

PAUL SCHERRER INSTITUT



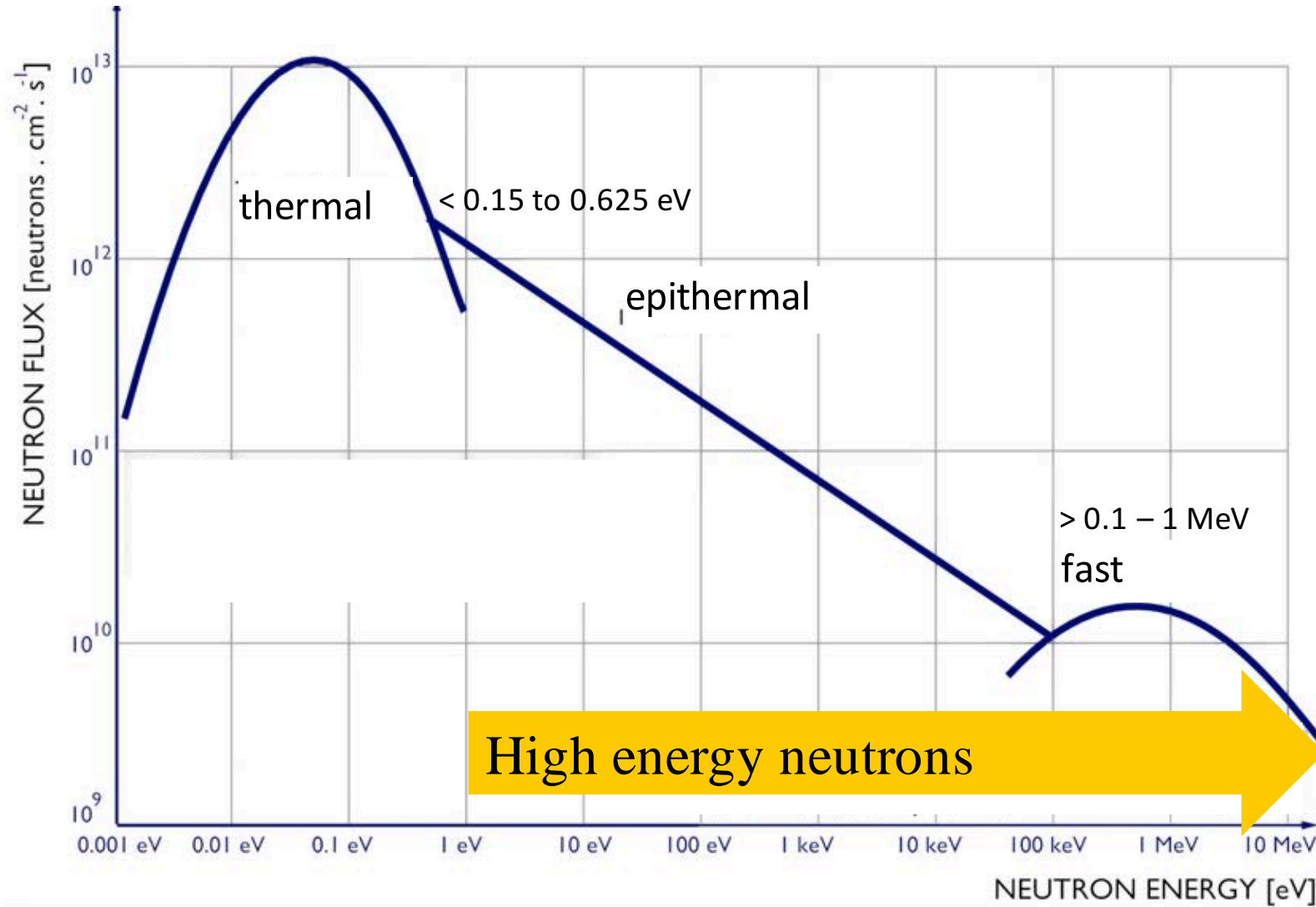
Uwe Filges, Paul Scherrer Institut
Phil Bentley, European Spallation Source

Shielding – High Energy Neutrons – Spallation vs. Fission

20th September 2018,

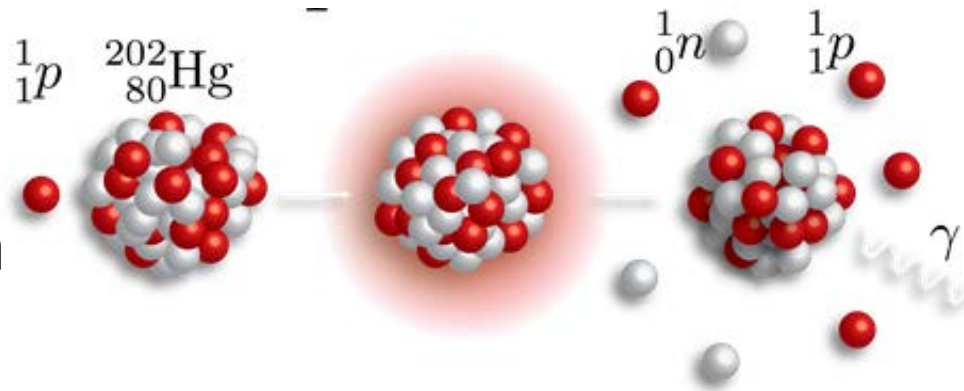


Neutron Energy Classification



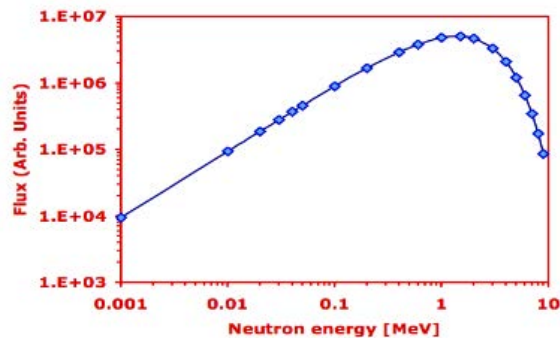
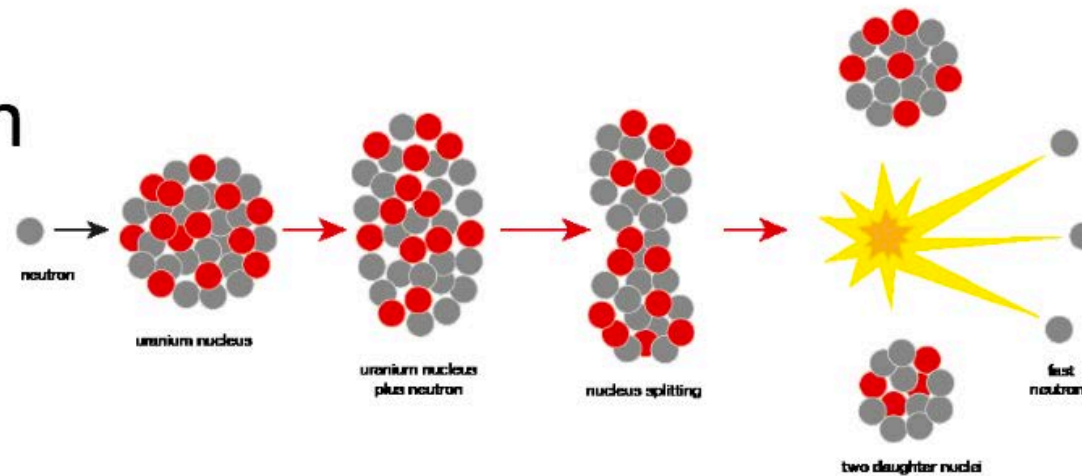
Spallation vs Fission

Spallation



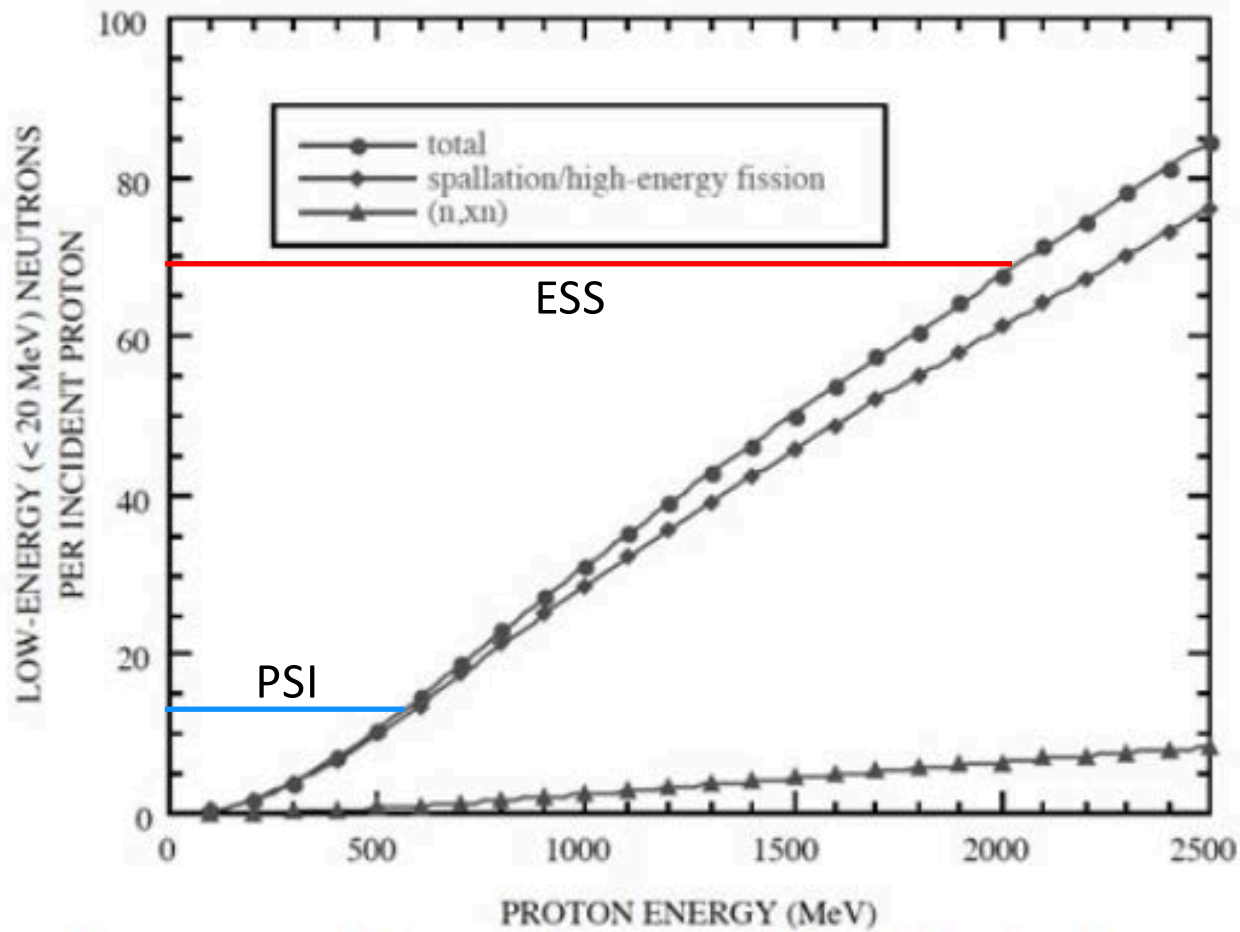
Neutron energy distribution: depends from proton energy and target !!!

Fission



Neutron energy average: 1.2 MeV
Watt-Fission Spectrum

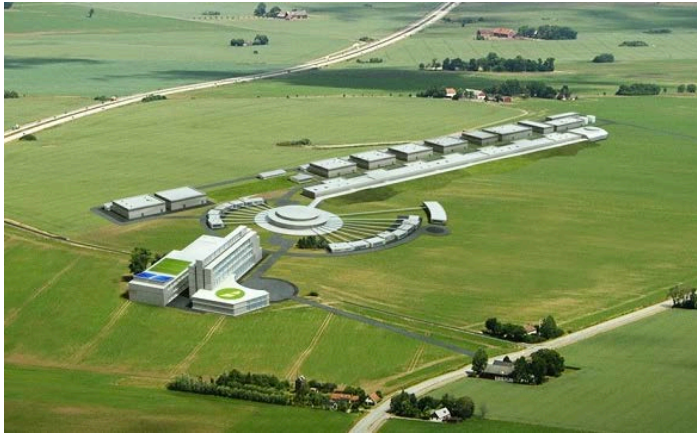
Neutron production – Proton energy



Neutron production versus beam energy for a 50-cm-diam by 200-cm-long tungsten cylinder bombarded on axis by protons.

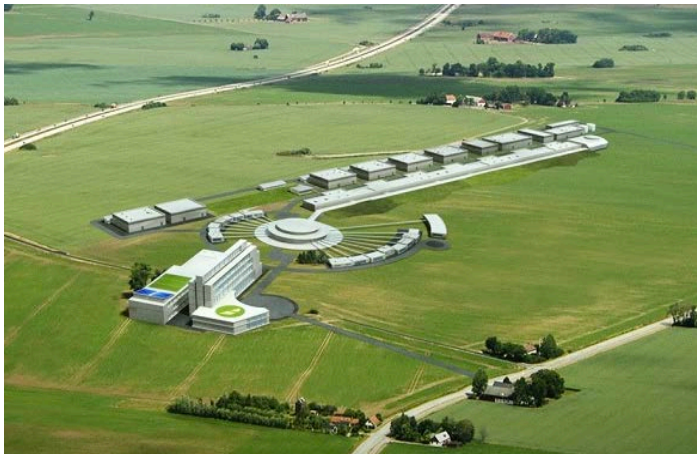
Goal: Increasing the proton energy

Pulsed spallation sources



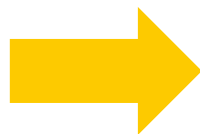
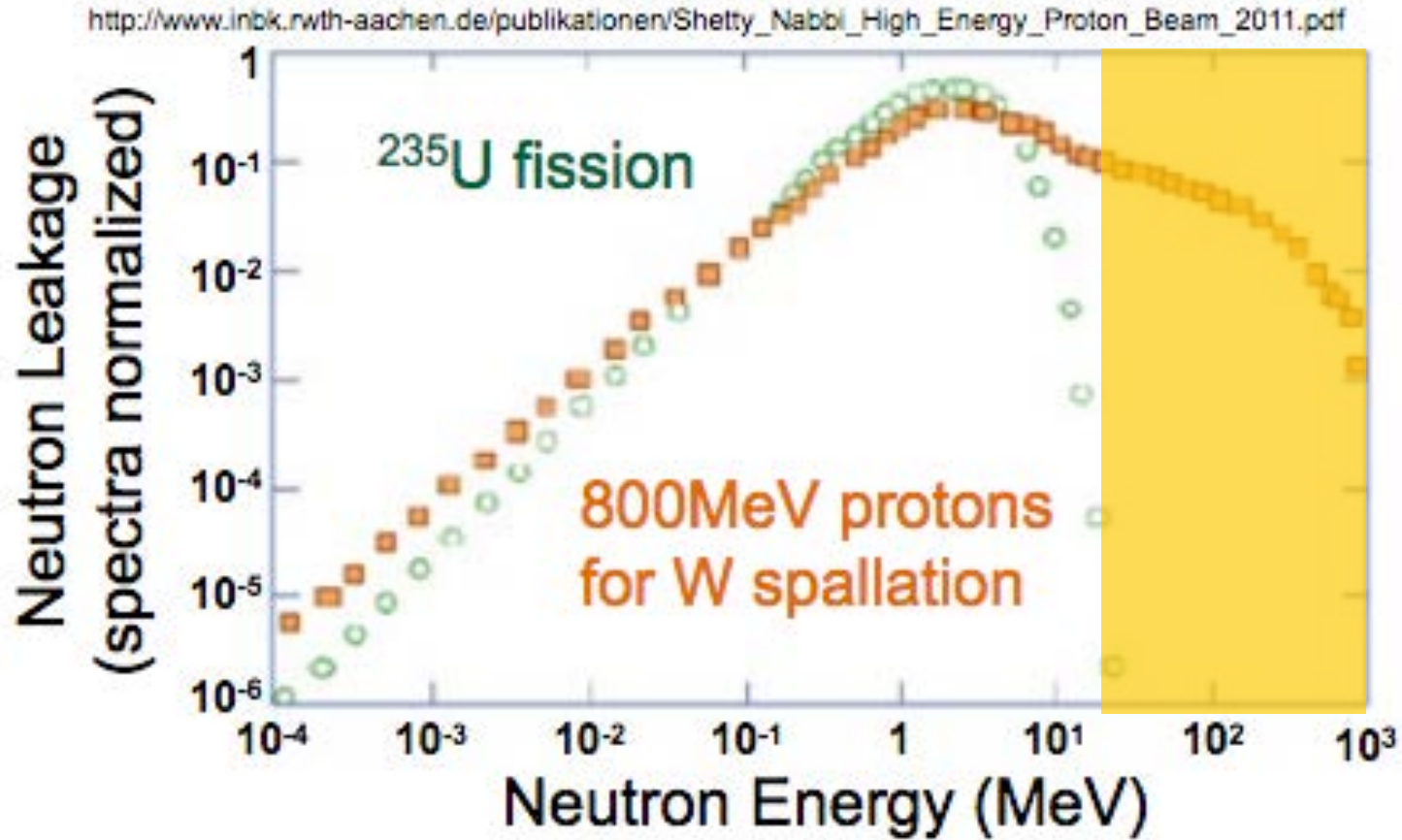
ISIS TS2 – 800 MeV proton beam

SNS– 1 GeV proton beam



ESS– 2 GeV proton beam

Released Neutron Spectra



Big difference in shielding efforts !!!

Moderation ?

- Reactor facilities: big volumes – based on hydrogen (heavy water & light water)

Goal: slowing down neutrons to thermal energy (no time dependency)

Continuous neutron flux

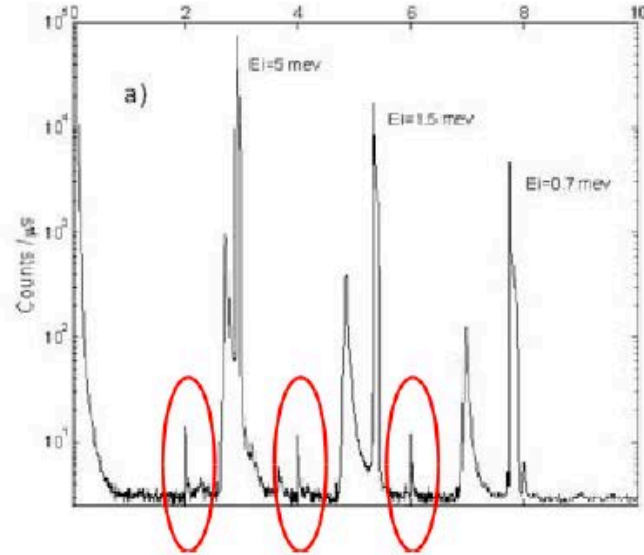
- Spallation sources: efficiently done only in small volumes
e.g. H₂-Moderators
Beryllium used as reflector (moderation is 50 times worse as D₂O)

Goal: keeping the time structure of the released neutrons
– minimize absorption/scattering between target and small moderator volume

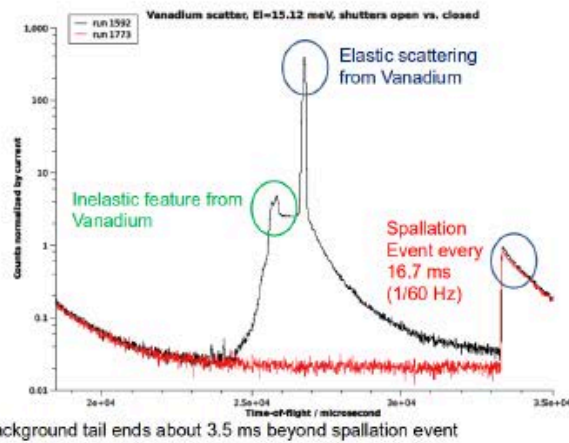
Pulsed neutron flux

 Big difference in shielding efforts !!!

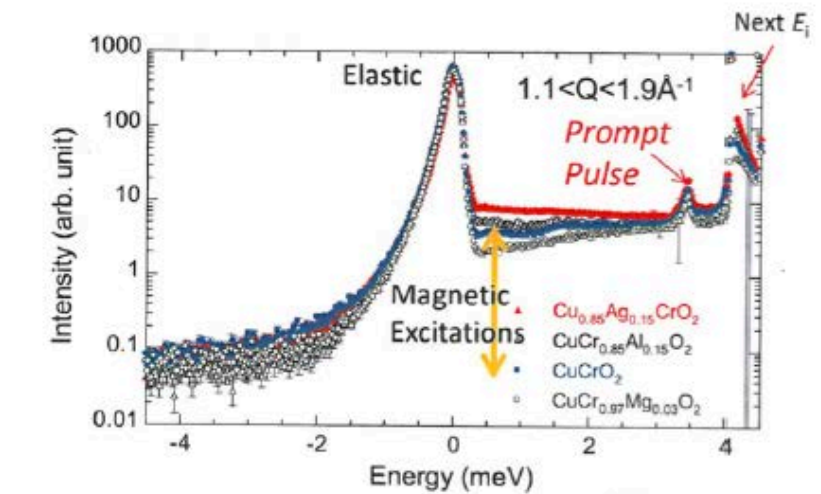
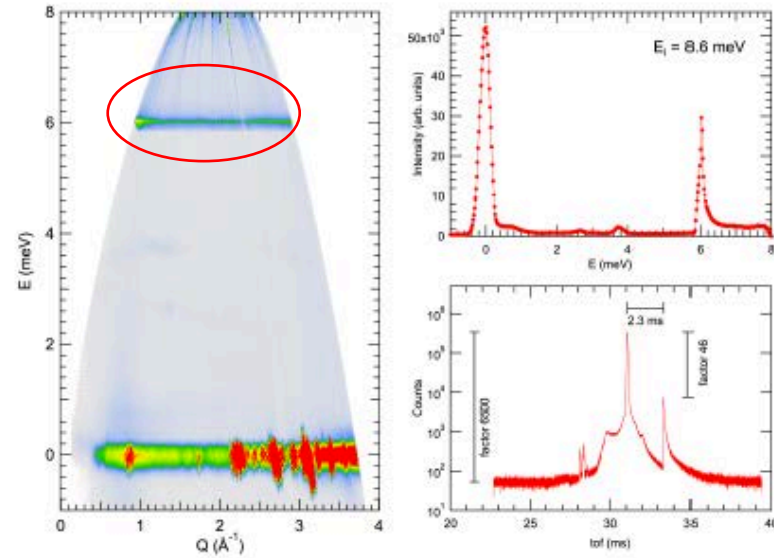
Effects on Neutron Scattering Experiments



