Shielding aspects of the new nELBE photo-neutron source

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A look at the research program at nELBE

Study of fast neutron reactions relevant for Nuclear Trasmutation program and of interest for the GEN IV reactors

- **Neutron Inelastic scattering (n,n'γ) for ^{56}Fe, Mo, Pb, Na and total neutron cross sections σ_{tot} (Ta, Au, Al, C, H)**
- **MA fission cross sections (radioactive Targets)**

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

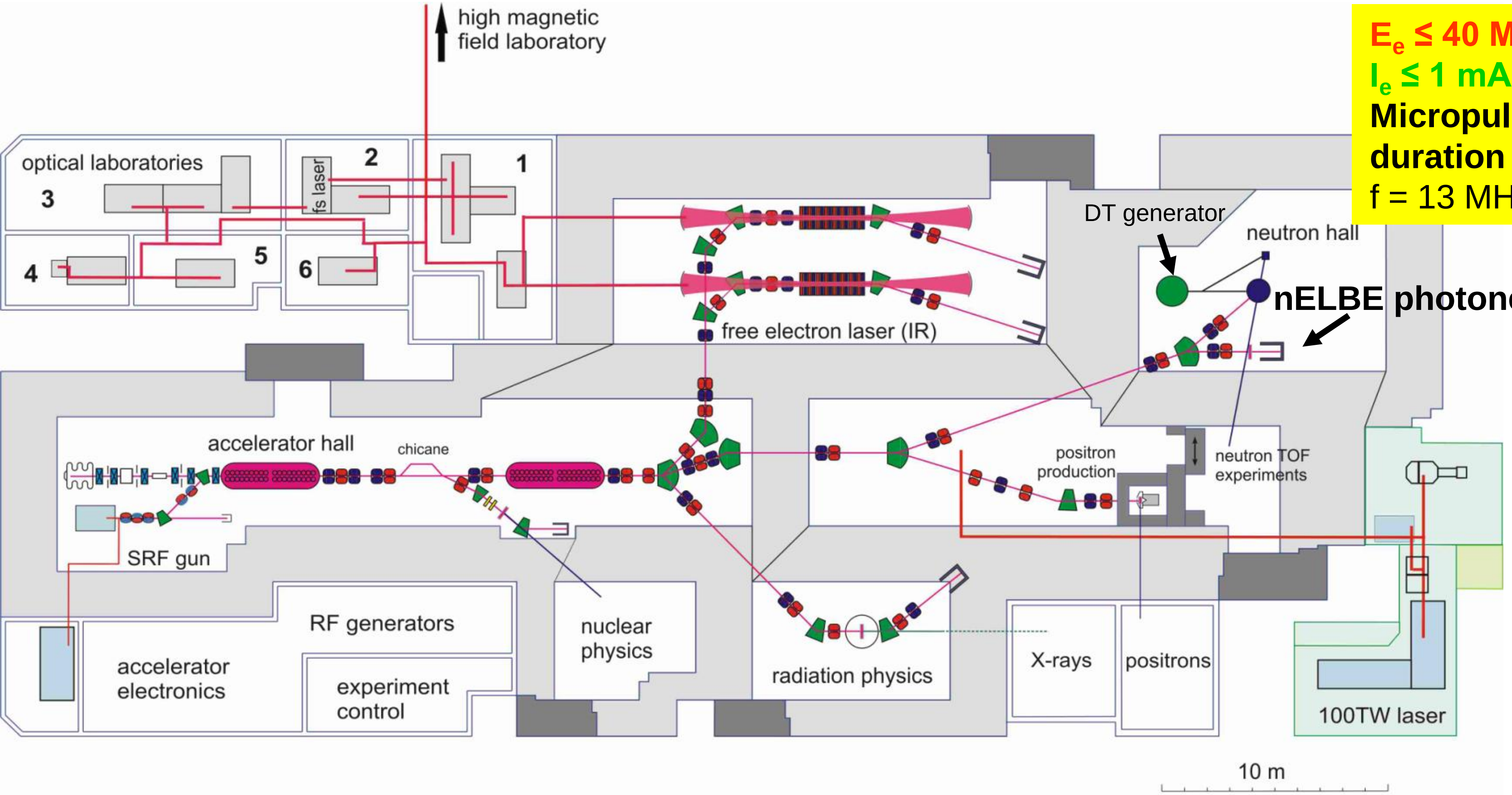
Co-ordinator: M. Salvatores, ANL, CEA

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

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

ELBE: Electron Linear accelerator with high Brilliance and low Emittance

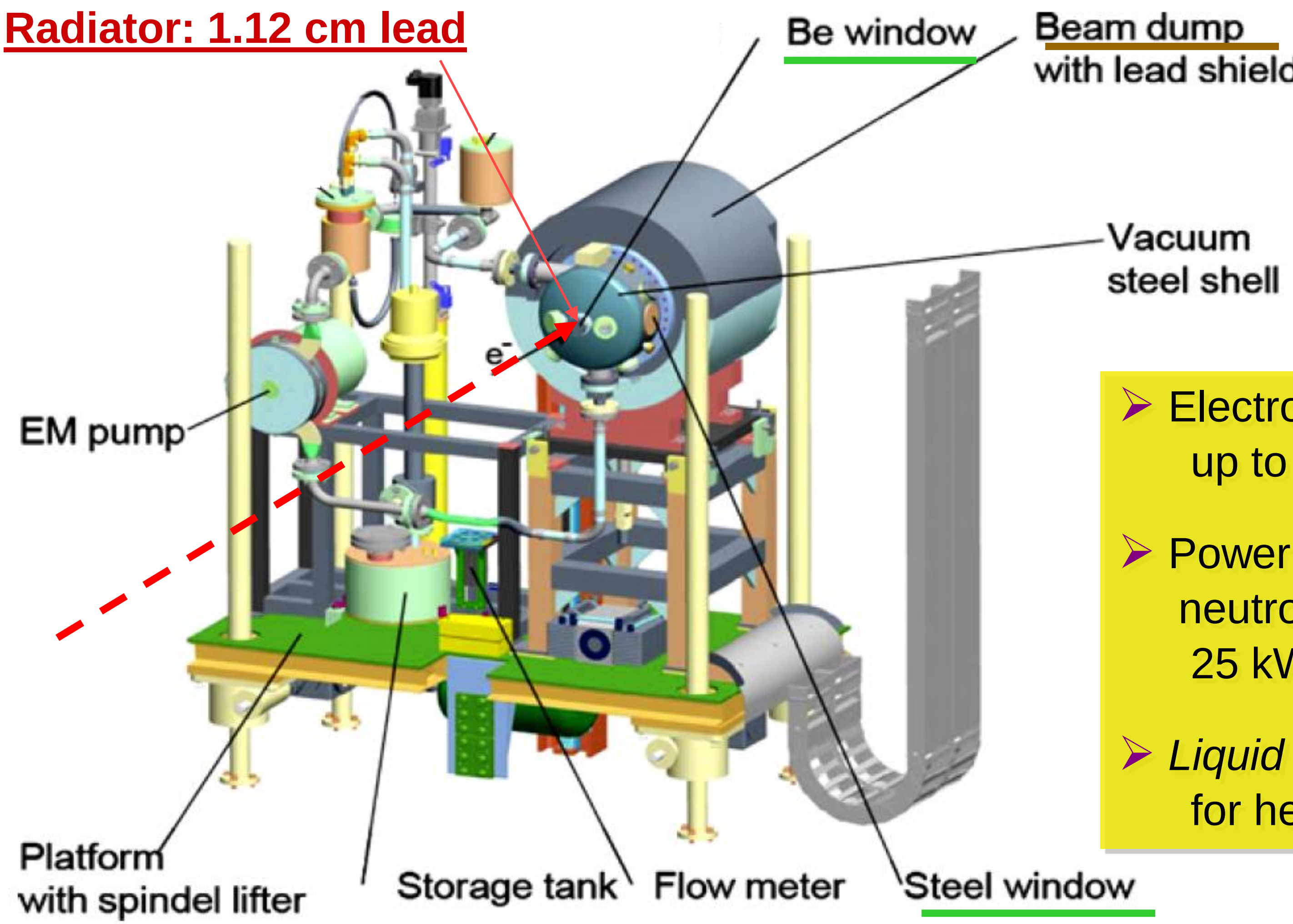


$E_e \leq 40$ MeV
$I_e \leq 1$ mA
Micropulse duration $\Delta t < 10$ ps
$f = 13$ MHz / 2^n

nELBE photoneutron source

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/cm3
- *Liquid lead circuit* for heat transport

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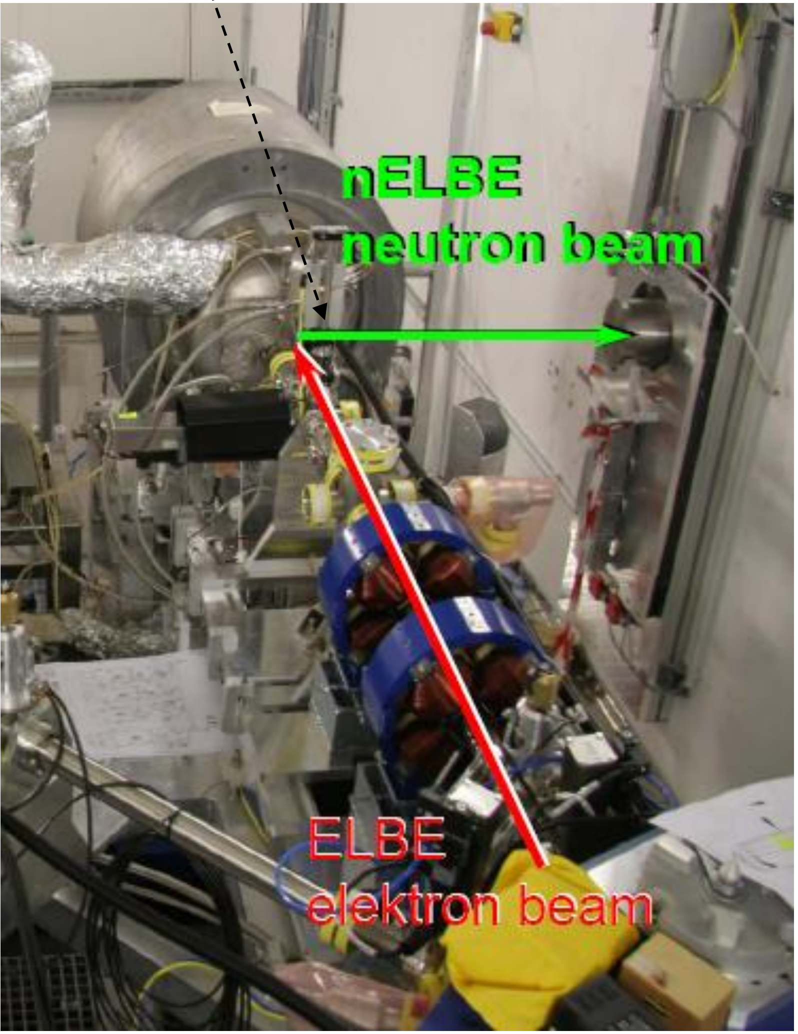
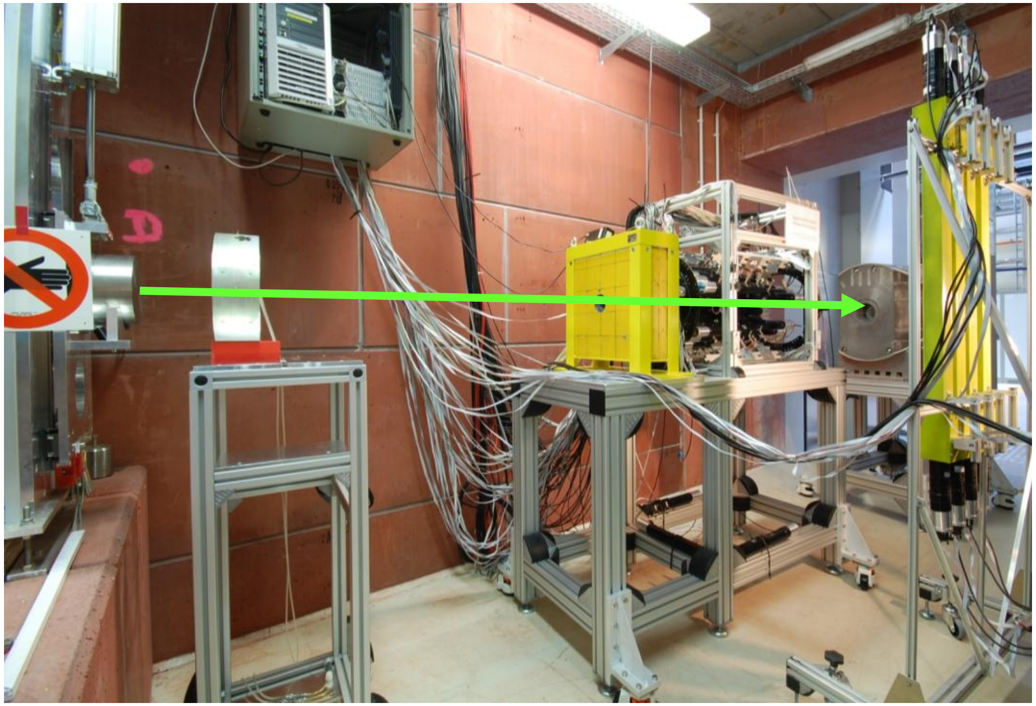
Actual selected neutron direction: 95.5°

