 20 MeV (260 energy groups)**

FLUKA is able to compute, in the same simulation, the entire cascade of secondary particles, from TeV energies down to thermal neutrons

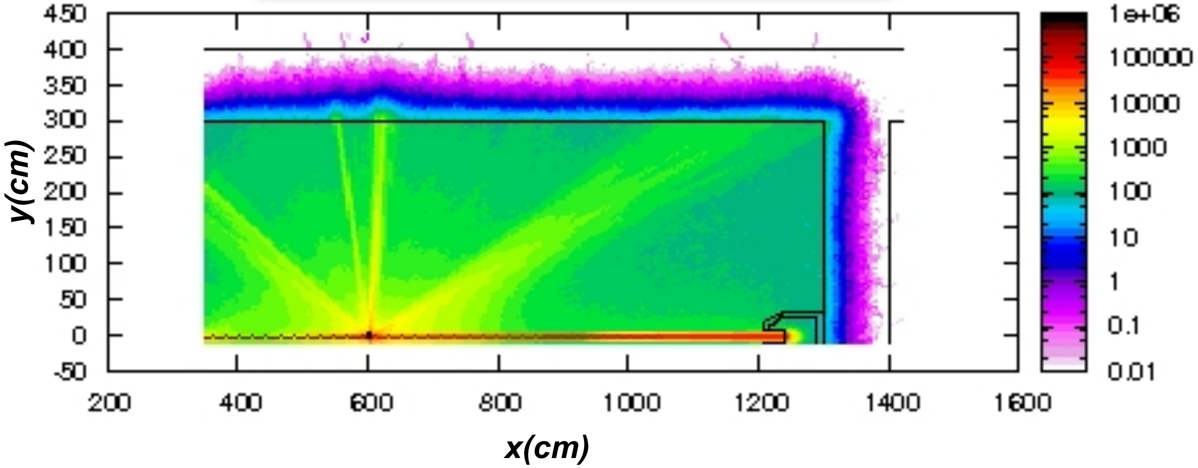
The effect of a typical target

Target: 4 cm Pb

H*(10) rate from neutrons (μSv(h)



H*(10) rate from neutrons (μSv(h)



The „cross effect“ visible for neutrons is due to the geometry of the target. Since I have used a slab with a square shape in the transversal plane (dimensions: 5 cm x 5 cm), the directions at 45° and 135° in θ with φ= 45° , 135°, 225° or 315° (*) are the directions, where the tracklength inside the target is bigger. As consequence, a secondary inelastic neutron emitted in that directions has a bigger probability to have a second interaction.

The behaviour at θ~ 90° is due to the contribution of the φ components, described above (the plot is the result of the average in a region defined by z in (-75 cm, 75 cm) respect to the PNQ source).

(*) θ is the polar angle respect to the photoneutron beamline (x), φ the azimuthal angle in the yz plane

Contribution of the single radionuclides to the total specific activity in the PbSb4 alloy after 6 weeks irradiation and 24 h cooling

Radionuclide	$t_{1/2}$	Production process	Main decay mode	Specific activity [Bq/cm3] after 24 h cooling
^{117}Sb	2.8 h	Charged particle reaction	β^+	2.5 E-2
^{119}Sb	38.19 h	Charged particle reaction	e capture	1.1 E+3
^{121}Sn	27.06 h	Fast and thermal neutron activation	β^-	0.3
^{122}Sb	2.72 d	Fast and thermal neutron activation	β^-	4.7 E+4
^{124}Sb	60.2 d	Fast and thermal neutron activation	β^-	8.3 E+3
^{203}Hg	46.61 d	Fast and thermal neutron activation	β^-	2.2
^{200}Pb	21.5 h	Charged particle reaction	e^- capture	4.4
^{201}Pb	9.33 h	Charged particle reaction	e^- capture, β^+	10.3
^{203}Pb	51.87 h	Charged particle reaction and fast neutron activation [mainly (γ, n) from ^{204}Pb, (p,n) from ^{203}Tl]	e^- capture, γ	6.5 E+3
^{209}Pb	3.25 h	Fast and thermal neutron activation [(n,γ) from ^{208}Pb]	β^-	8.5
^{204}Tl	3.78 y	Fast and thermal neutron activation	β^-	0.2
^{202}Tl	12.23 d	Charged particle reaction and fast neutron activation	e^- capture, γ, β^+	32.2
^{201}Tl	73.1 h	Charged particle reaction	e^- capture, γ	54.7
^{200}Tl	26.1 h	Charged particle reaction	e^- capture, β^+,γ	8.1
^{199}Tl	7.42 h	Charged particle reaction	e^- capture, β^+	0.3