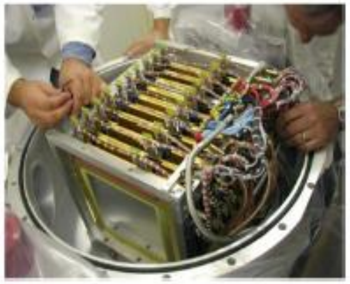
The n_TOF Collaboration, www.cern.ch/n_TOF

Measurements of Neutron-Induced Fission for Fundamental Nuclear Physics and Nuclear Technology

Nicola Colonna

Istituto Nazionale Fisica Nucleare, Sezione di Bari, Italy


Outline

- Motivations
- Neutron beams for fission studies
- The n_TOF facility
- Experimental method and detectors
- A few examples
- Conclusions

The fission process

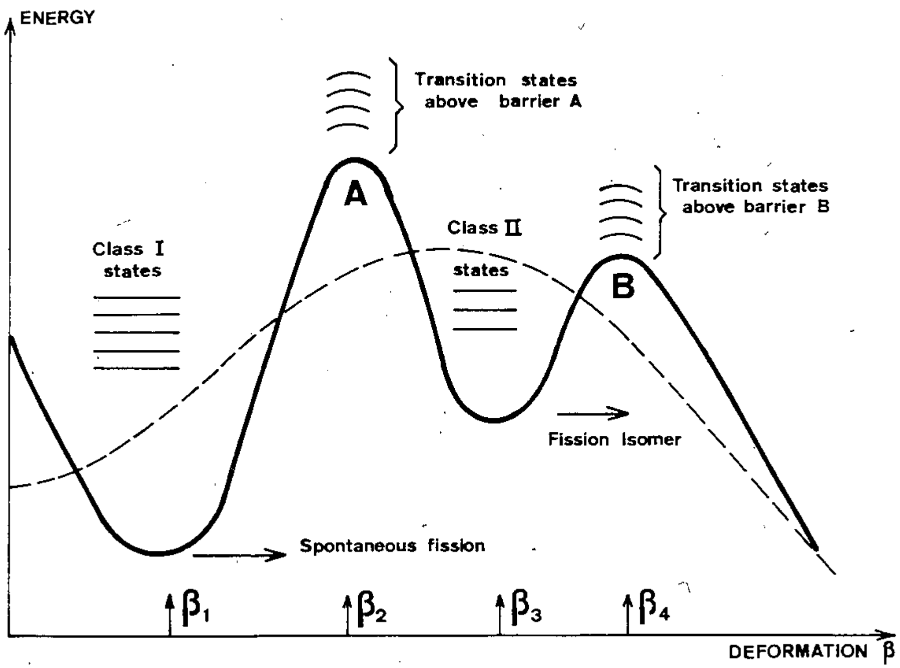


Fig. 65. Fission barrier (solid line) resulting from shell corrections to the LDM barrier (dashed line). As in Fig. 54, the abscissa β gives only an indication of the magnitude of the deformation but does not specify the type of deformation. For certain classes of nuclei, for instance, those having neutron number N in the vicinity of 146, the fission barrier presents two humps A and B, at deformation β_2 and β_4, respectively, where the shell-energy corrections are positive. These two humps can be separated by a deep second well, at deformation β_3, where the shell-energy correction is negative. This kind of barrier shape has consequences (discussed in Sect. 5) for the understanding of the fission process.

J. R. Huizenga e R. Vandenbosch, Nuclear Fission, Academic Press, 1973
C. Wagemans (editor), The Nuclear Fission Process, CRC Press, 1991

The **fission process** is governed by the **fission barrier**.

Neutron-induced fission on a nucleus (Z,N) goes through the formation of a **compound nucleus** (Z,N+1) with excitation energy:

$$E^* = S_n + E_k$$

S_n is the neutron separation energy and E_k the kinetic energy in the center-of-mass.

When **S_n is higher** than the barrier, fission occurs for **any neutron energy** (**fissile isotope**). Otherwise, there is a minimum neutron energy ("**threshold**") for which fission occurs (**fertile isotope**).

Important observables on neutron-induced fission:

- Differential cross-section
- Fission Fragment mass distribution
- Fission neutron multiplicity and spectra
- Total energy released
- Delayed neutrons

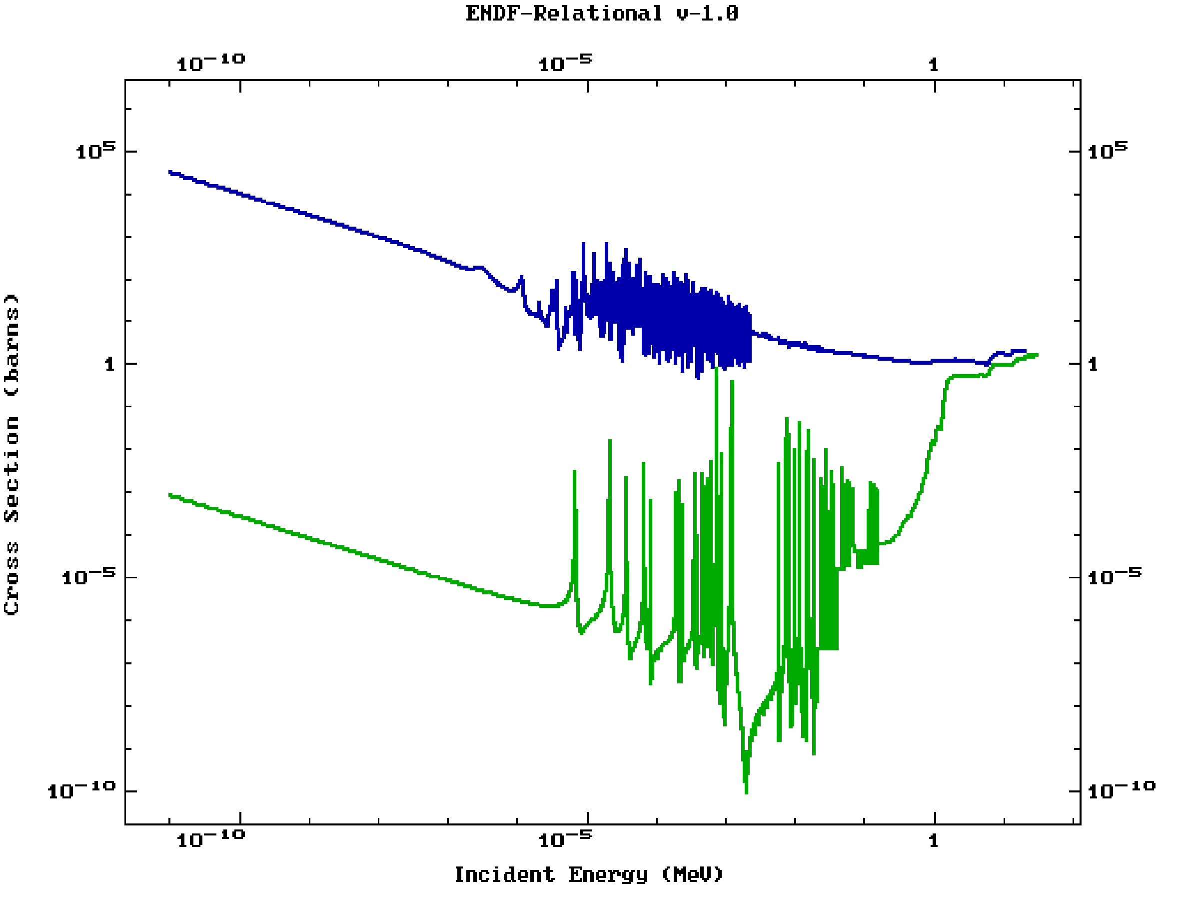
Fissile and fertile isotopes

^{235}U (blue curve):

- $S_n = 6.55$ MeV
- $E_A = 5.6$ MeV
- $E_B = 5.5$ MeV

^{238}U (green curve):

- $S_n = 4.81$ MeV
- $E_A = 6.3$ MeV
- $E_B = 6.1$ MeV



The nuclear waste problem

LLFP

$^{244,245}Cm$
1.5 Kg/yr

^{241}Am: 11.6 Kg/yr
^{243}Am: 4.8 Kg/yr

^{239}Pu: 125 Kg/yr

^{237}Np: 16 Kg/yr

LLFP
76.2 Kg/yr

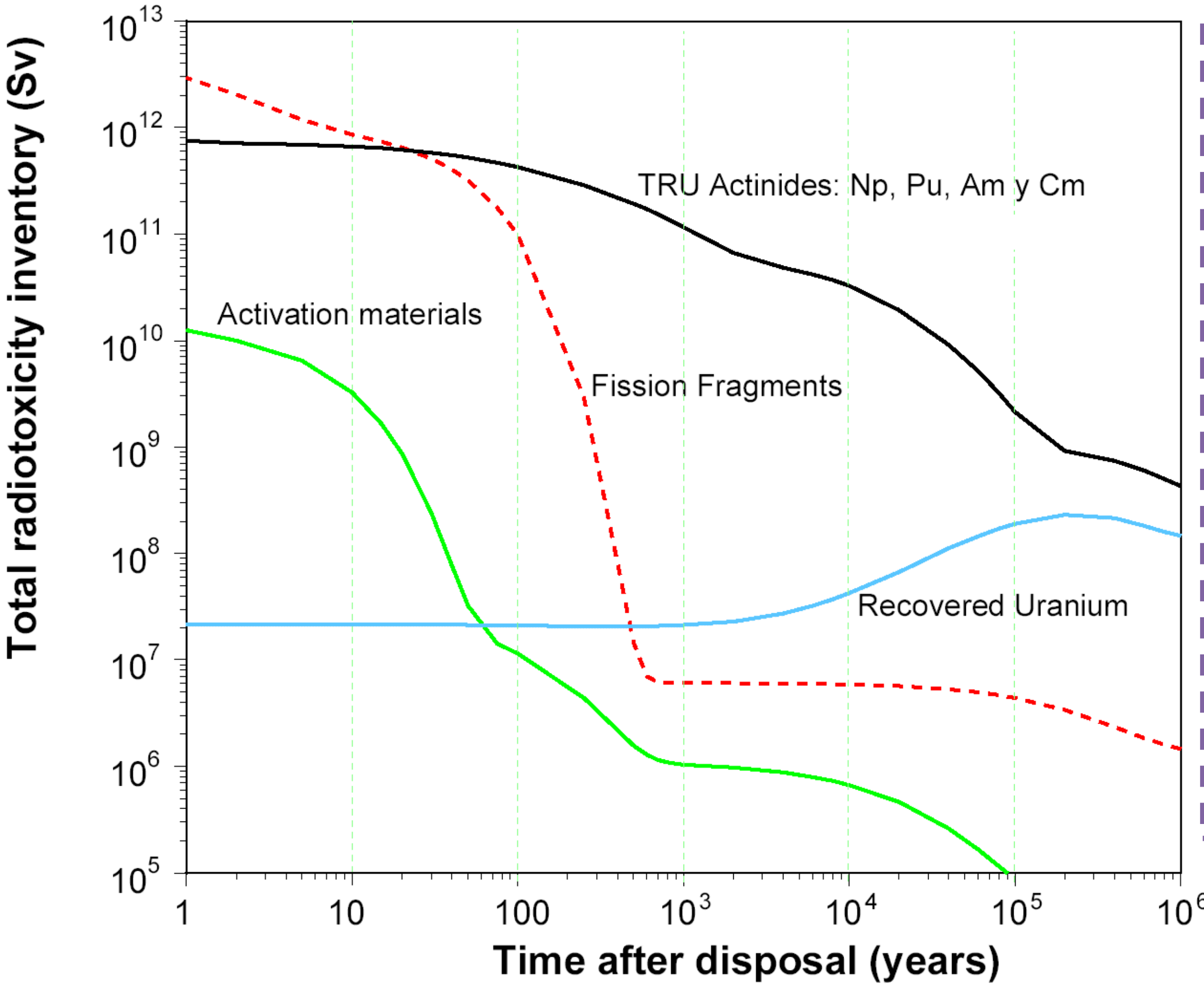
Quantities refer to yearly production in 1 GW$_e$ LW reactor