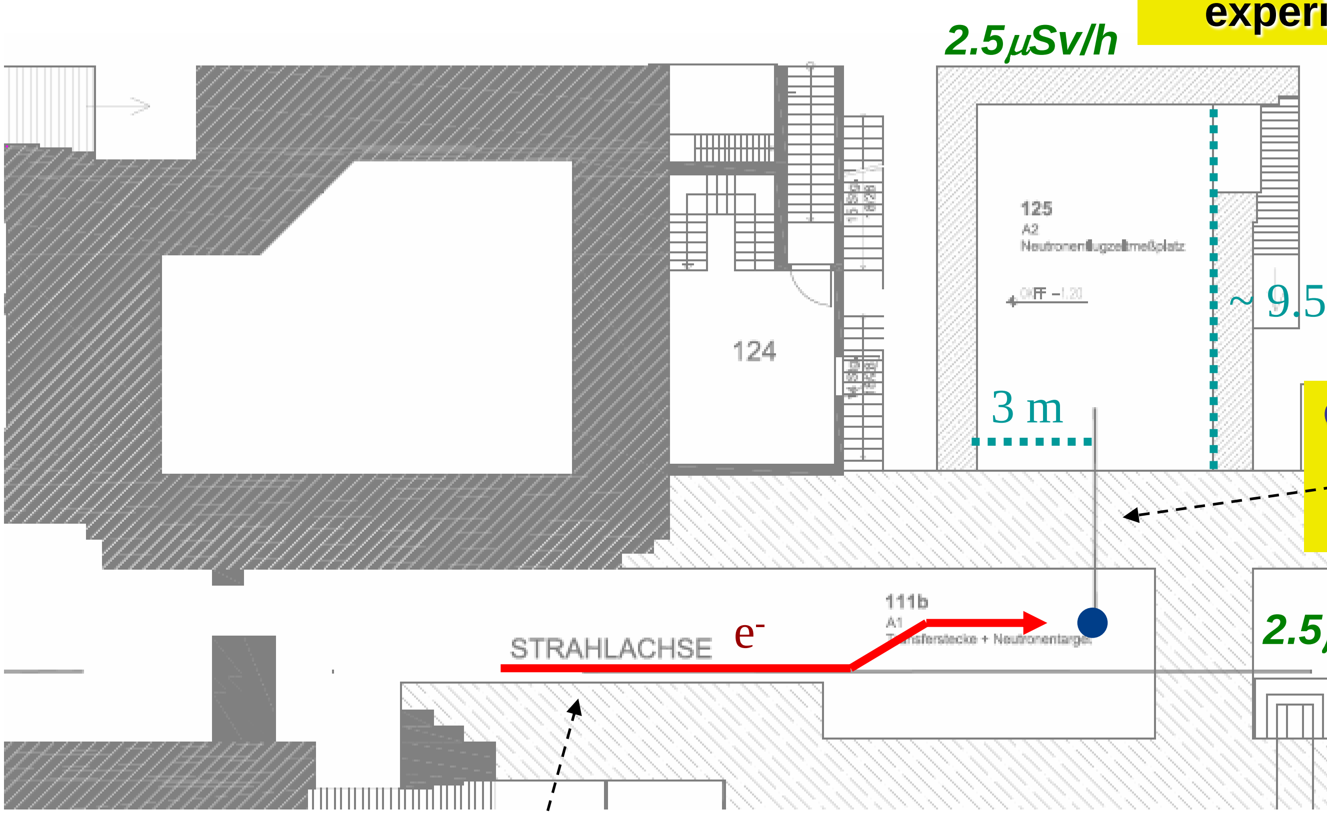




Actual experimental room

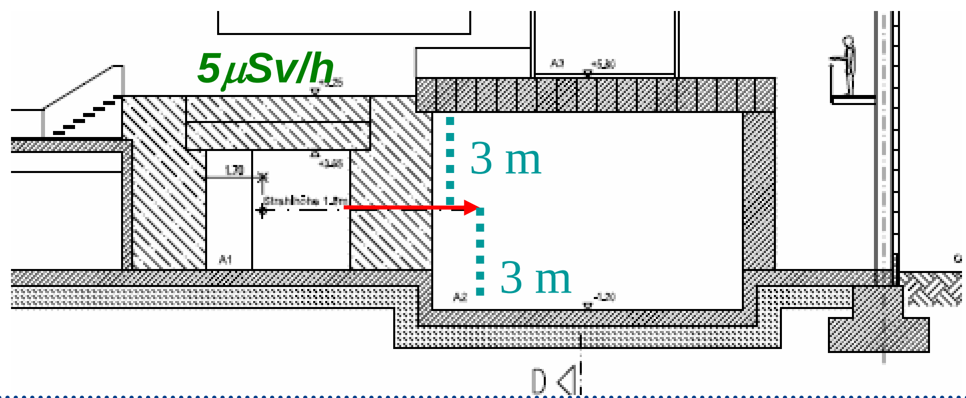
The new neutron experimental room

Larger dimensions and better experimental conditions

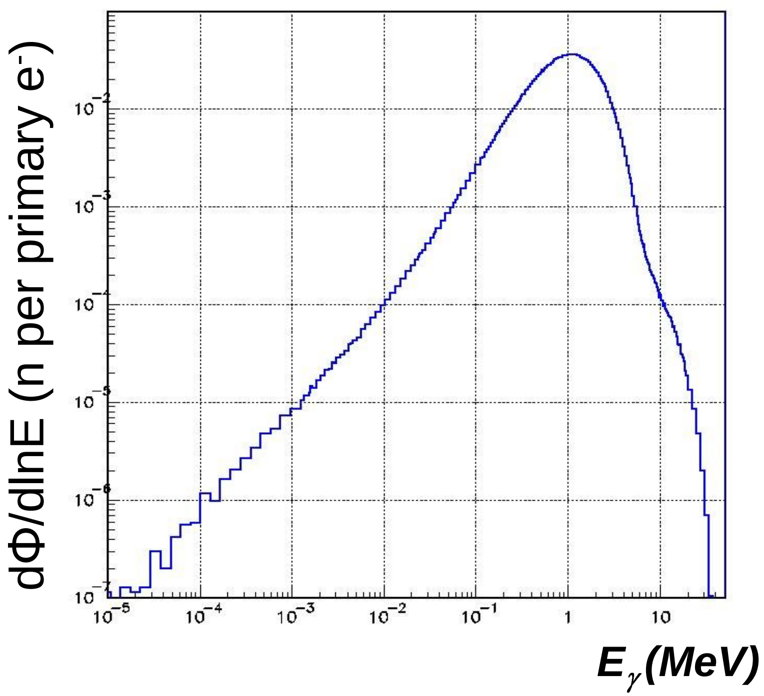


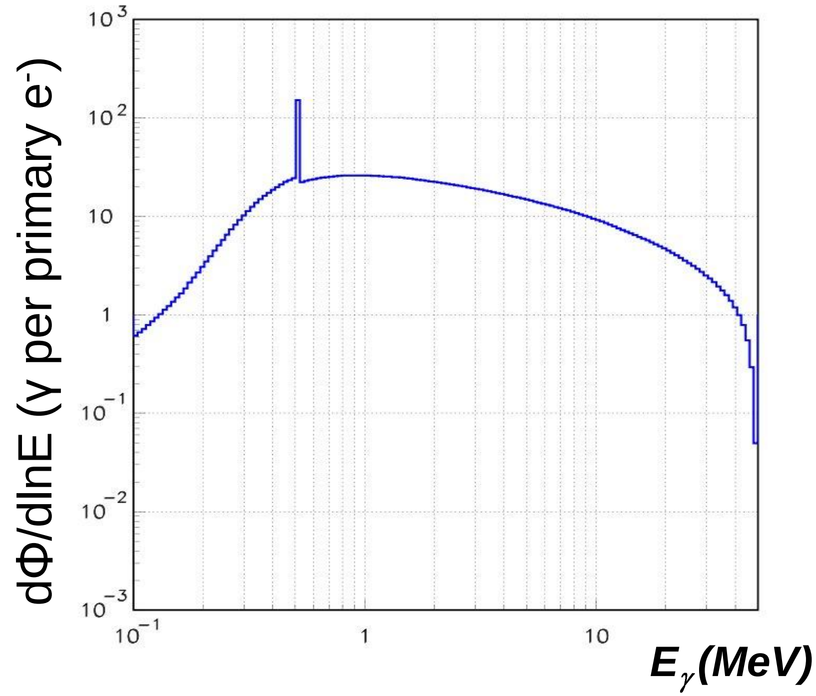
Optimized neutron beam-line with respect to the neutron/photon ratio

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



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:

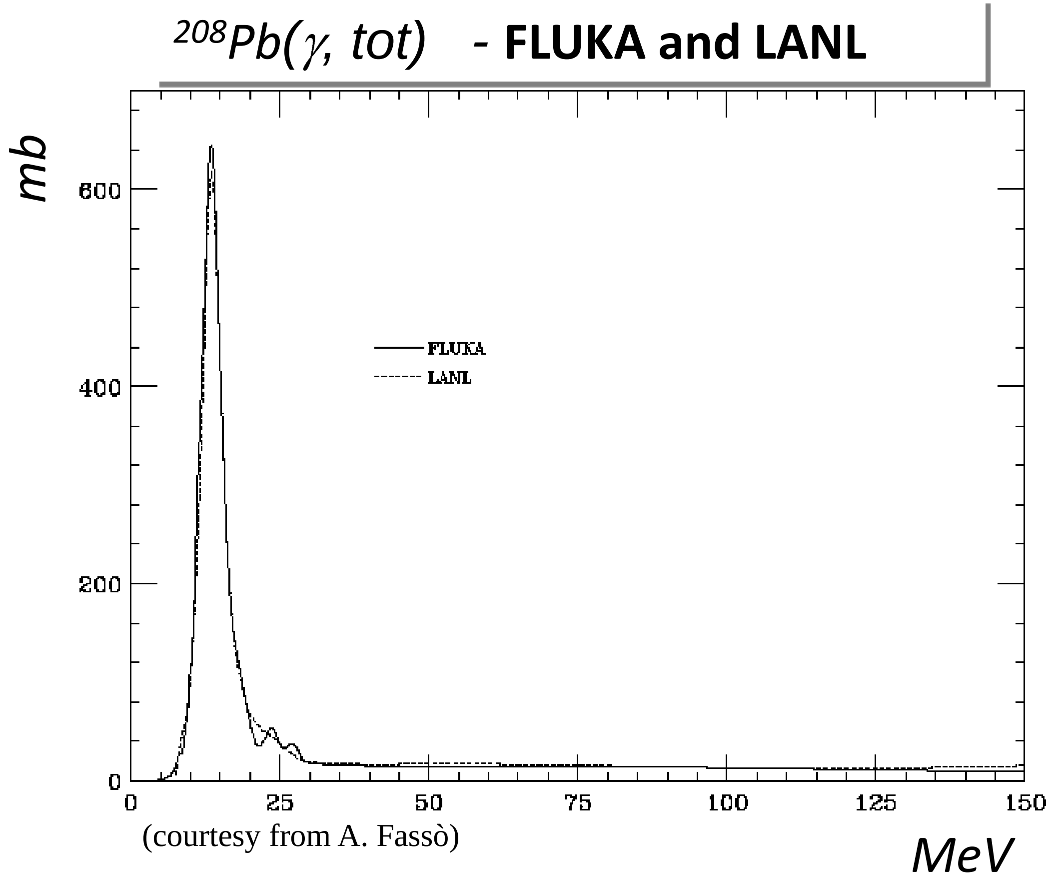
n_{yield} *= 4.34 10^{-8} n per cm^2 per primary e-*

