nELBE: A compact photoneutron source for measurements with fast neutrons

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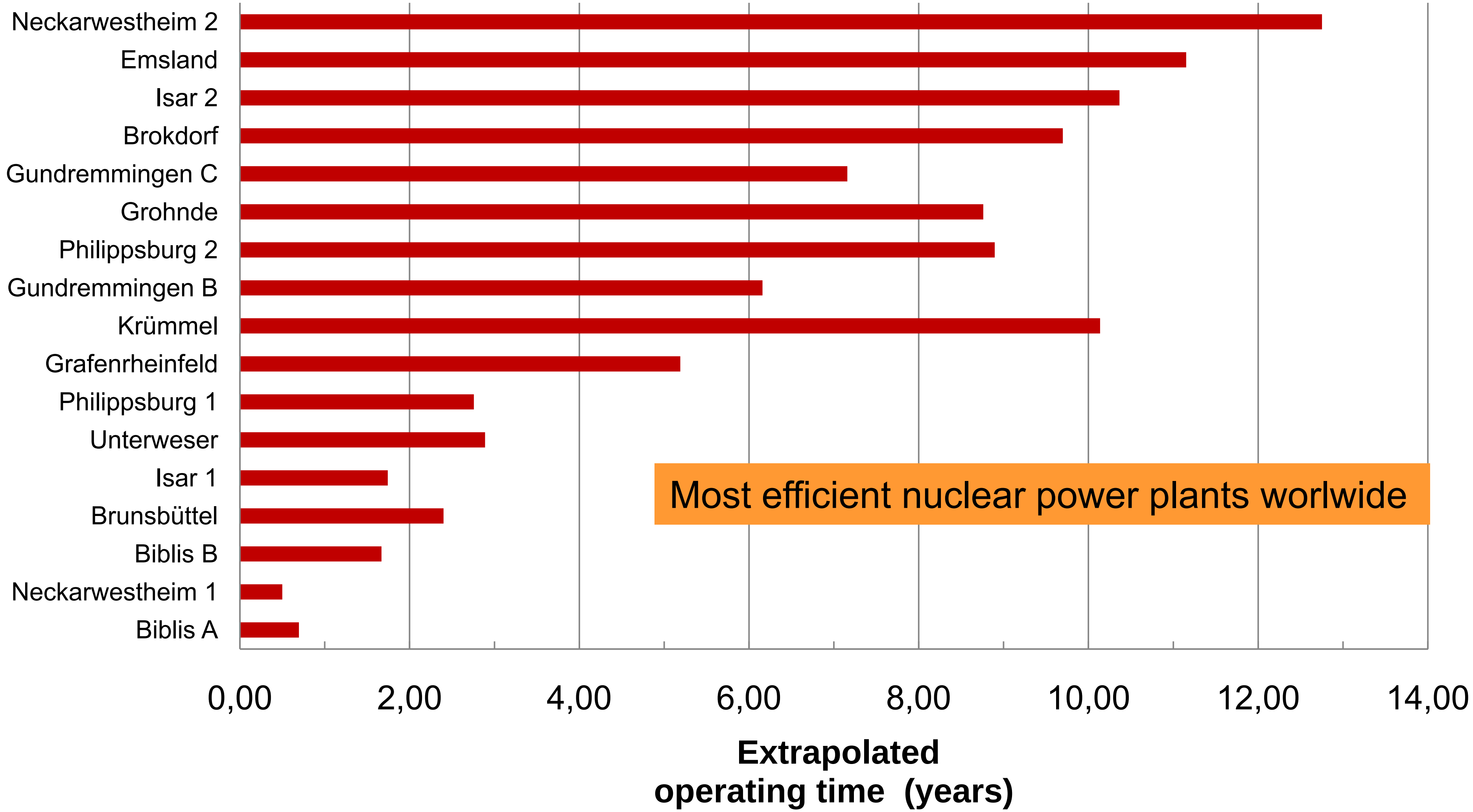
Spent nuclear fuel

Fast neutrons for transmutation

Measuring nuclear reactions relevant to transmutation at ELBE

Residual operating time of german nuclear power plants



Spent nuclear fuel from nuclear power plants worldwide

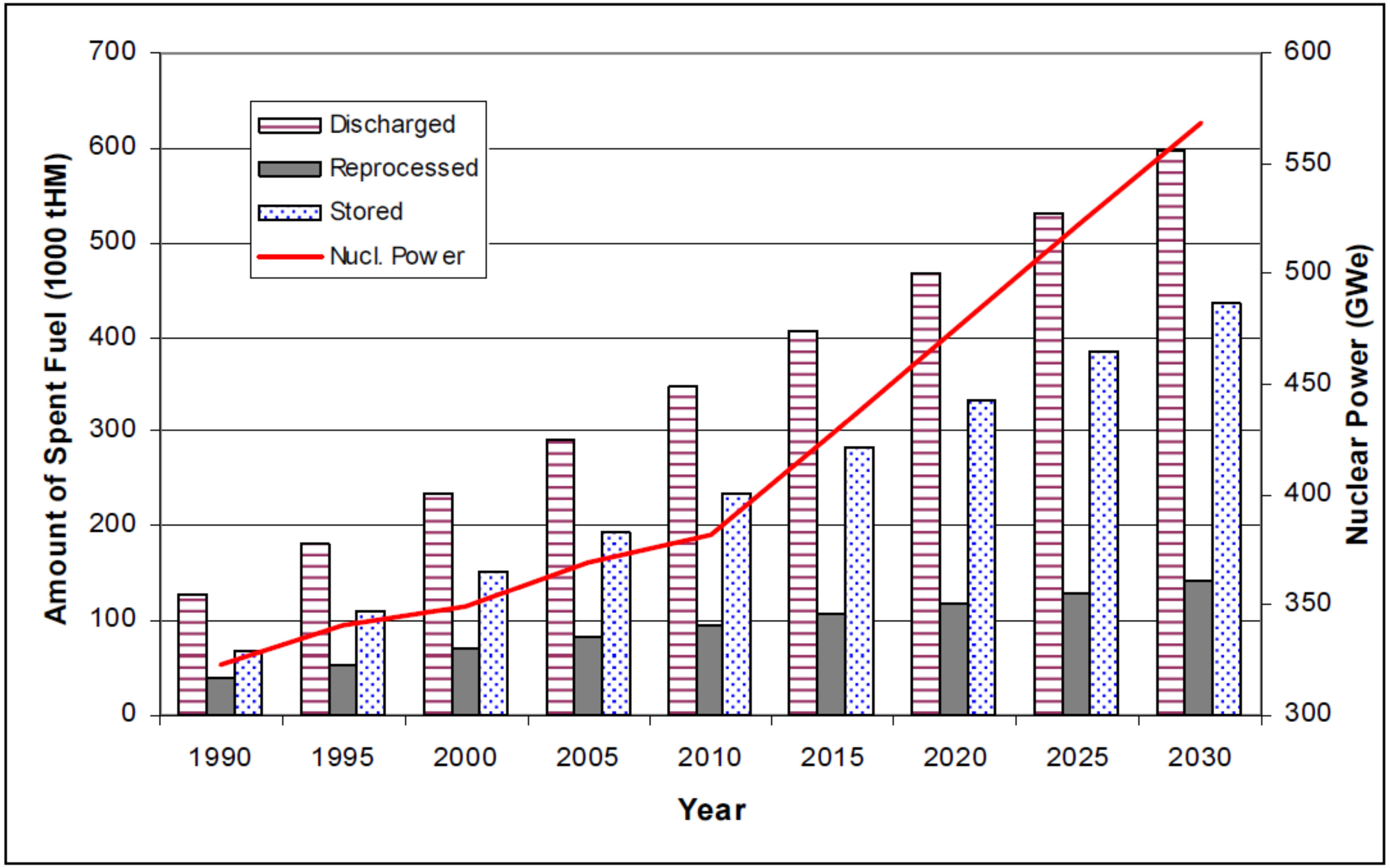
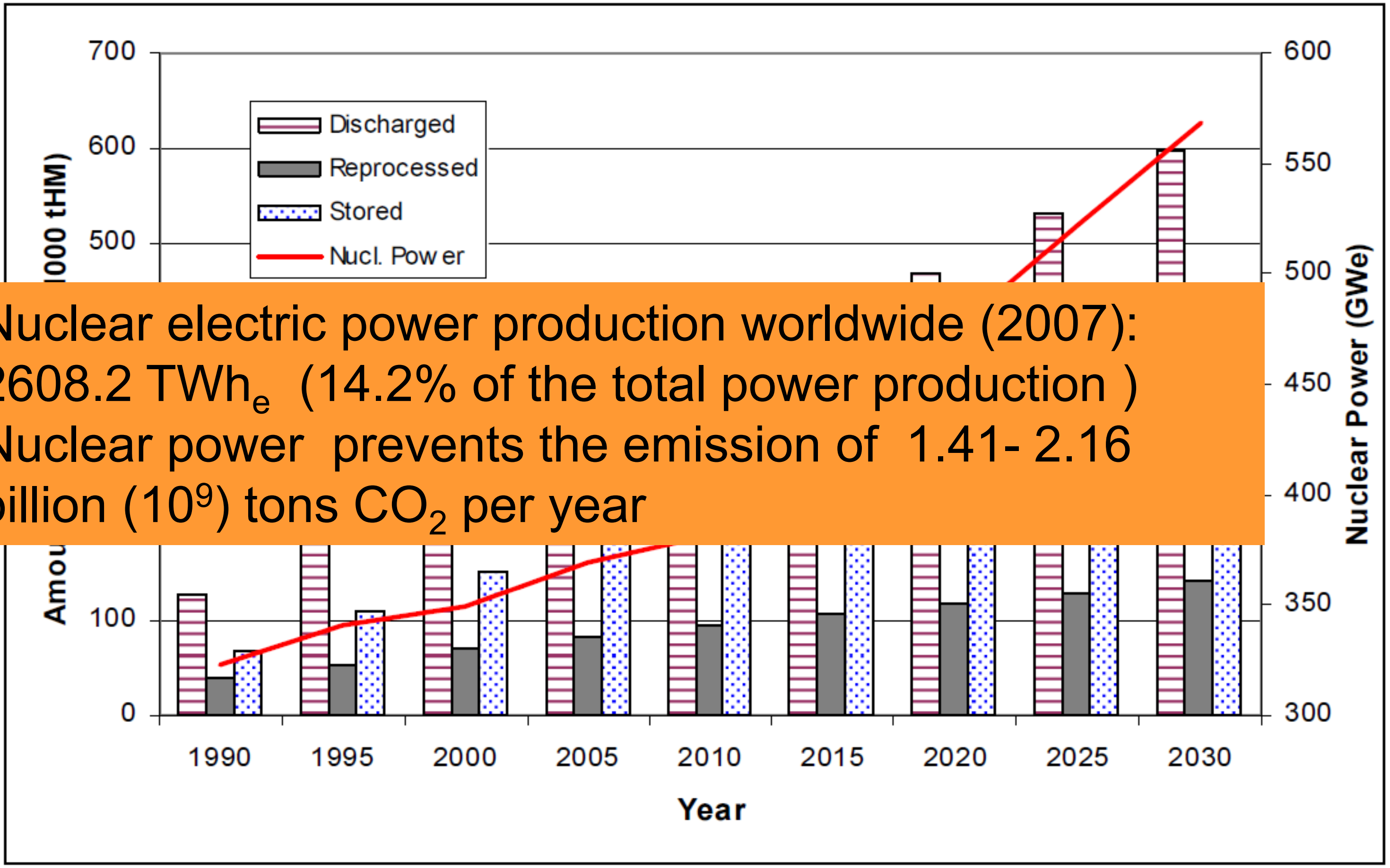


Fig. 14. Cumulative spent fuel discharged, stored and reprocessed from 1990 to 2030.

Quelle: IAEA-TECDOC-1613, April 2009

based on the median of the IAEA-RDS-1 Nuclear power estimate

Spent nuclear fuel from nuclear power plants worldwide



Nuclear electric power production worldwide (2007): 2608.2 TWh_e (14.2% of the total power production)
Nuclear power prevents the emission of 1.41- 2.16 billion (10^9) tons CO_2 per year

Fig. 14. Cumulative spent fuel discharged, stored and reprocessed from 1990 to 2030.

Quelle: IAEA-TECDOC-1613, April 2009
based on the median of the IAEA-RDS-1 Nuclear power estimate

Highly radioactive waste from german nuclear power plants

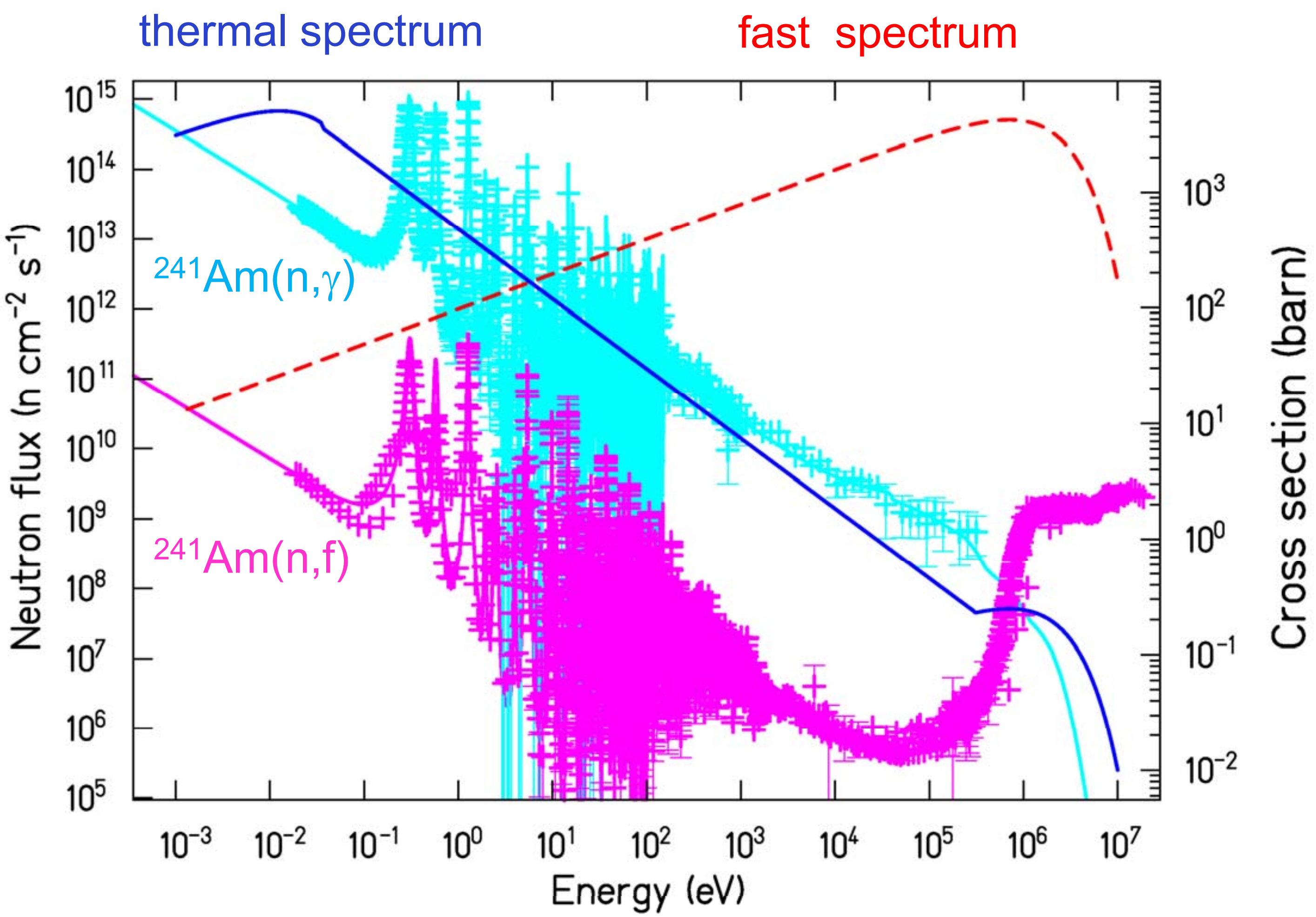
- 01.07.2005 Ban of reprocessing of irradiated nuclear fuel   (atomic energy act)
- 01.01.2022 Anticipated end of nuclear power production in Germany

Quantity	PWRUOX	PWRMOX	BWRUOX	BWRMOX	**Total SF**	HLW
Total (t)	5350	773	3470	246	**9840**	215.0
U (t)	5060	702	3310	227	**9290**	0.7
Pu (t)	51.7	34.3	32.9	7.95	**127**	0.2
Np (t)	3.6	0.234	2.16	0.0497	**6.04**	2.9
Am (t)	4.6	4.96	3.48	1.17	**14.2**	3.6
Cm (t)	0.23	0.226	0.148	0.0644	**0.669**	0.1

Quelle: M. Salvatores, et al., NFCSim Scenario Studies of German and European Reactor Fleets, 2004

SF = Verbrauchter Kernbrennstoff (spent nuclear fuel)
HLW = Hochradioaktiver Abfall (Spaltprodukte,…) (high level waste)

Neutron capture – neutron induced fission



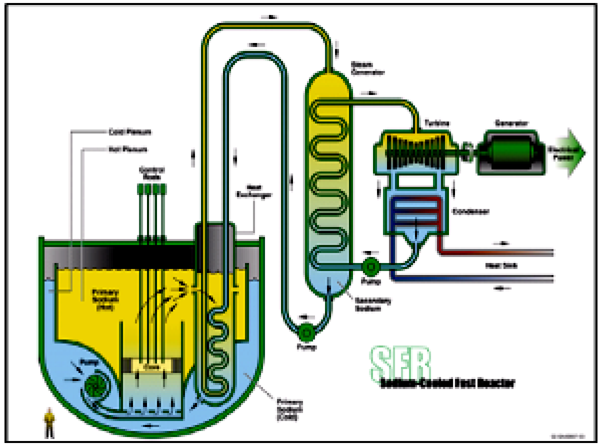
Neutron capture is dominating fission in a thermal spectrum

Fission is more probable than capture in a fast spectrum.

