Fast neutron inelastic scattering

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Data needs for transmutation facilities

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

For simulations and calculations to design Gen IV reactors/ADS **detailed knowledge about the neutron interactions in the relevant energy region are necessary**

➔ for nuclei to be transmuted as well as for structural materials

➔ fast neutron spectrum

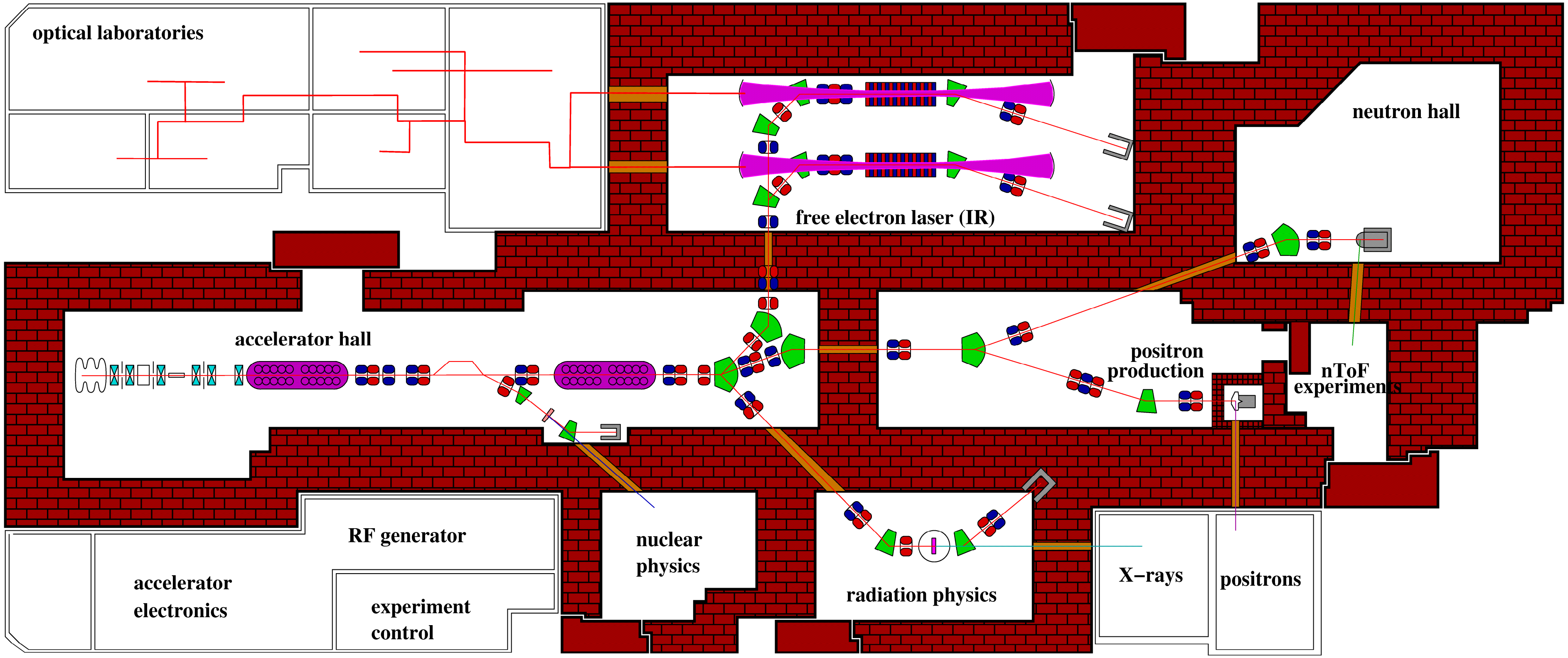
- neutron capture
- neutron induced fission
- neutron inelastic scattering

➔ ^{56}Fe (n,n'γ) ^{56}Fe

➔ ^{23}Na (n,n'γ) ^{23}Na

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

nELBE – neutron facility at ELBE



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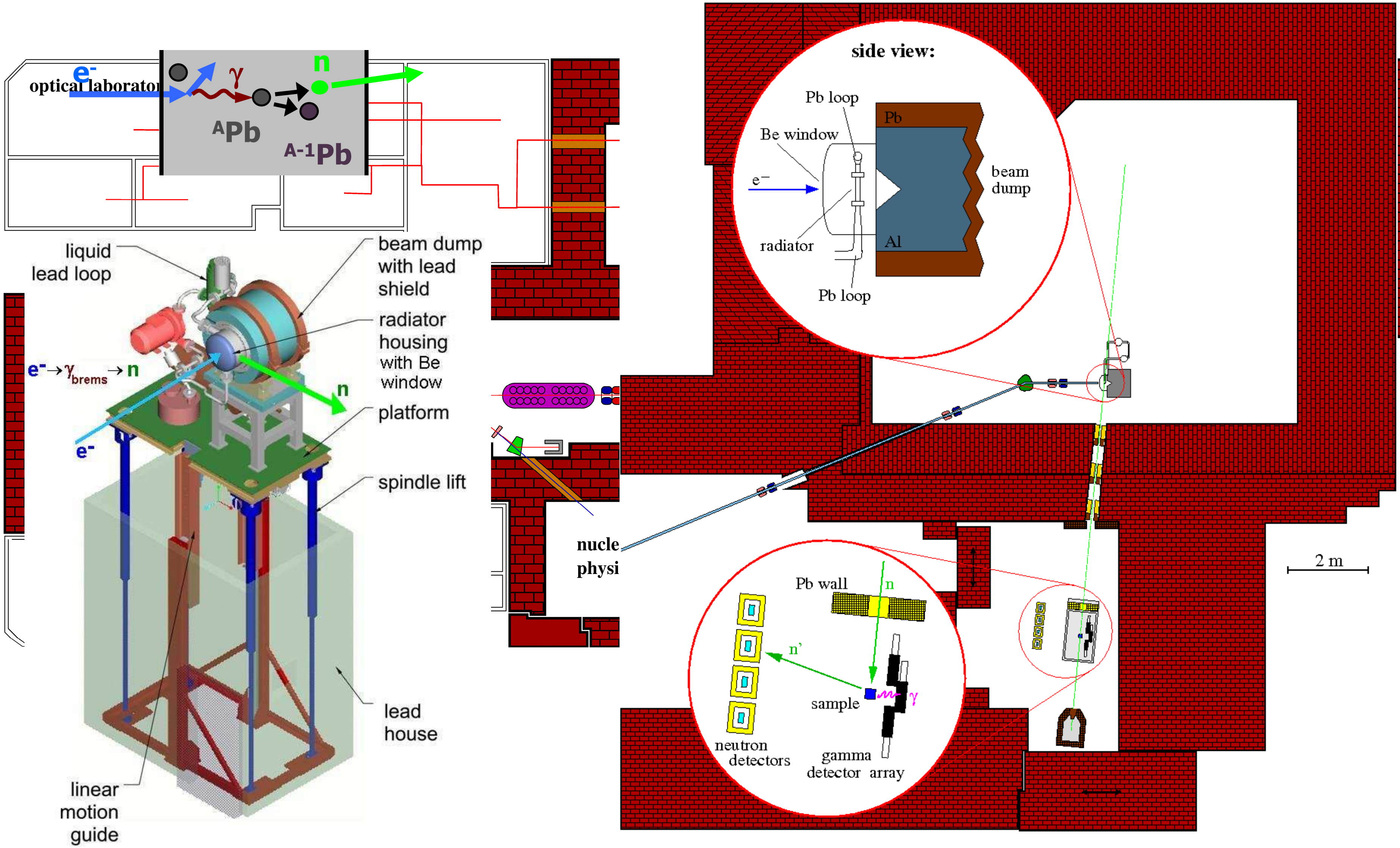
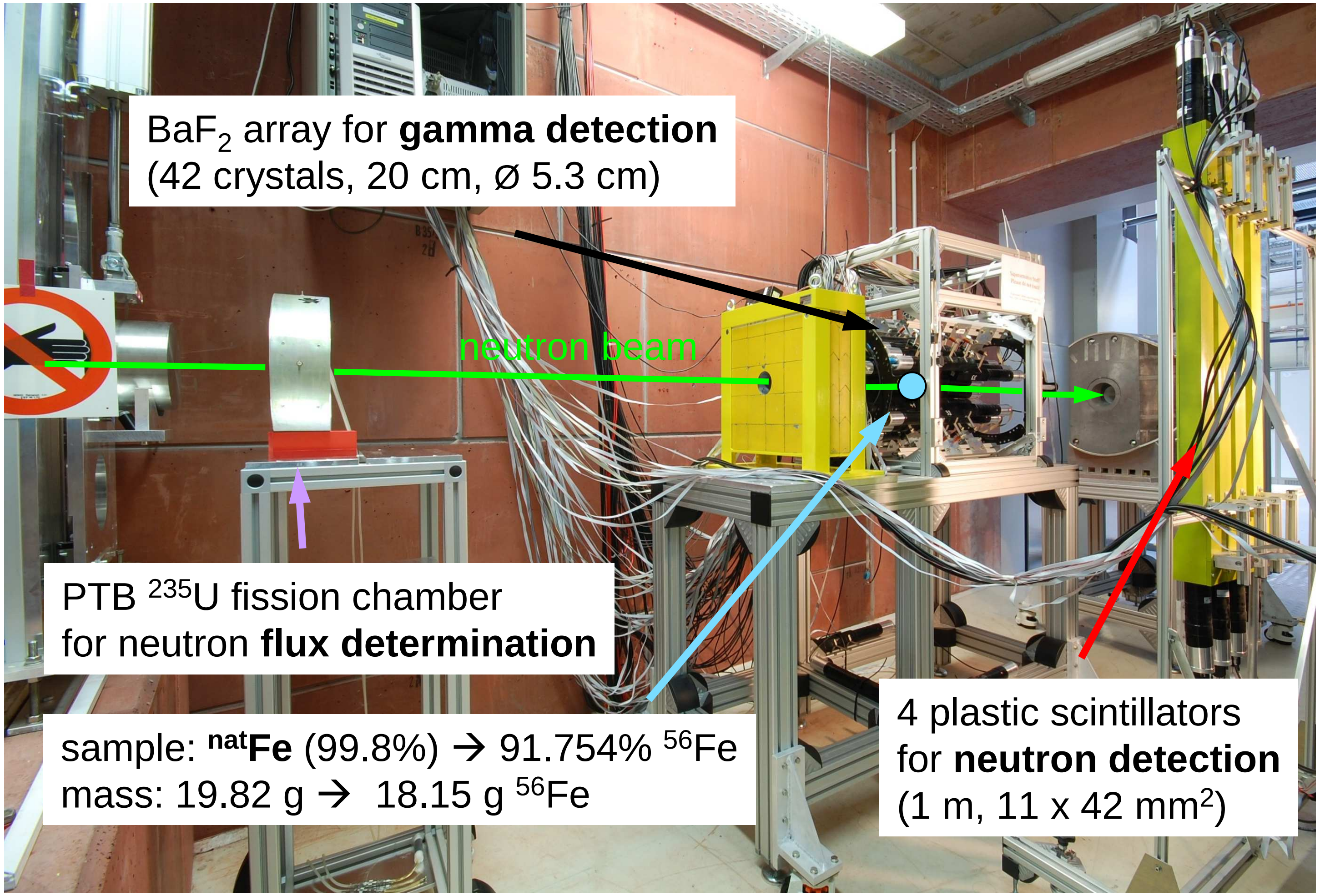