A deeper look at the photoproduction simulation

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 (evaporation, PEANUT)



(courtesy from A. Fassò)

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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 published photoneutron cross sections with the numerical integration of the photon track length distributions (derived from the analytical theory of the showers)

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

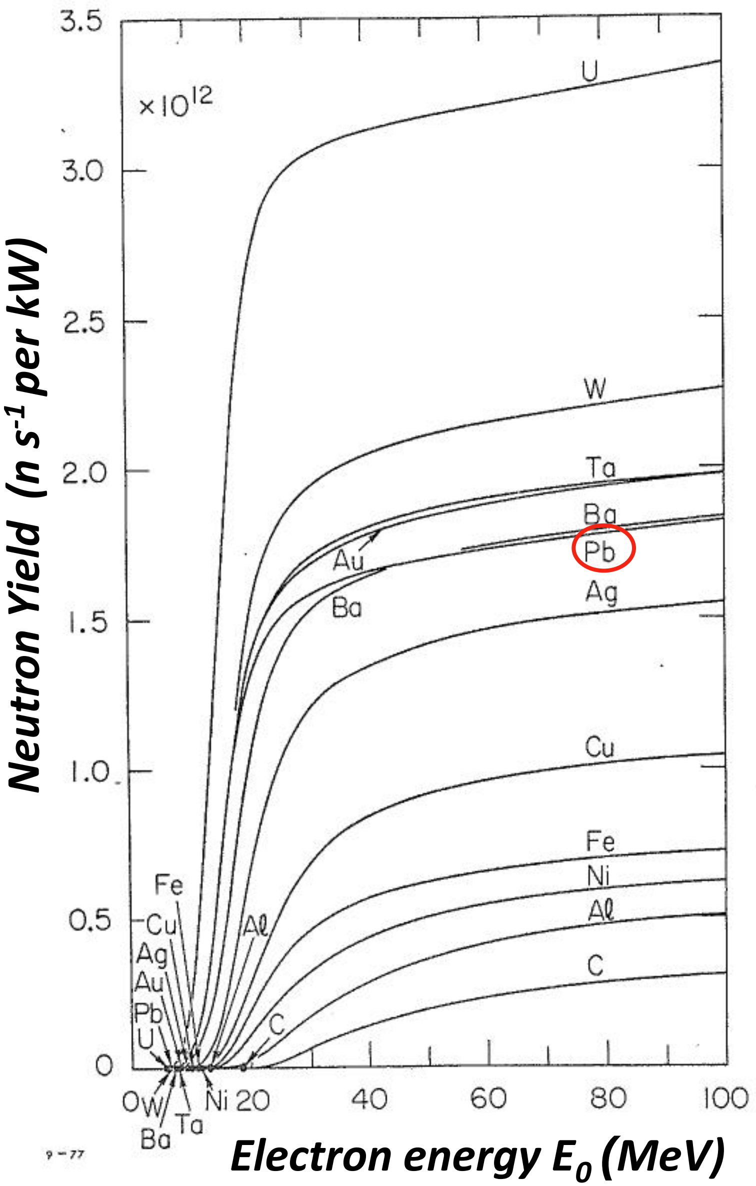
The formula gives, for the asymptote of the curve of the lead: $2.32 \cdot 10^{12}$ n s^{-1} kW^{-1}

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



Radiation protection calculations: the method

1. 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) beam + the Bremsstrahlung spectrum**

2. 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**

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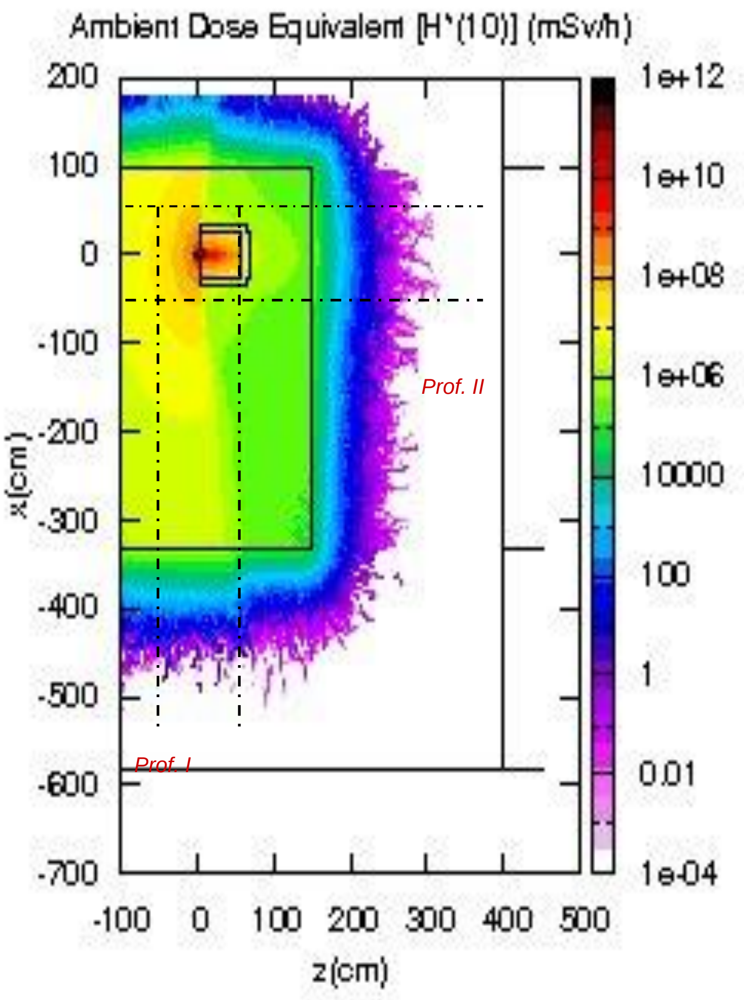
Horizontal section through the neutron hall



Definition of the volumes for the calculation:

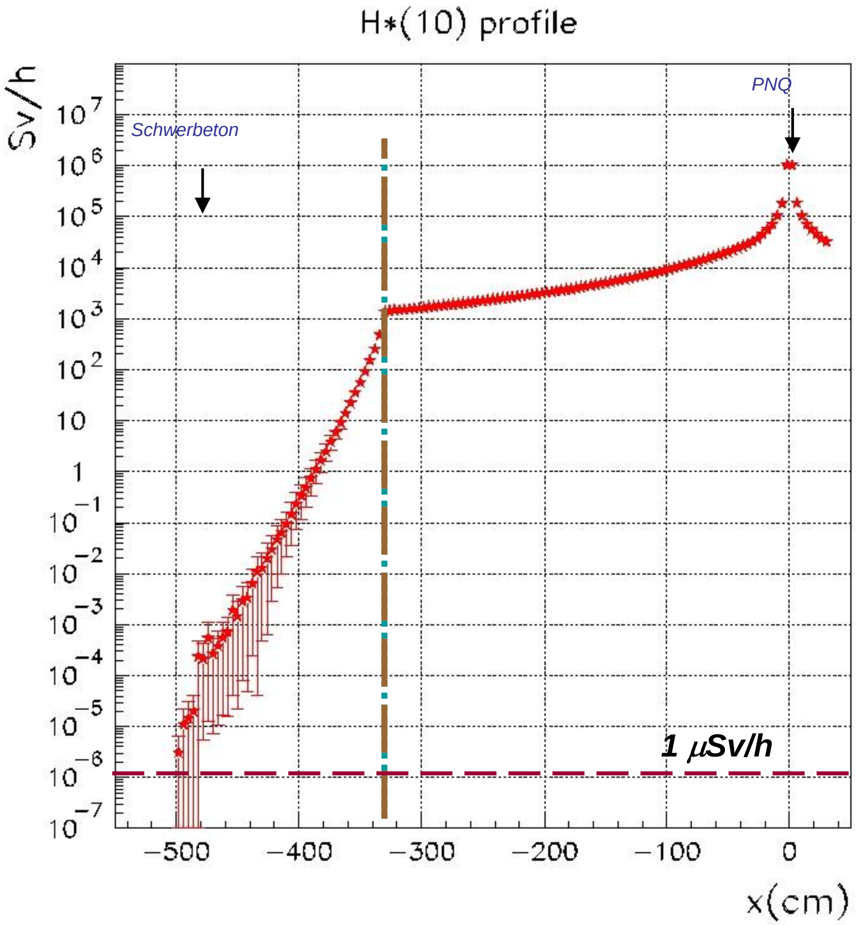
Profile I (wall opposite to the neutron beamline)

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

Profile II (wall behind the beam dump)

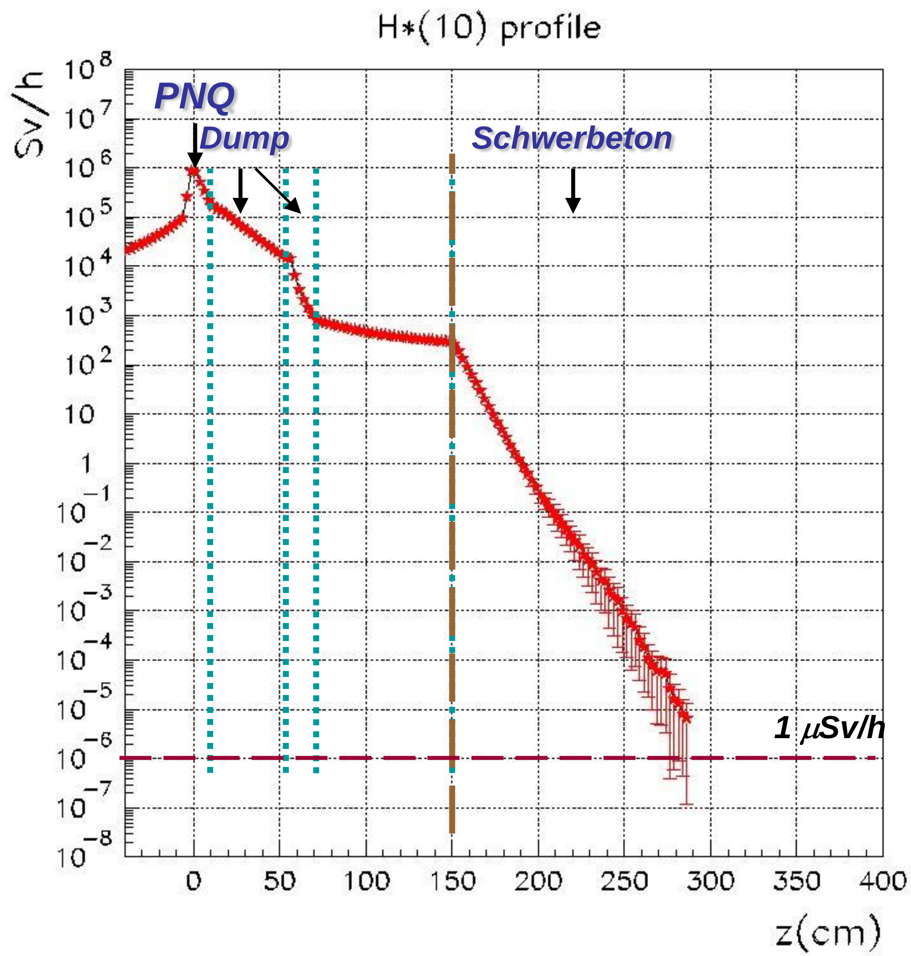
a column along z, large:
(-50 cm, 50 cm) in x
(-50 cm, 50 cm) in y