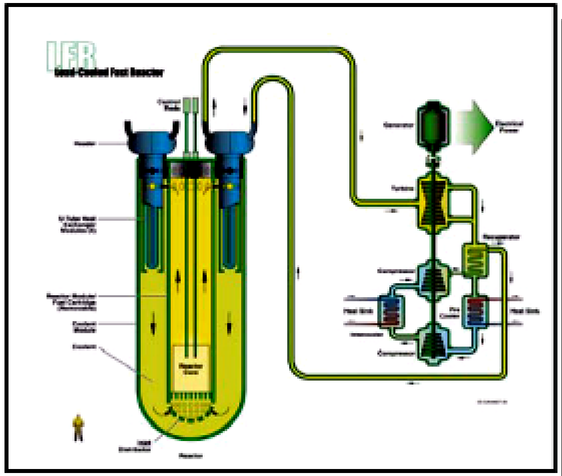
^{241}Am(n,γ) JEFF-3.1 Evaluation; Exp.(EXFOR): M. Jandel (2008), G.. Vanpraet (1985), N. Shinohara (1997),…

^{241}Am(n,f) JEFF-3.1 Evaluation, Exp.(EXFOR): B. Jurado (2007), J.W.T. Dabbs (1983), H.H. Knitter (1979), P.E. Vorotnikov (1986), ….

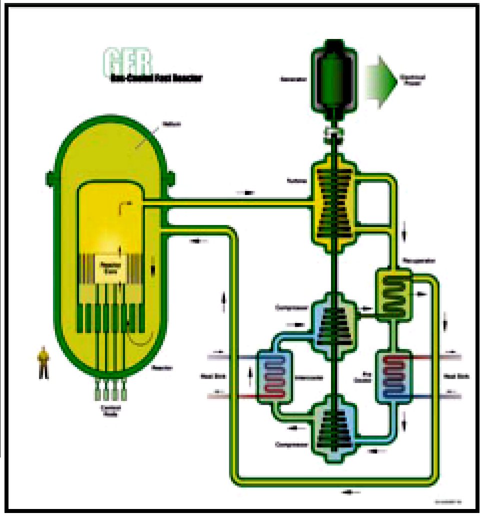
Generation IV nuclear power reactors



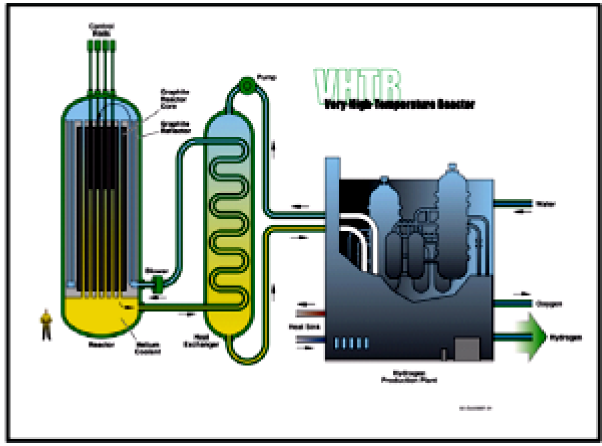
Sodium Fast Reactor



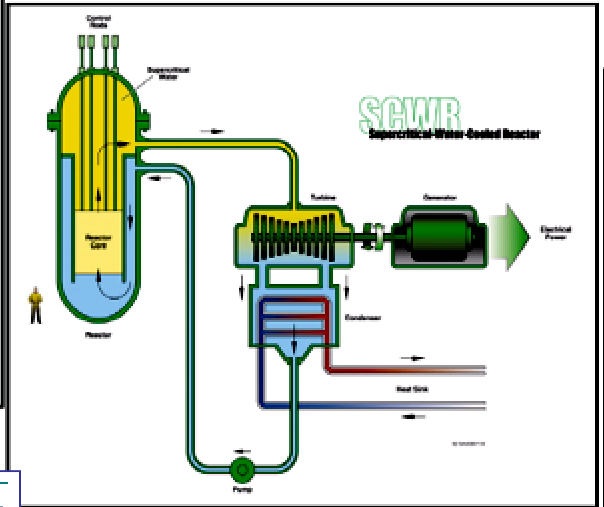
Lead Fast Reactor



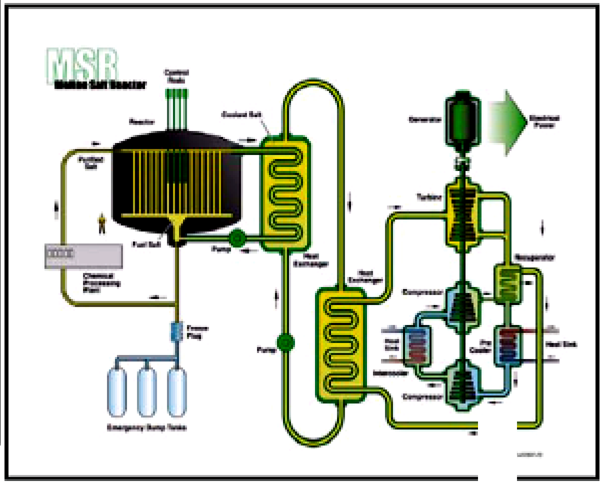
Gas Fast Reactor



Very High Temperature Reactor



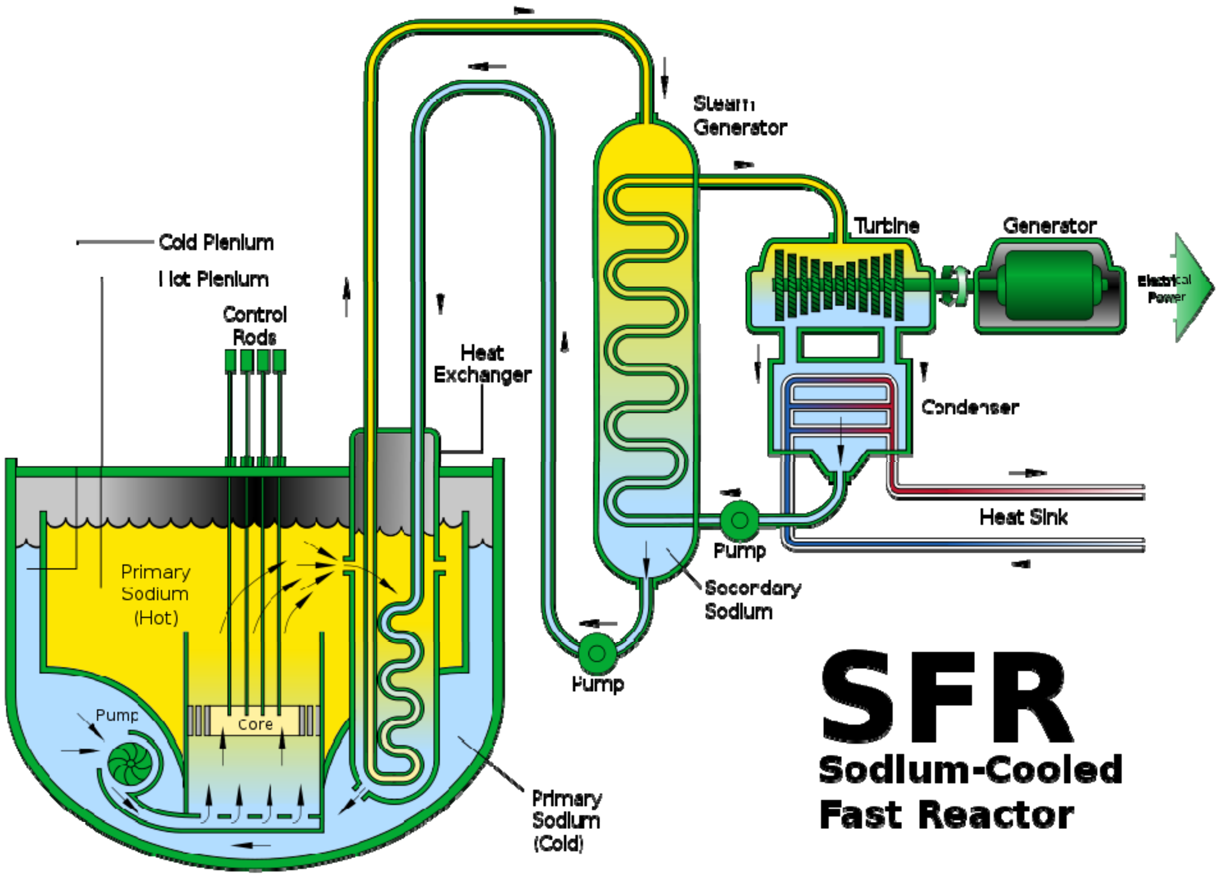
Superciritical Water Reactor



Molten Salt Reactor

GEN IV Nuclear Energy Systems

Sodium-cooled fast reactor



Optimized for transmutation:
Pu-M.A.-Zr fuel
metallic matrix

homogeneous recycling of Pu and m.a.

pyrometallurgical reprocessing (on site)

transmutational properties are largely known.
Operational time scale approx. 2015
(oxide based fuel)

France: „preliminary design parameter“ to be fixed (until 2012)
Industrial prototype in operation until 31.12. 2020

Zeitplan gemäss: THE 2006 PROGRAMME ACT ON THE SUSTAINABLE MANAGEMENT OF RADIOACTIVE MATERIALS AND WASTES

Accelerator Driven Systems (ADS)

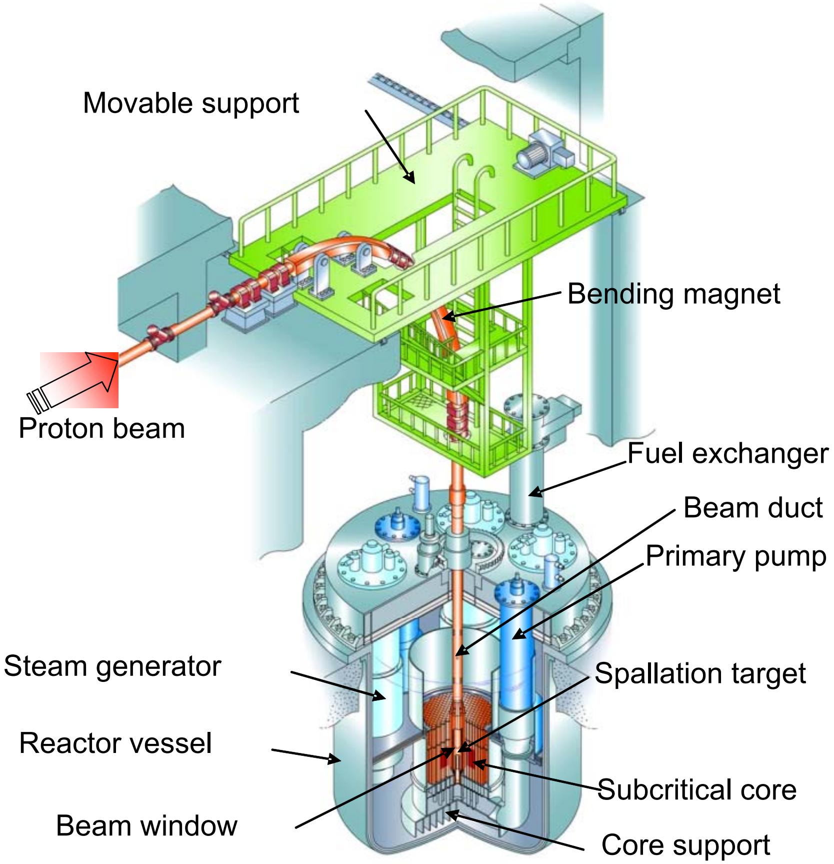


Abb. Hiroyuki OIGAWA
Euratom PARTRA Cluster Meeting Karlsruhe
Feb. 2008

- Accelerator driven intense thermal neutron source, C.D. Bowman 1992, Energy Amplifier, C. Rubbia, 1995
- subcritical core k ≈ 0.97
  thermal power: 400 MWt
- Highest Performance-proton-accelerator 800 MeV
  ca. 10 mA beam current 8 MW- beam power
- Liquid metal cooling Pb, Pb/Bi oder Na
- Criticality controlled by spallation neutrons
  ca. 15-30 n / proton

Challenges:

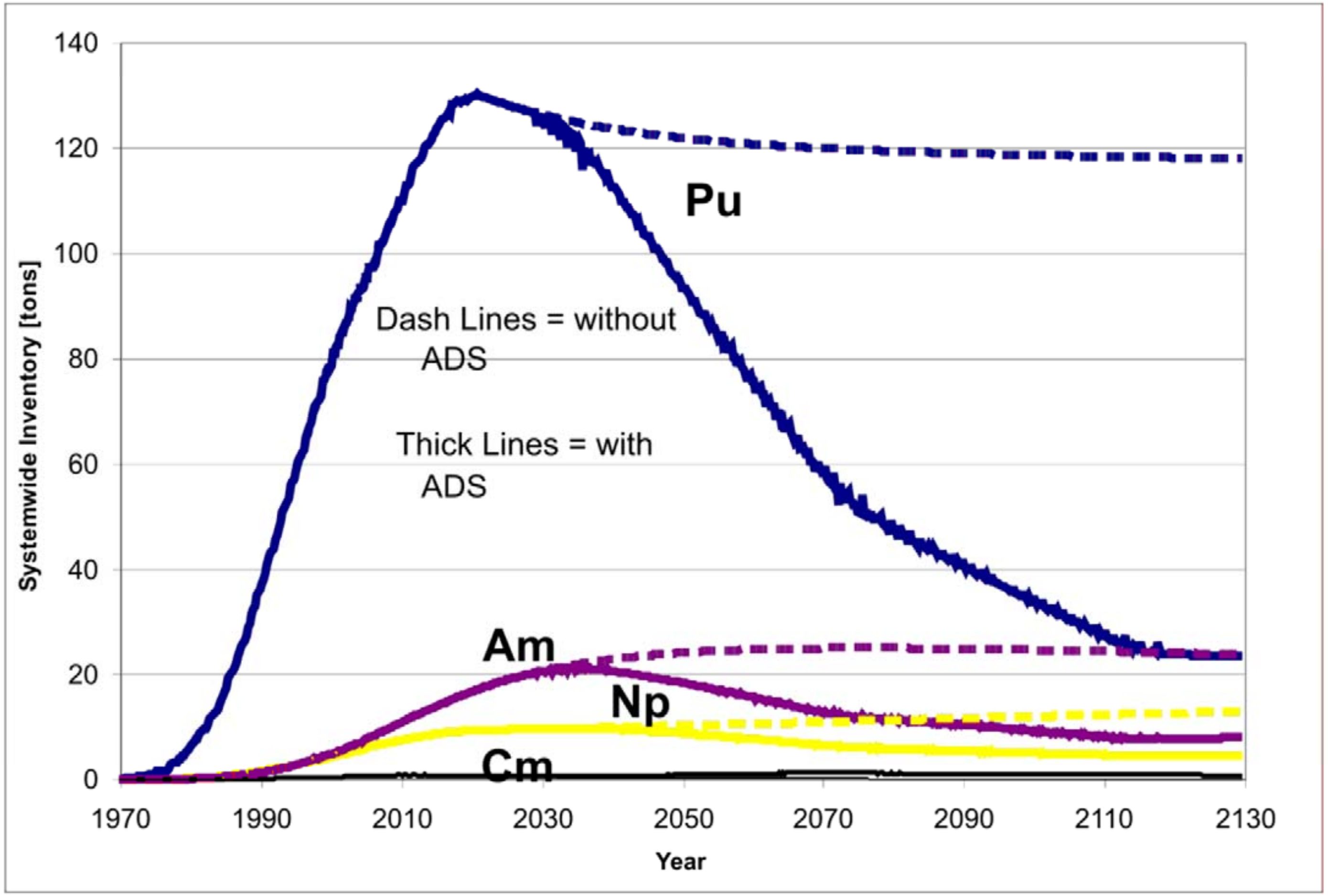
Reliability of the accelerator
(Linac, Cyclotron)

Development of the spallation target (window?)

