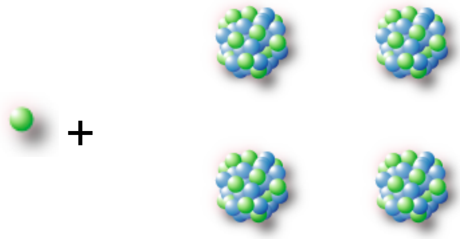
Minor actinide reaction cross sections at n_TOF at CERN

Frank Gunsing

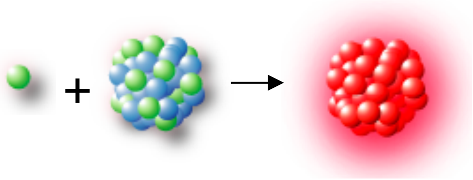
for the n_TOF Collaboration

Neutron induced reactions

solid state



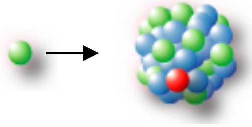
compound nucleus reactions



$\tau \sim 10^{-16}$

$E_n < 10\ \mathrm{MeV}$

direct reactions



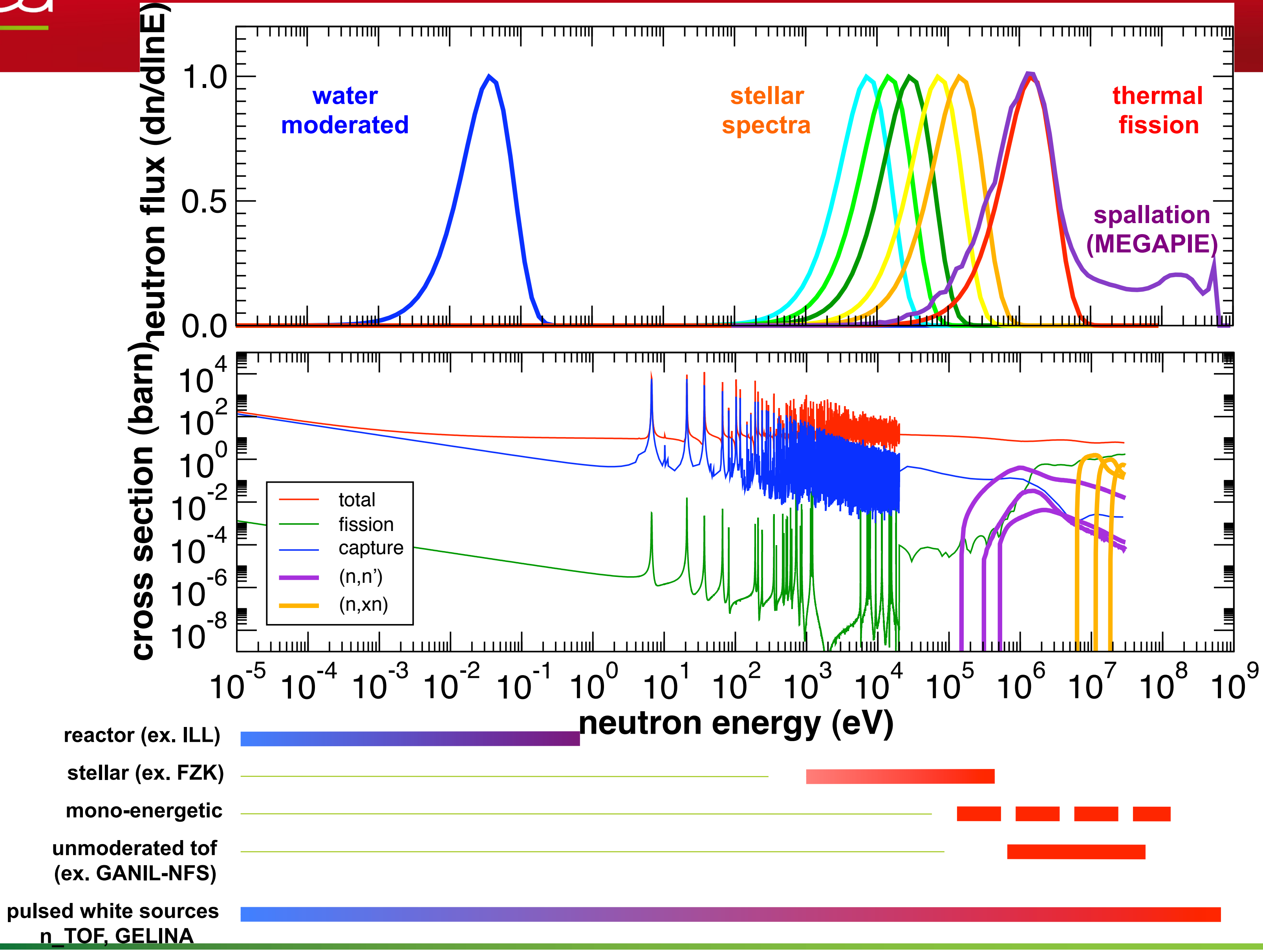
$\tau \sim 10^{-22}$

$E_n > 10\ \mathrm{MeV}$

1 nm — **neutron wave length** — 10 fm

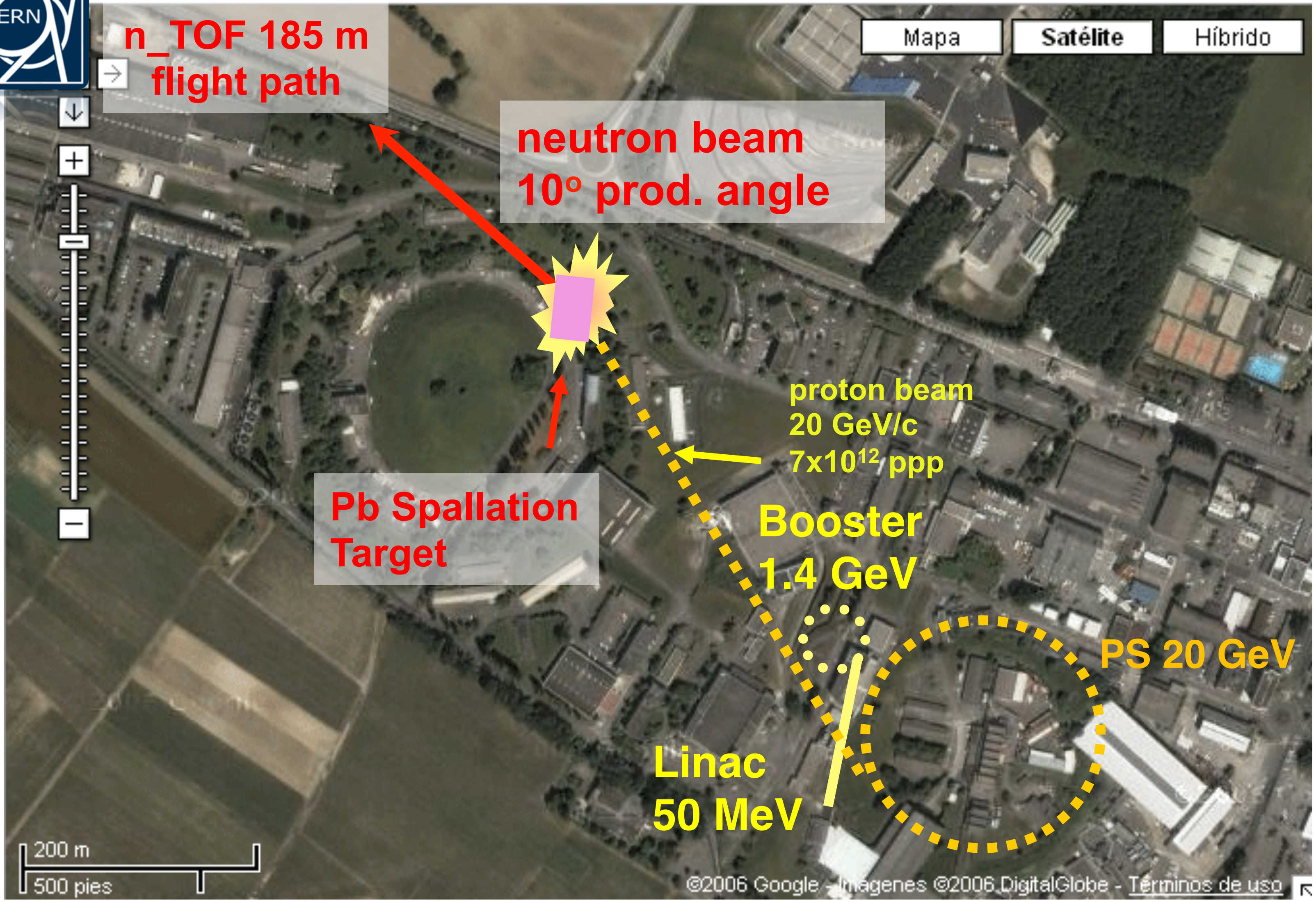
1 meV — **neutron kinetic energy** — 10 MeV

Neutron fluxes and cross sections

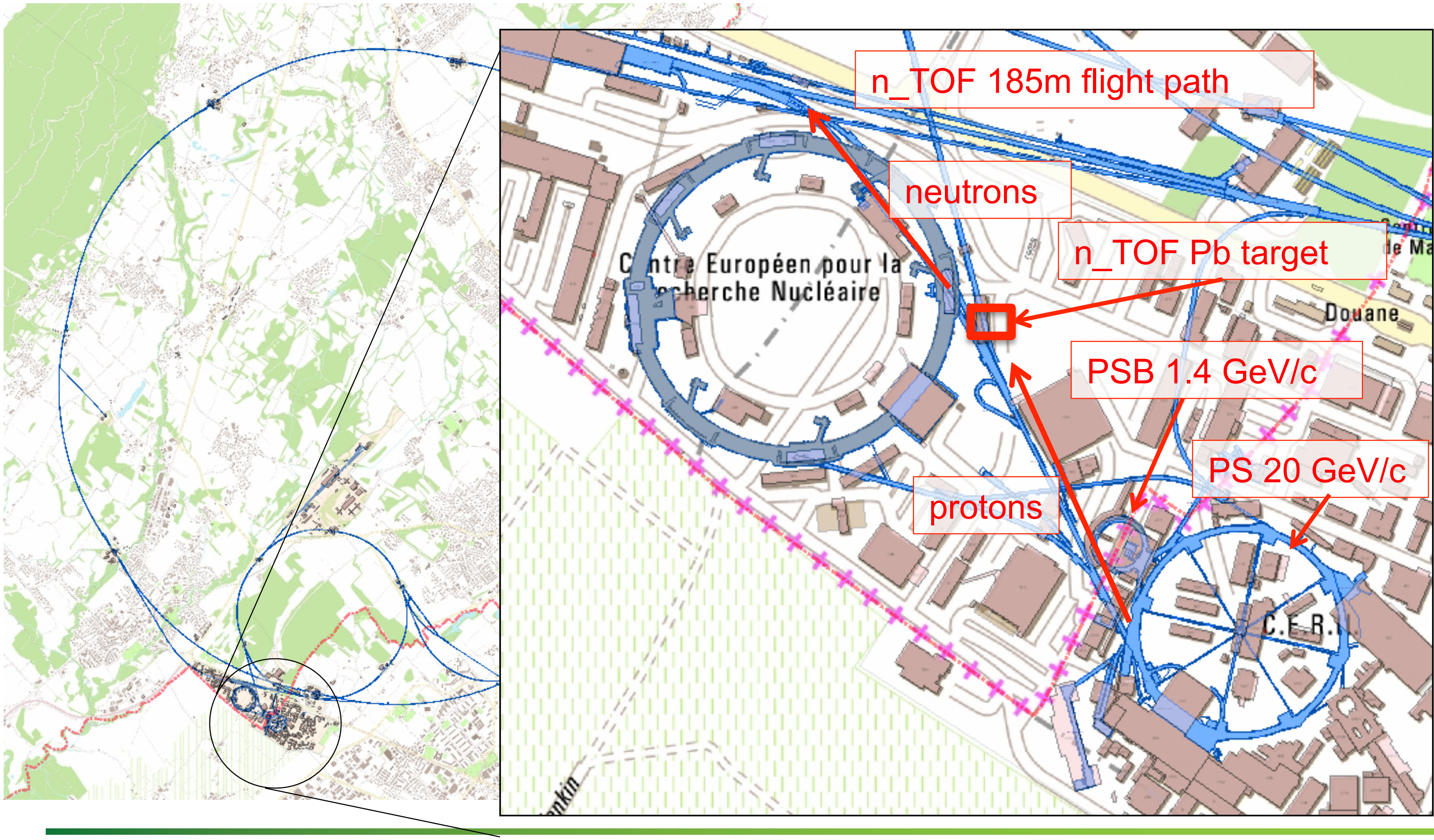


The n_TOF facility at CERN

The n_TOF facility at CERN



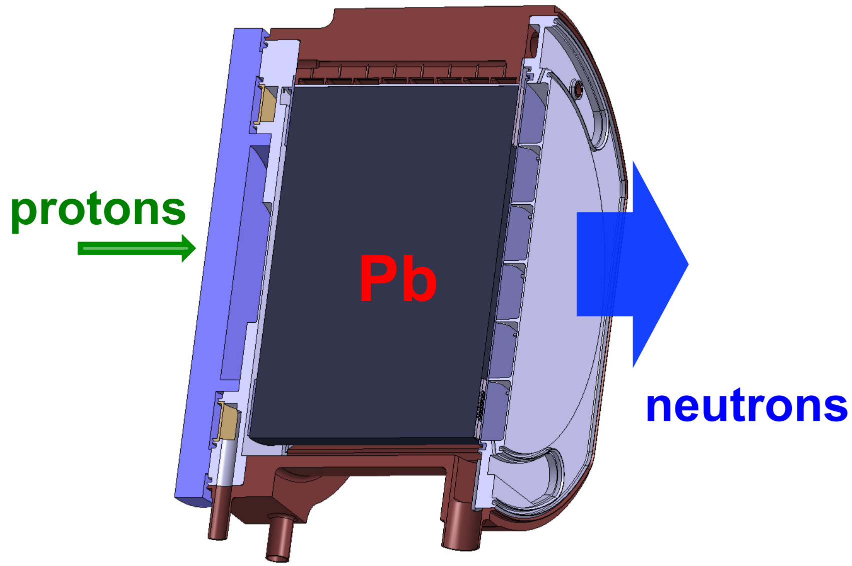
The n_TOF facility at CERN



The n_TOF facility at CERN

Pulsed white neutron source:

- 20 GeV/c protons
- neutrons from spallation
- 6 ns rms pulse width
- frequency 1 pulse/2.4 seconds
- separate cooling and moderation
- flight path length EAR1: 185 m
- @source: 7×10^{12} protons/pulse
- @source: 2×10^{15} neutrons/pulse
- @EAR1: $5 \cdot 10^{5}$(capture) – $5 \cdot 10^{7}$(fission) neutrons/pulse

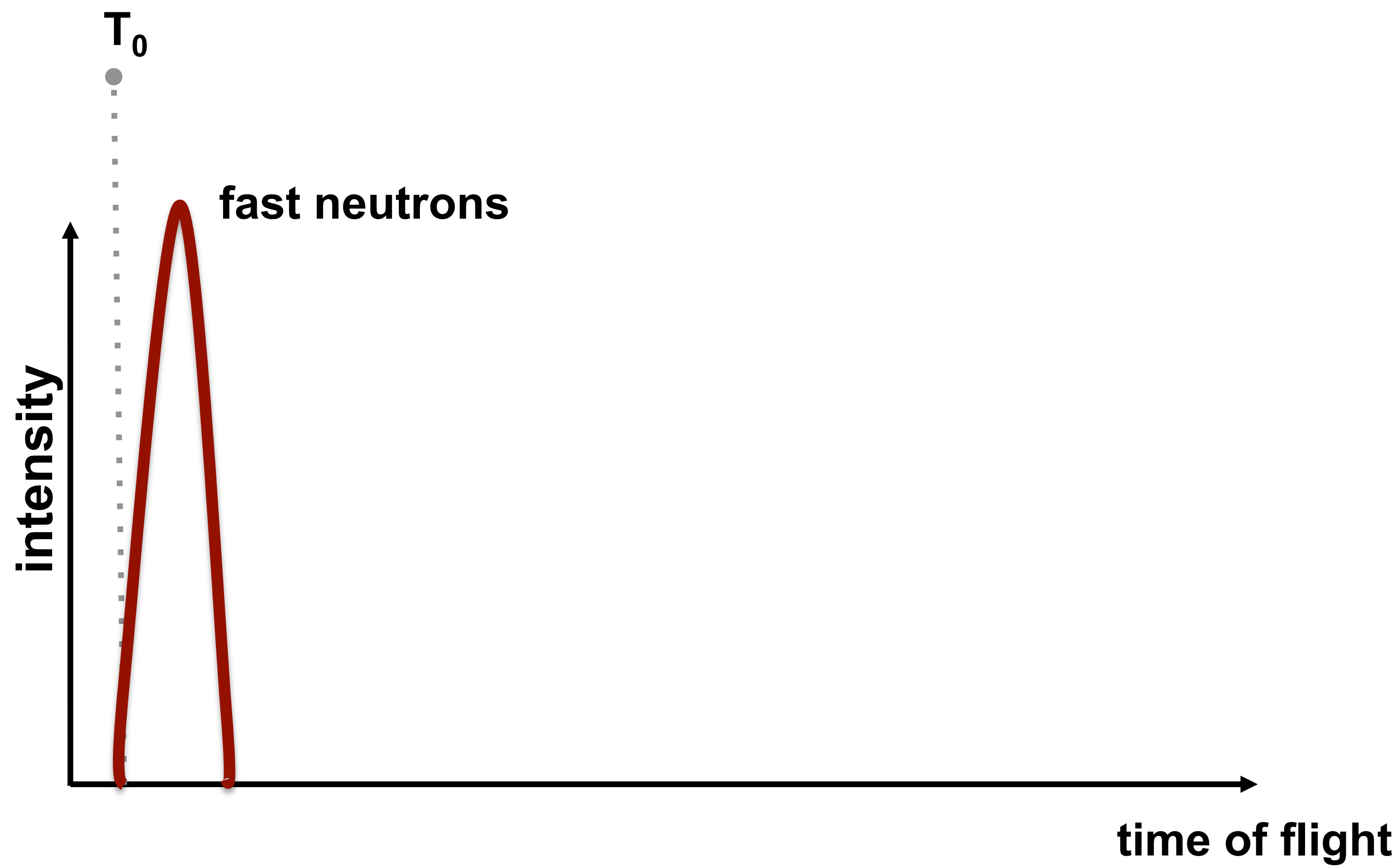


phase II target

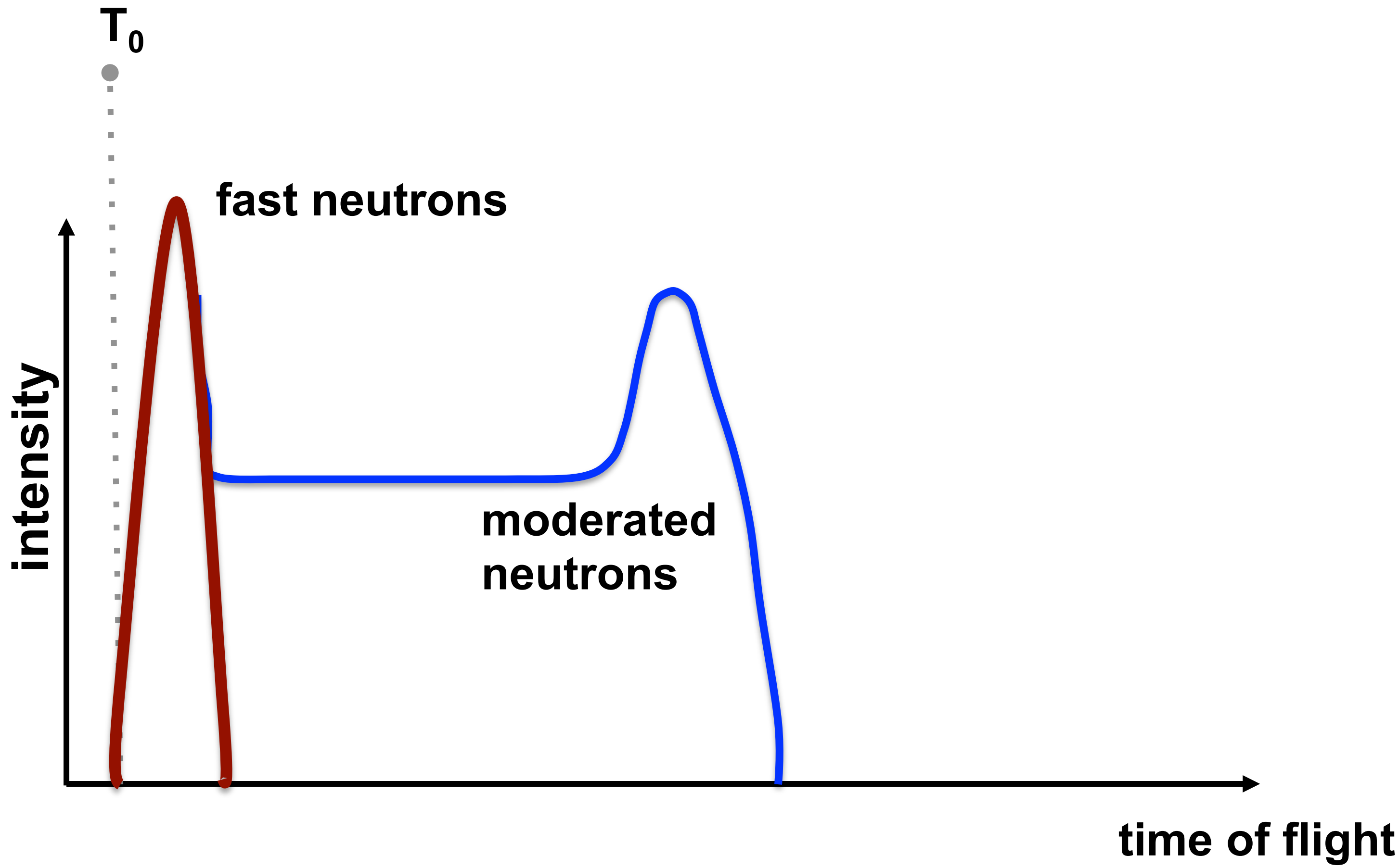
Main features:

- Large energy range in one experiment (0.1 eV - 250 MeV)
- Favorable signal to noise ratio for capture on radioactive isotopes (actinides, fission products)