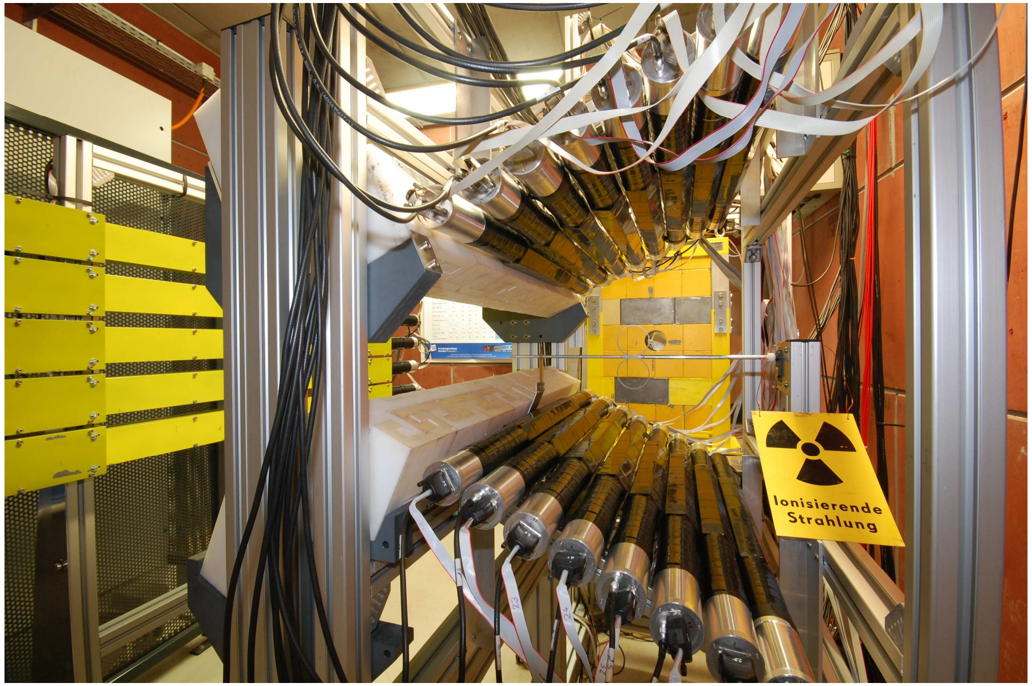
nELBE – double ToF detector setup

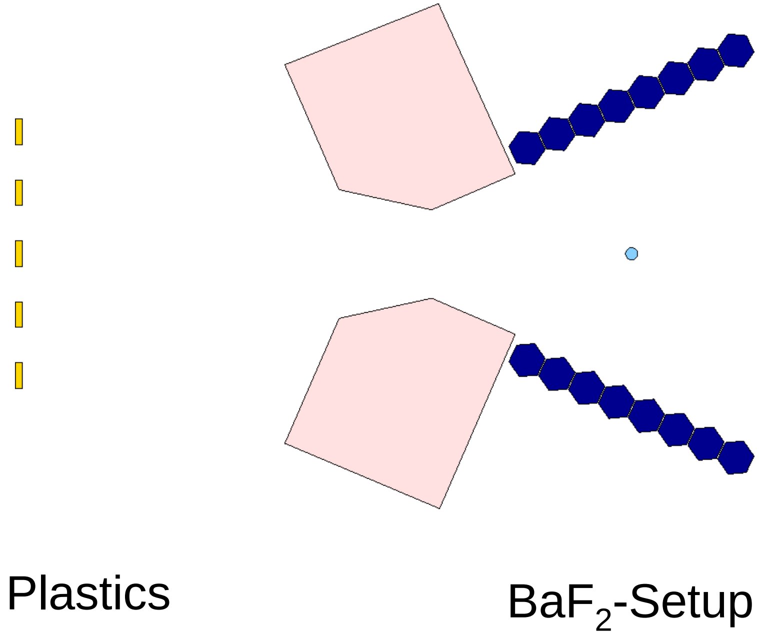


flight paths:
source - sample: 600 cm
sample - BaF_2: 30 cm
sample - plastics: 100 cm

too much background from elastic scattering to BaF_2 and subsequent inelastic scattering there → had to change geometry

Detector geometry - details

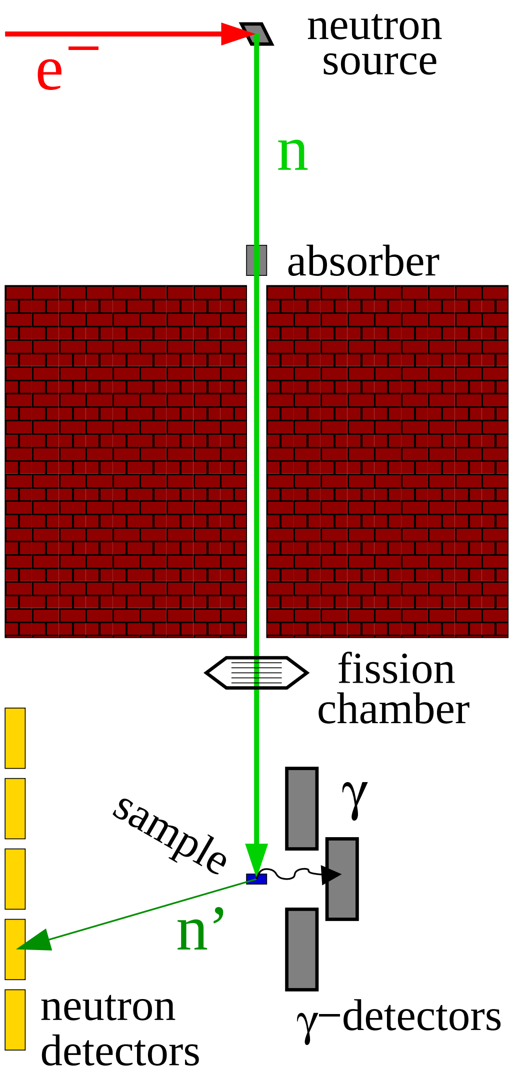


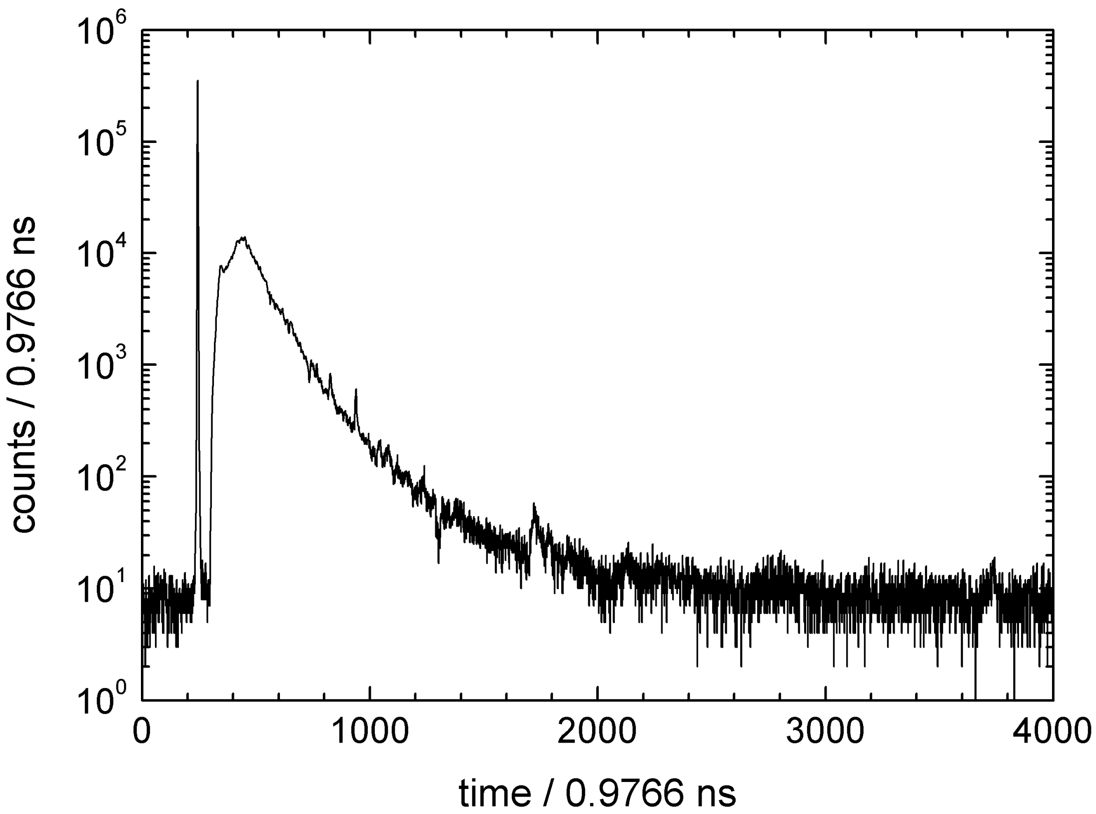


- ➔ borated polyethylene block between BaF_2 and plastics
- ➔ combination of two single sided readout 20 cm long crystals to one double sided readout 40 cm long detector
- ➔ number of random events reduced by one order of magnitude

angular coverage:
- θ_n = 60° - 120°
- θ_γ = 50° - 130°
- φ = +/- (30° - 130°)