EUROTRANS Projekt KIT (J. Knebel) ➔ XT-ADS

Myrrha project, SCK.CEN, Mol Belgien

Transmutation study for Germany (ADS based)

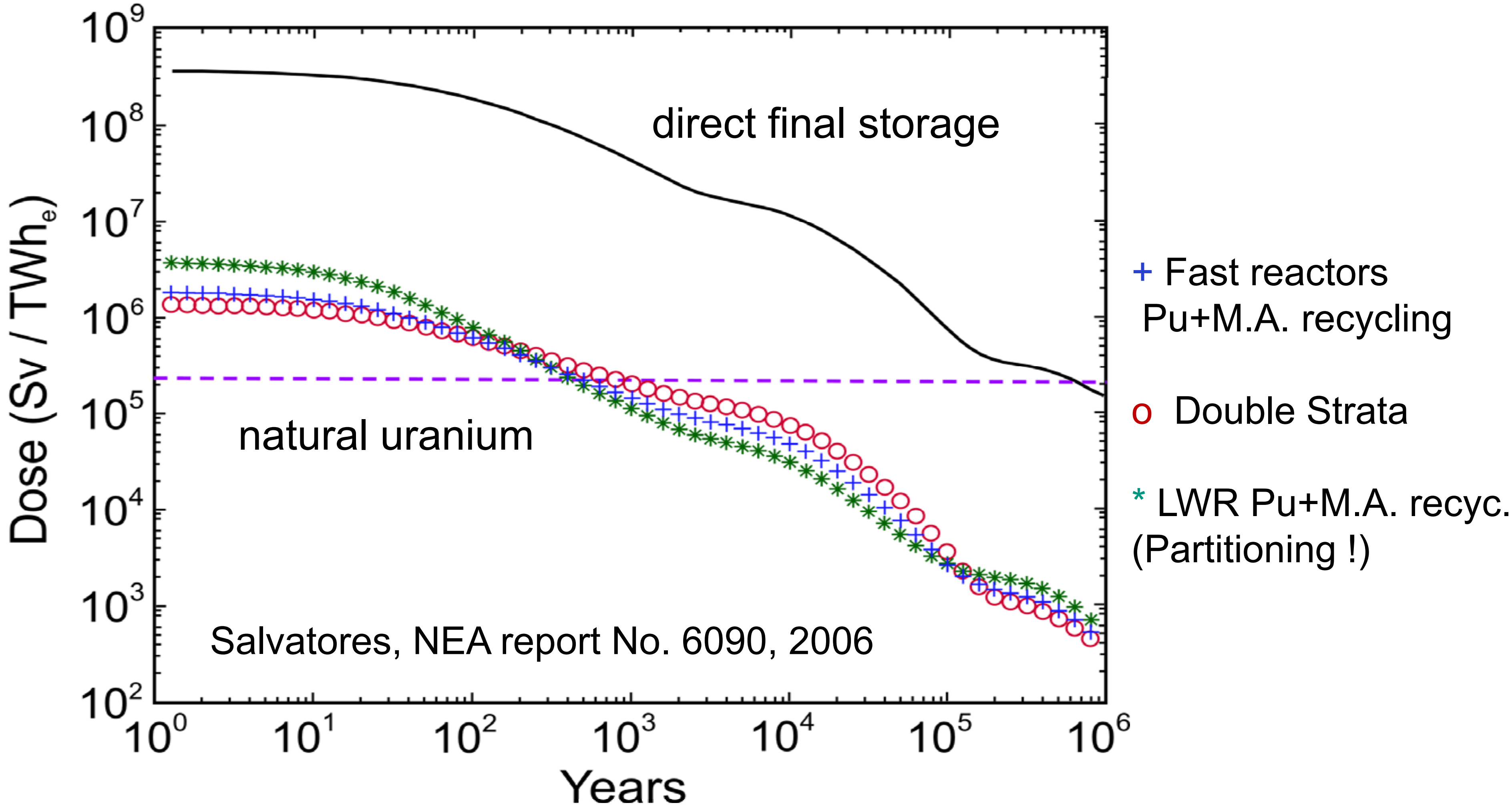


Begin: 2030
8 ADS Transmuter
(840 MWth)
3 ADS Transmuter

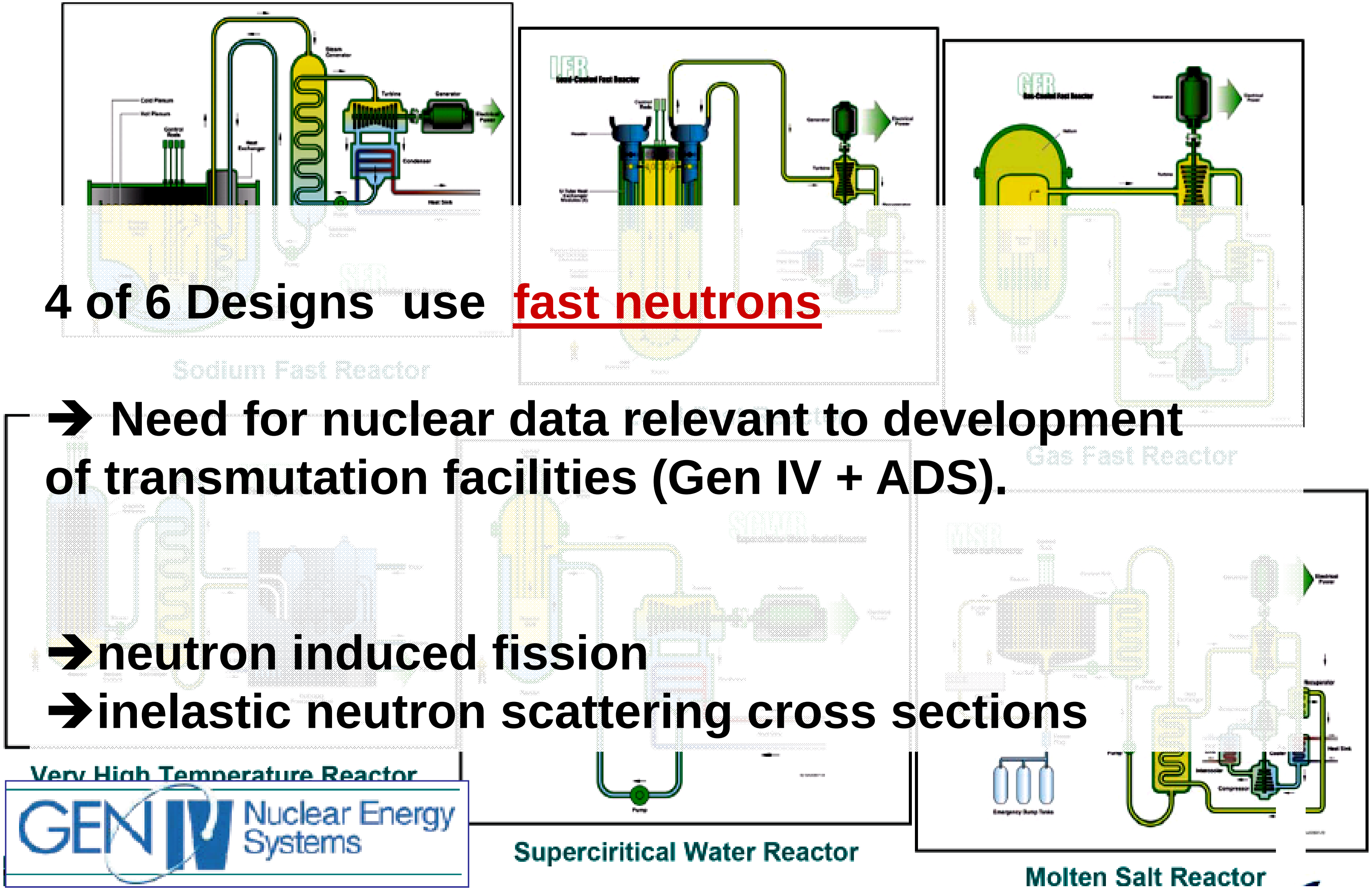
Transmutation
of 100 t Pu
and minor actinides
in 100 years

Bild: M. Salvatores et al., NEA report 6194, 2009

Transmutation of spend nuclear fuel



➔ Reduction of radiotoxicity by a factor ≈100. Final storage for approx. 1000 years



4 of 6 Designs use fast neutrons

➔ Need for nuclear data relevant to development of transmutation facilities (Gen IV + ADS).

➔neutron induced fission

➔inelastic neutron scattering cross sections

Data needs for fast reactors and ADS

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

➔ fast neutron spectrum

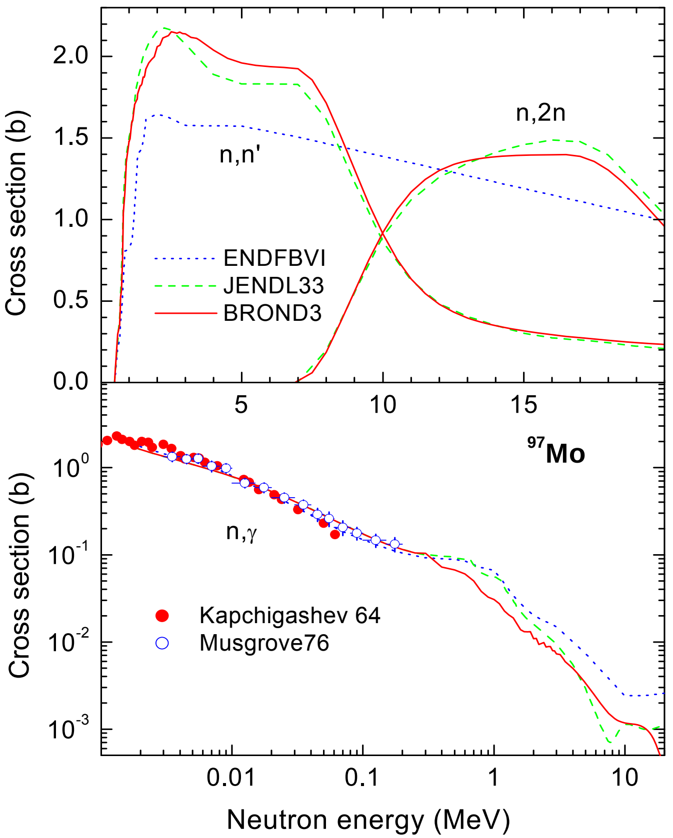
➔ U,Pu + minor actinides
structural & coolant materials

- neutron induced fission
- neutron capture
- neutron inelastic scattering

➔ $^{56}Fe\ (n,n'\gamma)\ ^{56}Fe$

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

nELBE research program:



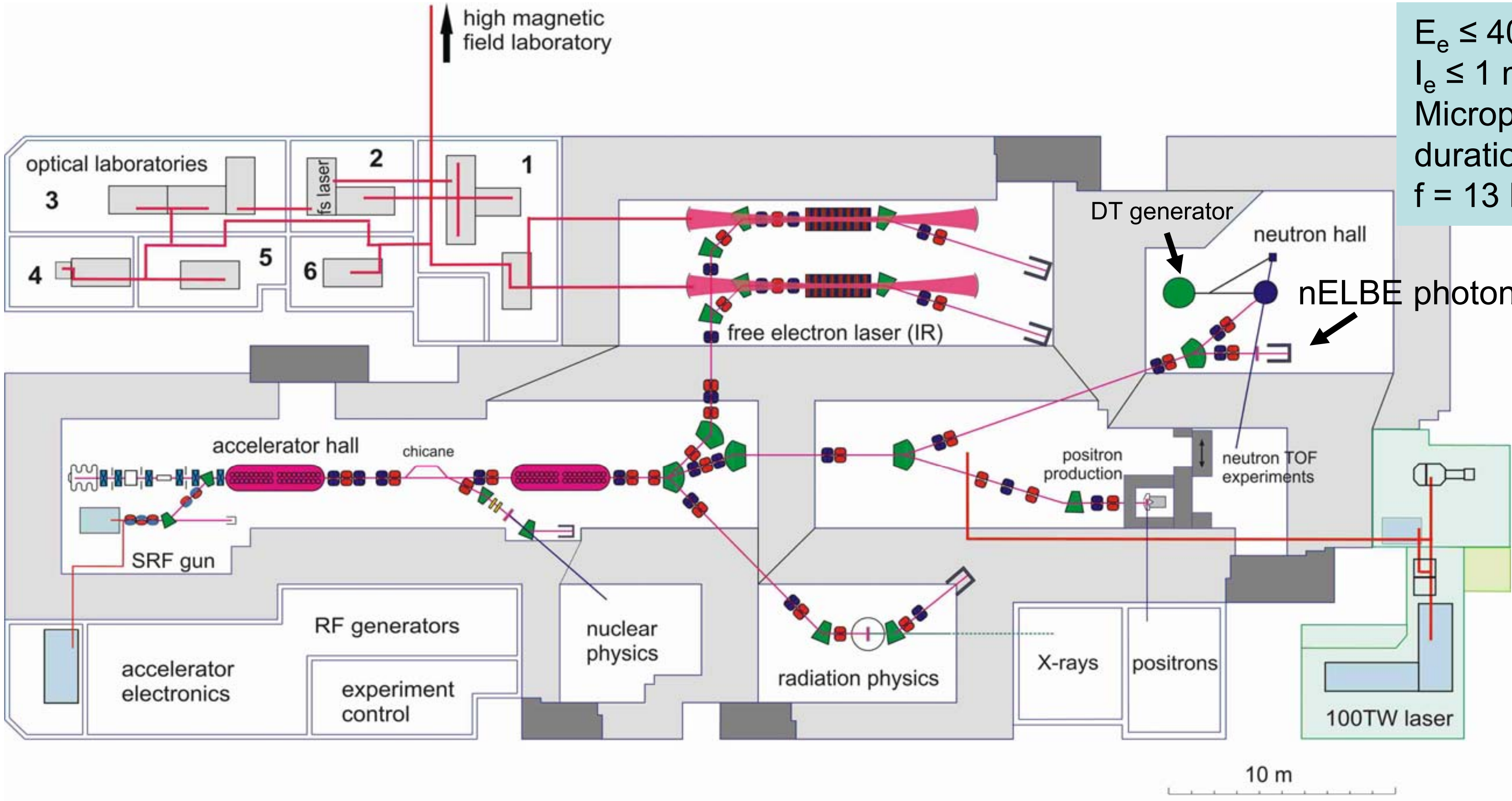
A. V. Ignatyuk, priv.com. 2008

- Investigation of fast neutron induced reactions of relevance for nuclear transmutation and the development of Gen IV reactor systems