I. Wall opposite to the neutron beamline



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

II. Wall behind the PNQ

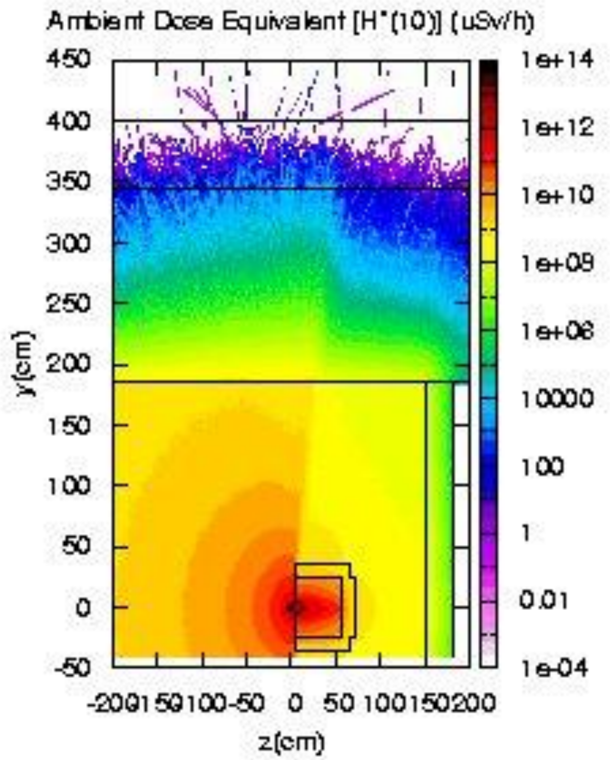


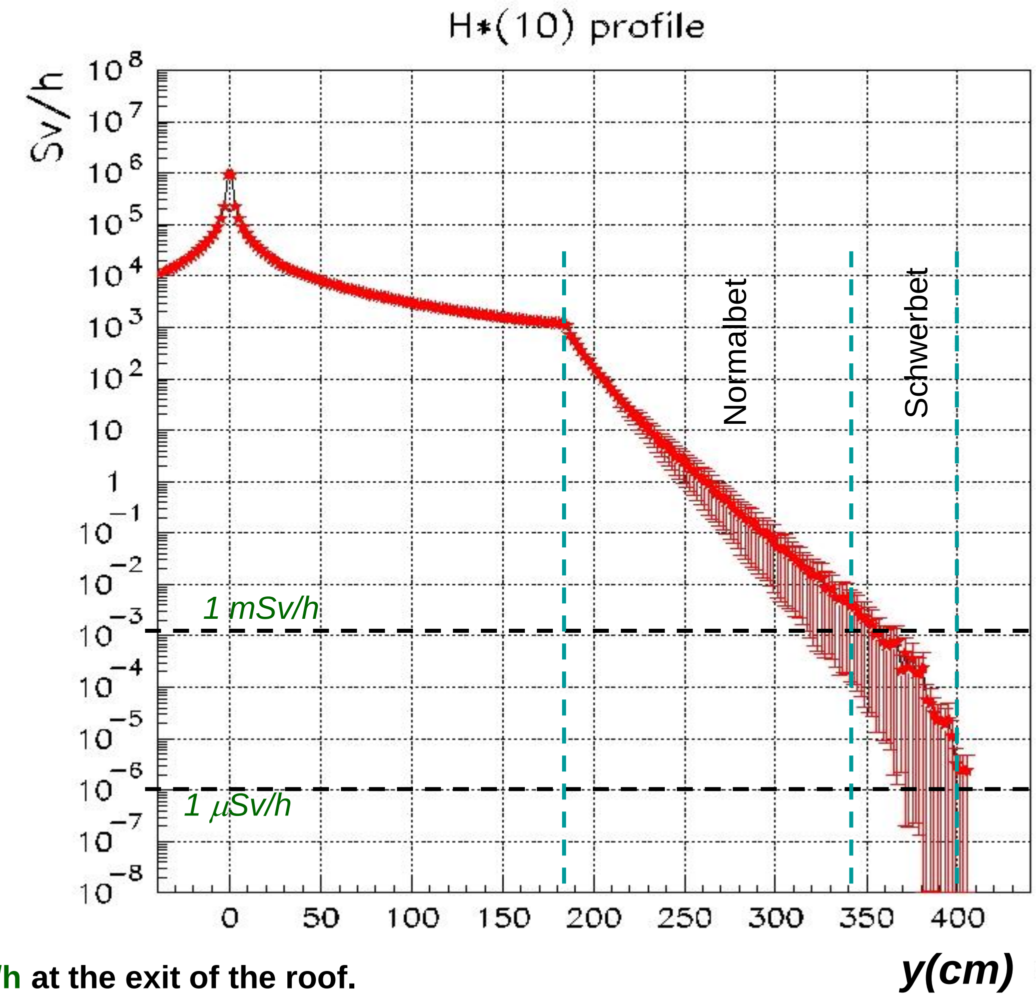
Extrapolation: **1 μSv/h** at ~300 cm
(after 150 cm in the heavy concrete)

The roof of the photo-neutron hall

We have tried different solutions to solve the problem of the high dose rate on the A1 roof (with 160 cm of normal concrete we have estimated around <u>3 mSv/h</u> on the top of the roof).

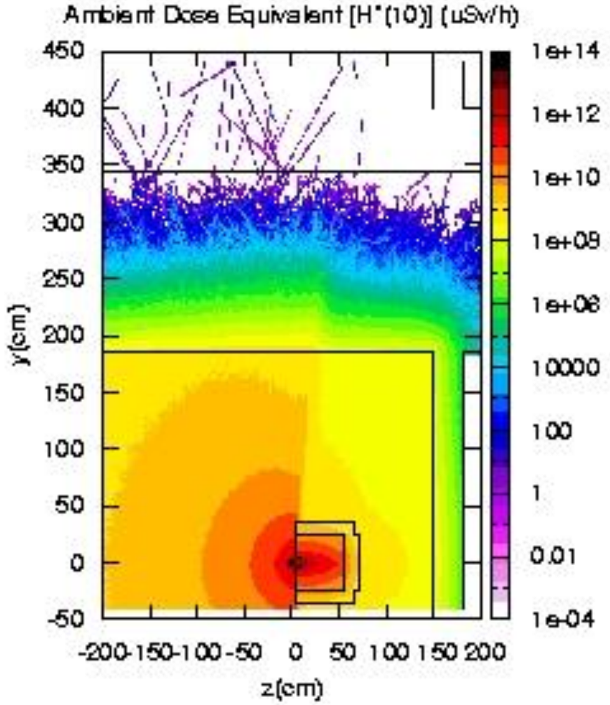
1. ***160 cm normal concrete + 55cm heavy concrete***

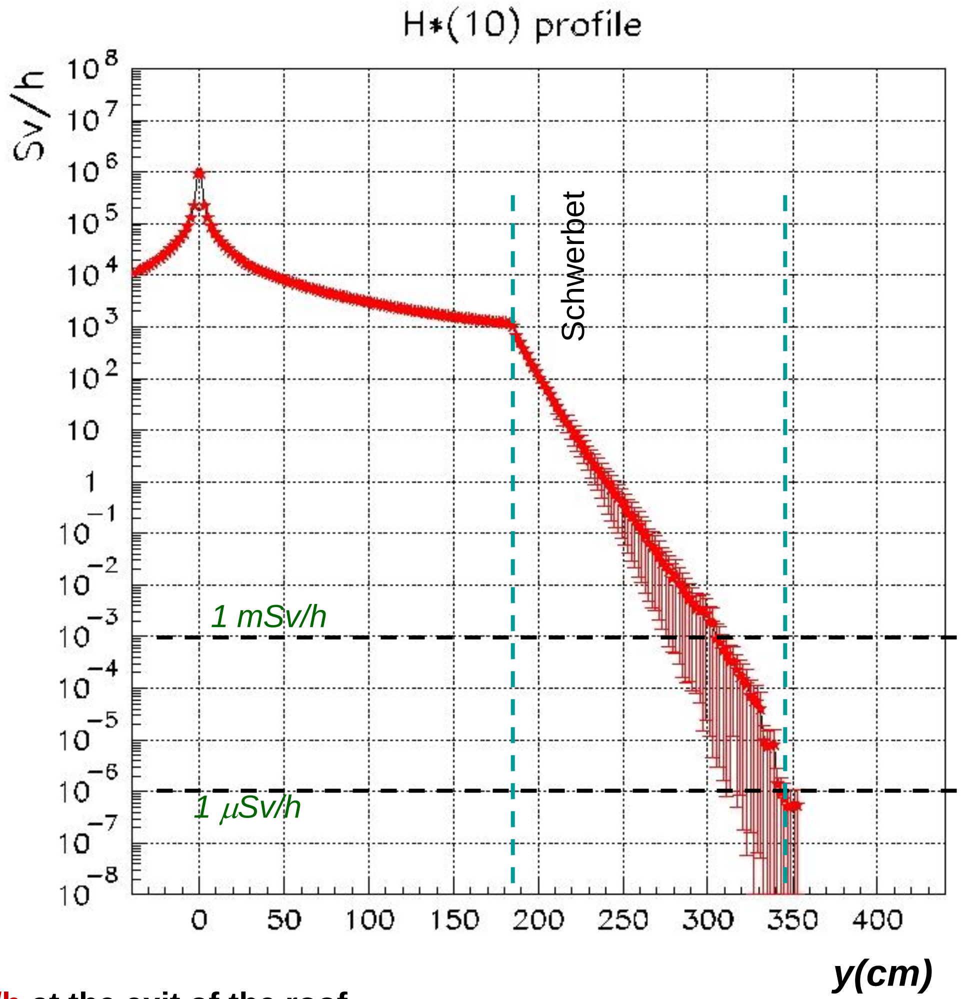




With this solution we find a dose rate of 2.4 μSv/h at the exit of the roof.

2. *160 cm heavy concrete*





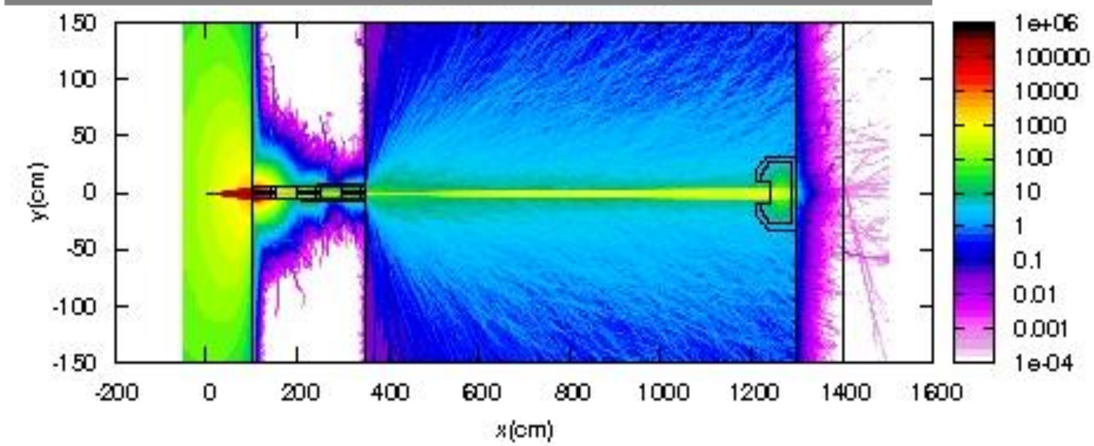
With this solution we find a dose rate of about 0.5 μSv/h at the exit of the roof. Even if the statistics can be improved (the statistical error increases till about the 70% in the last 20 cm), the behaviour is clear and there is no doubt about the fact that the result is robust.