The Th/U fuel cycle

$$^{232}Th(n,\gamma)^{233}Th \xrightarrow{\beta^-,\ t_{1/2}=22\ m} {}^{233}Pa \xrightarrow{\beta^-,\ t_{1/2}=27\ d} {}^{233}U$$

nTOF

The actinides in nuclear waste

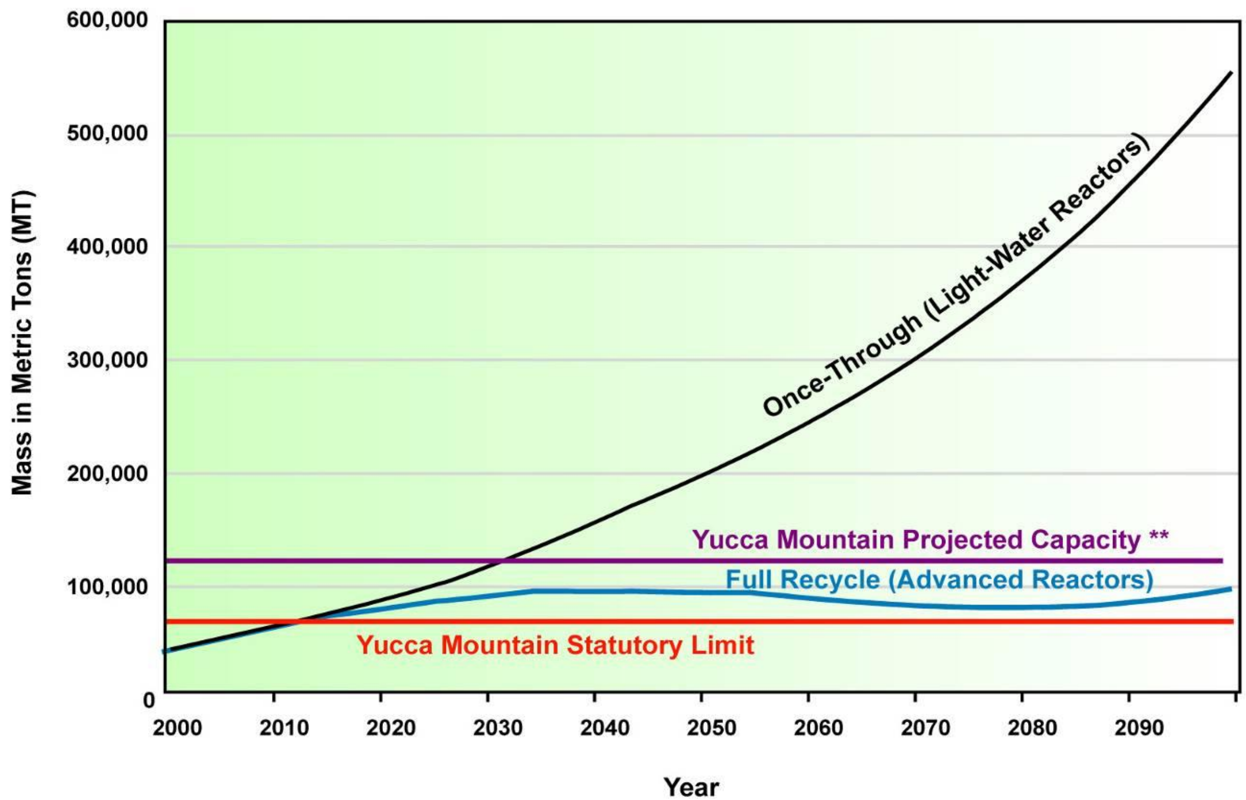


Main problem in the nuclear waste are the **transuranic actinides**: Pu and MA (Np, Am, Cm,...)

- 1.5% in mass but give the biggest contribution to **radiotoxicity** and heat after 100 y
- problem persists for more than **10^5 y**
- some isotopes are **fissionable** (proliferation and criticality concern)

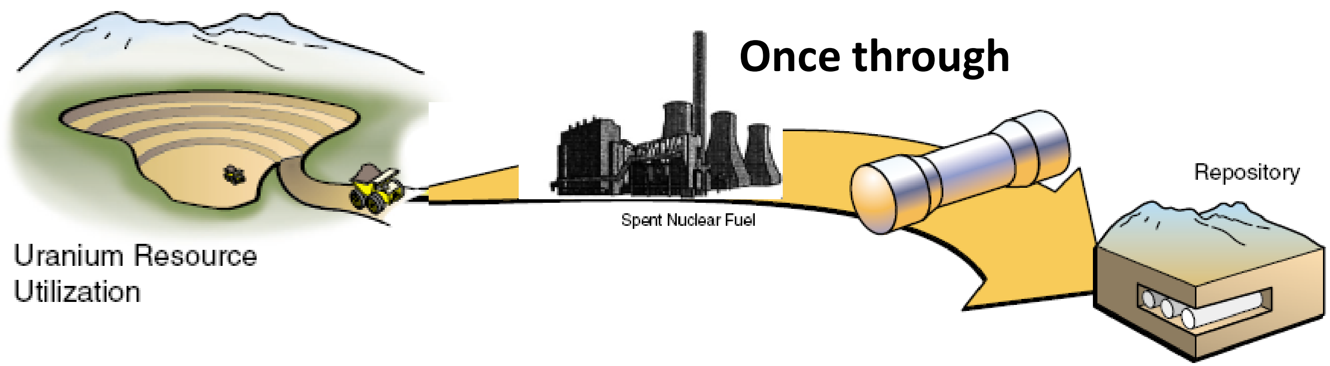
At present, only solution to the high radiotoxicity nuclear waste is **geological repositories**

Geological repositories

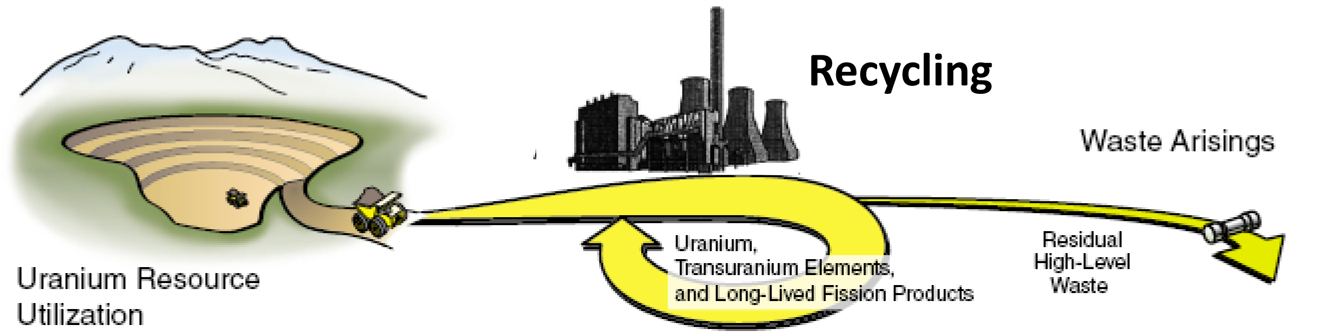


With current reactors, it would be necessary to find a new geological repository like Yucca Mountain every 20 years.

New generation reactors



Existing reactors have low **burn-up efficiency** and produce large amount of **radioactive waste**.



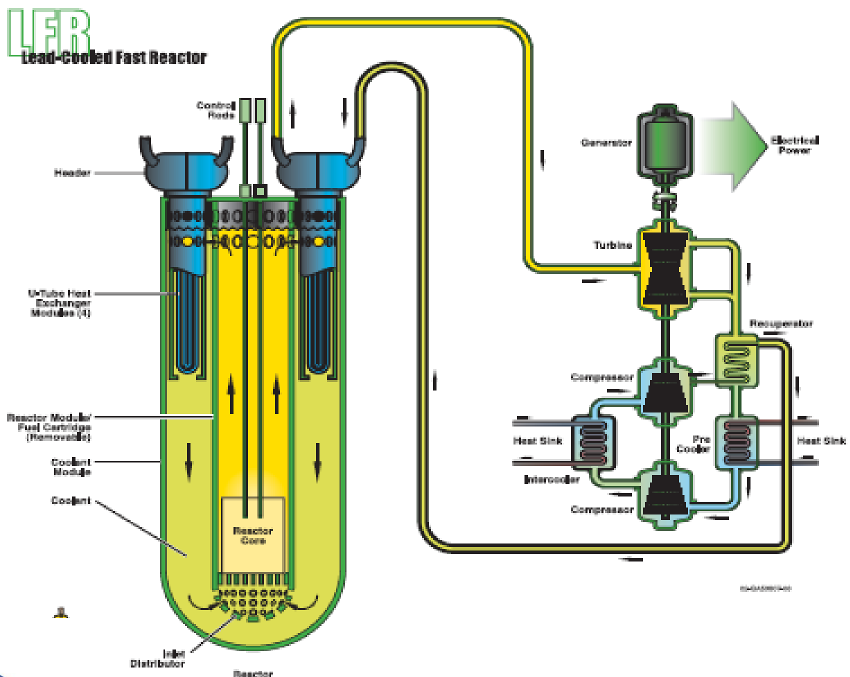
In **new generation reactors** at least part part of the spent fuel could be **recycled**.

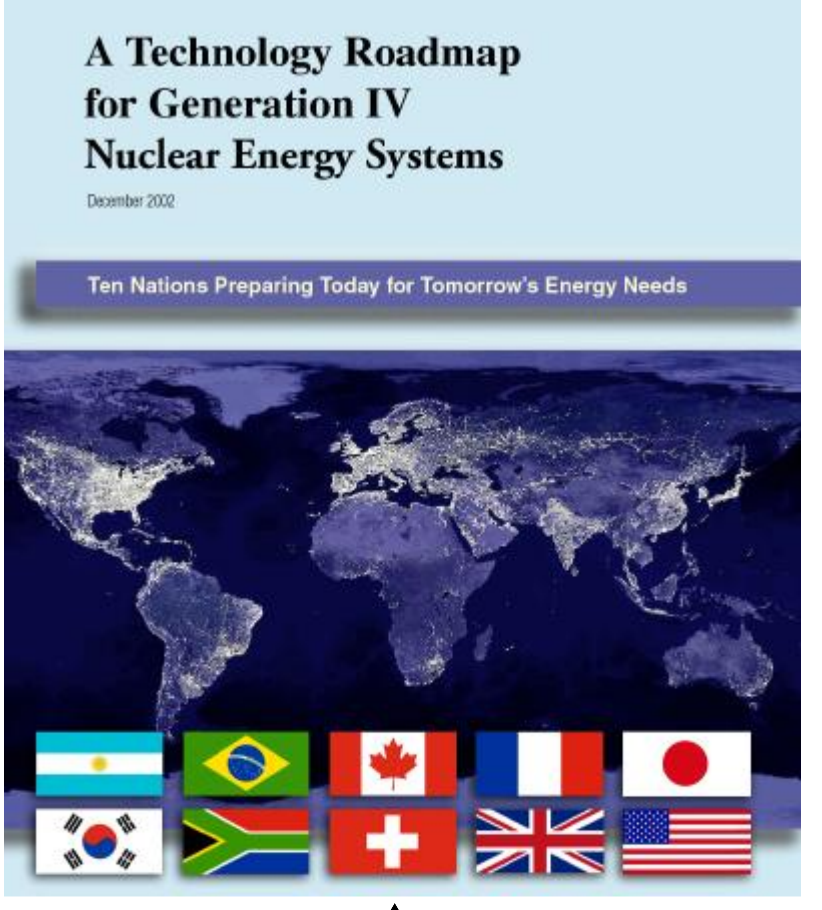
Advantages of **IV Generation** reactors (and Accelerator Driven Systems):

- Higher burn-up **efficiency** and lower production of waste
- Greater **safety and non-proliferation**
- lower **costs and construction time**

The Generation IV forum

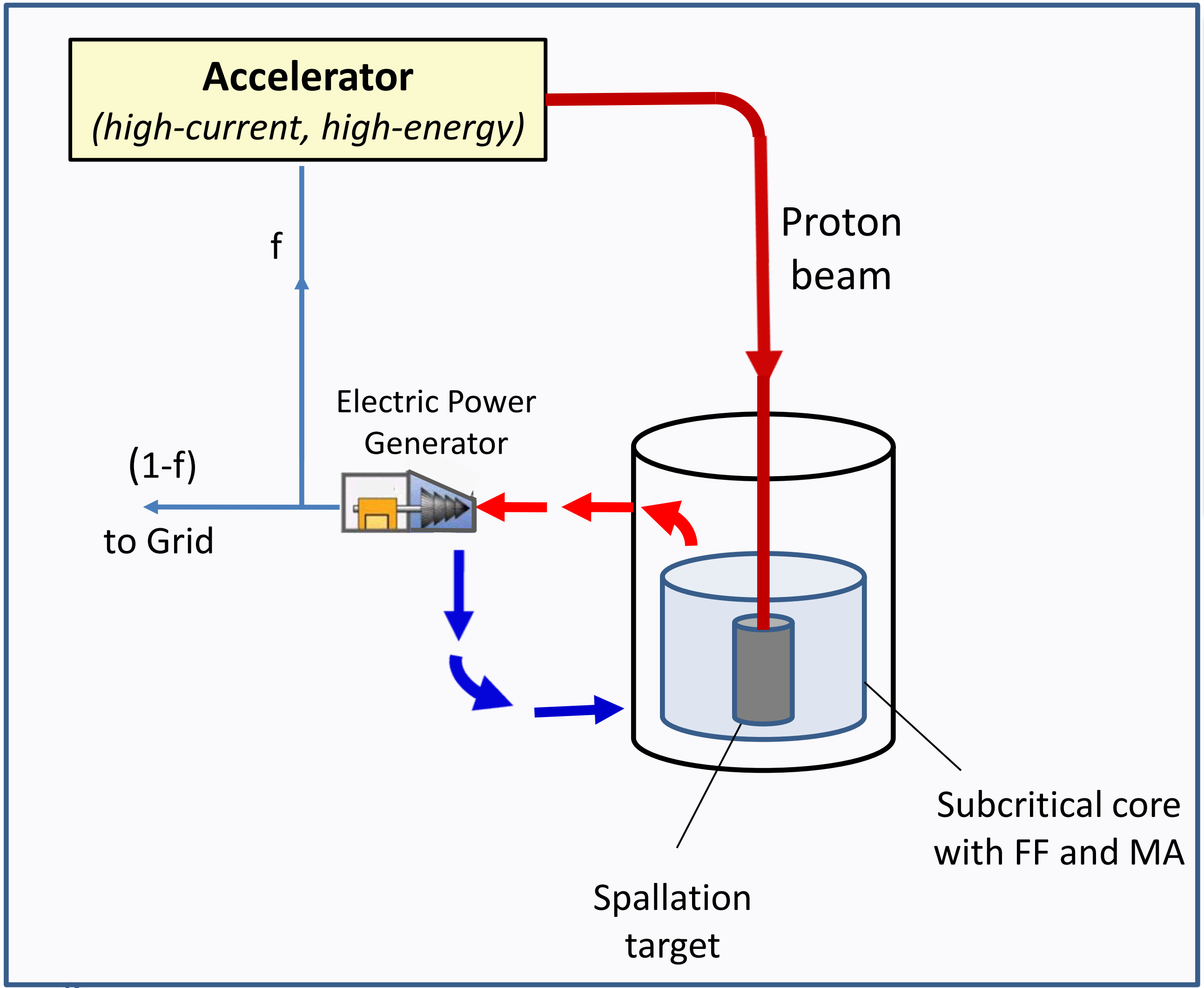
Generation IV System	Acronym
Gas-Cooled Fast Reactor System	GFR
Lead-Cooled Fast Reactor System	LFR
Molten Salt Reactor System	MSR
Sodium-Cooled Fast Reactor System	SFR
Supercritical-Water-Cooled Reactor System	SCWR
Very-High-Temperature Reactor System	VHTR