1. **Inelastic neutron scattering (n,n‘γ)**
   ^{56}Fe, Mo, Pb, ^{23}Na and total neutron cross sections σ_{tot} (Ta, Au, Al, C, H)
2. **Investigation of minor actinides (radioactive targets)**
   Collaboration with n-TOF at CERN
   Joint research project „Nuclear physics data of relevance for transmutation“ (German Federal Ministry for Science and Technology funded , 02NUK13)

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

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

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

FZ Dresden-Rossendorf invites external groups for experiments at ELBE

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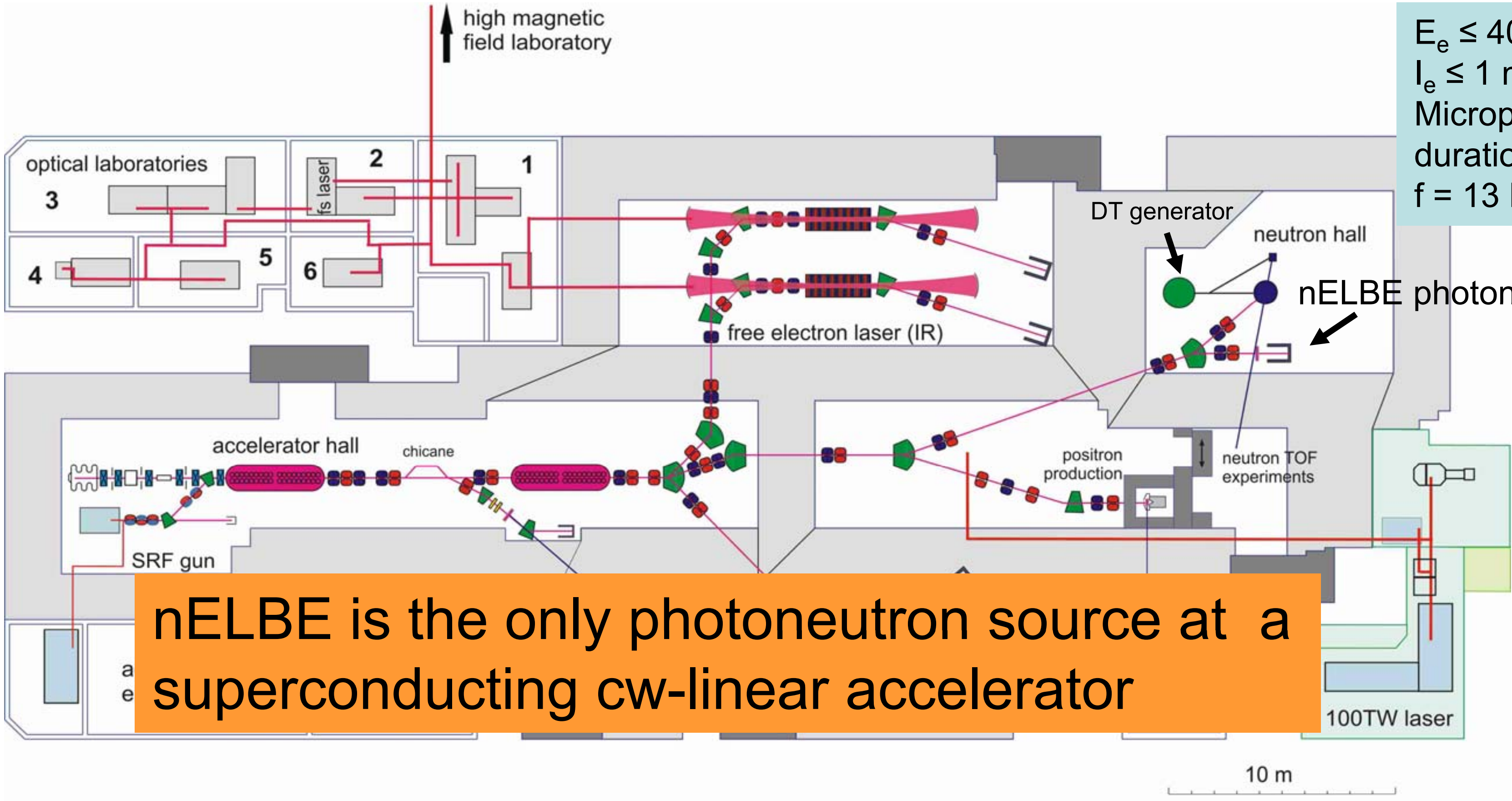
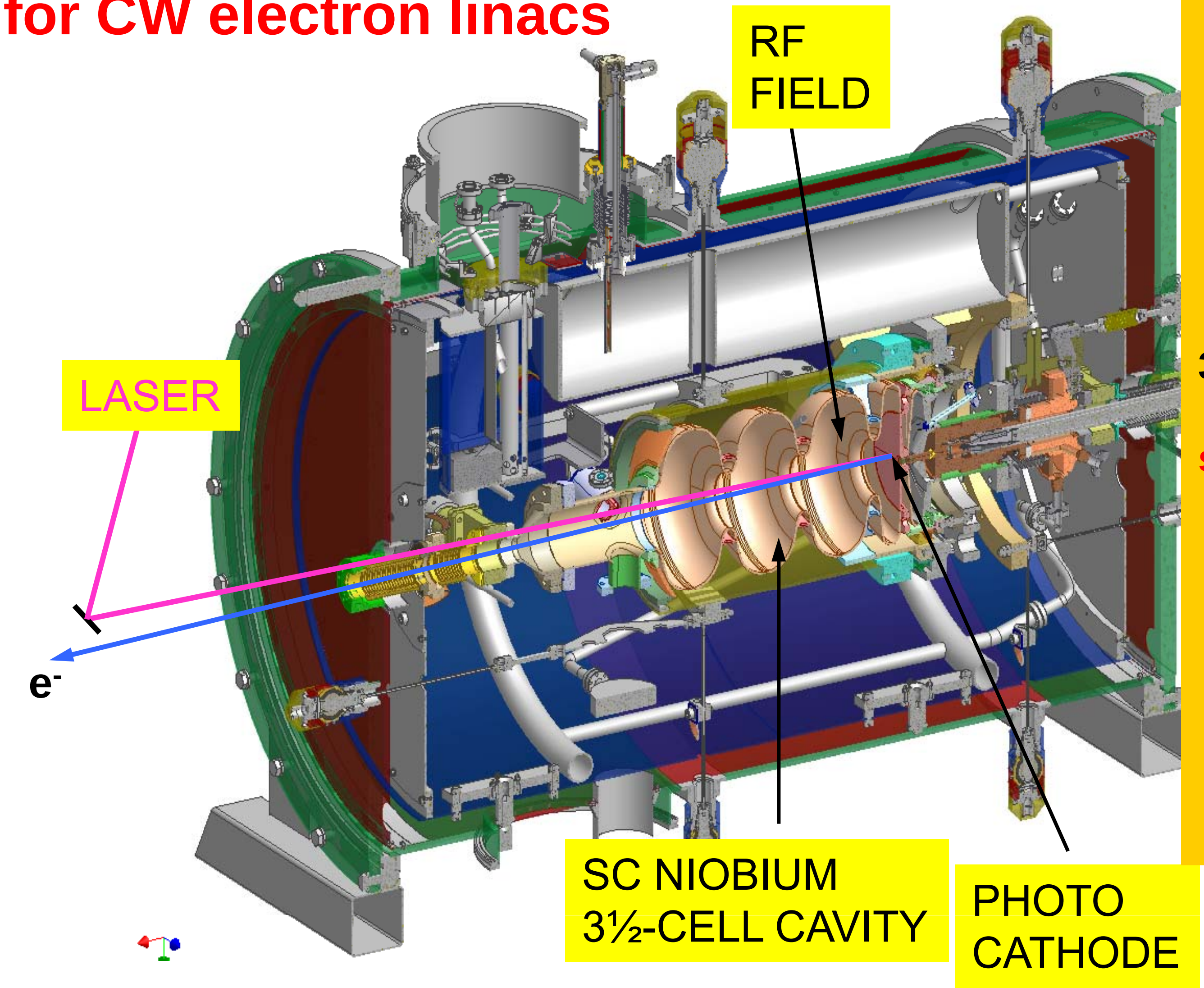


nELBE is the only photoneutron source at a superconducting cw-linear accelerator

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

FZ Dresden-Rossendorf invites external groups for experiments at ELBE

Generation of high-brightness beams for CW electron linacs



1. direct production of short pulses: laser & photo cathode
2. high acceleration field at cathode: radio frequency field
3. CW operation for high average current: superconducting cavity

⇩

ELBE SRF PHOTO INJECTOR

nELBE at ELBE : something special

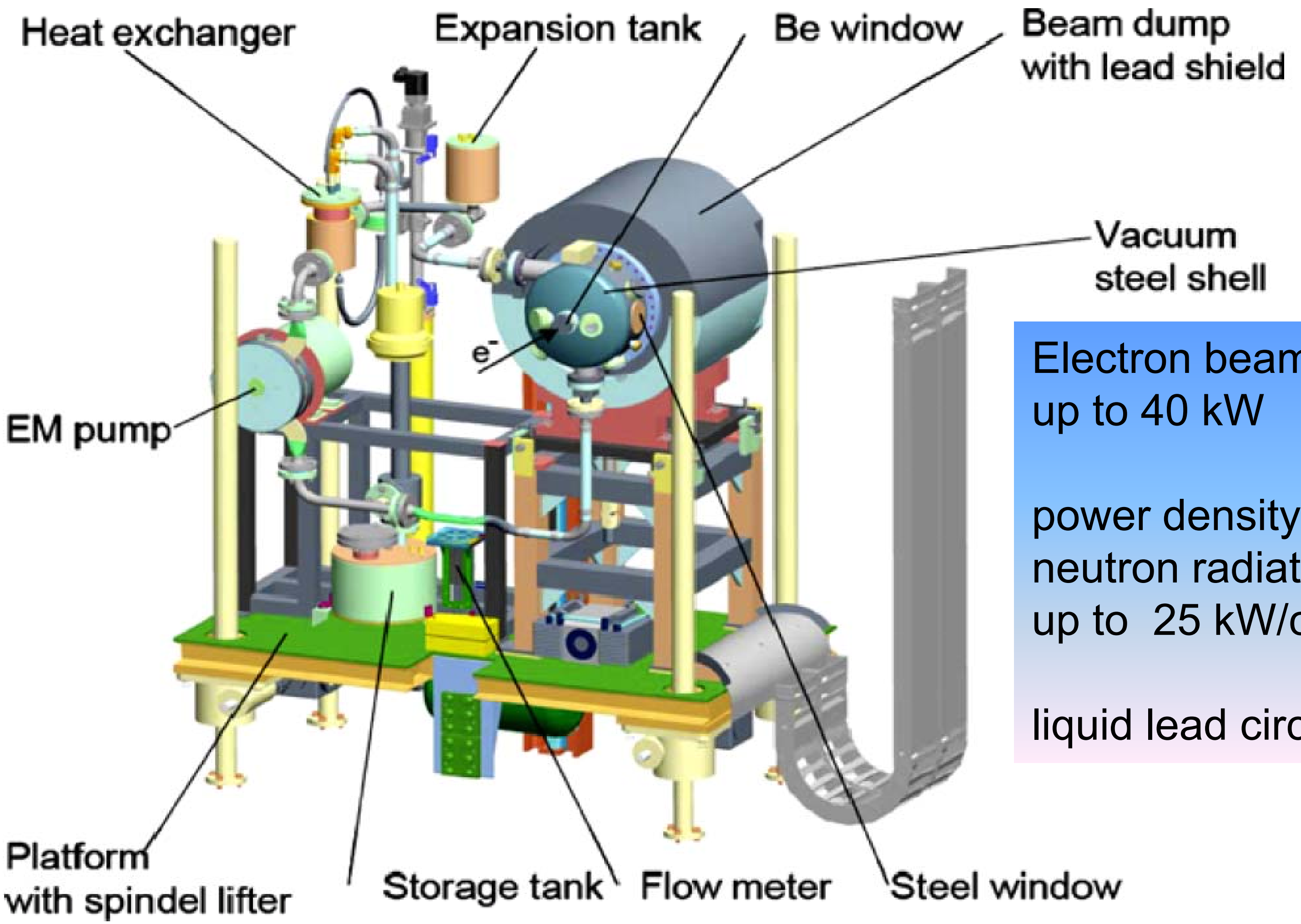
- superconducting electron accelerator cw operation with variable micropulse repetition rate
  - micropulse charge 80 pC (thermionic Injector)
  - micropulse length $\Delta t < 10$ ps ➔ precise definition of time of flight

- For time of flight measurements the repetition rate is adjustable 13 MHz / 2^n , n = 0,…,10
- Very high repetition rate (200 kHz), low instantaneous neutron-flux ➔ background of photon flash from bremsstrahlung is reduced

- Januar 2010 : SRF Laser-Injector (micropulse charge 0.4 - 1 nC)
  ➔ 500 kHz / 0.5 mA
  ➔ average beam power up to 20 kW for time of flight measurements!

• fligh path	4.0 - 8.0 m
• neutron flux on target sample	$0.8 \cdot 10^7$ cm^{-2} s^{-1}
• neutron energy range (Liquid lead target, without moderator)	100 keV < E_n < 10 MeV
• energy resolution with 6.0 m flight path	$\Delta E/E < 1$ %

nELBE photoneutron target

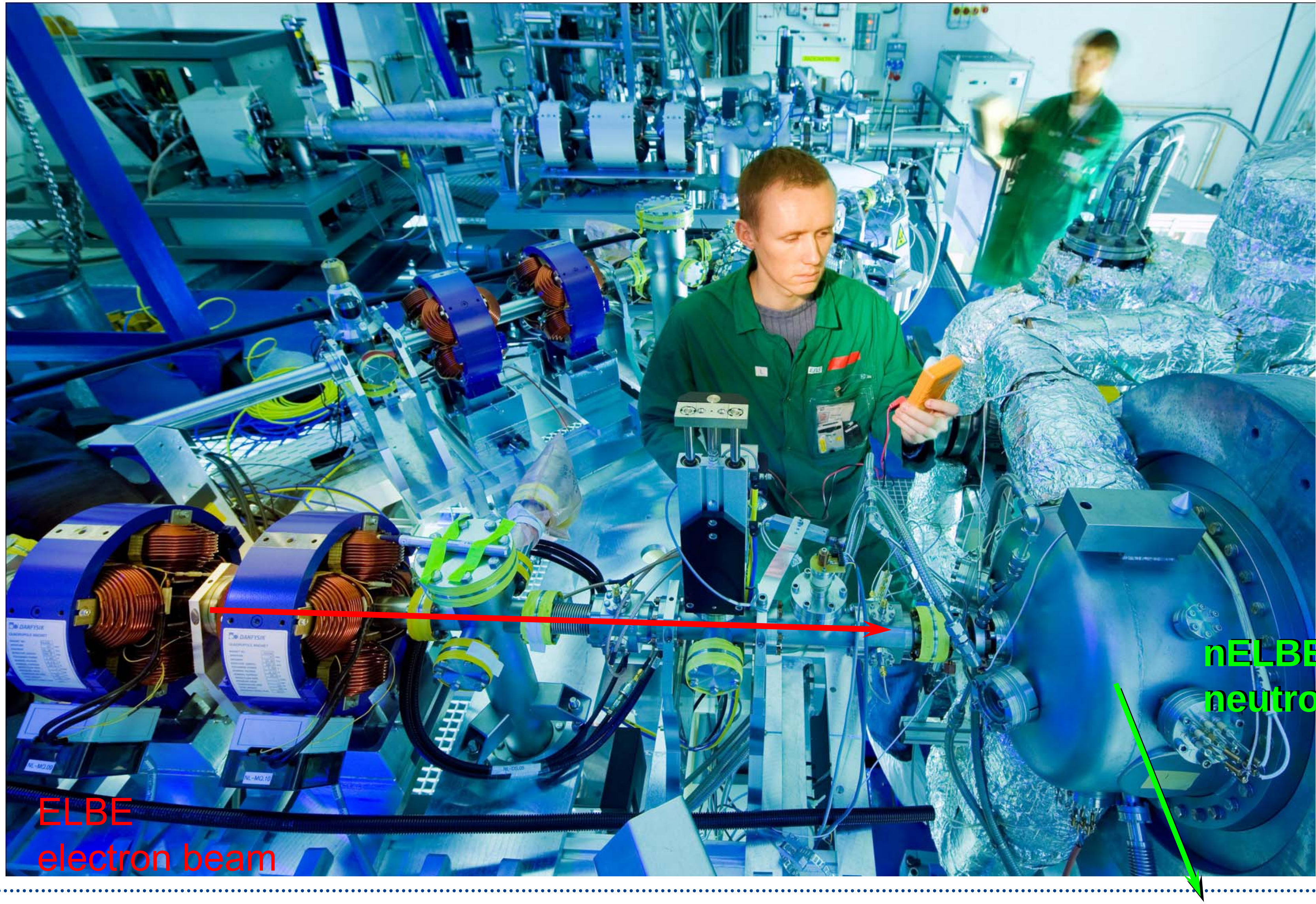


Electron beam power
up to 40 kW

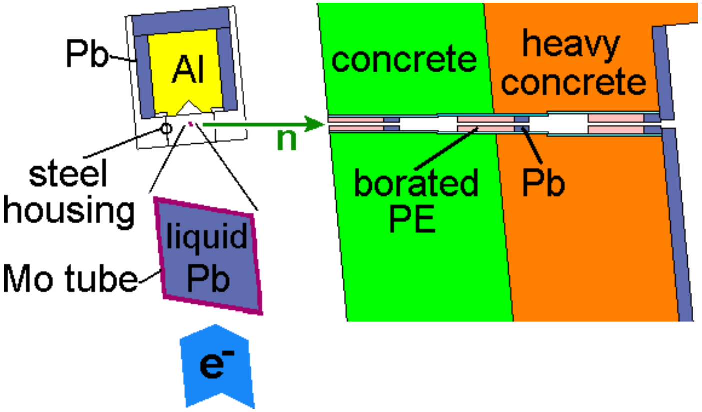
power density in the
neutron radiator
up to 25 kW/cm^3