(II) The neutron experimental room

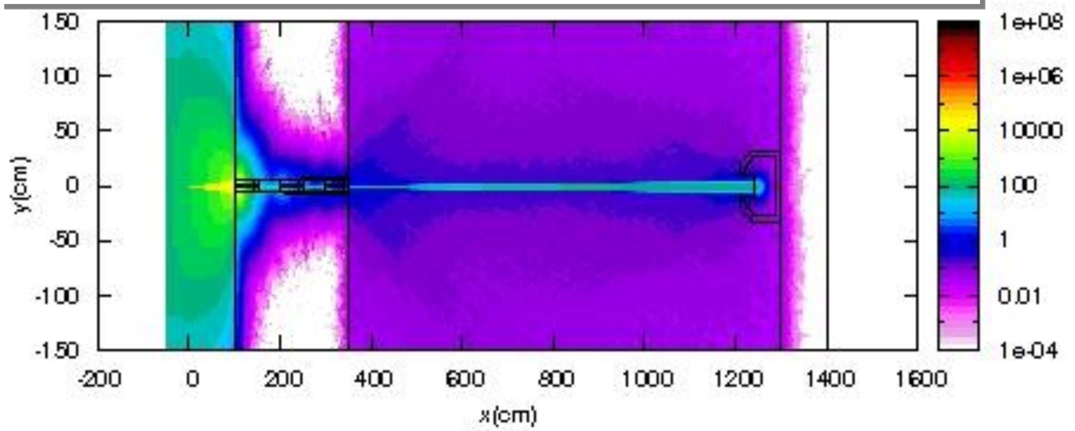
The wall at the end of the experimental room

Vertical view:

(a) H(10) rate from photons (mSv/h)*



(b) H(10) rate from neutrons (mSv/h)*



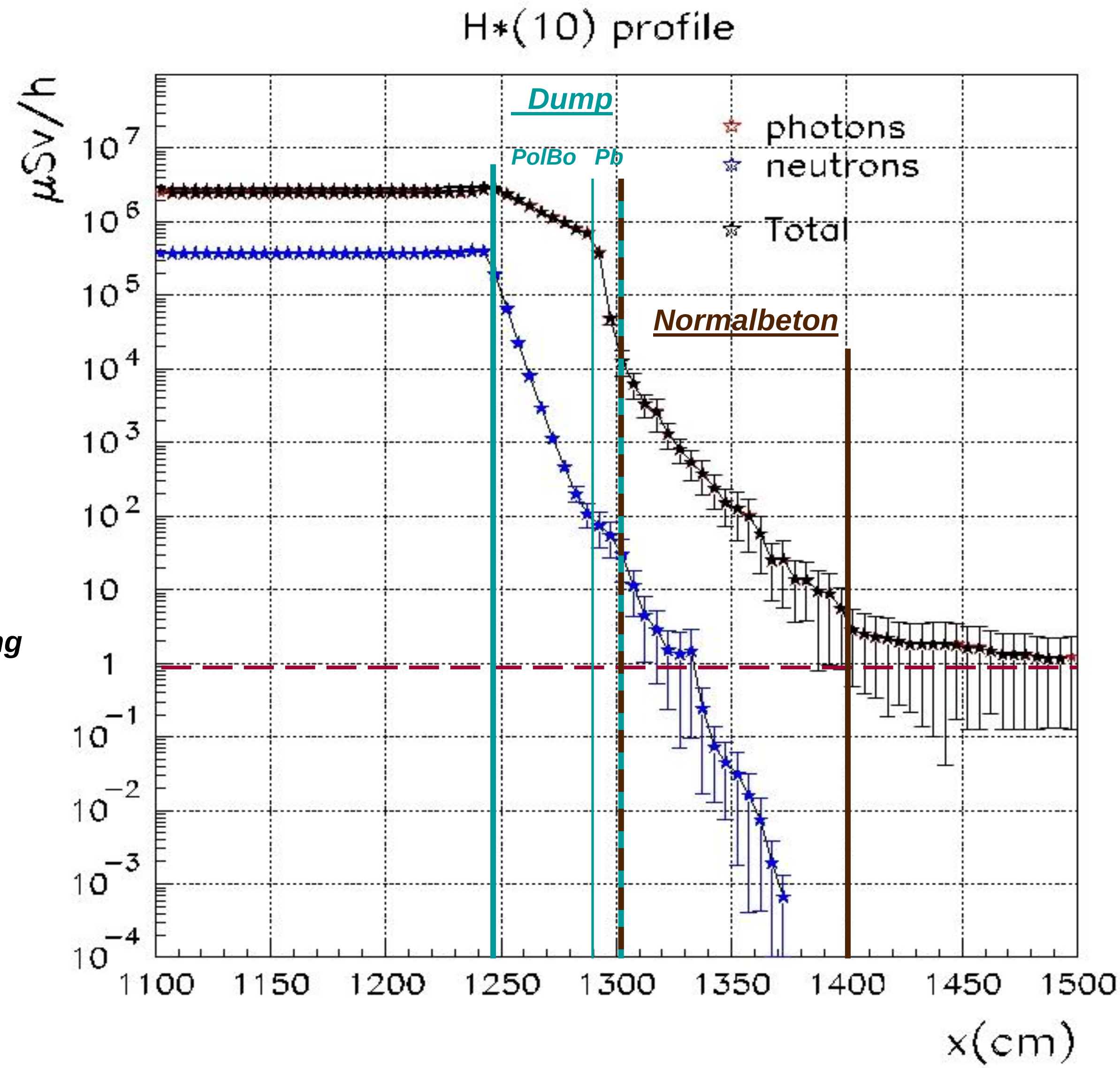
Summary of the previous results:
profile of the mixed field in the case of the actual beam dump (10 cm Pb at the end of the dump)

The H*(10) profile is calculated considering a column in the 'hot' region along the neutron beam direction x, large:
(-15 cm, 15 cm) in y
(-15 cm, 15 cm) in z
and averaging in steps of 4 cm in x.

We found, at the exit of the wall
(x = 1400 cm):

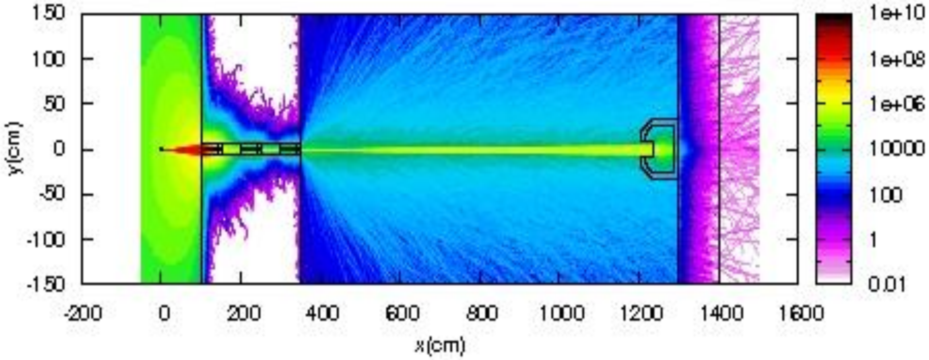
H*(10) rate = 4.8 μSv/h 3.5 μSv/h

This value is not satisfactory (exceeding our limit of 2.5 μSv/h)

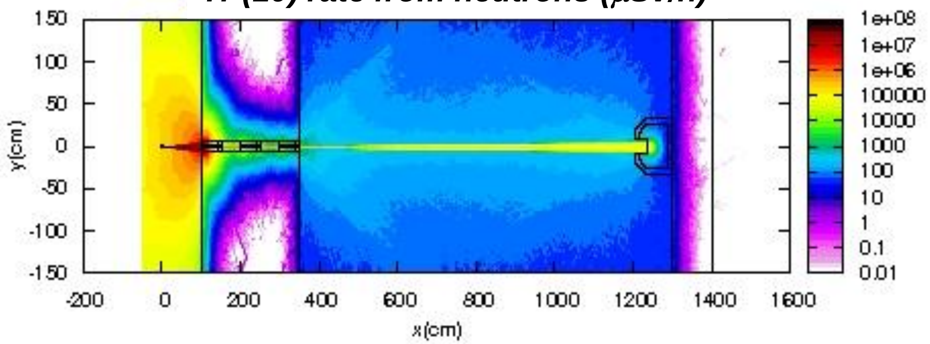


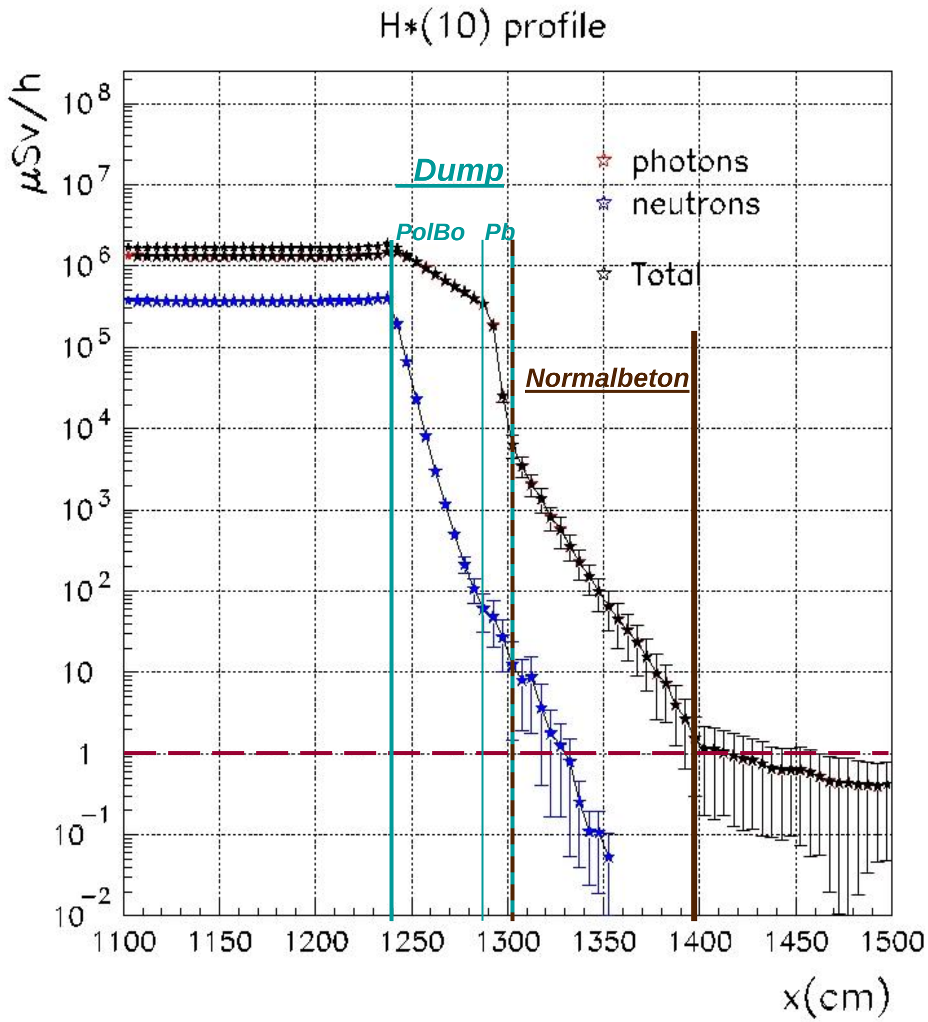
The effect of additional 5 cm Pb after the actual beam dump

H*(10) rate from photons (μSv/h)



H*(10) rate from neutrons (μSv/h)