HYSPEC data summed over all detectors



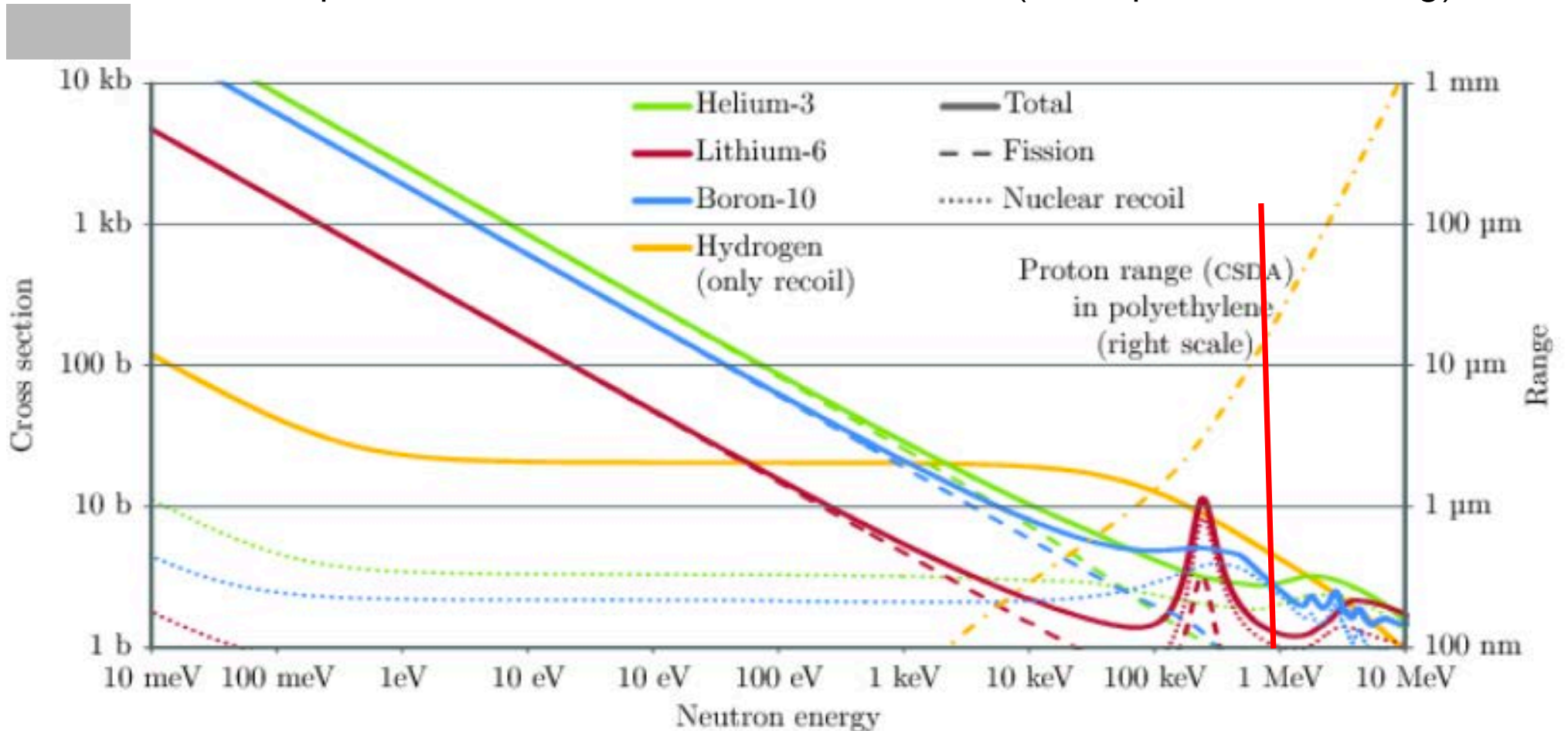
LET (ISIS), HYSPEC (SNS)



CNCS (SNS) and Amateras (JPARC)

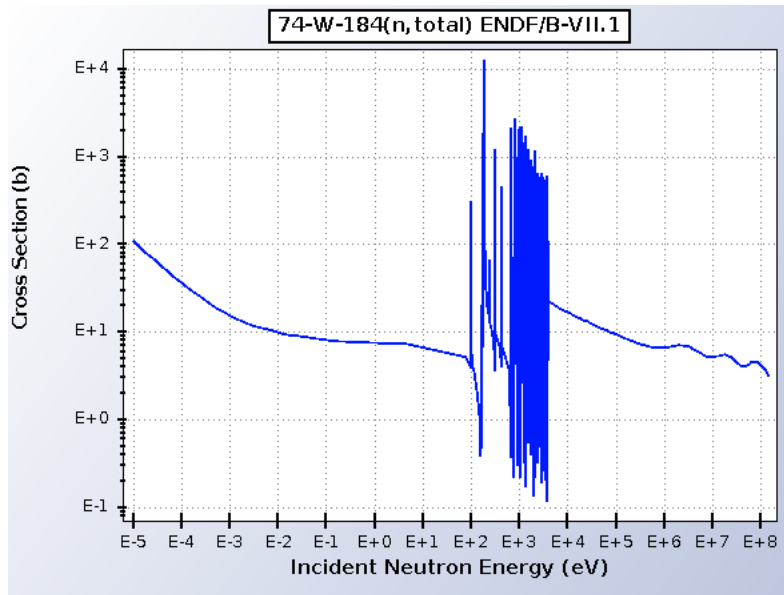
How you can shield high energy neutrons ?

Depends from the Material Cross Sections (Absorption & Scattering)

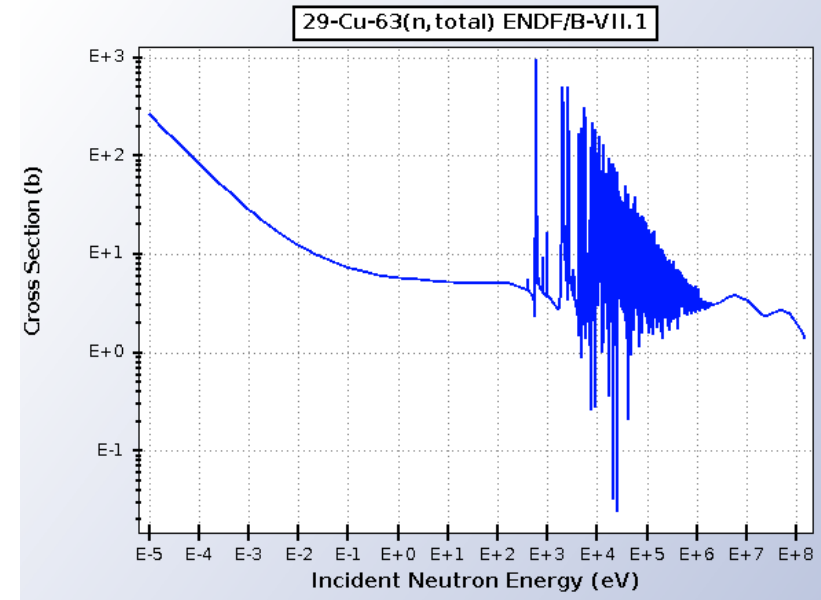


Good scattering materials are working well up to 1 MeV (scattering is dominating)

Density of the materials becomes more and more important.

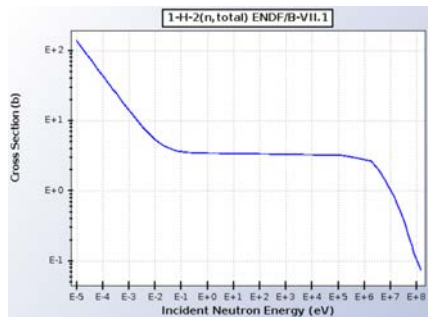


Tungsten – around 4-5 barn



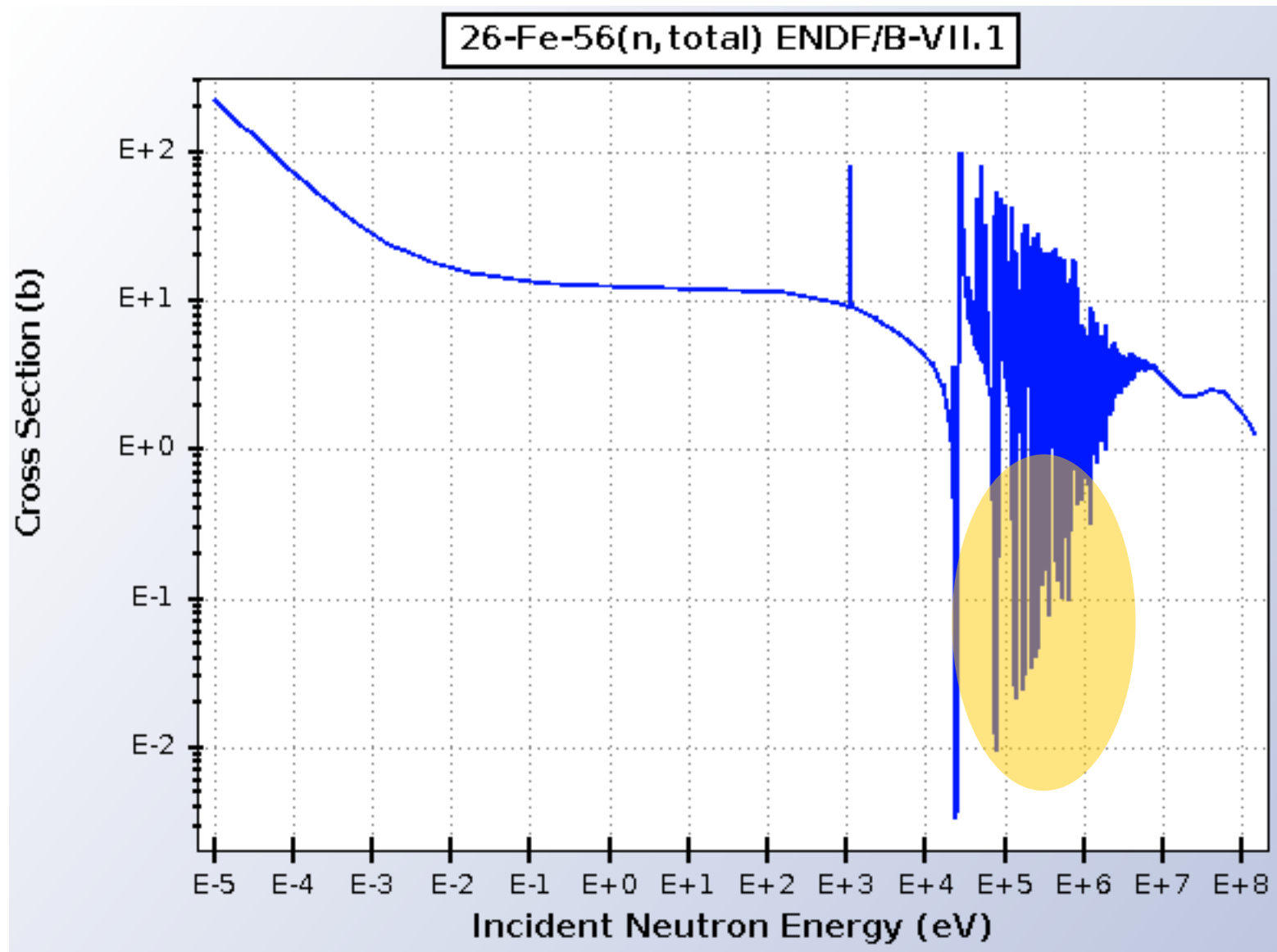
Copper – around 2-3 barn

Hydrogen has cross sections < 1 barn!!!



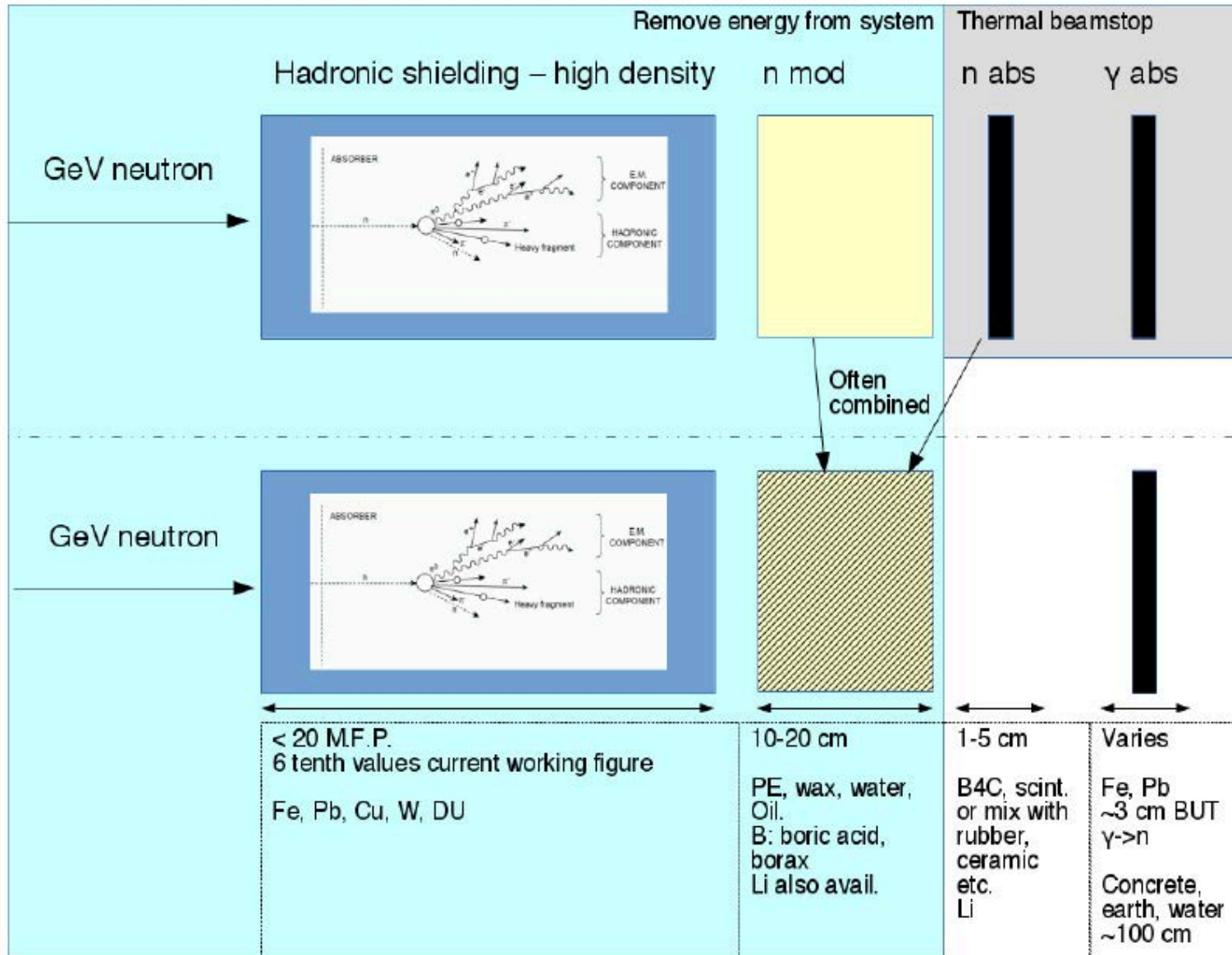
Data can be found on: <http://www.nndc.bnl.gov/sigma/>

Resonances !!!



Iron is not a „good“ shielding material for **epithermal** neutrons !!!!

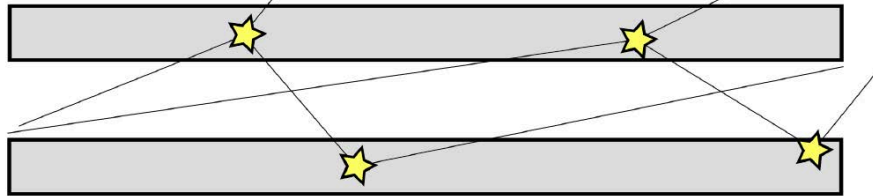
High Energy Neutron Shielding



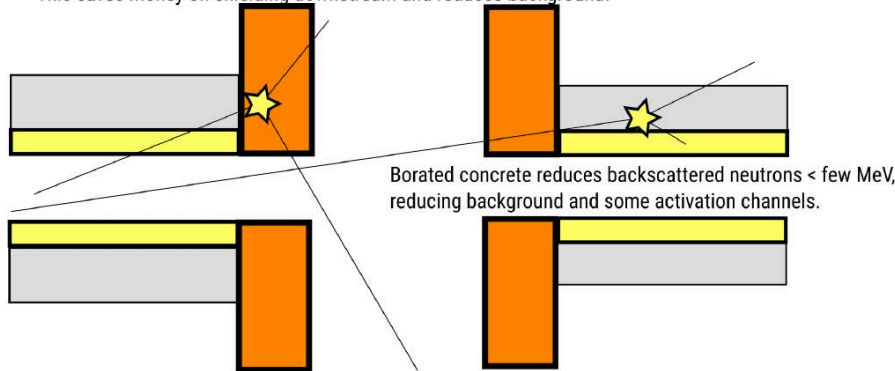
Elements borrowed from ATLAS/CERN and mathsconcepts.com

Collimators along the beamline & Layered structure (repetition of layers) of shielding material

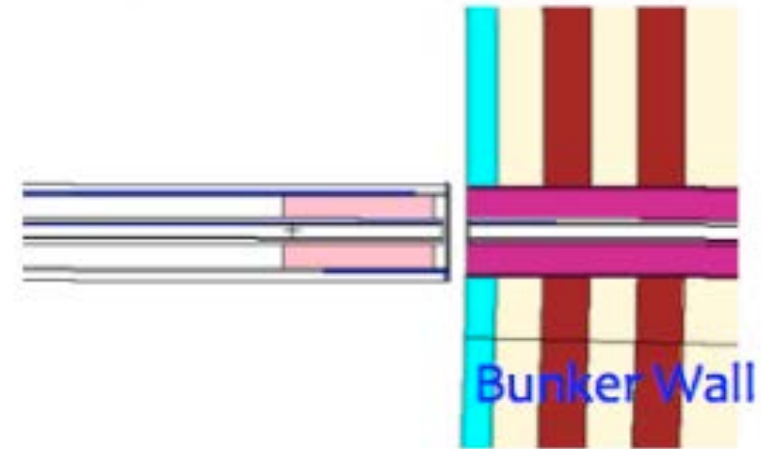
Fast neutrons scatter in steel, resulting in one or more lower energy neutrons, which continue scattering...



Collimator blocks induce controlled reactions, expansion zones let particles escape. This saves money on shielding downstream and reduces background.



Borated concrete reduces backscattered neutrons < few MeV, reducing background and some activation channels.

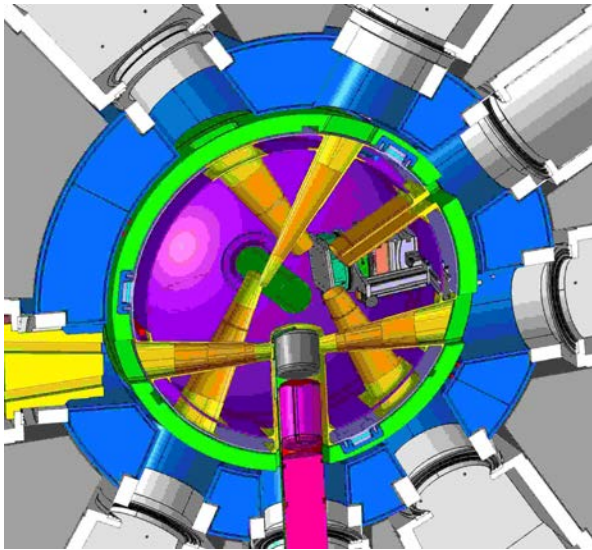


- **MCNPX** (an advanced Monte-Carlo Code for particle physics) is a perfect tool to describe a 3D neutron source, including moderator & shielding materials ... (alternatives: GEANT4 & PHITS)

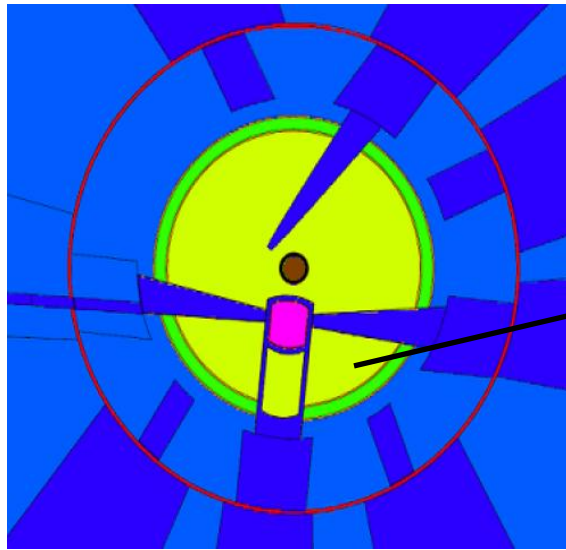
Input: proton beam or reactor core model

- **McStas**, a Monte Carlo ray-tracing code for neutron scattering instrumentation, simulates very efficient events (neutrons) from a source surface to the detector position (alternatives: VITESS & Restrax)

Input: neutron source description



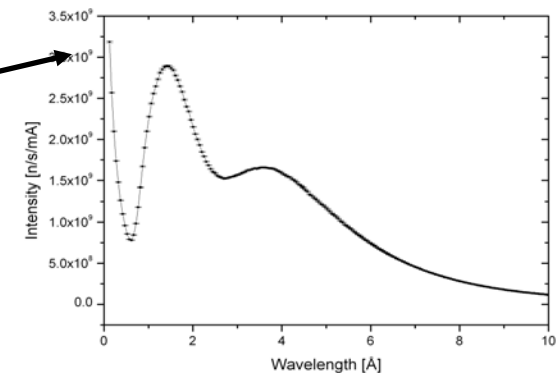
SINQ CATIA-Model



SINQ MCNPX-Model

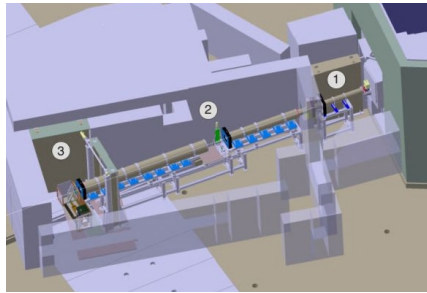
$$f(\lambda)d\lambda = \sum_{i=0}^{i=1} I_i * 2 * \left(\frac{\lambda_{Ti}}{\lambda}\right)^4 \exp\left(-\left(\frac{\lambda_{Ti}}{\lambda}\right)^2\right) \frac{d\lambda}{\lambda}$$

n- Maxwellian distribution

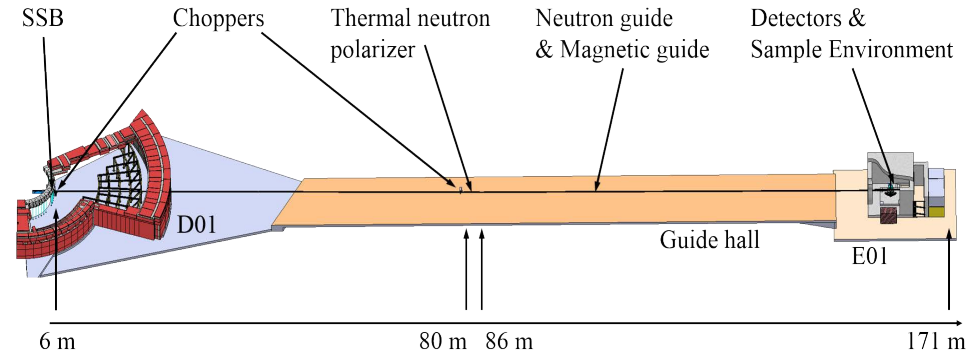


SINQ McStas-Model

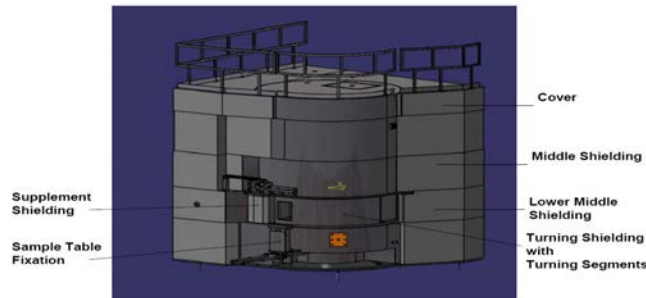
Examples – PSI & ESS



ICON – Imaging beamline
How good we can describe a source ?