10 Nations Preparing Today for Tomorrow's Energy Needs

Accelerator Driven Systems



- **Subcritical system** in which additional neutrons are supplied by a **high-energy, high-current** accelerator.
- Intrisecally **safe**
- Mostly for **nuclear waste incineration**
- Possible use of the different fuel cycles (**Th/U**)

R&D needs

- Accelerator with **high-current** beam (several mA) and **high stability** (few interruptions per year)
- **Nuclear data** on spallation and on neutron-induced reactions on FF and actinides

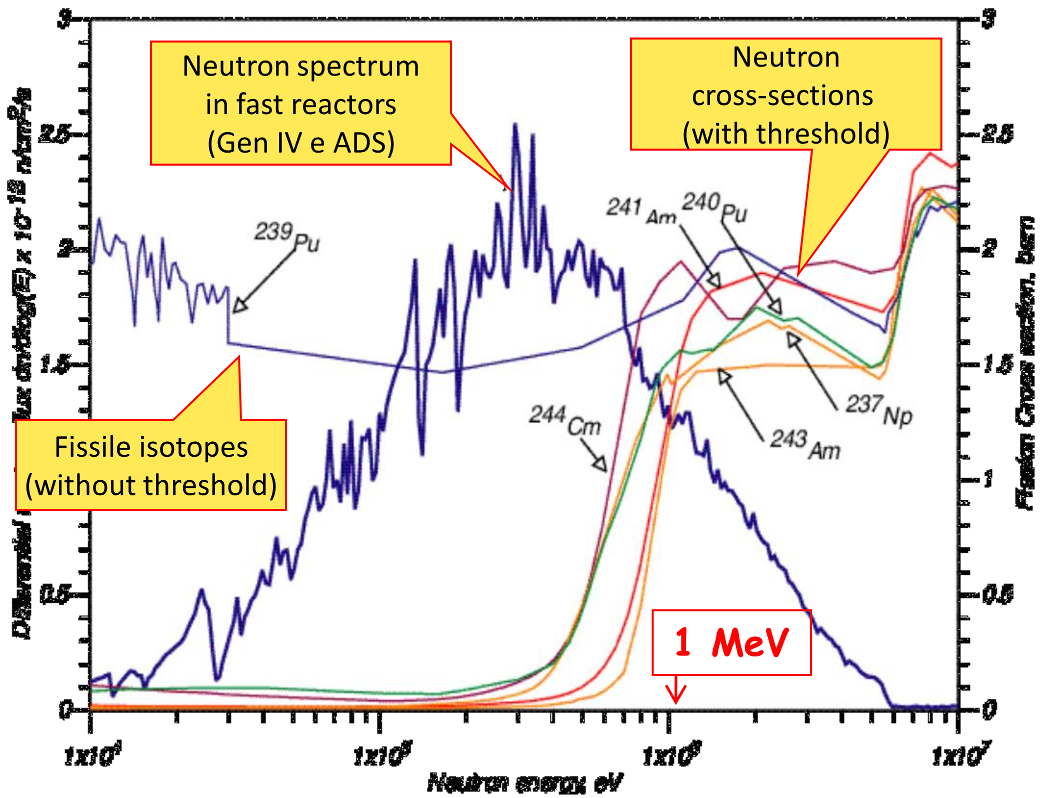
Reactor physics in Gen IV and ADS

The main innovation concerns the possibility to produce energy by burning the nuclear waste with higher radiotoxicity (minor actinides) : **Np, Am, Cm**

Apart for ^{245}Cm, minor actinides present a **fission threshold** around **MeV**.

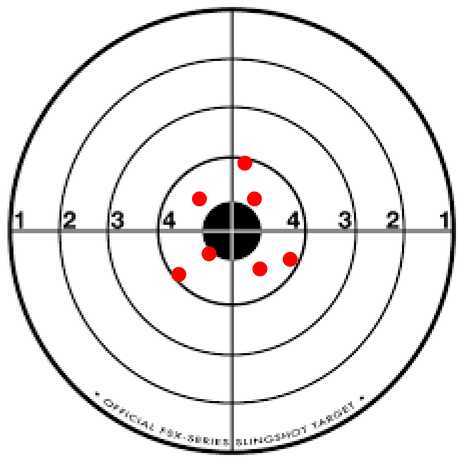
To burn-up minor actinides, **fast neutrons** have to be used (E_n > 1 MeV).

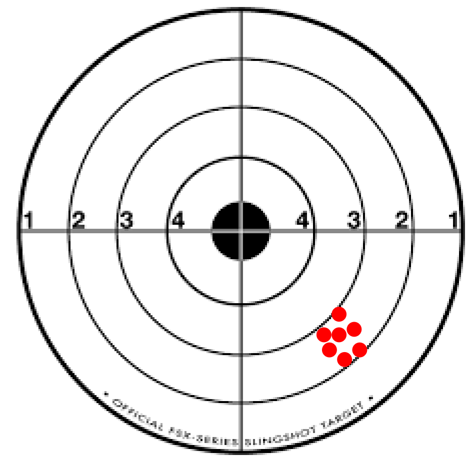
Data in the fast energy region are required with **high accuracy,** to minimize uncertainties in calculations for reactor **design** and **safety** parameters.



The development of Gen IV reactors **fast reactors** requires data on minor actinides

Accuracy vs Precision





It is better to be roughly right than .... precisely wrong !!

John Maynard Keynes

Control of **systematic errors** is fundamental in measurements of fission cross sections

Needs for new data on fission cross-sections

New and accurate nuclear data for **U**, **Pu** and **Minor Actinides** needed for:

- increasing fuel burn-up for all types of nuclear reactors (including existing)
- utilization of accumulated plutonium
- recycling of nuclear fuel (closed cycle)
- Transmutation of minor actinides in different types of nuclear power reactors and accelerator-driven systems

HPRL The NEA High Priority Request List

Nuclear Data Standards | Dosimetry Reactions | Fusion Technology | Fission Reactor Technology | Medical and Industrial Applications | Intermediate Energies

OECD

www.nea.fr/html/dbdata/hprl/

For many isotopes (in particular Minor Actinides), current **evaluation** of neutron cross-sections (**ENDF, JENDL, JEFF, BRONDL**, etc…) are **incomplete or discrepant** among themselves or with experimental data.

Clearly inadequate for the needs related to **advanced nuclear technologies**

Pressing need of **new and accurate data on neutron-induced fission** for several isotopes, many of which of “short” half-life (tens or hundreds of years).

Table 1. Summary Target Accuracies for Fast Reactors

		Energy Range	Current Accuracy (%)	Target Accuracy (%)
U238	inel	0.5 ÷6.1 MeV	10 ÷ 20	2 ÷ 3
	capt	2.04 ÷24.8 keV	3 ÷ 9	1.5 ÷ 2
Pu241	fiss	454. eV ÷1.35 MeV	8 ÷ 20	2 ÷ 5
Pu239	capt	2.04 ÷498 keV	7 ÷ 15	4 ÷ 7
Pu240	fiss	0.498 ÷1.35 MeV	6	1 ÷ 3
Pu242	fiss	0.498 ÷2.23 MeV	19 ÷ 21	3 ÷5
Pu238	fiss	0.183 ÷1.35 MeV	17	3 ÷5
Am242m	fiss	67.4 keV ÷1.35 MeV	17	3 ÷4
Am241	fiss	2.23 ÷6.07 MeV	9	2
Am243	fiss	0.498 ÷6.07 MeV	12	3
Cm244	fiss	0.498 ÷1.35 MeV	50	5
Cm245	Fiss	67.4 ÷183 keV	47	7
Fe56	Inel	0.498 ÷2.23 MeV	16 ÷ 25	3 ÷ 6
Na23	inel	0.498 ÷1.35 MeV	28	4 ÷10
Pb206	inel	1.35 ÷2.23 MeV	14	3
Pb207	Inel	0.498 ÷1.35 MeV	11	3
Si28	inel	1.35 ÷6.07 MeV	14 ÷ 50	3 ÷ 6
	capt	6.07 ÷19.6 MeV	53	6

On n-induced fission cross sections, necessary accuracy better than **3 %** for most Pu isotopes and Minor Actinides, in the energy range from a few keV to several MeV.

Source: Aliberti, Palmiotti, Salvatores, NEMEA-4 workshop, Prague 2007

Nuclear energy and the need of nuclear data – EU programs

Objectives of the nuclear industry/research in Europe:

- improve safety and efficiency of current reactors (LWR)
- develop a new generation of reactors (Gen IV fast reactors and Accelerator Driven Systems)

Strategic Research Agenda of the European Sustainable Nuclear Energy Technology Platform (SNETP)

Availability of **accurate nuclear data** (cross sections, decay constants, branching ratios, etc.) is the basis **for precise c** … fe extension) and **new generation r** … iled analysis and interpretation **are** … his is particularly true **for fuels containing minor actinides** for their transmutation in fast spectra.

Need to measure fission cross section of actinides (**from Th to Cm**) with half-life from a few years up.

NEA/WPEC-26 (ISBN 978-92-64-99053-1)

UNCERTAINTY AND TARGET ACCURACY ASSESSMENT FOR INNOVATIVE SYSTEMS USING RECENT COVARIANCE DATA EVALUATIONS

The overall list of requirements is rather long:

- capture cross sections of **^{235,238}U, ^{237}Np, $^{238\text{-}242}$Pu, ^{241,242m,243}Am, ^{244}Cm**
- fission cross sections of **^{234}U, ^{237}Np, $^{238,240\text{-}242}$Pu, ^{241,242m,243}Am, $^{242\text{-}246}$Cm**

Experimental challenges

^{241}Pu(n,f) ($\tau_{1/2}$=14.4 years) **500 eV < E_n < 2 MeV**

- Data needed for SFR, GFR, LFR
- Current uncertainty: 10-20 % Target accuracy: 2-6 %
- Similar needs for ^{240}Pu ($\tau_{1/2}$=6.5e3 years) and ^{242}Pu ($\tau_{1/2}$=3.75e5 years)

^{241}Am, ^{242m}Am, ^{244}Cm, ^{245}Cm(n,f) **En < 2 MeV**

- Data needed for SFR and ADS
- Current uncertainty: 10-40 % Target accuracy: 2-6 %

There is a **strong need** for more accurate measurements.

The various neutron facilities around the world can contribute to fulfill part of the **still open nuclear data requests**.

However, the most difficult measurements require **improvements** on the **experimental methods** and on **neutron facilities** (but there is still a question whether some measurements will be feasible in the near future).

Some "impossible" measurements can at present be done with other methods **(surrogate)**.

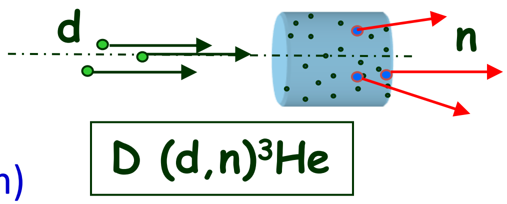
The neutron sources

Low-energy neutron beams:

- high fluxes available at **nuclear reactors at thermal energy (25 meV)**
- **moderated** neutrons produced with **accelerators** (see below)

Monoenergetic neutron sources:

- typically based on **p- or d-induced** reaction
- D(d,n), T(p,n), T(d,n), ^{7}Li(p,n), ^{9}Be(p,n), ec…,
- based on **low- and medium-energy** accelerators (VdG, Pelletron, …)
- **accordable** neutron energy (by changing energy of the primary beam)
- neutron energies up to **20 MeV**



Time-of-flight facilities (ToF):

- wide energy spectrum, neutron energy determined from ToF
- choice of flight base trade-off between flux and energy resolution
- Requires pulsed accelerator

Time-of-flight facilities

Different types of neutron **time-of-flight** facilities

(p,n) and (d,n) reactions:
- Low and medium energy accelerator (pulsed)
- thick targets (for higher flux)
- moderated spectrum

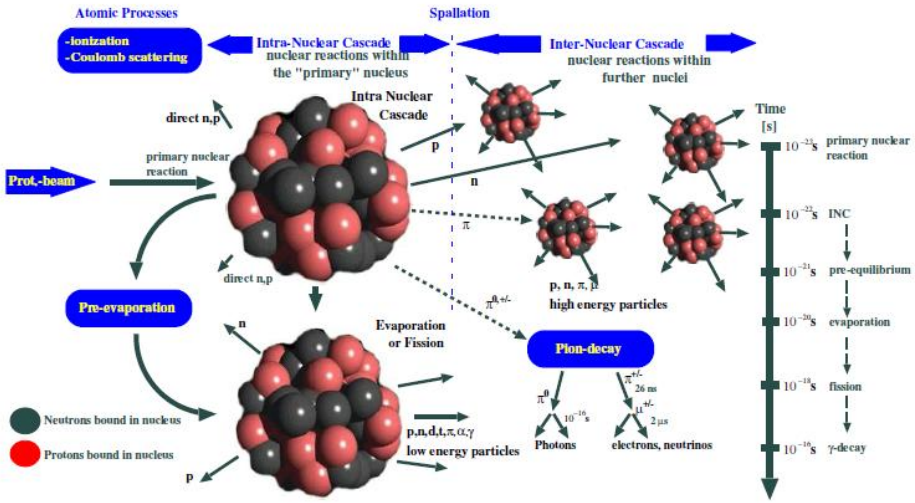
GELINA (JRC-IRMM, Geel, Belgium)