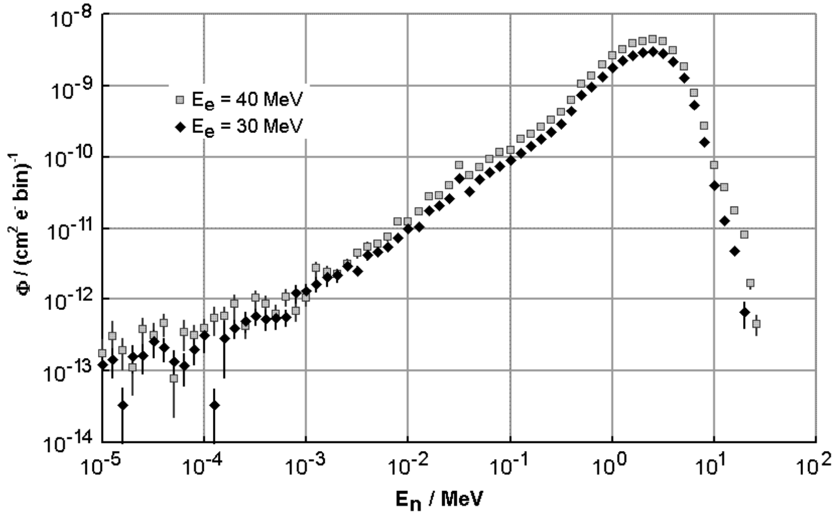
liquid lead circuit for heat transport

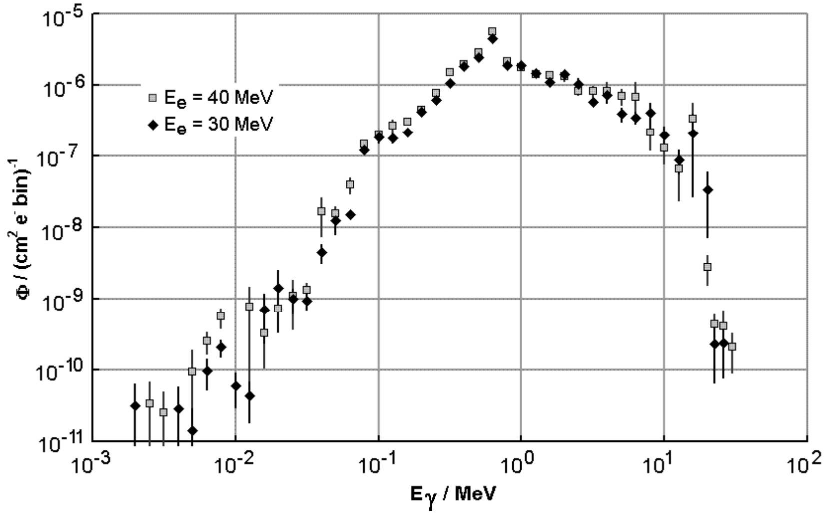
nELBE – photoneutron source



MCNP: Neutron and photon source spectra







- *Mode e p n* calculation with photonuclear physics turned on
- Photonuclear cross sections for Pb and Mo adopted
- Electrons started uniformly outside Mo channel from circular disc, $\varnothing = \varnothing_{beam}$ = 8 mm
- Neutron and photon source distributions detected in collimator direction
- Distributions used as source spectra in later simulations – n & γ started uniformly from a cylindric volume (= intersection between e^- beam and Mo/Pb radiator)

➔ J. Klug et al. NIM A 577 (2007) 641

Total neutron cross section of Tantalum

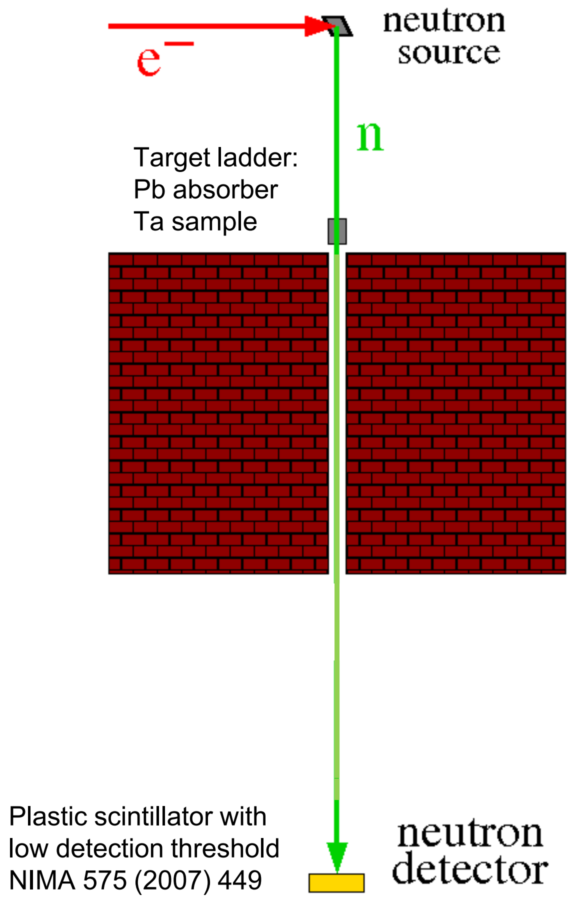
- Transmission measurement

$$T = \frac{N}{N_0} = \exp(-\sigma_{tot} n_t t)$$

Target: ^{nat}Ta 3.52 cm
Bremsstrahlungabsorber:
^{nat}Pb 3 cm

- Counting cycle*:
80% target in 20% target out

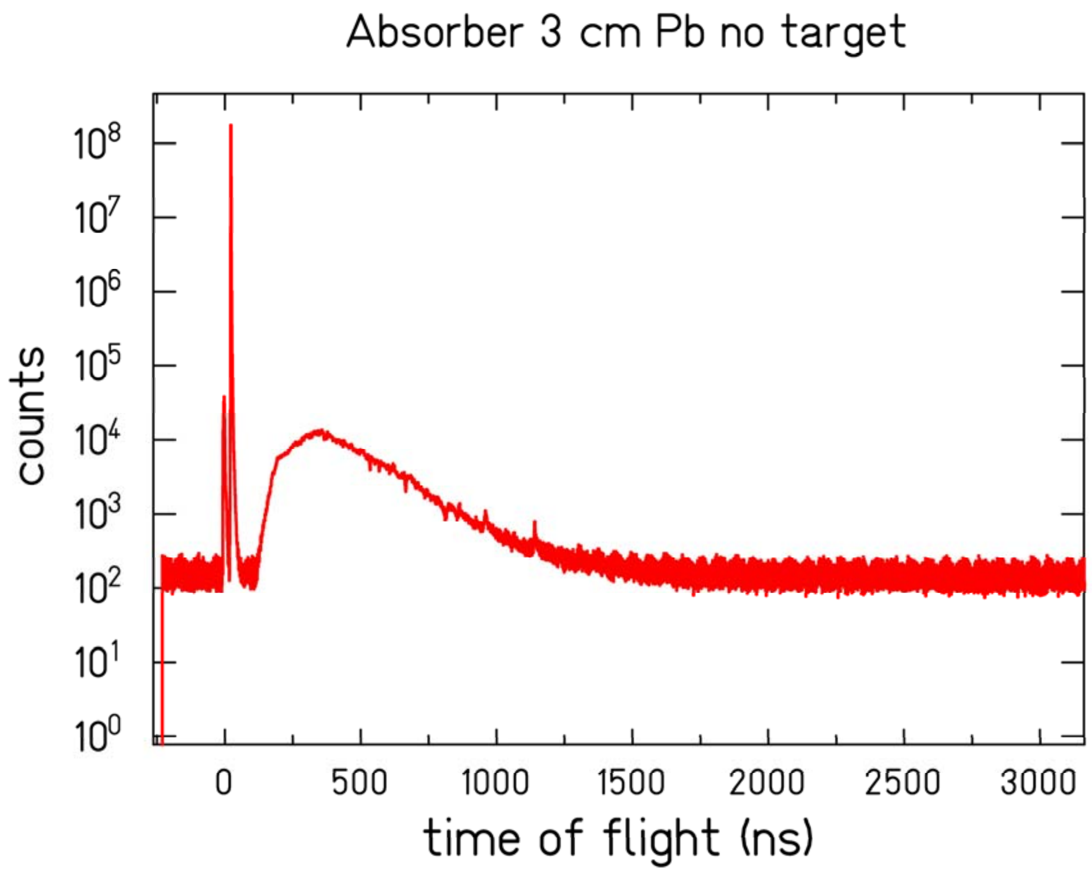
- Measurement time 48 hours
live time - target in 92% (2 kHz)
live time – target out 80% (7 kHz)
measured with scalers



Flight path: 6.52 m
Repetition rate: 100 kHz

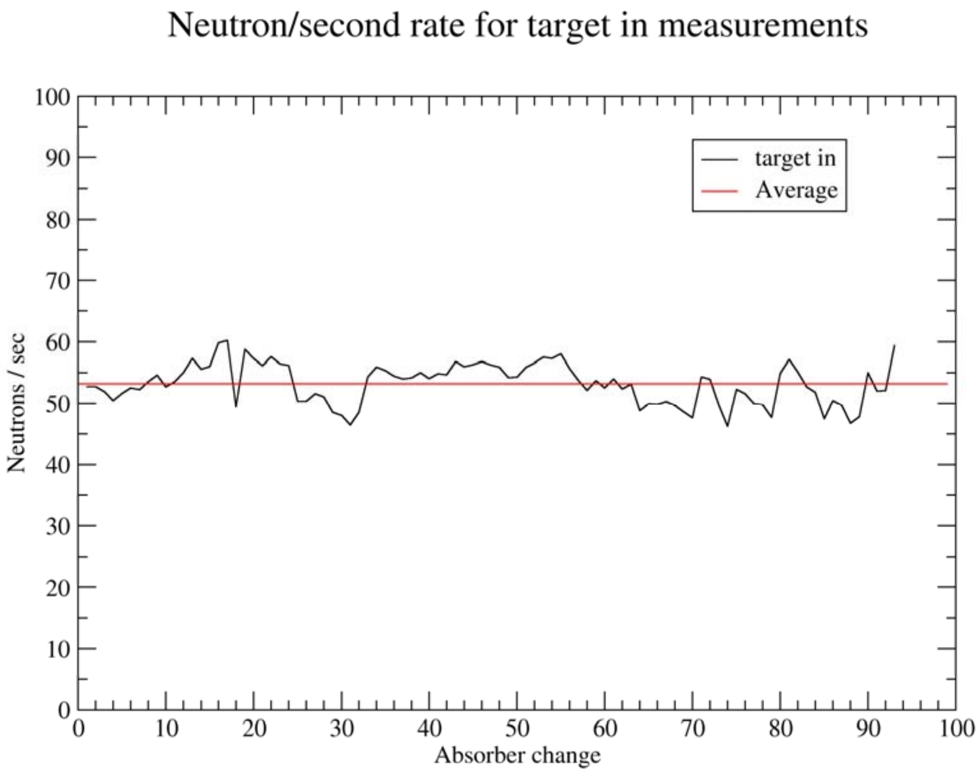
* Y. Danon, NIM A 485 (2002) 585

Neutron time of flight spectrum



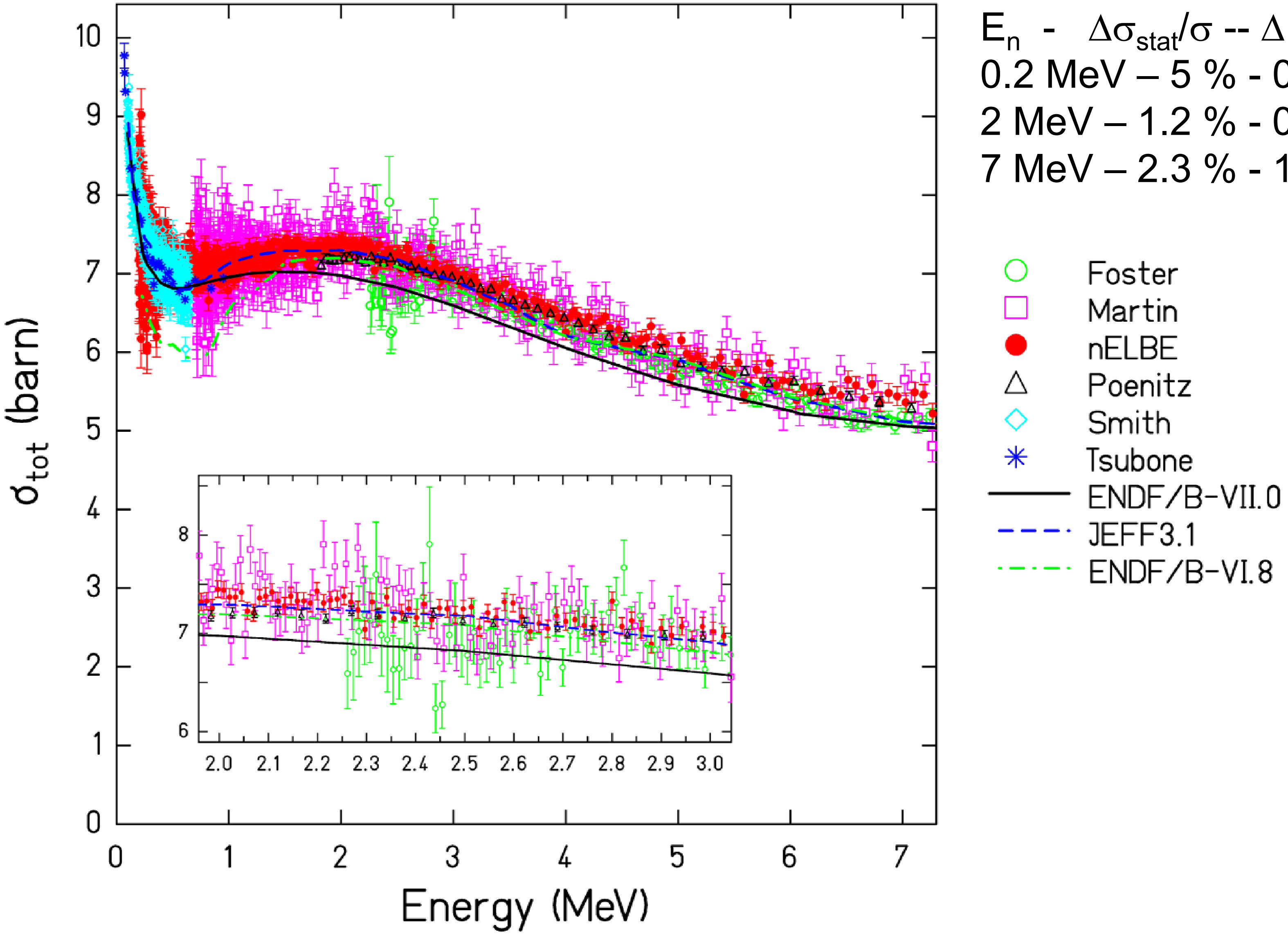
- Beam current reduced to ≈10 nA neutron intensity 150 n/s
- Bremstrahlung intensity 40-50 times higher than neutrons with (Pb absorber 3cm)
- Preflash from beam losses in adjacent room
- Ripple (4 ns) from beam buncher RF 260 MHz