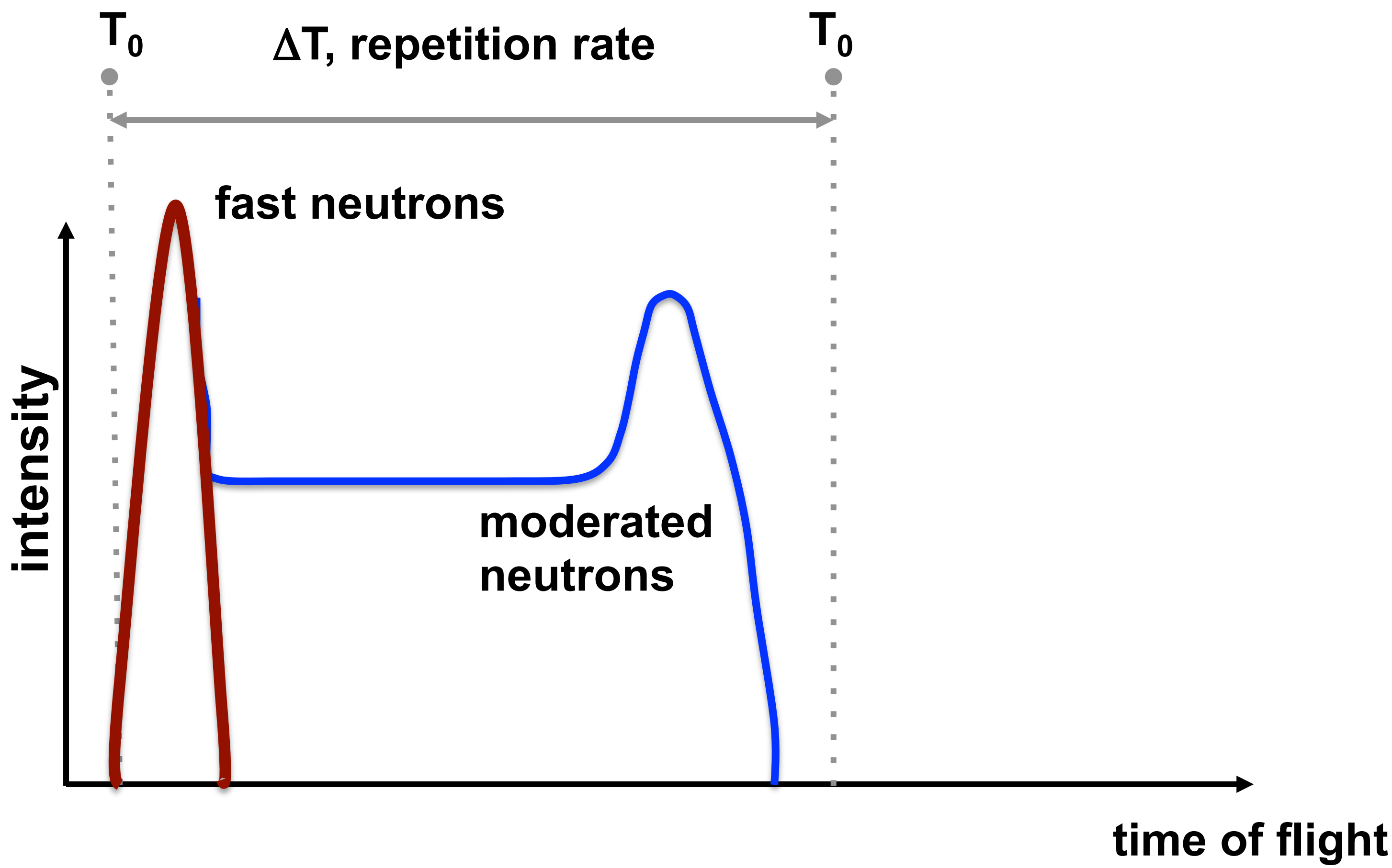
Time of flight



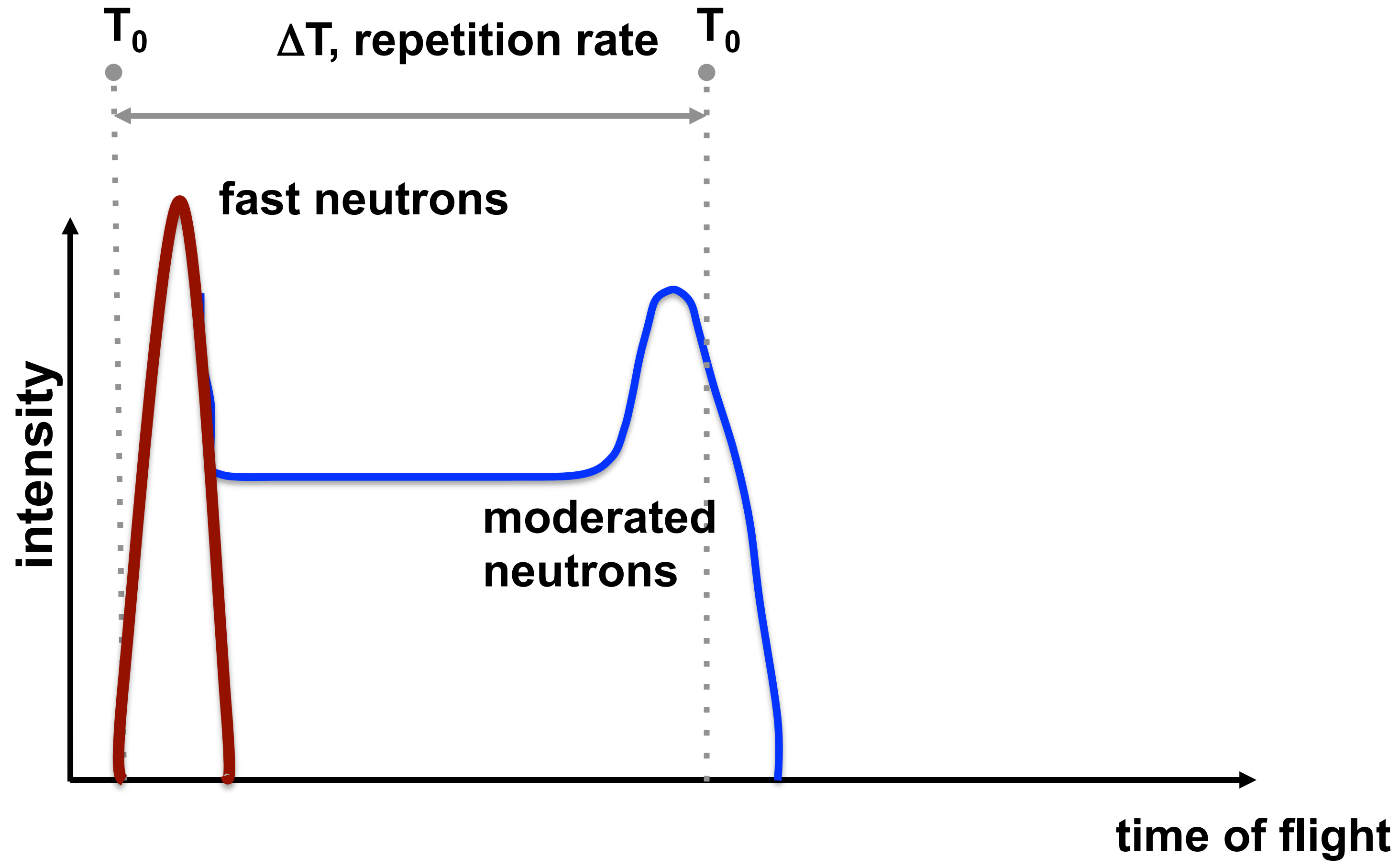
Time of flight



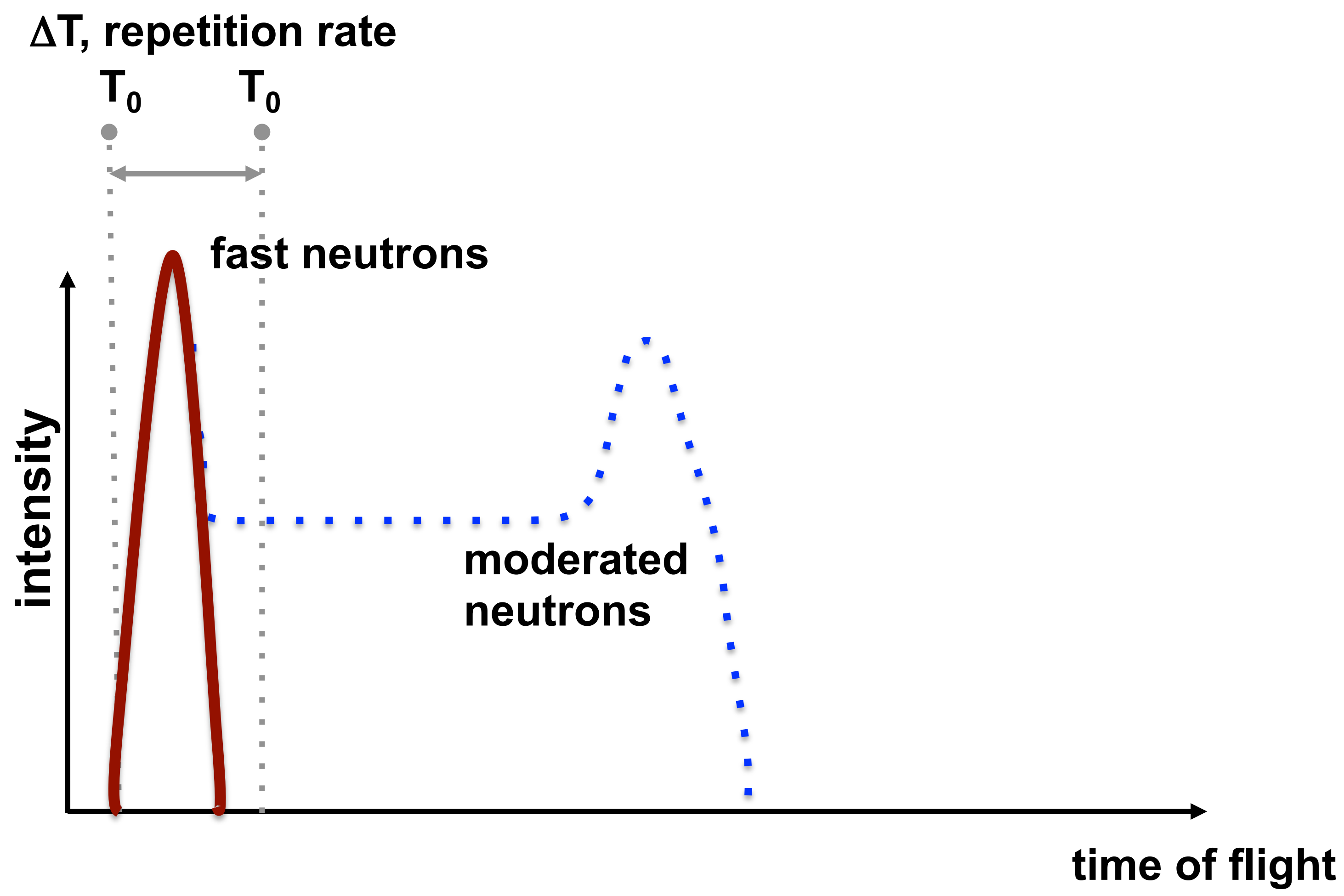
Time of flight



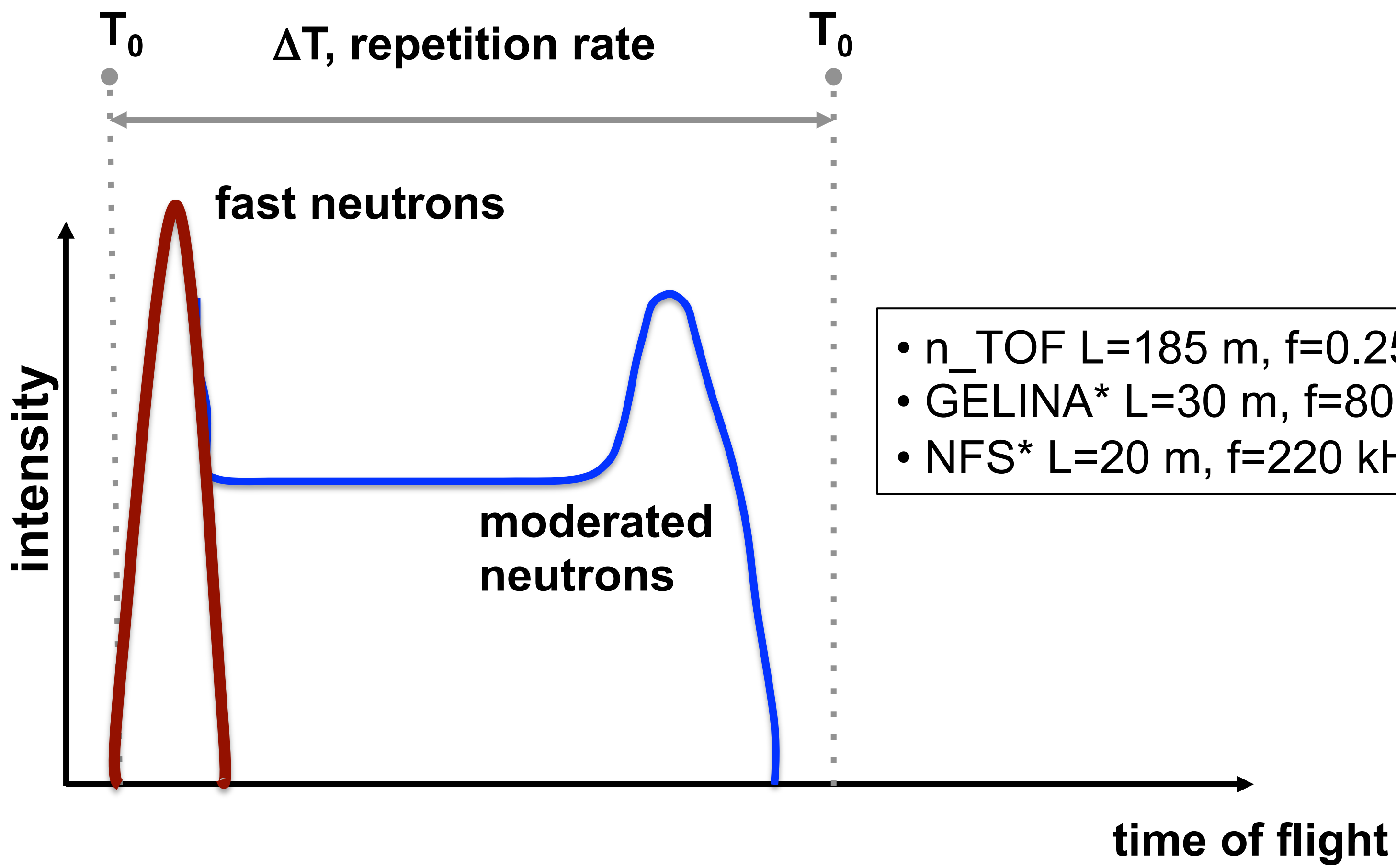
Time of flight



Time of flight

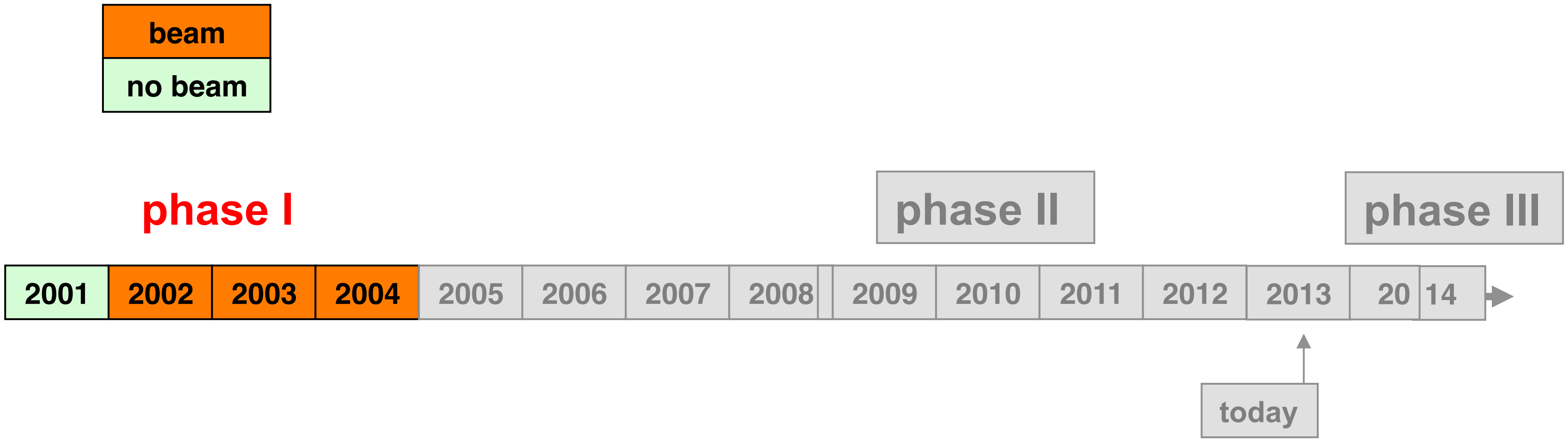


Time of flight



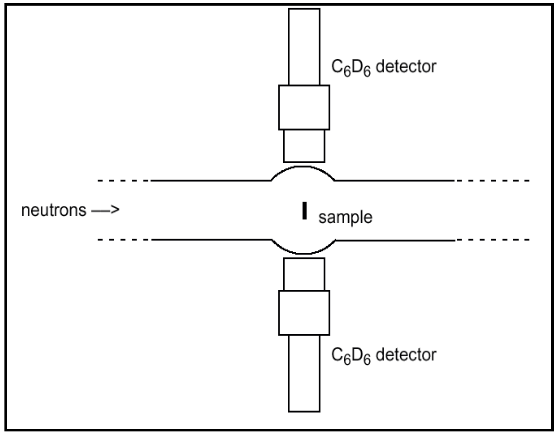
- n_TOF L=185 m, f=0.25 Hz
- GELINA* L=30 m, f=800 Hz
- NFS* L=20 m, f=220 kHz

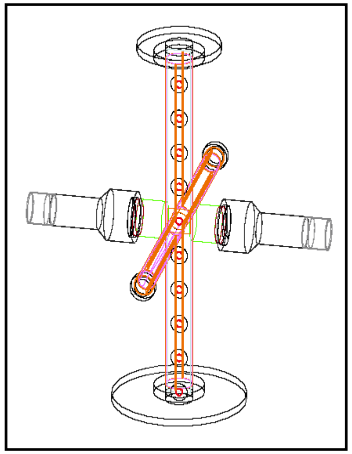
The n_TOF facility at CERN: phase I

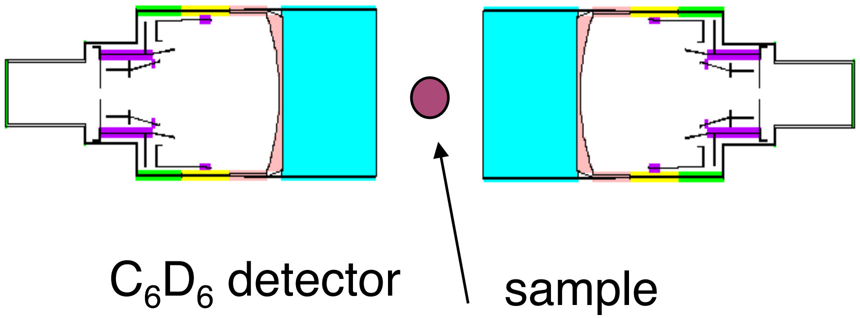


- 1998 - 2001 preparation and commissioning
- 2002 - 2004 **phase I** data taking

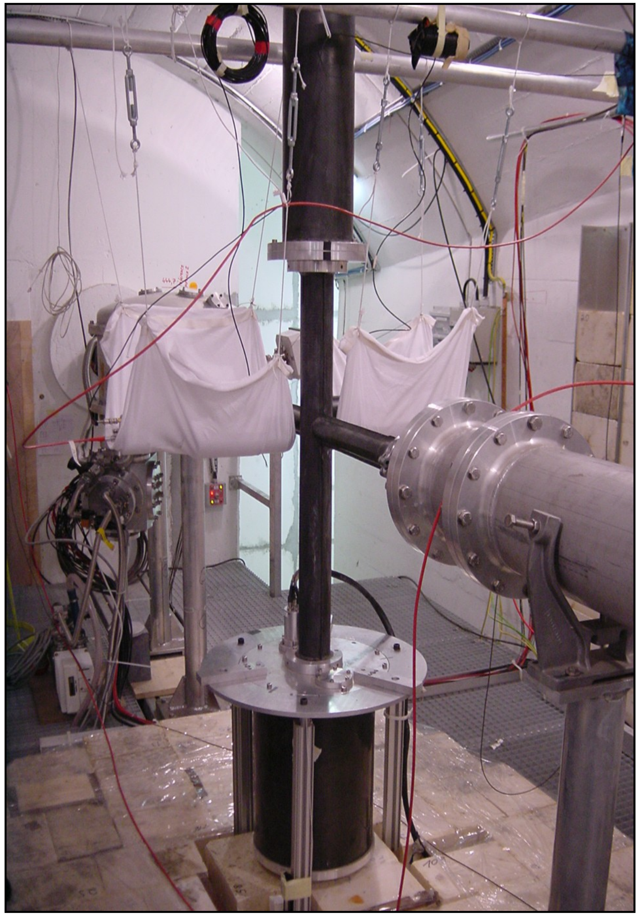
Capture measurement setup with C_6D_6 detectors



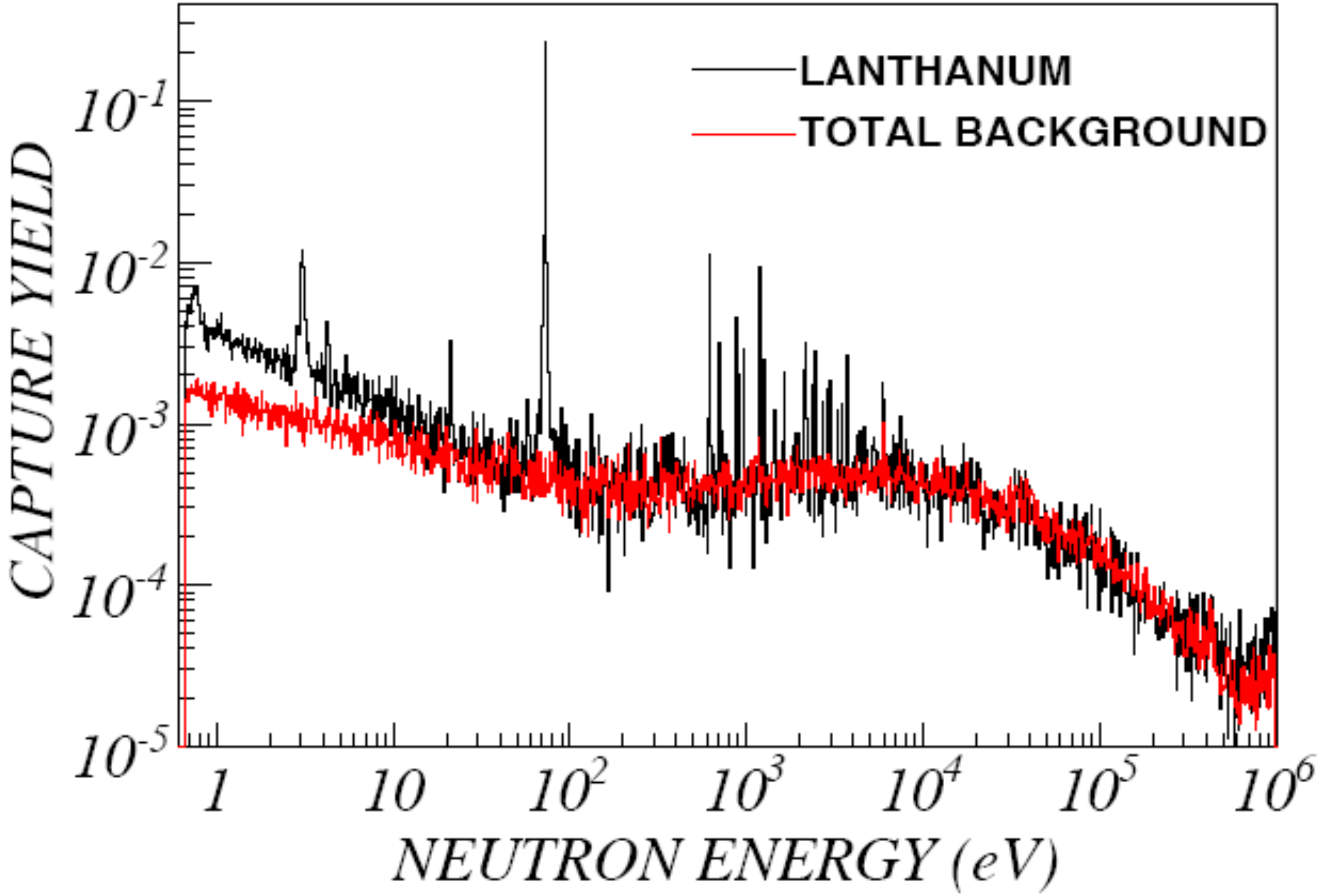




C_6D_6 detector   sample



$^{139}La(n,\gamma)$

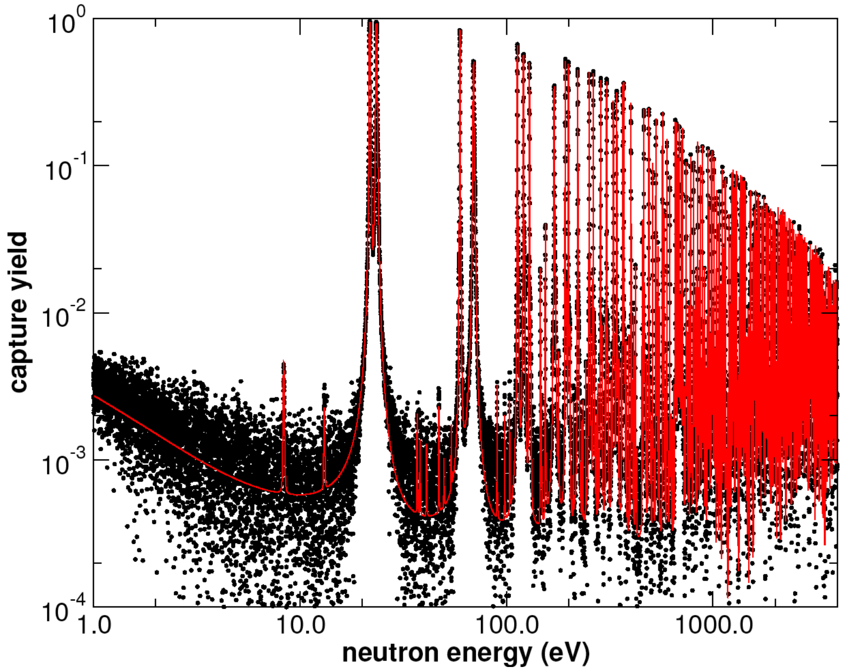


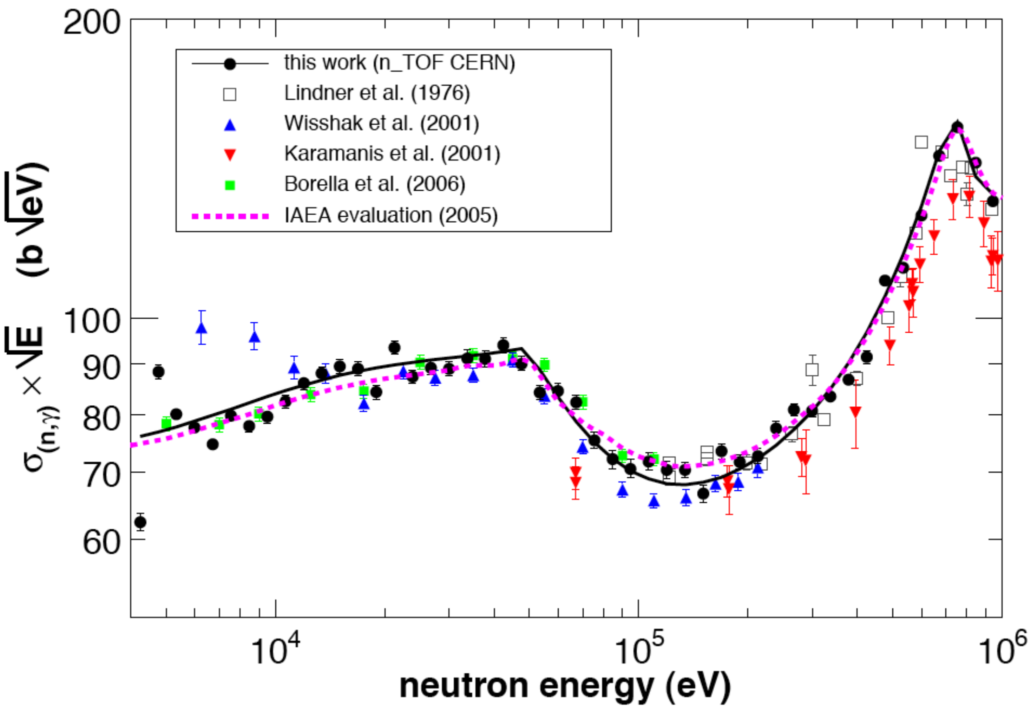
Phys. Rev. C 75 (2007) 035807

$^{232}Th(n,\gamma)$

Resolved resonances

Unesolved resonances

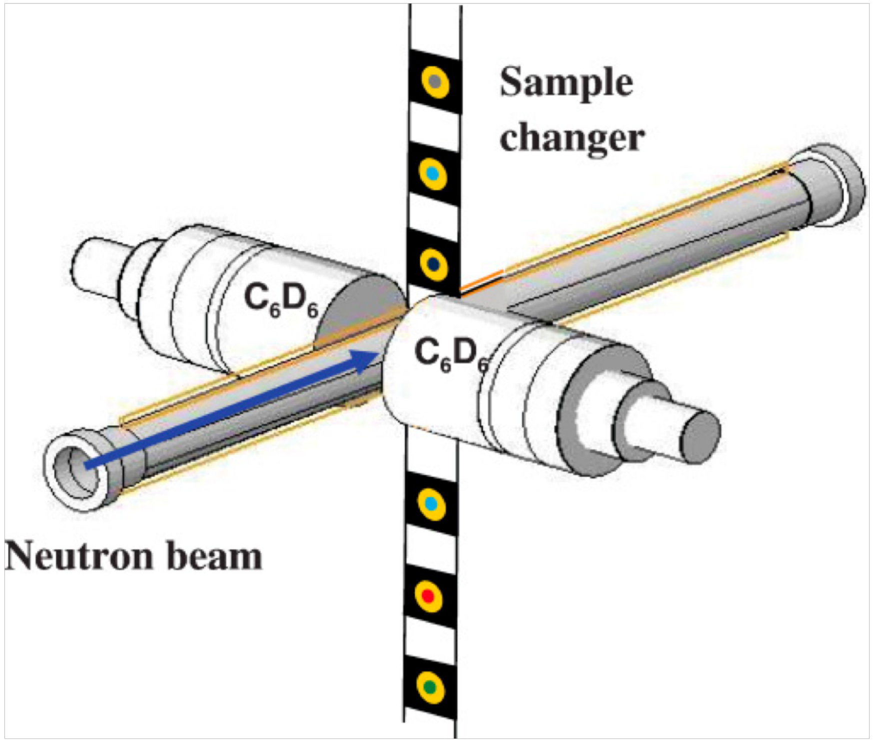


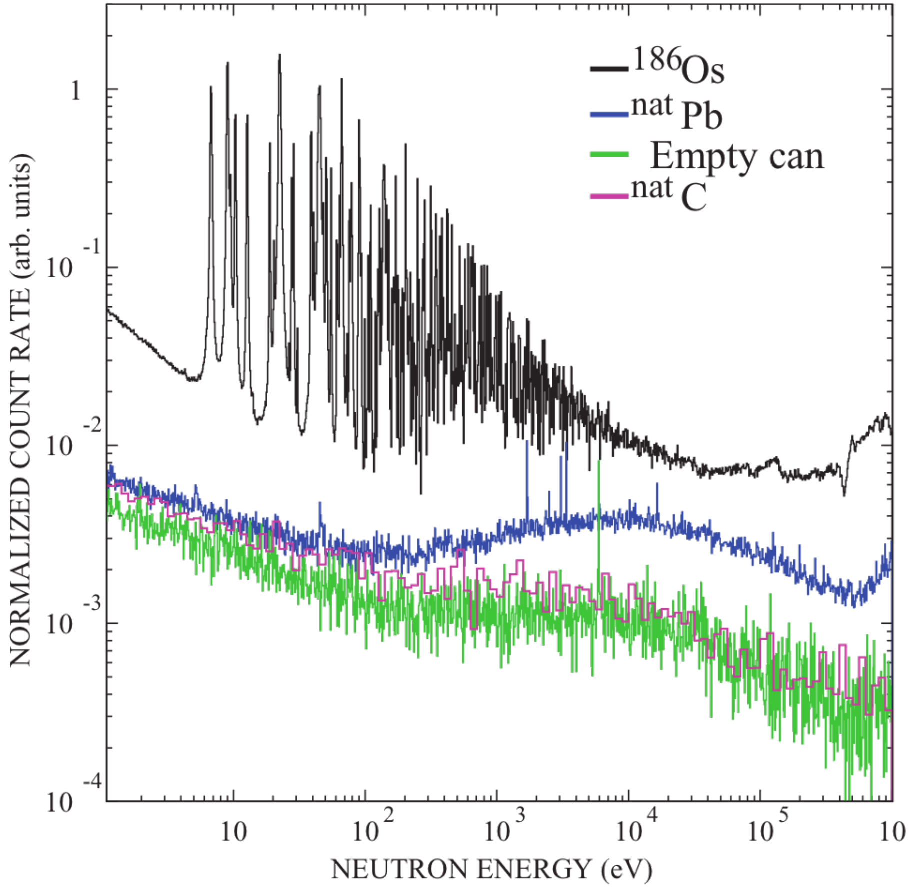


Phys. Rev. C 85 (2012) 064601

Phys. Rev. C 73 (2006) 054610

$^{186, 187, 188}Os(n,\gamma)$ at n_TOF

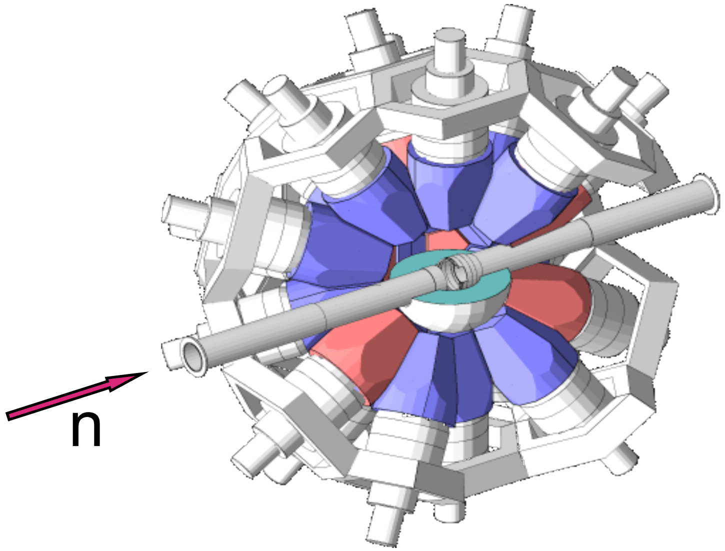


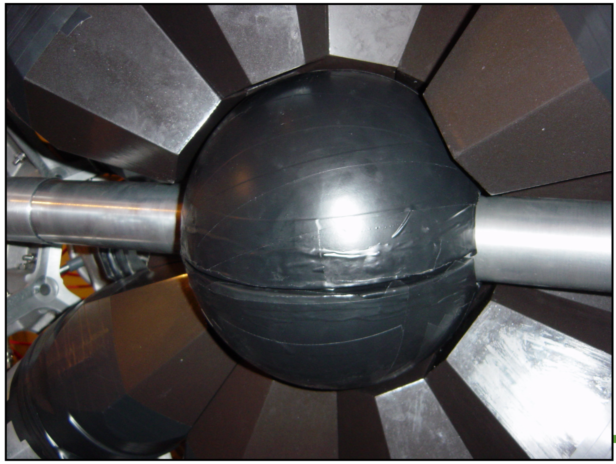


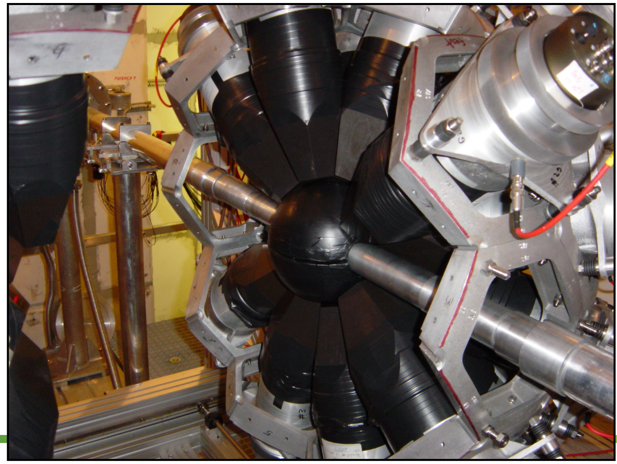
Phys. Rev. C 82 (2010) 015804

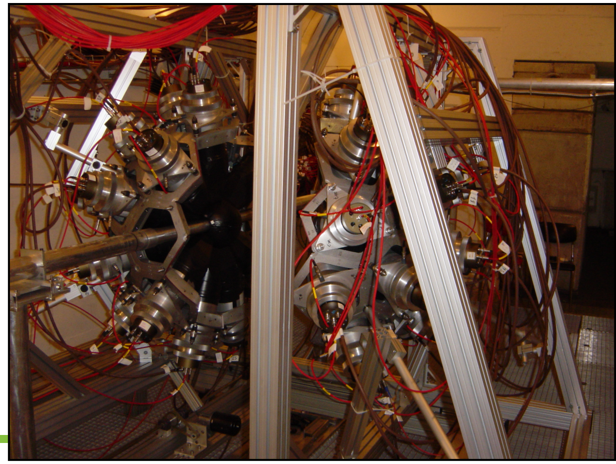
Measurements with BaF_2 detector

- calorimeter with 40 BaF_2 crystals
- 4π solid angle
- 100% efficiency for gamma rays
- operating since 2004