Experimental methods and results – Inelastic scattering





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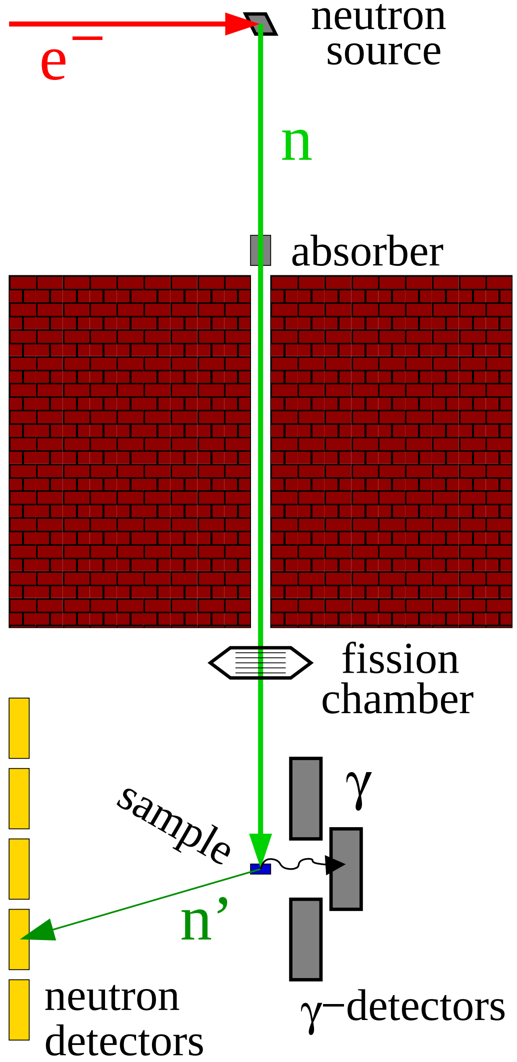
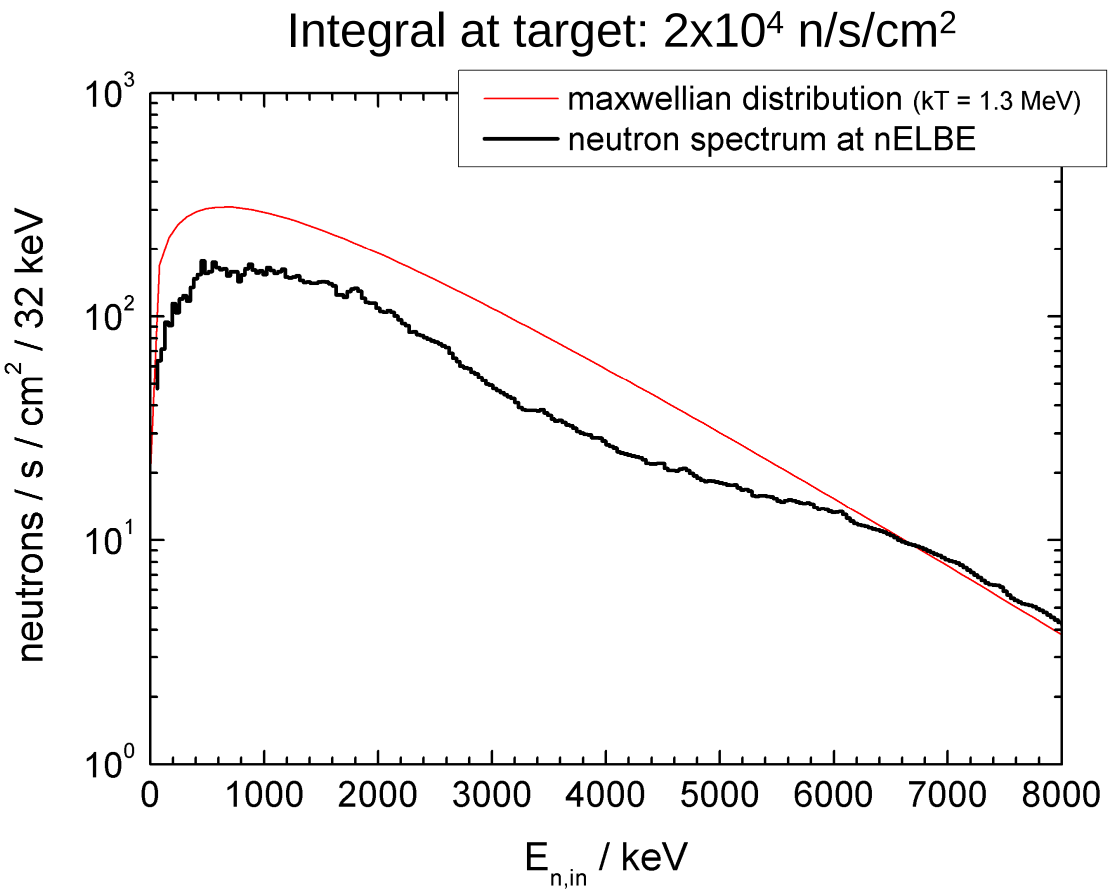
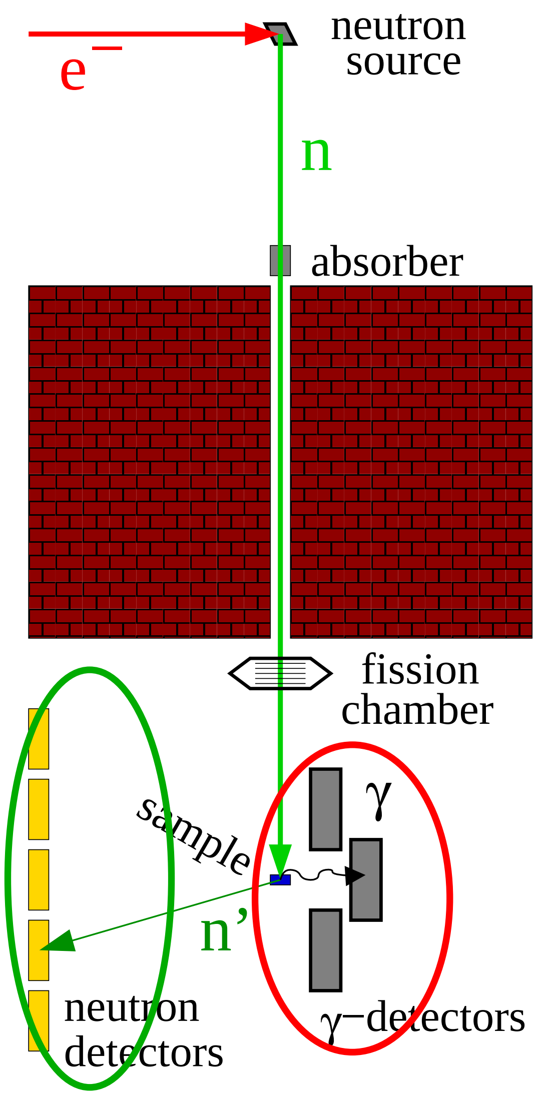
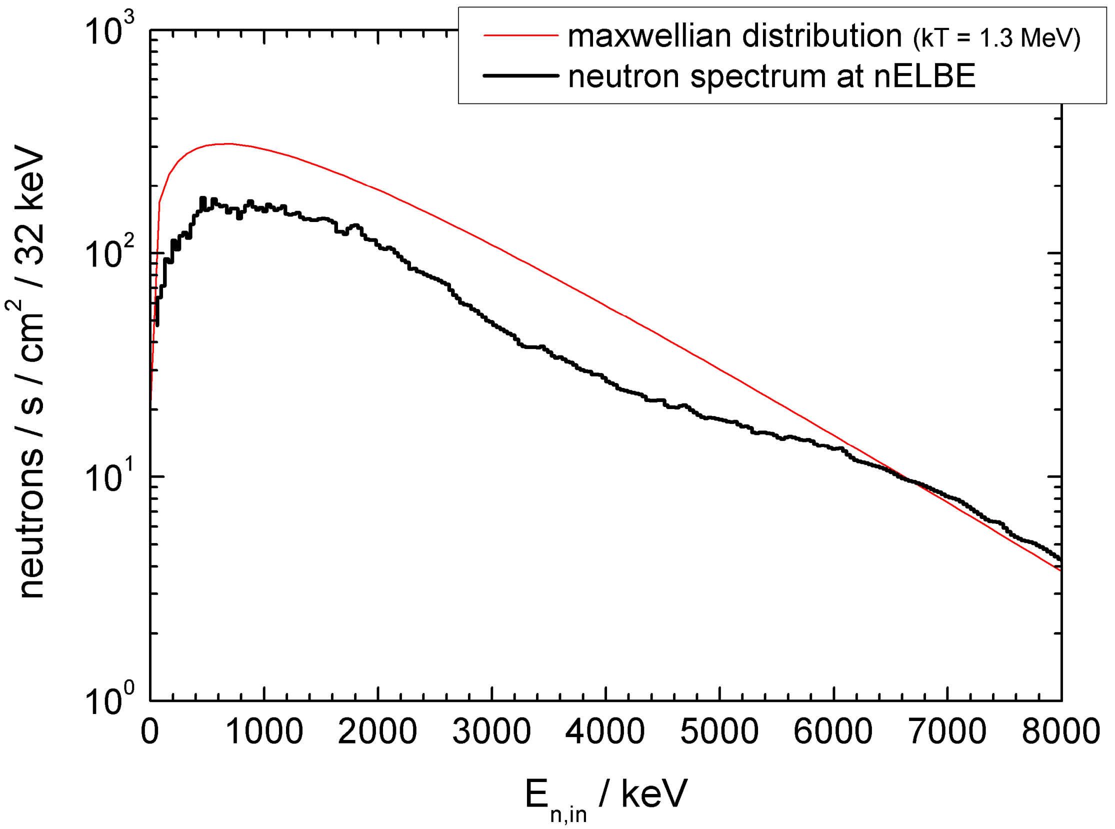




Experimental methods and results – Inelastic scattering

$$^{56}Fe(n,n'\gamma)^{56}Fe \begin{cases} ^{56}Fe + n \rightarrow {}^{56}Fe^{*} + n' \\ ^{56}Fe^{*} \rightarrow {}^{56}Fe + \gamma \end{cases}$$





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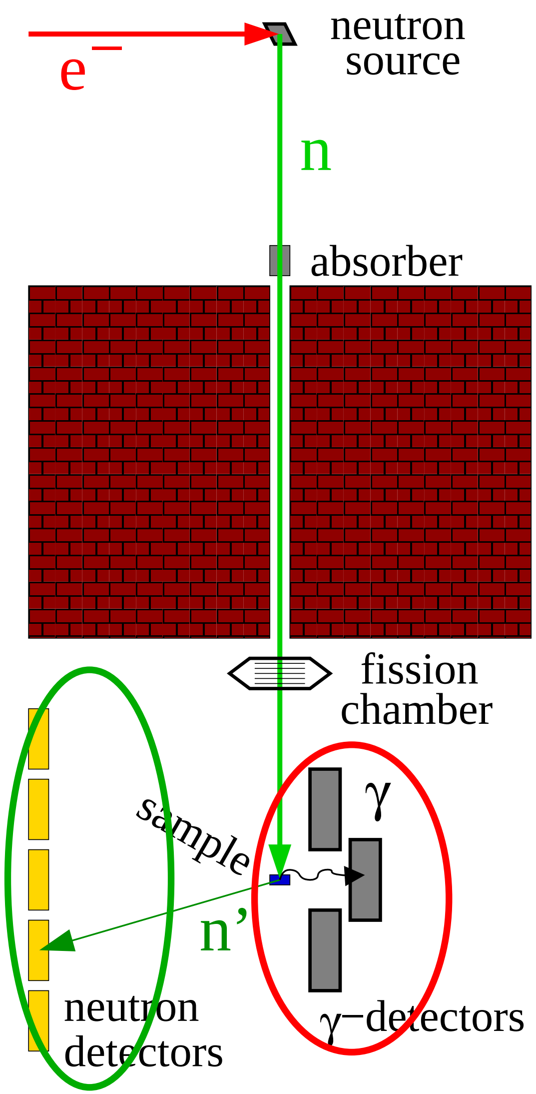
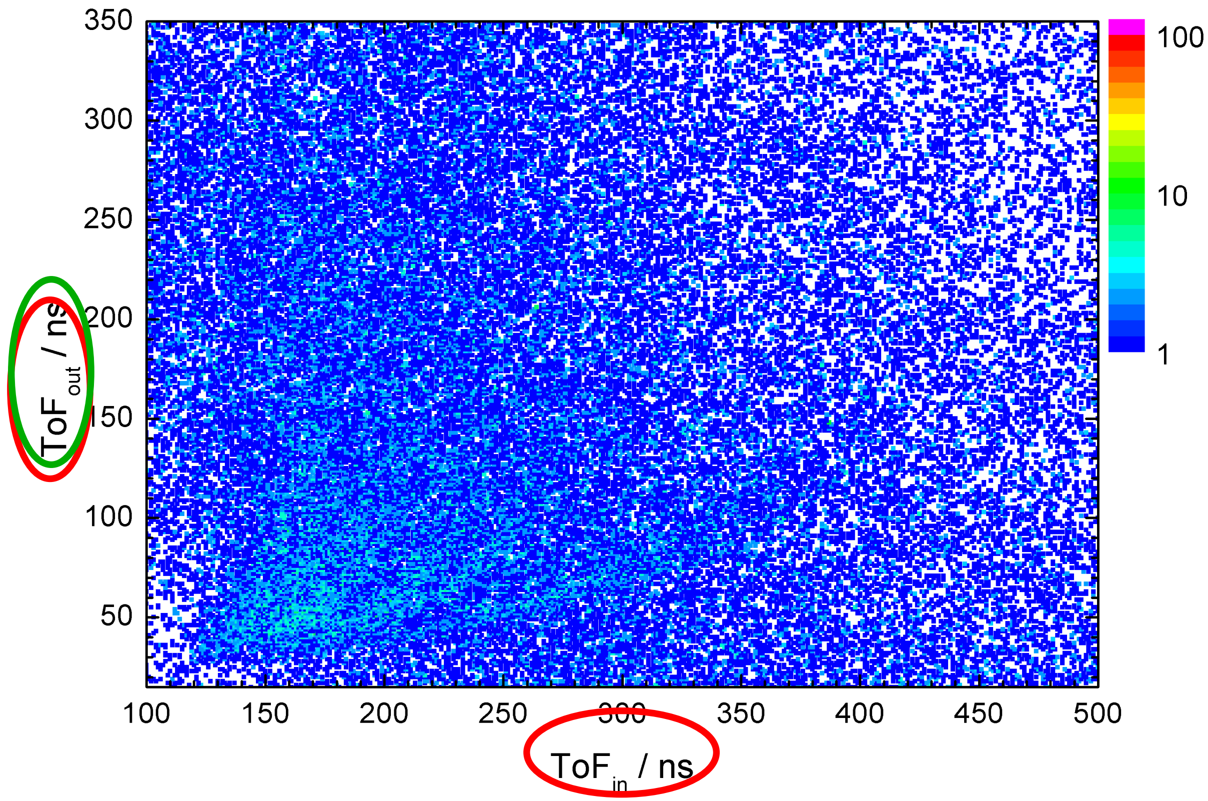


$$^{56}\mathrm{Fe}(n,n'\gamma)^{56}\mathrm{Fe} \left\{ \begin{array}{l} ^{56}\mathrm{Fe} + n \rightarrow {}^{56}\mathrm{Fe}^{*} + n' \\ \quad {}^{56}\mathrm{Fe}^{*} \rightarrow {}^{56}\mathrm{Fe} + \gamma \end{array} \right.$$

without sample (82 h live time)