High-intensity **electron beams**:
- neutron production though **(γ,n) reactions**
- target made of high-Z material (and U, in some cases)
- moderated spectra

Spallation neutron sources:
- based on high-energy (GeV) protons beams
- Large blocks of heavy material
- Moderated spectrum

LANSCE (USA)
n_TOF (CERN)
J-PARC (Japan)
GNEIS (Russia)

Spallation neutron sources



Neutrons produced by a **series of nuclear reactions** (intranuclear cascade, preequilibrium, evaporation, etc…)

Need **high-energy proton** beams

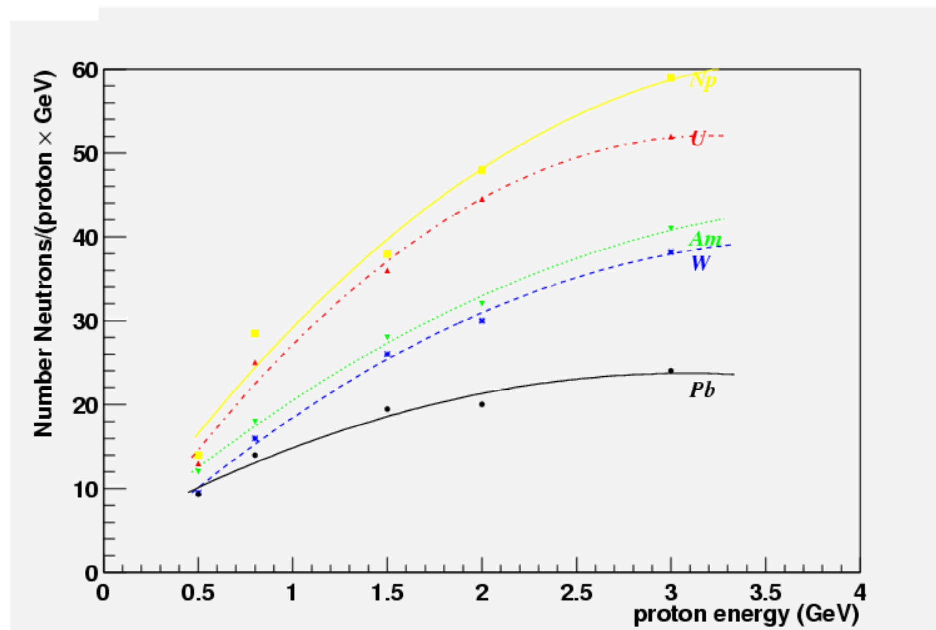
Large volume spallation targets

F. Goldenbaum, The Physics of Spallation Processes, 2003

Neutron production depends on:

- **atomic weight** and **density** of the material (high-Z material desired).
- **proton energy**

Choice of **target** depends also on other factors (radiation resistance, costs, etc…)

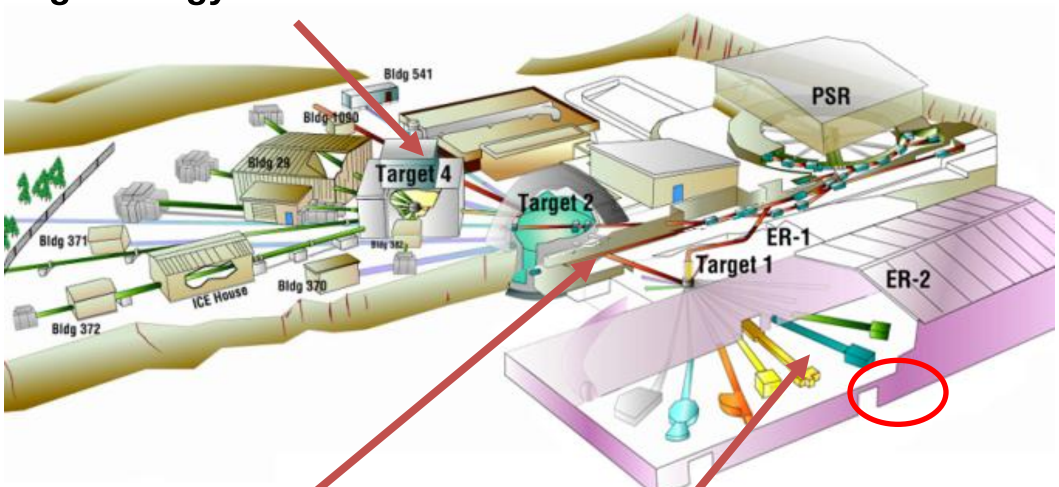


The Los Alamos Neutron Science Center (LANSCE)

Based on the **spallation** of 800 MeV proton beam on Tungsten **targets**

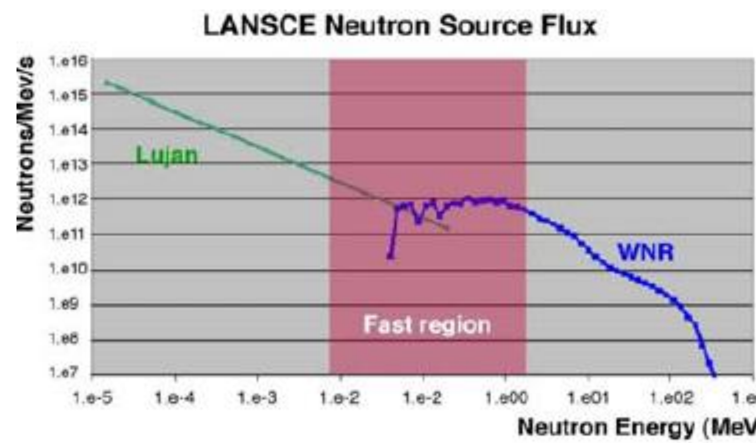
Use of the **proton storage ring** to increase proton beam current (and therefore, neutron flux)

Target-4 WNR
High-energy neutron research



Different **target/moderator** assemblies allow measurements in a wide energy range:

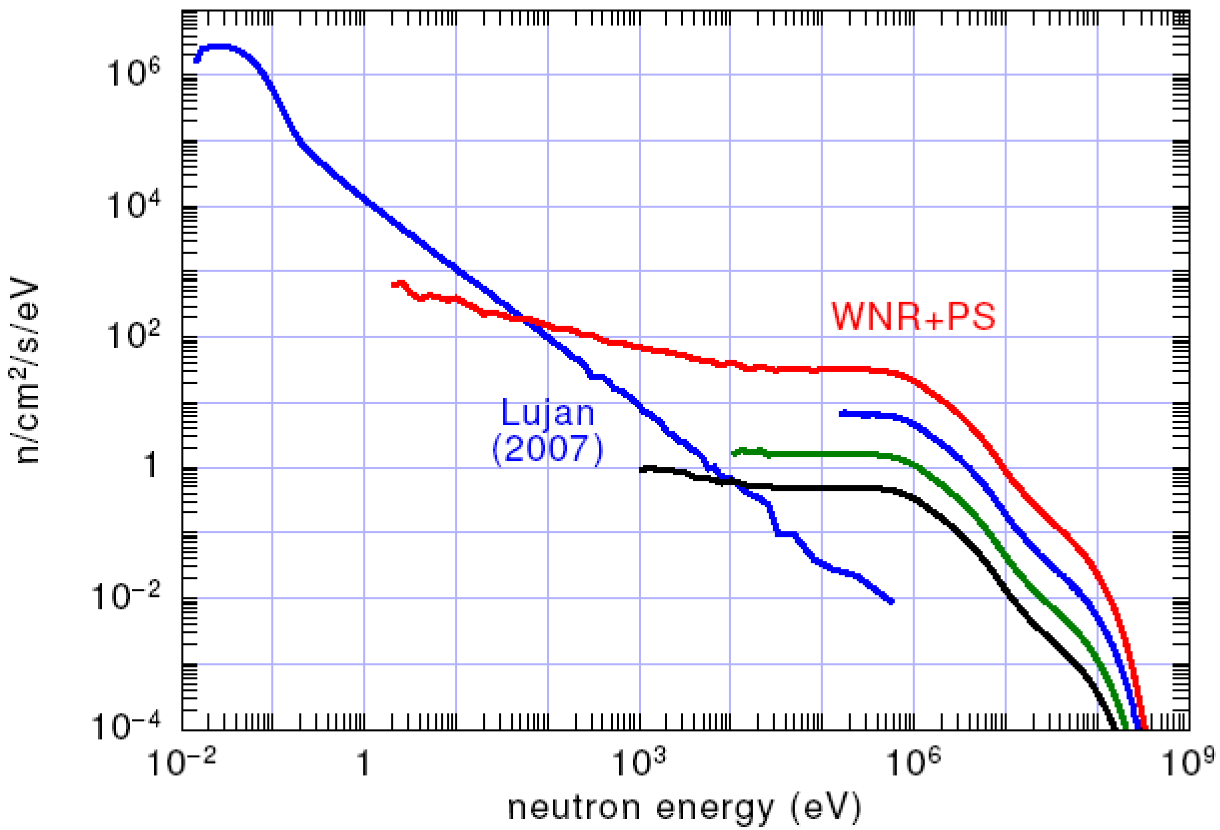
- W target **with moderator** for **low-energy** measurements
- W target **without moderator** for measurements **up to 200 MeV**



Target-2
- **Proton-induced reactions**
- **Single-pulse experiments (Sandia)**
- **Lead Slowing-Down Spectrometer**

Lujan Center
Low-energy neutrons
- **Material science**
- **Nuclear science**

Neutron flux available at LANL



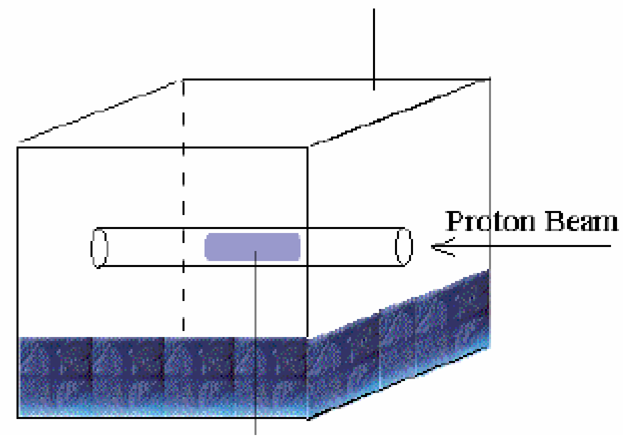
The "pulse stacking" mode, using the **proton storage ring**, increases neutron flux and decreases repetition rate (neutrons wrap-around at lower energy)

20 μA WNR pulse stacking
4 μA WNR 1.8 μs spacing
1 μA WNR 7.2 μs spacing
4/13 μA 23.4 μs spacing

Lead Slowing Down Spectrometer

Fission cross section measurements for isotopes **highly radioactive** or available in small quantities need **extremely high** neutron flux

The solution is the **"Lead Slowing Down Spectrometer"**



Neutrons interactions in Pb: only **inelastic** and **elastic** collisions (small capture cross-sections)

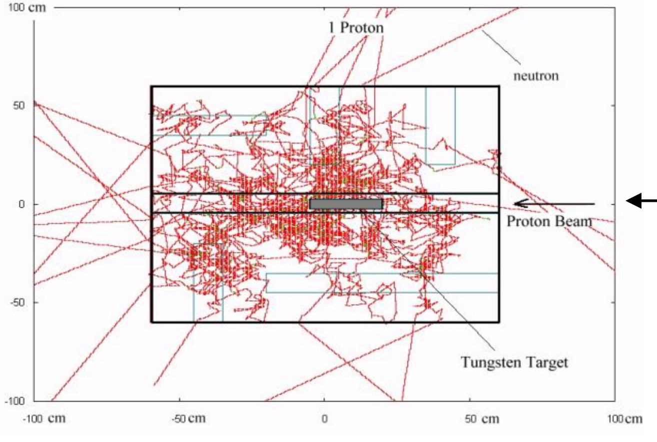
In each interaction, **little energy** is lost

Neutrons are **trapped** inside Pb block

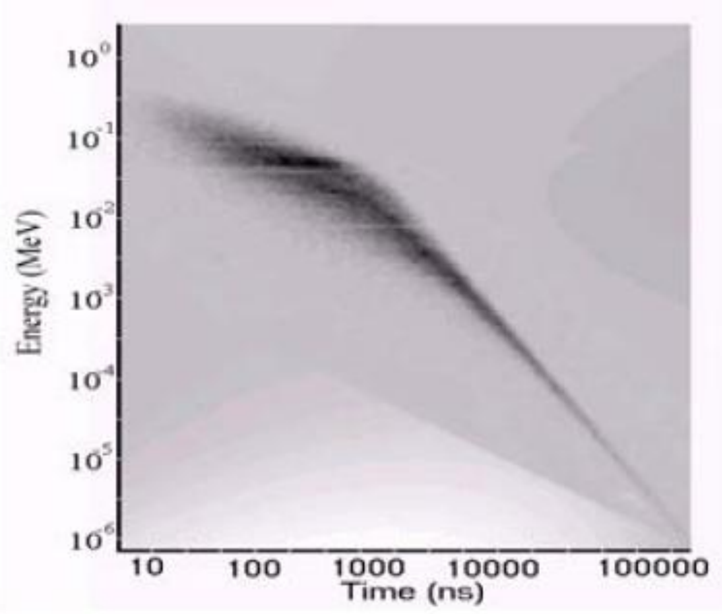
At LANL, 800 MeV p on W, inside 1 m^3 Pb cube