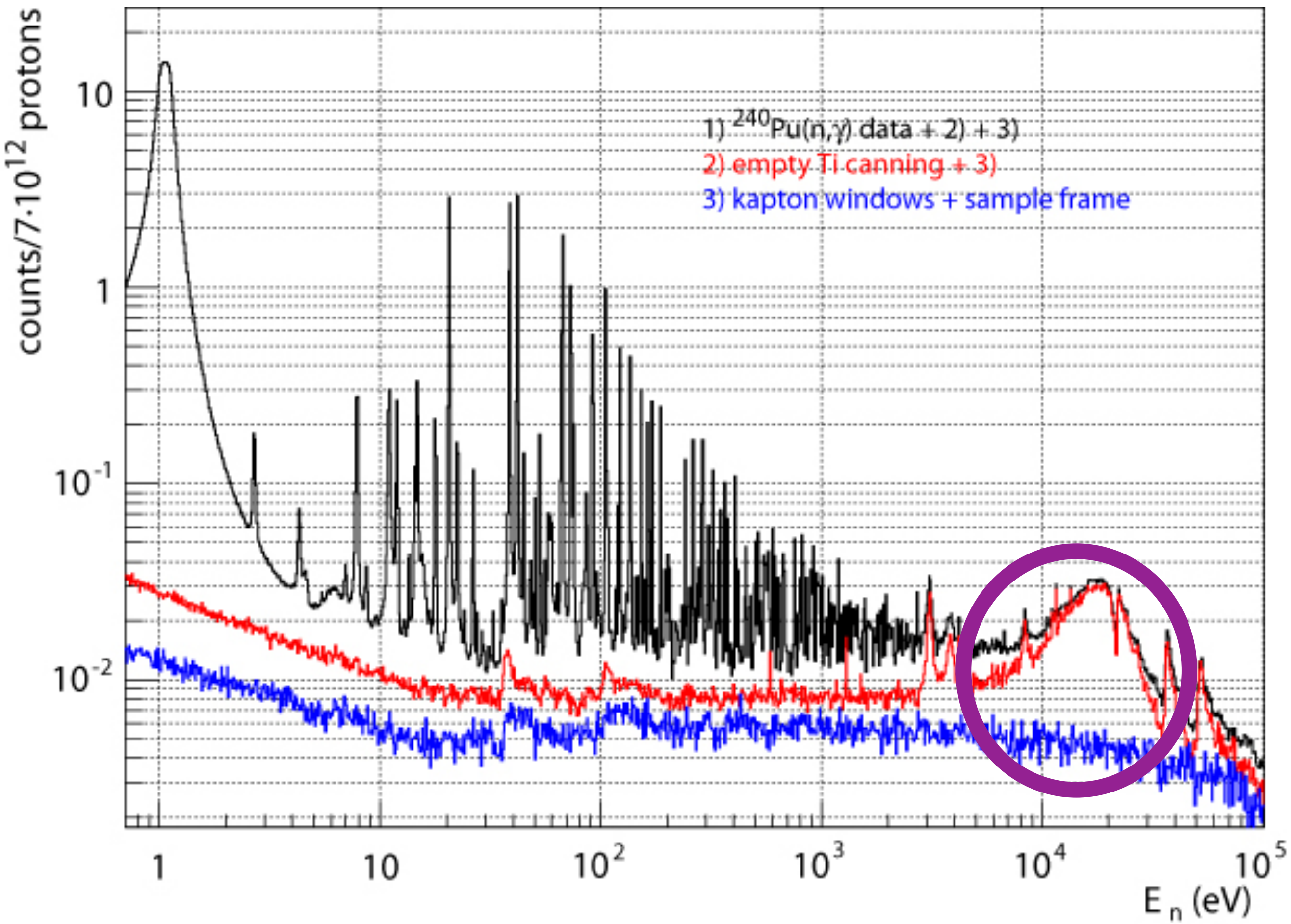




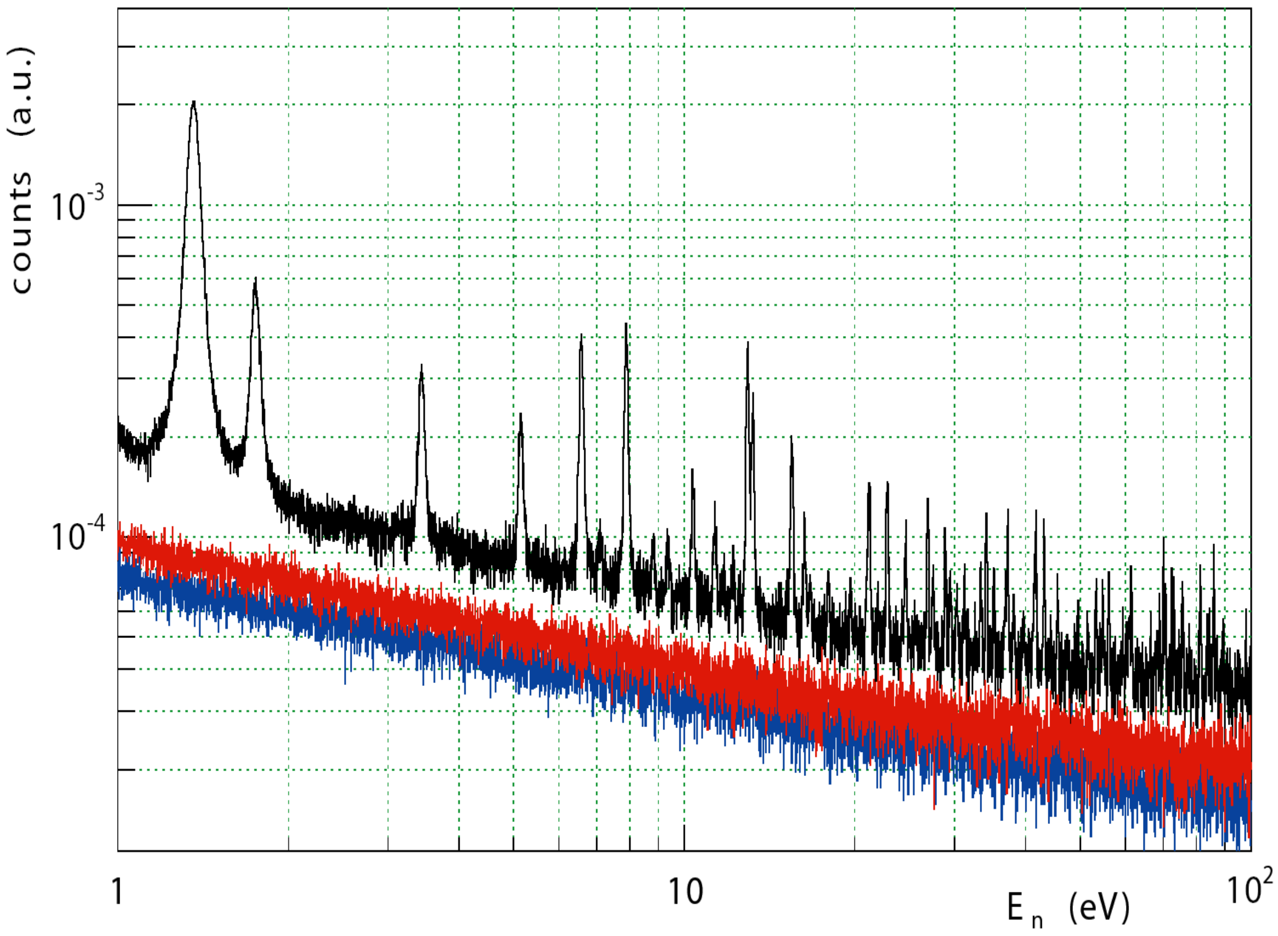




$^{240}Pu(n,\gamma)$



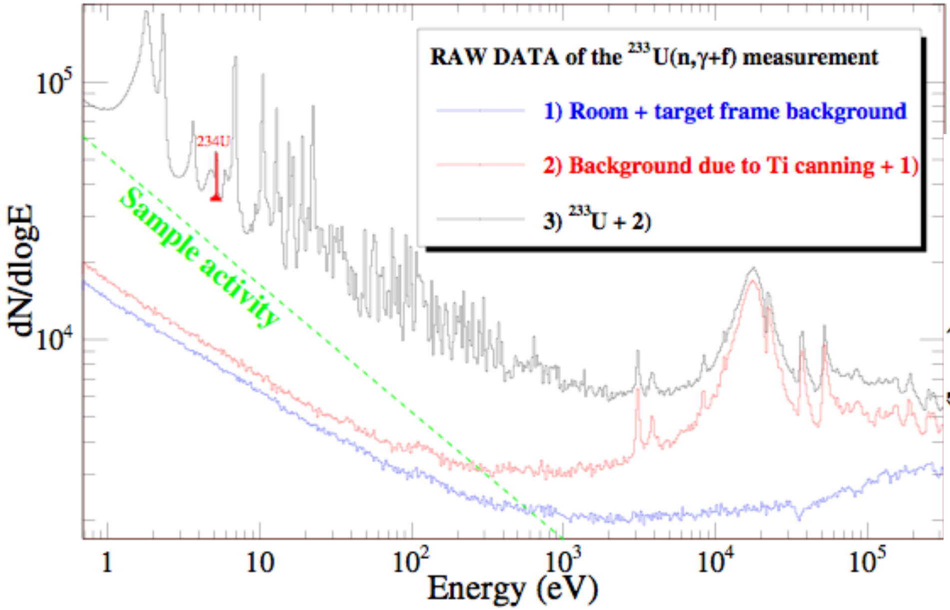
$^{243}Am(n,\gamma)$
10 mg sample

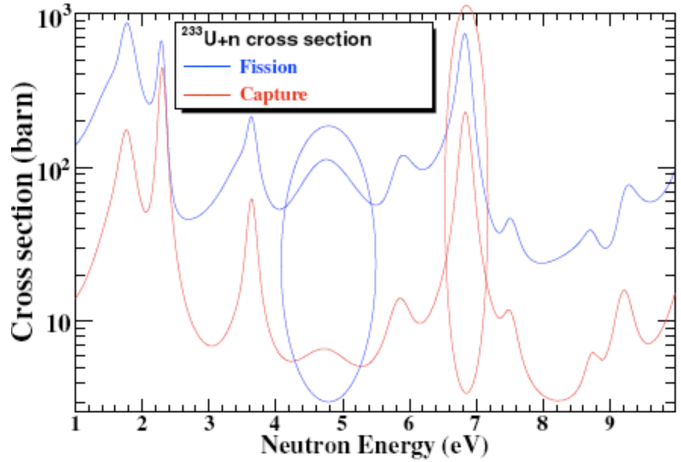


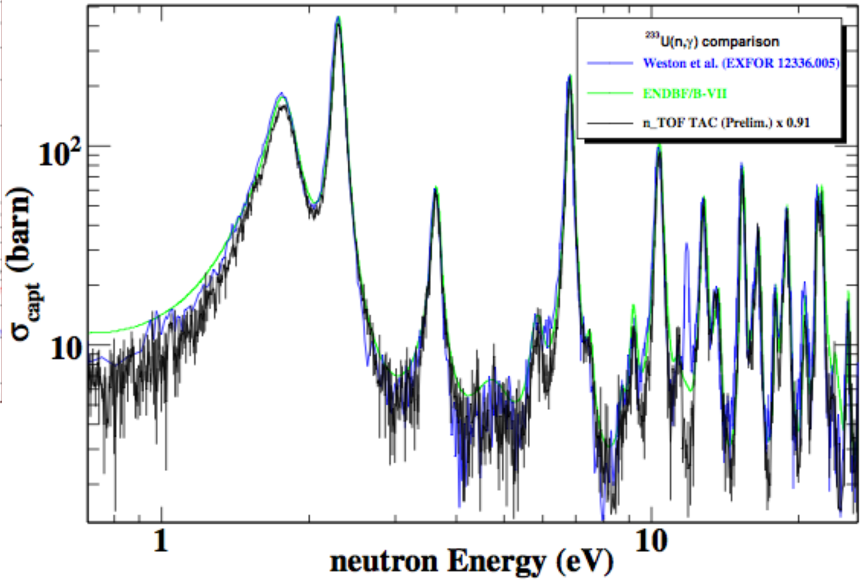
$^{233}U(n,\gamma)$

Fission background in capture spectrum deduced from fission-only resonance

91 mg ^{233}U

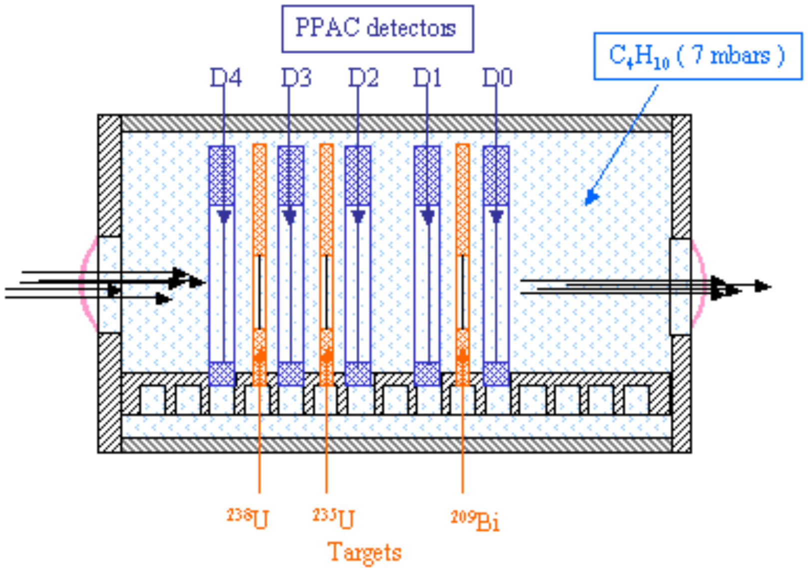




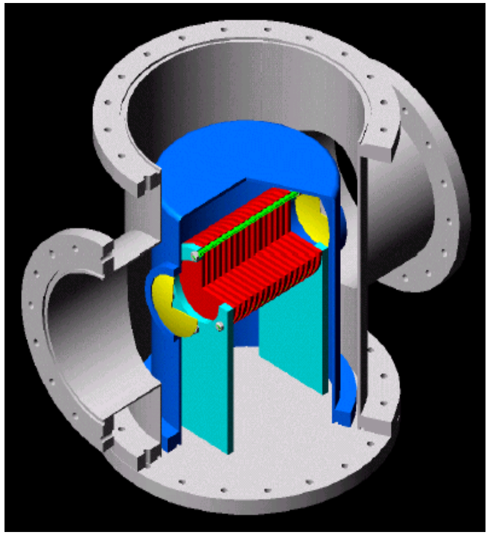


Fission detectors

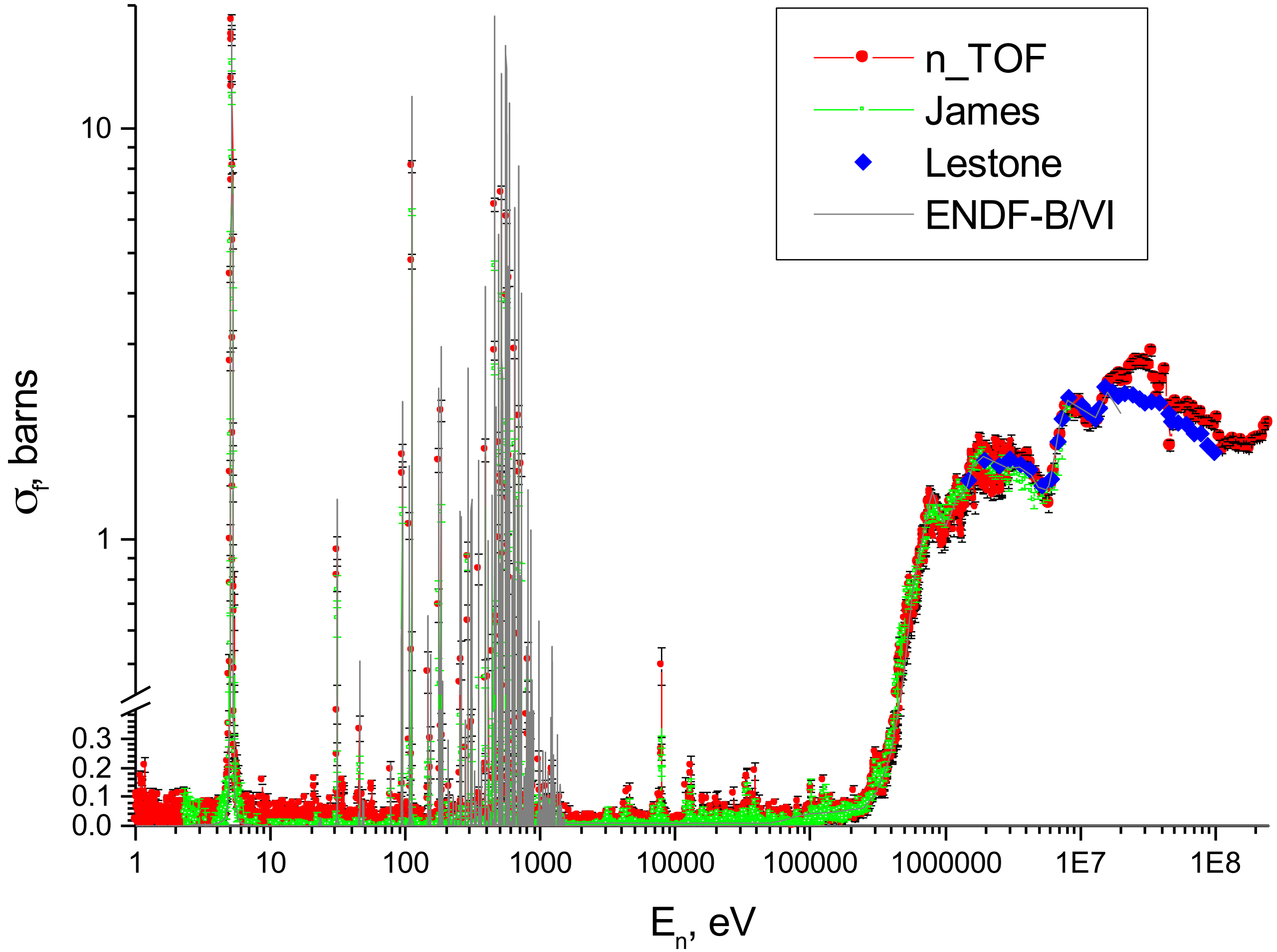
Parallel plate avalance counters (PPACS) fission detectors



Fission ionization chamber detectors

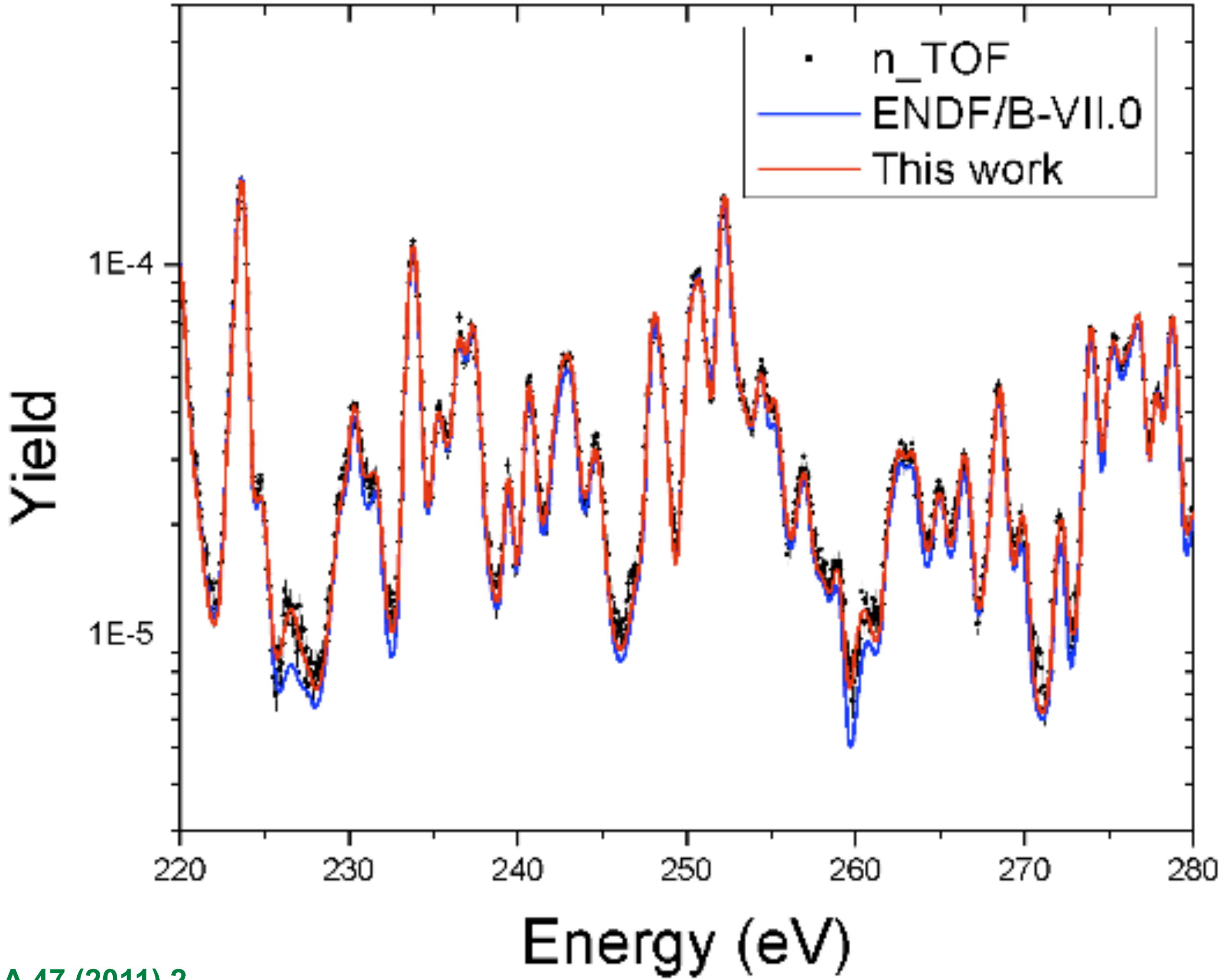


PPAC $^{234}U(n,f)$



Phys. Rev. C 82 (2010) 034601

$^{233}U(n,f)$



Eur. Phys. J. A 47 (2011) 2

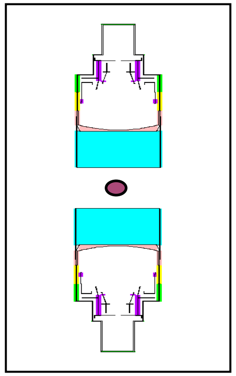
n_TOF CERN phase I (2001-2004)
Summary of measurements

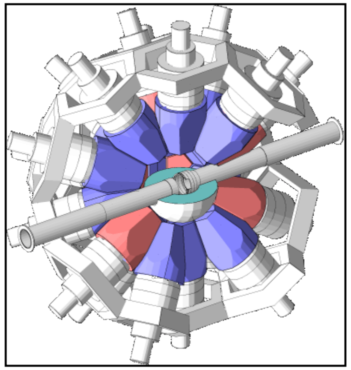
capture C_6D_6
- ^{24,25,26}Mg
- ^{56}Fe
- ^{90,91,92,93,94,96}Zr
- ^{139}La
- ^{151}Sm
- ^{186,187,188}Os
- ^{197}Au
- ^{204,206,207,208}Pb
- ^{209}Bi
- ^{232}Th

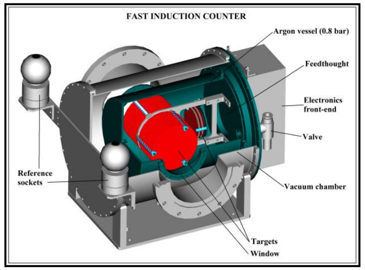
capture BaF_2
- ^{197}Au
- ^{233,234}U
- ^{237}Np
- ^{240}Pu
- ^{243}Am

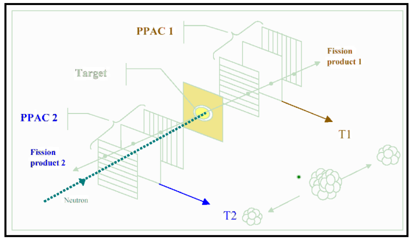
fission FIC
- ^{232}Th
- ^{237}Np
- ^{233,234,235,236,238}U
- ^{241,243}Am
- ^{245}Cm

fission PPAC
- ^{nat}Pb
- ^{209}Bi
- ^{232}Th
- ^{237}Np
- ^{233,234,235,238}U

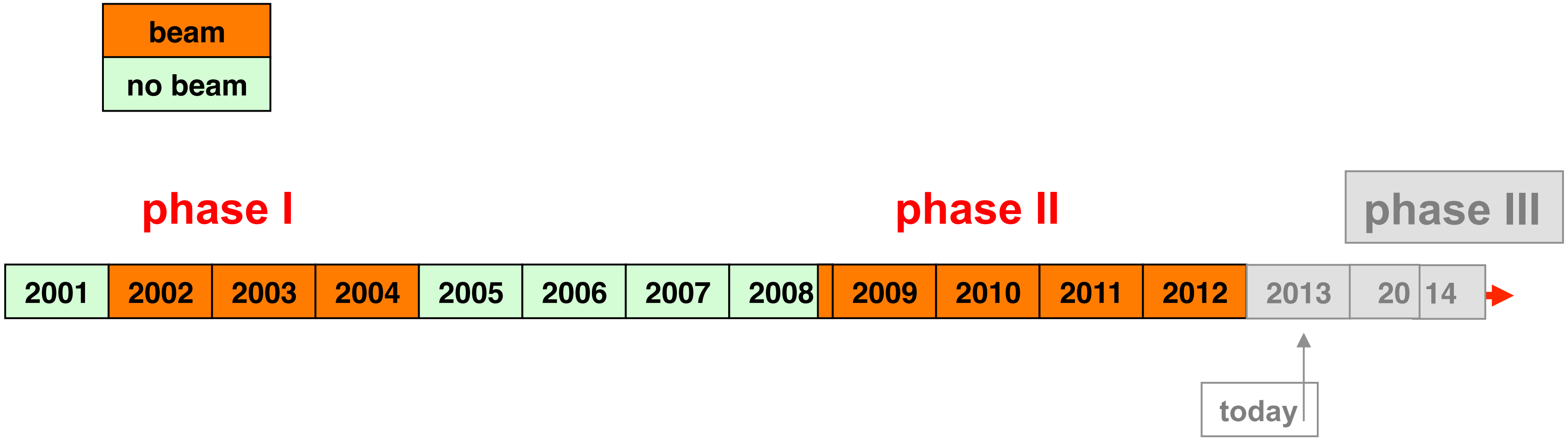








The n_TOF facility at CERN



- 1998 - 2001 preparation and commissioning
- 2002 - 2004 **phase I** data taking
- 2005 - 2007 spallation target upgrade
- 2008 first protons on target
- 2009 **phase II** data taking
- 2010 - 2012 class A lab. borated water

n_TOF CERN phase II
New Spallation Target

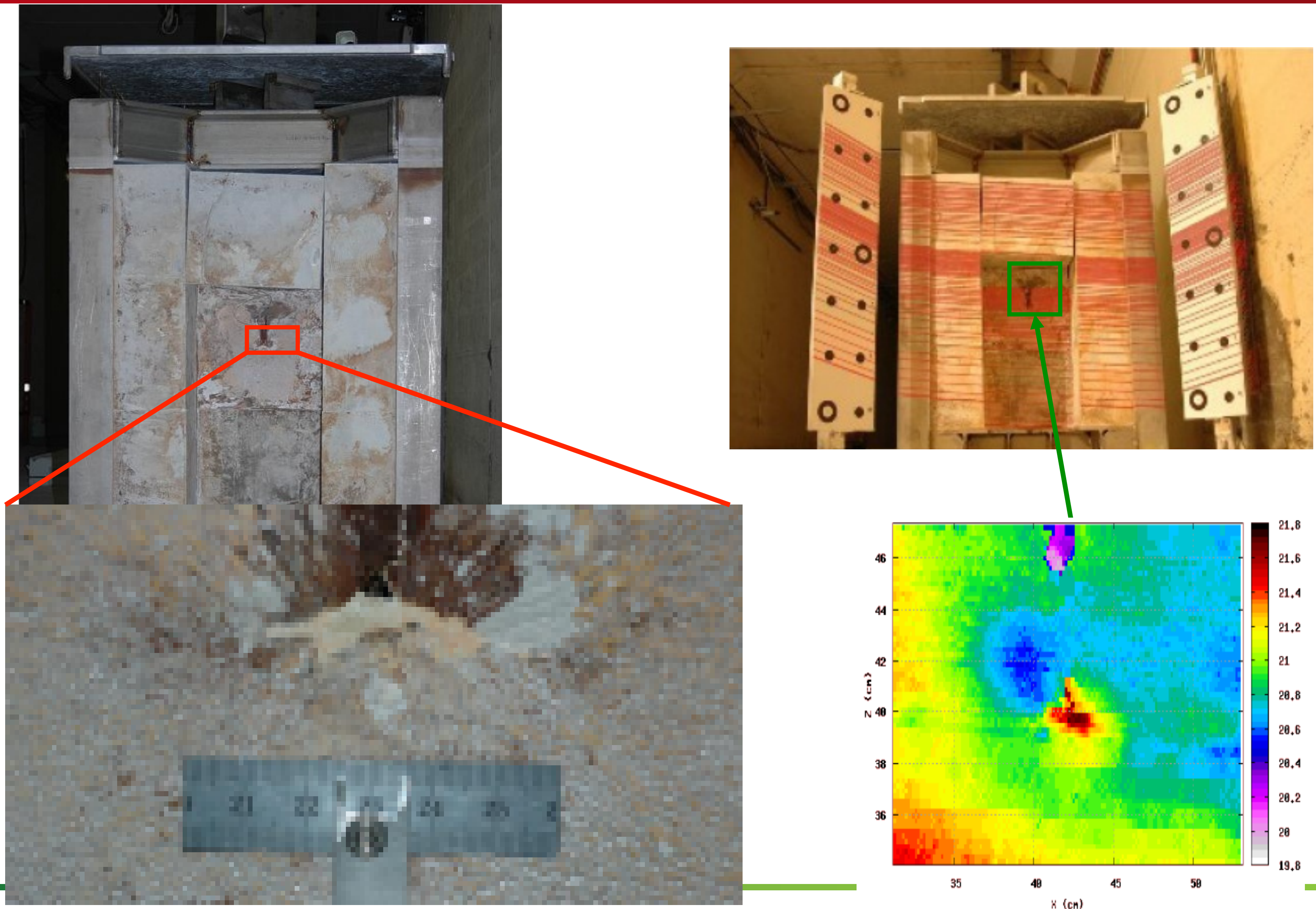
- At the end of 2004 an increased radioactivity was observed in the filters of the cooling water circuit. Stop of n_TOF beam.

- In 2007 the target has been thorougly investigated and a new design was made.
  - new lead spallation target
  - separated cooling and moderation water circuit
  - cooling system with monitoring of pH, O_2, T etc.
  - new ventilation station

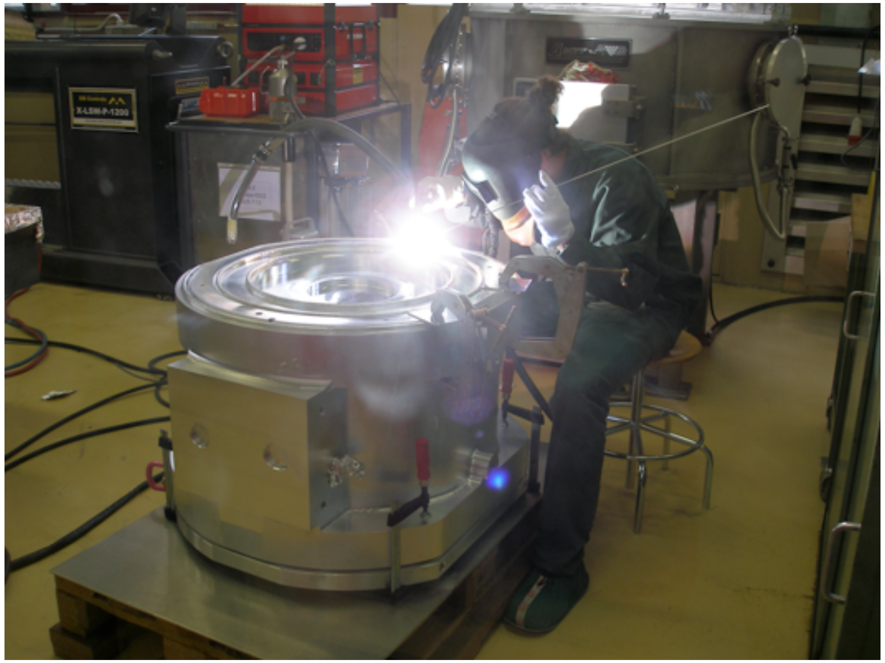
- upgraded facility was ready by the end of 2008