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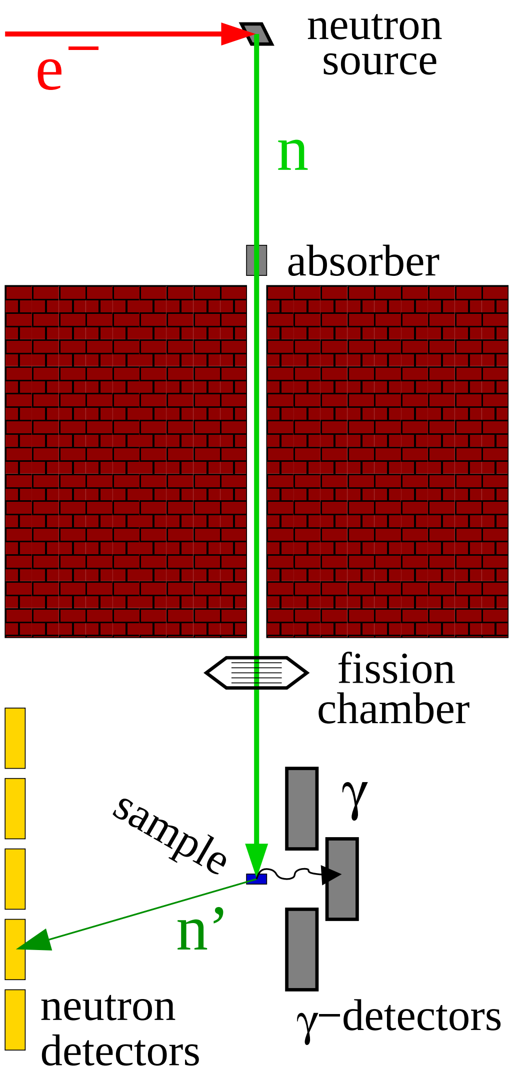
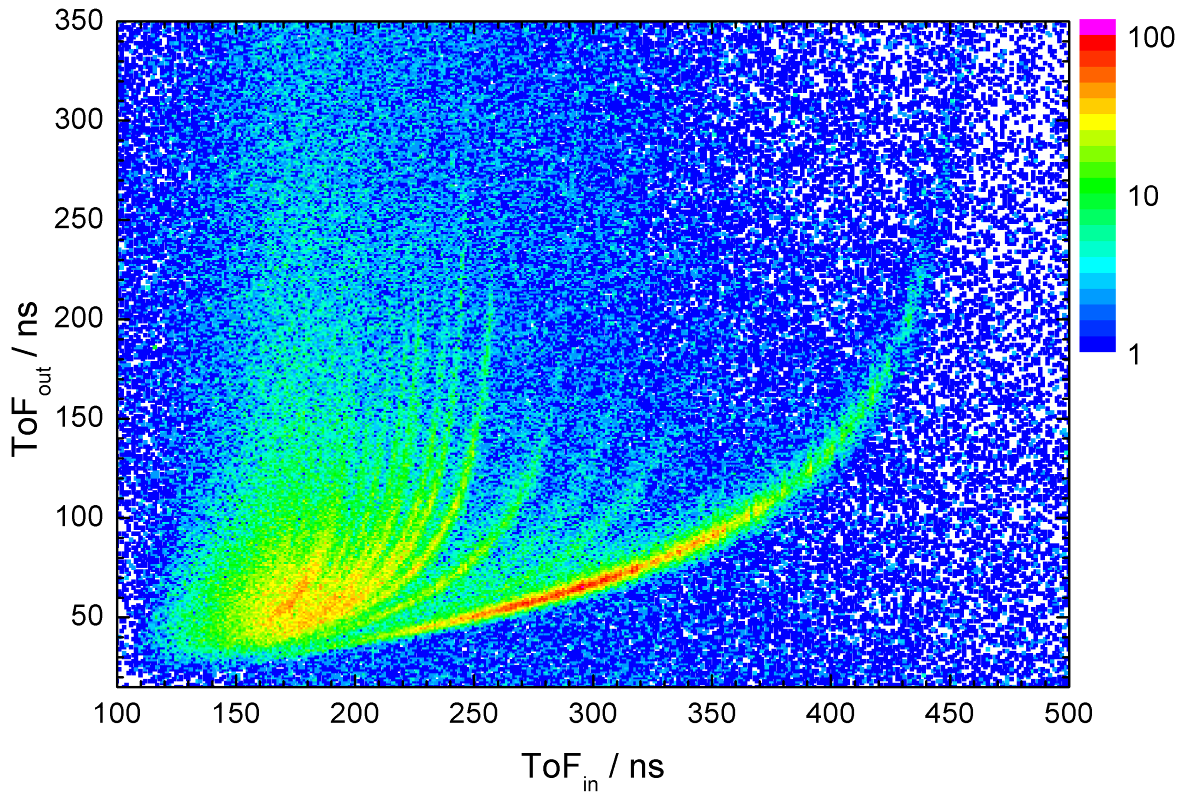
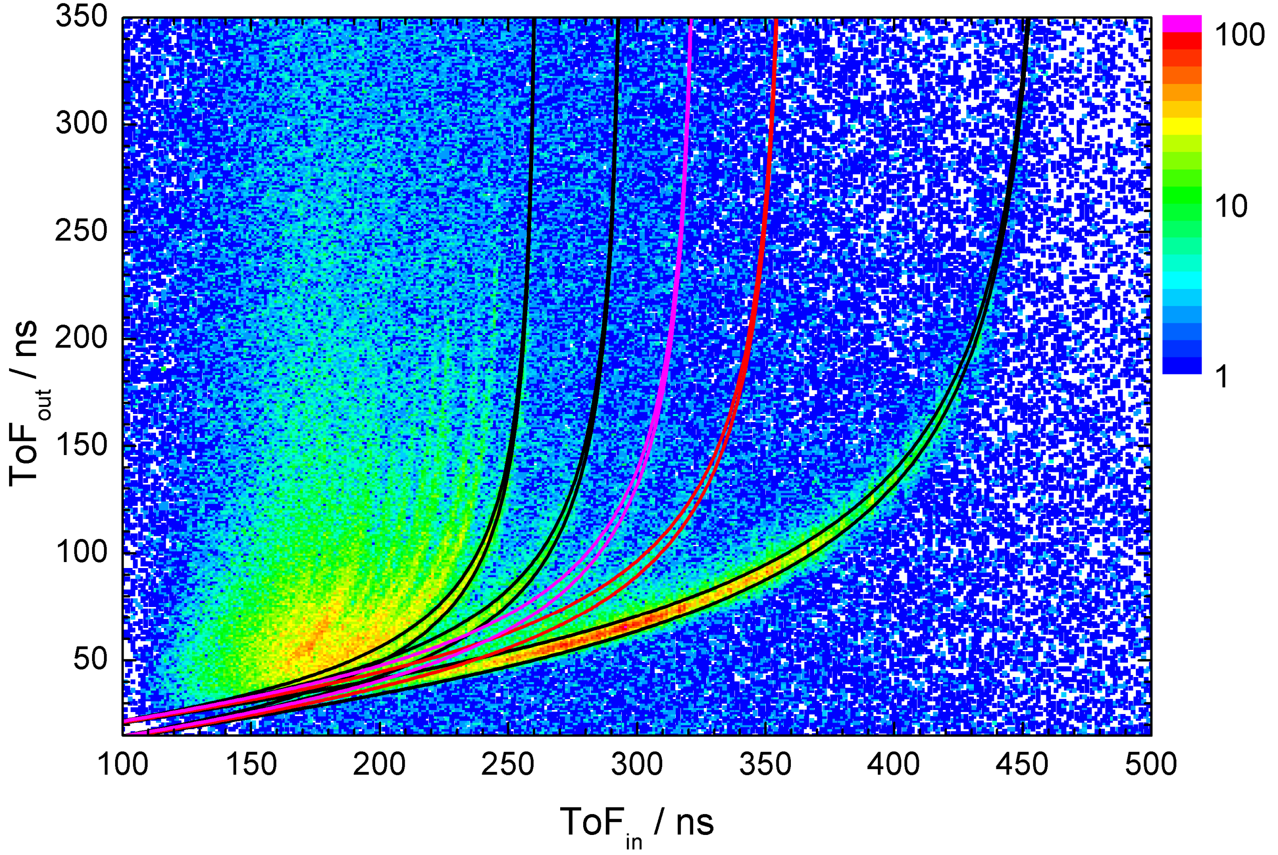


$$^{56}\mathrm{Fe}(n,n'\gamma)^{56}\mathrm{Fe} \left\{ \begin{array}{l} ^{56}\mathrm{Fe}+n \rightarrow {}^{56}\mathrm{Fe}^{*}+n' \\ \qquad\quad {}^{56}\mathrm{Fe}^{*} \rightarrow {}^{56}\mathrm{Fe}+\gamma \end{array} \right.$$

with sample (78 h live time)



Kinematic calculations



- Fe-56 (1.,2.,3. Level)
- Fe-54 (1. Level)
- Fe-56 (2 x 1. Level)

Neutron Flux $\Phi_{n,targ}$

		at $E_{n,in}$ = 2 MeV ($ToF_{n,in}$ = 304 ns)	
σ_{fis}	… ^{235}U fission cross section	= 1.29(2) b	[1]
N_n	… number of fissionable nuclei	= 5.164(1) $\times 10^{20}$	[2]
d	… diameter of fissionable deposit	= 76 mm	[2]
ε_{fis}	… fission detection efficiency	= 0.945(1)	[2]
$N_{FC,with}$	… counts measured by fission chamber	= 4515(67)	
N_{back}	… random background level	= 2.28(4)	(from Fit)
f_{loss}	… correction factor for losses due to ADC gate	= 1.03(1)	(from Fit)
f_{scal}	… scaling factor neutrons(target)/neutrons(FC)	= 7.11(2)	(from MCNP)
f_{scal}	… attenuation factor (air + target)	= 0.87(2)	(from MCNP)
A_{targ}	… area of target	= π cm^2	

$$\varepsilon(FC) = \sigma_{fis} \cdot \frac{N_n}{\pi \cdot \left(\frac{d}{2}\right)^2} \cdot \varepsilon_{fis}$$

= 1.38(6) $\times 10^{-5}$

$$\Phi_{n,targ} = \frac{(N_{FC,with} - N_{back}) \cdot f_{loss}}{f_{scal} \cdot \varepsilon(FC) \cdot A_{targ}}$$

= 5.3(1) $\times 10^7$ n/cm^2/4ns (binwidth)