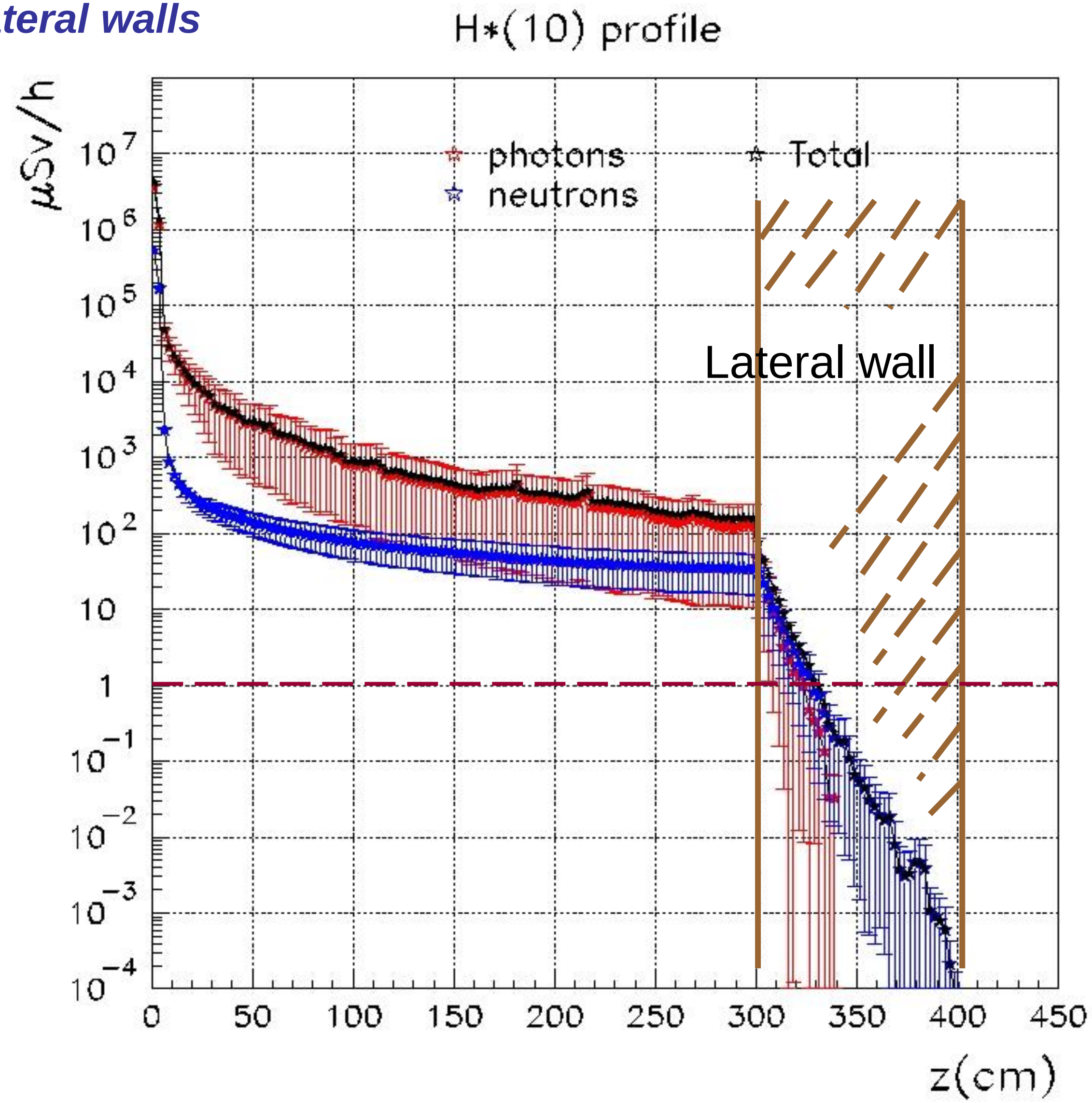


By adding **5 cm Pb** after the beam dump the photon spot is not yet completely shielded before entering the concrete wall, but the behaviour of the Ambient Dose Equivalent is already acceptable:

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)

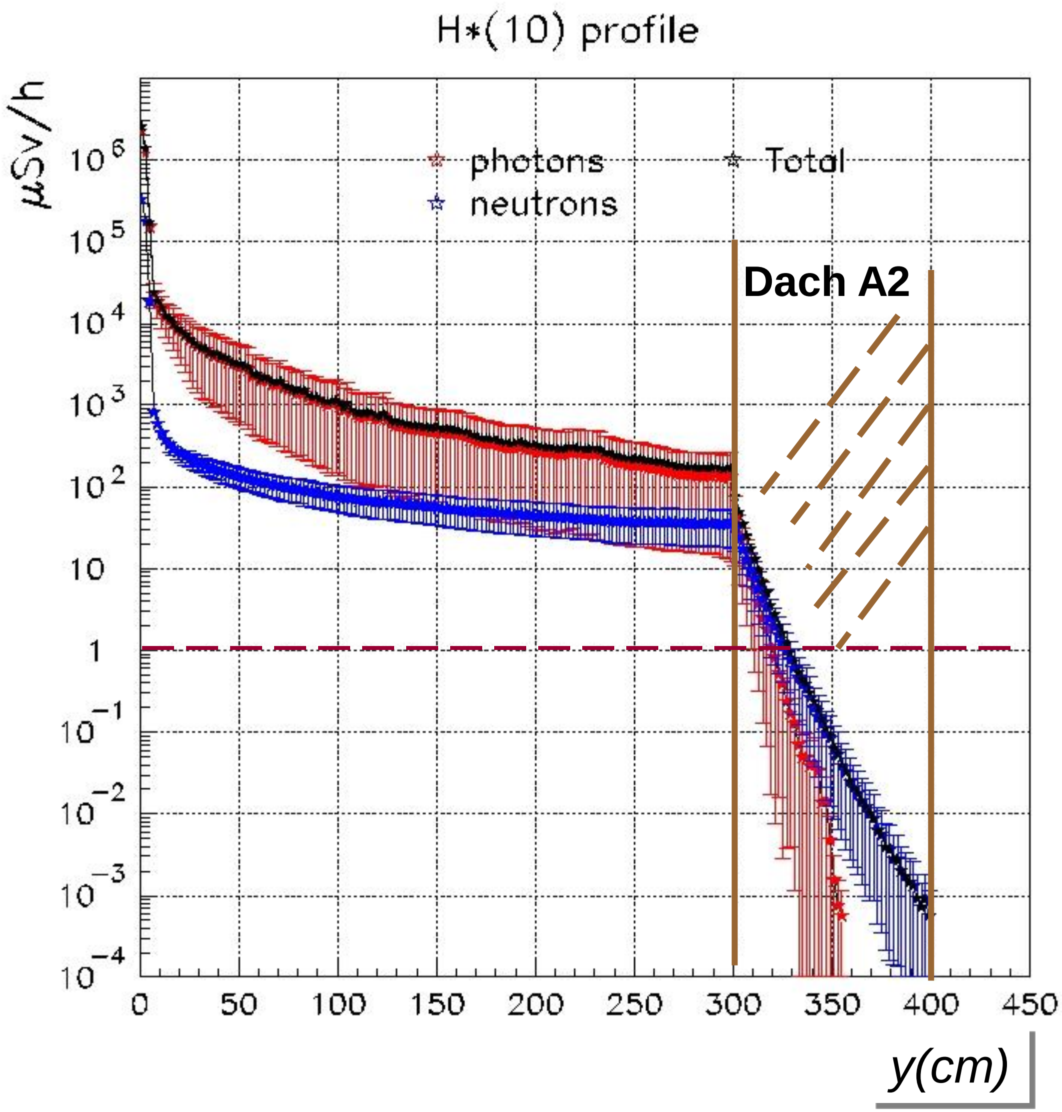
I. Lateral walls



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 H*(10) profile is calculated by averaging:

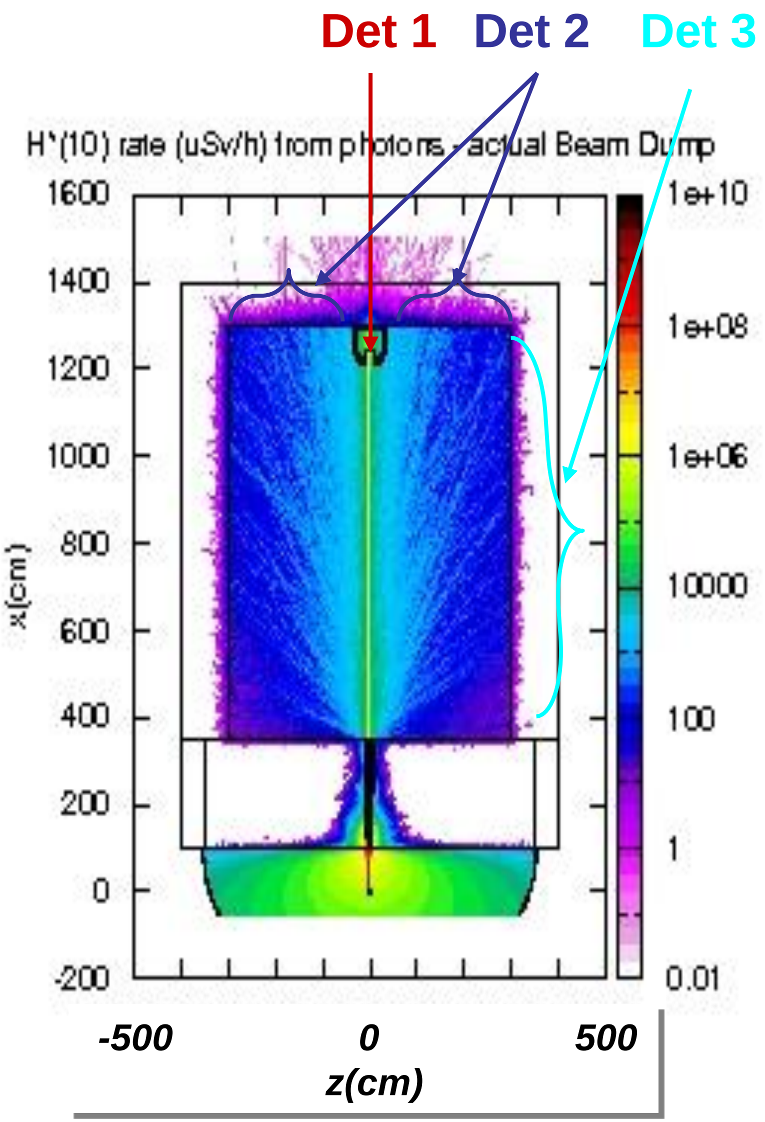
- on a quite narrow region above the beam (the photon-neutron beam direction is x): (-25 cm, 25 cm) in z
- on a large region in x (covering all the roof)

and in steps of 2 cm in the vertical direction y.

In this plot, as in the previous one, the gamma component of the radiation is rapidly attenuated, faster then the neutron one.

This behaviour is different if compared with the radiation profiles, that we have studied for the (more critical) wall at the end of the beam-line.

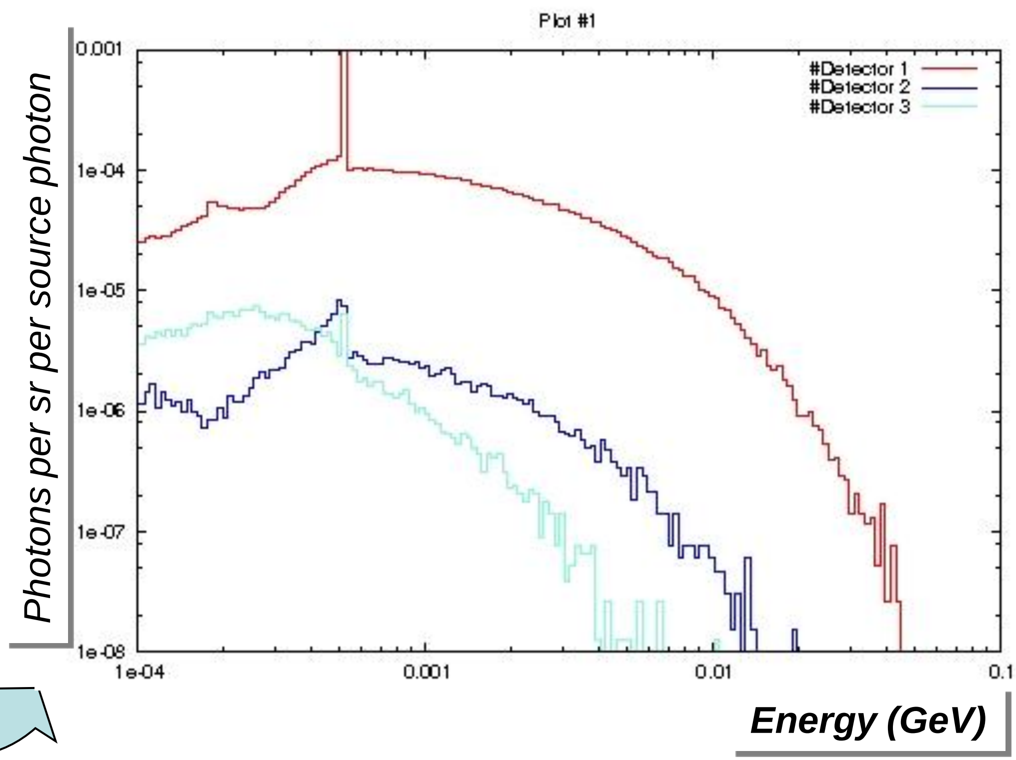
The reason is in the different energy spectrum of the photon radiation