- new measurement programme started in 2009

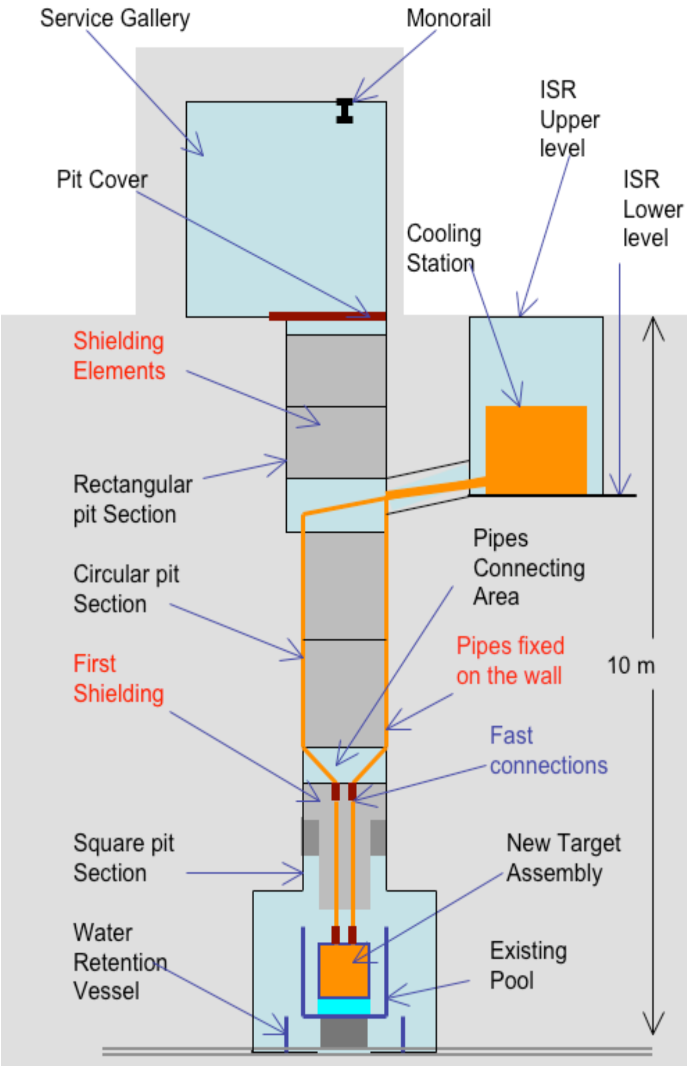
Old Spallation Target

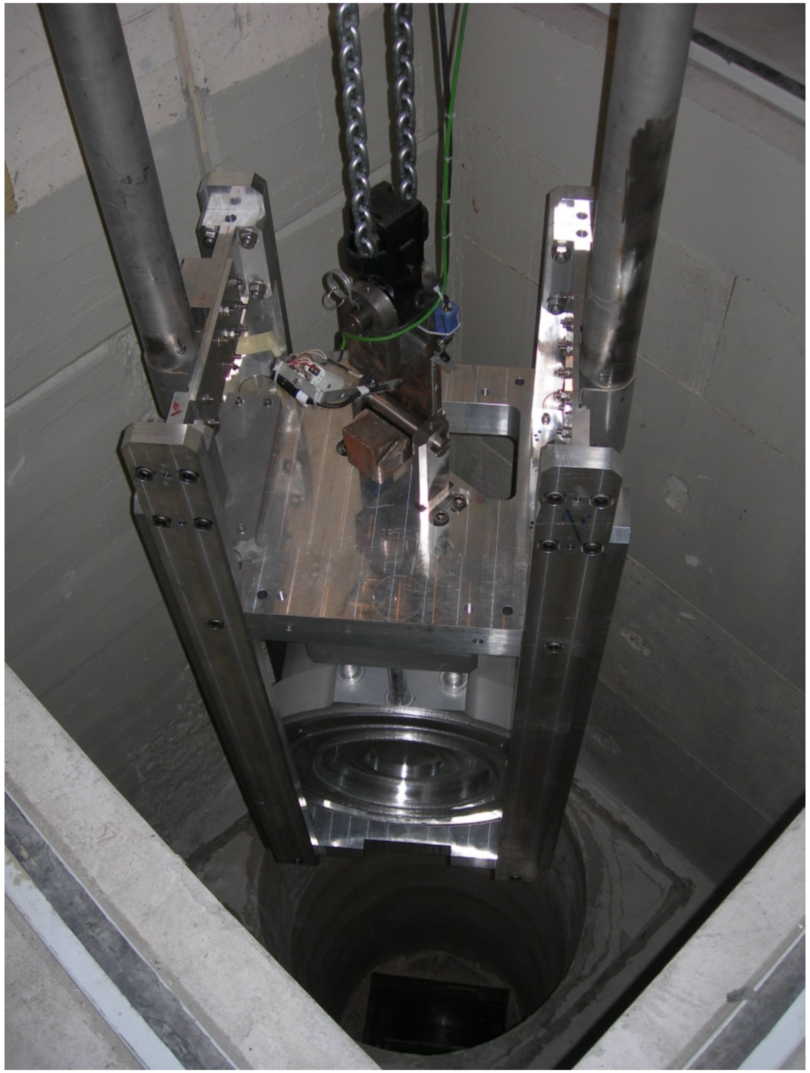


New Spallation Target



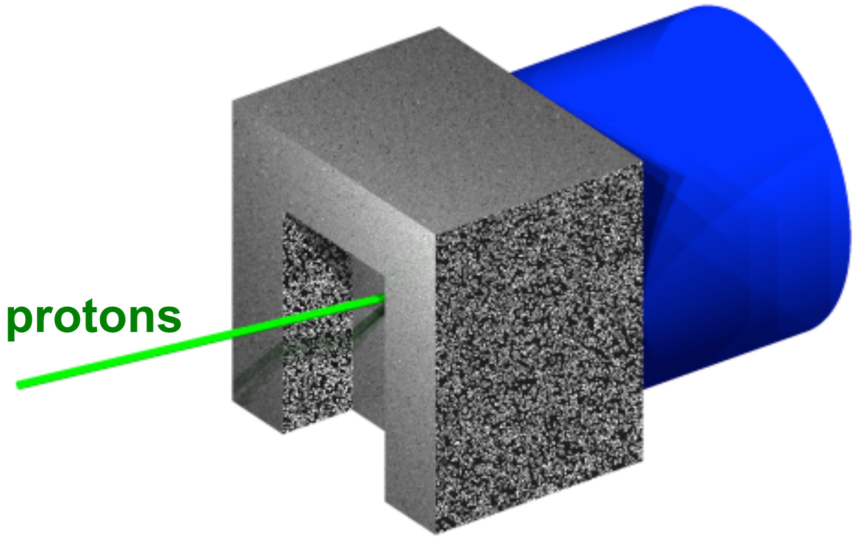
New Spallation Target in 2009





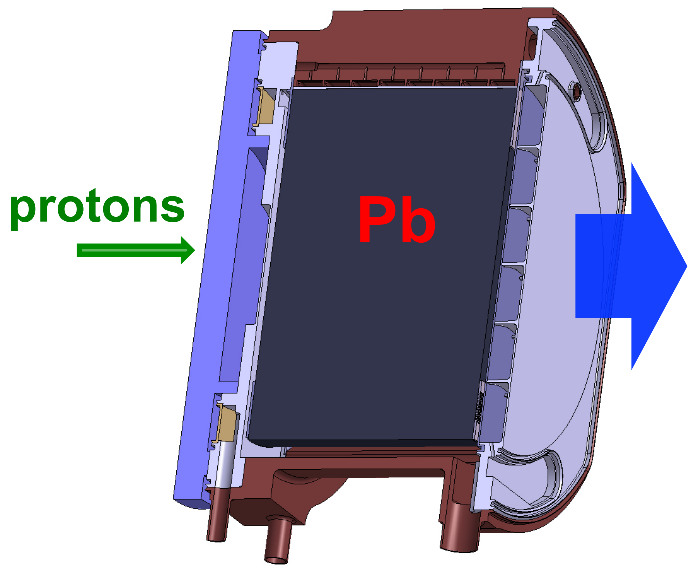
n_TOF CERN: Target/moderator configurations

phase I target
2001-2004



1 configuration

phase II target
2009-2012



2 configurations:
water, water+^{10}B

The n_TOF facility at CERN

Pulsed white neutron source:

- 20 GeV/c protons
- neutrons from spallation
- 6 ns rms pulse width
- frequency 1 pulse/2.4 seconds
- separate cooling and moderation
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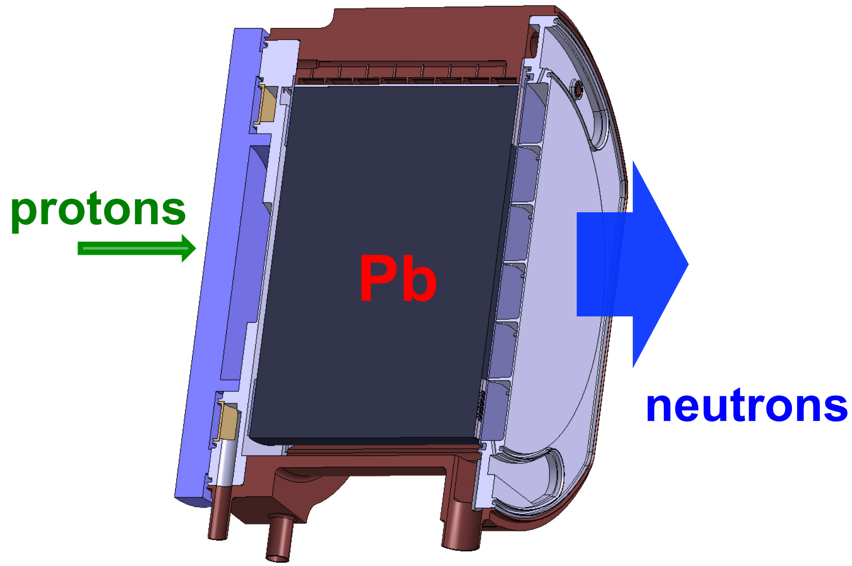
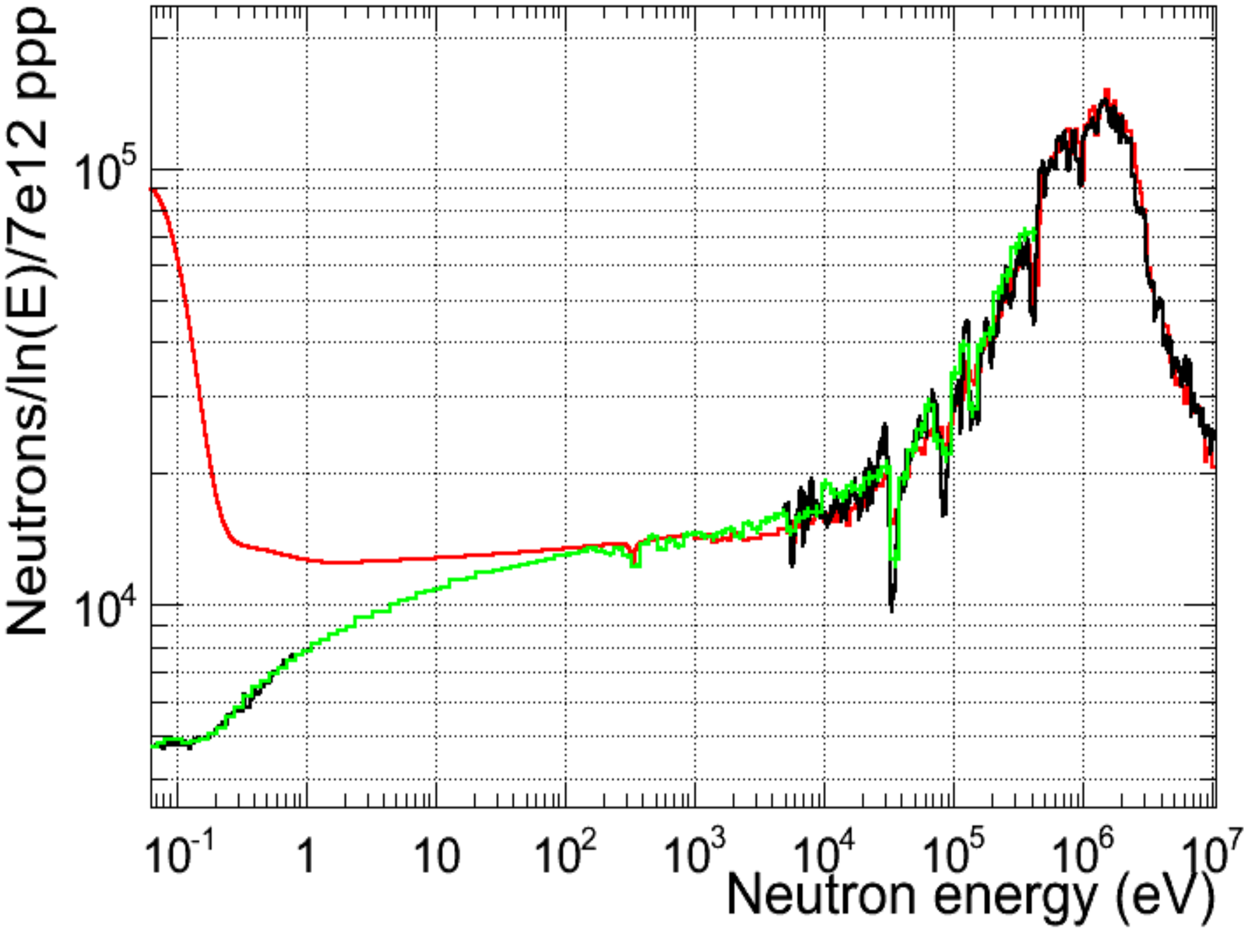


phase II target

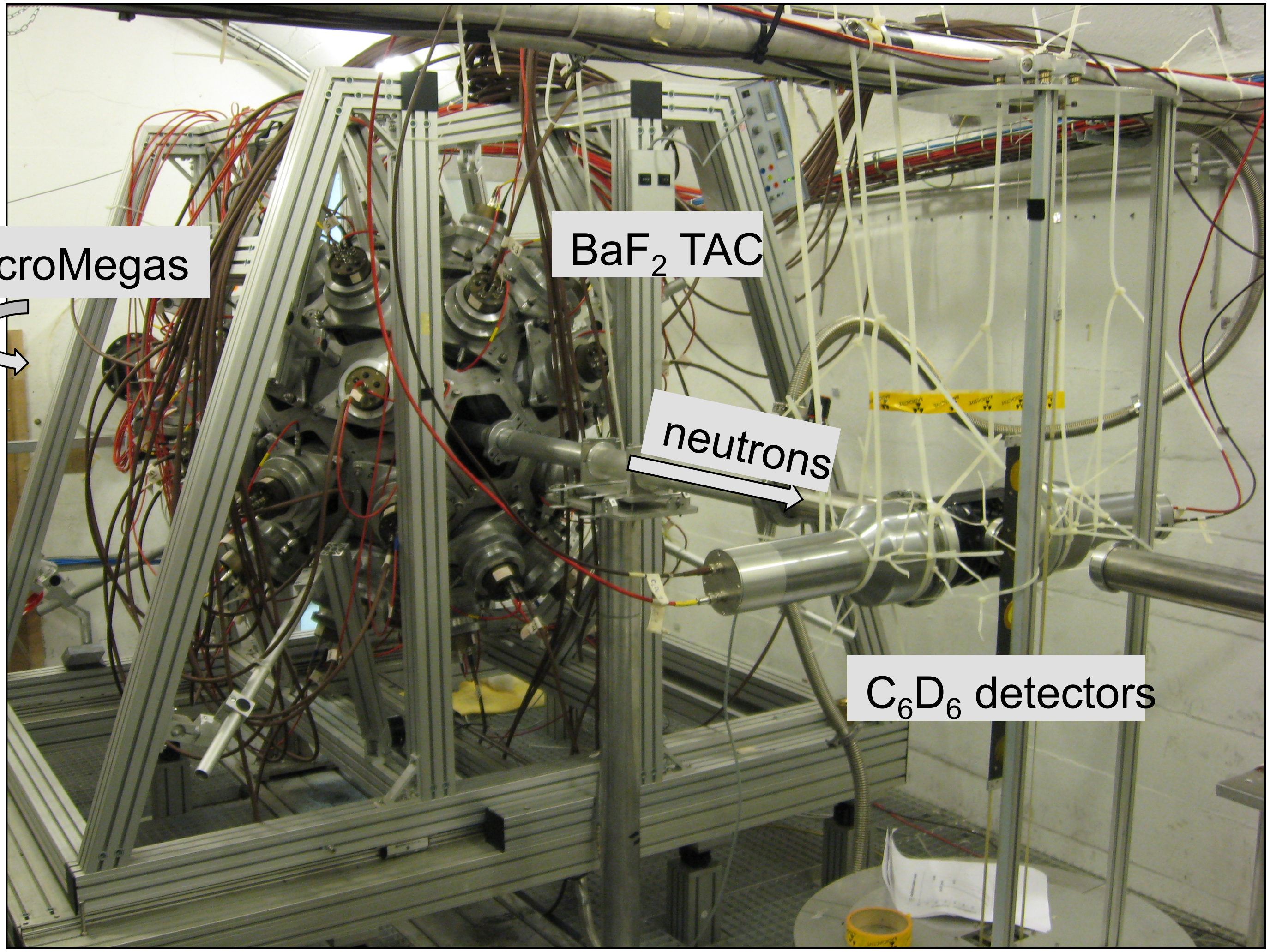
Main features:

- Large energy range in one experiment (0.1 eV - 250 MeV)
- Favorable signal to noise ratio for capture on radioactive isotopes (actinides, fission products)

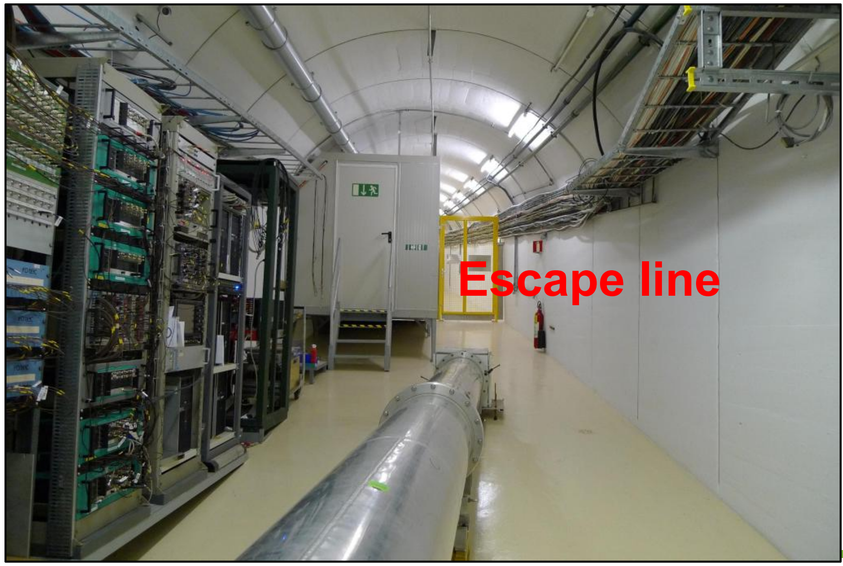
The n_TOF neutron spectrum moderator with/without boron