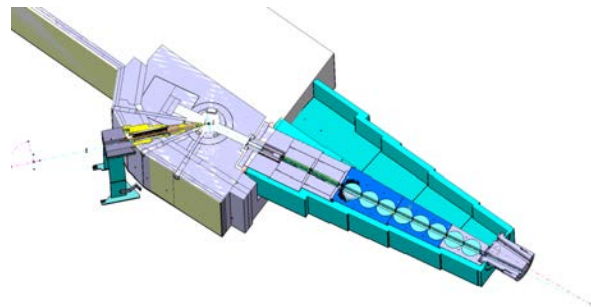


MAGiC – Single crystal diffractometer

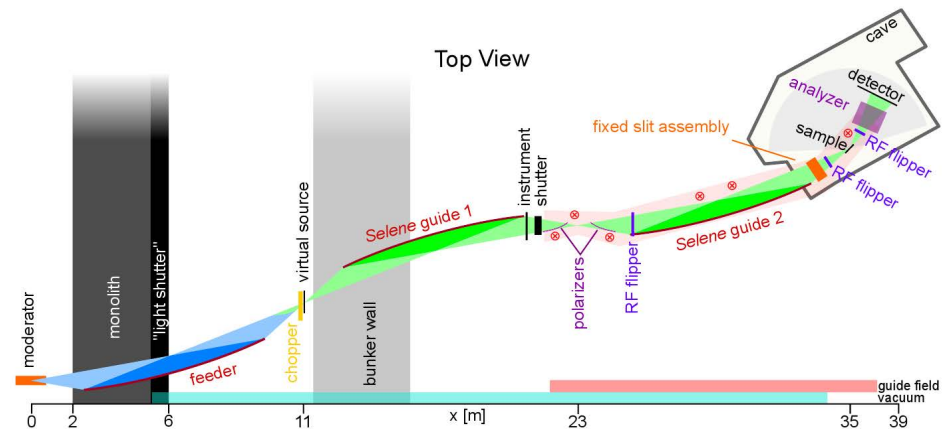


Eiger – thermal triple axes instrument
Non-magnetic / compact shielding

ODIN – TO investigations



Zebra – thermal single crystal diffractometer

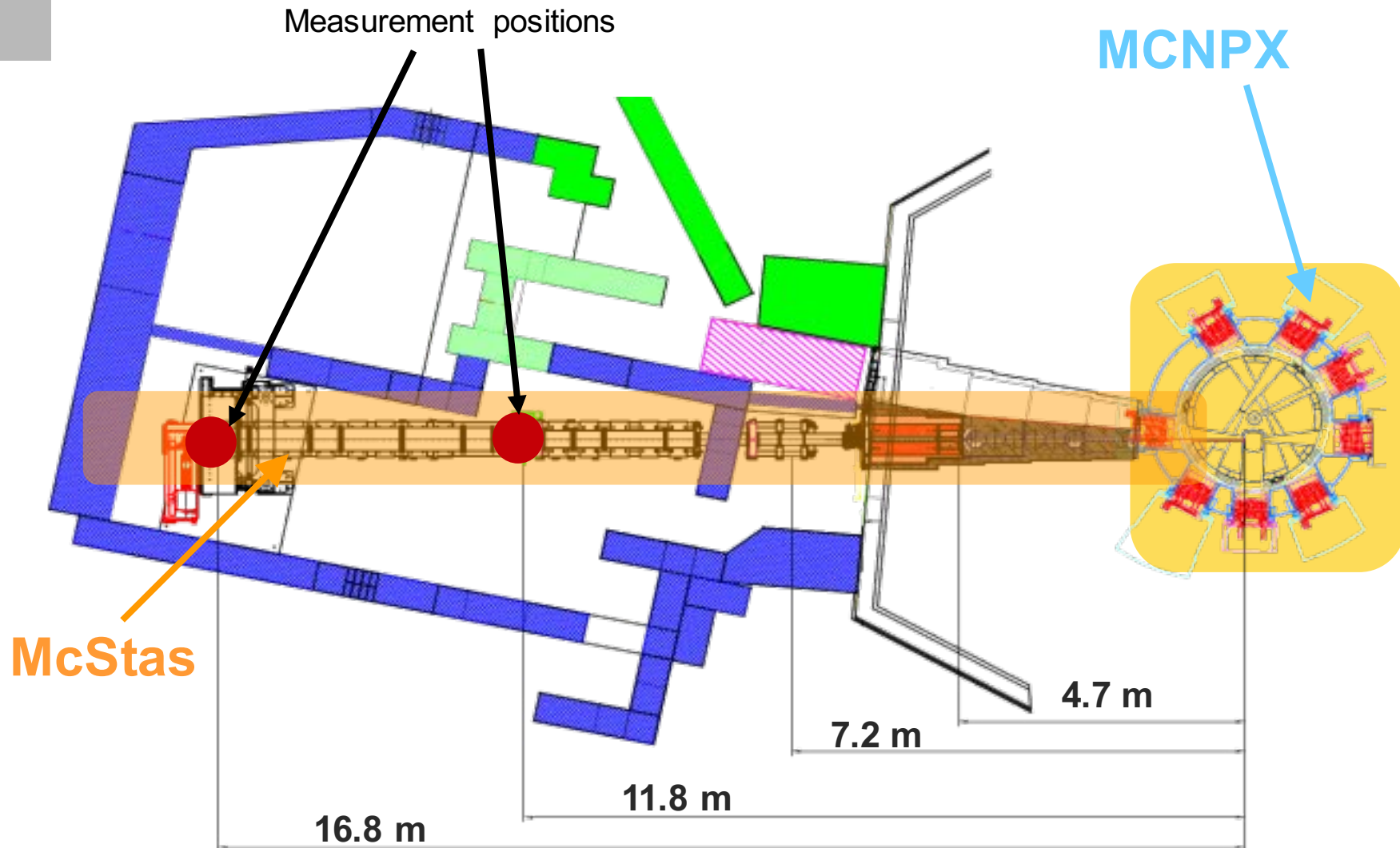


ESTIA – Reflectometer

Cold Source Simulations/Measurements at SINQ

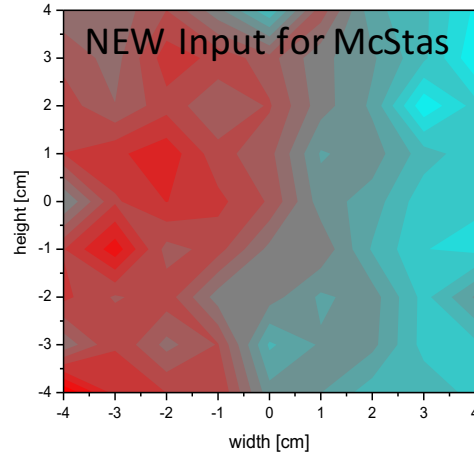
ICON beamline

no supermirrors are installed, different pinhole geometries are possible, measurement positions are closed to the source with direct view

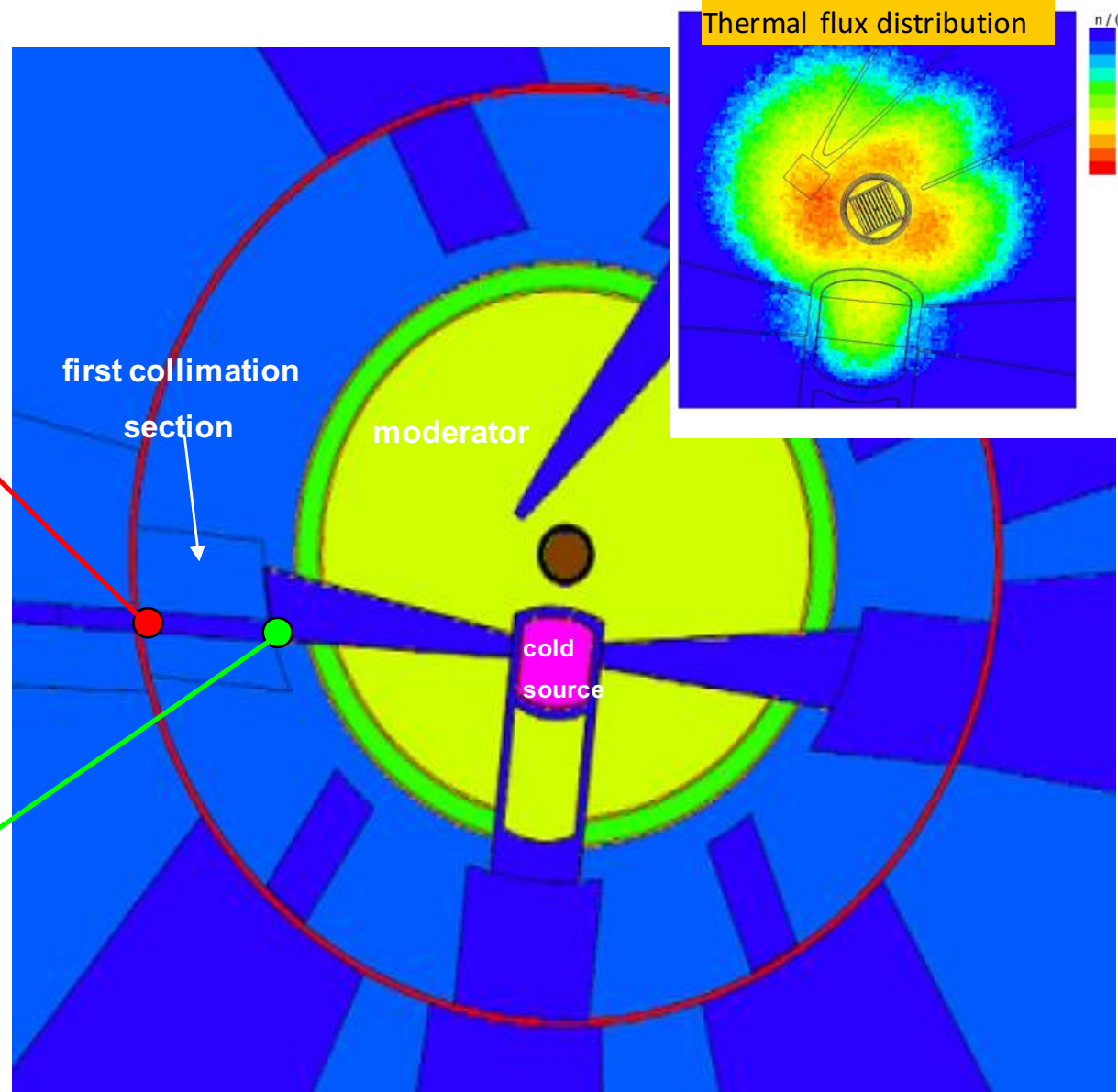
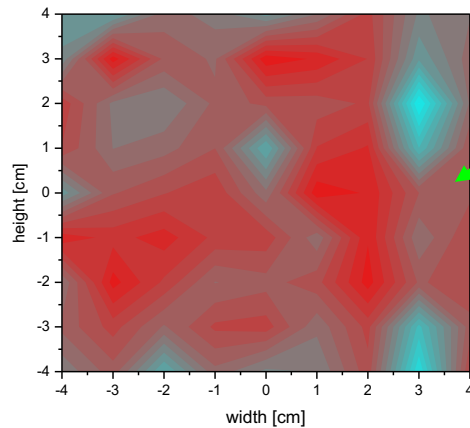


MCNPX results

9x9 tally grid 50 cm inside of first collimation



9x9 tally grid at collimation entrance



energy range: 1eV - 0.3 meV (200 bins) – 3000 h computing time

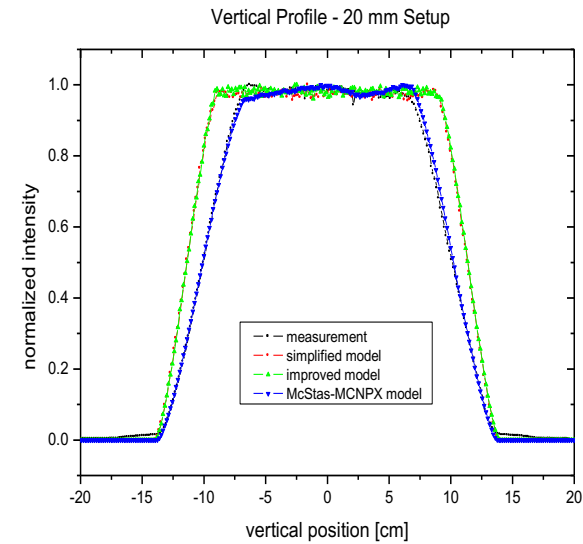
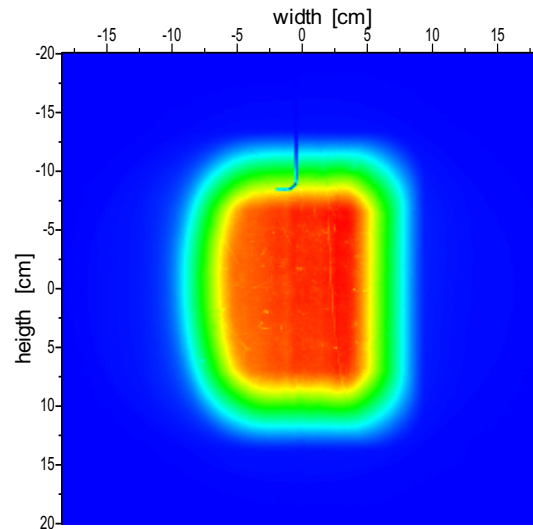
Neutron flux distribution at ICON middle position

Comparison of horizontal and vertical beam profiles at middle position (11.8m)

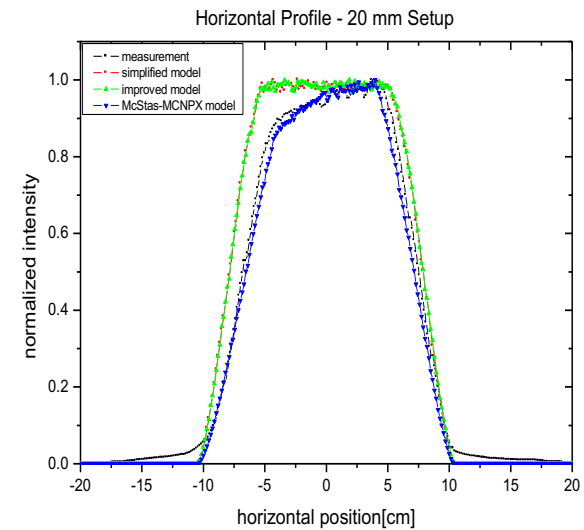
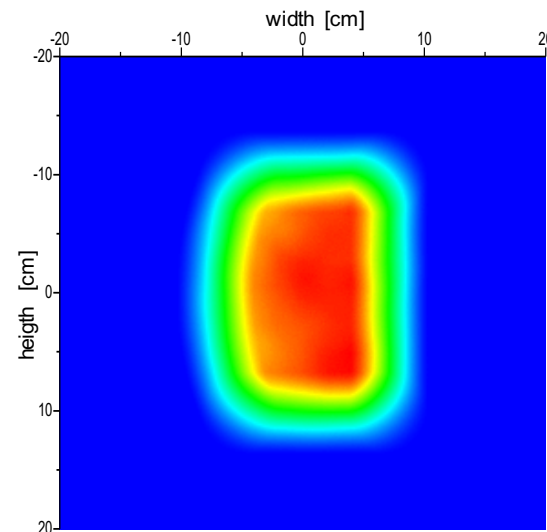
using the McStas-MCNPX model - 20 mm aperture



measurement



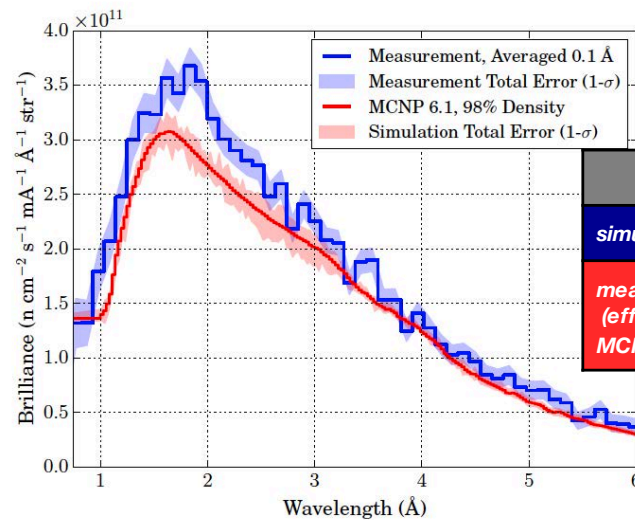
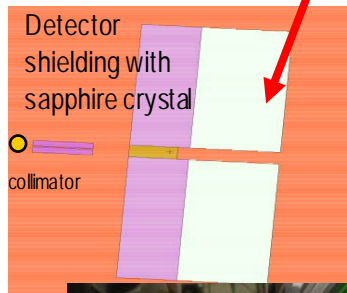
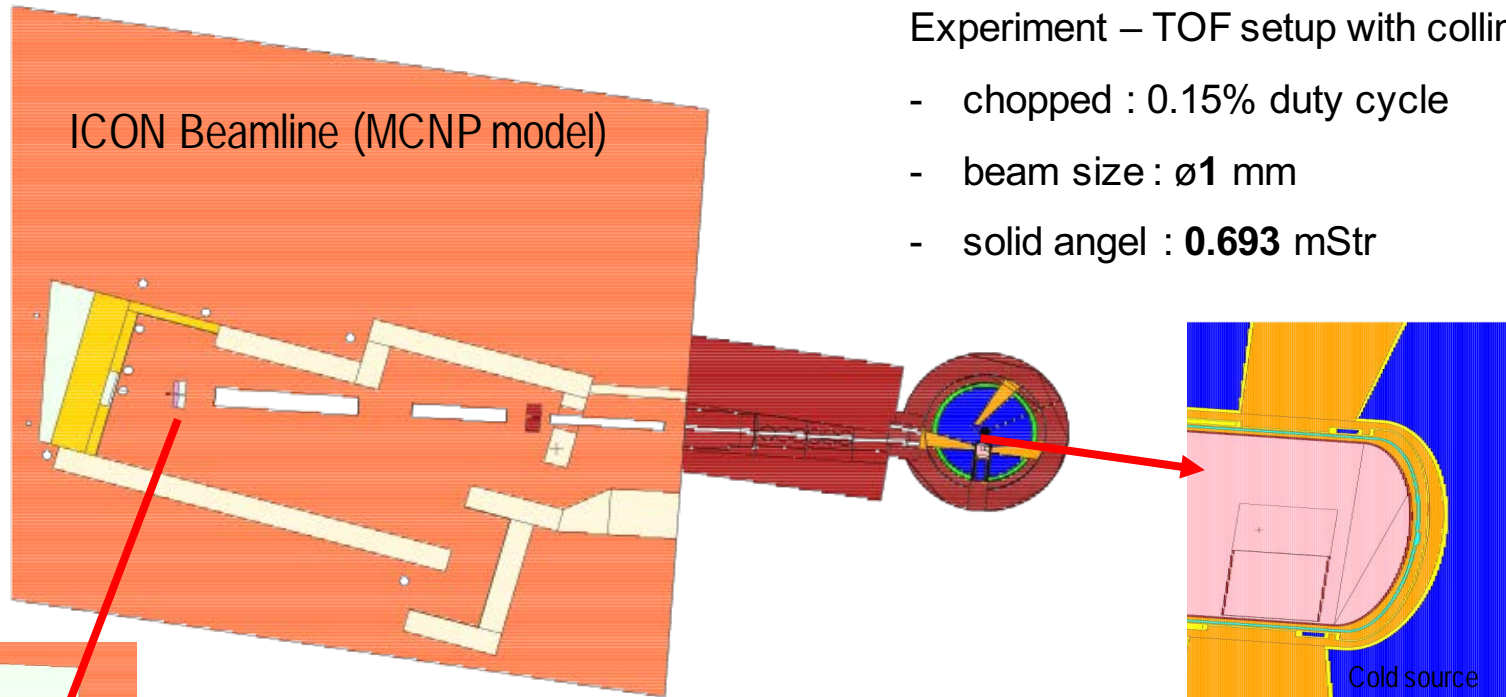
simulation



Measurement/simulation of cold source brightness at SINO

Experiment – TOF setup with collimator system

- chopped : 0.15% duty cycle
- beam size : $\varnothing 1$ mm
- solid angel : **0.693** mStr

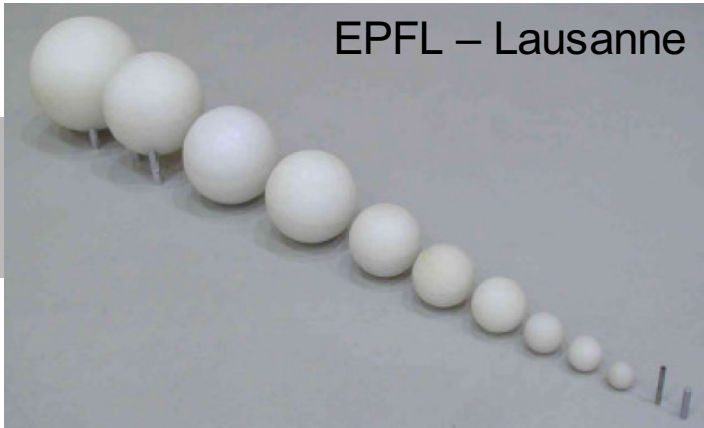


	peak factor
simulation(detailed)	1.0
measurement (efficiency by MCNP)	1.2

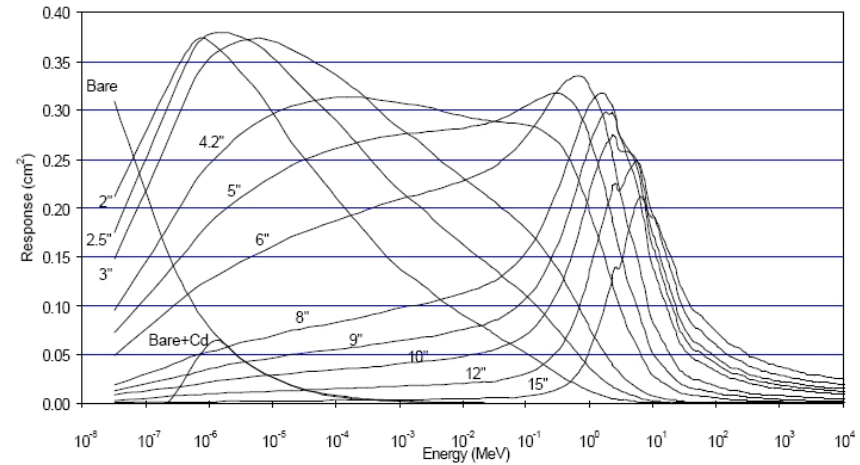


NIMA in preparation

Background measurements with Bonner Sphere Spectrometer

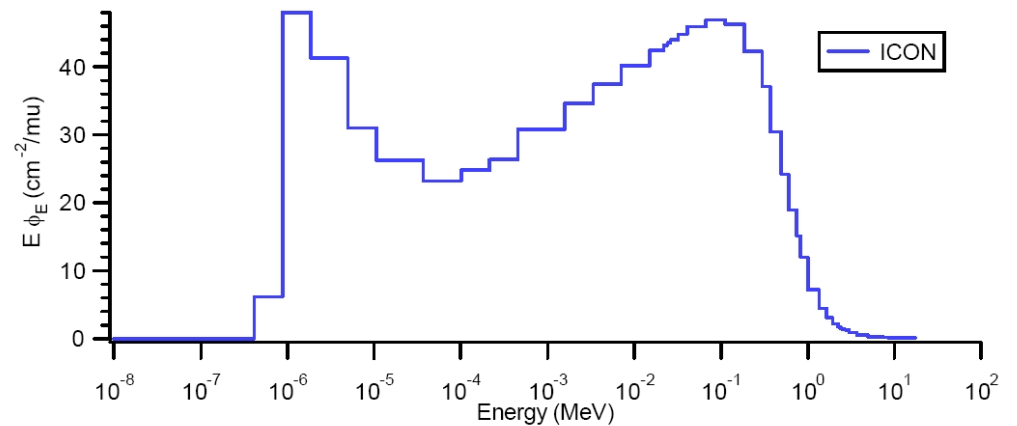
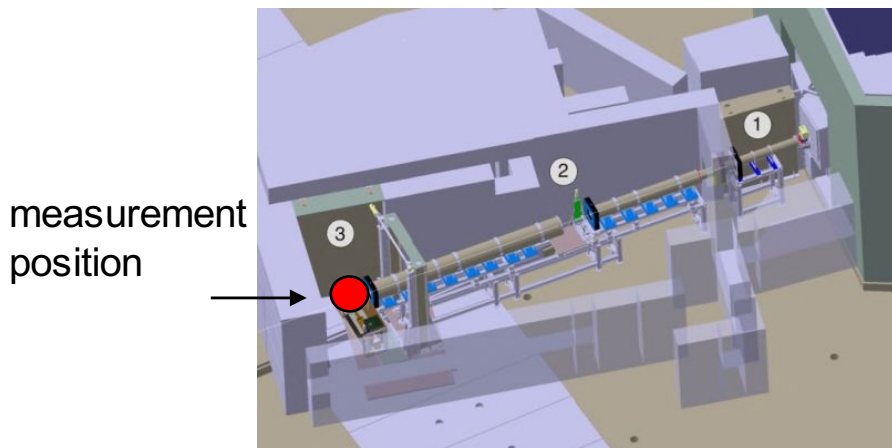