Lead Slowing Down Spectrometer

Simulations



One proton



Time-energy relation

LSDS @ LANL:

- 20 tons of high purity lead
- pulsed proton beam ➡ pulsed neutron source in center
- Different channels in the lead assembly
- Fission chamber (with sample) inserted in the channels

Properties:

- Some time-energy relation is retained, but relatively poor energy resolution
- Trapped neutrons allows measurements on extremely small samples (ng)

Neutron facilities in Japan and Russia

JAPAN

Reactors: JRR-3 (JAEA, 20MW), KURRI (Kyoto, 1MW)

Time-of-flight facilities:

- Kyoto: 30 MV Electron LINAC
- Tokio Institute of Technology: 3 MV Pelletron
- JAEA: 4 MV Pelletron

J-PARC (Japan Proton Accelerator Research Center):

- Innovative high-intensity neutron beam facility based on 3 GeV proton beam (1 MW power)

RUSSIA

Monoenergetic neutrons (VdG, IPPE, Obninsk);

Time-of-Flight facility at LU-50 electron accelerator (Sarov);

Lead slowing down spectrometer (Troitsk)

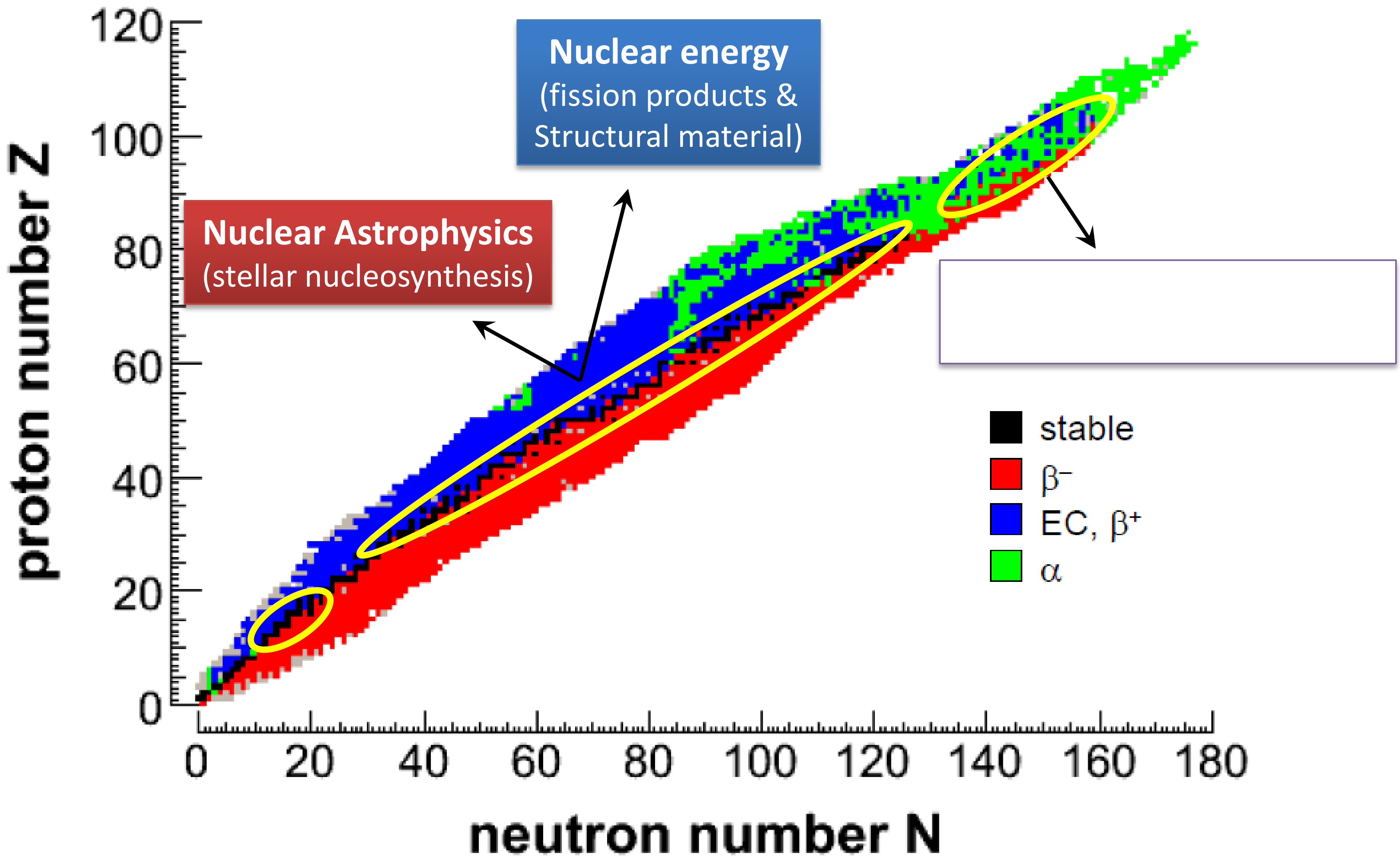
GNEIS (PNPI, S. Petersbourg)

The n_TOF Collaboration

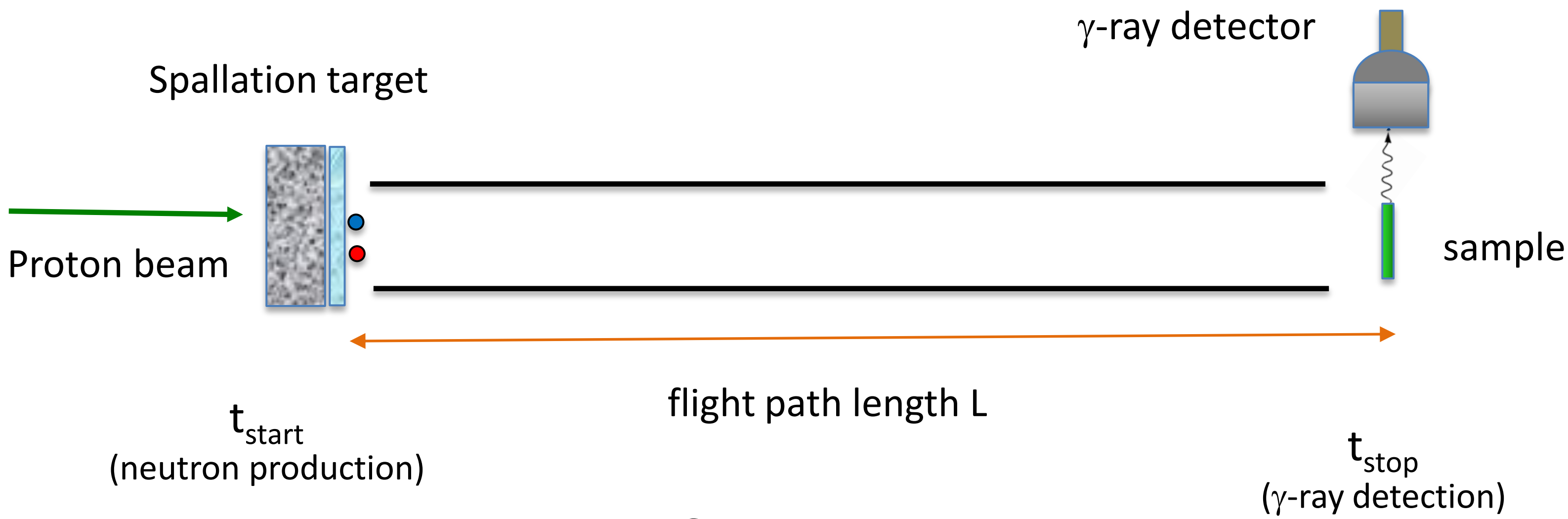
(~100 Researchers from 30 Institutes)

CERN	
Technische Universitat Wien	Austria
Univ. of Camberra	Australia
IRMM EC-Joint Research Center, Geel	Belgium
Charles Univ. (Prague)	Czech Republic
IN2P3-Orsay, CEA-Saclay	France
Univ. of Athens, Ioannina, Demokritos	Greece
INFN Bari, Bologna, Catania, LNL, Trieste, ENEA – Bologna	Italy
BARC	India
Univ. of Tokio, JAEA	Japan
Univ. of Lodz	Poland
ITN Lisbon	Portugal
IPPE-Obninsk, JINR-Dubna	Russia
IFIN – Bucarest	Rumania
CIEMAT, Univ. of Valencia, Santiago de Compostela, University of Cataluna, Sevilla, Granada	Spain
Univ. of Manchester, Univ. of York, Hearthfordshire, Univ. of Edinbourgh	UK

Neutron cross sections



Time-of-flight technique

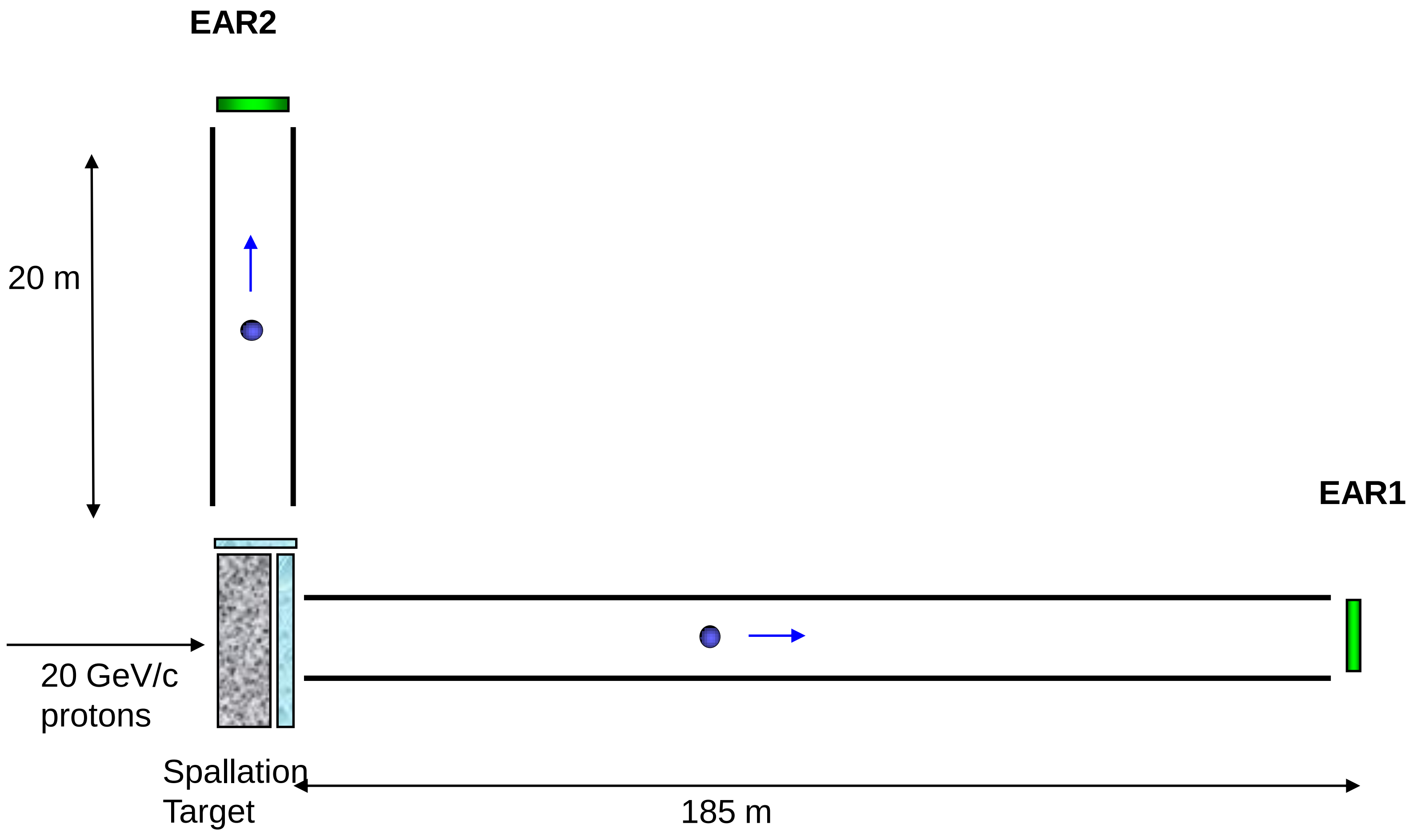


$$tof = t_{stop} - t_{star}$$

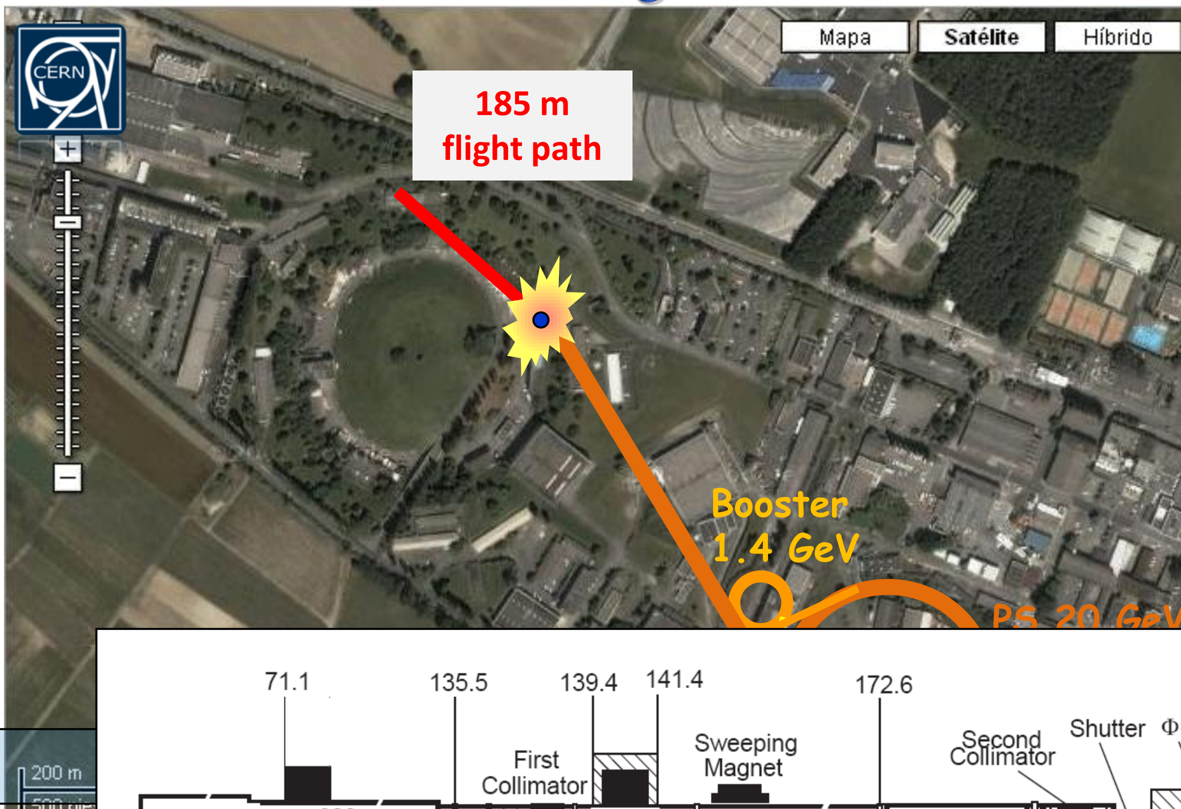
$$E_n = \left(\frac{72{,}2977 \cdot L}{tof} \right)^2$$

$$E_n = m_n c^2 \left(\frac{1}{\sqrt{1 - \frac{L^2}{tof^2 \cdot c^2}}} - 1 \right)$$