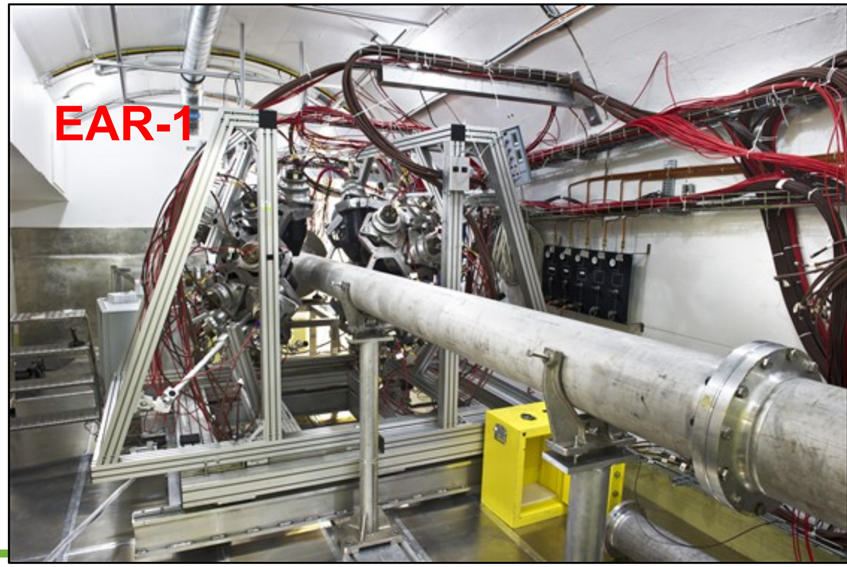


n_TOF setup EAR1

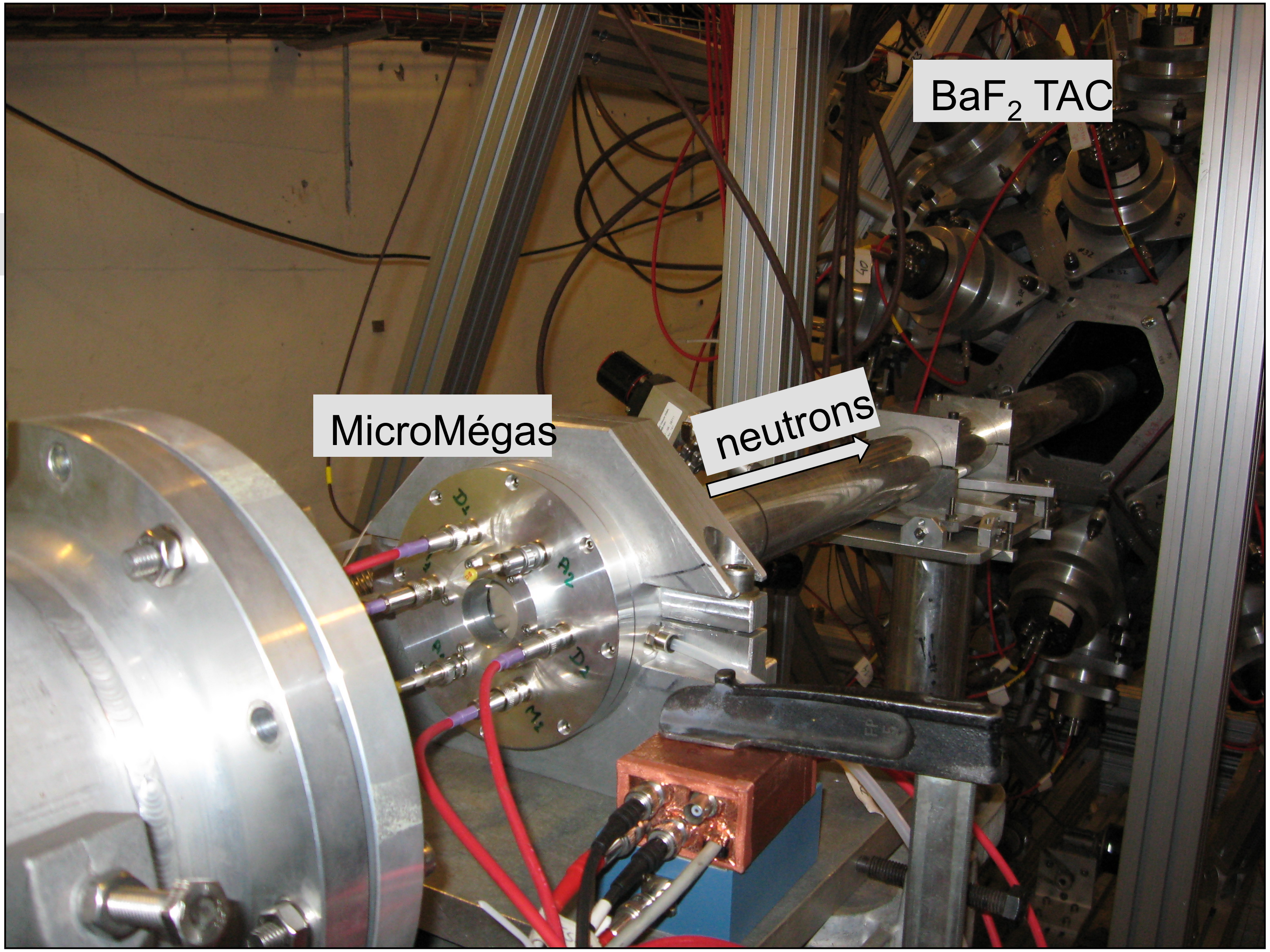


The n_TOF beam line EAR1

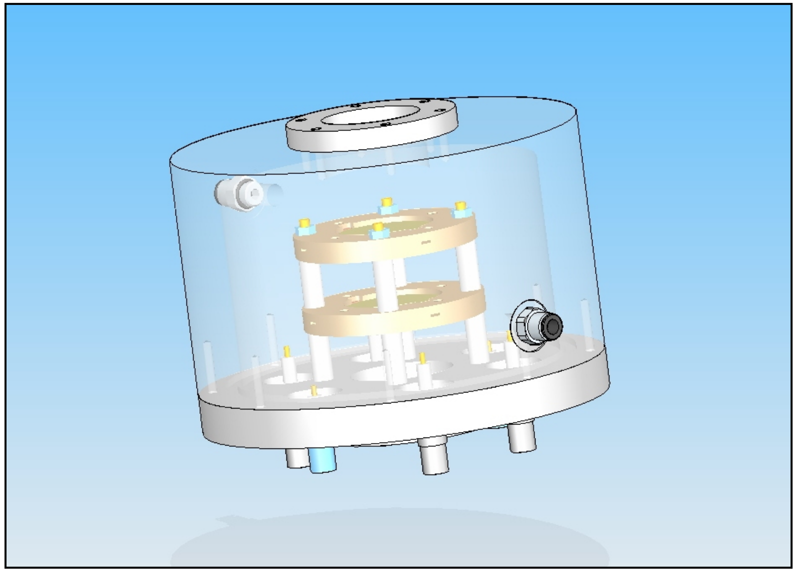


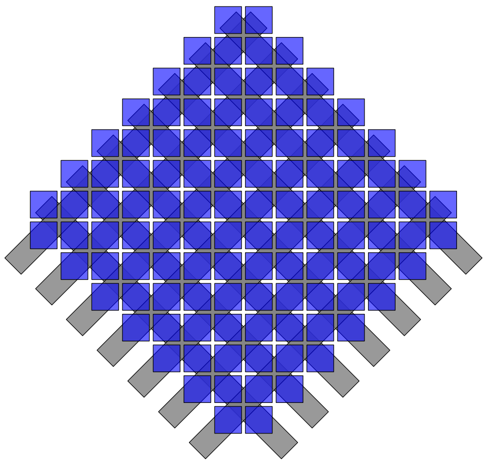


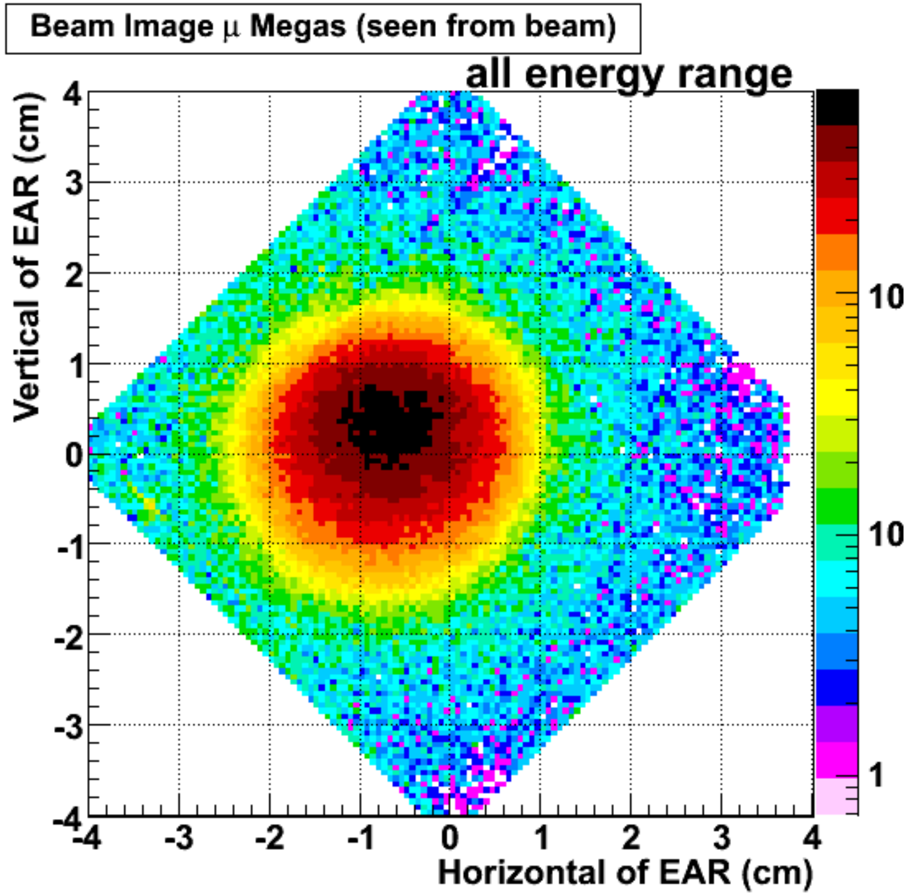
n_TOF setup EAR1



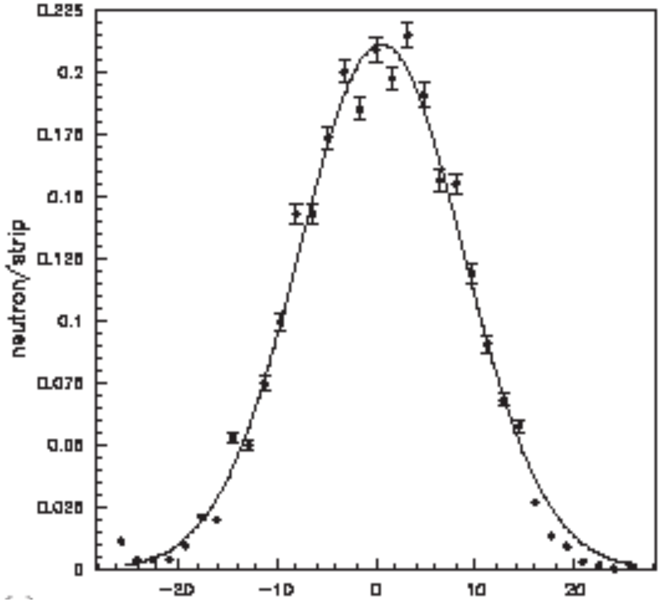
MicroMegas-based neutron beam profiler

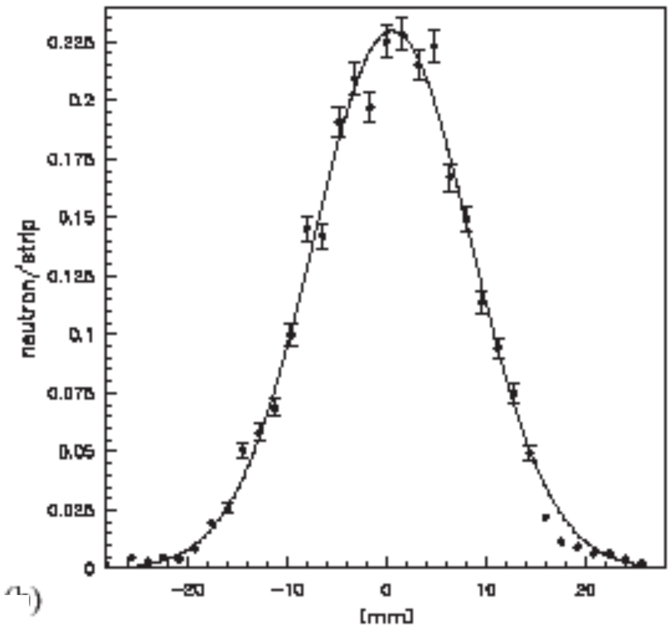


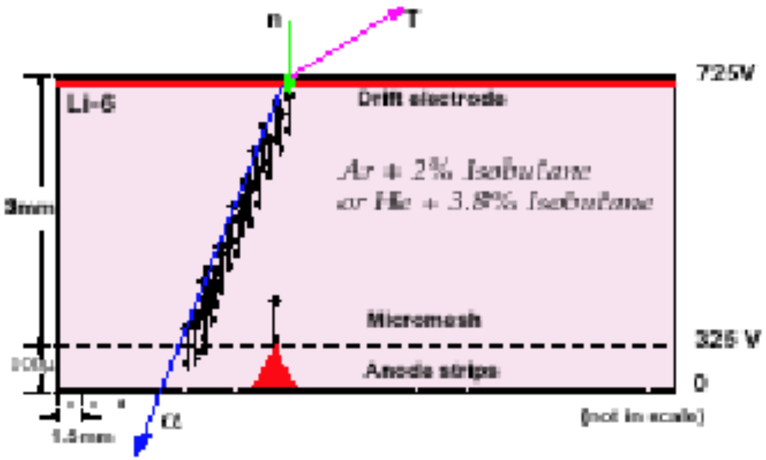


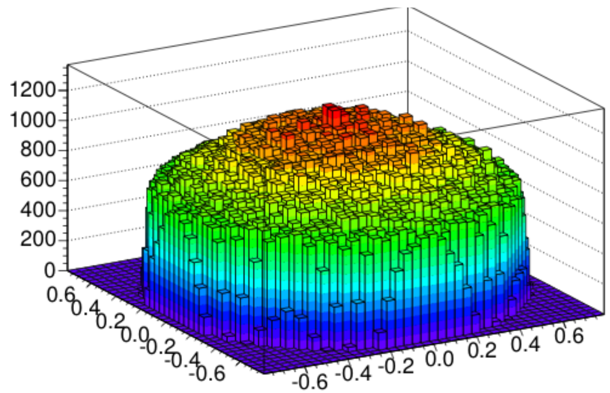


Beam profile using MicroMegas

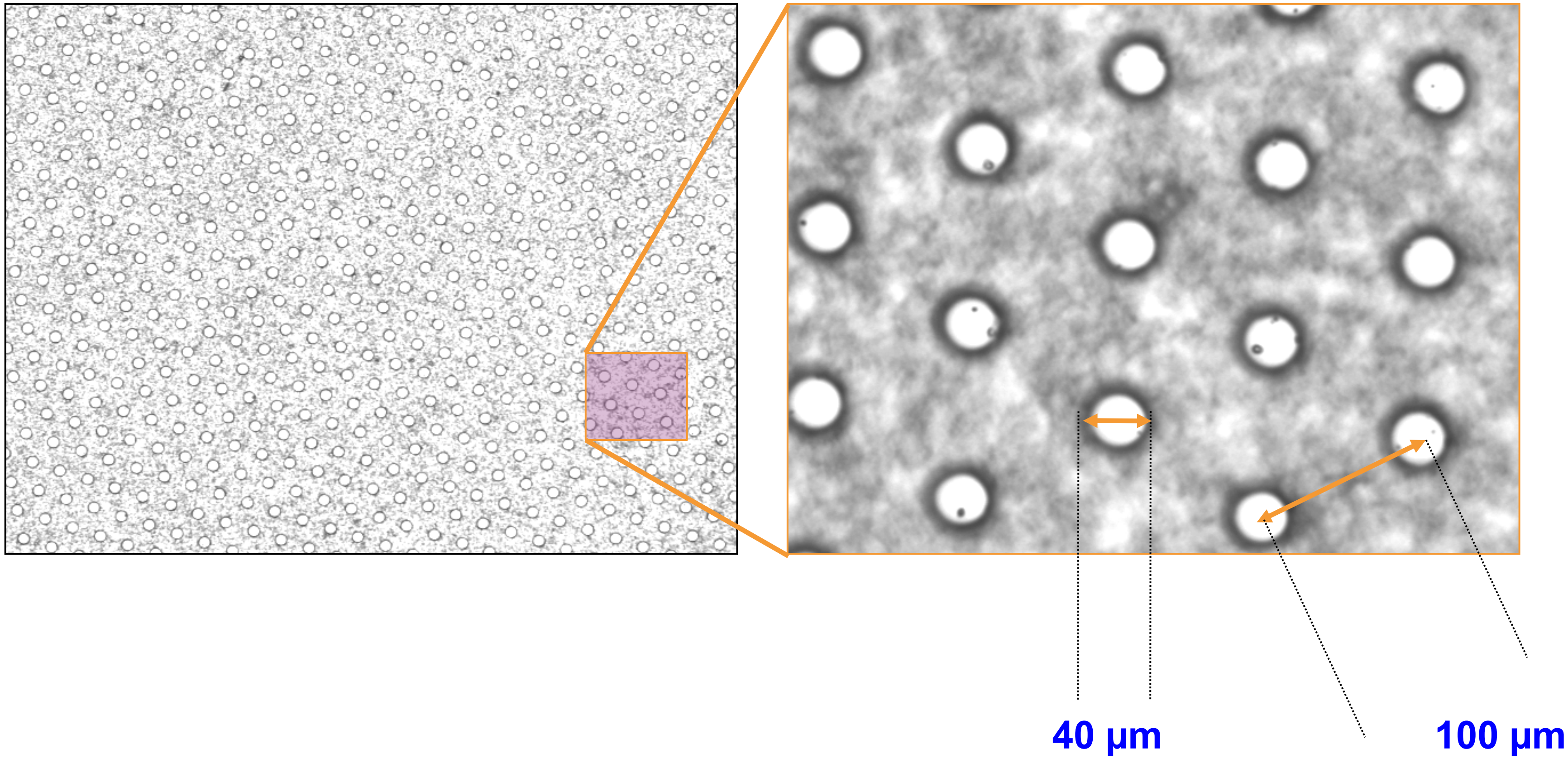




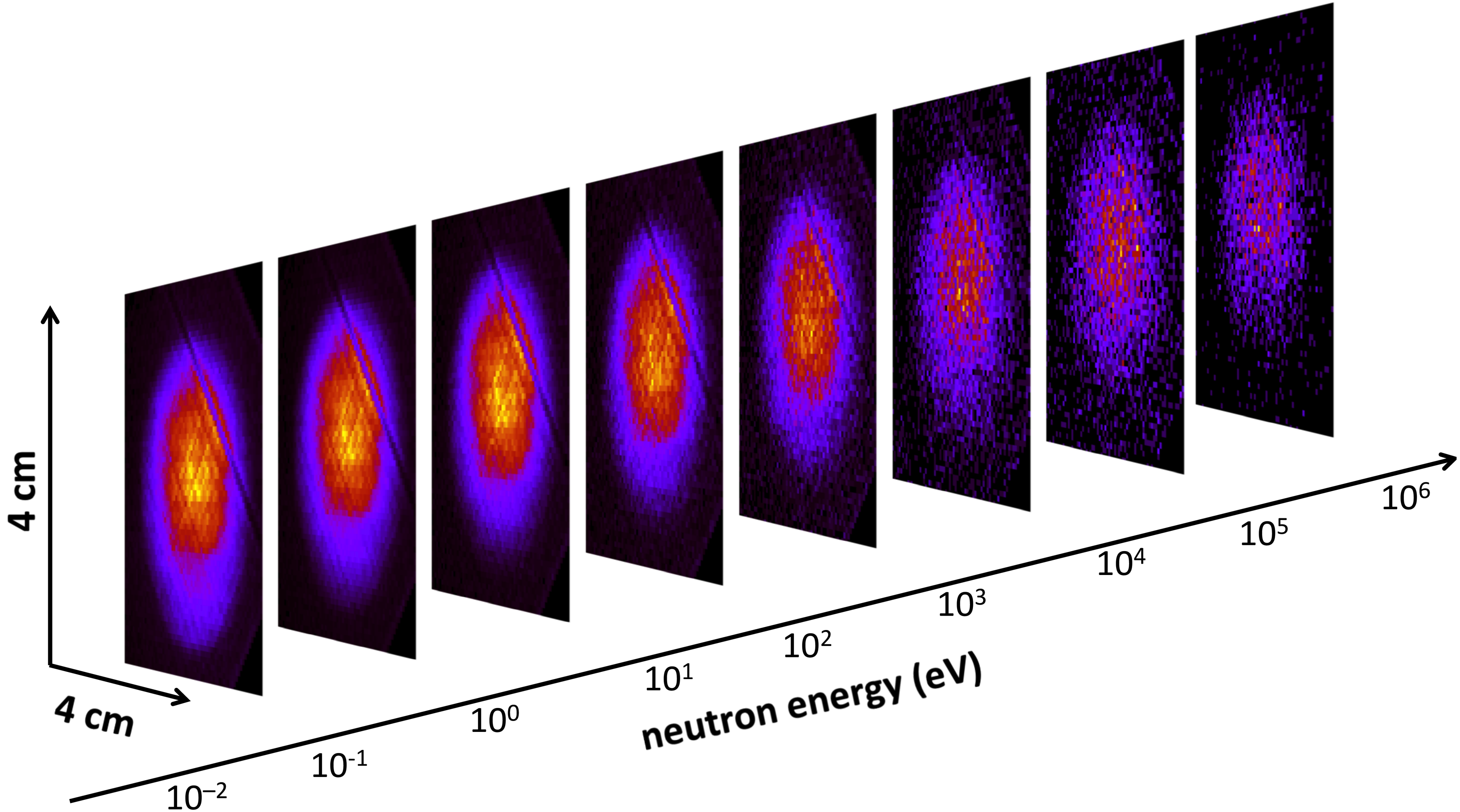




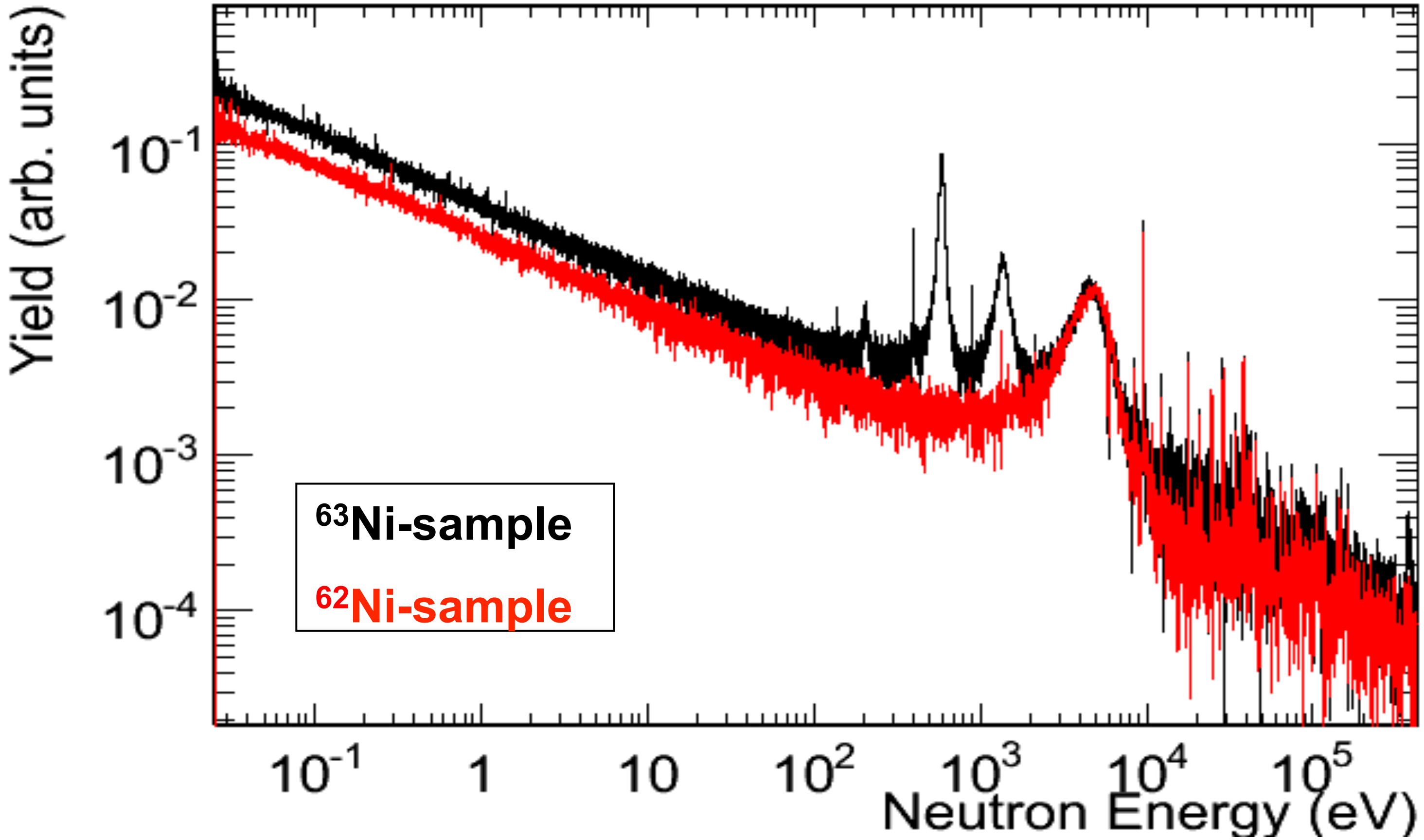
Microbulk microscope picture



MicroMegas-based neutron beam profiler



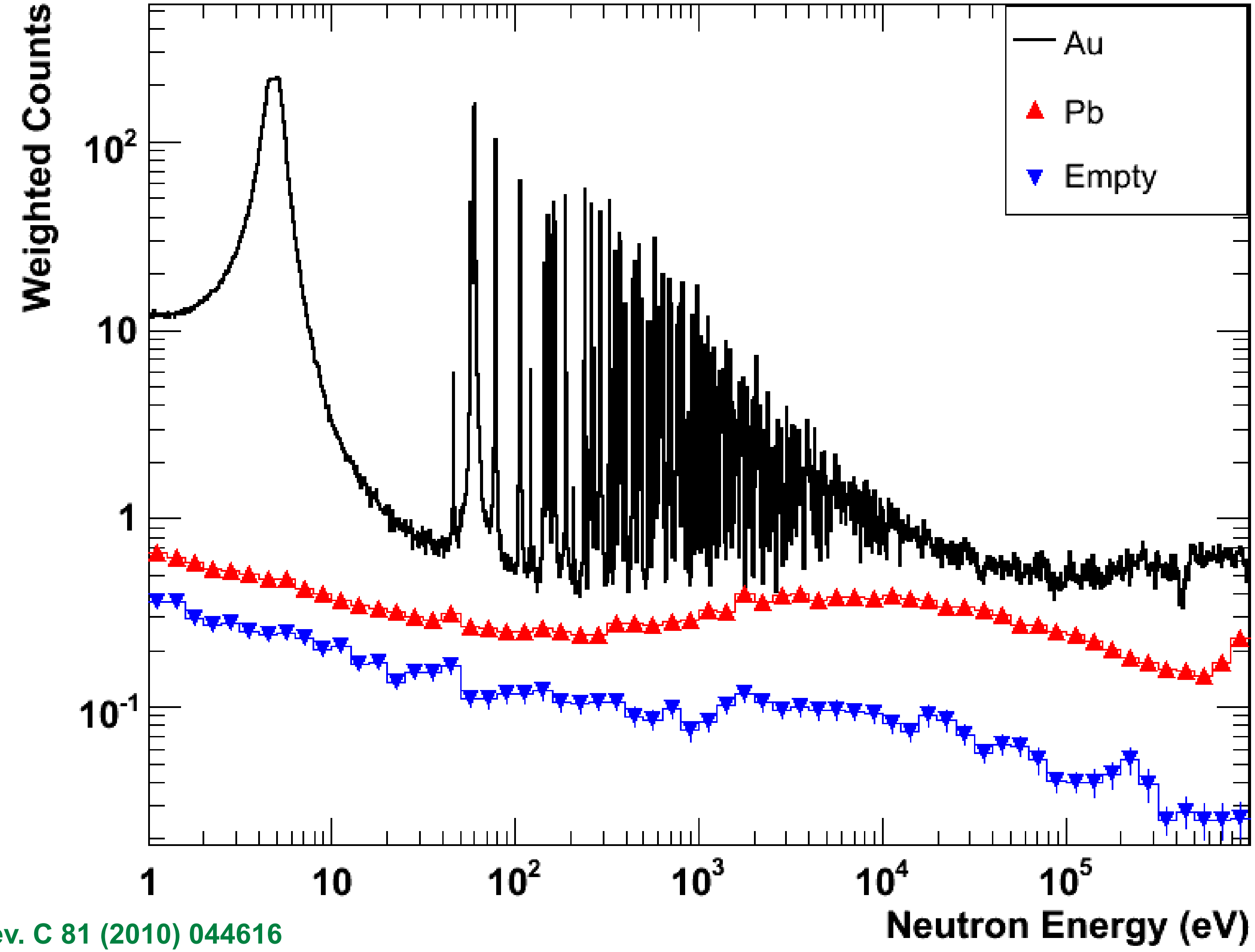
$^{63}Ni(n,\gamma)$



Sample material ^{62}Ni and ^{63}Ni (12%, 112 mg), same as at DANCE (LANL), but now chemically cleaned from 2% Cu impurities at PSI, Switzerland.

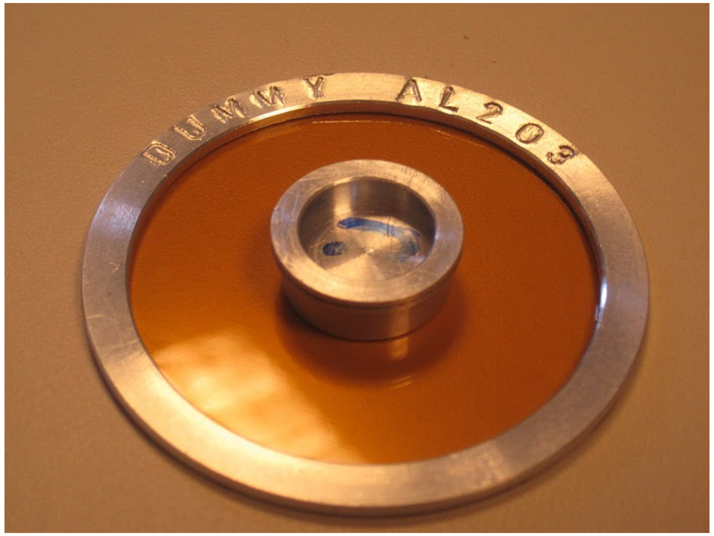
PRL 110 (2013) 022501
PRC 89 (2014) 025810

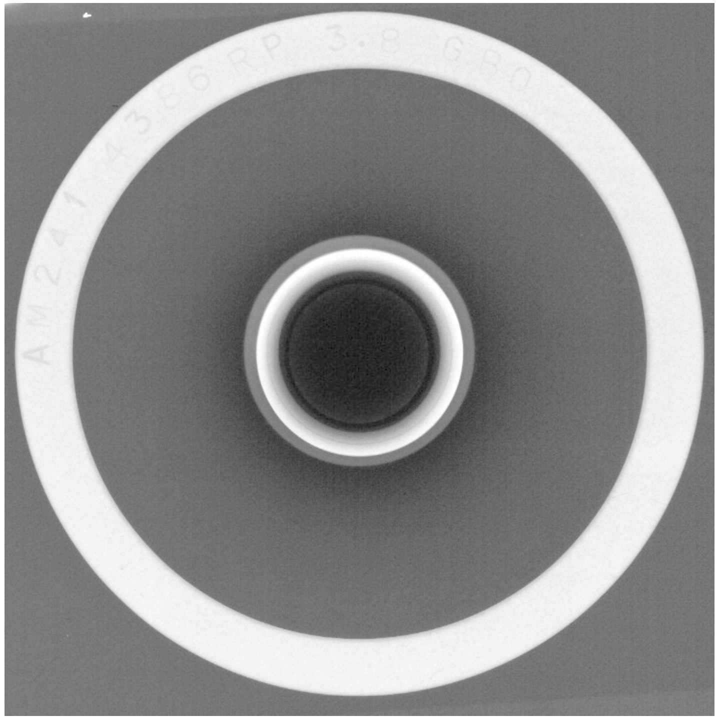
$^{197}Au(n,\gamma)$

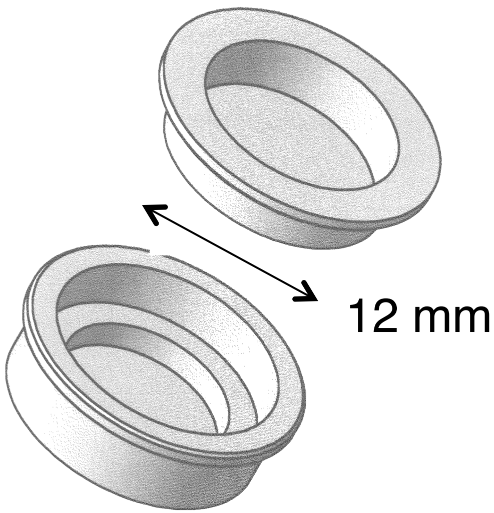


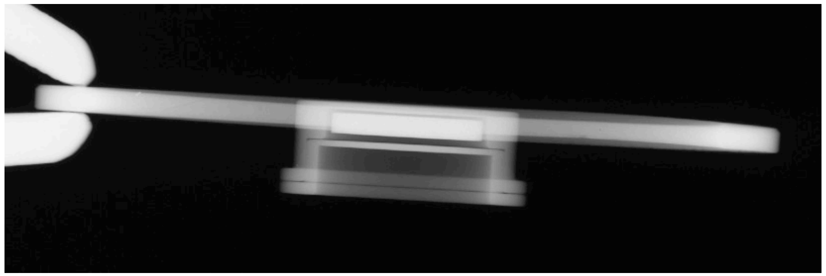
Phys. Rev. C 81 (2010) 044616

^{241}Am sample

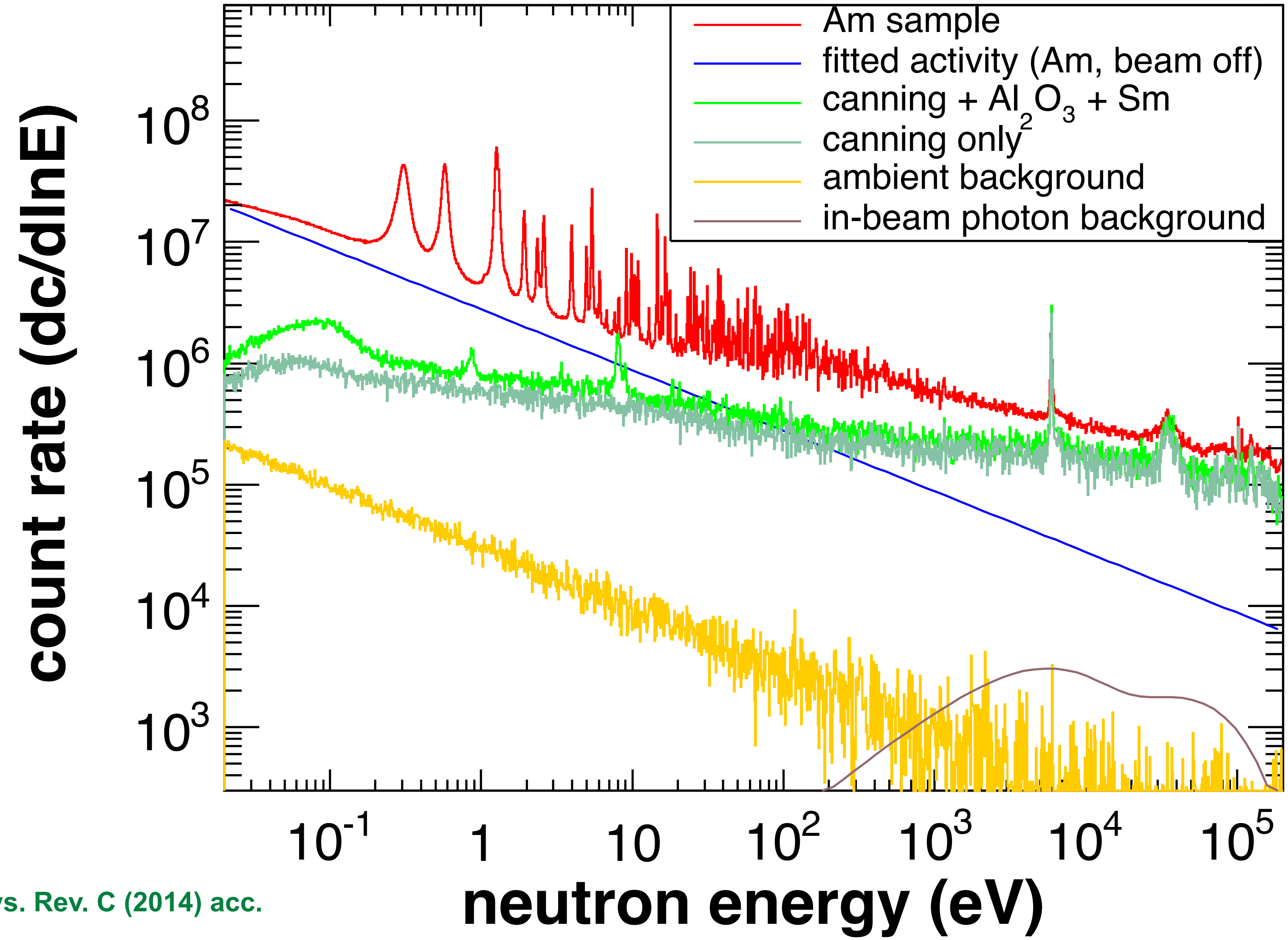






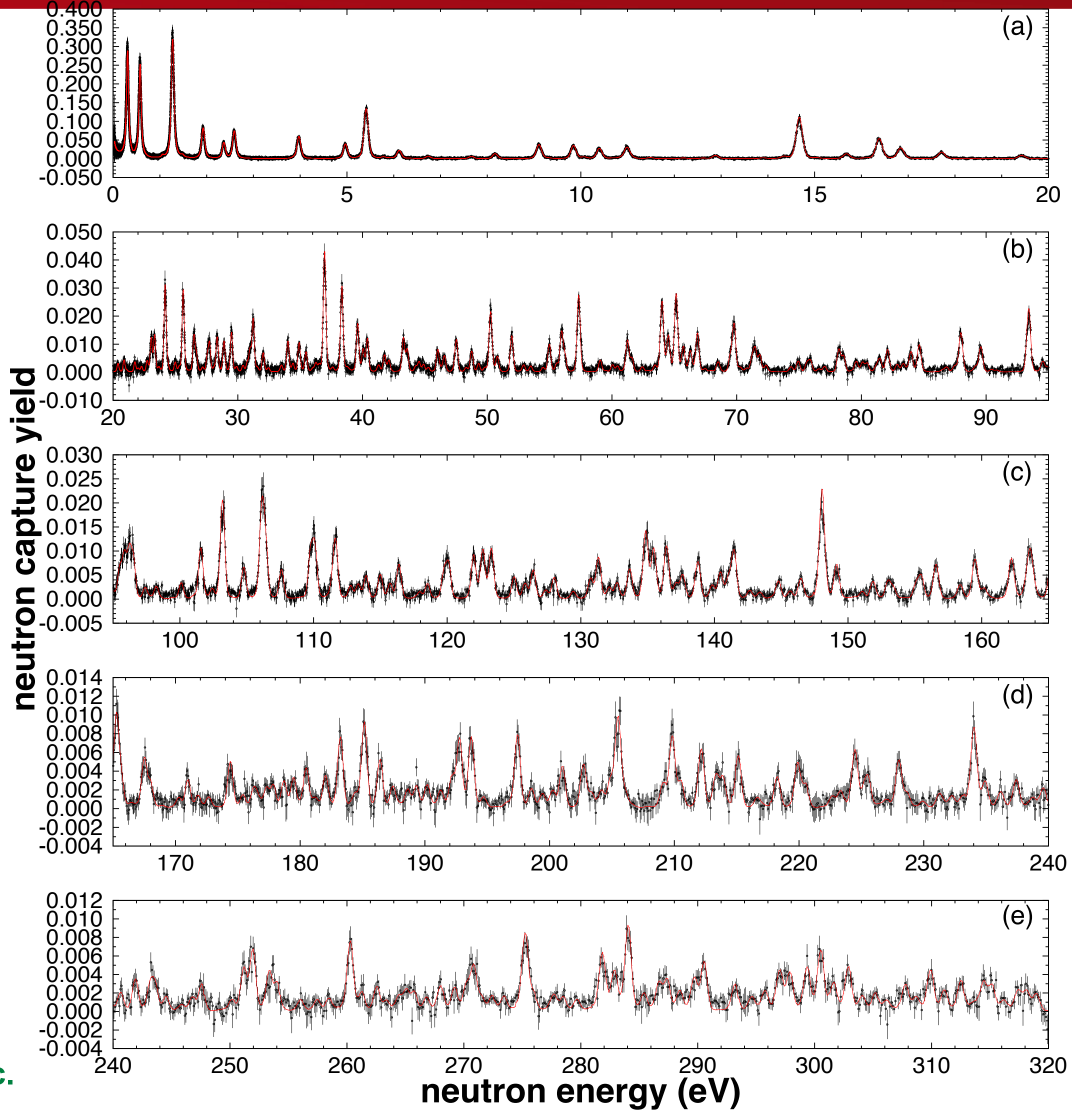


^{241}Am (n,γ) data (C_6D_6)



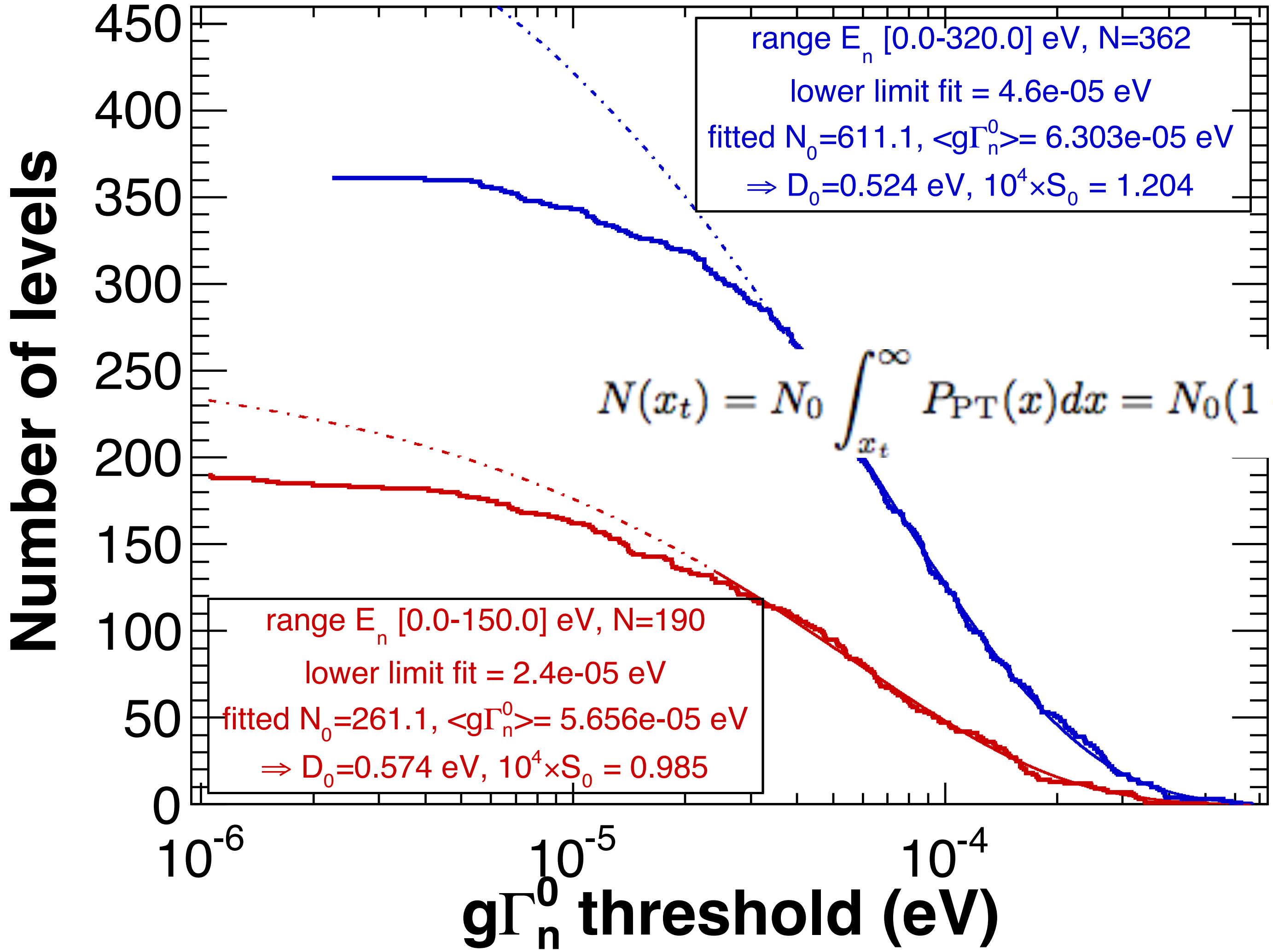
Phys. Rev. C (2014) acc.

^{241}Am (n,γ) data (C_6D_6)



Phys. Rev. C (2014) acc.

^{241}Am (n,γ) data (C_6D_6)

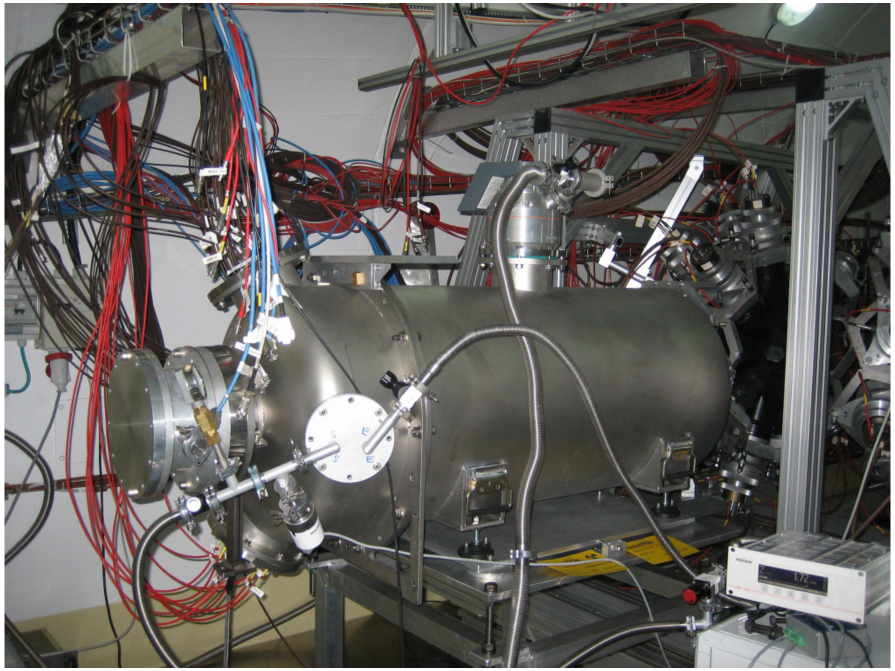


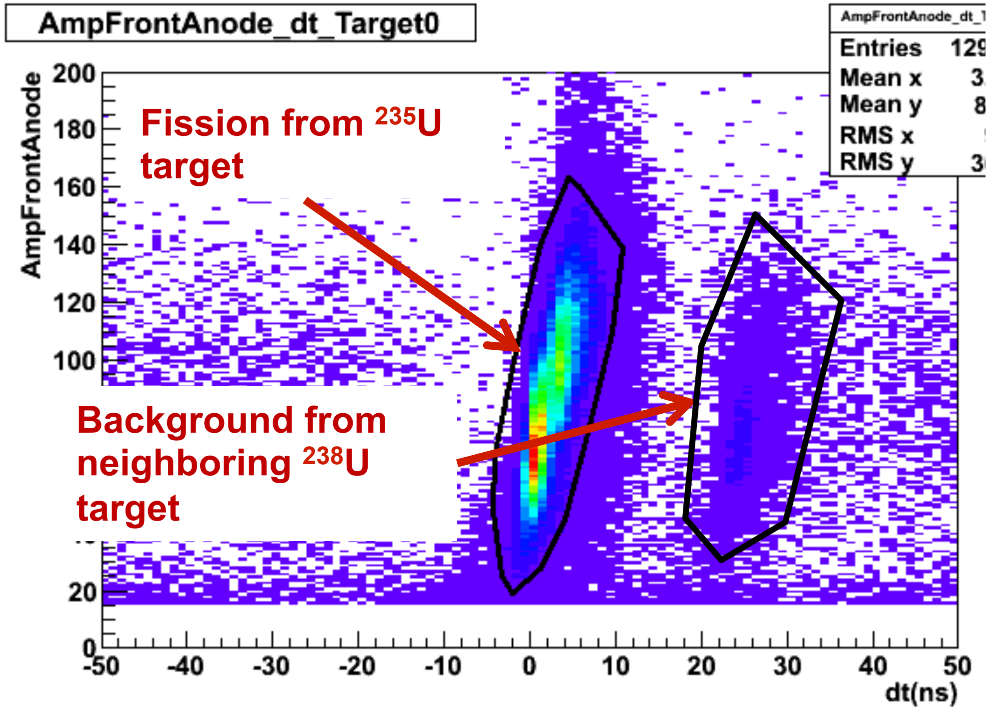
$$N(x_t) = N_0 \int_{x_t}^{\infty} P_{\mathrm{PT}}(x)dx = N_0(1 - \mathrm{erf}\sqrt{x_t/2})$$

Phys. Rev. C (2014) acc.