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

- Det.1 at the beam dump surface, inside a cylinder with a 9 cm diameter;
- Det. 2 at the surface of the wall, where the beam is impinging (and out of the final beam dump);
- Det. 3 at the surface of the lateral walls and (not shown in the figure) 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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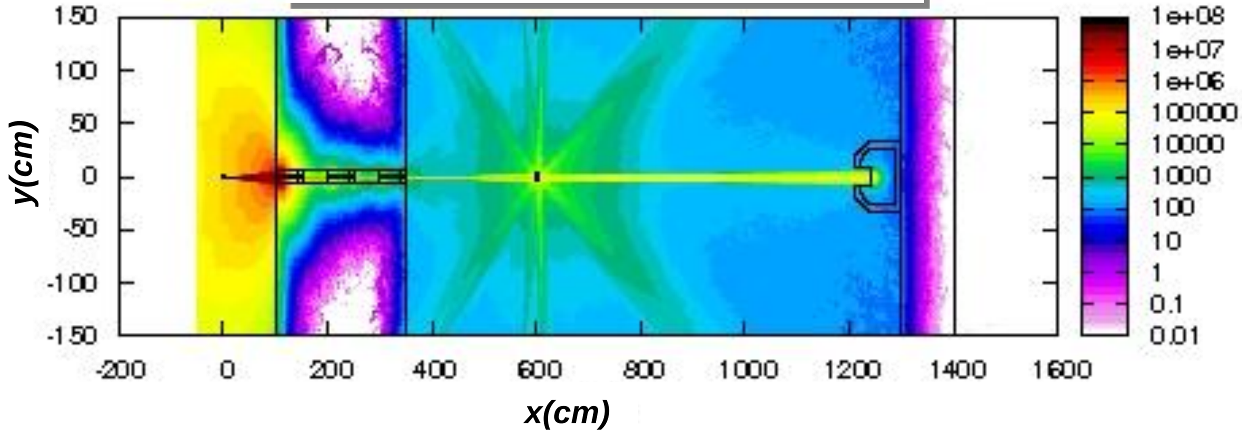
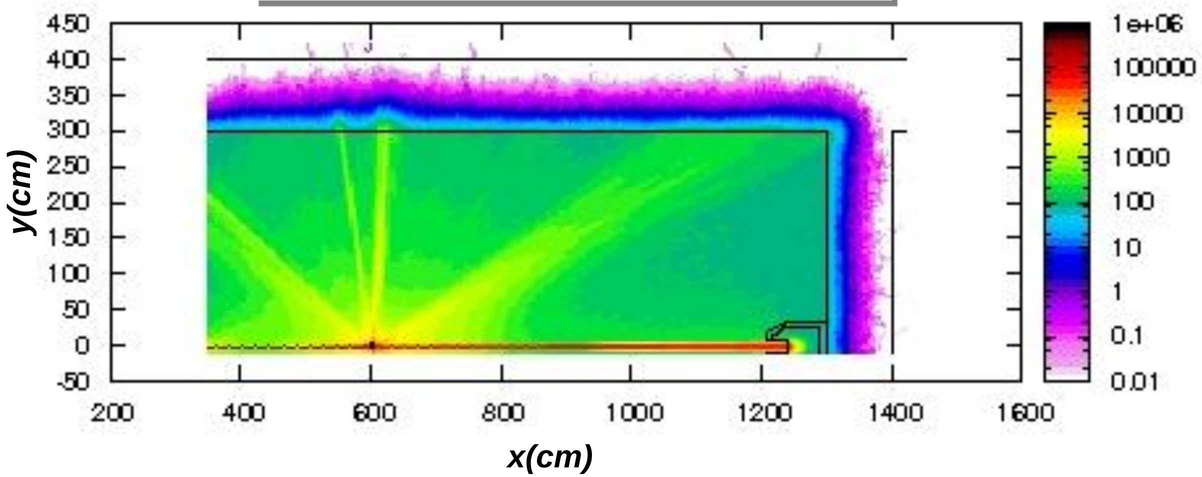
Target: 4 cm Pb

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.

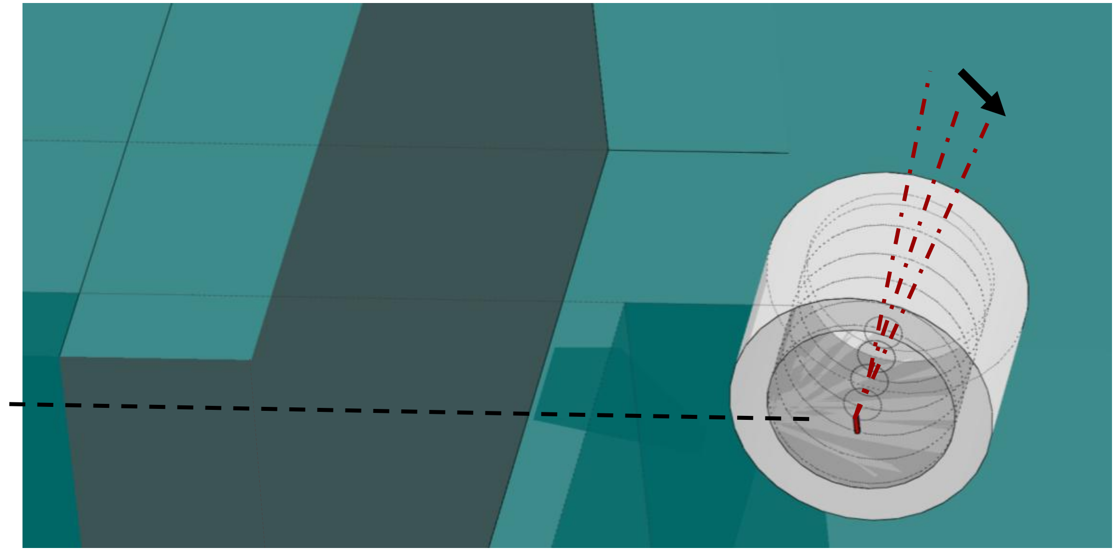
The behaviour at θ~ 90 is due to the contribution of the φ components, described above (the plot is the result of the average in a region defined by z in (-75 cm, 75 cm) respect to the PNQ source).

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

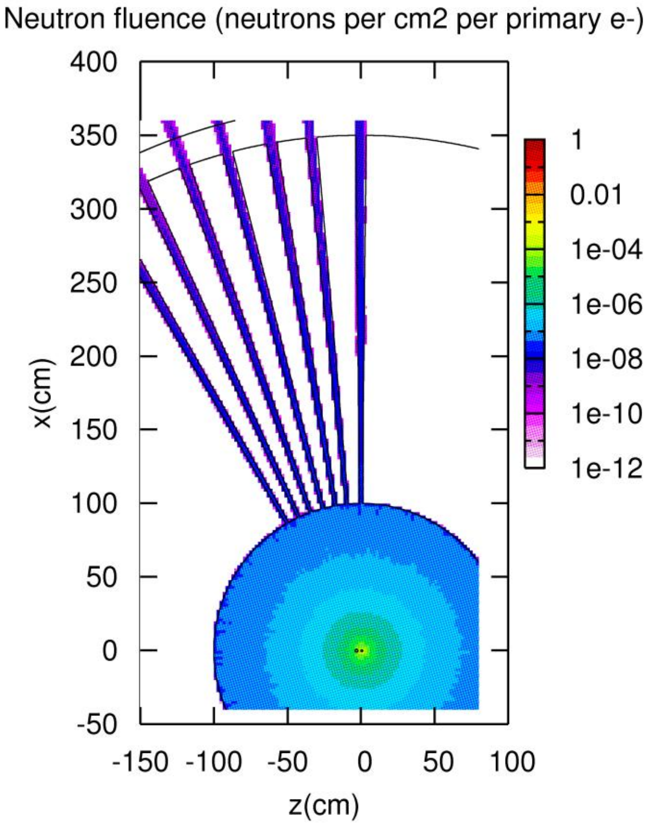
- Goal: choose a direction of the neutron beam-line that maximize the ratio n_{yield}/γ_{yield}, taking into account the isotropy of the neutron production and the typical shape of the bremsstrahlung

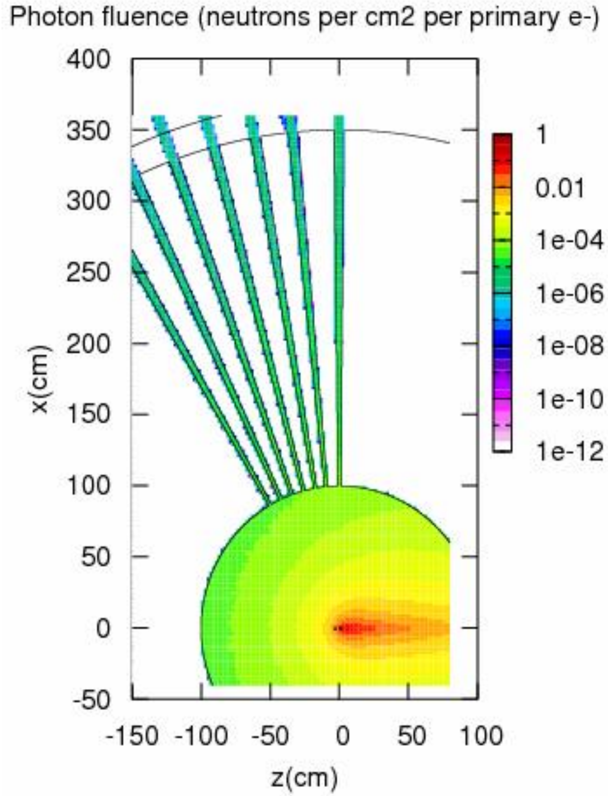
⬇

The optimized direction will be 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)