[1] ENDFB-VII.0
[2] Nolte, Nucl.Sci.Eng.156(2007)197

Number of detected reactions

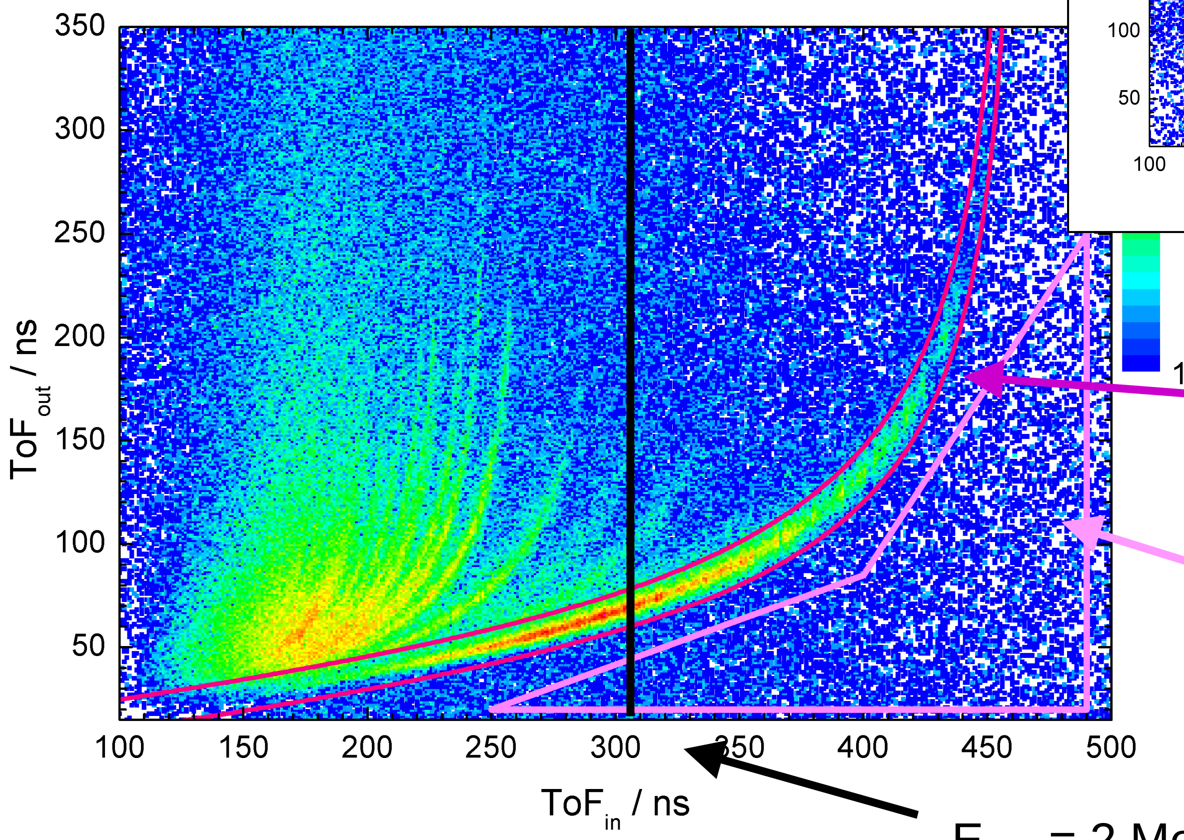
at $E_{n,in}$ = 2 MeV

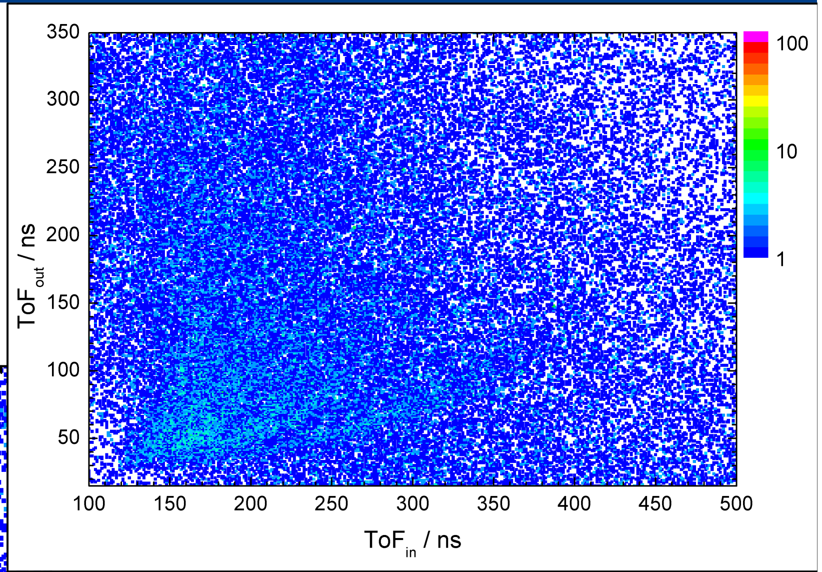
N_{with}, $N_{without}$	… number of detected events with/without target in beam inside kinematic window	= 1941(44) counts/4ns (binwidth) = 61(8)
ΣN_{with}, $\Sigma N_{without}$	… number of detected events with/without target in beam inside background banana	= 7640 = 5830

$$f_{norm} = \frac{\Sigma N_{with}}{\Sigma N_{without}}$$ = 1.31(2)

$$N_{with,backsub} = N_{with} - N_{without} \cdot f_{norm}$$ = 1861(45)

Background subtraction





kinematic window for event counting

Banana for background determination

$E_{n,in}$ = 2 MeV ➔ ToF_{in} = 305 ns

Number of detected reactions

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$\varepsilon(BaF_2)$	… total efficiency of a single BaF_2	= 7.5(1) x10^{-2}
ε_i	… intrinsic efficiency of a single plastic	= 0.20(1)
$\Omega / 4\pi$	… solid angle of a single plastic	= 0.003247

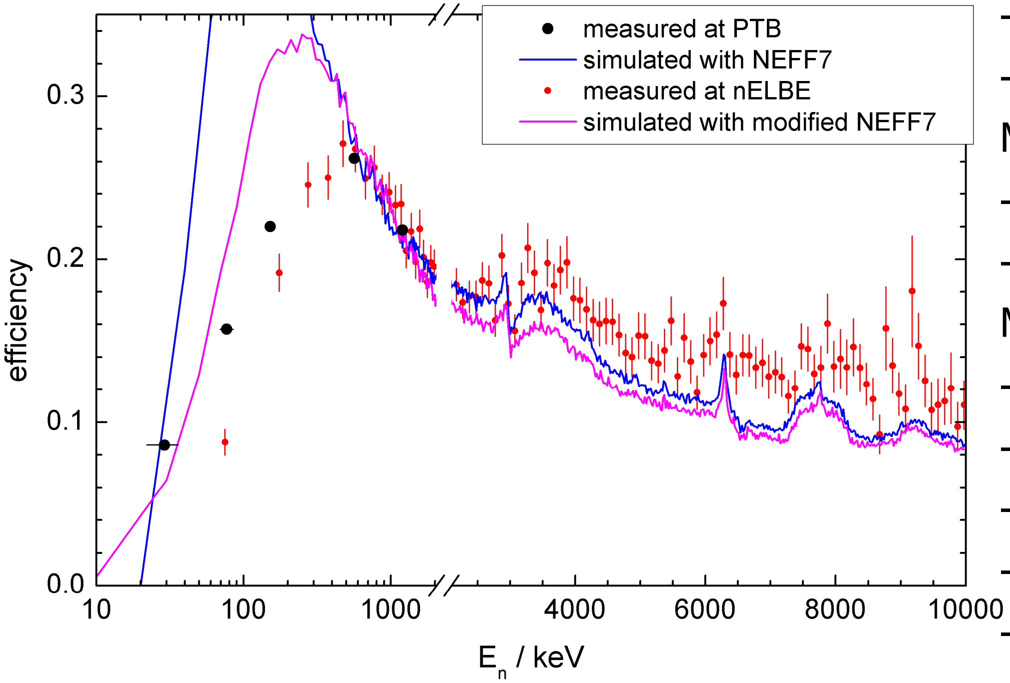
$$f_{norm} = \frac{\Sigma N_{with}}{\Sigma N_{without}}$$ = 1.31(2)

$$N_{with,backsub} = N_{with} - N_{without} \cdot f_{norm}$$ = 1861(45)

$$\varepsilon(Pl) = \varepsilon_i \frac{\Omega}{4\pi}$$ = 3.7(1) x10^{-3}

$$R = \frac{N_{with,backsub}}{\varepsilon(BaF_2) \cdot \varepsilon(Pl)}$$ = 6.6(3) x10^{6} react / 4ns

Plastics Efficiency



Measurement at PTB:

- Monoenergetic neutrons
- Beyer et al., NIMA 575 (2007) 449

Measurement at FZD:

- nELBE spectrum
- Relative to ^{235}U fission chamber

Modified NEFF7:

- Cuboid detector geometry
- Double sided readout
- Scintillation light propagation/attenuation
- PMT Quantum efficiency
- Threshold = one photo electron per PMT

Problems:

In simulation:

- Unknown light output function at low energy transfer

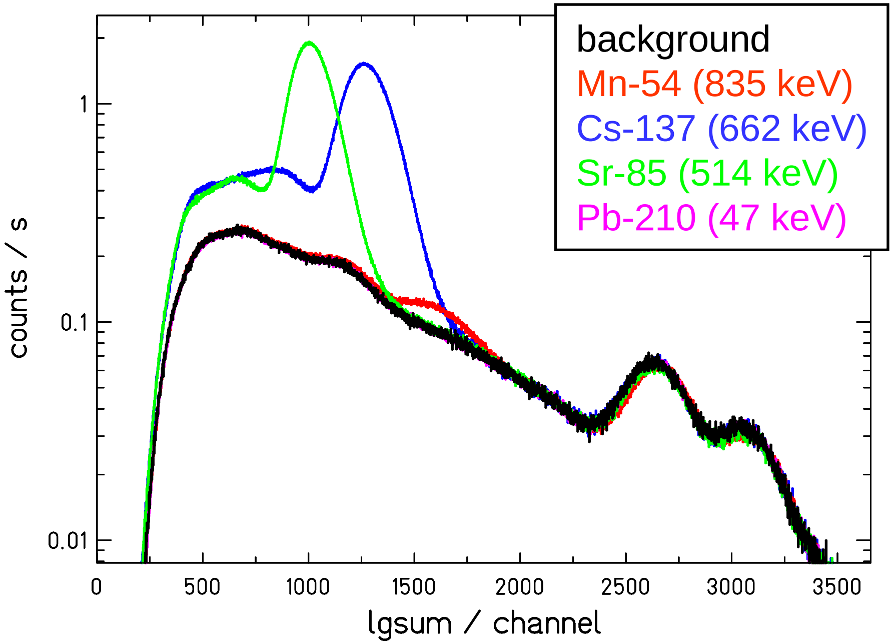
In measurement:

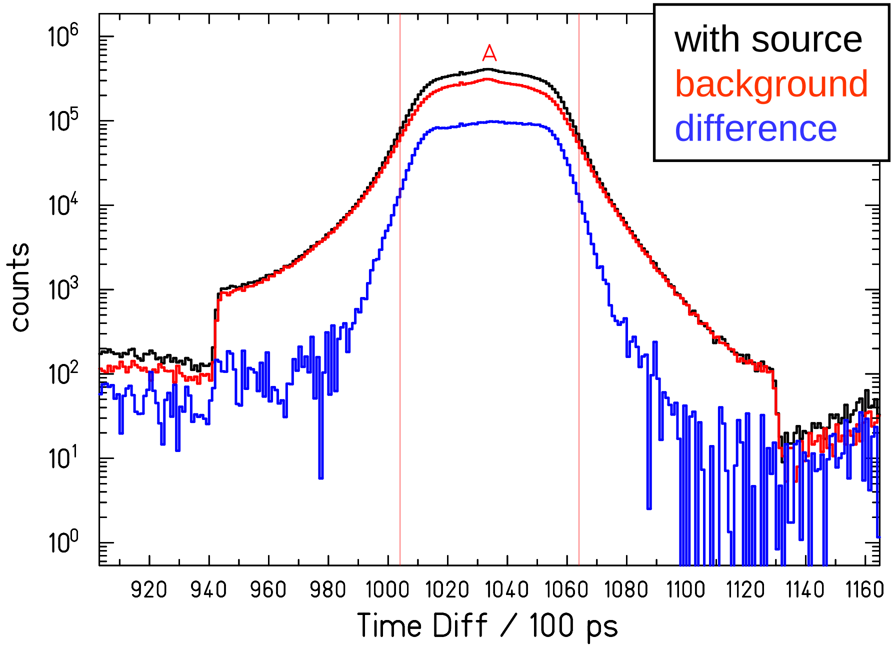
- Collimated beam at nELBE
- Influence of lead shielding