Angular distribution of fission fragments

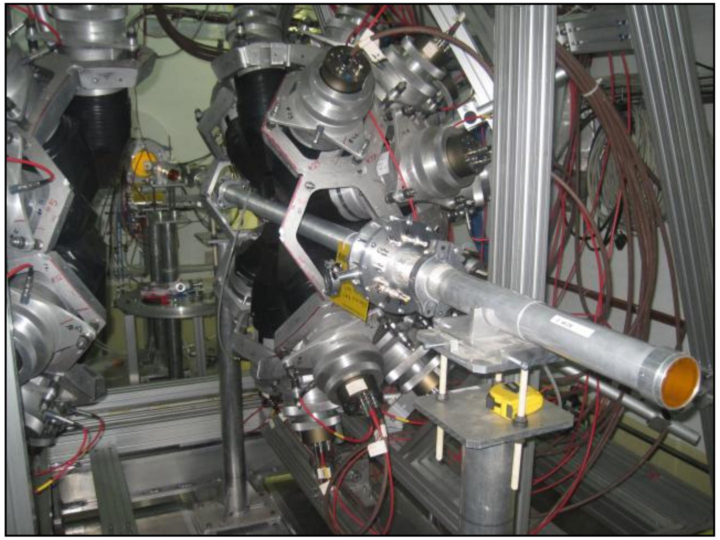
- PPAC with 10 parallel plate detectors tilted 45 degrees with respect to the beam.
- 9 samples: ^{235}U, ^{238}U, ^{237}Np and 6x^{232}Th.



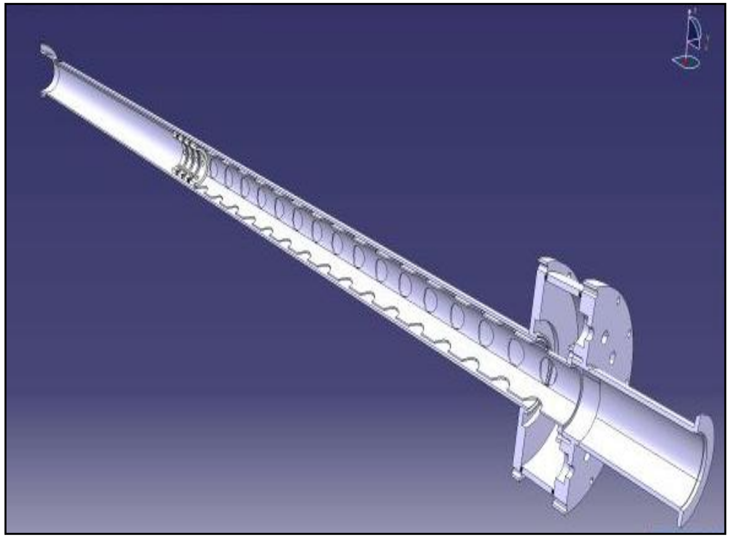


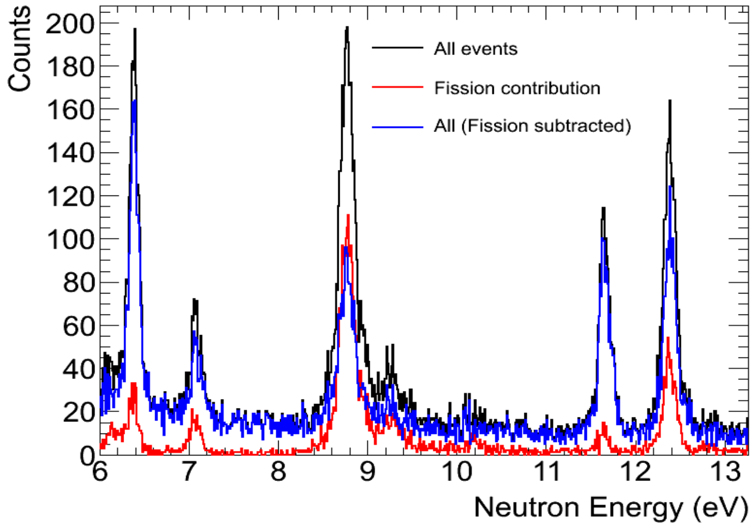
NIM A743 (2014) 79

Simultaneous capture and fission of ^{235}U



Fission tagging: TAC+MGAS

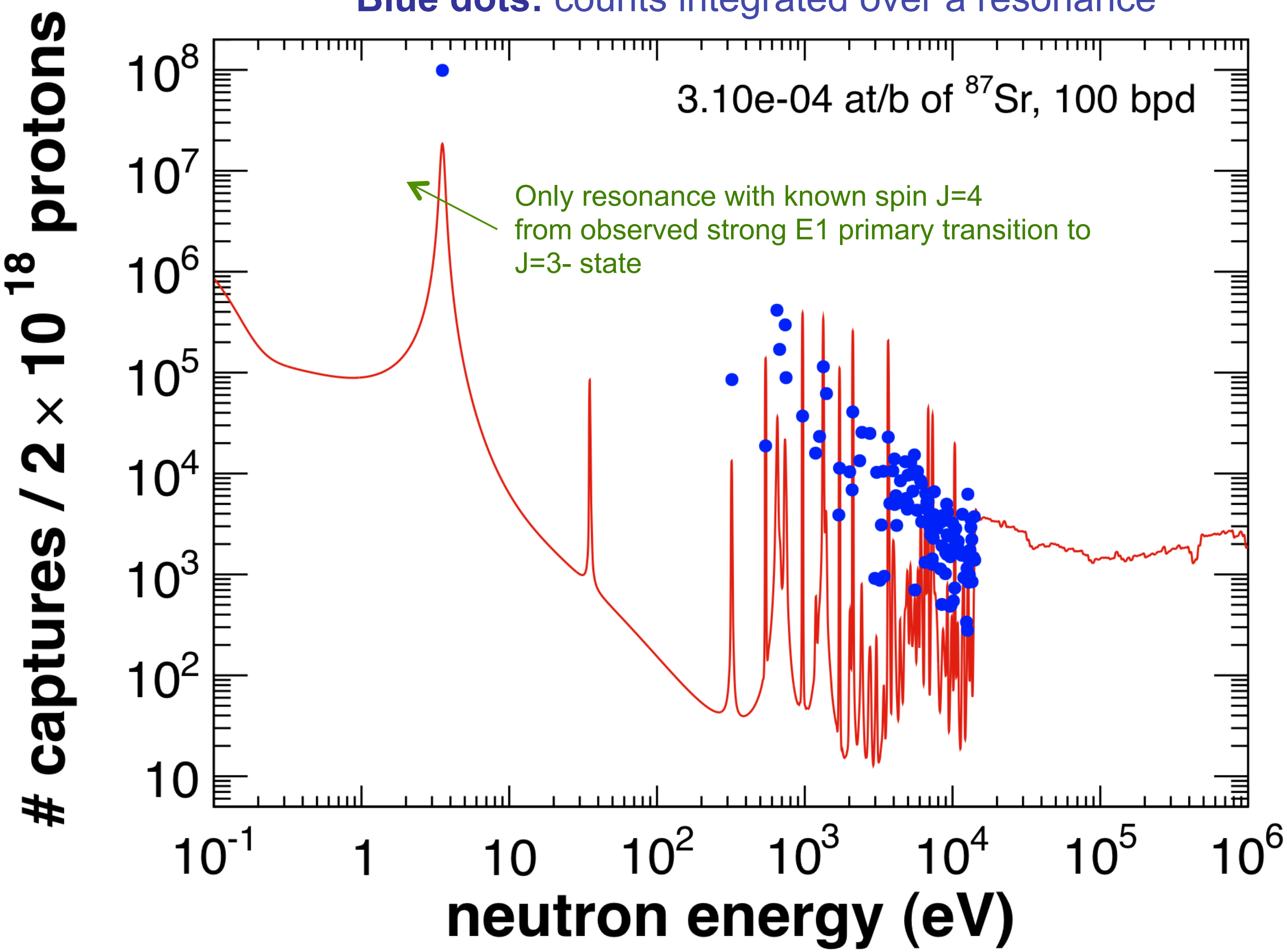




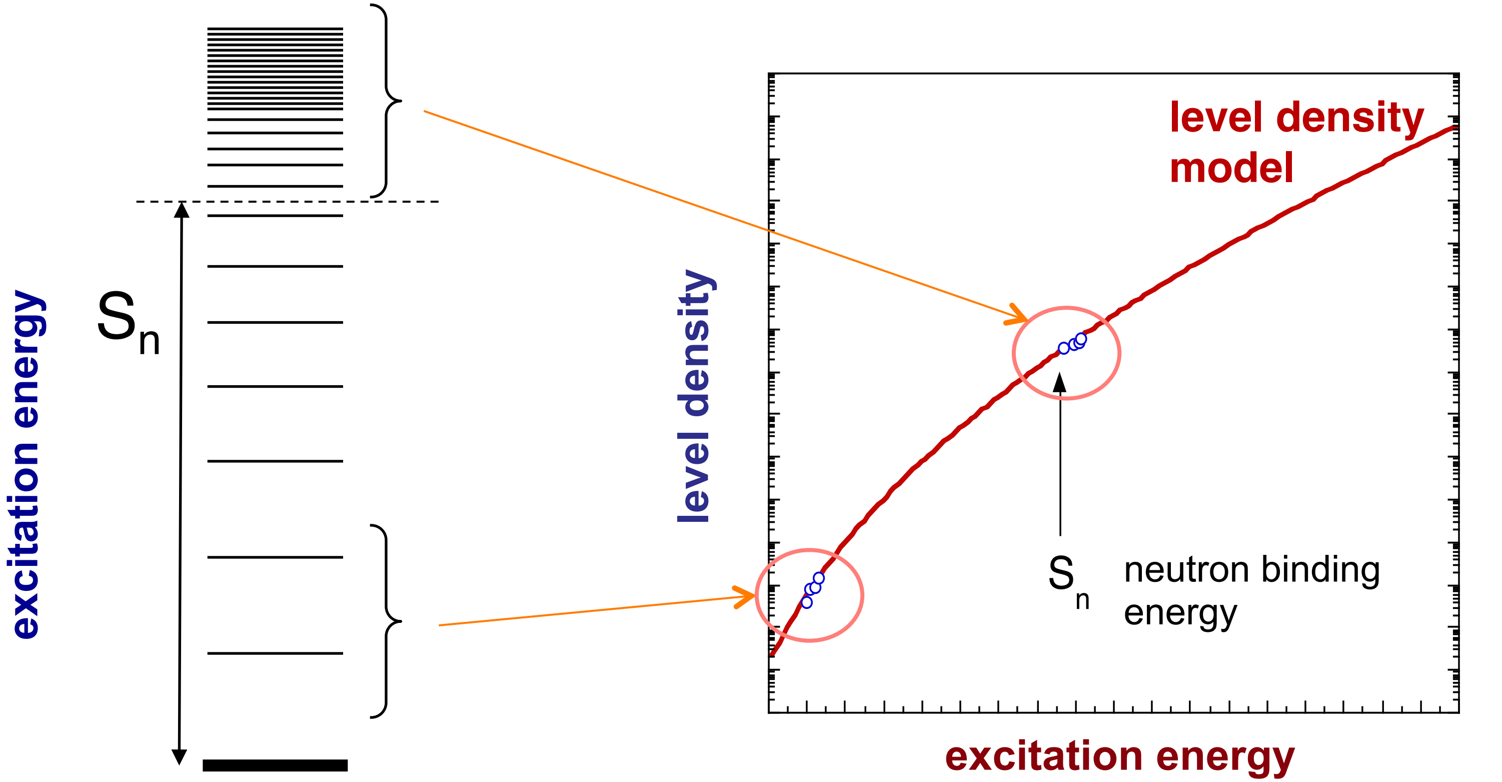
EPJ A48 (2012) 29

^{87}Sr spin assignments

Blue dots: counts integrated over a resonance



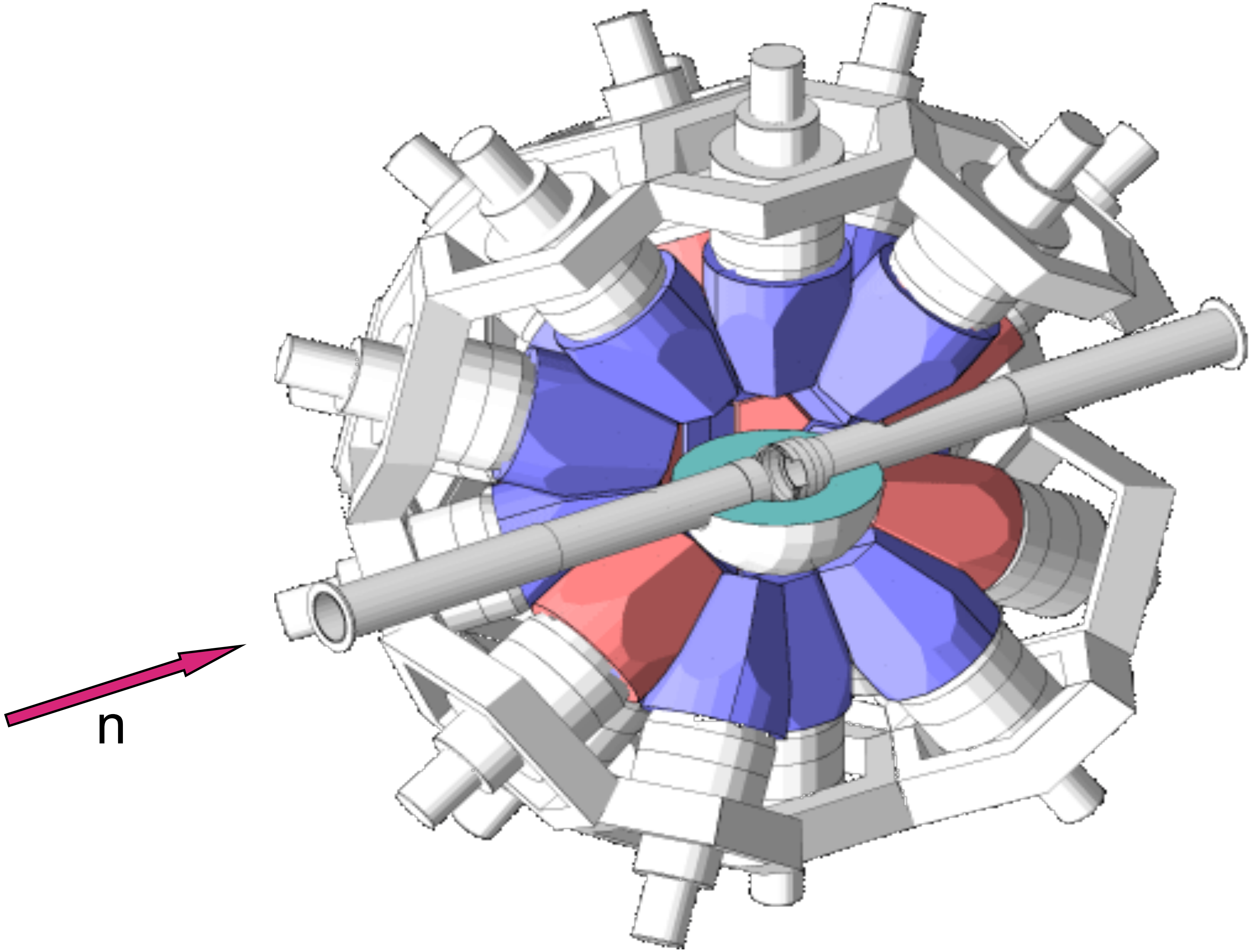
Nuclear level densities



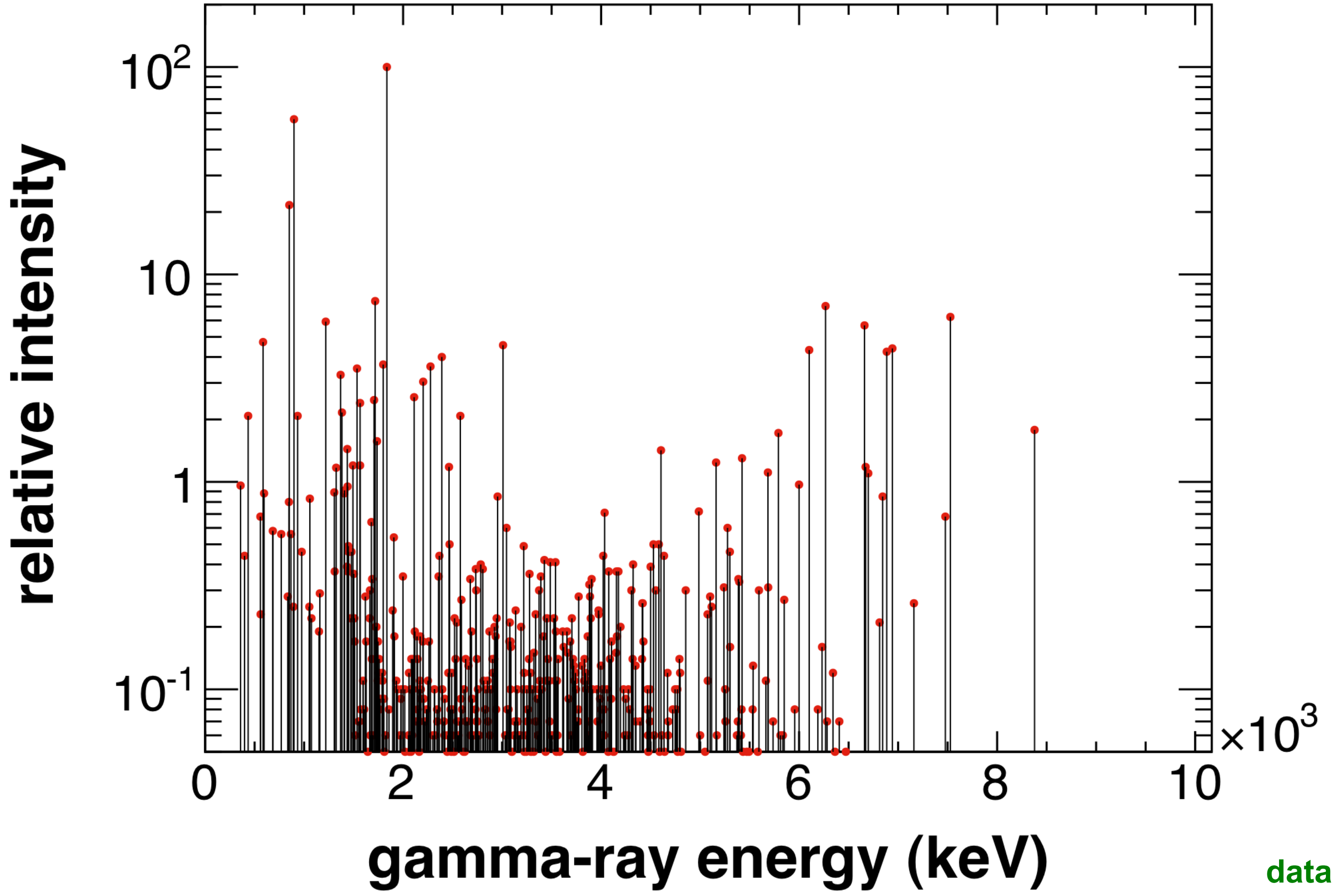
low-lying levels:
Count levels, all J^π

neutron resonances:
Count levels, selected J^π,
extract $\mathbf{D_0}$

Gamma-ray spectra from $^{87}Sr+n$ with TAC

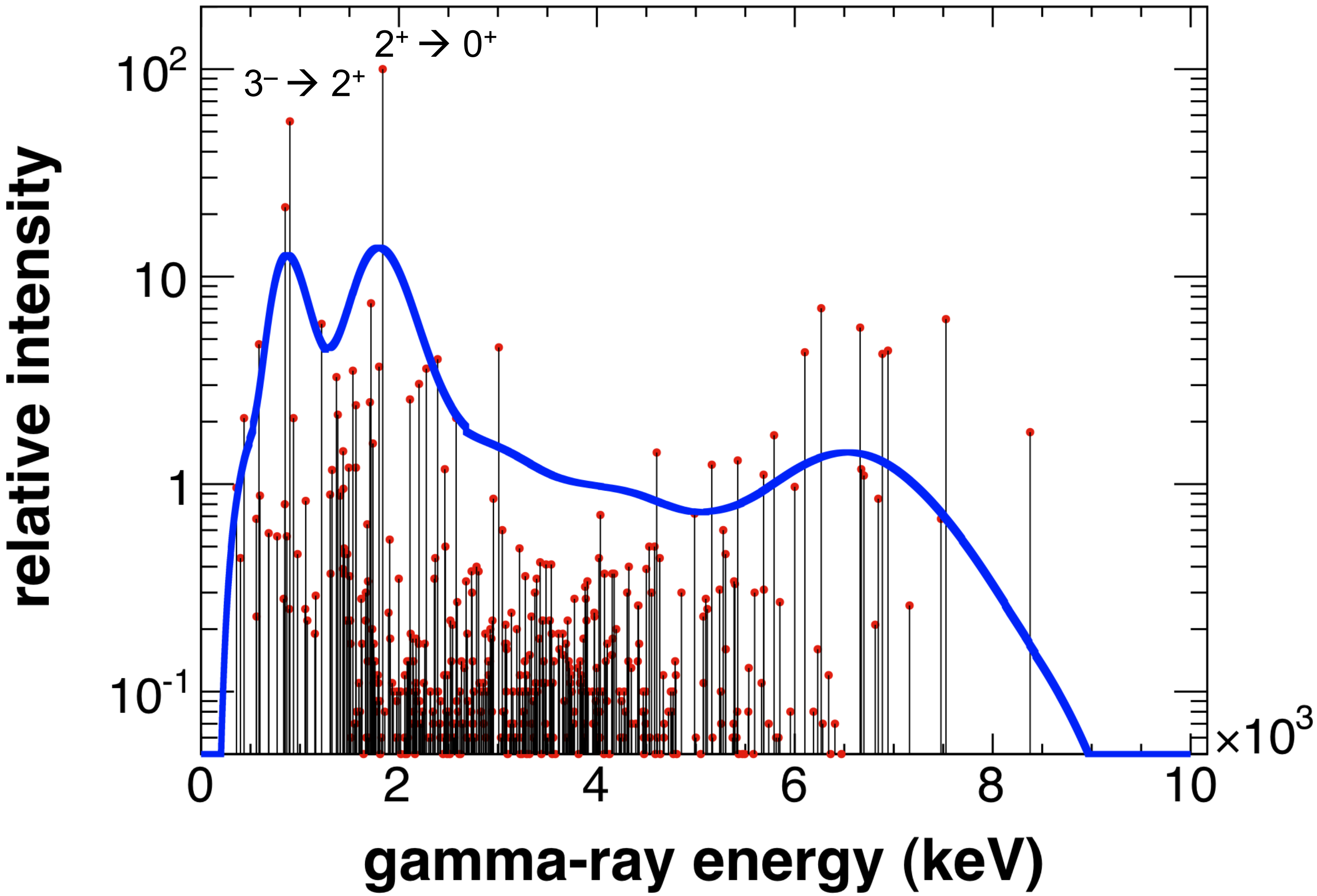


$^{87}Sr(n,\gamma_{thermal})^{88}Sr$ spectrum

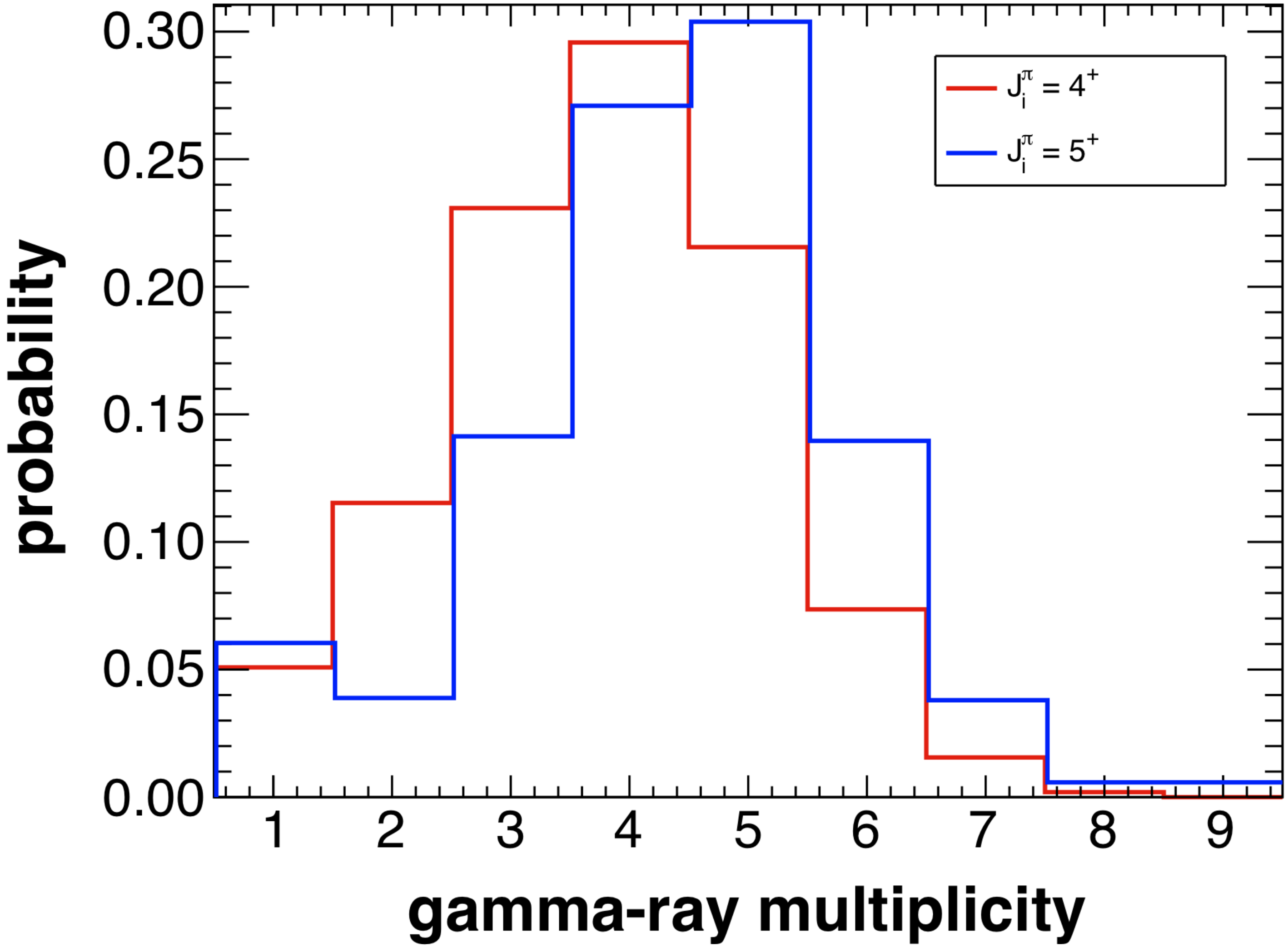


data ENSDF

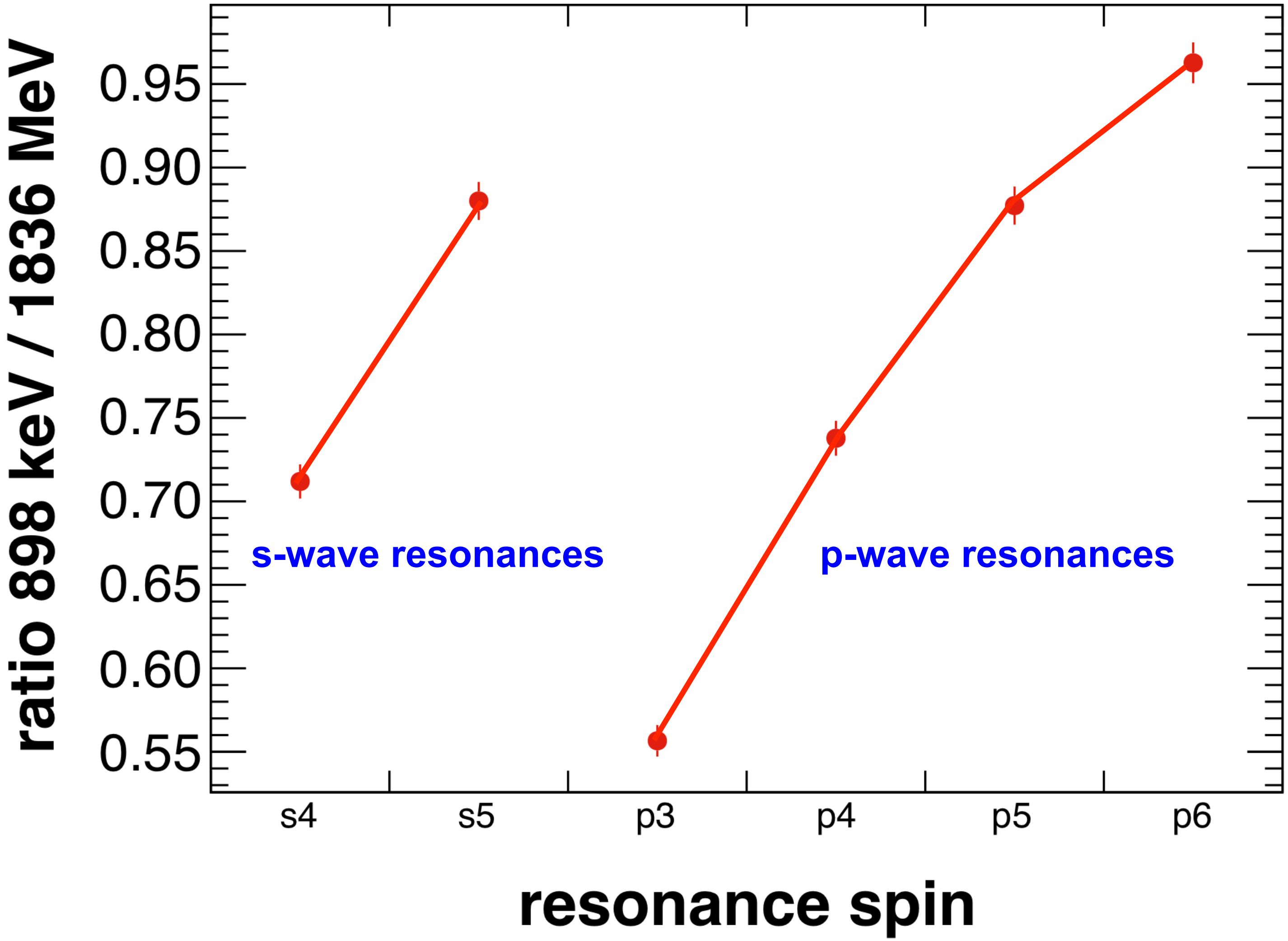
$^{87}Sr(n,\gamma_{thermal})^{88}Sr$ spectrum