Bonner spheres spectrometer (BSS)



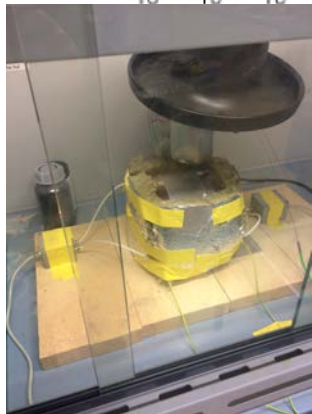
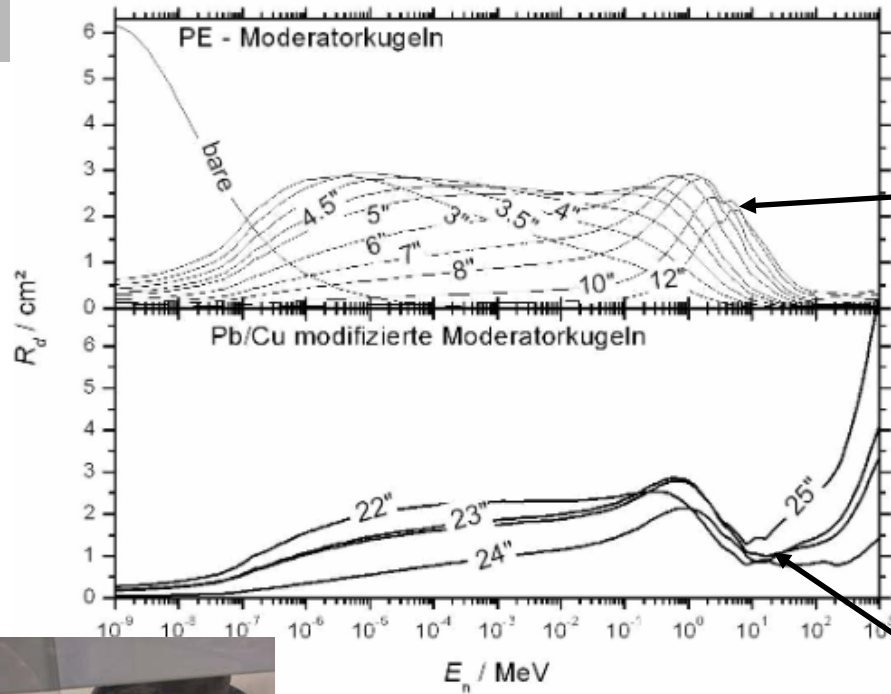
Response matrix of the Bonner spheres system

standard Bonner sphere system consists of a He-3 neutron detector and a set of 10 polyethylene spheres of diameters from 2 to 15 inches (each sphere has a different energy response)



Extension of BSS System

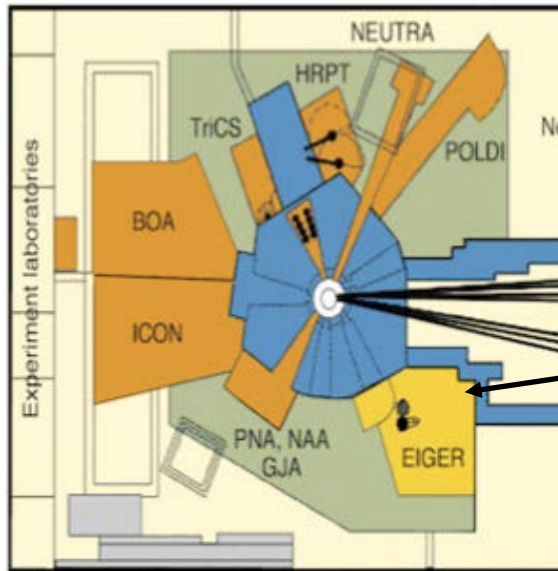
Extended energy range: > 2 GeV (interesting also for SwissFEL, ESS ...)



Index (i)	$d_{\text{PE,inside}}$	Material	d_{Inlay}	$d_{\text{PE,outside}}$
22"	3"	Pb	5"	7"
23"	4"	Cu	5"	7"
24"	4"	Pb	5"	7"
25"	4"	Pb	6"	8"

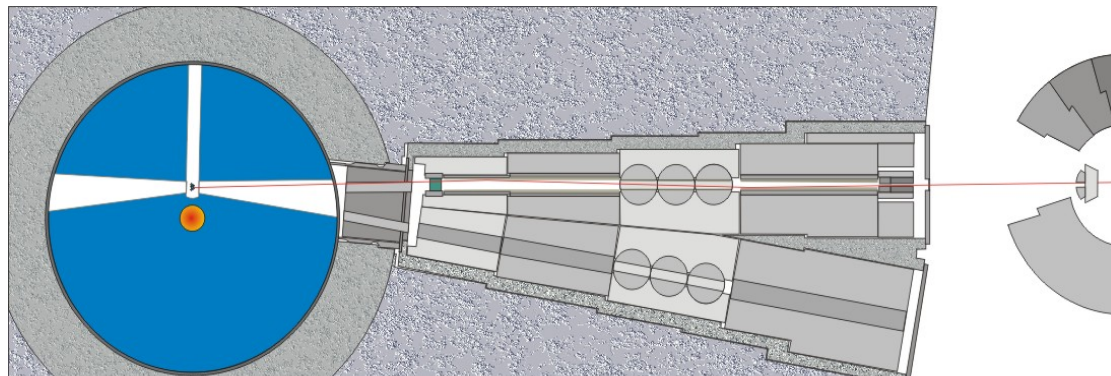
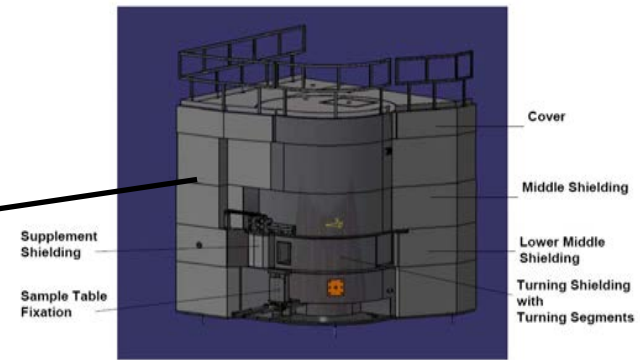
Shielding Design for the Triple Axes Spectrometer EIGER

- Design of a non-magnet shielding with a maximum thickness of 85 cm

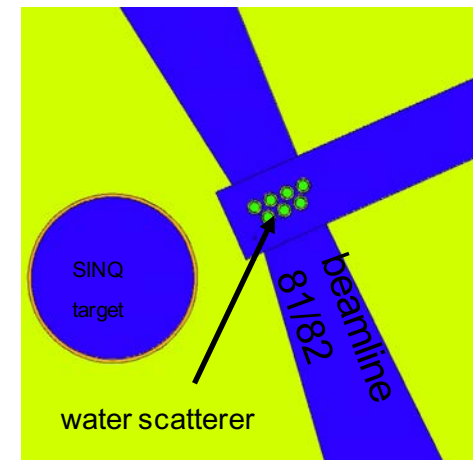


Thermal spectrometer EIGER at SINQ

EIGER Monochromator shielding design



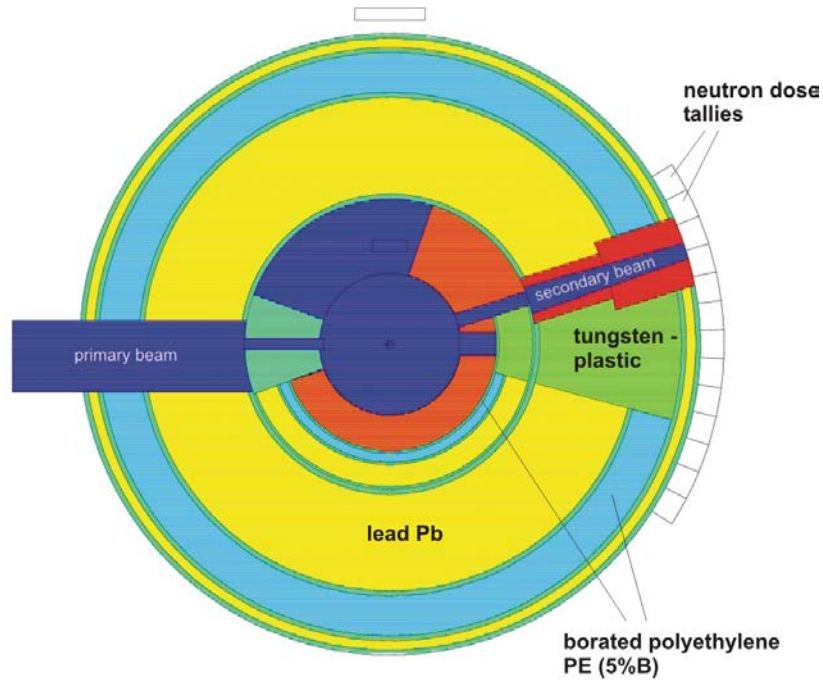
Primary beamline layout



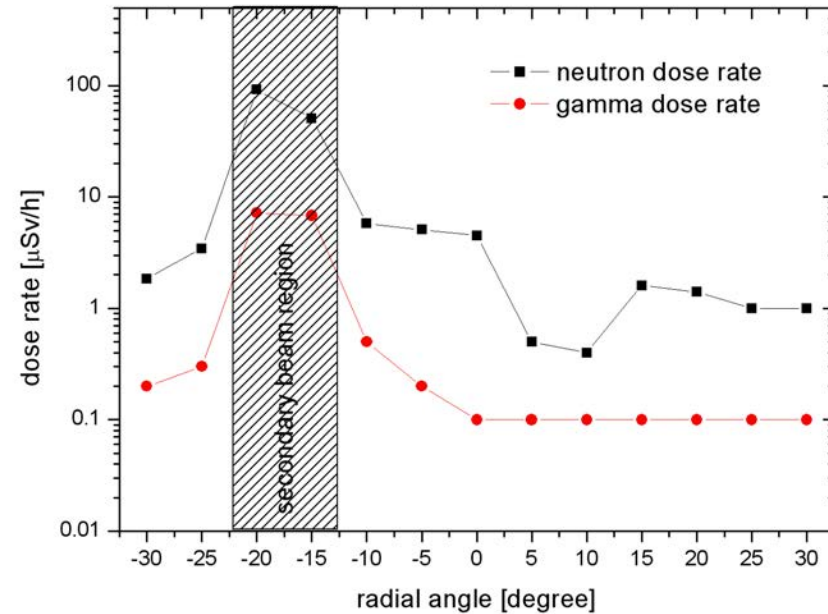
MCNPX model

Gamma and Neutron Dose Rates behind the Shielding

- dose rate $< 10 \mu\text{Sv/h}$ with a shielding thickness of 85 cm



MCNPX geometry layout for the shielding calculations – 17° position



Calculated gamma and neutron dose rate distribution at the outer surface of monochromator shielding – 17° position

- developing/simulations of different compositions of heavy concrete (non-magnetic) with a density of approx. 5.1 g/cm^3
- developing a special material composition (tungsten/paraffin) for absorbing (slowing down) fast neutrons

Heavy concrete developments

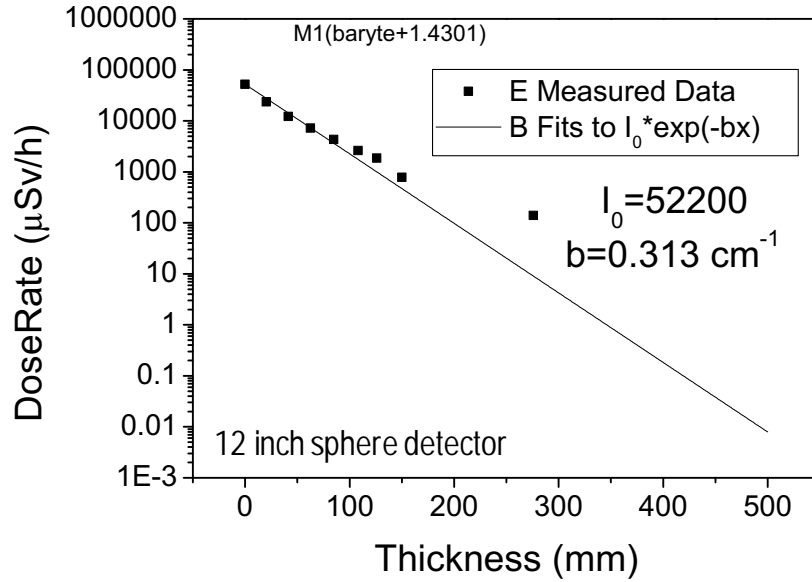
- 7 different concrete compositions were tested and simulated (all are special PSI compositions)
- non-magnetic / magnetic samples for different applications
- Sample 1: special efforts - stainless steel balls with different sizes and thermal treatment
- In addition **Sample 1** includes as mineral Barite – very good gamma shielding material

calculated density [kg/dm ³]	5.000	4.800	4.800	4.800	4.800	4.800	4.800
effective measured density [kg/dm ³]	5.200	4.850	4.770	4.880	4.860	4.890	4.740
	sample 1	sample 2	sample 3	sample 4	sample 5	sample 6	sample 7
	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
Barite							
Magnetite							
Hematite							
Fe-granulate St. 37							
Fe-granulate St. 37							
Fe-granulate, stainless , 1.4301							
Boron-carbide 5%							
measured attenuation factor [1/cm]	0.313	0.213	0.204	0.213	0.208	0.217	0.207

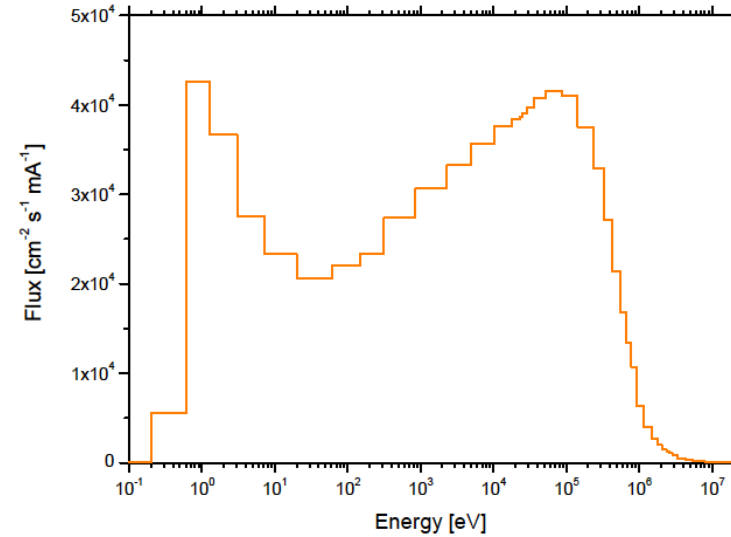
Comparison: normal concrete: < 0.13 cm⁻¹

Heavy concrete Measurements

Attenuation for the fast Neutrons



Incoming spectrum at ICON beamline



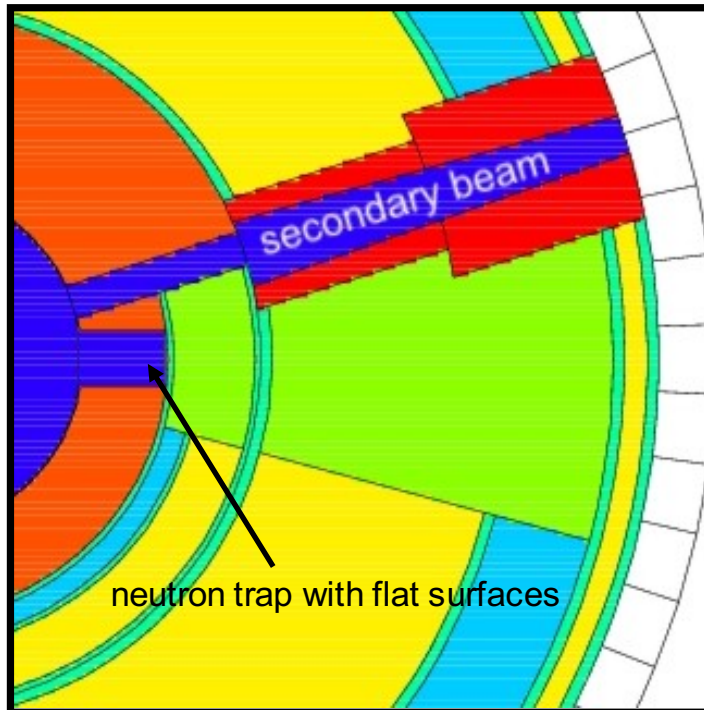
Sample with strong steel collimator (1m)



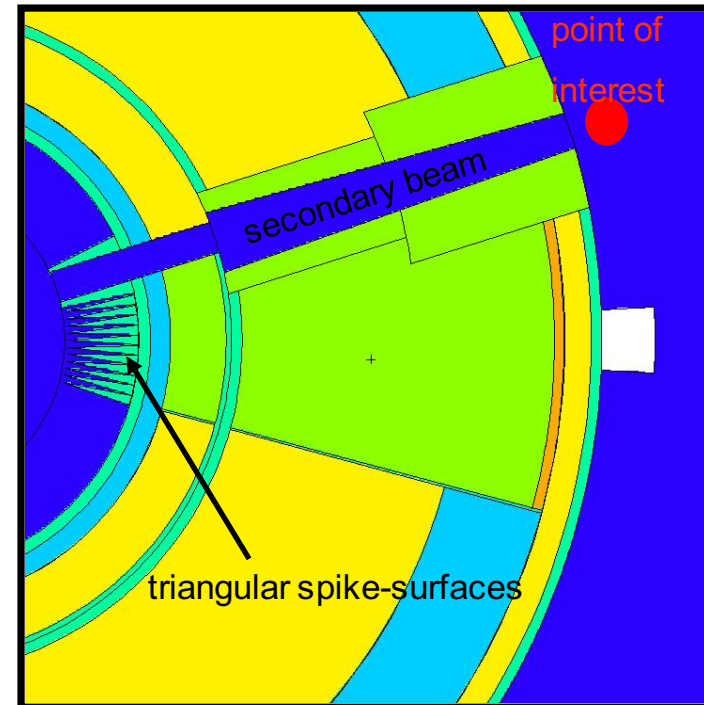
Shielding for background reduction was needed

Neutron Trap Design for Eiger

- design reduces the background by around a factor of 2



Original neutron trap proposal



Optimized neutron trap

- triangular volume is filled with B_4C powder
- in addition Eiger uses a Sapphire filter for background reduction

Neutron Filter Data for MCNPX/McStas

Sapphire filter setup on BOA



Sapphire crystals
within shielding

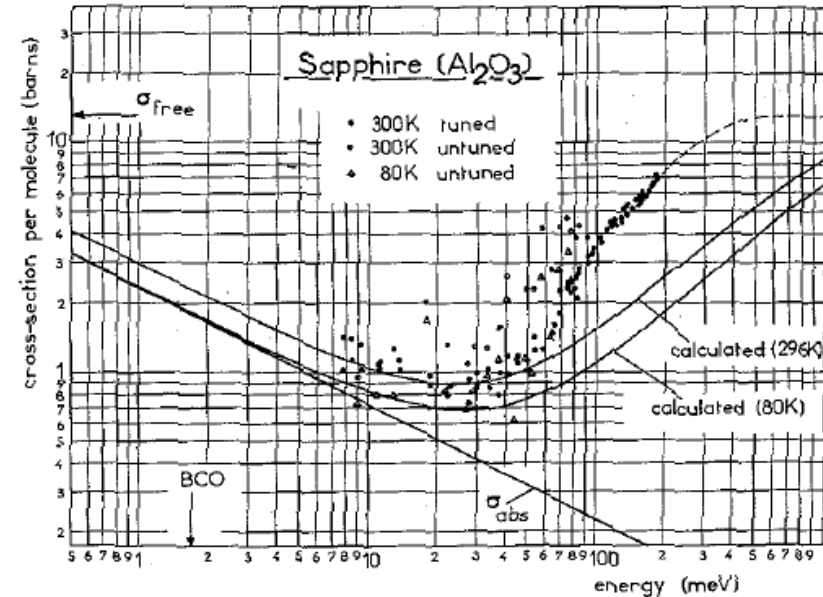


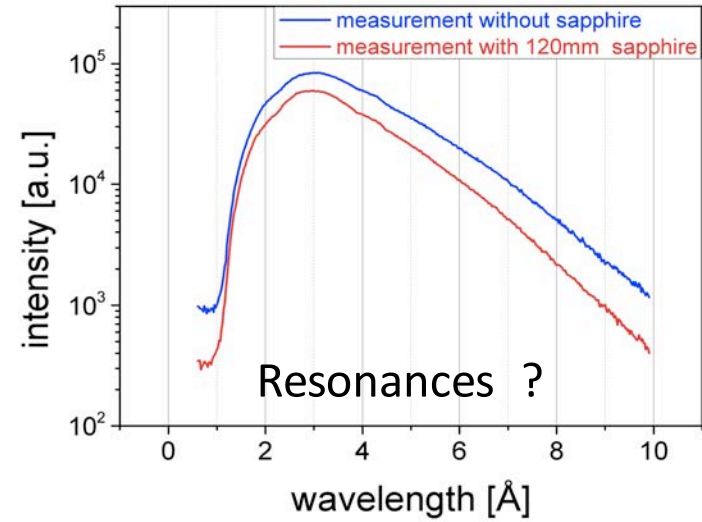
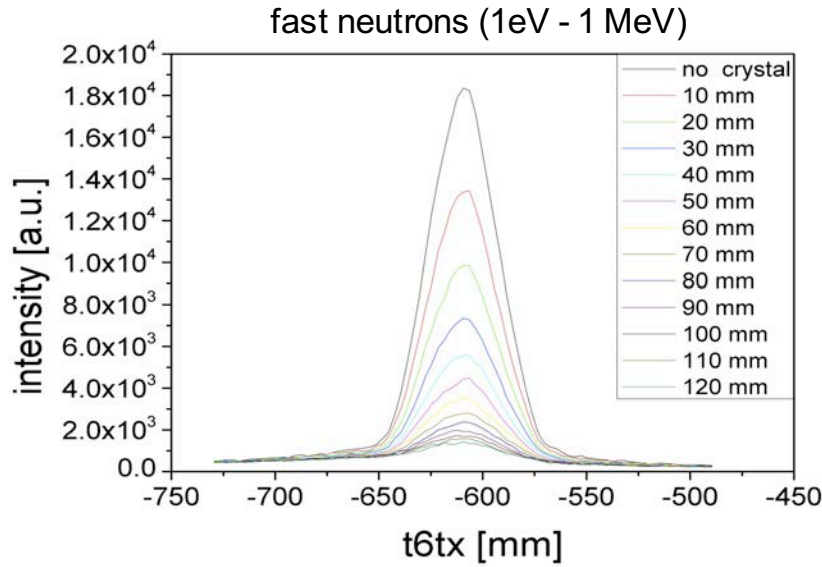
Fig. 5. Total cross-section of sapphire. The experimental data are taken from ref. 6.