Beam intensity and stability



- Neutron beam intensity ca. 53 n/s
- Averaged beam intensity fluctuation from run to run +- 5%
- Interleaved runs with target in /out
  1200 s / 300 s
  to reduce effect of beam intensity drifts

Total neutron cross section of ^{nat}Ta



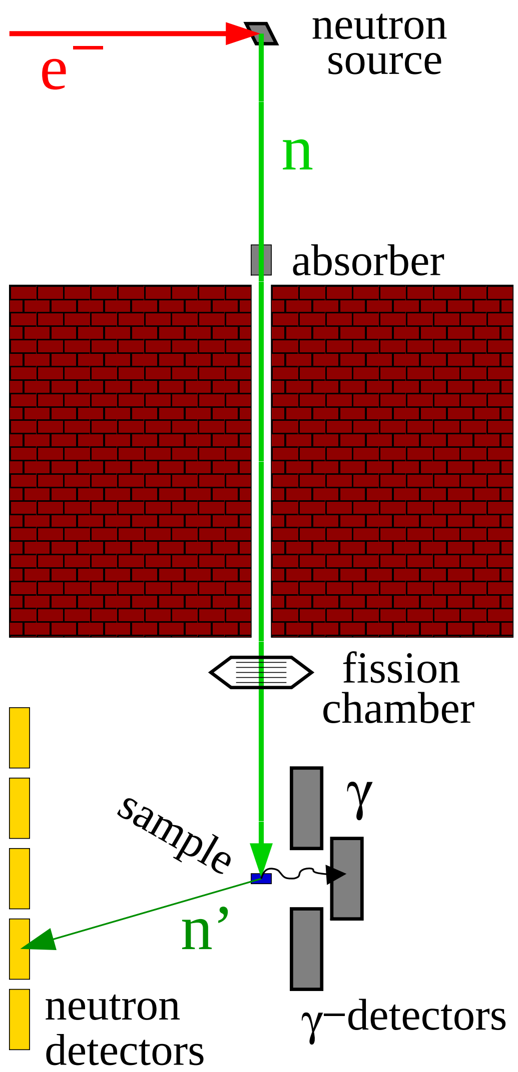
E_n - $\Delta\sigma_{stat}/\sigma$ -- $\Delta E_n/E_n$

0.2 MeV – 5 % - 0.6%

2 MeV – 1.2 % - 0.8%

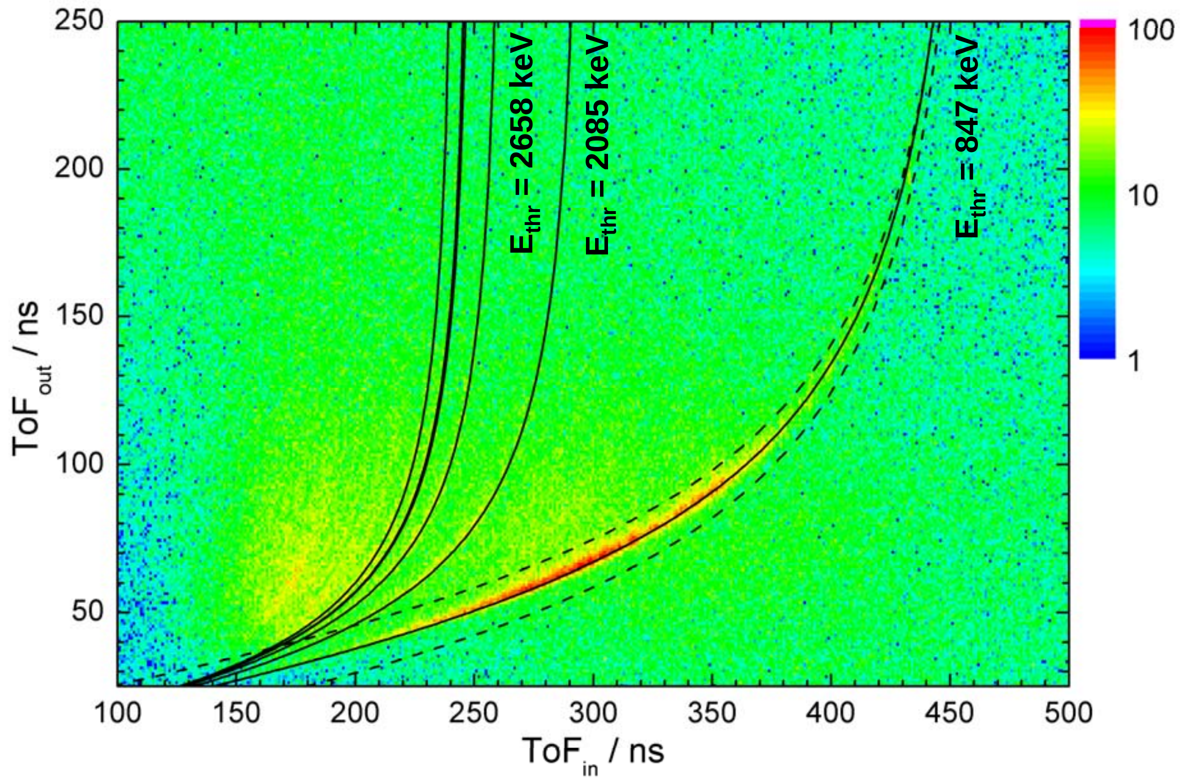
7 MeV – 2.3 % - 1.0%

Experimental methods and results – Inelastic scattering

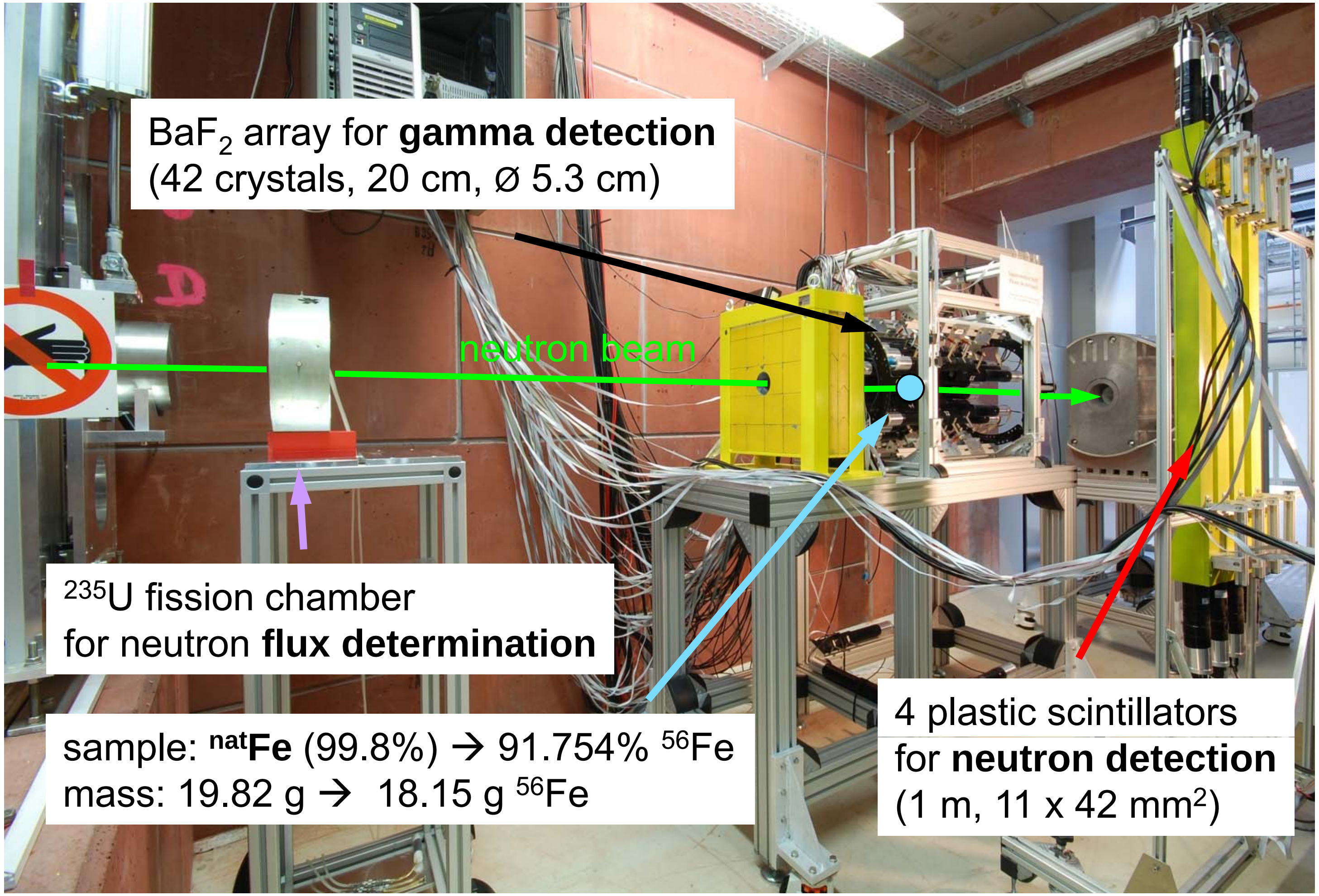


$$^{56}Fe(n,n'\gamma)^{56}Fe \quad \begin{cases} ^{56}Fe + n \rightarrow {}^{56}Fe^{*} + n' \\ \qquad ^{56}Fe^{*} \rightarrow {}^{56}Fe + \gamma \end{cases}$$

with sample + kinematics calculation

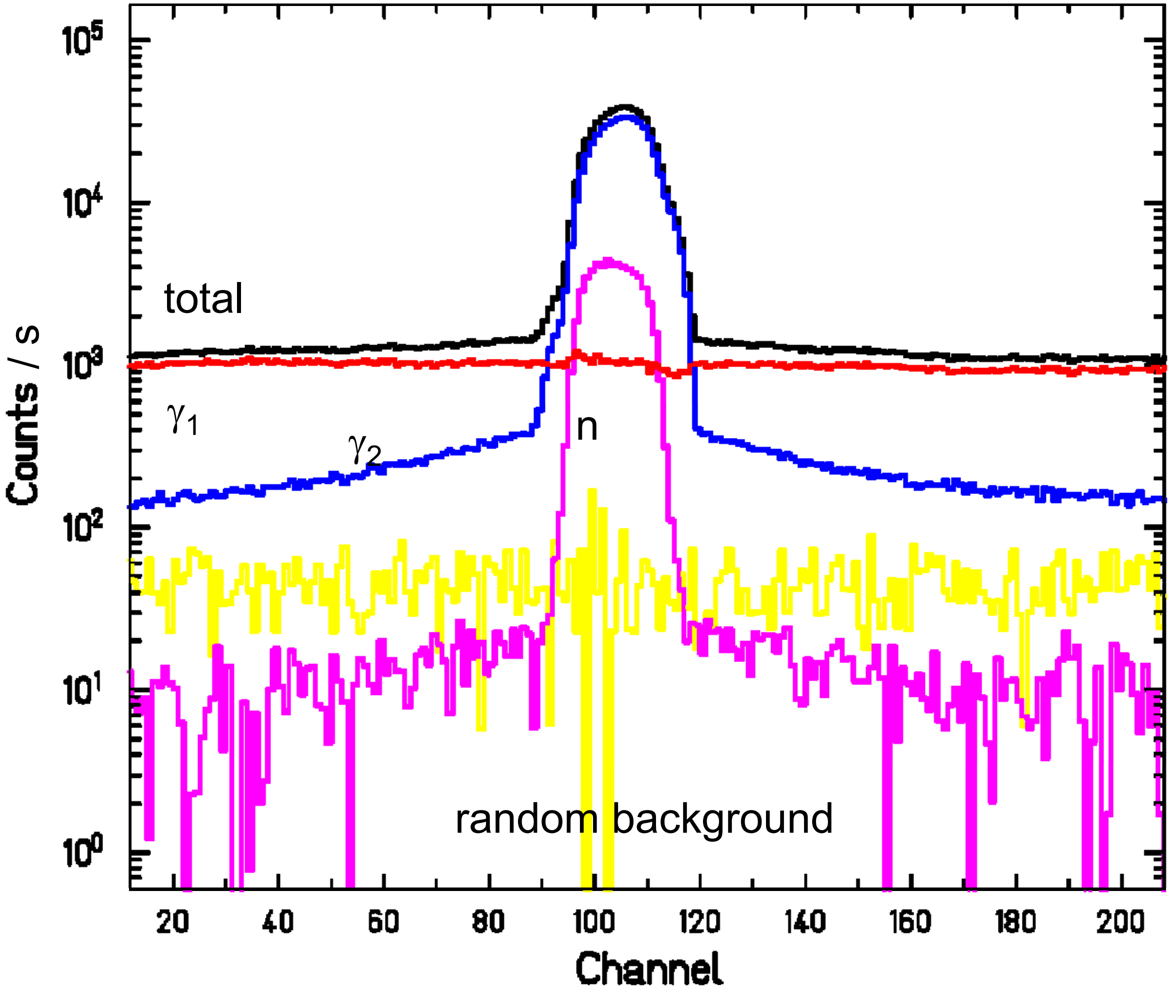


nELBE – inelastic neutron scattering setup



flight paths:
source – sample:
600 cm
sample – BaF_2 scint.:
30 cm
sample – plastic scint.:
100 cm

Vertical Beam Scan



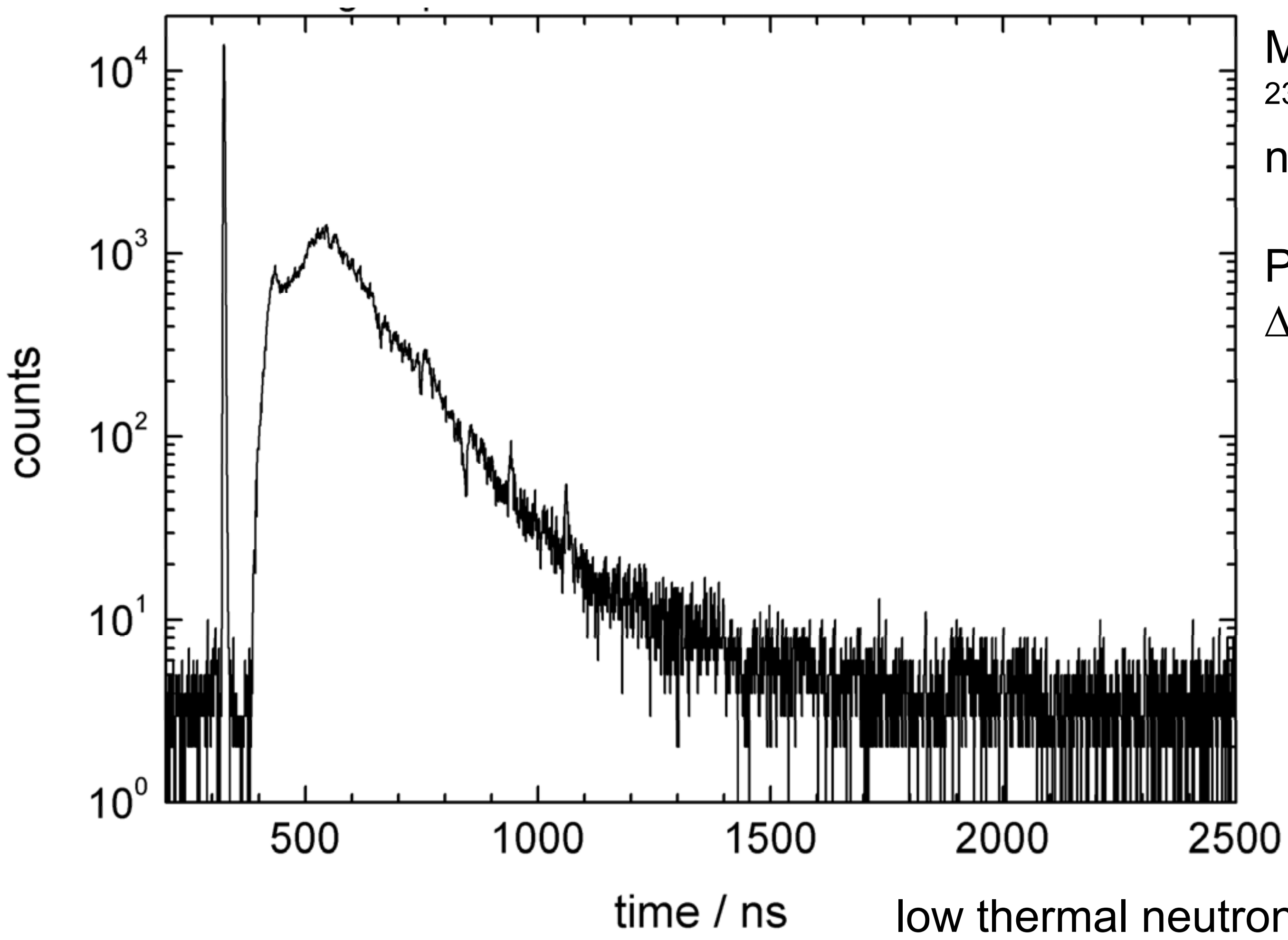
Plastic scintillator stepped through the beam both vertical and horizontal.