The time-of-flight facility (n_TOF) at CERN

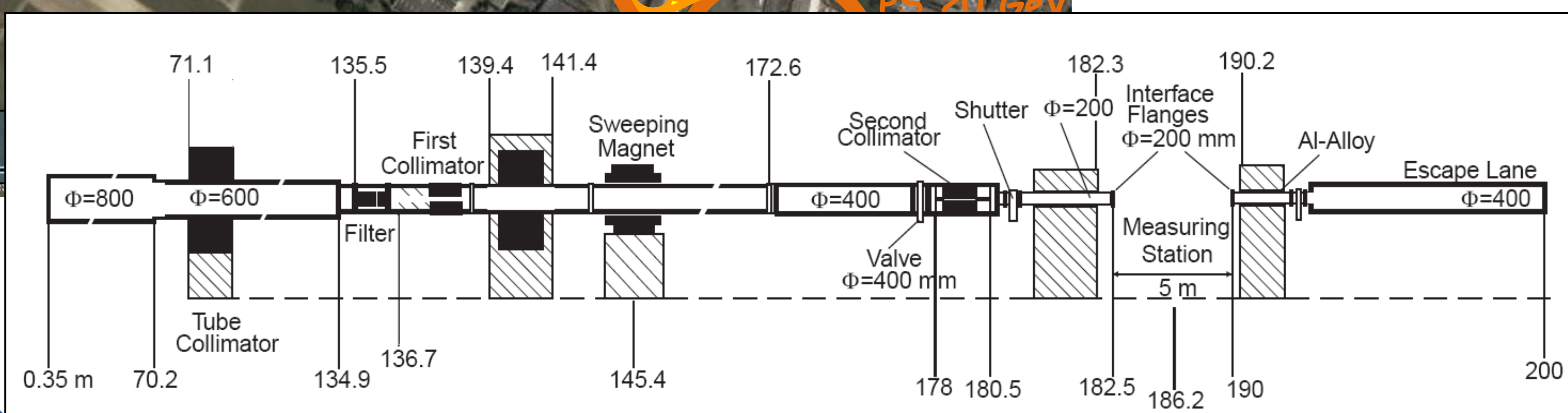


The n_TOF facility at CERN



n_TOF is a **spallation** neutron source based on **20 GeV/c protons** from the CERN PS hitting a **Pb block** (~360 neutrons per proton).

Experimental area at **185 m** (now a second one at **20 m**)



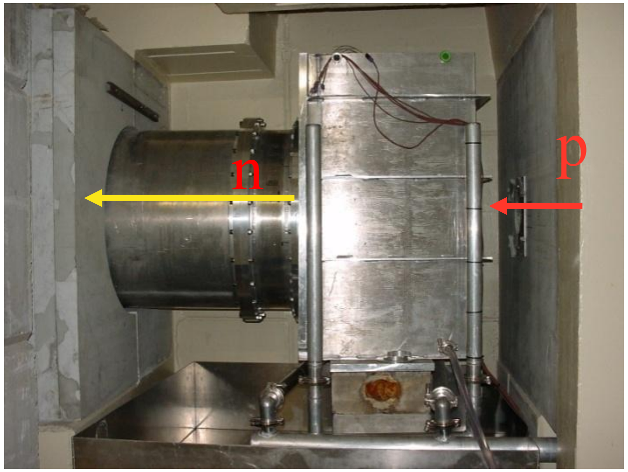
The spallation target(s)

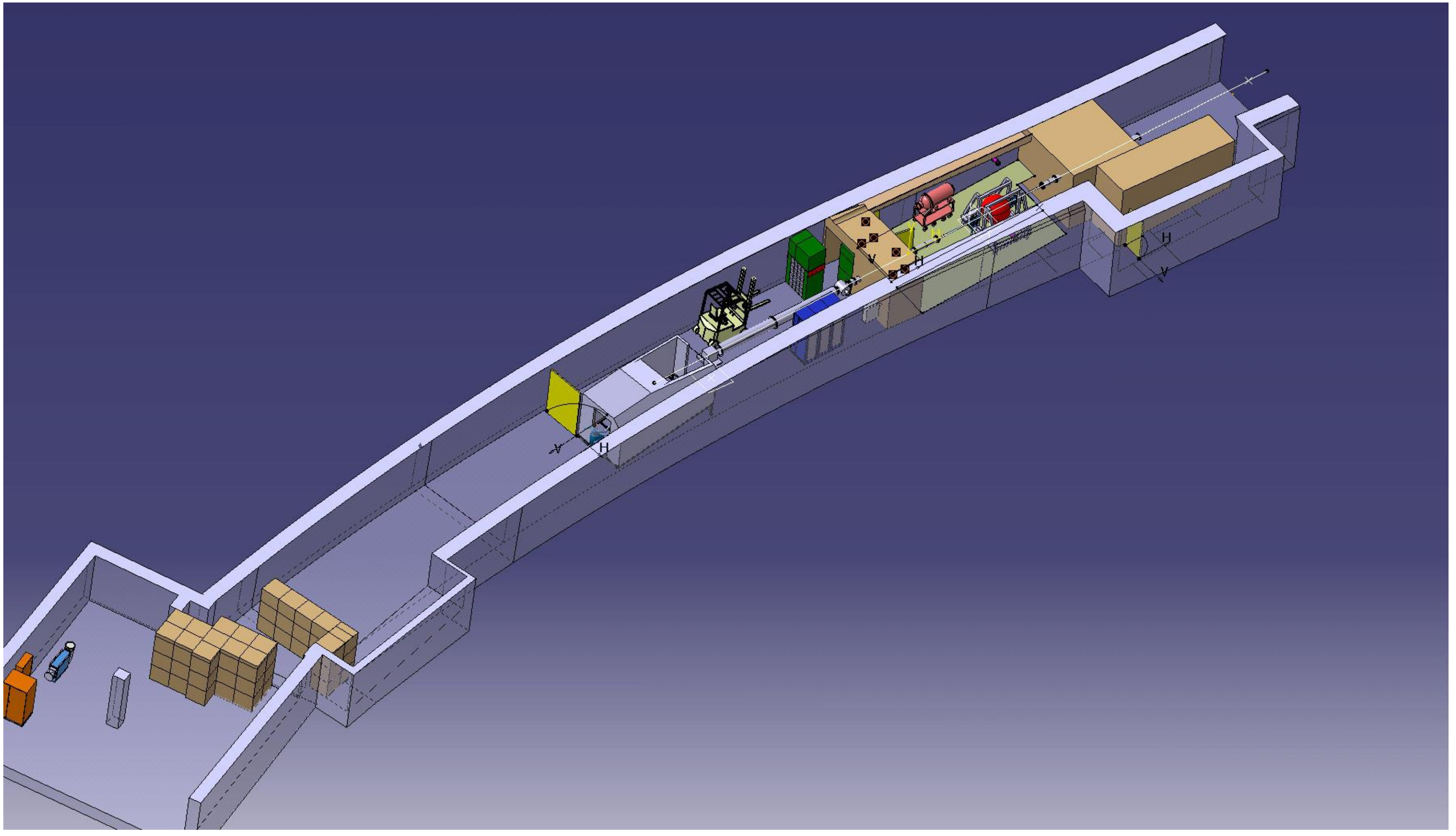
Phase 1: 2001 – 2004

Phase 2: 2008 – today

Some pictures

- Spallation target: block of Pb 80x80x40 cm^3
- Moderator: 5 cm water (used also for neutron moderation, to produce isolethargic flux)
- 200 m time-of-flight tunnel
- Walls of iron and concrete for shielding n, γ, μ, etc…
- Deflecting magnet for charged particles
- Collimators (2 cm for capture, 6 cm for fission)

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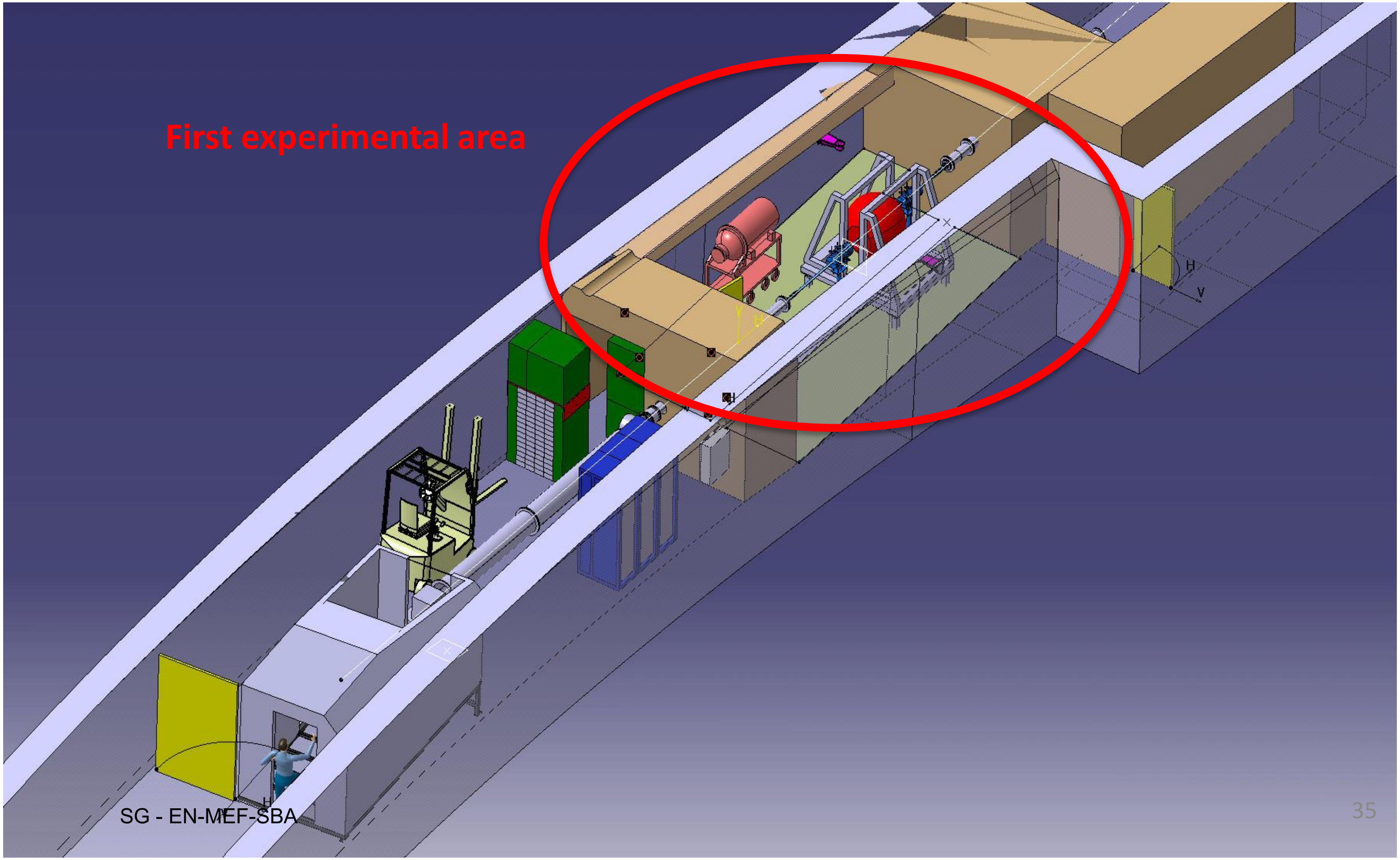
First experimental area
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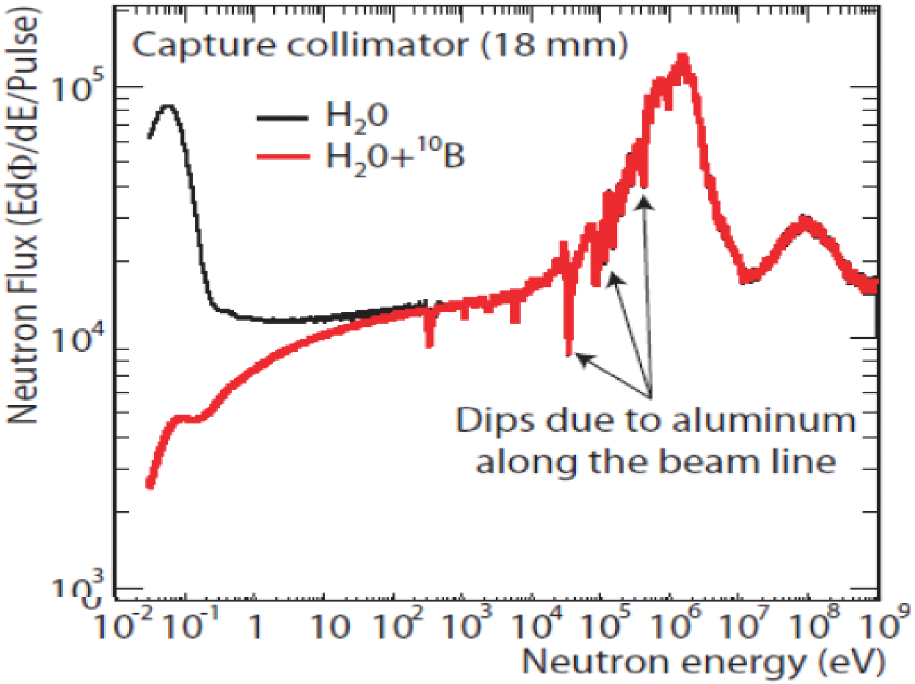
The real thing