A.Freund NIMA 213 (1983) 495-501

Samples from three different suppliers
(Stettler – 4 crystals; Korth – 4 crystals; Kyburz – 4 crystals)

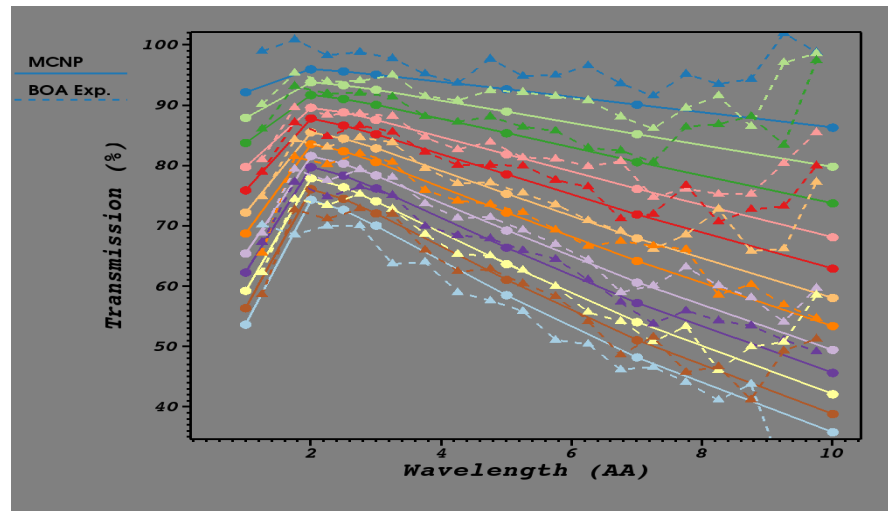
- Dimension: 26 mm x 26 mm x 10 mm
- Orientation: c-plan
- Precision of orientation: 1 deg

Sapphire - Neutron Filter Measurements at BOA



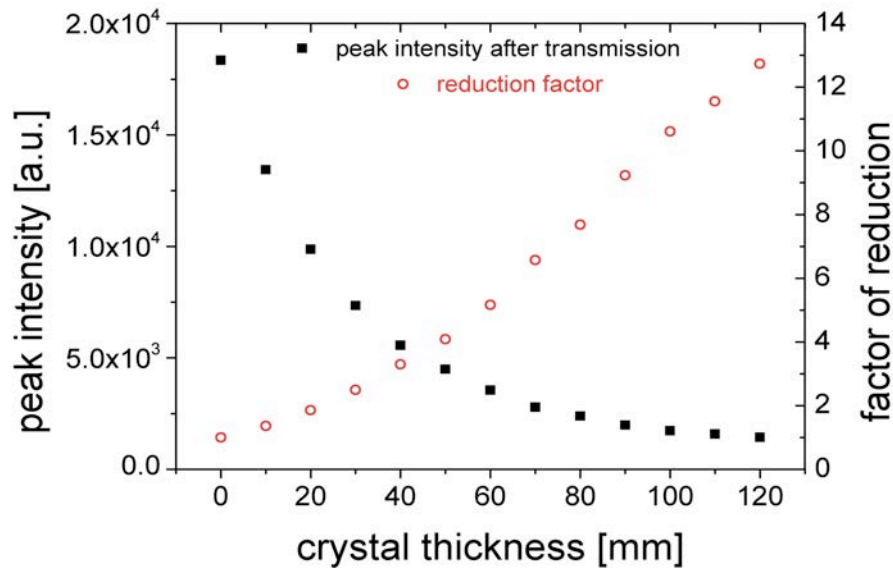
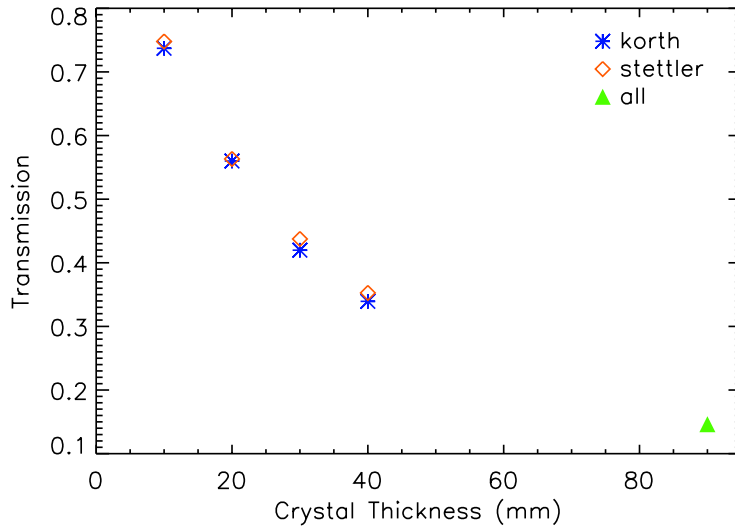
fast neutron flux can be reduced by a factor of 12.5 (120 mm sapphire) – Peak Intensity

cold neutron flux is reduced by 30 – 60% (120 mm sapphire)



Comparison MCNPX simulations and Measurements

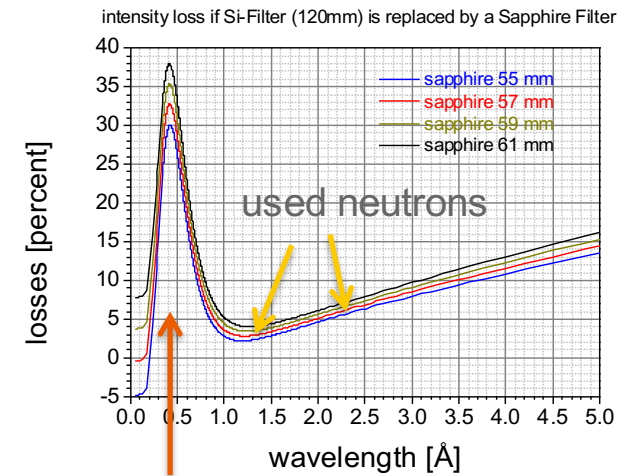
Sapphire - Neutron Filter Measurements at BOA



- Quality of the crystal are comparable between suppliers
- Signal-to-noise can be chosen depending from the application
- Performance of the crystals is relative non-sensitive to the alignment (< 5% within 1 deg)

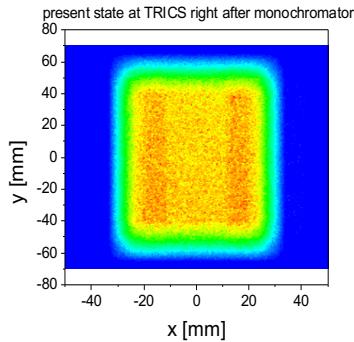
- fast neutron background reduced by a factor of 3
(only primary instrument)
- minimal intensity loss for the used thermal neutrons (1.2 & 2.4 Å)

Sapphire-Filter vs. Si-Filter

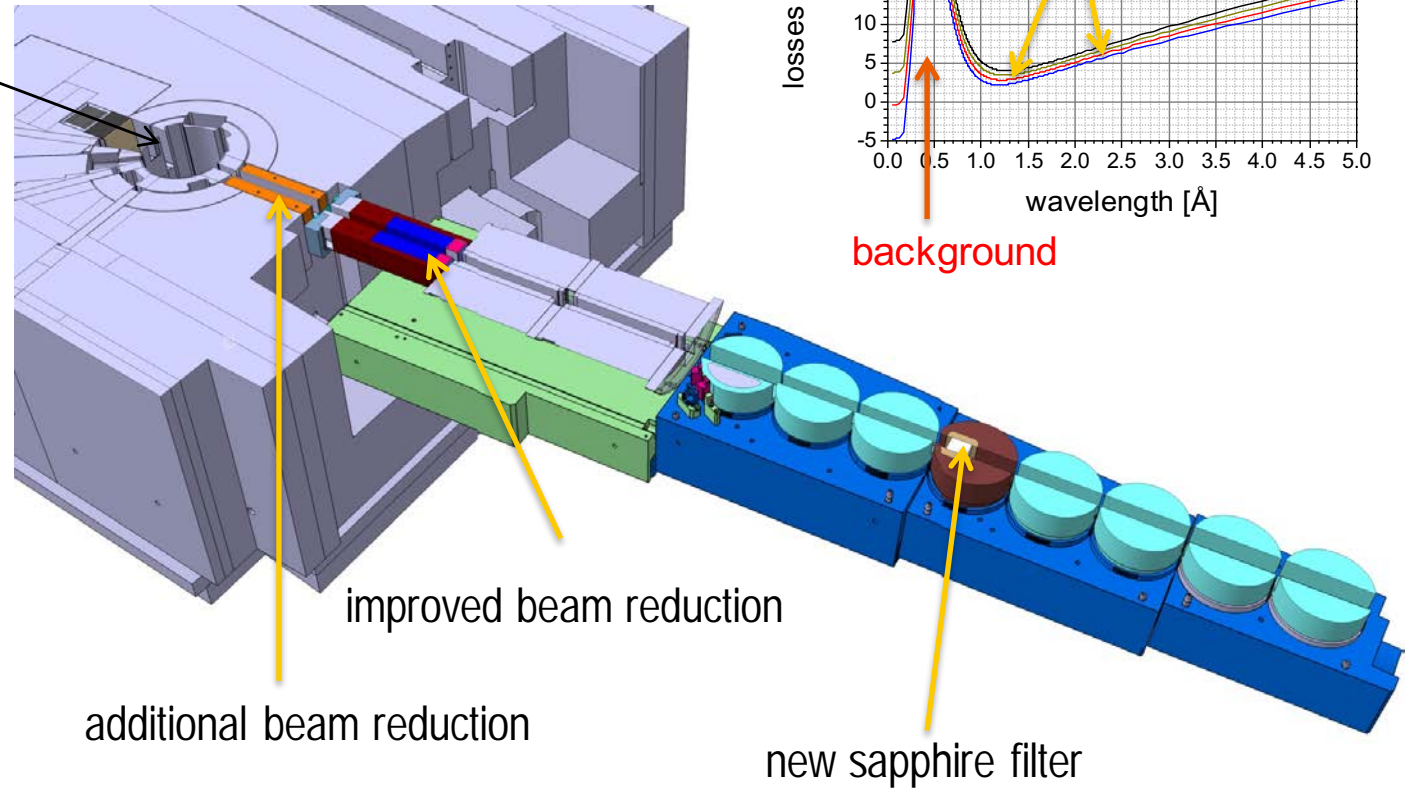
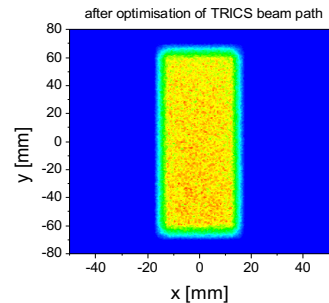


Monochromator

OLD
47.5 cm²
(120 cm²)

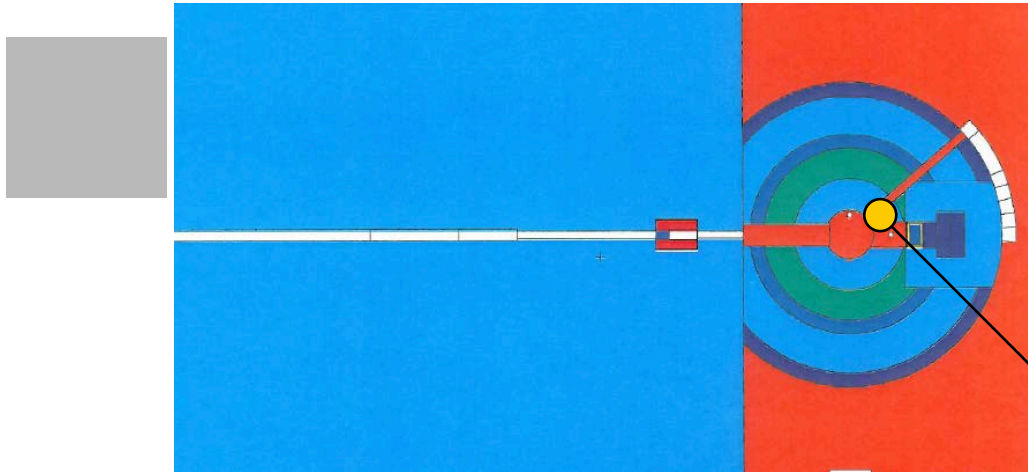


NEU
39 cm²



TRICS to Zebra

Reference model (TRICS)



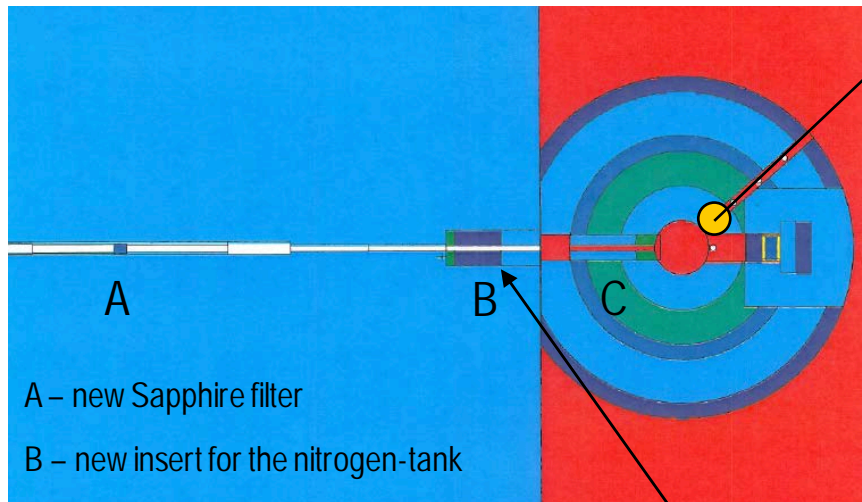
Dose Rates (DR) are valid for 1500 μA – SINO power

n-flux (n/s/cm ² / mA)	n-DR (mSv/h/mA)	g-DR (mSv/h/mA)
$2.4 \cdot 10^5$	4.2 +/- 0.7	0.55 +/- 0.1

Point of Interest

(entrance to secondary beam opening)

ZEBRA upgrade model



A – new Sapphire filter

B – new insert for the nitrogen-tank

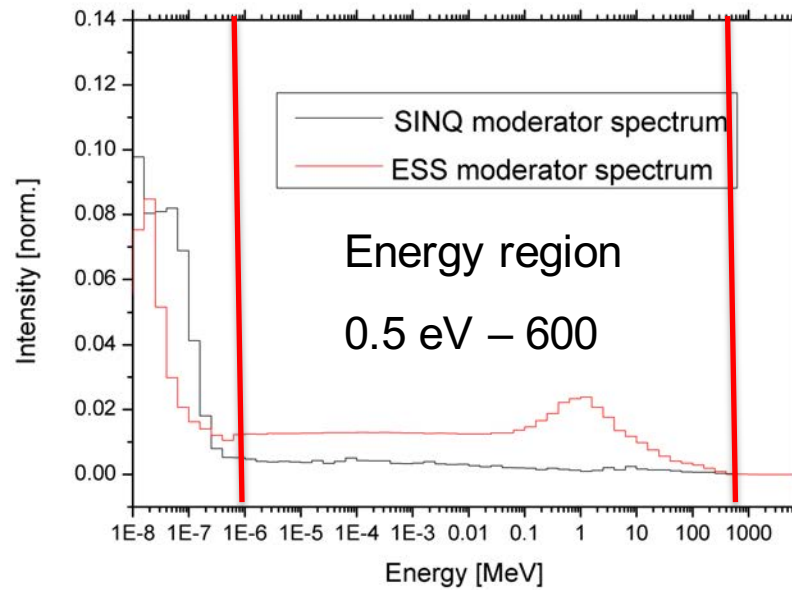
C – new insert within Monochromator shielding

n-flux (n/s/cm ² / mA)	n-DR (mSv/h/mA)	g-DR (mSv/h/mA)
$1.25 \cdot 10^5$	1.39 +/- 0.3	0.57 +/- 0.2

Collimator: B4C/borated PE/ borated Steel

Comparison – Source Spectra

Comparison SINQ / ESS – Nov. 2013

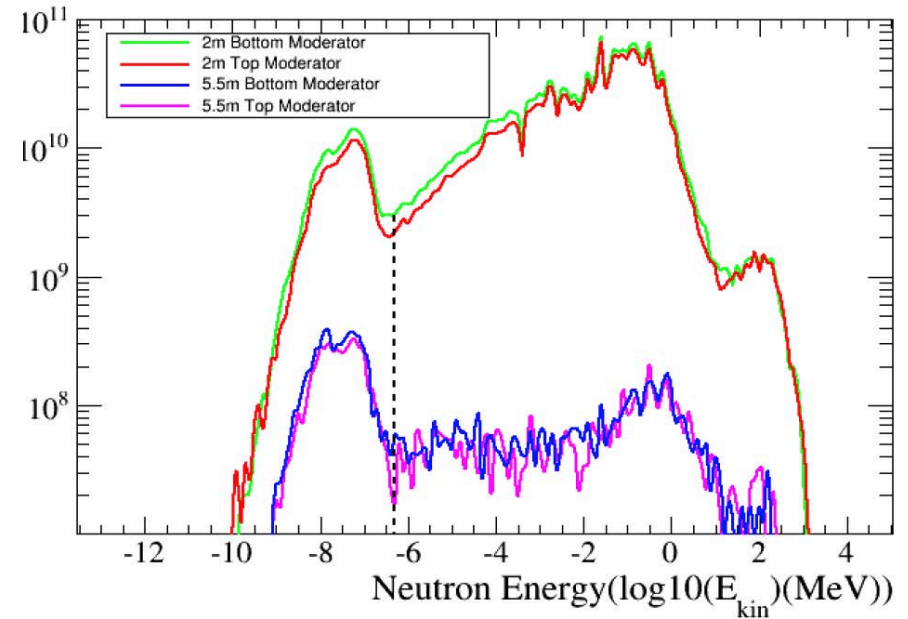


neutron spectrum inside cold moderator

SINQ ratio: 8:1 (thermal to fast)

ESS ratio: 1:1 (thermal to fast)

ESS – April 2016 (bunker report)

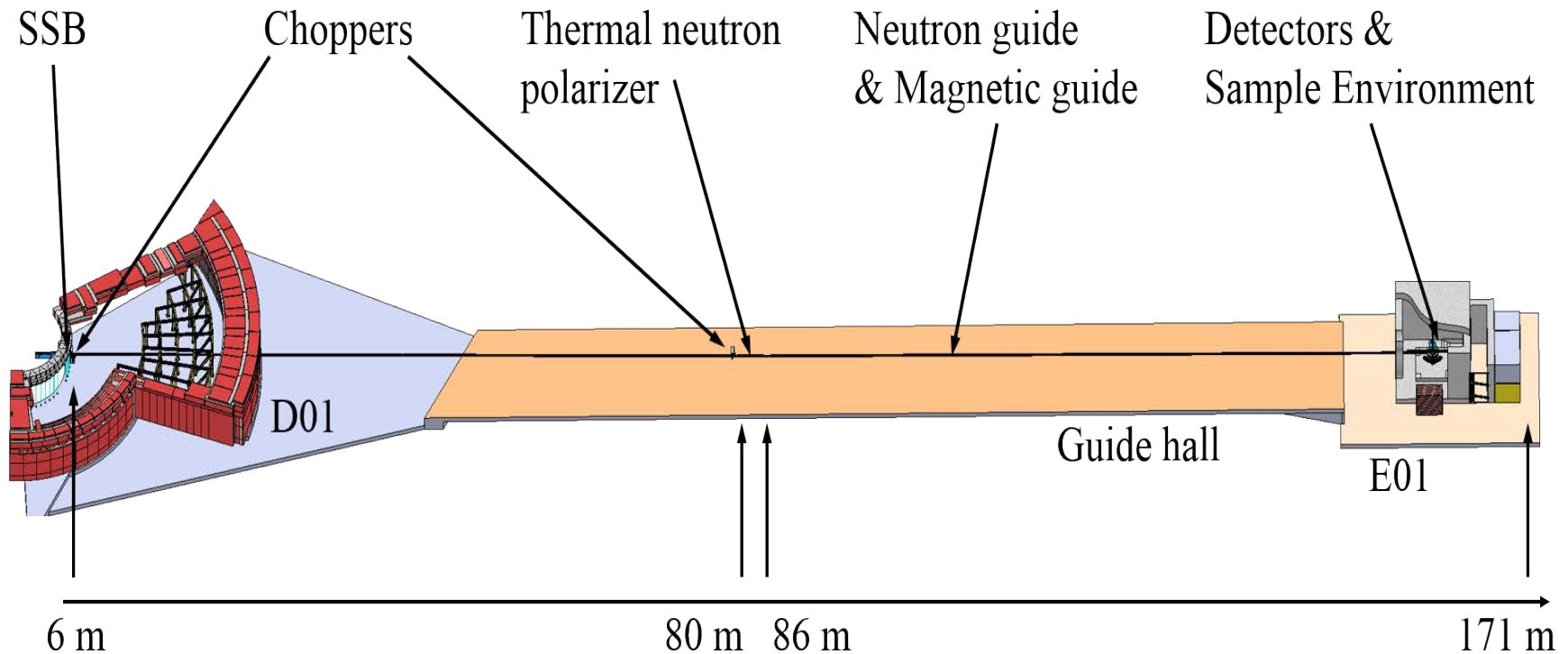


neutron spectrum in front of the beamports

ESS ratio: about 1:5 (thermal to fast)