ToF measurement ➔ separation of different components in the spectrum

Detector- diameter 11 mm

N-beam diameter ca. 6 cm

Neutron time of flight spectrum with fission chamber

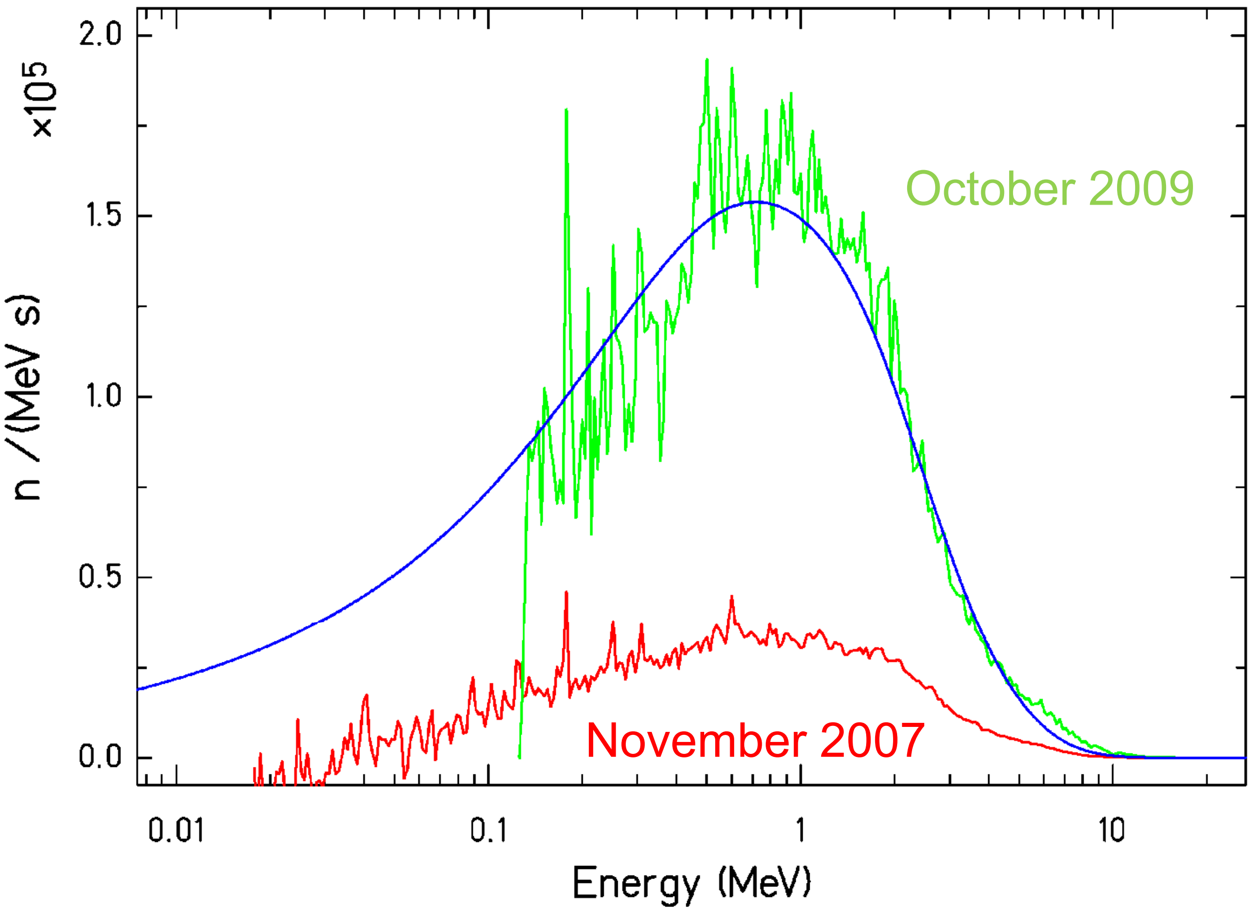


Measured with PTB
^{235}U fission chamber
n_t = 5 mg/cm^2

Photofission:
Δt(FWHM) = 4 ns

low thermal neutron background
$J_{Cd}/J < 8*10^{-5}$
from comparison with/without Cd absorber

nELBE neutron spectrum

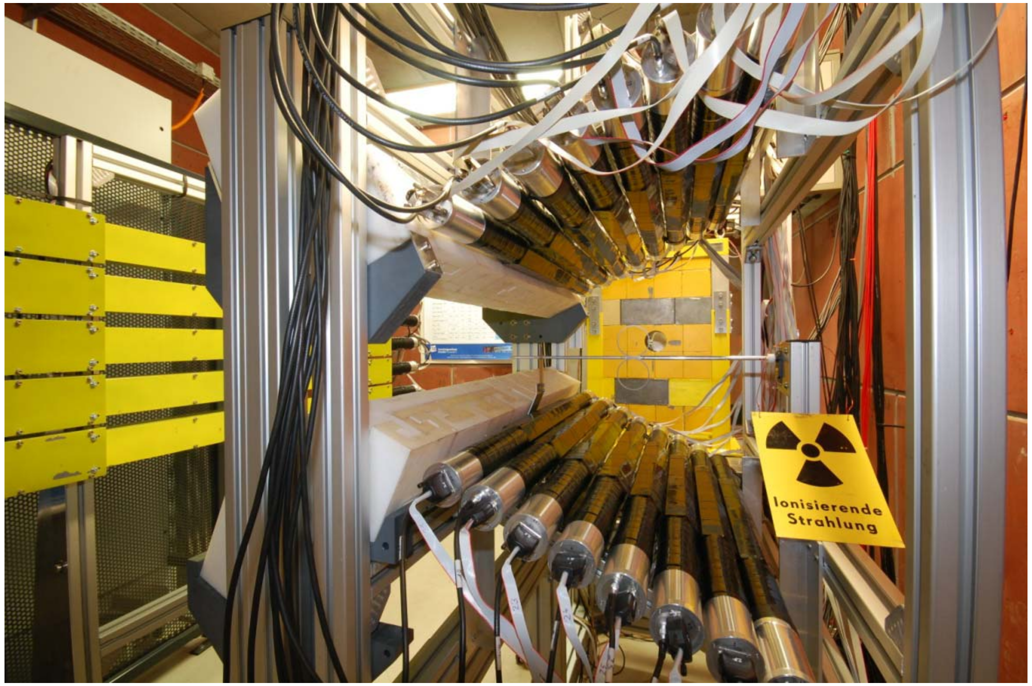


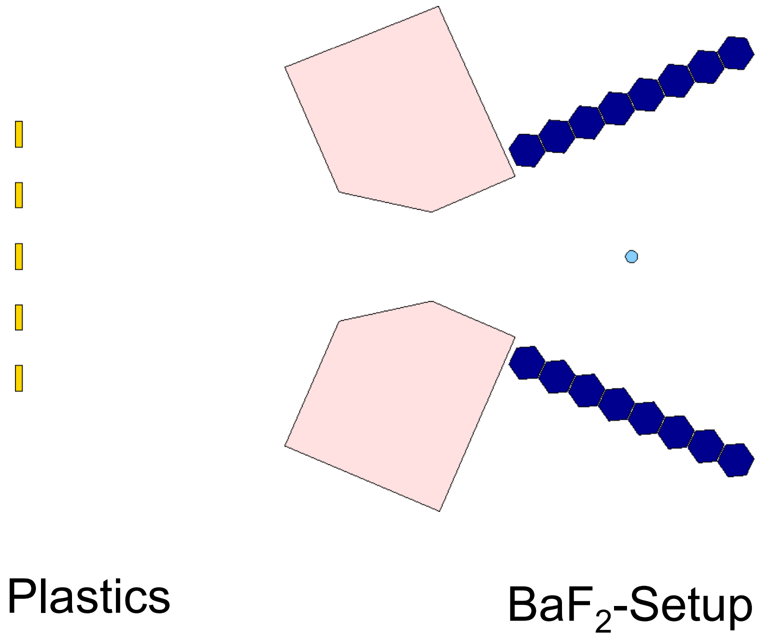
28.10.2009:
neutron source strength:
$1.4 \cdot 10^{11}$ n/s
neutrons on target:
$4.5 \cdot 10^{4}$ n/(cm^2 s)

$\langle I_{e-} \rangle = 19\ \mu A$
Max. thermionic injector
at 200 kHz rate

Fission chamber as primary beam monitor (from PTB, Braunschweig)
Spectrum is very similar to fast neutron spectrum e.g. $^{235}U(n,f)$ (ENDF-VII)

Optimization of the experimental setup

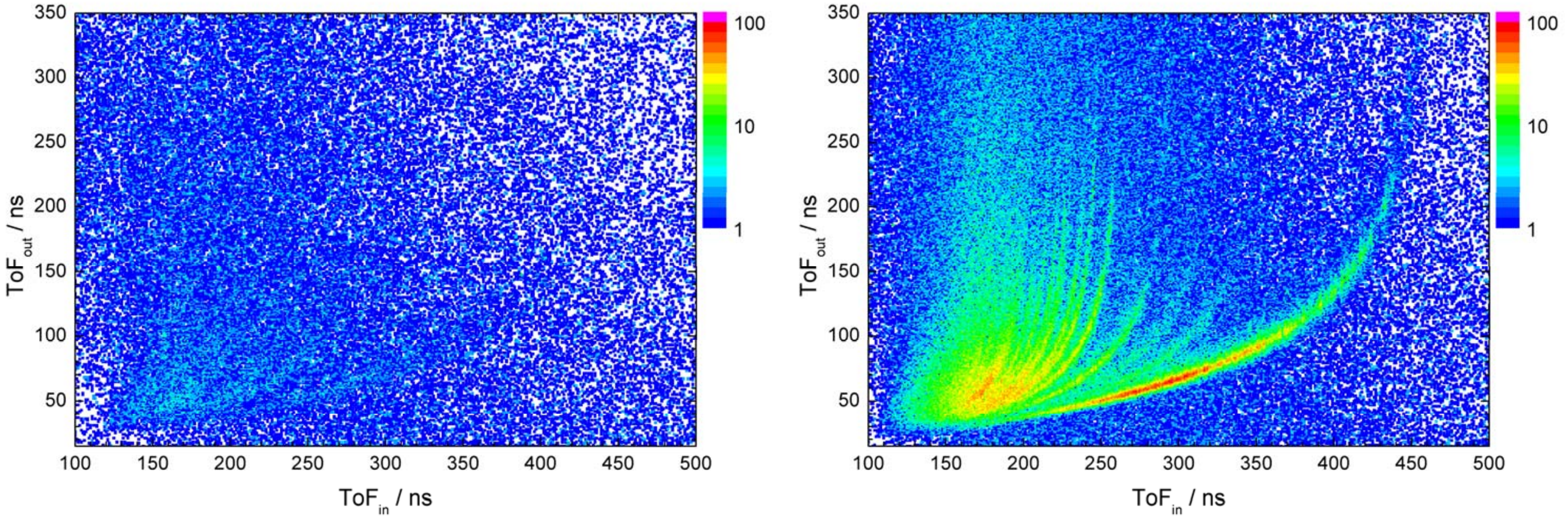




- ➔ borated polyethylene block between BaF_2 and plastics
- ➔ change in geometry
- ➔ combination of two single sided readout 20 cm long crystals to one double sided readout 40 cm long detector

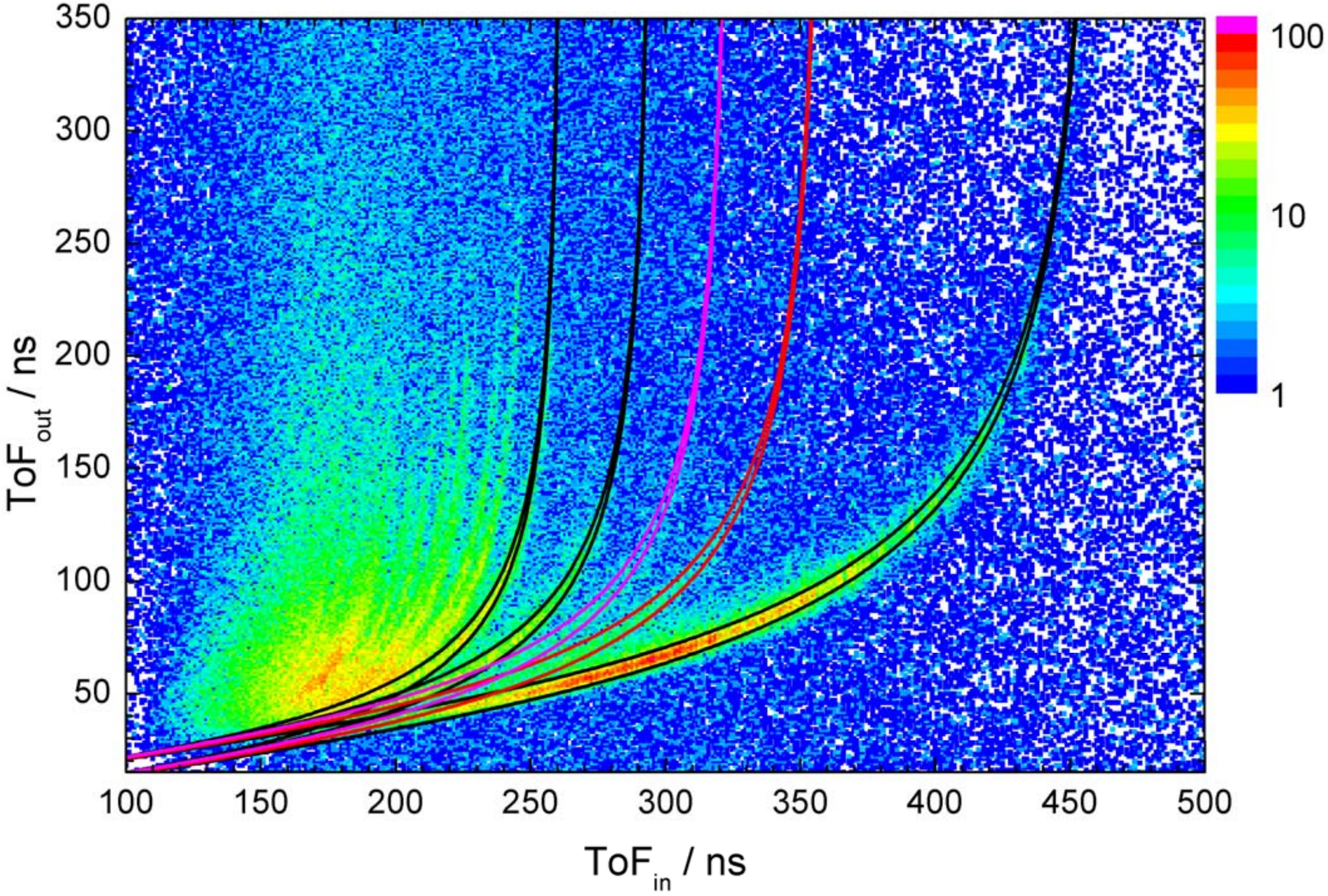
2D ToF spectra from May'10 beamtime

empty target t_{live} = 294 515 s Fe-nat t_{live} = 280 567 s (83 %)