BaF_2 photon detection efficiency

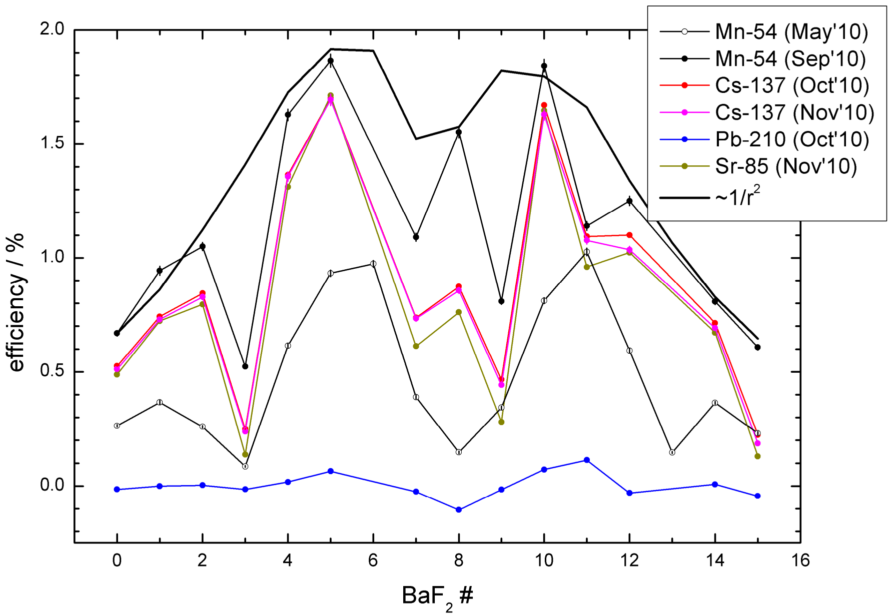
need total photon detection efficiency
→ have to use mono-energetic gamma sources

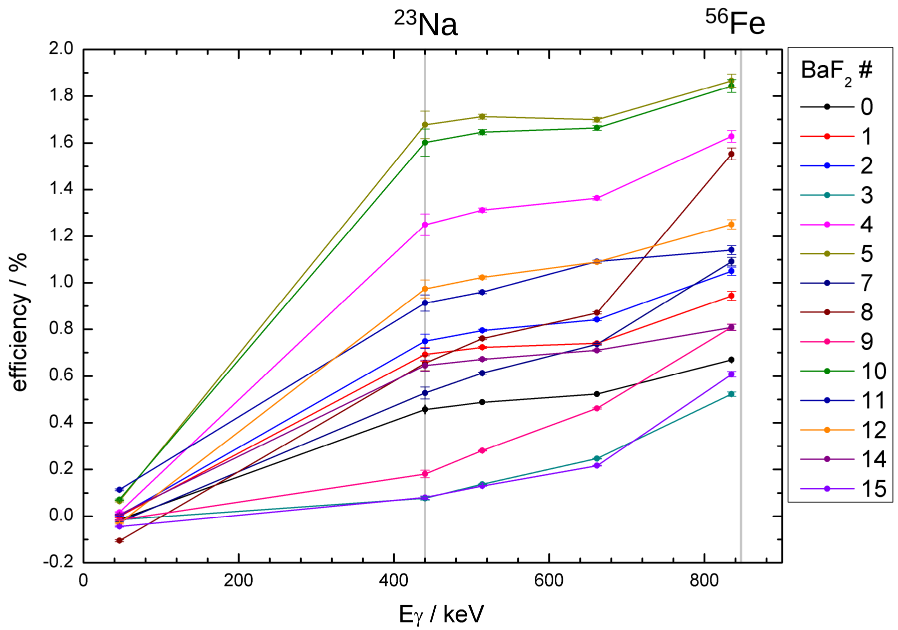
Fe-56: 1. Level = 847 keV → can use Mn-54 (835 keV)
Na-23: 1. Level = 440 keV → extrapolation





BaF$_2$ photon detection efficiency





- efficiency not only influenced by solid angle
- strong position dependence

➔ should use mono-crystalline detectors (new BaF2 or LaBr3 or Plastic)

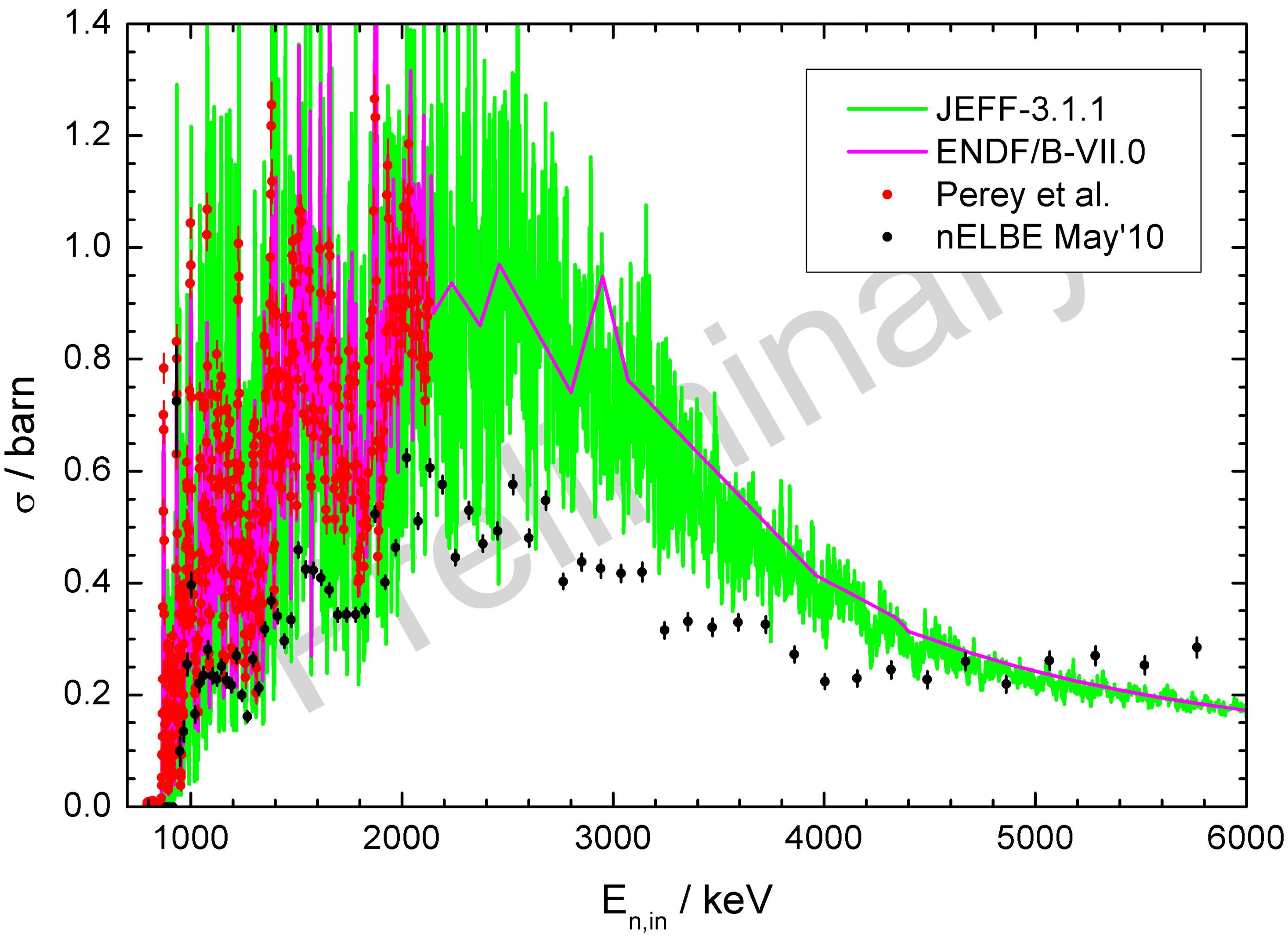
Number of target nuclei & inelastic scattering cross section

m_{targ}	… target mass	= 19.81809 g	at $E_{n,in}$ = 2 MeV
M_{Fe}	… molar mass of target	= 55.845 g/mol	
$n(Fe)$	… purity of target	= 0.998	
$n(Fe\text{-}56)$	… abundance of isotope	= 0.9172	
N_A	… Avogadro constant		

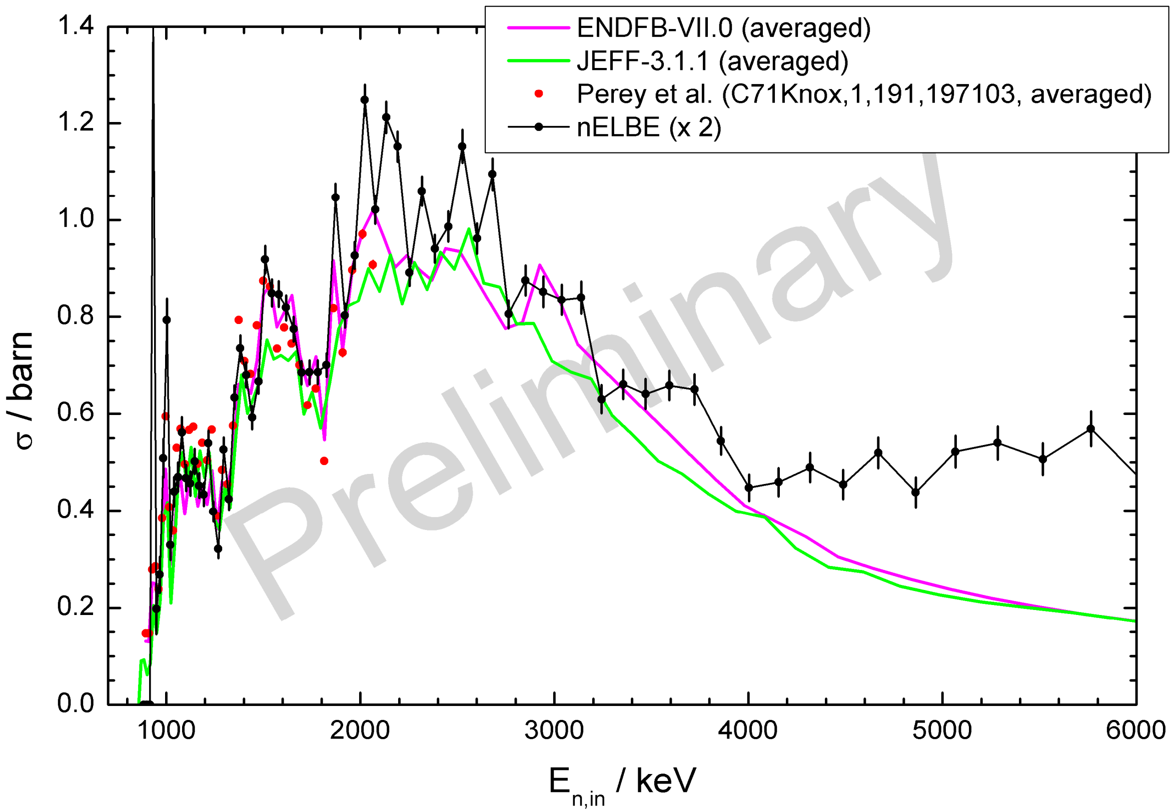
$$N_{targ} = \frac{m_{targ} \cdot n(Fe) \cdot n(Fe\text{–}56) \cdot N_A}{M_{Fe}}$$ = 1.956 x10^{23}

$$\sigma = \frac{R}{\Phi_{n,targ} \cdot N_{targ}}$$ = 1.5(1) b

The $^{56}Fe(n,n'\gamma)$ cross section for the 1st excited state



The ^{56}Fe(n,n'γ) cross section for the 1st excited state

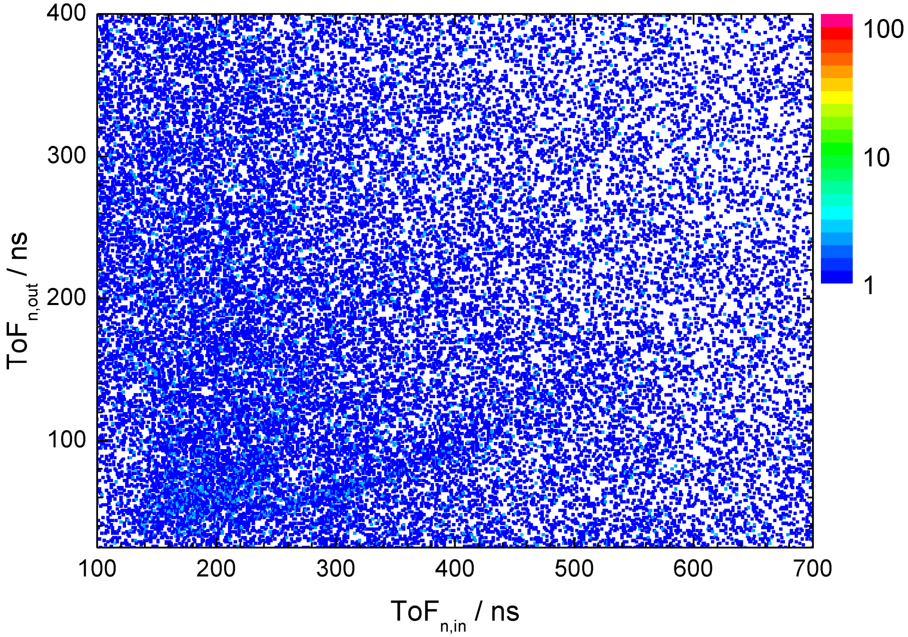


Uncertainties:	@ 2 MeV
Fission chamber efficiency	2.1 %
Fission chamber counts	0.7 %
Fission chamber background	1.8 %
Loss due to ADC range	0.1 %
Scaling factor FC<->Target	0.3 %
Attenuation factor	0.9 %
→ Neutron flux	2.4 %
Sample in counts	2.3 %
Sample out counts	12.8 %
Normalization factor	1.7 %
BaF_2 efficiency	1.9 %
Plastic efficiency	(2.3 %)
→ Reaction rate	3.8 %
→ Cross section	**4.5 %**