Simulated decay of $^{88}Sr^*$ multiplicity, method 1



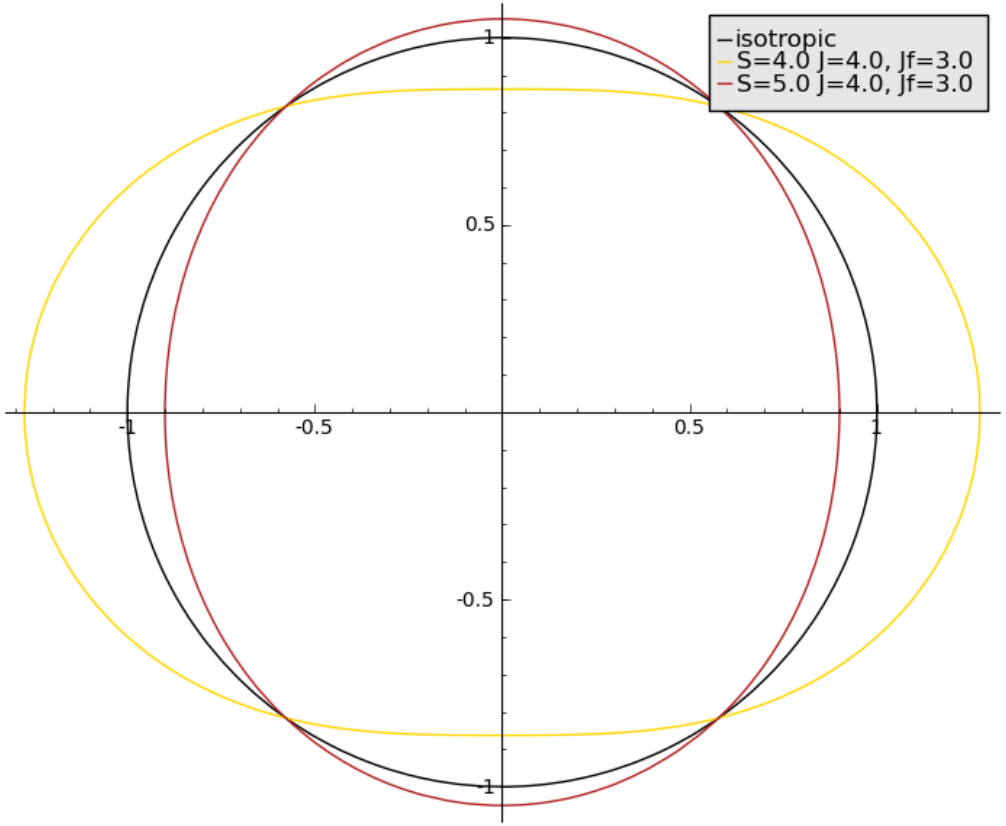
Spin dependence of population ratio method 2



Angular distribution of primary dipole transitions method 3

For s-waves: isotropic
For p-waves: may be anisotropic, depends on channel spin S, resonance spin J_r and final state J_f

$$W(\theta) = 1 + A_2 P_2(\cos\theta)$$
$$A_2 = A_2(S, J_r, J_f)$$



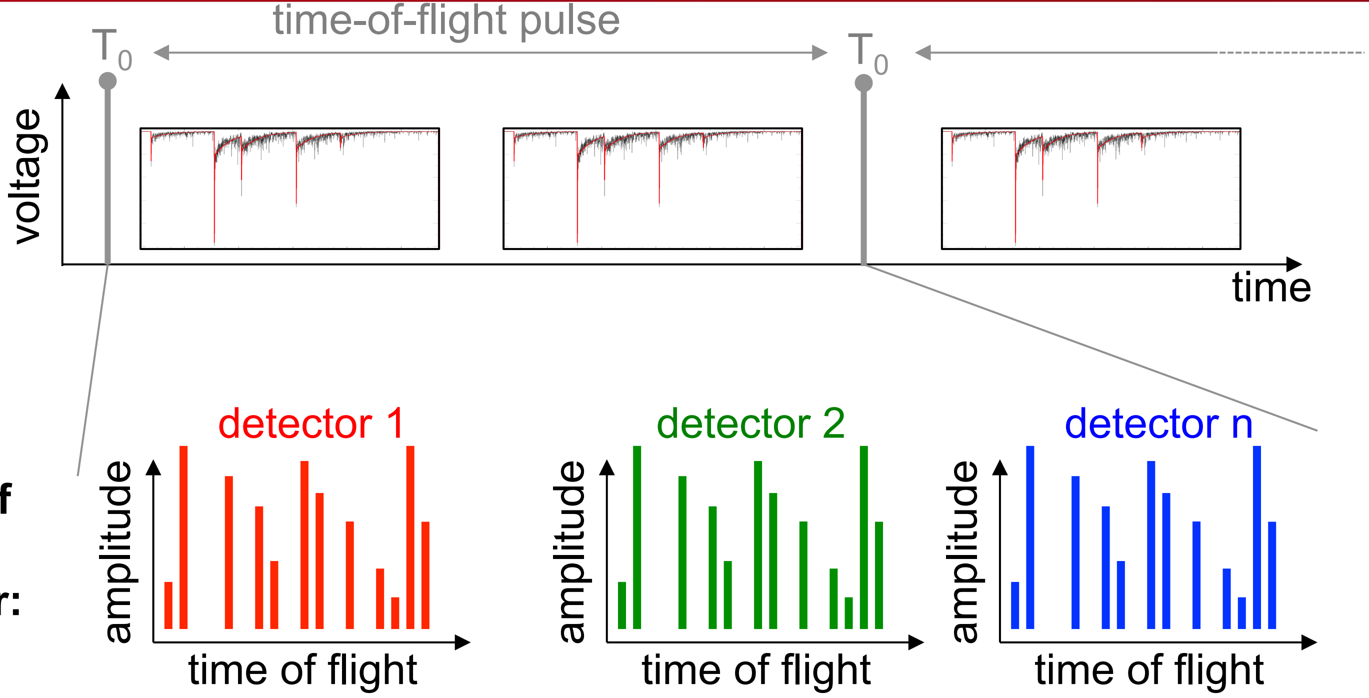
Example: the primary transition from a J_r=4 resonance state to a J_f = 3 final state.

J_r = 4 has to possible channel spins: S=4 and S=5 with an unknown mixing.

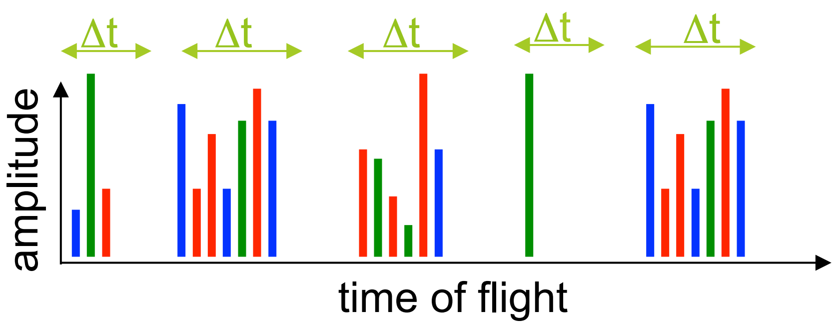
Data reduction

raw data, waveforms: 45000 TB

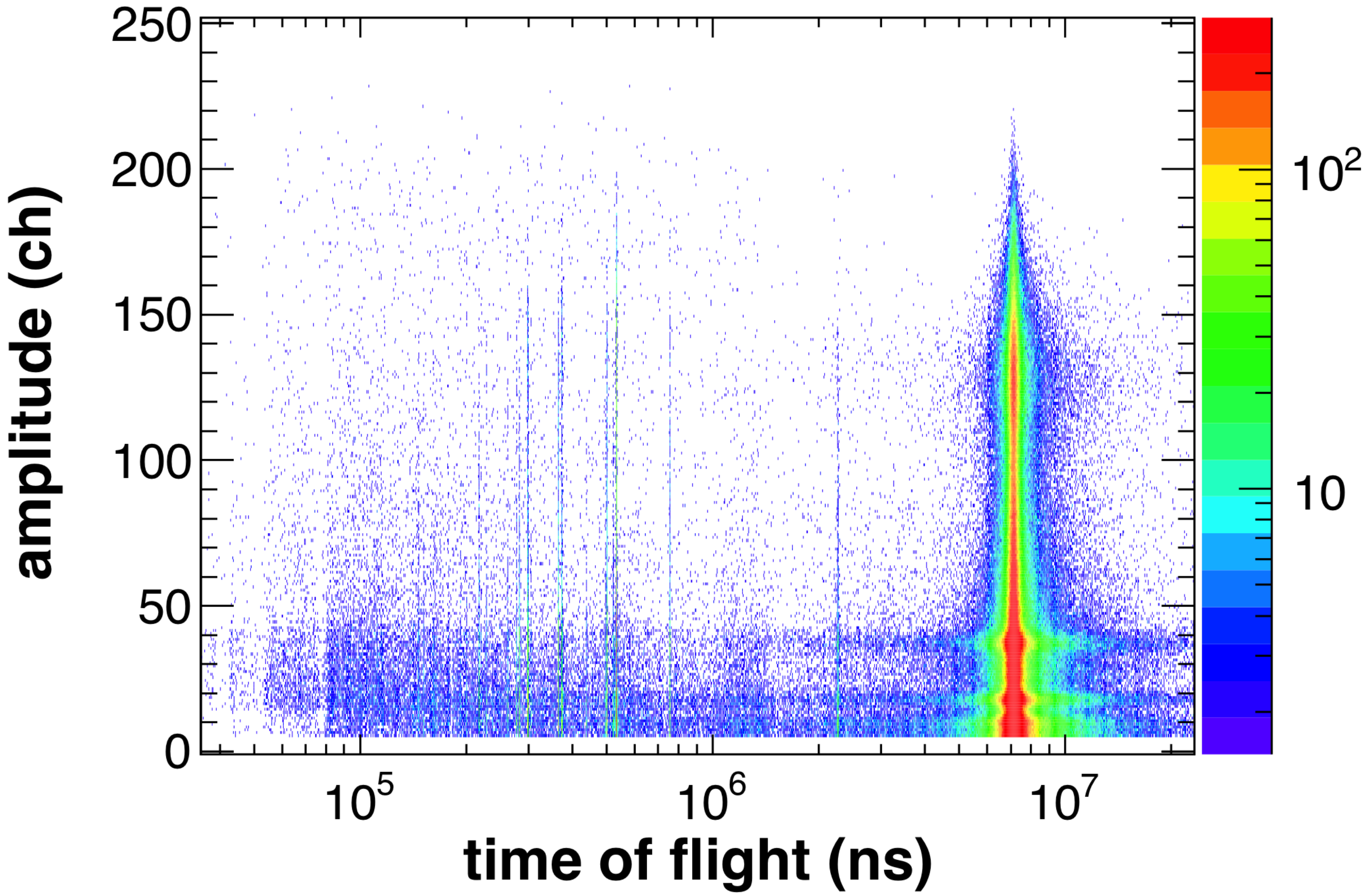
event data, list of amplitude, time for each detector: 60 TB



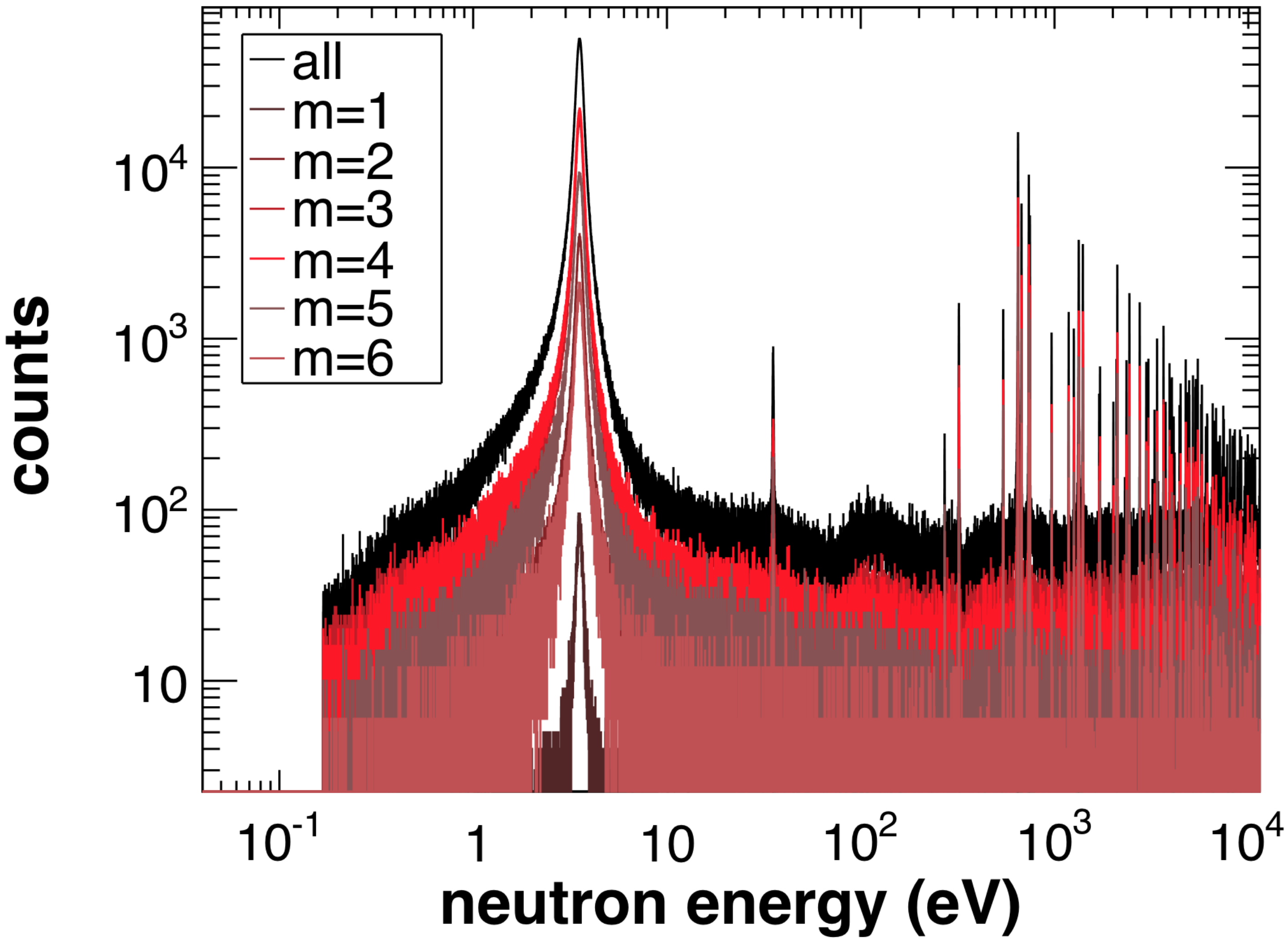
- align events in time to find coincidences



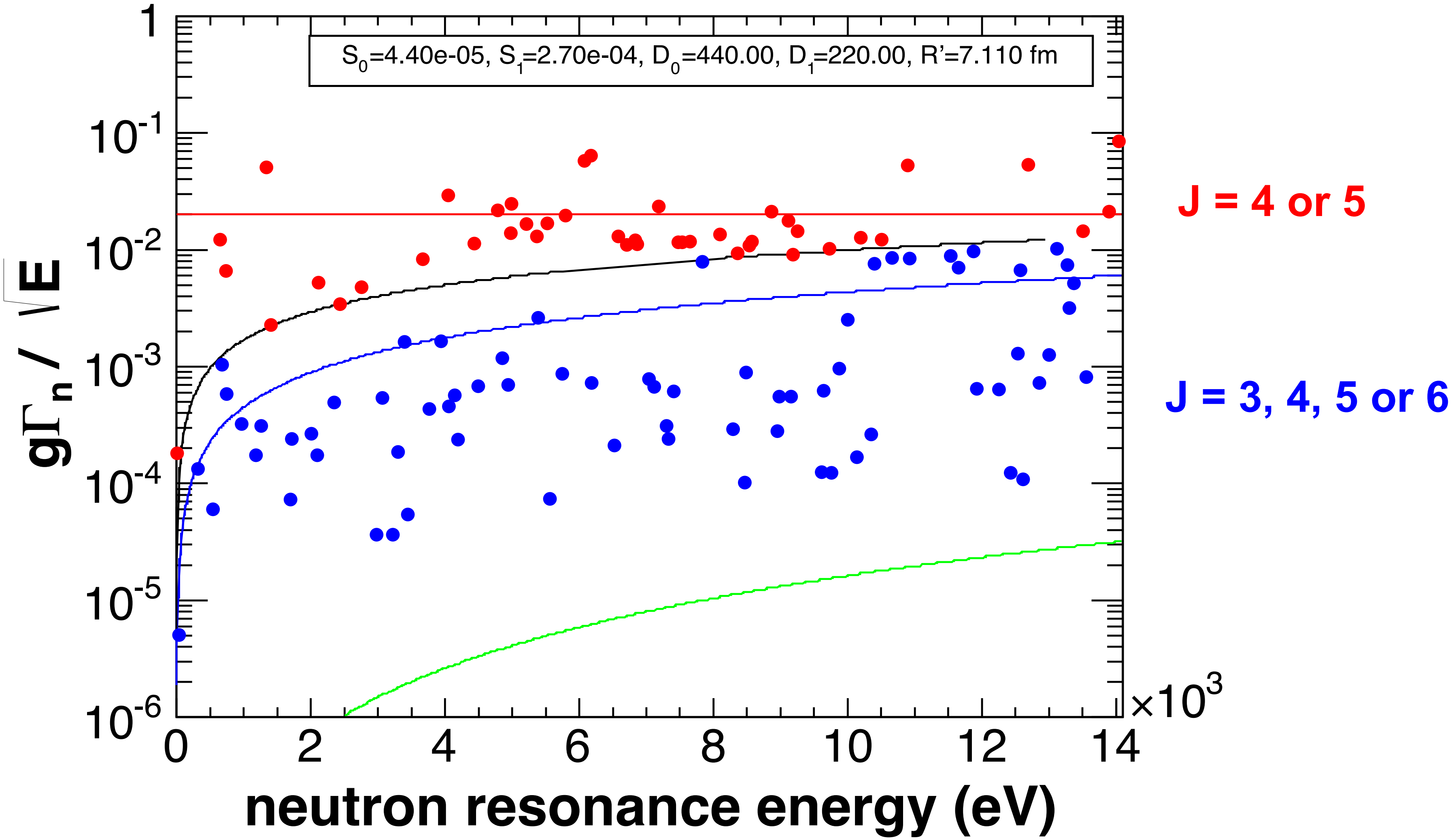
Spectrum TOF-amplitude



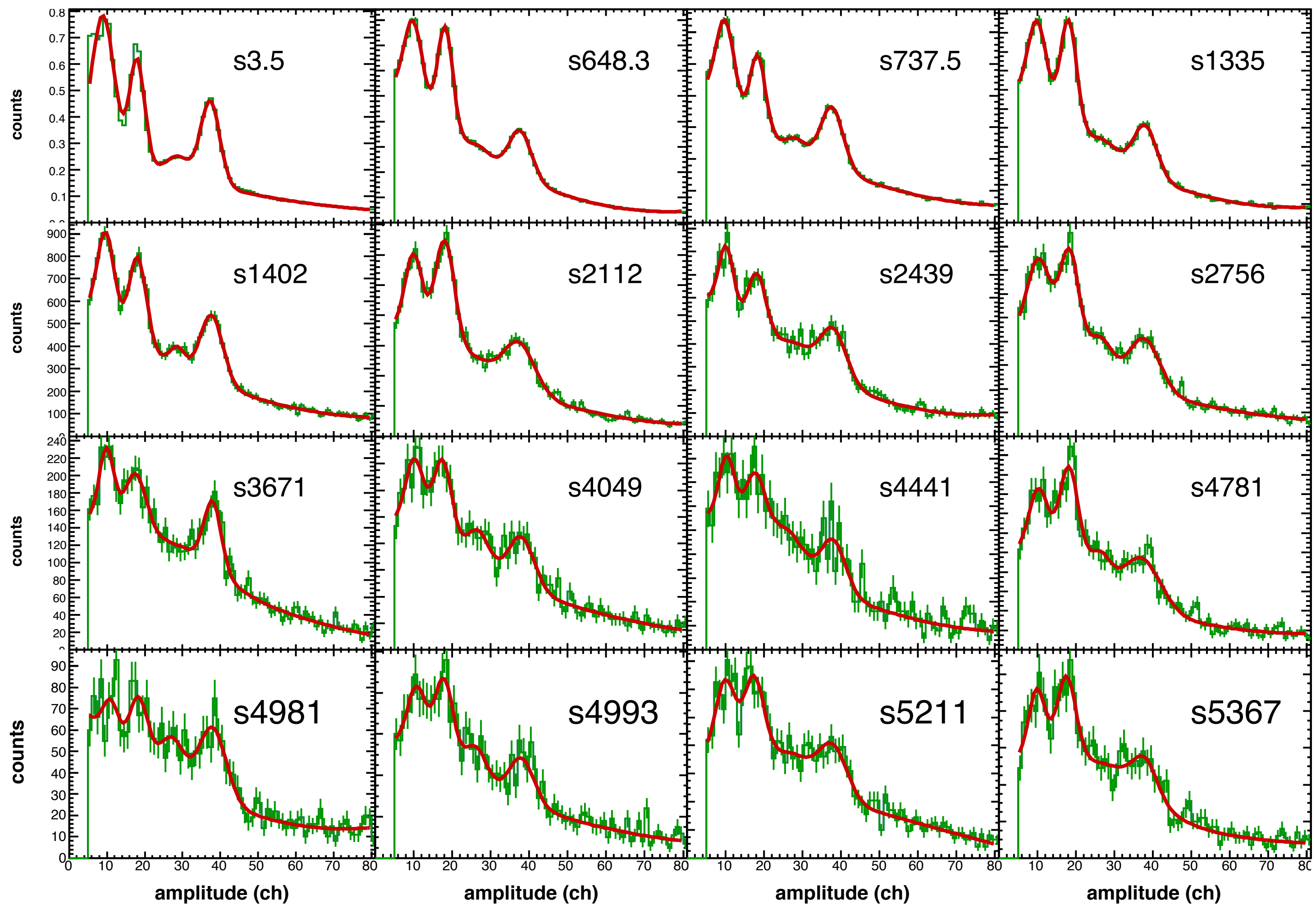
Multiplicity decomposition



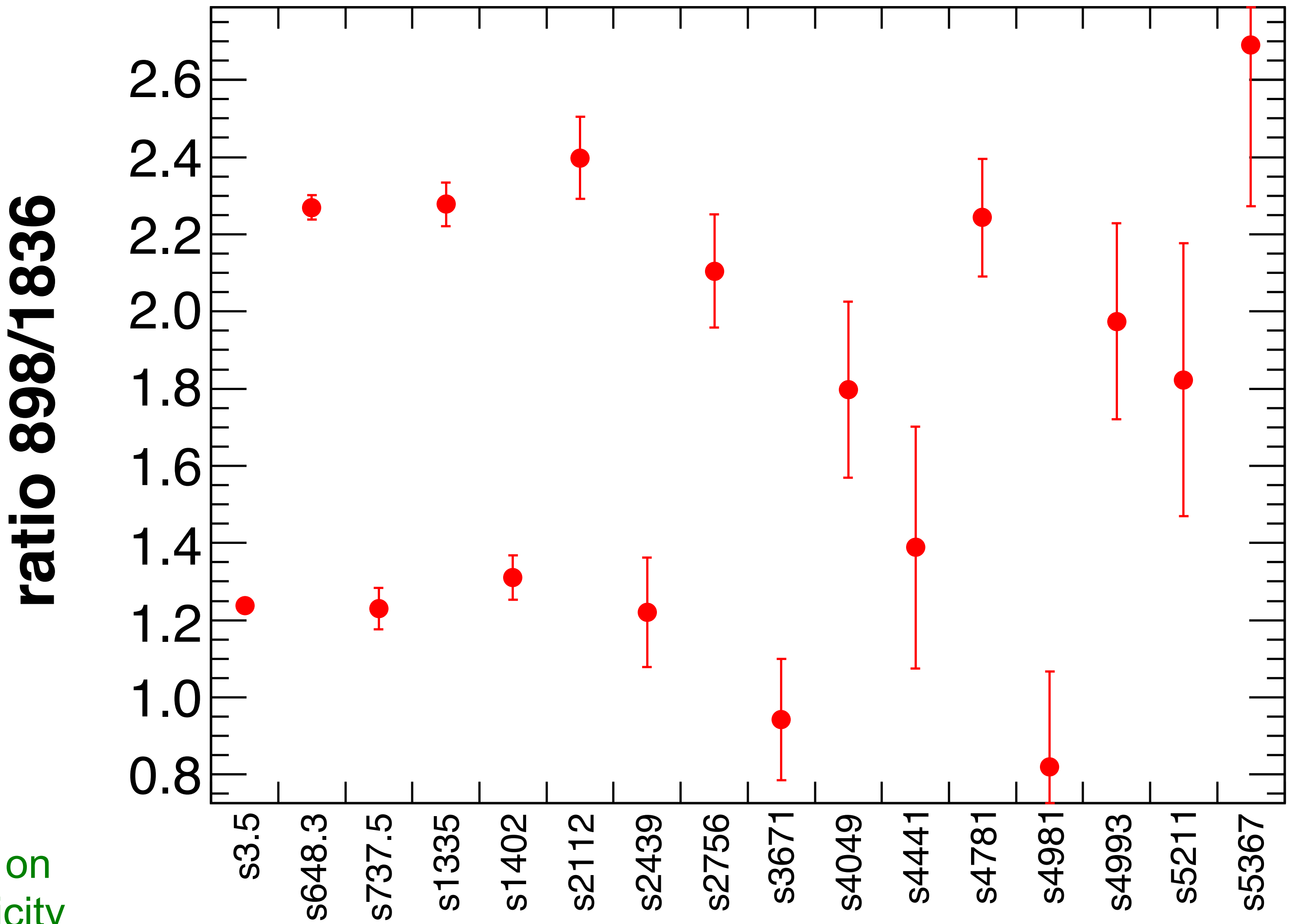
Assign orbital momentum



Low-level population using pulse height spectra

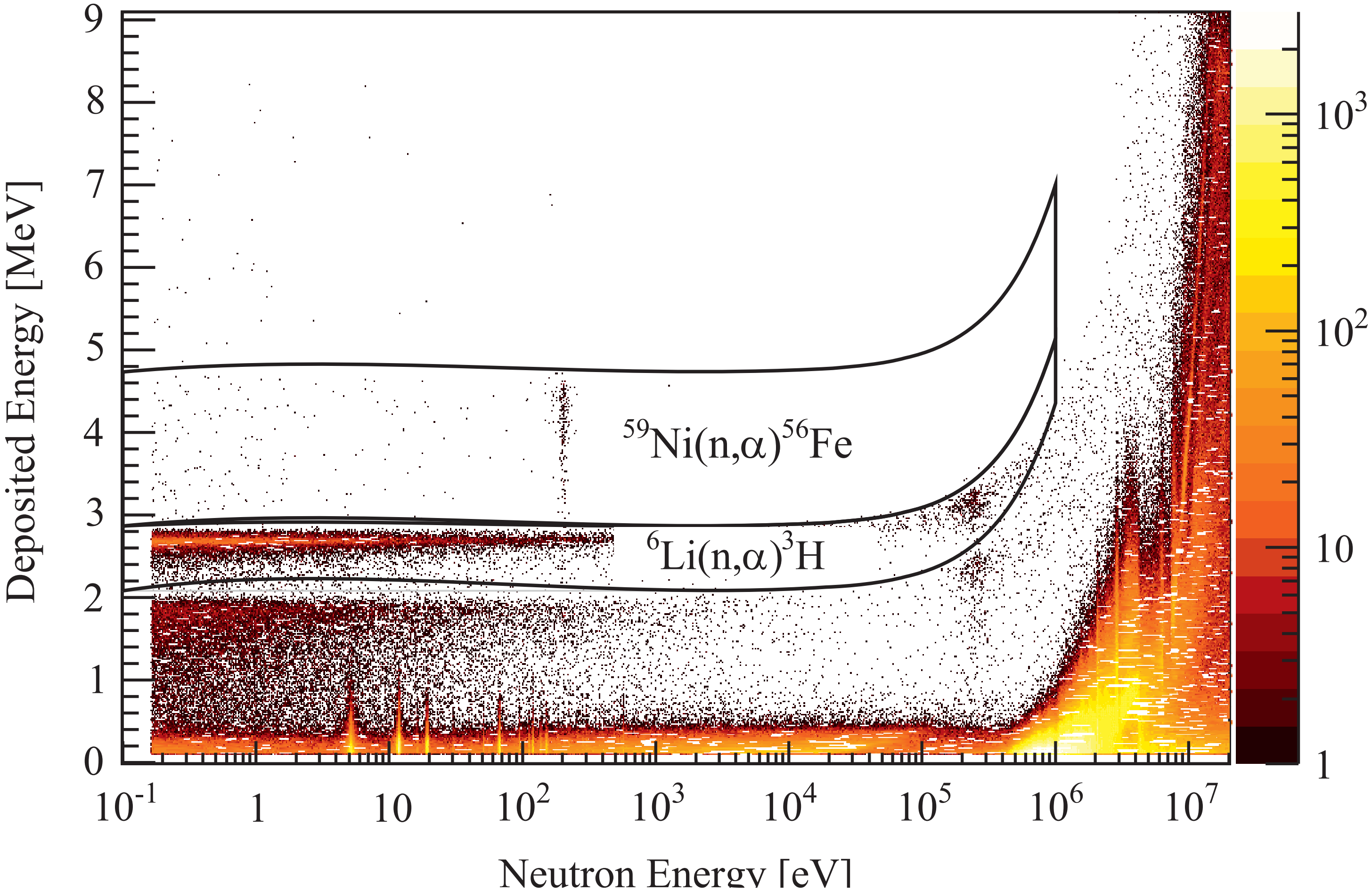


Low-level population using pulse height spectra



No cut on multiplicity

CVC diamond detectors for (n,α) reactions



NIM A 732 (2013) 190

n_TOF CERN phase II (2008-2012)
Summary of measurements

capture C_6D_6
^{25}Mg
^{54,56,57}Fe
^{58,60,62,63}Ni
^{93}Zr ^{197}Au
^{236,238}U
^{241}Am
^{240}Pu

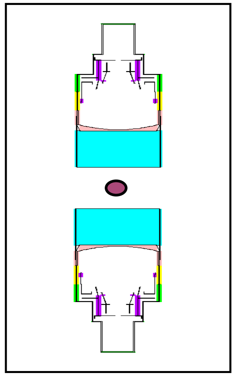
capture BaF_2
^{87}Sr (spin)
^{197}Au
^{235}U (+fis)
^{236,238}U
^{241}Am

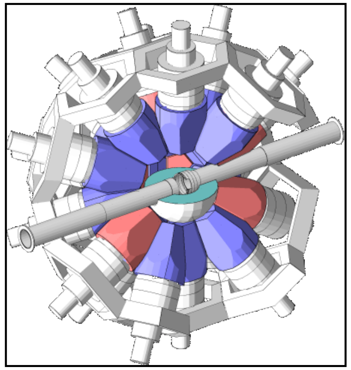
fission PPAC
^{232}Th (FF ang)
^{237}Np (FF ang)
^{235,238}U (FF ang)