The n_TOF facility

The advange of n_TOF are a direct consequence of the characteristics of the **PS proton beam**: **high energy, high peak current, low duty cycle.**



Main feature: **high instantaneous neutron flux** (*10^6 n/pulse).*

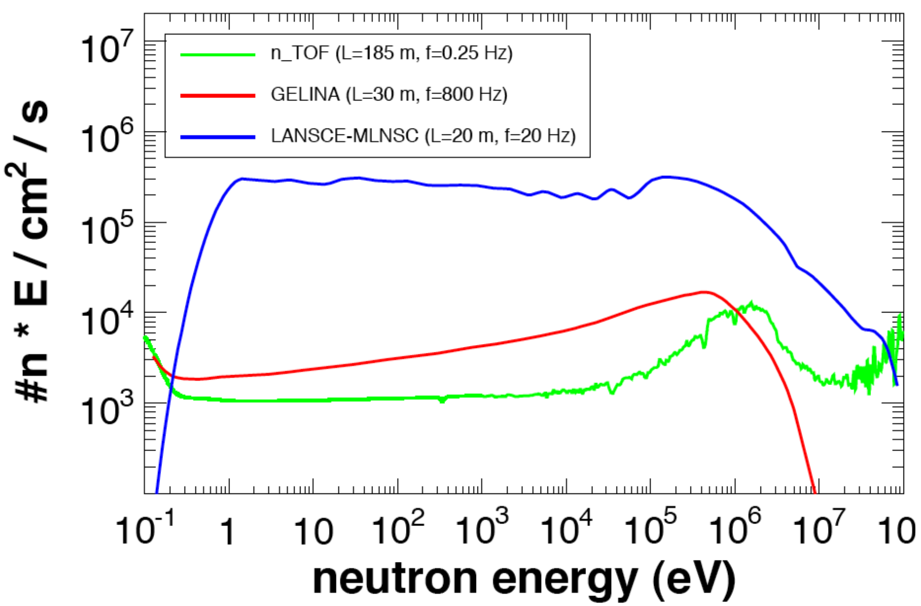
- very convenient for measurements of **radioactive isotopes** (maximizes signal-to-background ratio)
- ideal for ideal for **branching point isotopes** (Astrophysics) and **actinides** (nuclear technology)

Other features of the neutron beam:

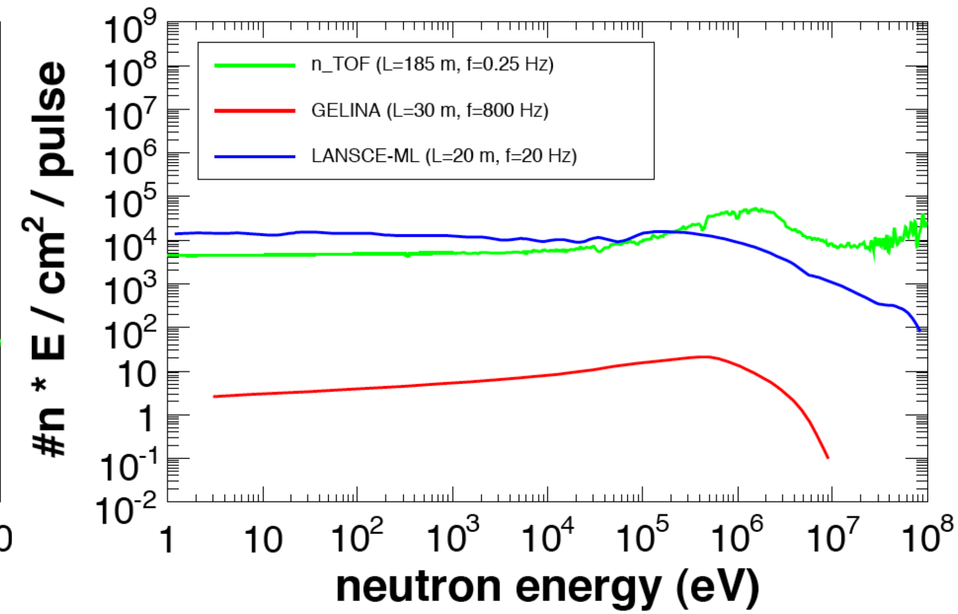
- high **resolution in energy** (*$\Delta E/E = 10^{-4}$*) .... study **resonances**
- wide **energy range** (*25 meV<E_n<1GeV*) .... all data are **collected at the same time**
- low **repetition** rate (*< 0.8 Hz*) ....no **wrap-around**

n_TOF vs other facilities

Average flux



Instantaneous flux



Innovative facility, allows to:

- measure **radioactive isotopes** (actinides)
- extend the **resolved resonance** region to **higher energy**
- measure **fission up to very high energies** (at least 500 MeV)

A **second** experimental area has recently been built at **20 m** (flux x 30 !!)

The n_TOF measurements

Phase 1 (2001-2004)	Phase 2 (2009-2012)	Phase 3 (2014-today)

Phase 1 (2001-2004)

Capture

^{151}Sm

^{232}Th

$^{204,206,207,208}Pb$, ^{209}Bi

$^{24,25,26}Mg$

$^{90,91,92,94,96}Zr$, ^{93}Zr

$^{186,187,188}Os$

$^{233,234}U$

^{237}Np, ^{240}Pu, ^{243}Am

Fission

$^{233,234,235,236,238}U$

^{232}Th, ^{209}Bi, ^{237}Np

$^{241,243}Am$, ^{245}Cm

Phase 2 (2009-2012)

Capture

^{25}Mg, ^{88}Sr

$^{58,60,62}Ni$, ^{63}Ni

$^{54,56,57}Fe$

$^{236,238}U$, ^{241}Am

Fission

$^{240,242}Pu$

$^{235}U(n,\gamma/f)$

^{232}Th, ^{234}U

^{237}Np (FF ang.distr.)

(n,α)

^{33}S, ^{59}Ni

Phase 3 (2014-today)

Capture

^{171}Pm	EAR2
Ge	EAR1
^{171}Tm	EAR1
$^{203,204}Tl$	EAR2

Fission

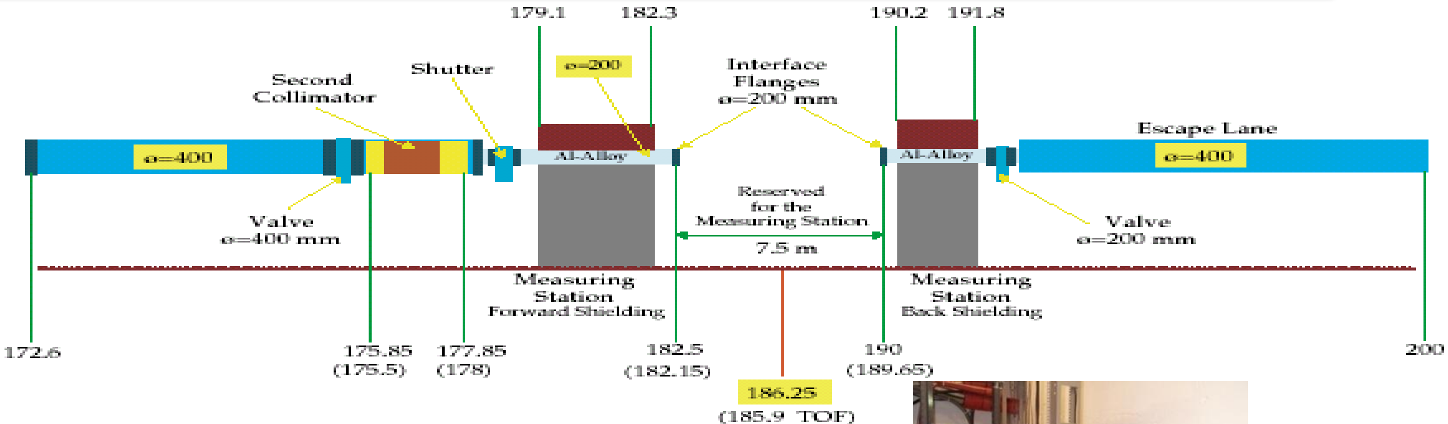
^{240}Pu	EAR2
^{237}Np	EAR1&2

Reactions (n,cp)

$^{7}Be(n,\alpha)$	EAR2
$^{33}S(n,\alpha)$	EAR2

The n_TOF experimental set-ups

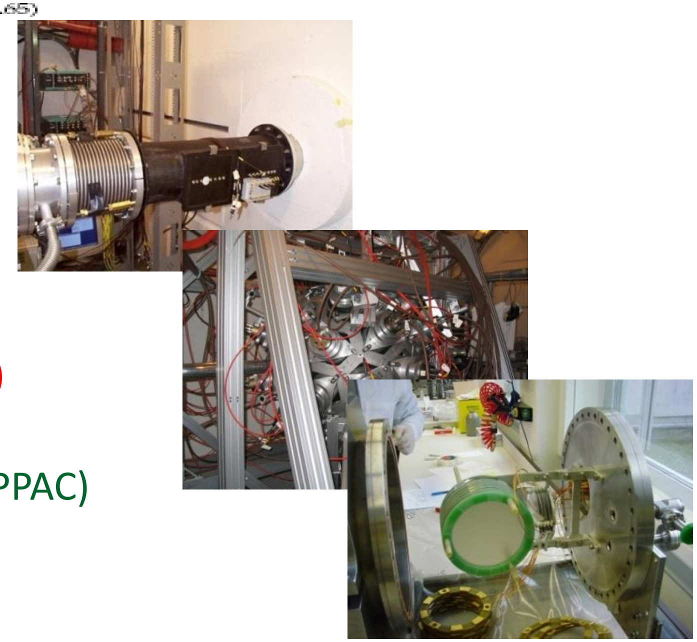
Experimental area located at 180 mt from spallation target



Neutron flux monitor
- Silicon detectors (SiMon)
- Micromegas detectors

Capture detectors
- C_6D_6 liquid scintillator detectors
- Total Absorption Calorimeter (BaF_2)

Fission detectors
- Parallel Plate Avalanche Counters (PPAC)
- Fission Ionization Chamber (FIC)
- Micromegas detectors



The fission detectors

General concepts:

- Fission cross-sections are measured by detecting **fission fragments**
- Two methods: **single** fragment or **coincidence**
- Several **choices of detectors**

Cross-sections measured **relative to a reference**:

- isotopes with **well-known cross-sections** (some are defined **"standards"**)
- $^{235}U(n,f)$, $^{238}U(n,f)$, $^{209}Bi(n,f)$, ^{239}Pu, $H(n,n)$

Ratio measurements minimize systematic uncertainties (in principle down to a few percent)

The reference reactions (cross-section standards)

Neutron cross-section **"standards"** are very important, since avoid need of absolute measurements of neutron flux. Widely used to normalize cross-section data.

Some reactions **have gained** the status of "standards", since their cross-sections in the years have been determined **very accurately**.

Cross-section standards based on a **large number of experimental data**, and on evaluations (specific committee are set-up to this purpose IAEA-CRP, NEA-WPEC, CSEWG)

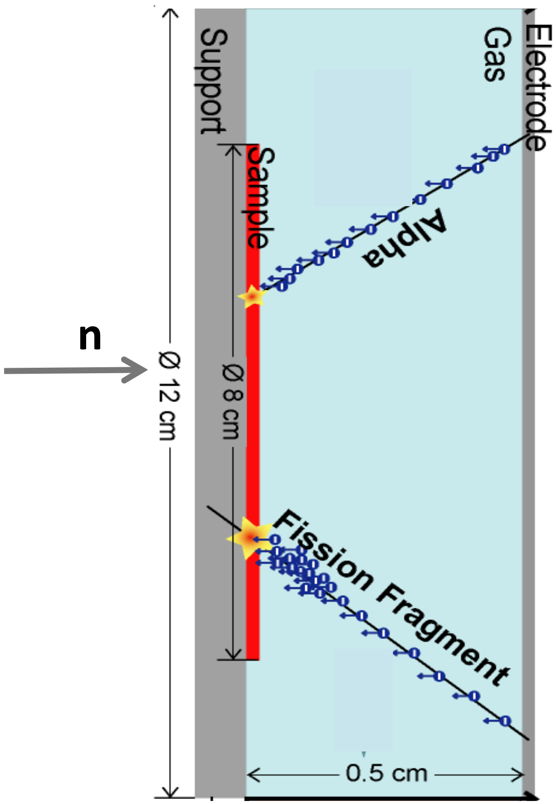
Reaction	Energy range
H(n,n)	1 keV – 20 MeV
^{3}He(n,p)	25.3 meV – 50 keV
^{6}Li(n,t)	25.3 meV – 1 MeV
^{10}B(n,α)	25.3 meV – 250 keV
C(n,n)	up to 1.8 MeV
Au(n,γ)	25.3 meV and 0.2 – 2.5 MeV
^{235}U(n,f)	25.3 meV and 0.15 eV – 200 MeV
^{238}U(n,f)	2 – 200 MeV

In fission measurements most common references are **^{235}U** or **^{239}Pu**.