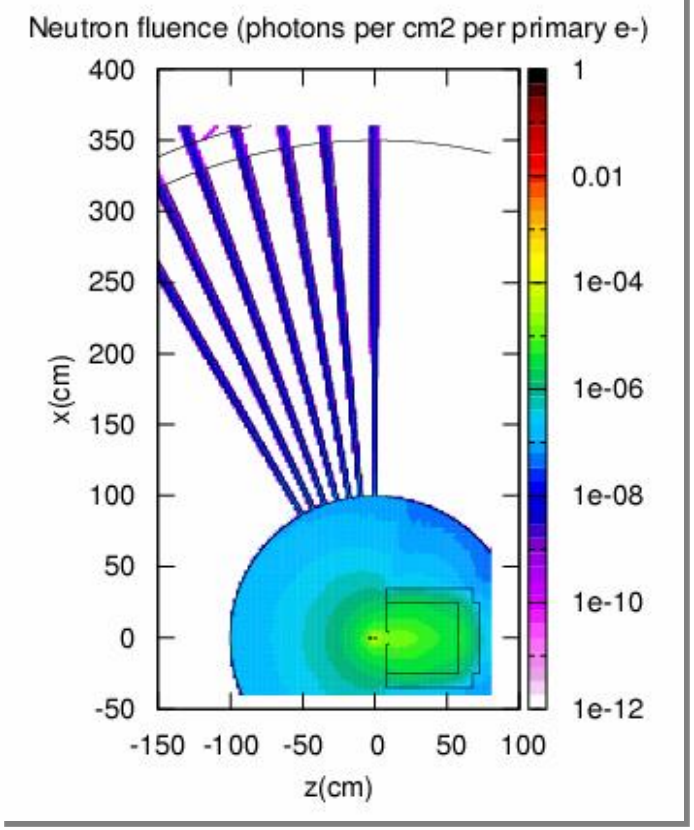


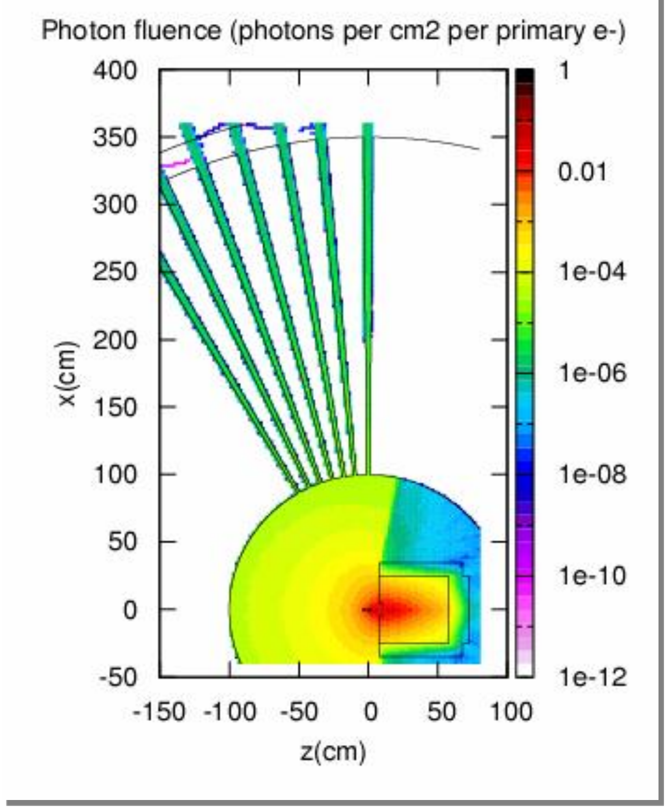
Statistical accuracy of the FLUKA fluence simulation: $\leq$ 1%

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

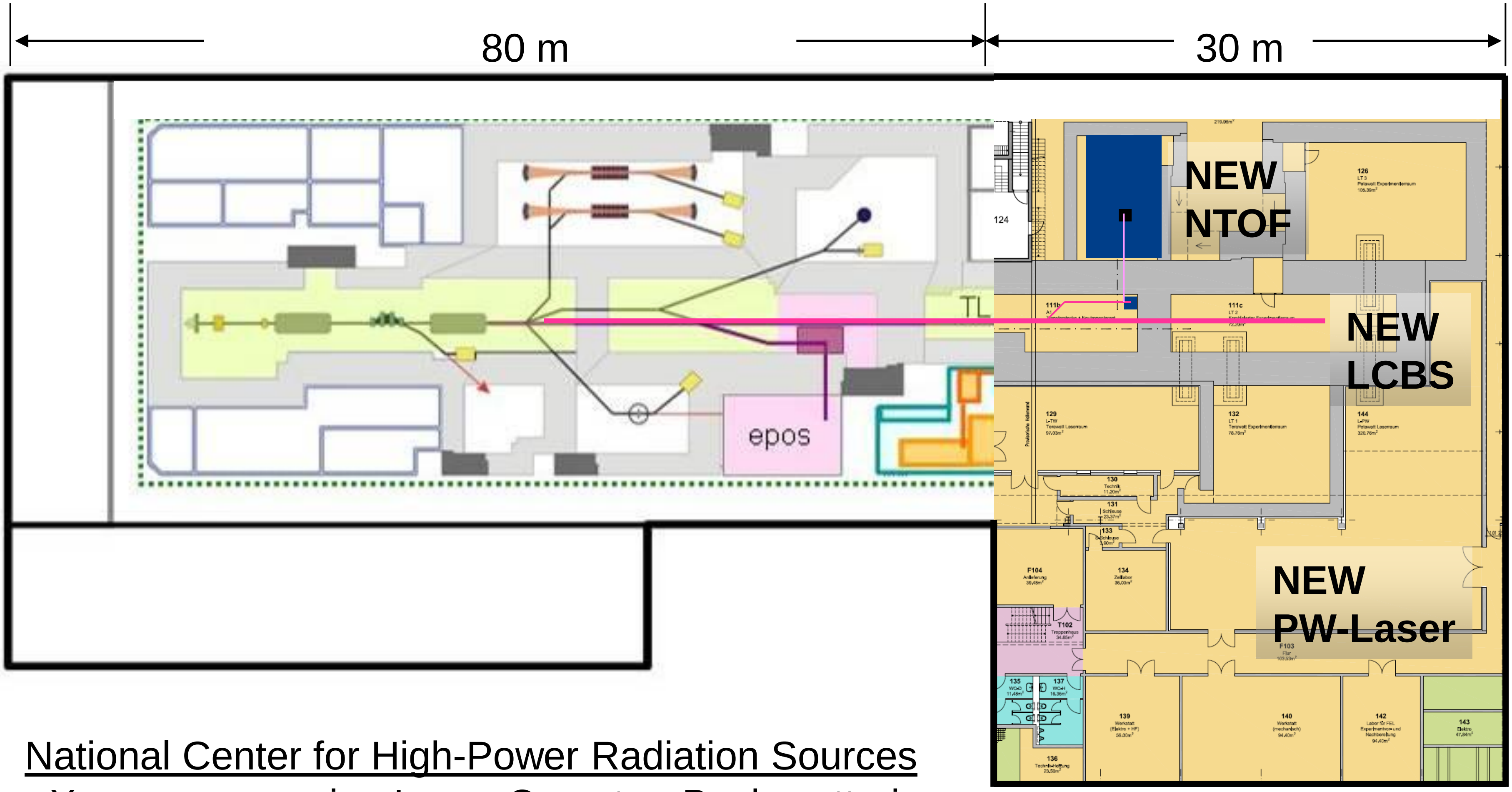




In real life we must avoid the 'contamination' coming from the neutrons scattered on the beam dump (or photoproduced in the dump material).

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

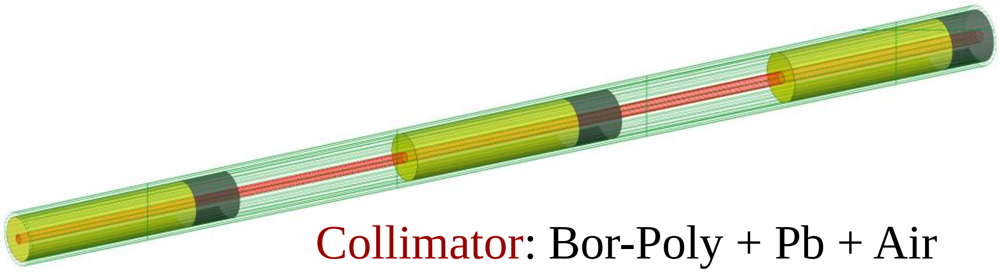
	90	95.5	100	105	110	115
Ideal source n_{yield}/γ_{yield}	$2.20\ 10^{-3}$	$2.38\ 10^{-3}$	$2.52\ 10^{-3}$	$2.77\ 10^{-3}$	$2.88\ 10^{-3}$	$3.05\ 10^{-3}$
Real source n_{yield}/γ_{yield}	$2.17\ 10^{-3}$	$2.39\ 10^{-3}$	$2.53\ 10^{-3}$	$2.78\ 10^{-3}$	$2.92\ 10^{-3}$	$3.14\ 10^{-3}$



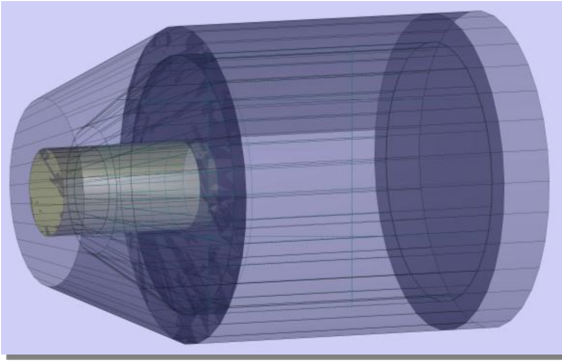
National Center for High-Power Radiation Sources

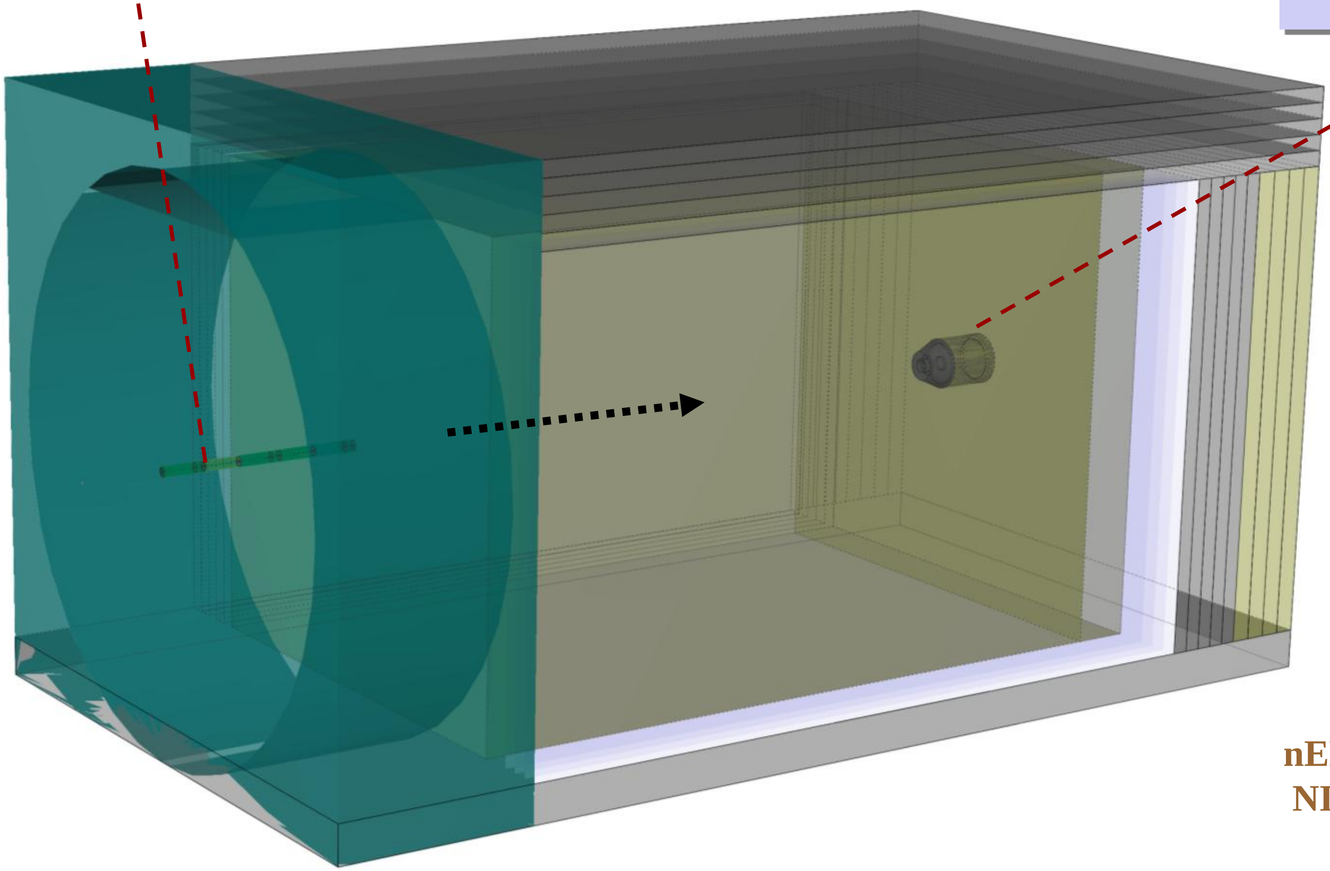
- X-ray source using Laser-Compton-Backscattering
- High-Power Laser (PW) for Ion Acceleration
- New Neutron Time-of-Flight Facility for Transmutation Studies

Spares



Collimator: Bor-Poly + Pb + Air





Beam Dump:
Bor-Poly +
Lead +
Cadmium foil

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