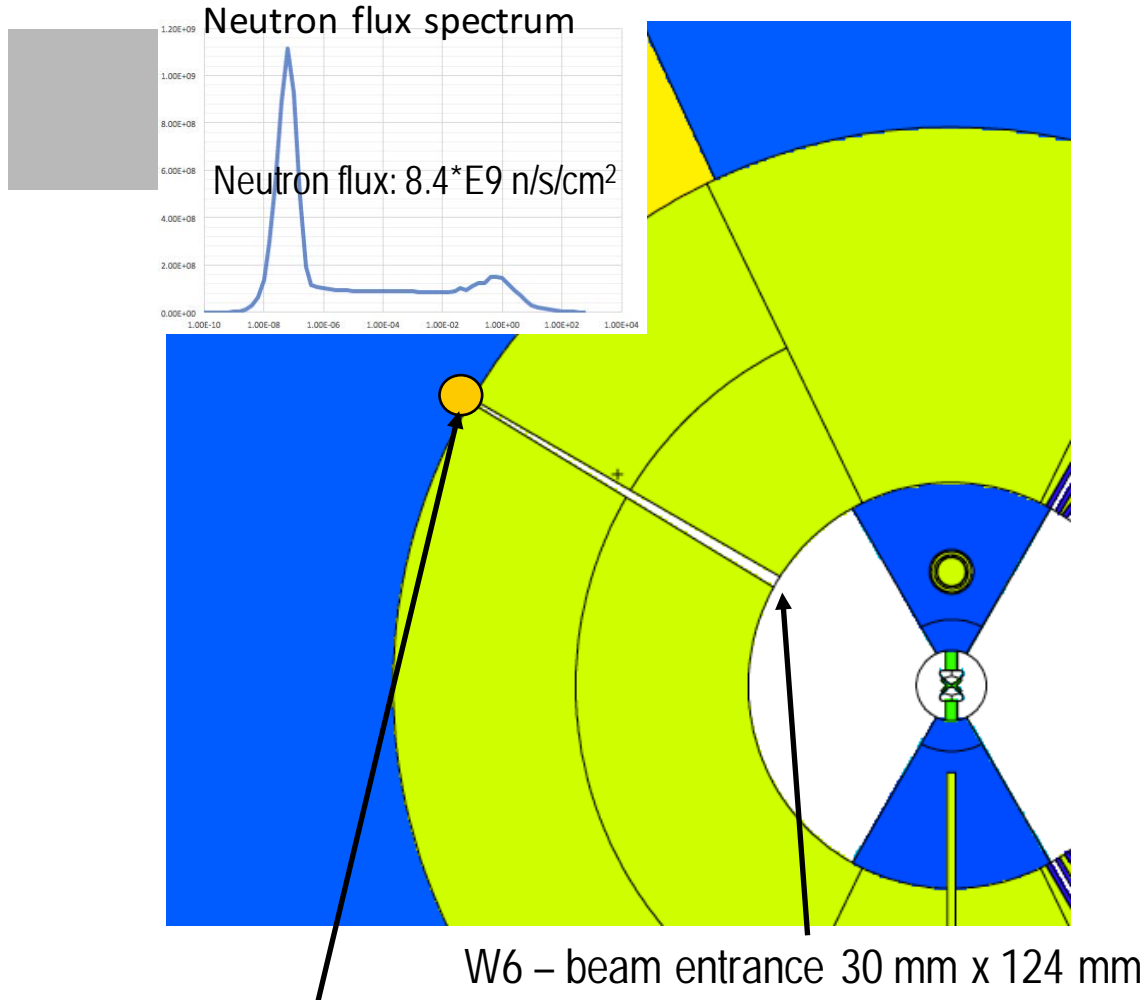
MAGiC Beamline Layout

Partners: LLB, FZ-Jülich and PSI



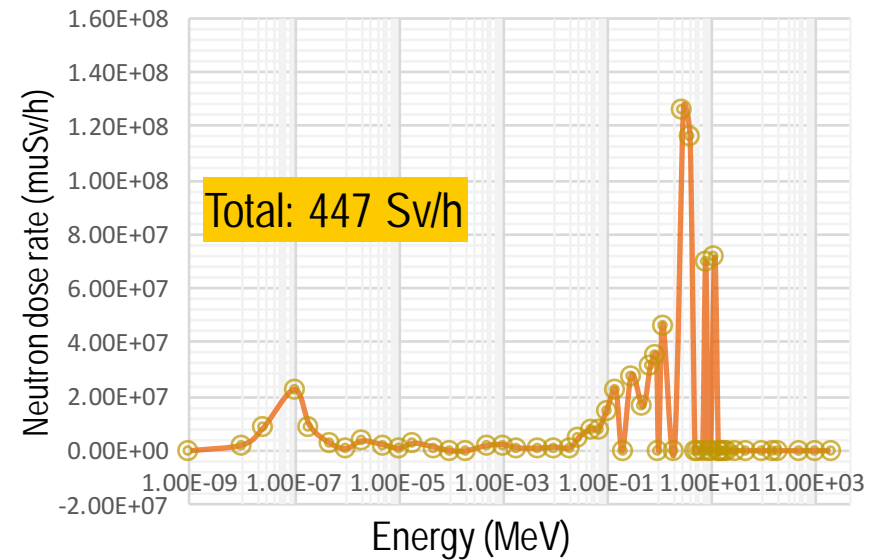
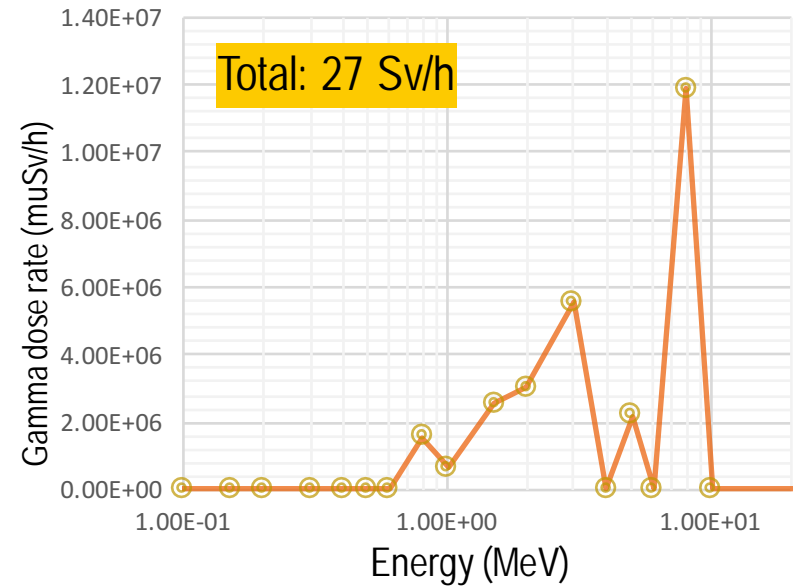
- polarized single crystal diffractometer at beamport W6
- Cold & thermal beam extraction
- Elliptic guide system with a kink at 80 m

Neutron and Prompt Gamma Dose Rate at 5.5 m



W6 – beam entrance 30 mm x 124 mm

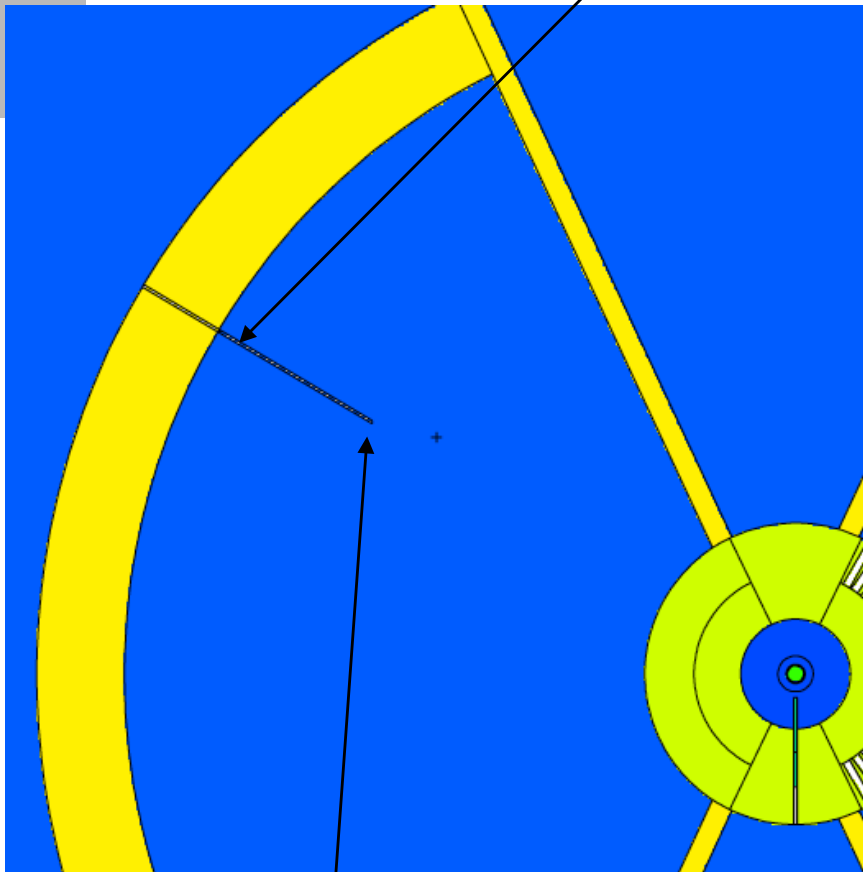
W6 – beam exit 30 mm x 38 mm



In comparison SINQ: around 15 Sv/h

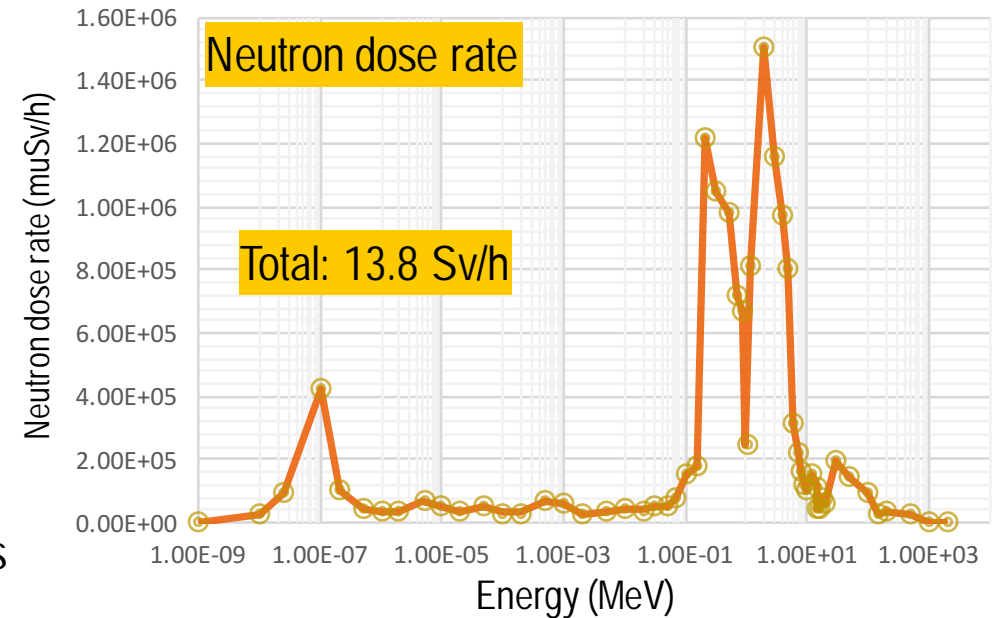
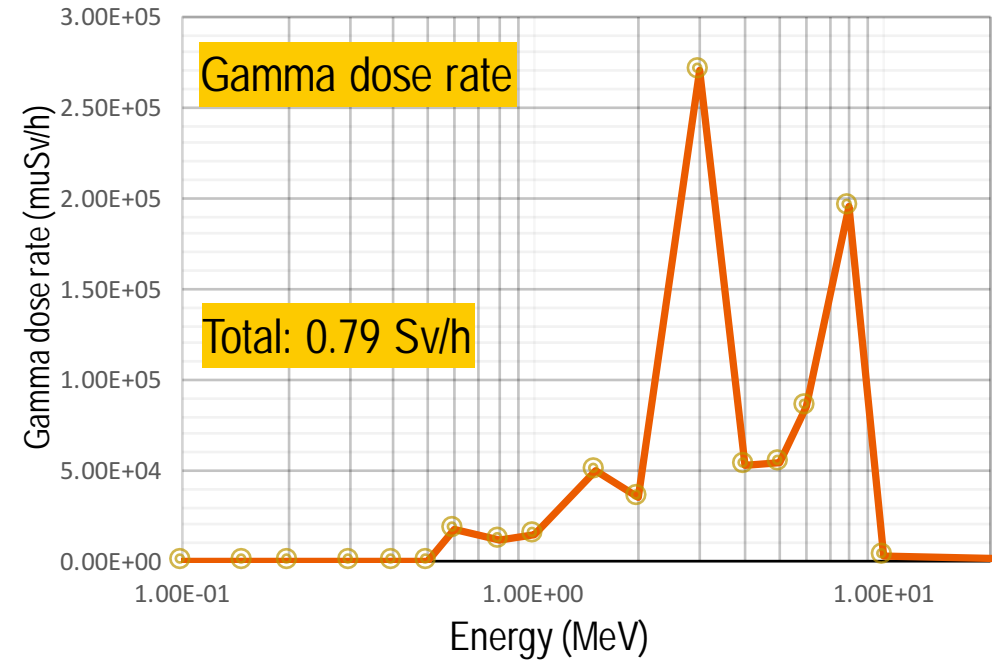
Neutron and Prompt Gamma Dose Rate at 24.5 m

Dose rates @ 24.5m

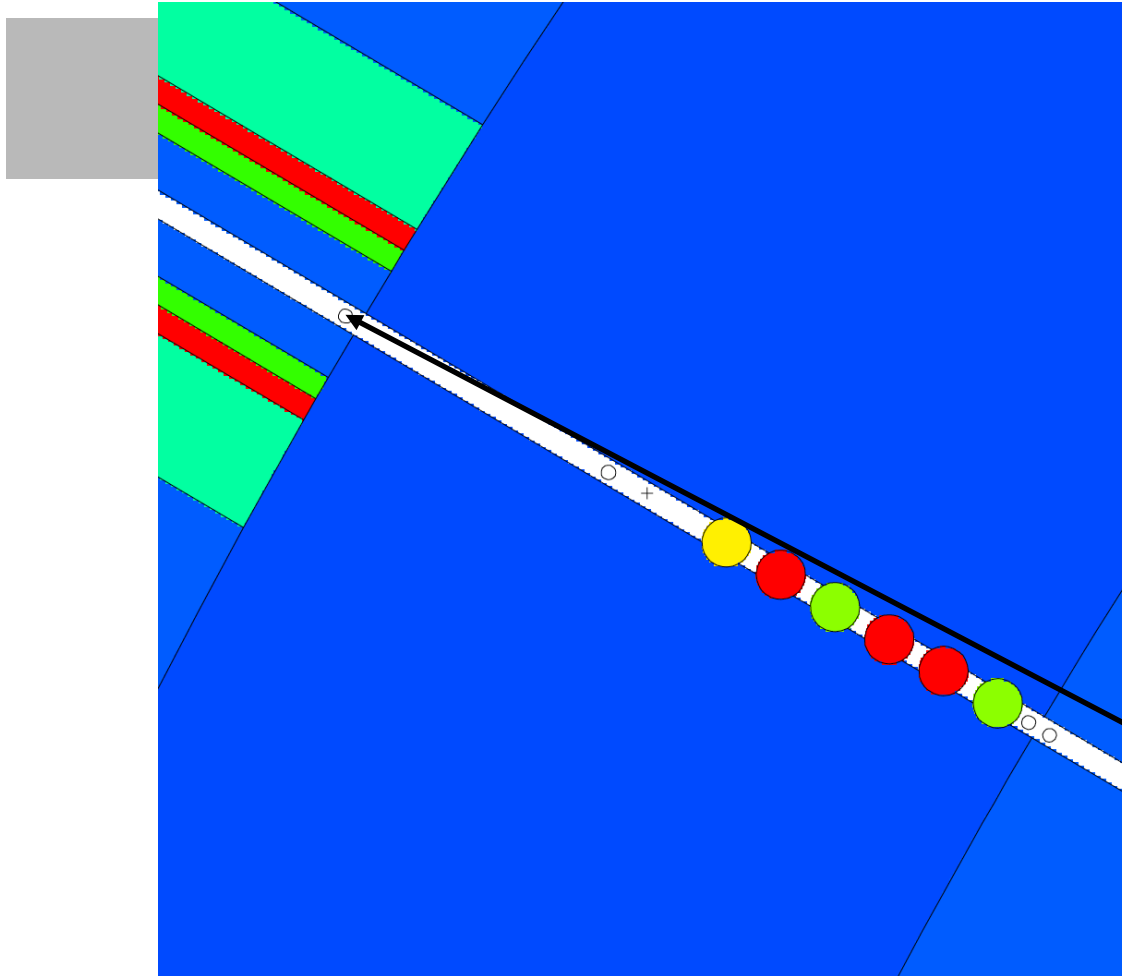


W6 – vacuum channel 10 cm x 10 cm (0.5 deg tilt)

New SDEF-card defined for guide shielding calculations



High Energy Shutter



6 drums are positioned within the neutron bunker wall.

Drum Sequence:

1. Borax (50% epoxy / 50% B₄C)
2. Standard steel
3. Standard steel
4. Borax
5. Standard steel
6. Tungsten/parafin (density 11.8 g/cm³)

Effective thickness: each drum 20 cm

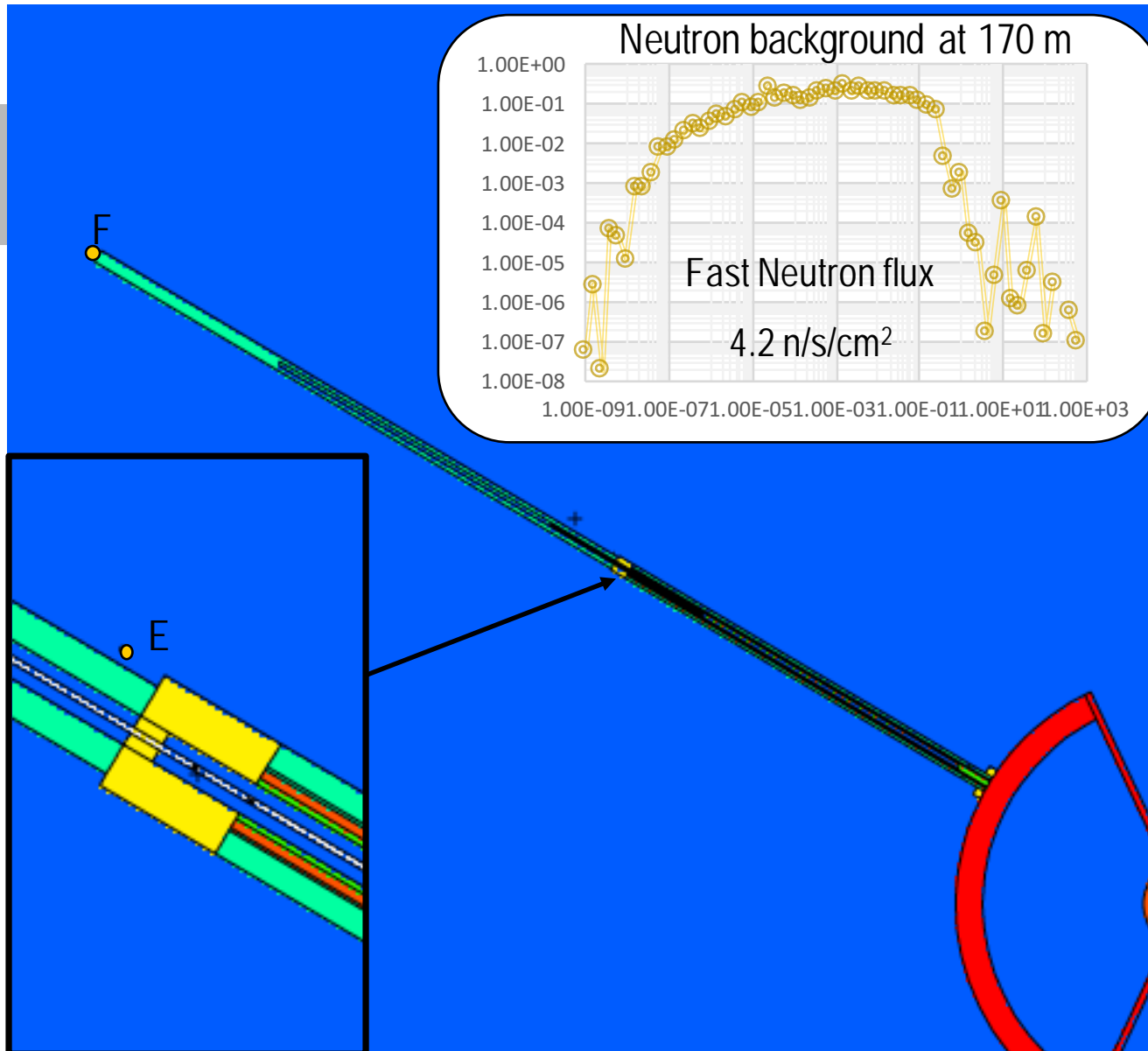
n-dose rate: 15.2 μ Sv/h

g-dose rate: 0.5 μ Sv/h

(only prompt gammas from the drums)

N-Dose rate can be reduced more by replacing steel with tungsten drums.

Neutronic Background at Sample Position



Shielding around guide behind 77m:

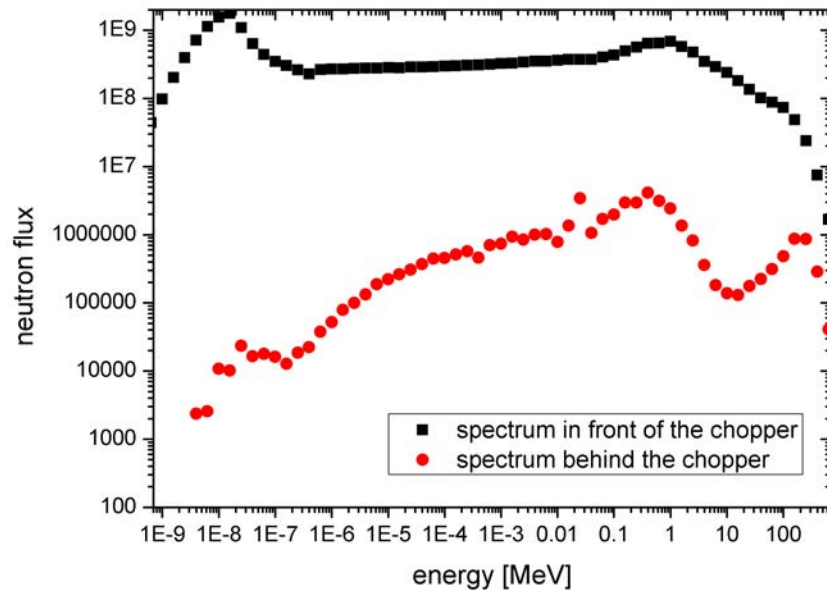
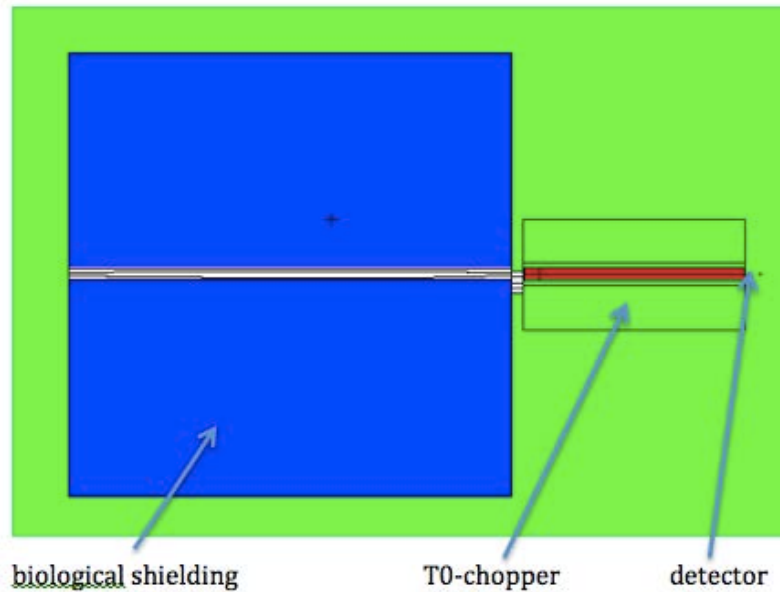
- 2m heavy concrete with vacuum tube belt
- 75m standard concrete (0.5 m thickness)

Neutron dose rates

@80m outside guide shielding
tally E: 1.3 μ Sv/h

@150m inside guide shielding
tally F: 0.2 μ Sv/h

T0 – Chopper thickness



Tungsten

Thickness (in cm)	0 (in front of the chooper)	50	100	200
Dose rate γ	47.1 Sv/h	8.3 mSv/h	1.9 mSv/h	0.47 mSv/h
Dose rate n	8.1 kSv/h	2.7 Sv/h	0.54 Sv/h	0.12 Sv/h
Total neutron flux ϕ (in n/cm ² /s)	2.3E10	3E6	6.3E5	2.6E5