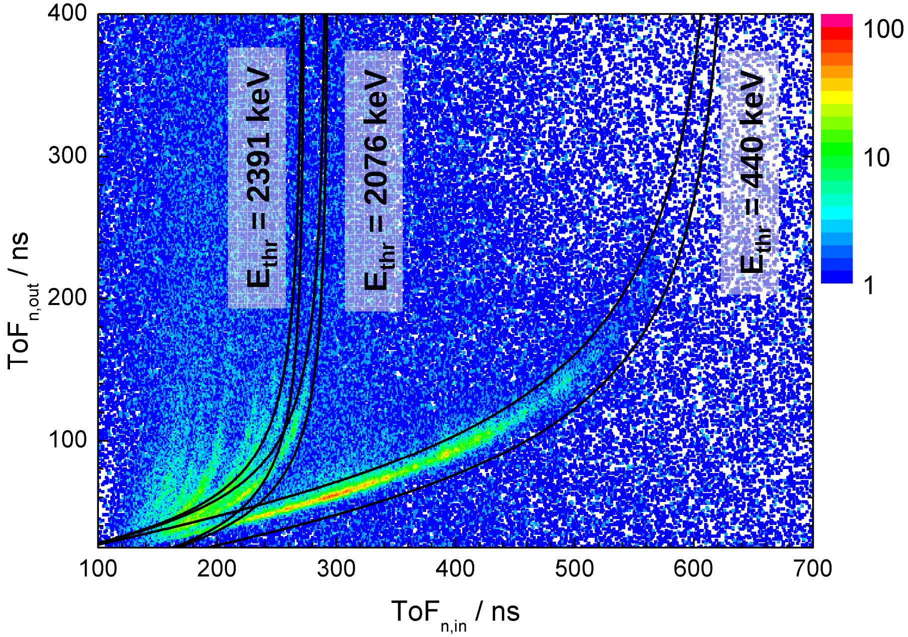
➔ absolute normalization still missing

Inelastic neutron scattering on ^{23}Na

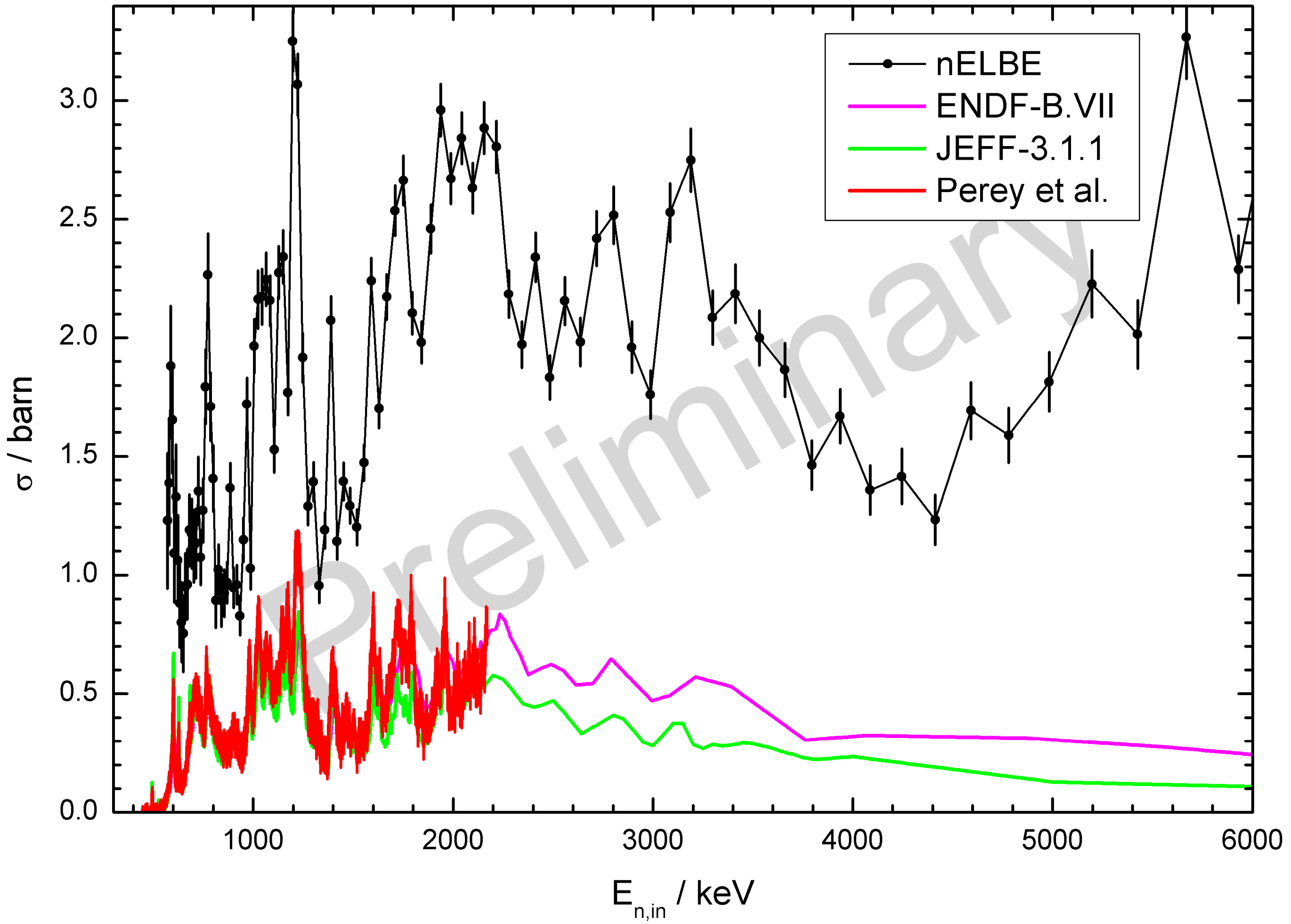
without target



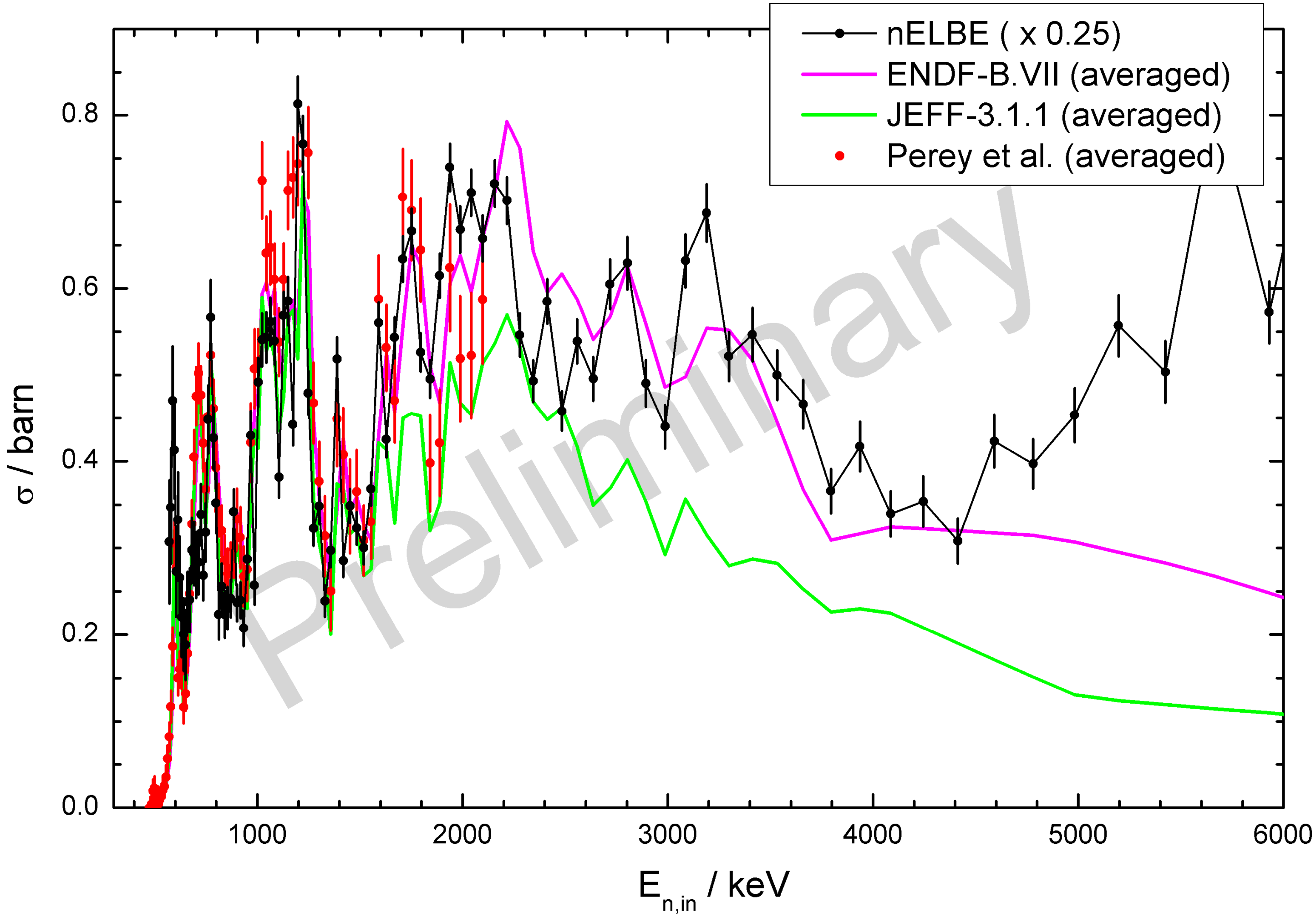
Na-23



Inelastic neutron scattering on ^{23}Na



Inelastic neutron scattering on ^{23}Na



Summary and outlook

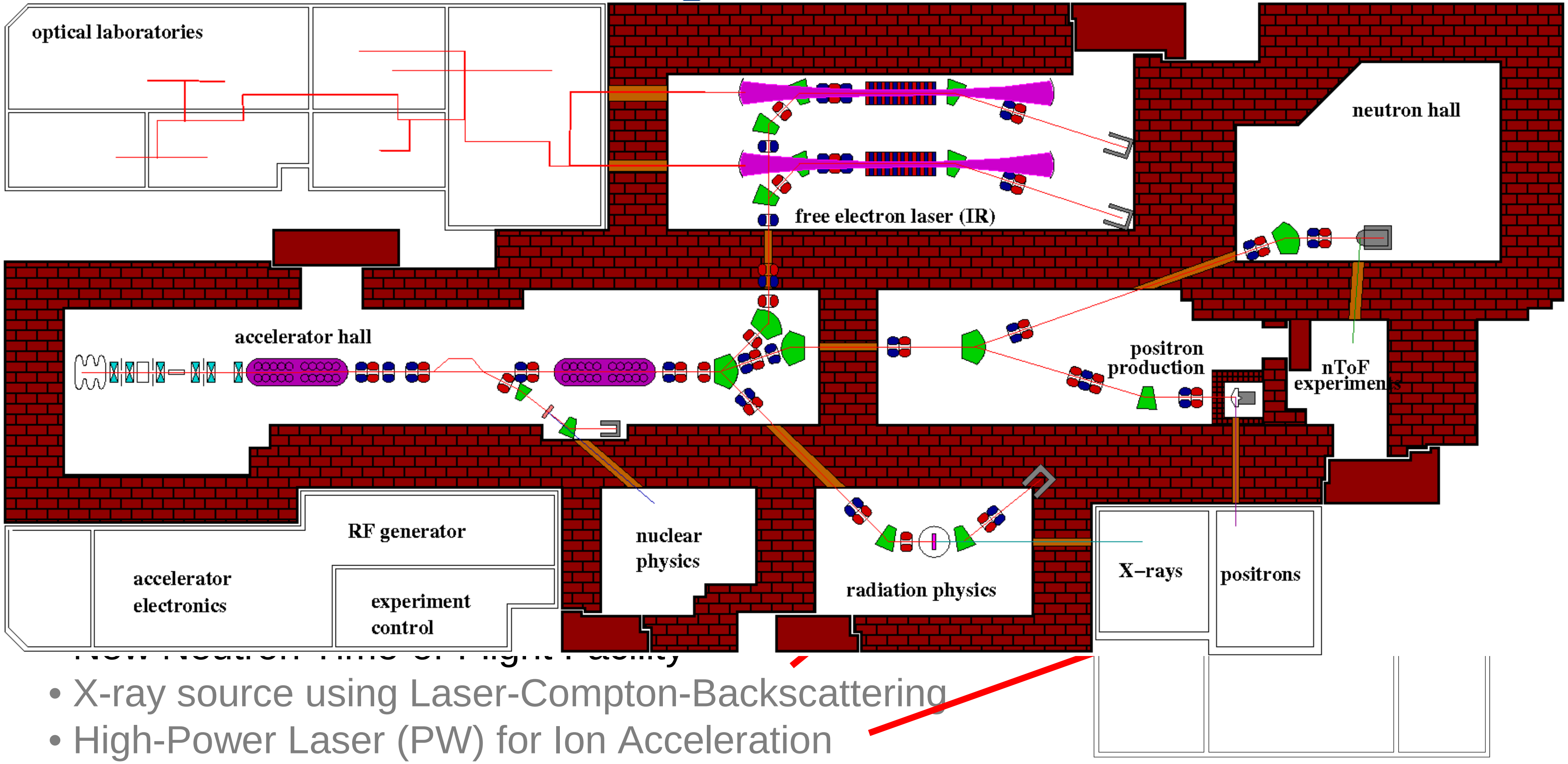
- nELBE is intended to deliver data on fast neutron induced reactions
- the ELBE electron beam delivers a high neutron flux
  (new injector will deliver ~60 times more)

- first experiments were performed on inelastic neutron scattering using a double time of flight setup on Fe-56 and Na-23
- further investigations have to be done to:
  - re-measure plastics efficiency
  - determine influence of double scattering
  - correct for angular effects → neutron-gamma angular correlation