→ lower background (5x in empty, 10x in target run)
→ 10x better signal to background ratio
→ target structures also visible in in empty spectrum
(due to too small distance of target out position)

2D ToF spectra from May'10 beamtime



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

- Fe-54 (1. Level)

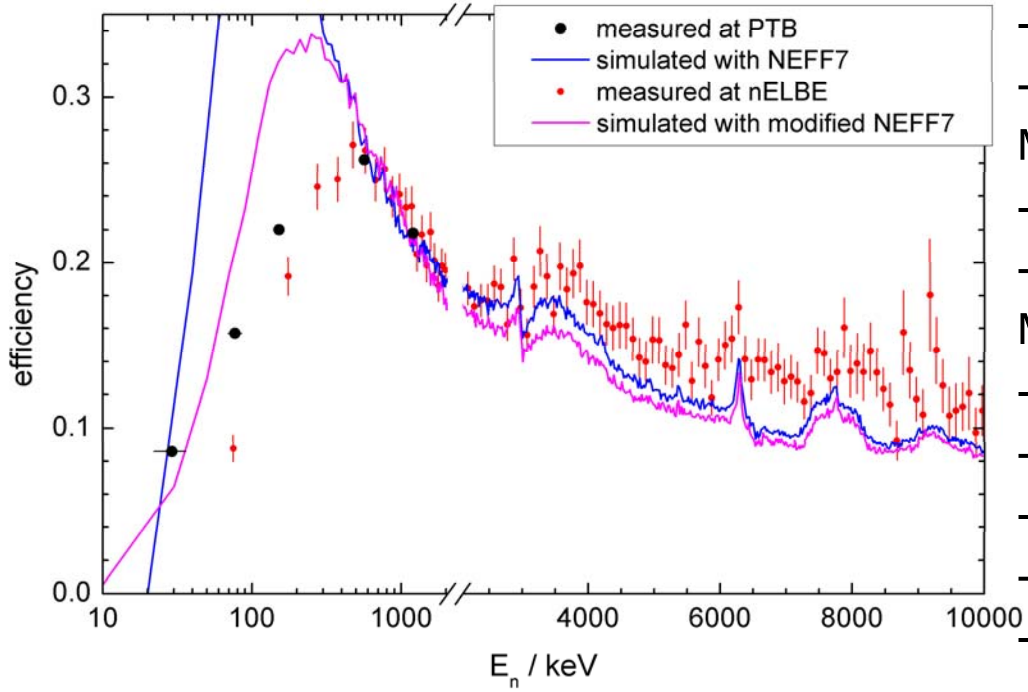
- ? 1700 keV

→is not:

  - Al-27
  - C-14
  - Fe-57
  - Mn-55
  - N-14
  - O-16
  - Pb-207
  - Pb-208
  - …

➔ double-scattering on Fe-56 1st level (847 keV)

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:

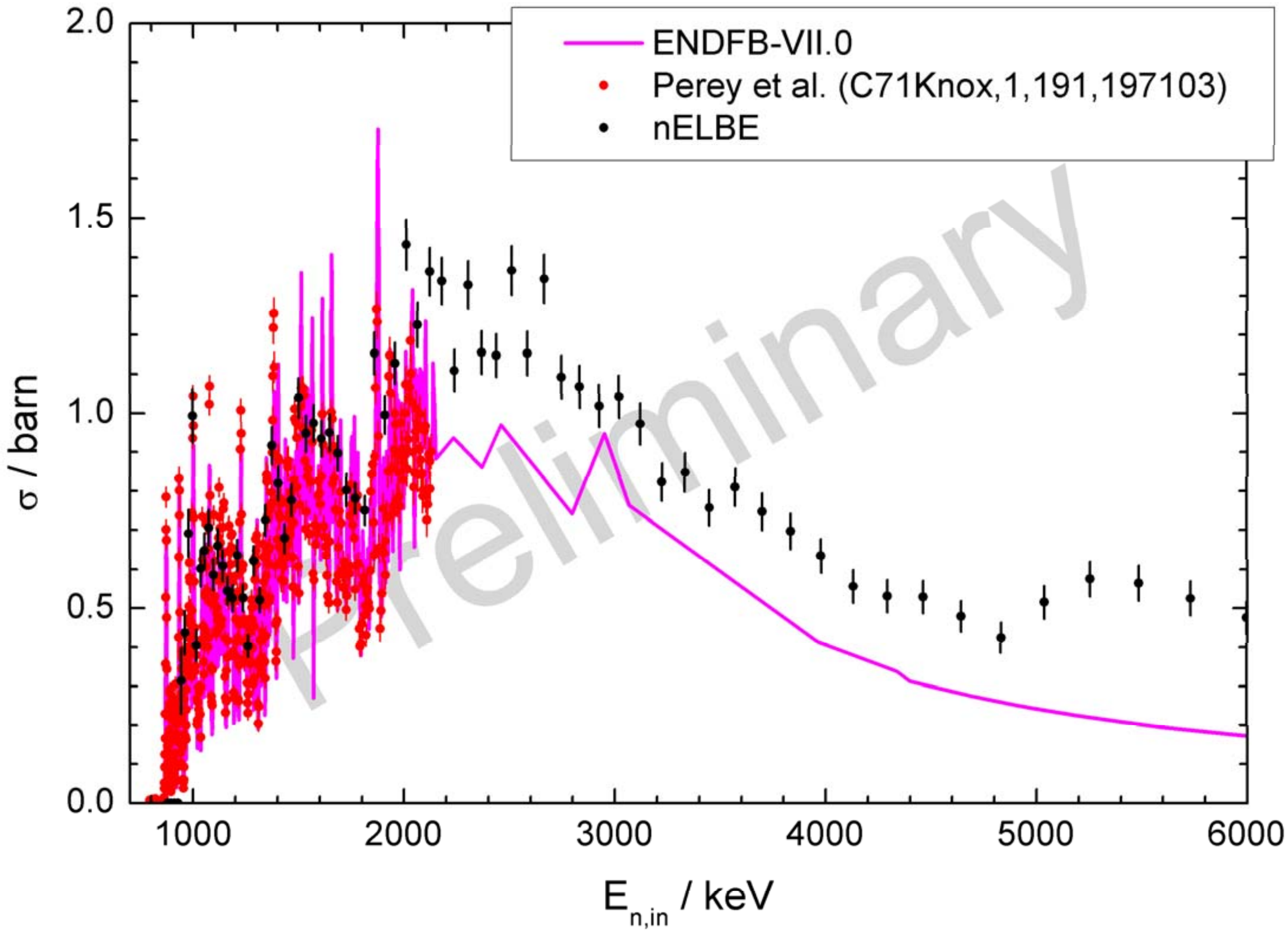
In simulation:

- Unknown light output function at low energy transfer

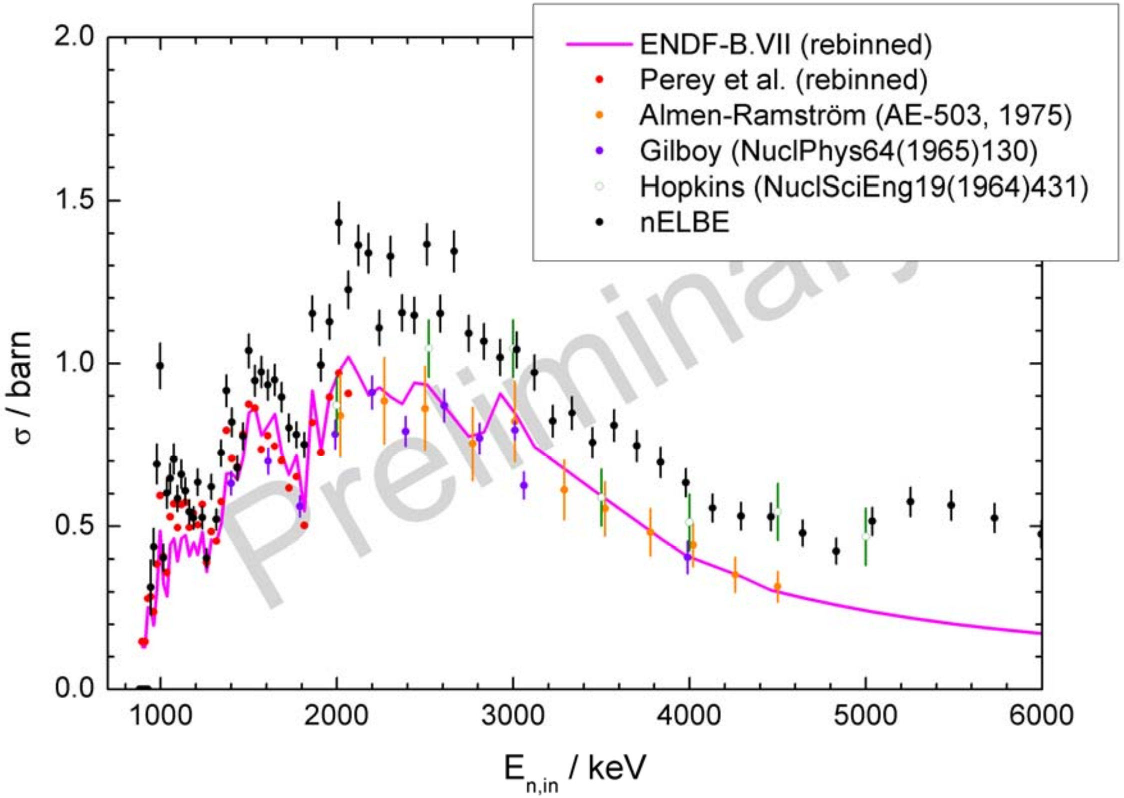
In measurement:

- Collimated beam at nELBE
- Influence of lead shielding

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

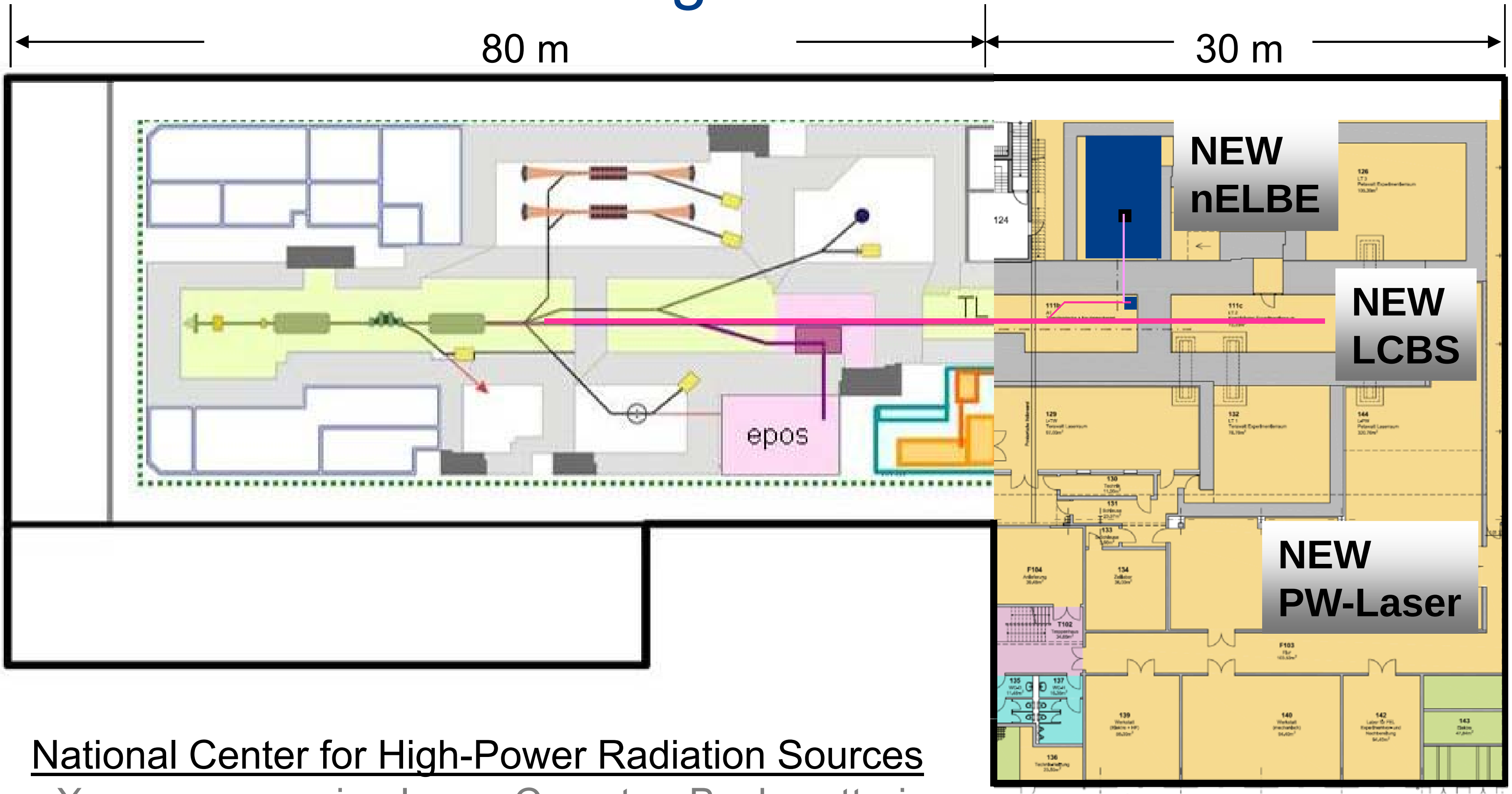


The $^{56}Fe(n,n'\gamma)$ cross section for the 1st excited state



Uncertainties:	@ 2 MeV
Fission chamber efficiency	2.2 %
Fission chamber counts	0.7 %
Fission chamber background	1.8 %
Loss due to ADC range	0.1 %
Scaling factor FC<->Target	0.9 %
→ Neutron flux	2.5 %
Sample in counts	2.3 %
Sample out counts	15.1 %
Normalization factor	1.7 %
BaF_2 efficiency	1.8 %
Plastic efficiency	5.1 %
→ Reaction rate	5.9 %
→ Cross section	6.4 %

National Center for High-Power Radiation sources



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

ground breaking started April 2010

Results and Outlook

- Fast neutrons are decisive for the transmutation of long-lived minor actinides in shorter-lived fission products.
- The time frame for final storage can be reduced to historical times (< 1000 years) through a closed nuclear fuel cycle including partitioning and transmutation.

- Precise experimental data for fast-neutron induced reactions like (n,n'γ) (n,tot) and (n,f) using radioactive targets are required for the development of transmution facilities (fast reactors, ADS)

- BMBF joint research project
„Nuclear Physics Studies relevant to Nuclear Transmutation…"
together with TU Dresden, Uni Mainz, TU München, Uni Köln und PTB Braunschweig seit 01.10.2009

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Nuclear Transmutation Project

- Roland Beyer, Evert Birgersson, Anna Ferrari, Daniel Gehre*, Roland Hannaske, Mathias Kempe, Toni Kögler, Michele Marta, Ralf Massarczyk, Andrija Matic, Georg Schramm

- Arnd Junghans, Daniel Bemmerer, Eckart Grosse*, Klaus-Dieter Schilling, Ronald Schwengner, Andreas Wagner

- Development of the nELBE photoneutron source together with the Institut für Sicherheitsforschung, Frank-Peter Weiss and also with IKTP, TU Dresden, Hartwig Freiesleben, Klaus Seidel through a DFG project.

* (also at IKTP Dresden)