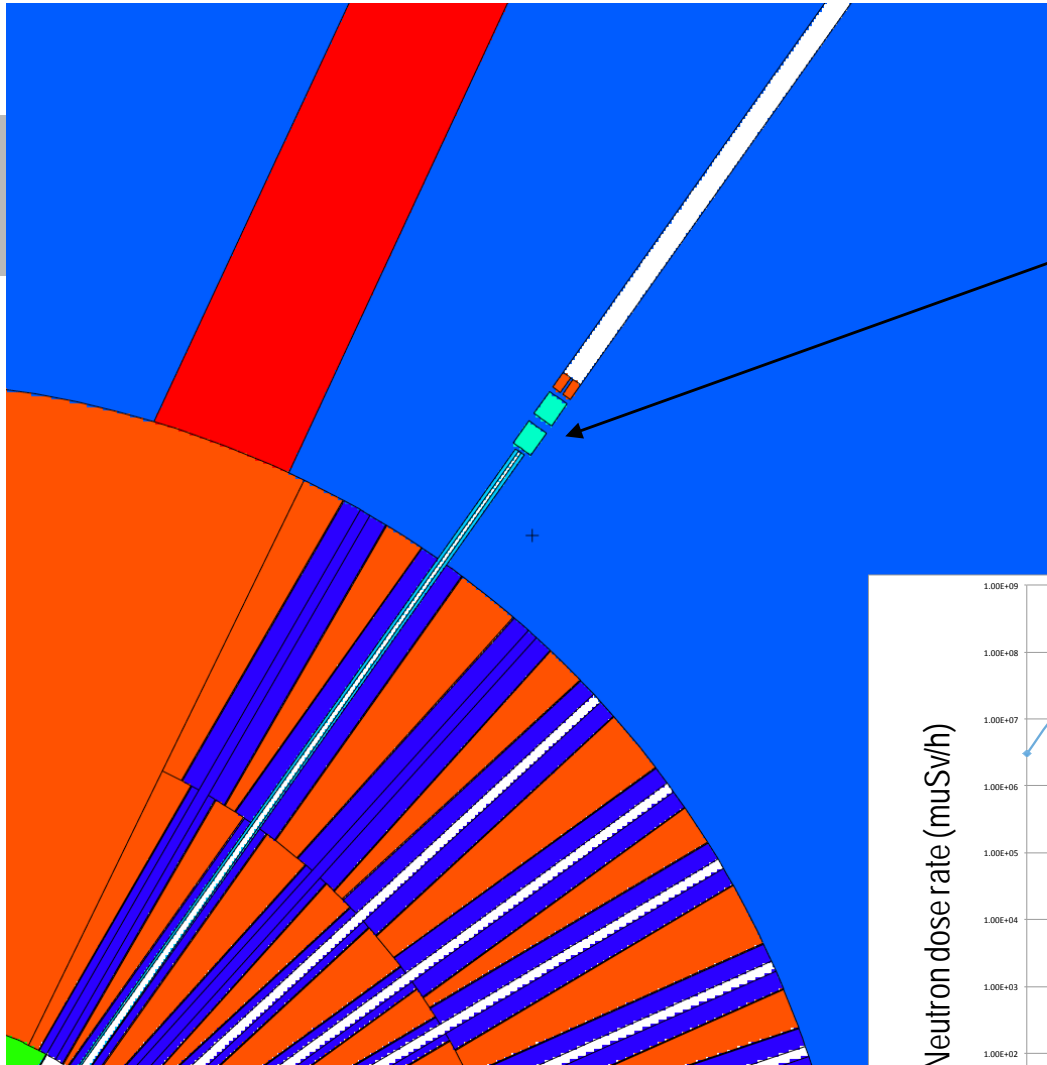
3-4 times better as St37

Inconel 650

Thickness (in cm)	0 (in front of the chooper)	50	100	200
Dose rate γ	47.1 Sv/h	16.7 mSv/h	2.5 mSv/h	0.61 mSv/h
Dose rate n	8.1 kSv/h	5.1 Sv/h	0.55 Sv/h	0.12 Sv/h
Total neutron flux ϕ (in n/cm ² /s)	2.3E10	4.8E6	7.6E5	2.45E5

Slightly worse as tungsten

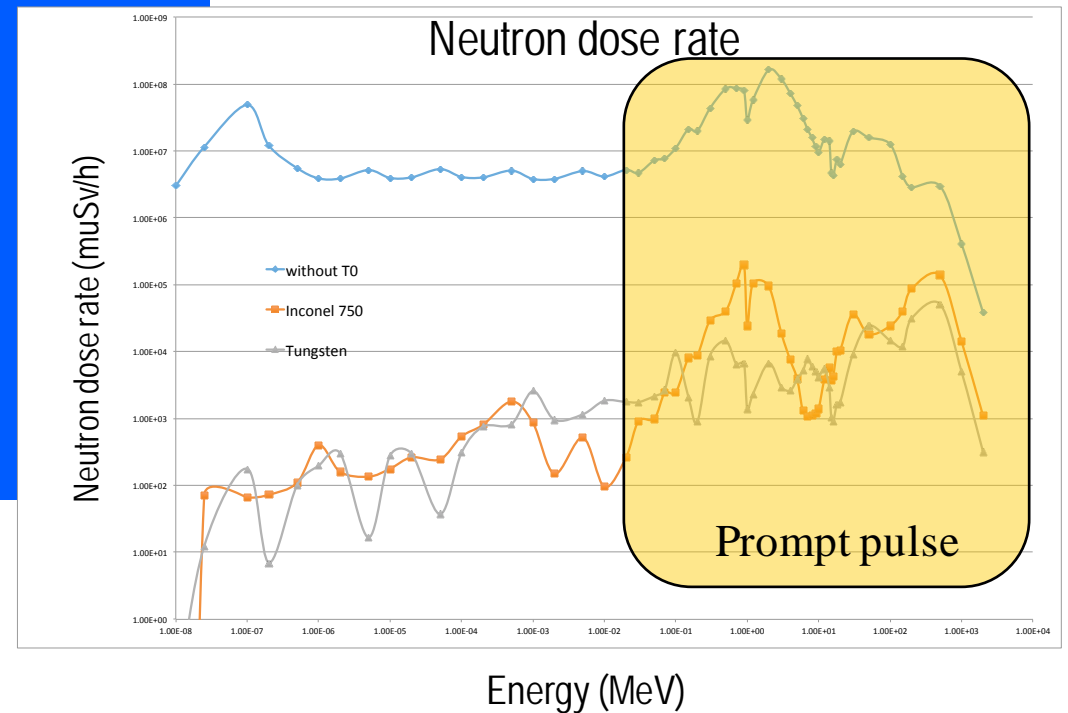
TO - Chopper



Position: @ 6.25 m

Materials:

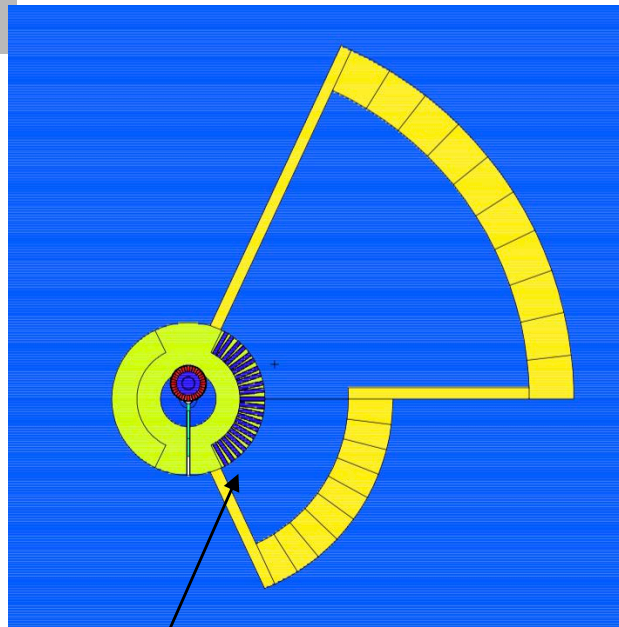
- Inconel 750
- Tungsten



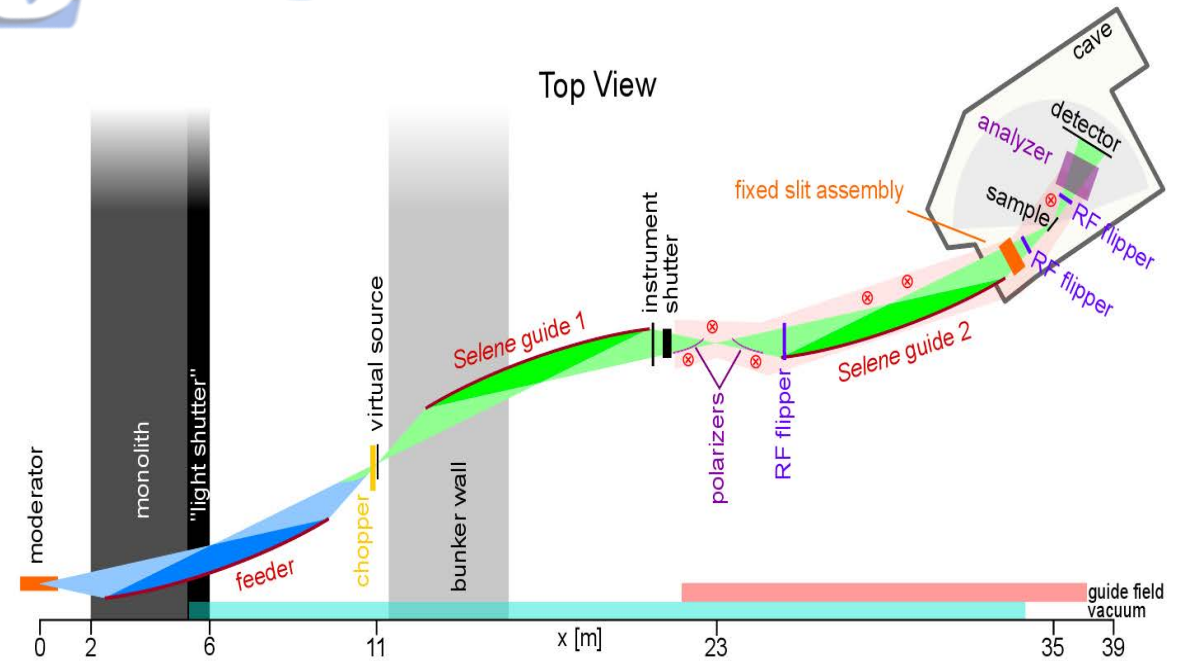
@ 1 MeV -> reduction factor >100 (Inconel)

@ 1 MeV -> reduction factor >500 (Tungsten)

Estia

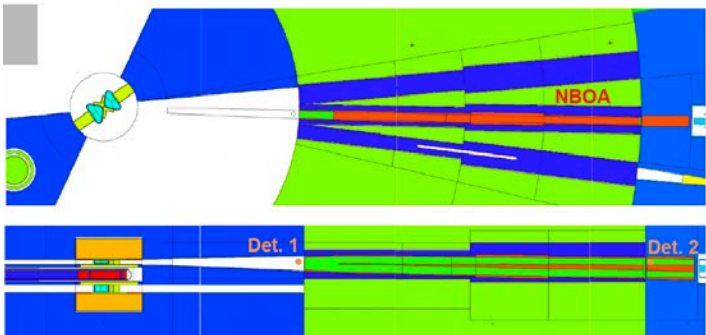
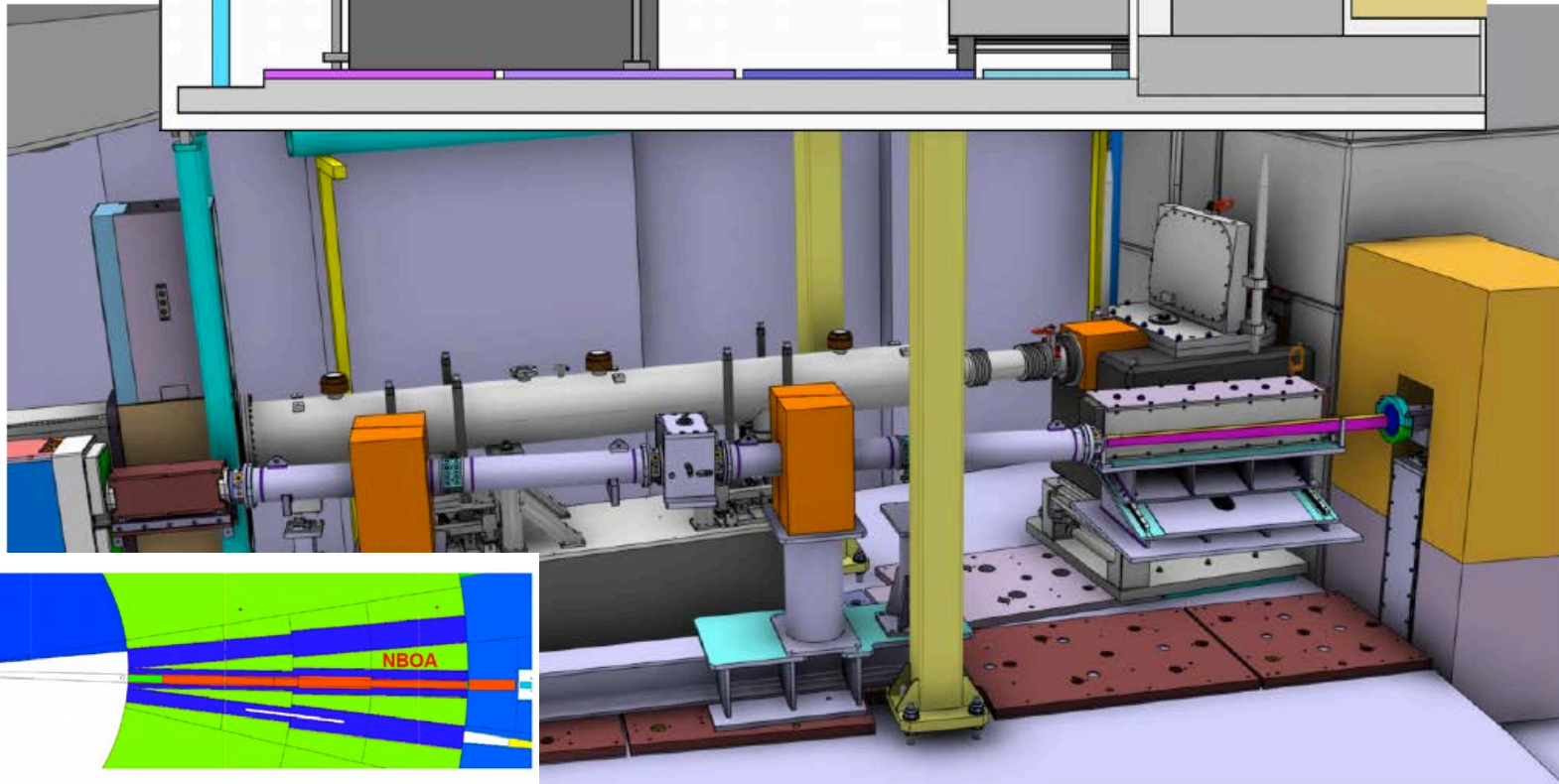
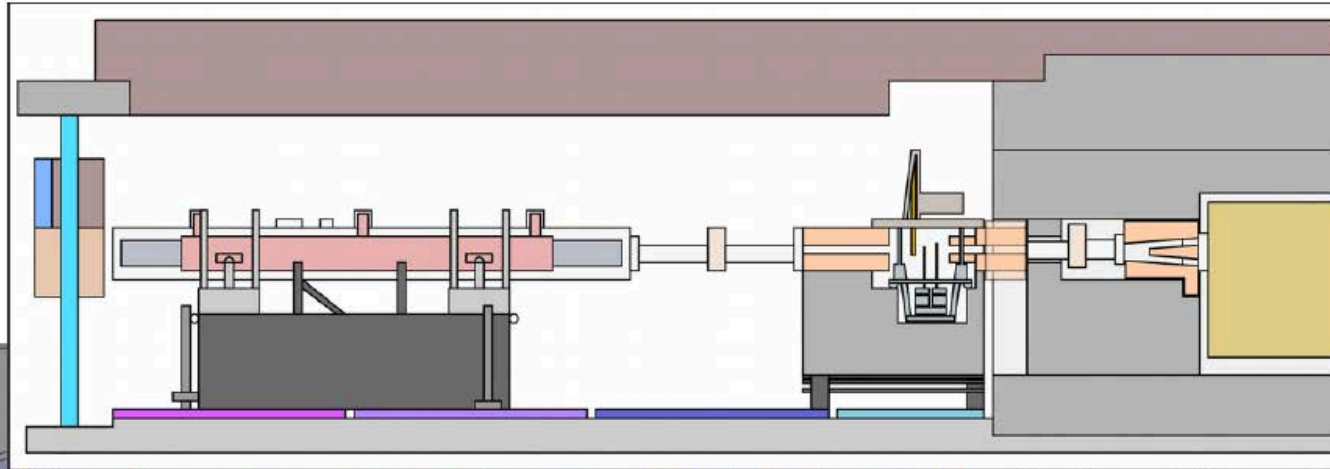


E2 – Estia beamport

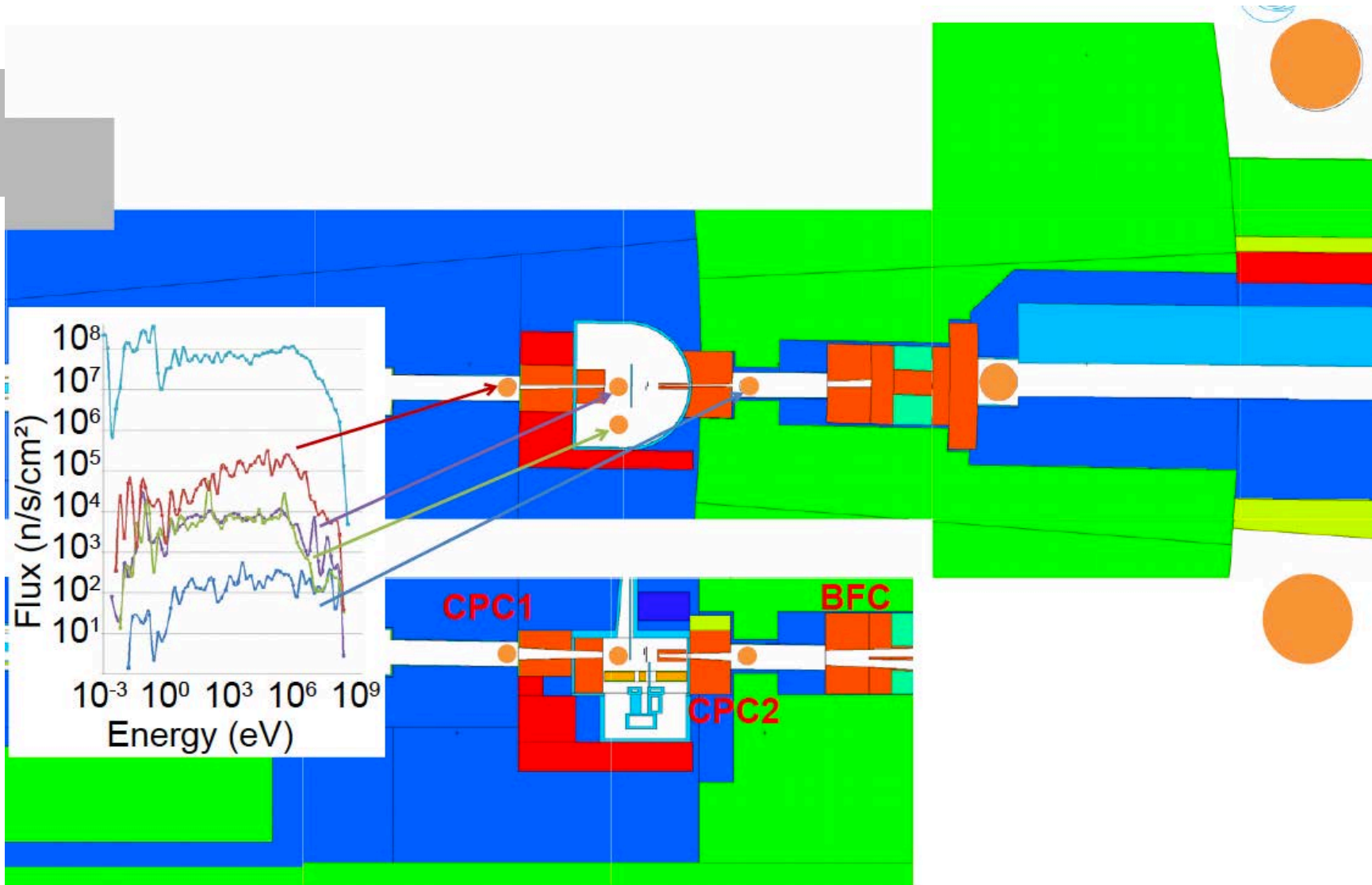


- Reflectometer at beamport E
- Cold neutron beam line
- Elliptic guide system (Selene) – only 40 m long

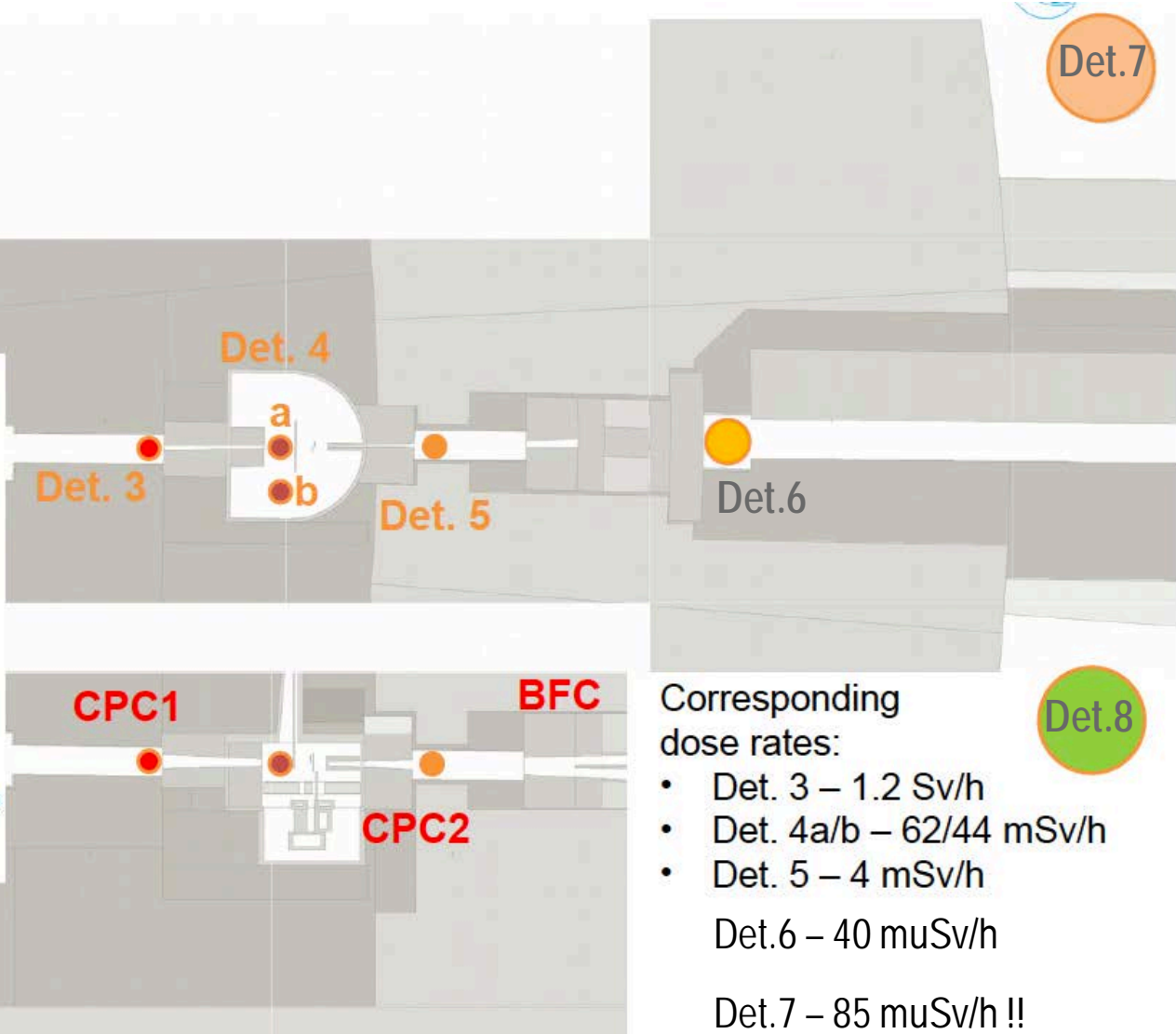
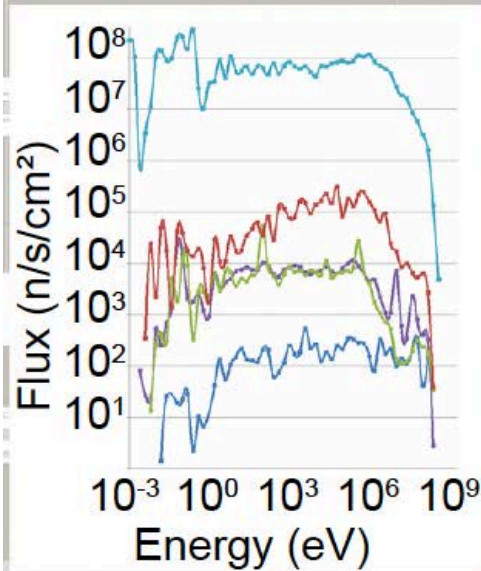
Bunker Components – Detailed Simulations