- prepare measurements of neutron fission cross sections

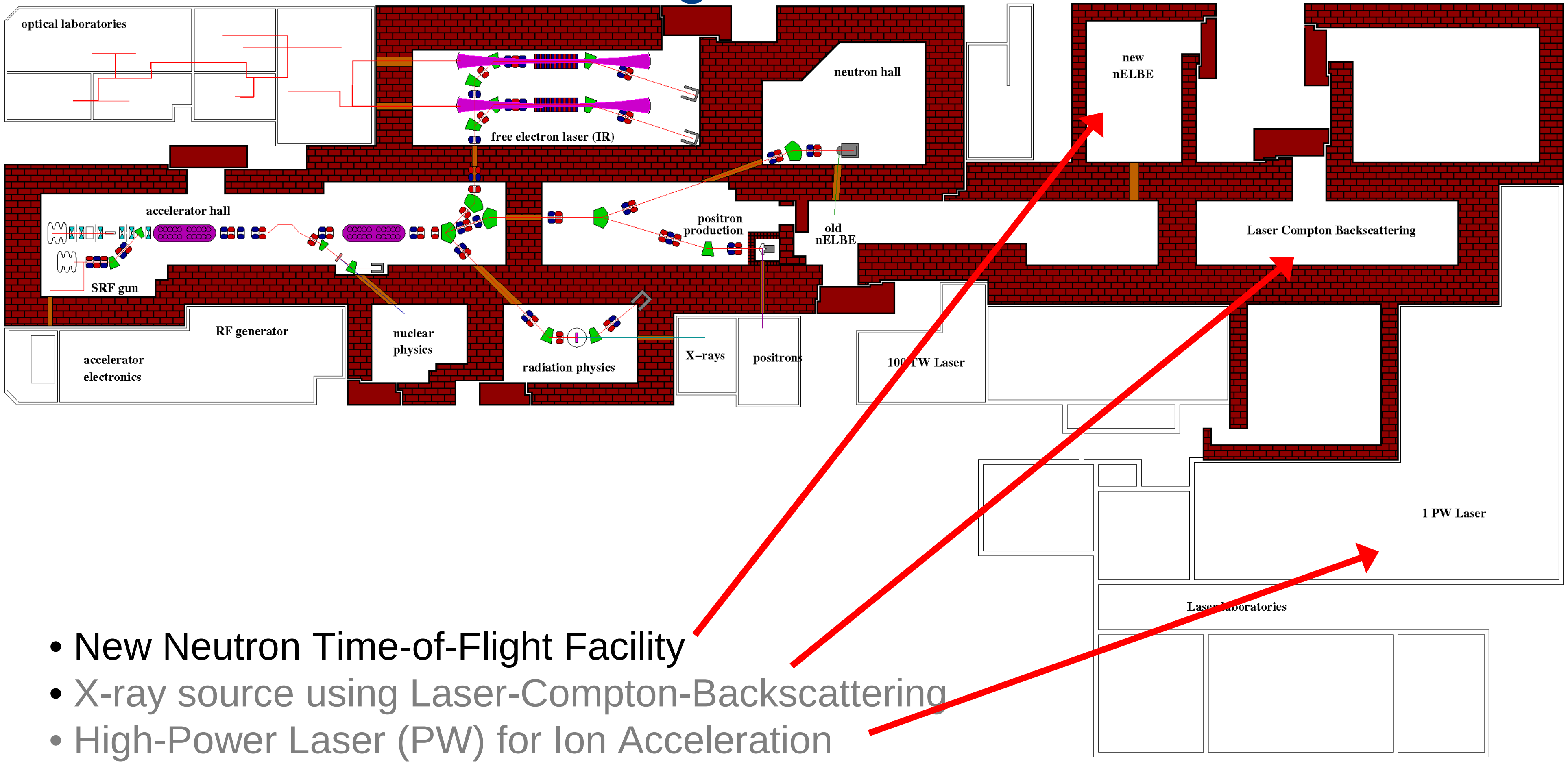
- new bigger experimental area within extension of ELBE facility

National Center for High-Power Radiation sources



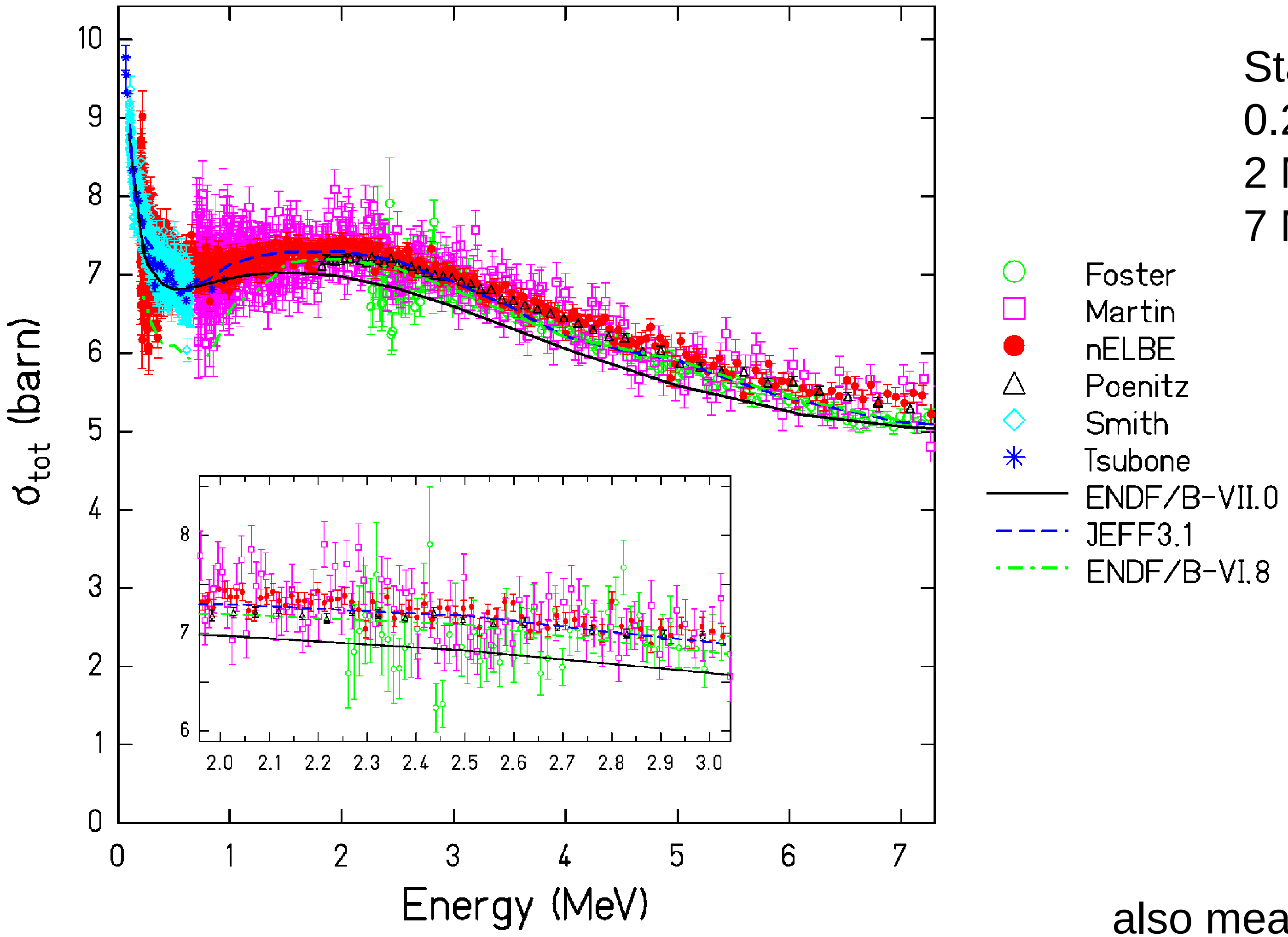
- X-ray source using Laser-Compton-Backscattering
- High-Power Laser (PW) for Ion Acceleration

National Center for High-Power Radiation sources



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

Total neutron cross section of ^{nat}Ta



Statistical uncertainty:
0.2 MeV – 5 %
2 MeV – 1.2 %
7 MeV – 2.3 %

also measured: ^{nat}Au

Thanks to all collaborators

FZD, Institute of Radiation Physics:

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FZD, Department Radiation Protection and Safety:

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M. Mosconi, R. Nolte, S. Röttger

Others:

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