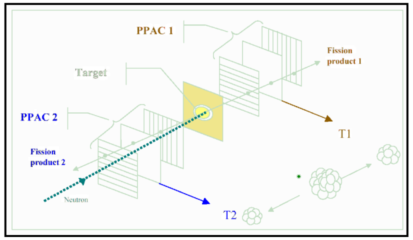
Detector tests and developments
- several

fission MGAS
^{240,242}Pu

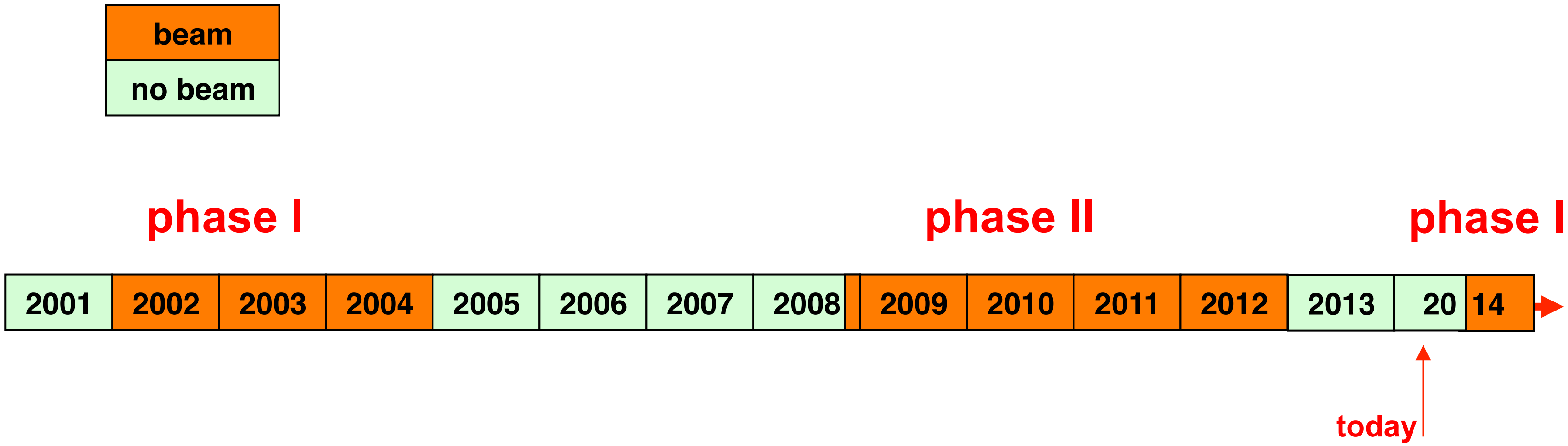
(n,a) MGAS/ CVD
^{59}Ni
^{33}S





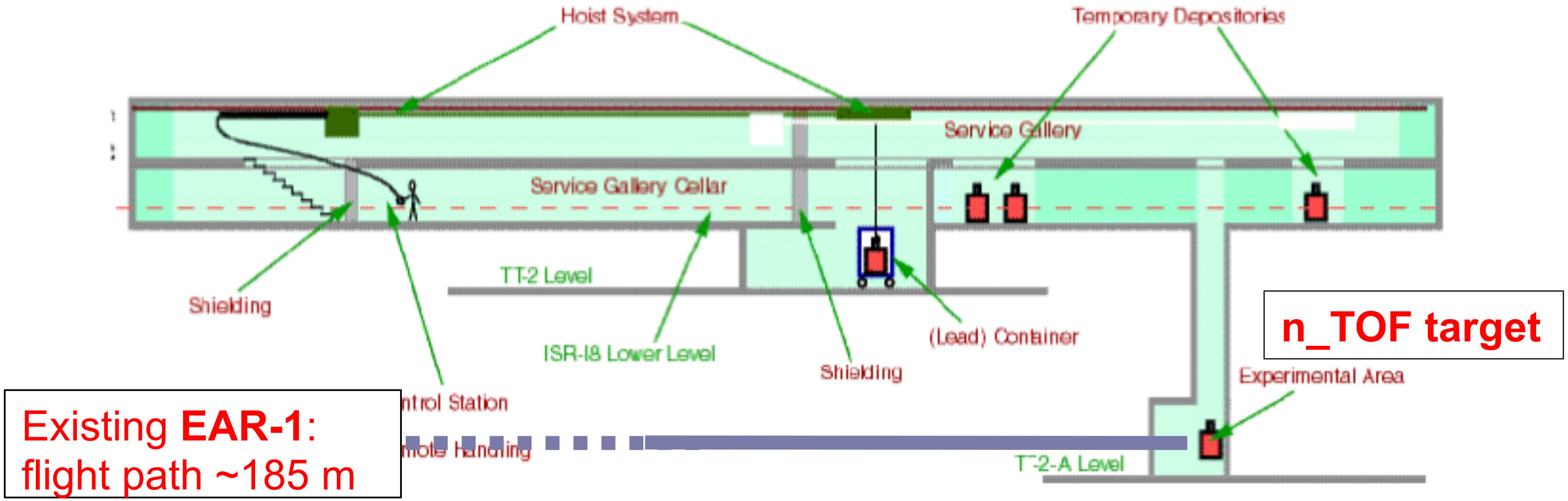


The n_TOF facility at CERN: the future



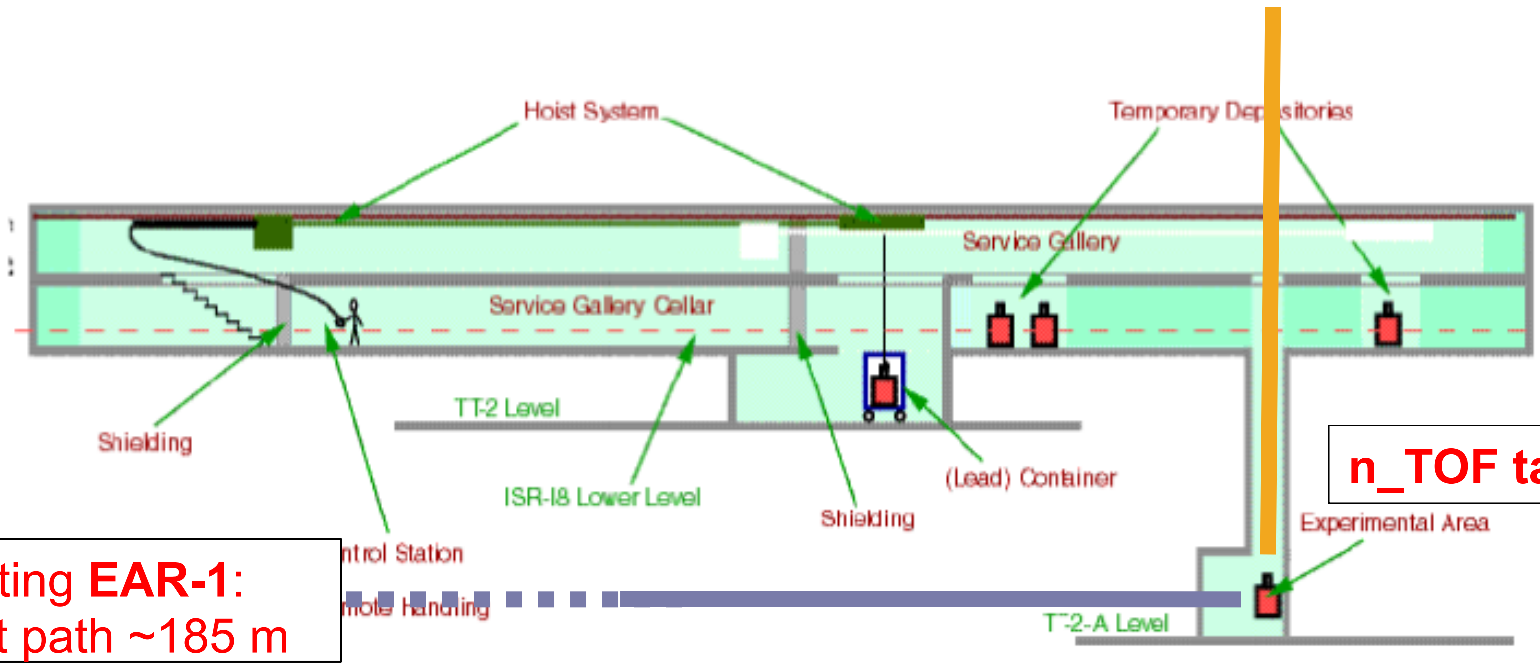
- 1998 - 2001 preparation and commissioning
- 2002 - 2004 **phase I** data taking
- 2005 - 2007 spallation target upgrade
- 2008 first protons on target
- 2009 **phase II** data taking
- 2010 - 2012 class A lab. borated water
- **2013 construction second, short flight path (20 m) EAR2**
- **2014 commissioning**
- **2015 measurement programme**

n_TOF 2nd experimental area (EAR2)



n_TOF 2nd experimental area (EAR2)

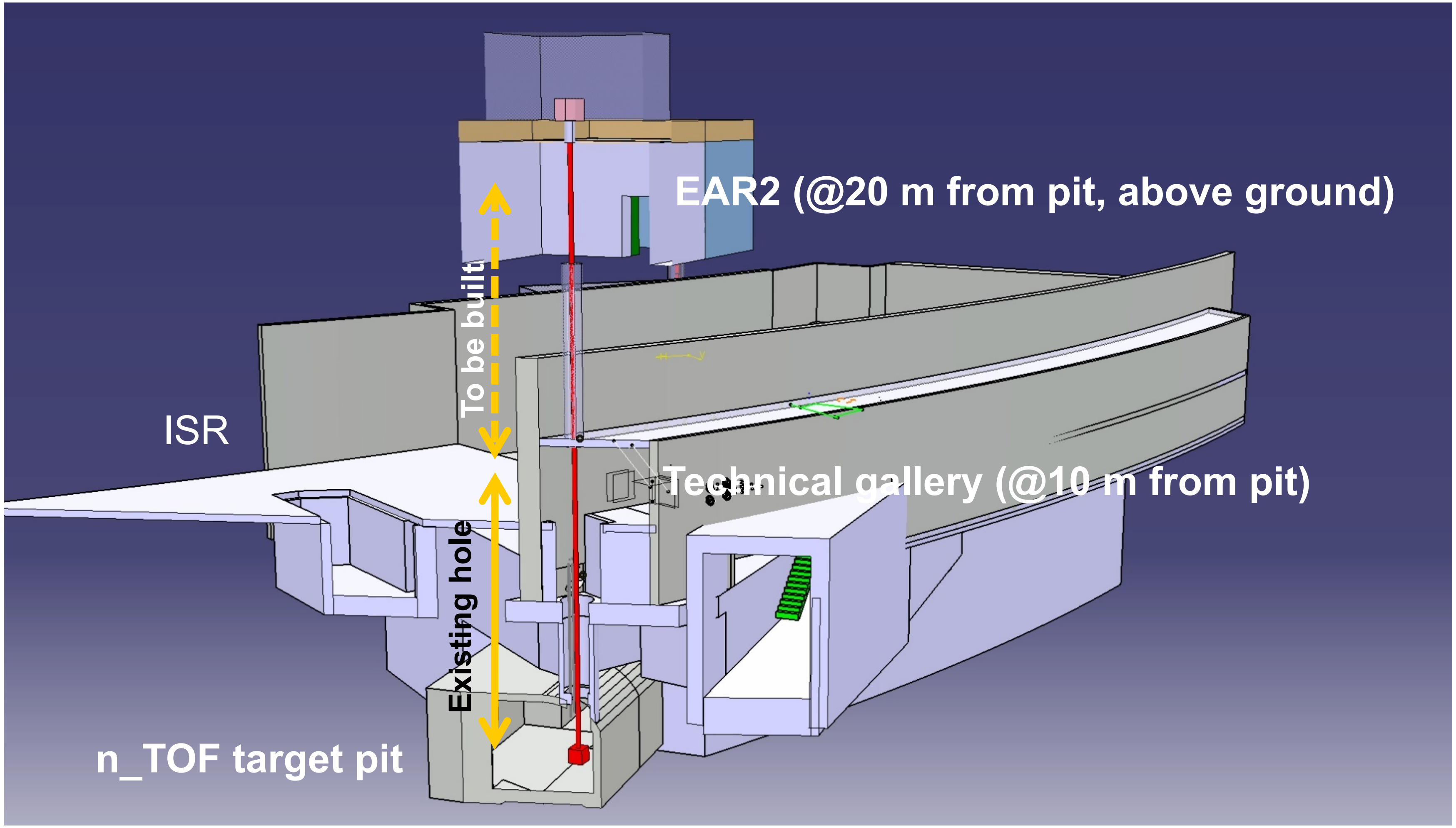
Future **EAR-2**: flight path ~20 m at 90° with respect to the proton beam



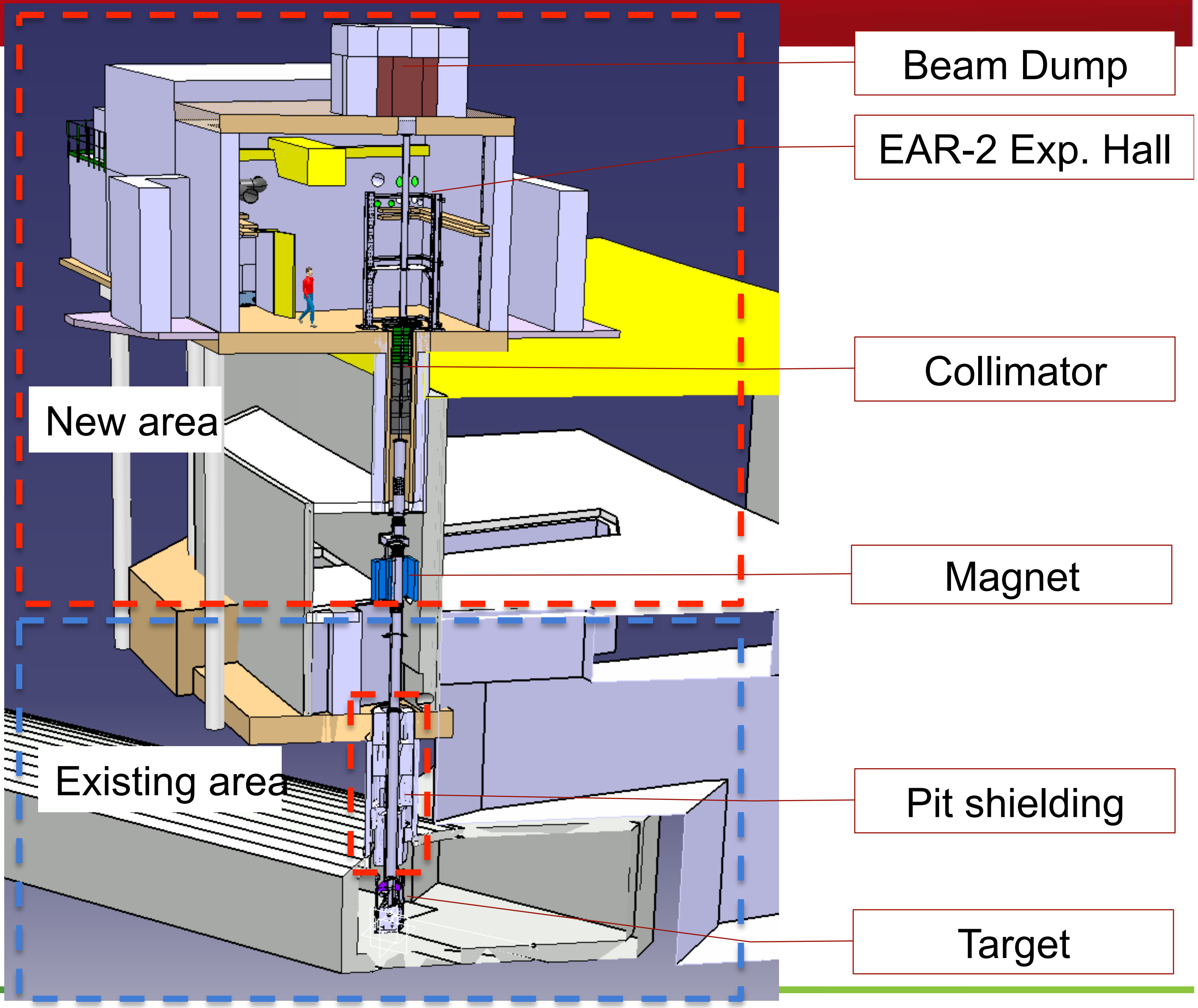
n_TOF target

Existing **EAR-1**: flight path ~185 m

The spallation target area

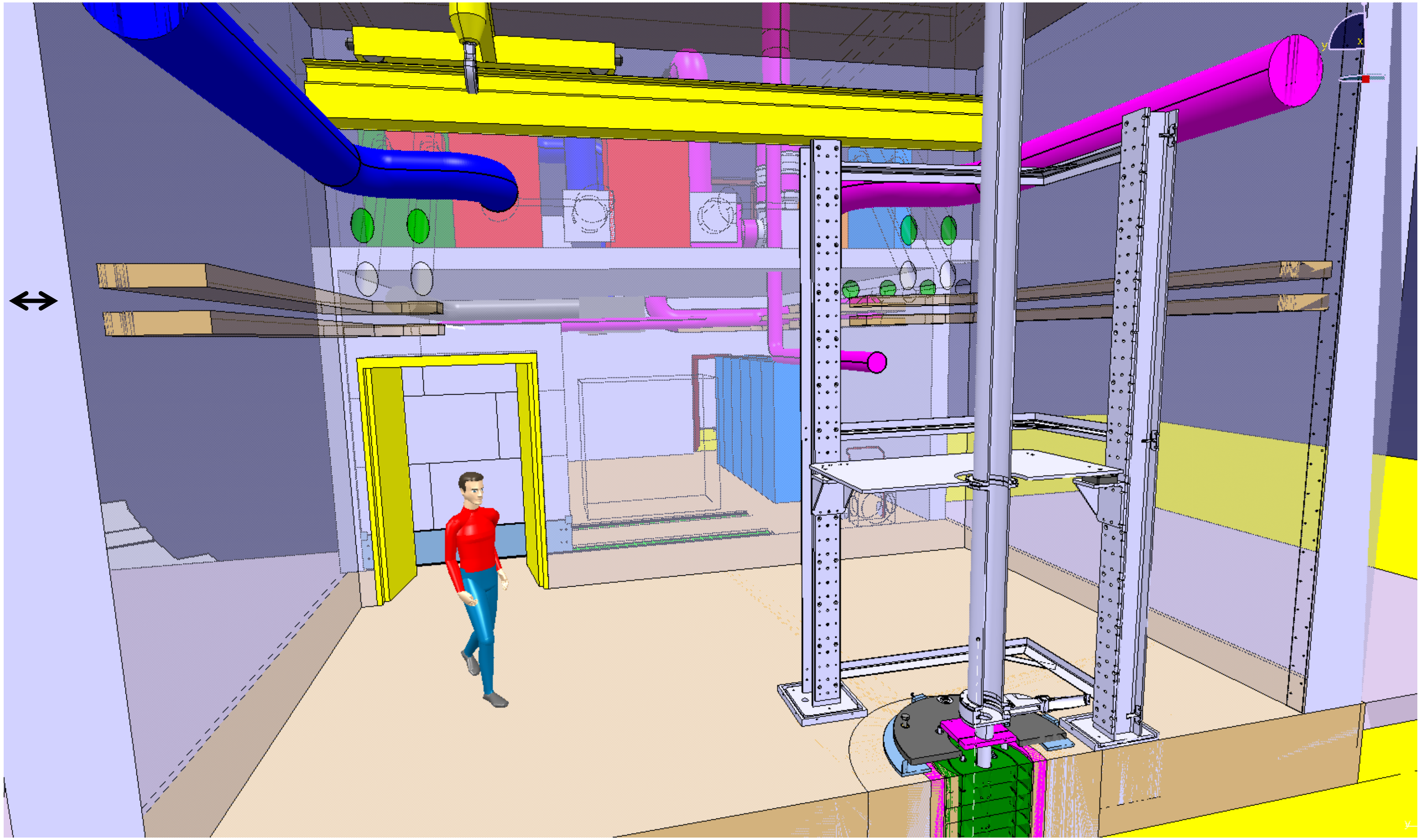


Layout EAR2



Beam Dump
EAR-2 Exp. Hall
Collimator
Magnet
Pit shielding
Target
New area
Existing area

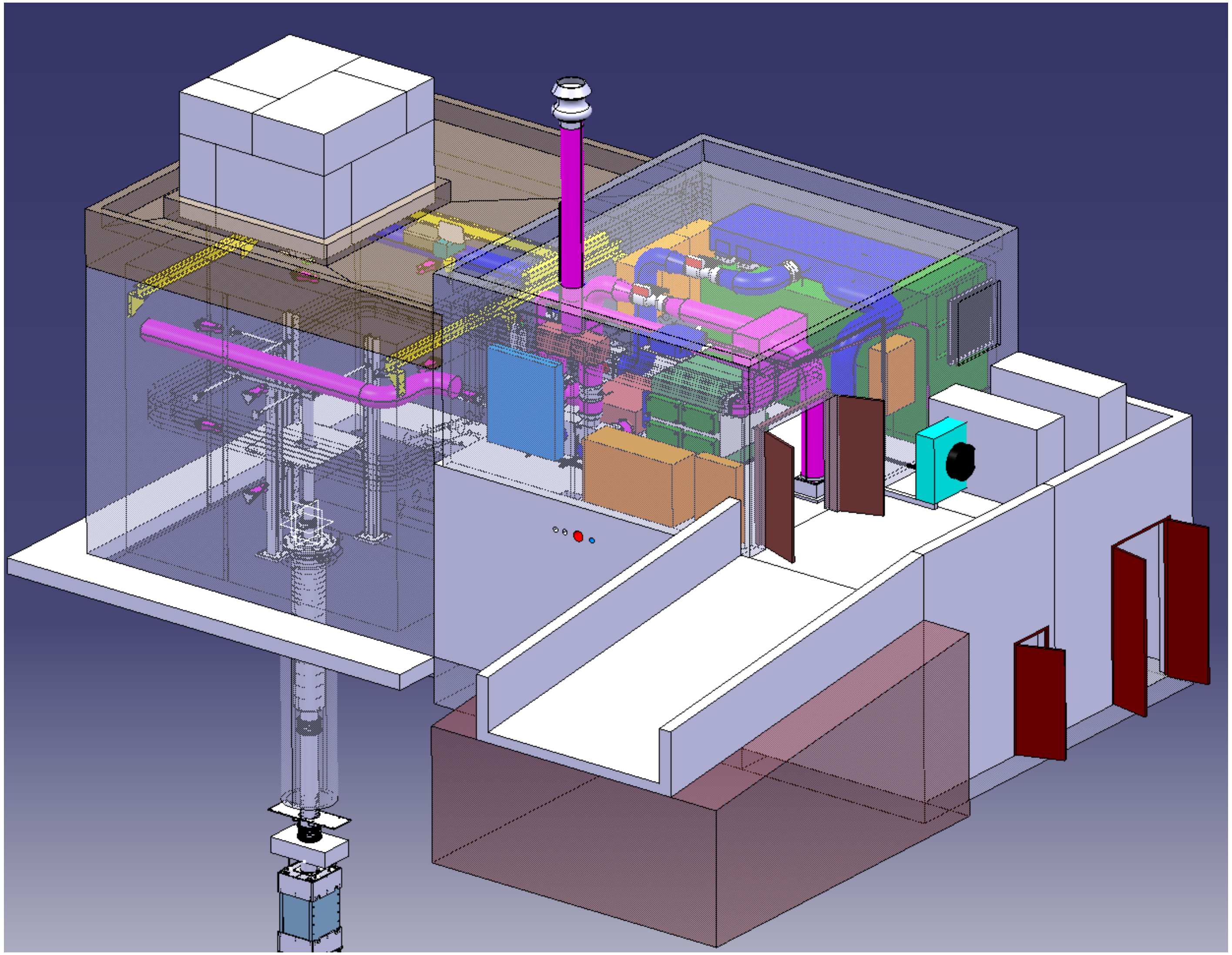
Experimental Hall EAR2



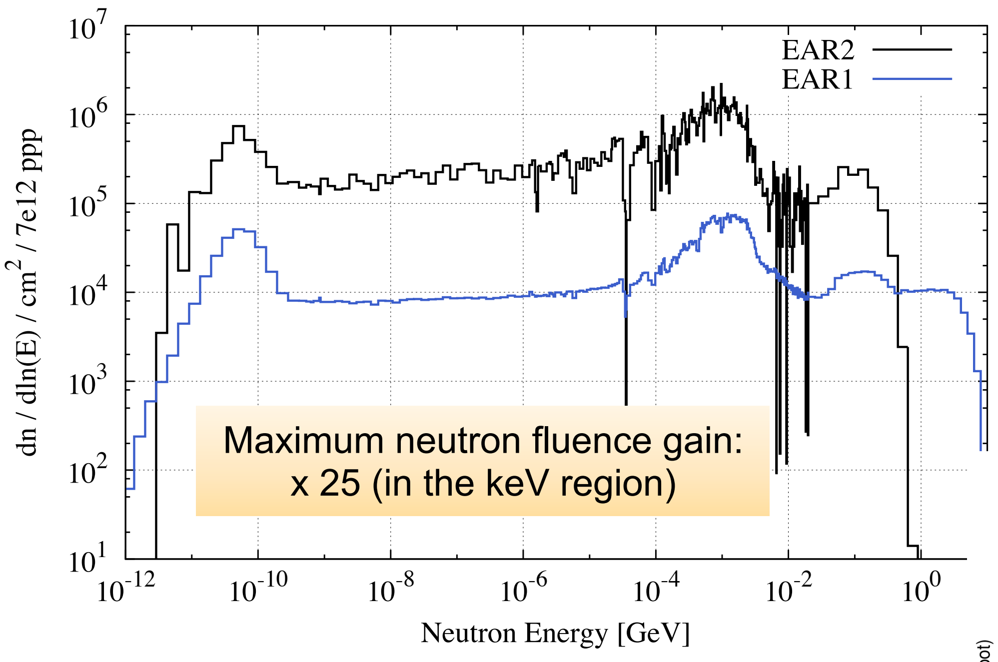
n_TOF EAR2 building 380

n_TOF EAR2

n_TOF EAR2 building 380



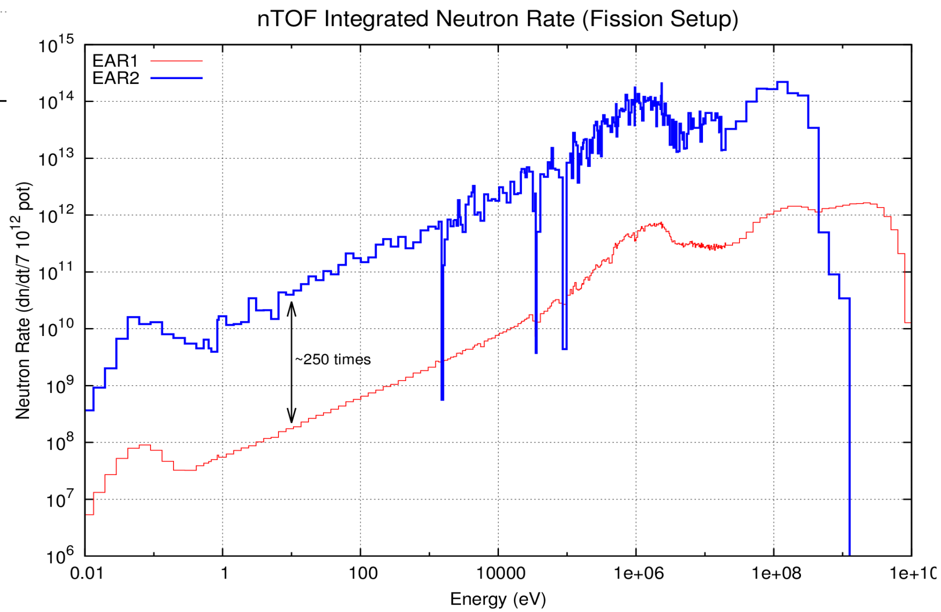
EAR2 enhanced flux



Higher flux, by a factor of 25, relative to EAR1.

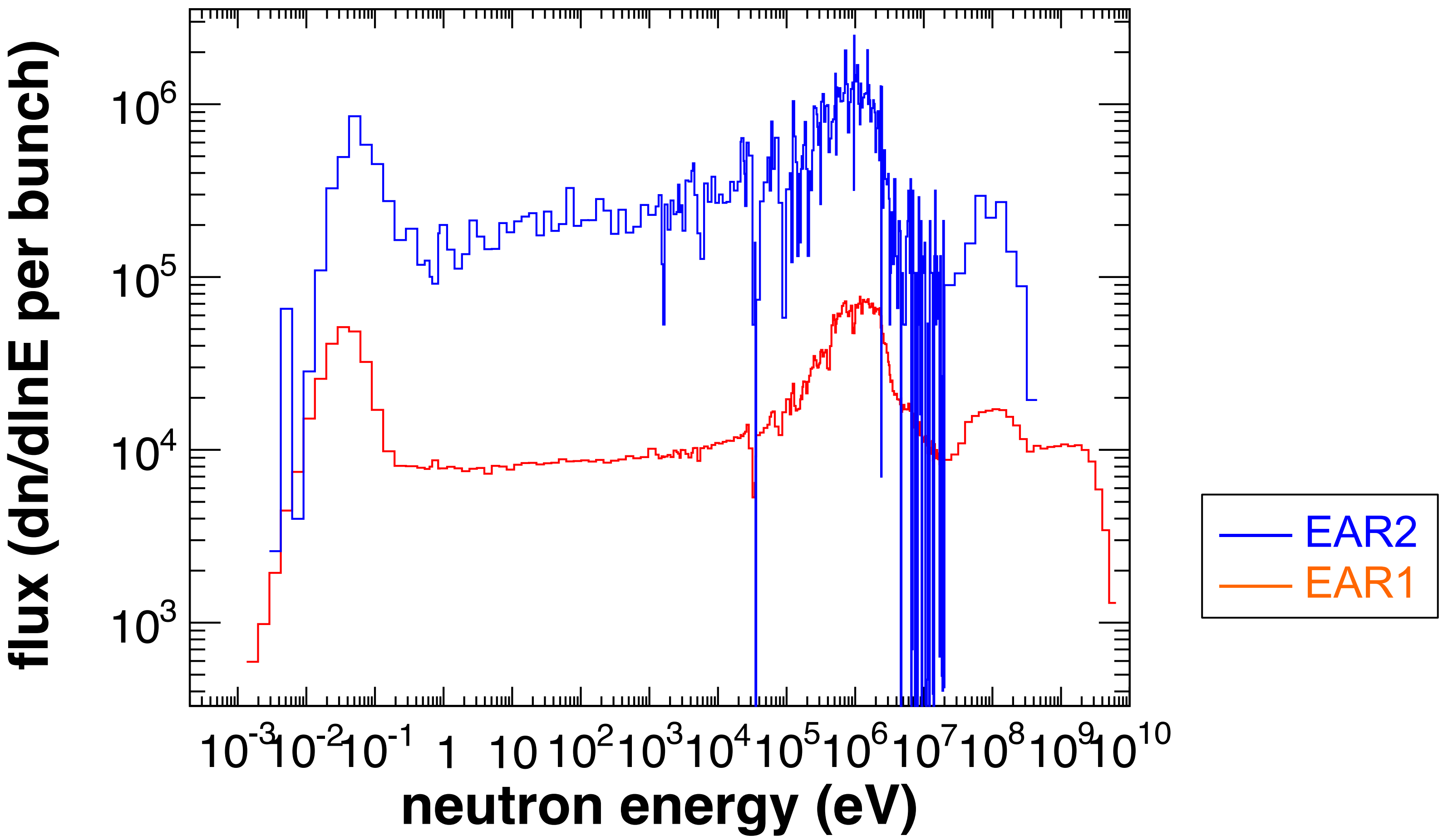
The **shorter flight path** implies a factor of 10 smaller time-of-flight.

Global gain by a factor of **250 in the signal/background ratio** for radioactive isotopes!



The huge gain in signal-to-background ratio in EAR2 allows to measure radioactive isotopes with **half lives as low as a few years.**

Neutron flux



n_TOF Collaboration

- The n_TOF Collaboration operates the facility since 2001.

- Members as of 2012:
  - 33 Institutions (EU, USA, India) + coll. with Japan and Russia
  - 100 scientists
  - 16 PhD students

- From July 2014, after the planned beam stop, n_TOF will take data again simultaneously in EAR1 (185 m) and EAR2 (20 m)

Thank you for your attention.

The n_TOF Collaboration

E. Chiaveri, S. Andriamonje, J. Andrzejewski, L. Audouin, V. Avrigeanu, M. Barbagallo, V. Bécares, F. Bečvář, F. Belloni, E. Berthoumieux, J. Billowes, D. Bosnar, M. Brugger, M. Calviani, F. Calviño, D. Cano-Ott, C. Carrapiço, F. Cerutti, M. Chin, N. Colonna, G. Cortés, M.A. Cortés-Giraldo, M. Diakaki, I. Dillmann, C. Domingo-Pardo, I. Duran, N. Dzysiuk, C. Eleftheriadis, M. Fernández-Ordóñez, A. Ferrari, K. Fraval, S. Ganesan, Y. Giomataris, G. Giubrone, M.B. Gómez-Hornillos, I.F. Gonçalves, E. González-Romero, F. Gramegna, E. Griesmayer, C. Guerrero, F. Gunsing, M. Heil, D.G. Jenkins, E. Jericha, Y. Kadi, F. Käppeler, D. Karadimos, P. Koehler, M. Kokkoris, M. Krtička, J. Kroll, Ch. Lampoudis, C. Lederer, H. Leeb, L.S. Leong, R. Losito, M. Lozano, A. Manousos, J. Marganiec, T. Martinez, C. Massimi, P.F. Mastinu, M. Mastromarco, M. Meaze, E. Mendoza, A. Mengoni, P.M. Milazzo, M. Mirea, W. Mondelaers, Th. Papaevangelou, C. Paradela, A. Pavlik, J. Perkowski, A. Plompen, J. Praena, J.M. Quesada, T. Rauscher, R. Reifarth, A. Riego, F. Roman, C. Rubbia, R. Sarmento, P. Schillebeeckx, G. Tagliente, J.L. Tain, D. Tarrìo, L. Tassan-Got, A. Tsinganis, S. Valenta, G. Vannini, V. Variale, P. Vaz, A. Ventura, M.J. Vermeulen, V. Vlachoudis, R. Vlastou, A. Wallner, T. Ware, C. Weiß, T.J. Wright

More information: www.cern.ch/ntof

Flux comparison n_TOF EAR1/EAR2, GELINA, NFS

Typical neutron spectra

Instantaneous neutron flux

Average neutron flux