Re-design of the MCNPX model (includes the geometry from CATIA)



n - Dose Rates



Corresponding
dose rates:

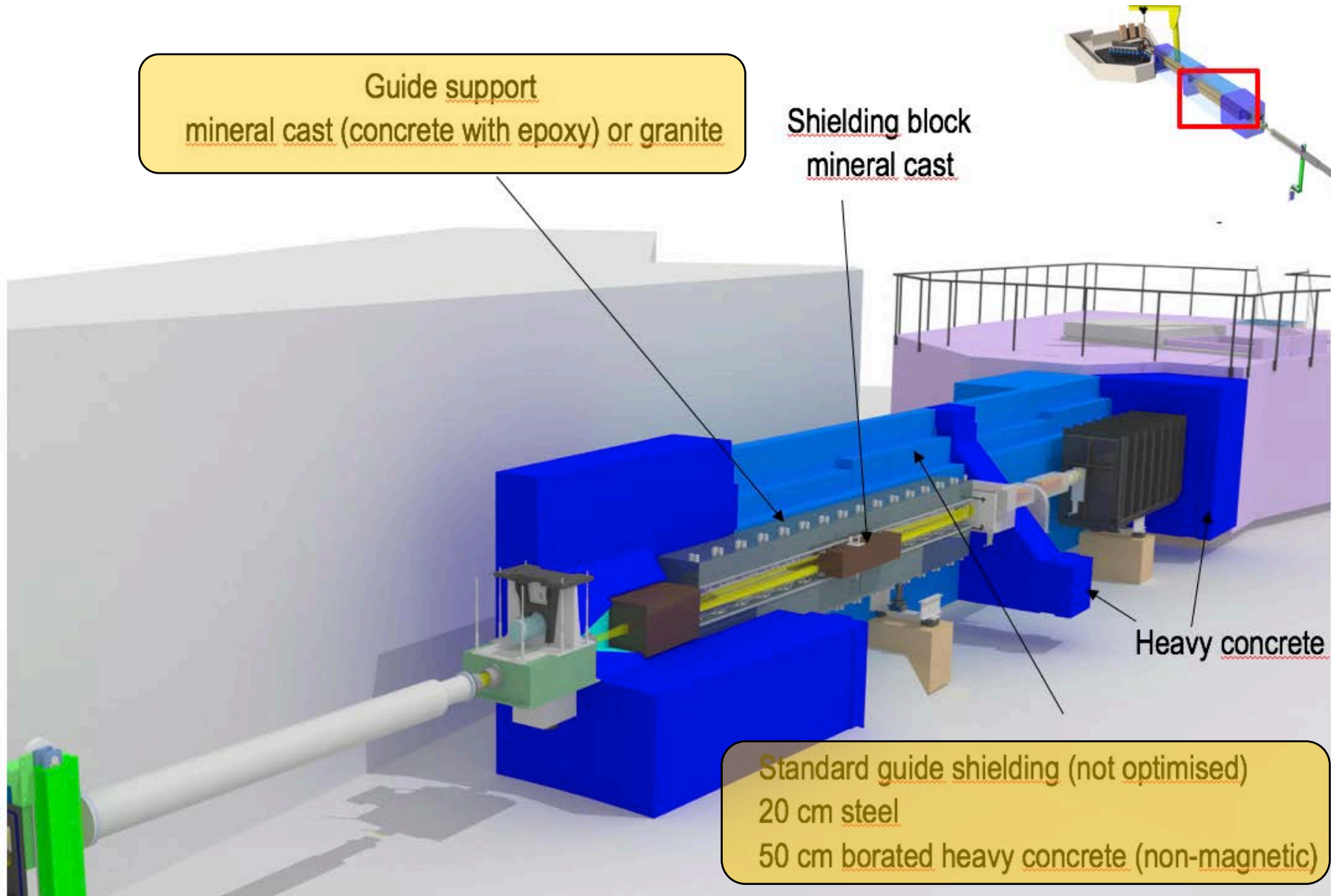
- Det. 3 – 1.2 Sv/h
- Det. 4a/b – 62/44 mSv/h
- Det. 5 – 4 mSv/h

Det.6 – 40 μ Sv/h

Det.7 – 85 μ Sv/h !!

Det. 8 – 0.2 μ Sv/h

Shielding materials for ESTIA



New high-precision Shielding Material – Mineral Cast



Epustone



Epument

Mineral cast is used as the base of high-precision machines

Epustone has the mechanical properties of granite – interesting for our ESTIA project

Epument has a high hydrogen content – (composition of quartz, basalt and epoxy)

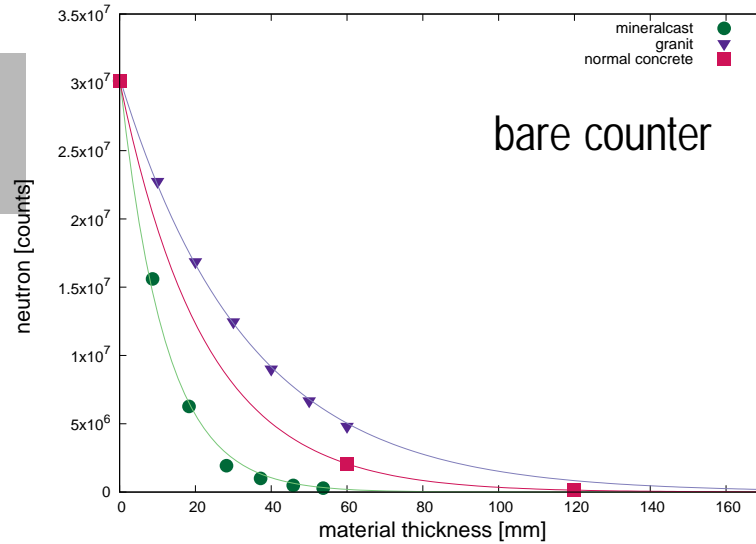
Optimisation: add a thermal neutron absorber (B4C) in the composition.

First test series (14 compositions) on BOA@SINQ (activation, attenuation for diff. E) with BSS system

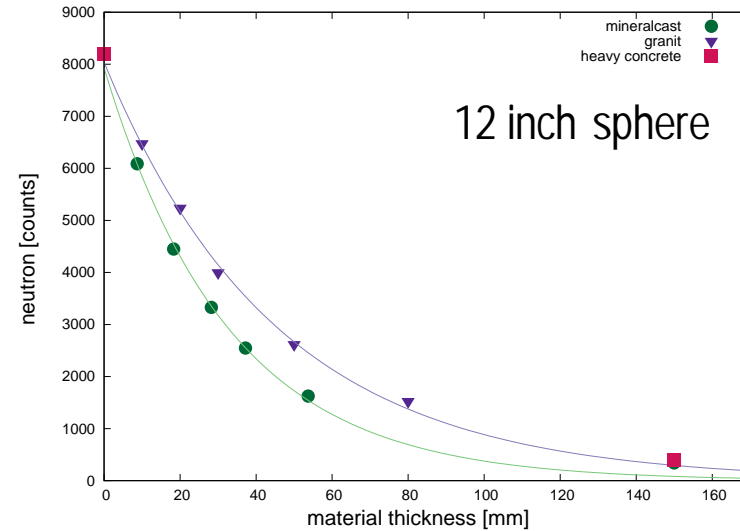
Partner: **RAMPF Machine Systems GmbH & Co. KG**

Comparison 1 – Standard mineral cast

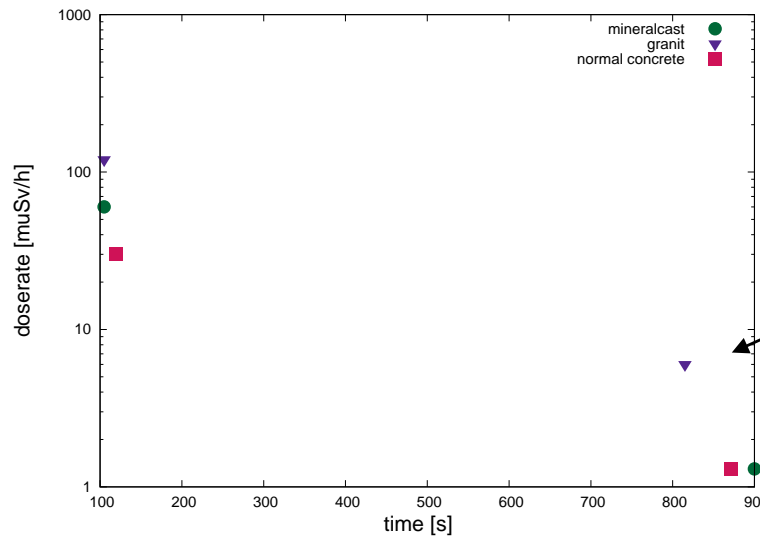
Thermal neutron transmission



Fast neutron transmission



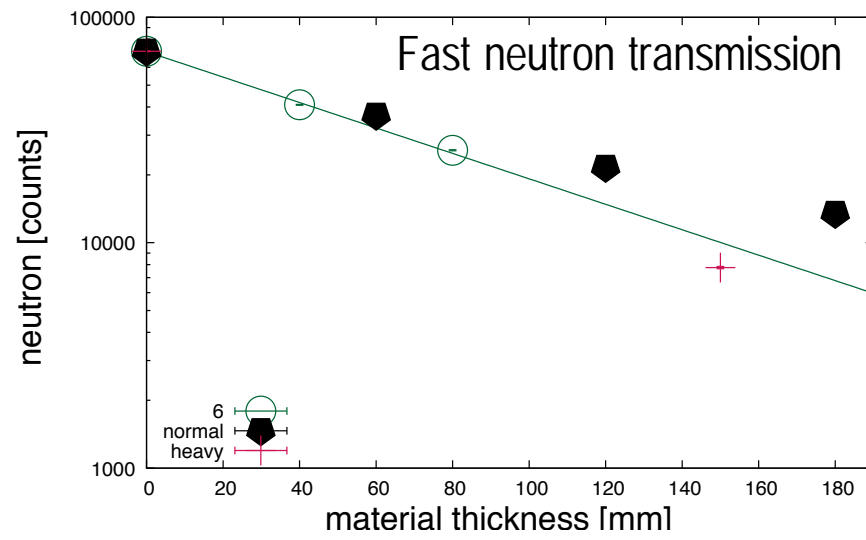
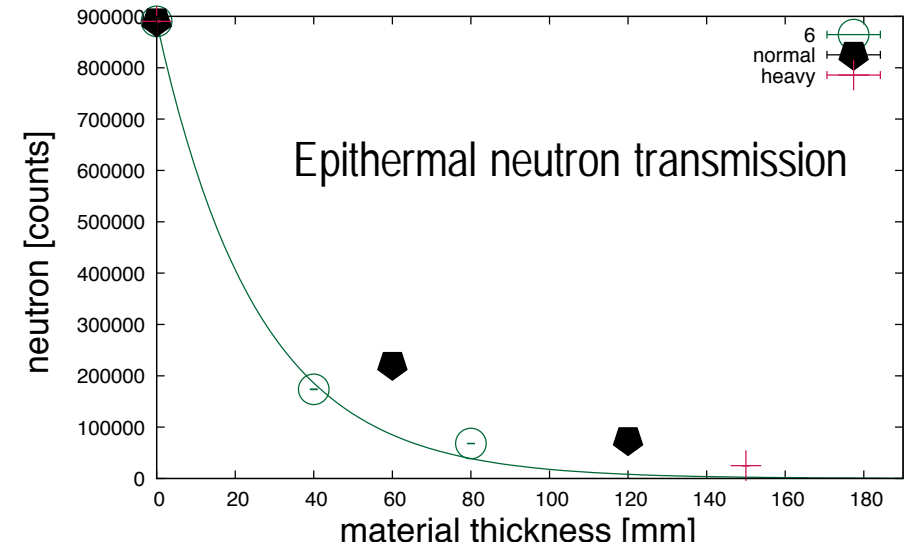
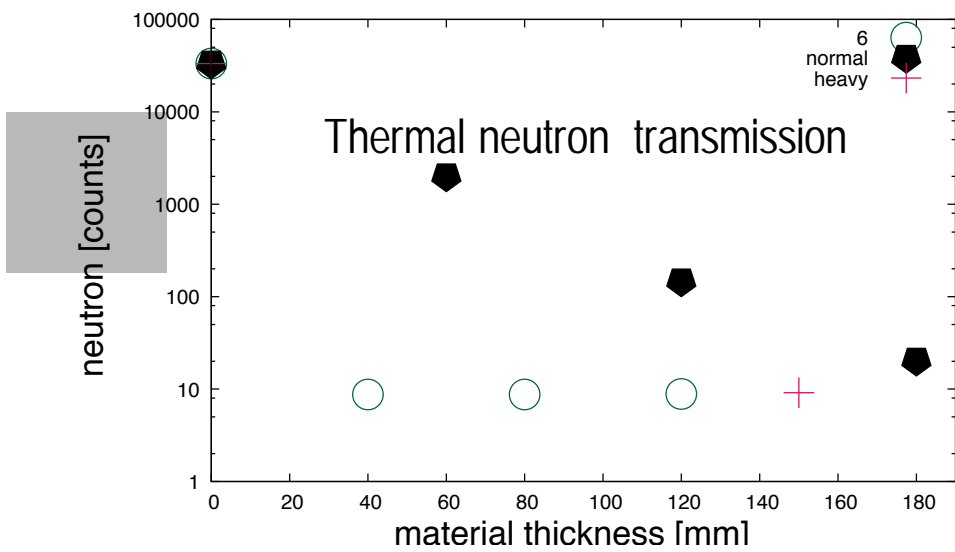
Activation decay (irradiation time 10 sec)



Mineral cast is better as standard concrete or granite

The tested Granite includes Thorium!

Comparison 2 – Borated mineral cast – Composition 6

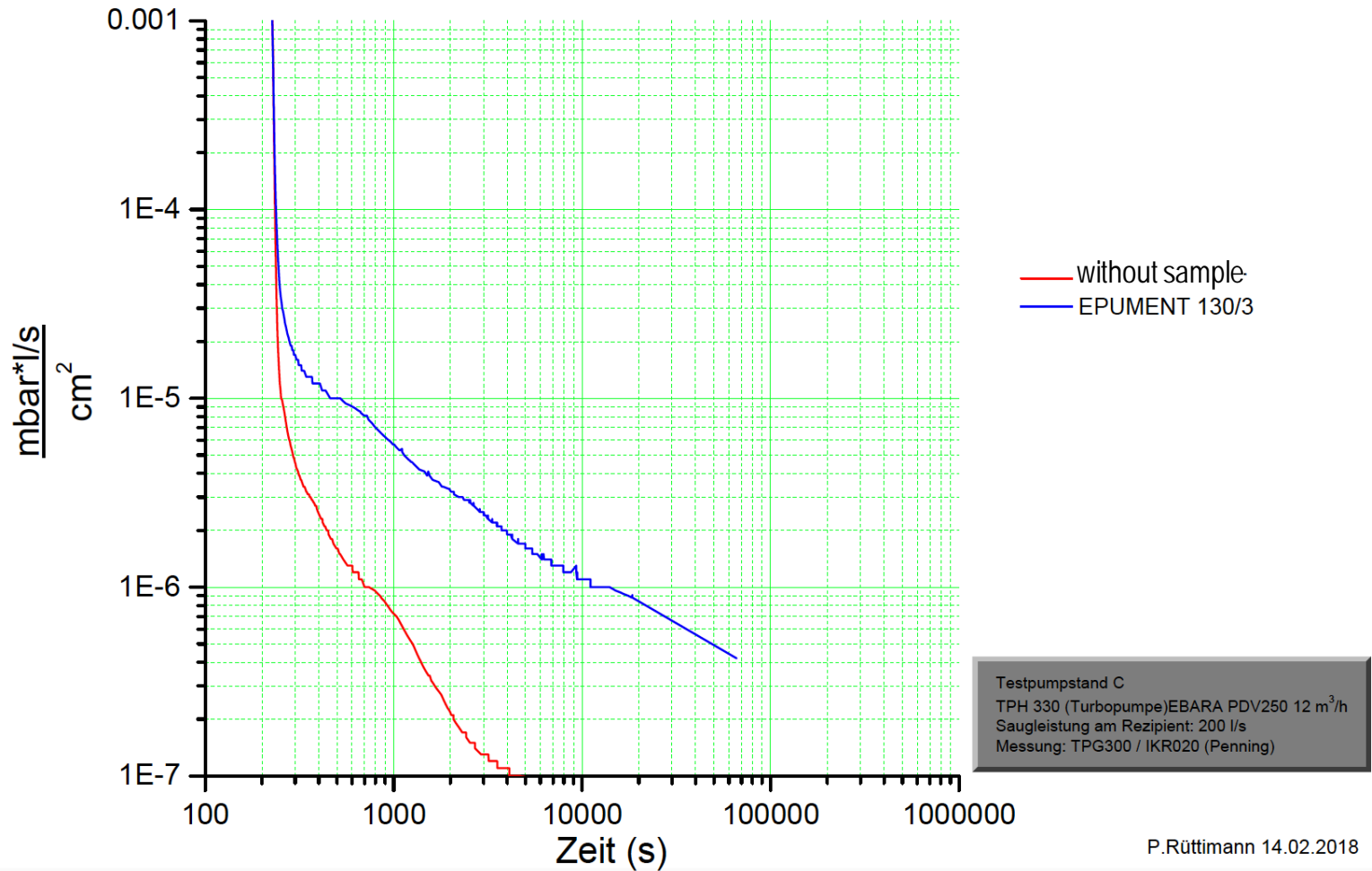


Mineral cast has similar properties as heavy concrete !!!

Best samples are: without ash and a high B4C (5%) content -> sample 6 and 9

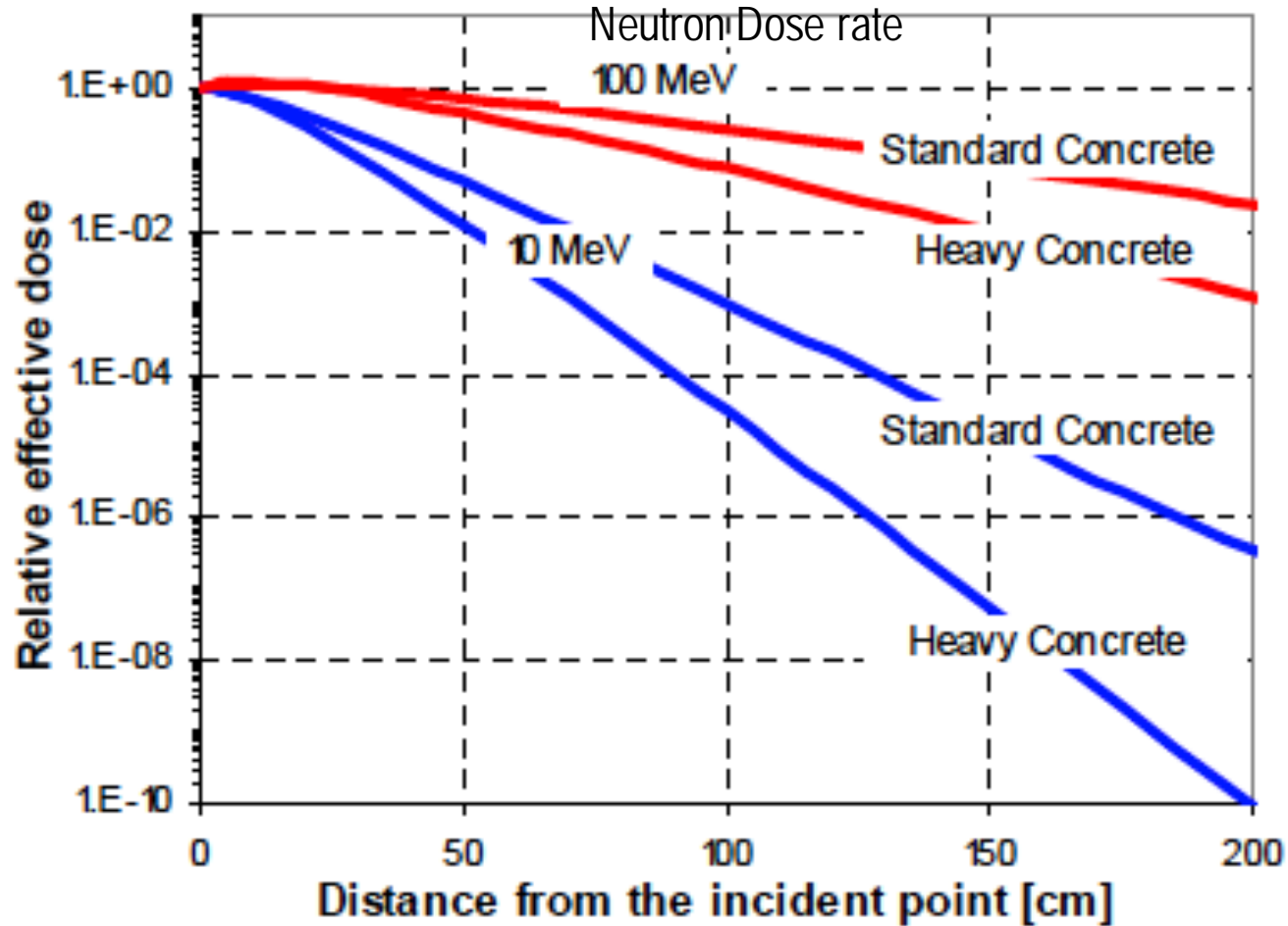
Next Step: increasing hydrogen in sample 6 (was measured in July 2018)

EPUMENT 130/3 – Gas Treatment



Only for high vacuum environment mineral cast shows a delayed behaviour, but neutron guides require only $1\text{E-}3$ mbar

Attenuation of Concrete



Standard concrete: without Boron

Heavy concrete: without Boron, density: 4.4 g/cm³ 66 wt% Fe