Reference samples are measured simultaneously (in the same detector) to:

- eliminates the need for many **corrections** (see later)
- **minimizes** uncertainties

The fission chamber



Fission Chamber is the most common detector used for fission cross-section measurements:

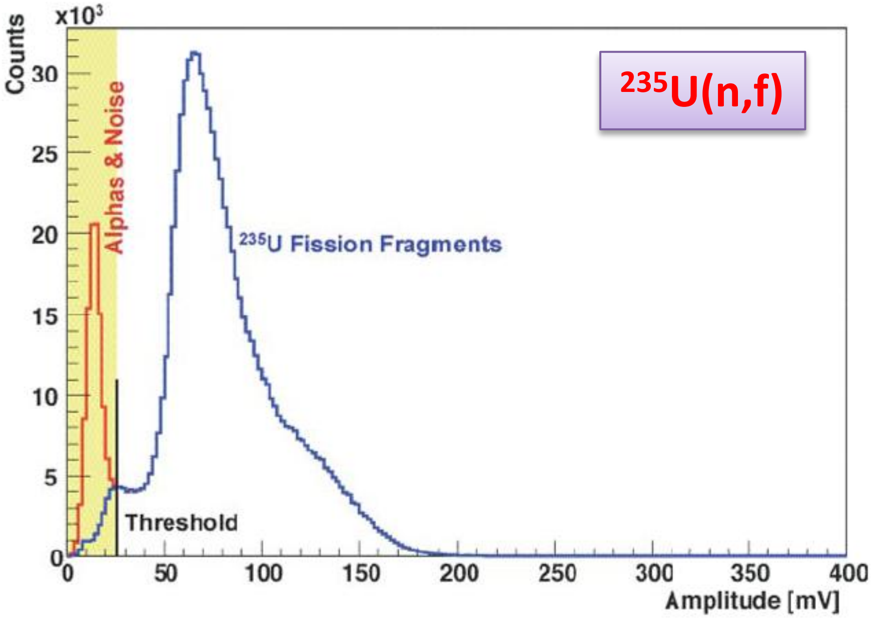
- easy to build and operate
- **high** efficiency (close to 100 %)
- good **background rejection** capability

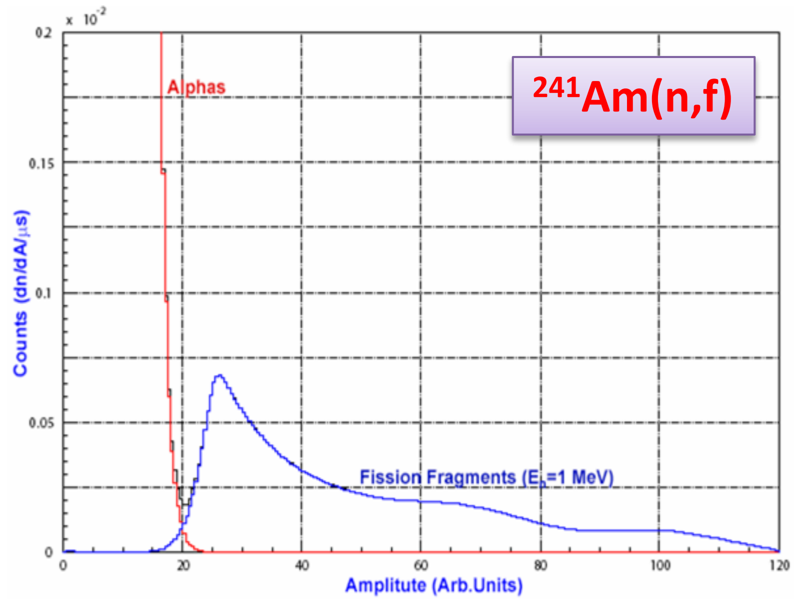
How does it work:

- **two parallel electrodes**, with gas in between (typically at atmospheric pressure)
- Sample attached (or deposited) on one electrode
- Usually contains sample of interest + reference (^{235}U, ^{238}U, …)
- Often used for neutron flux measurements and monitoring

Only one fragment per event is detected, the second one is absorbed in the backing

Amplitude distribution in fission ionization chamber





For ^{235}U, easy to reject α-background, simply by chosing a proper amplitude threshold.

For high-radioactivity sample, in theory, still good separation FF (see for example a 250 MBq ^{241}Am target).

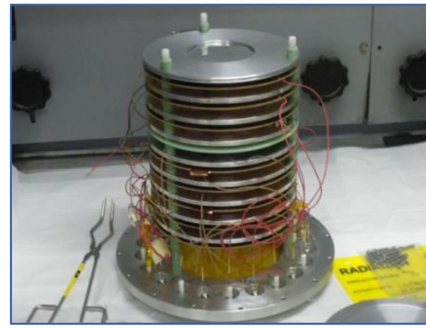
However, problems with detector response and pile-up of signals.

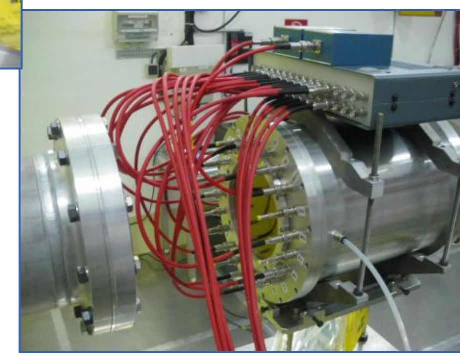
The fission experimental setups at n_TOF

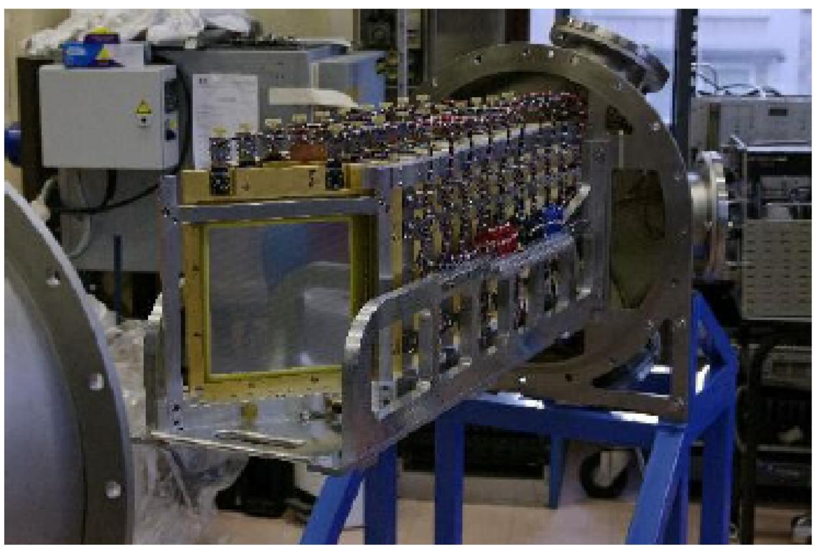
Over the years, **several systems** have been used for detecting fission fragments, with **two different techniques**.

Micromegas chamber

- low-noice, high-gain, radiation-hard detector







Parallel Plate Avalanche Counters (PPAC)

- Fission fragments detected **in coincidence**
- Very good rejection of **α-background**
- Low sensitivity to **γ-flash**
- **Position sensitive** to measure angular distribution

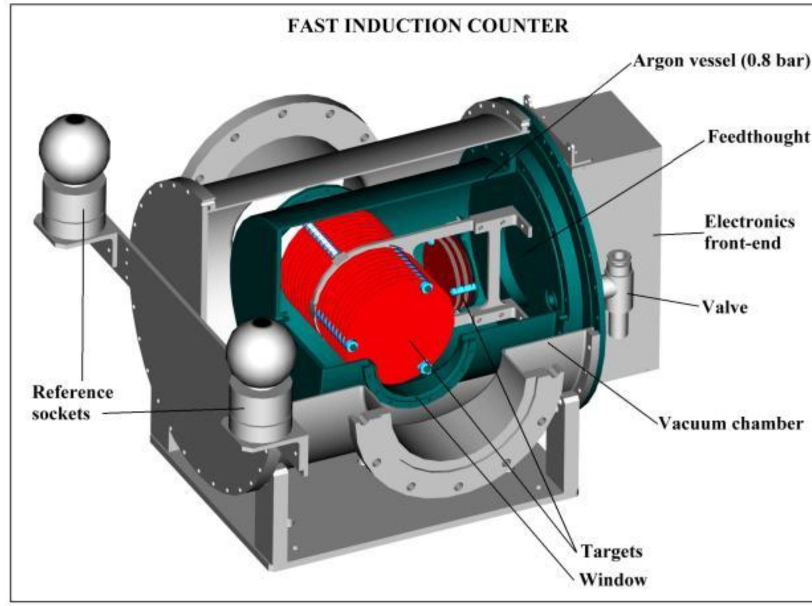
The n_TOF fission chamber (FIC)

The detector is a stack of 16 ionization chambers mounted along the beam direction.

Mounted together to allow the simultaneous measurement of fission cross sections for various isotopes:

- 13 chambers in the beam
- 3 chambers normal to beam

Developed by CERN, JINR (Dubna), IPPE (Obninsk) and INFN



Gas	Ar (90%) + CF4 (10%)
Gas pressure	720 mbar
Electric field	600 V/cm
Sample diameter	8 cm
Sample thickness	4-450 $\mu g/cm^2$
Backing thickness	100 μm
Sample uniformity	5-10 %

The Fission Ionization Chamber at n_TOF

FIC1 – sealed source ISO2919
$^{233,235,238}U$, $^{241,243}Am$ ^{245}Cm

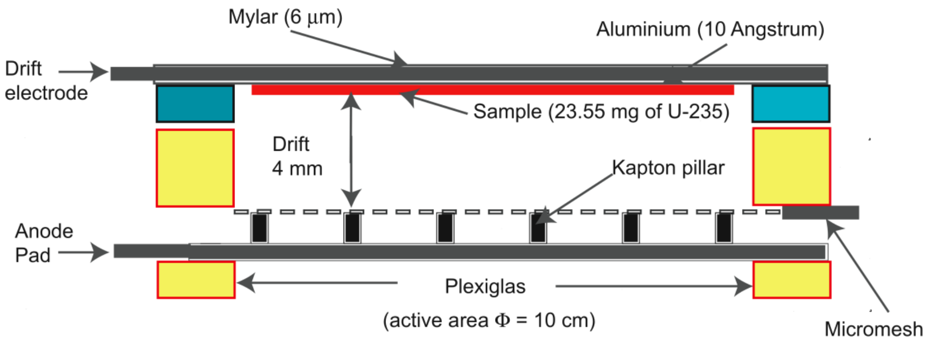
FIC2 – low activity isotopes
$^{235,238}U$

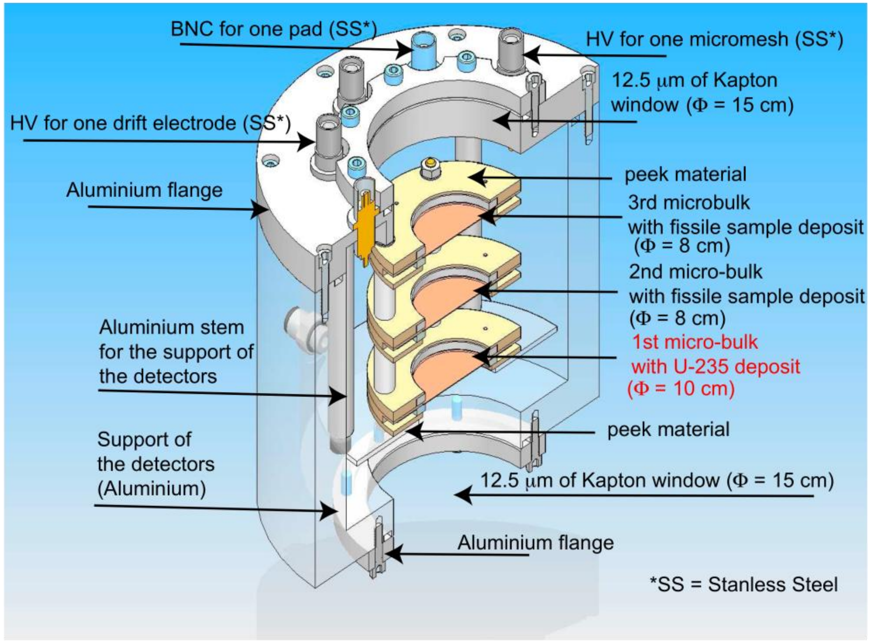
- Large samples and neutron beam (8 cm diameter collimator) for count-rate optimization
- Background from scattered neutrons measured with off-beam samples
- Background from α-decay measured with beam off

The MicroMegas detector

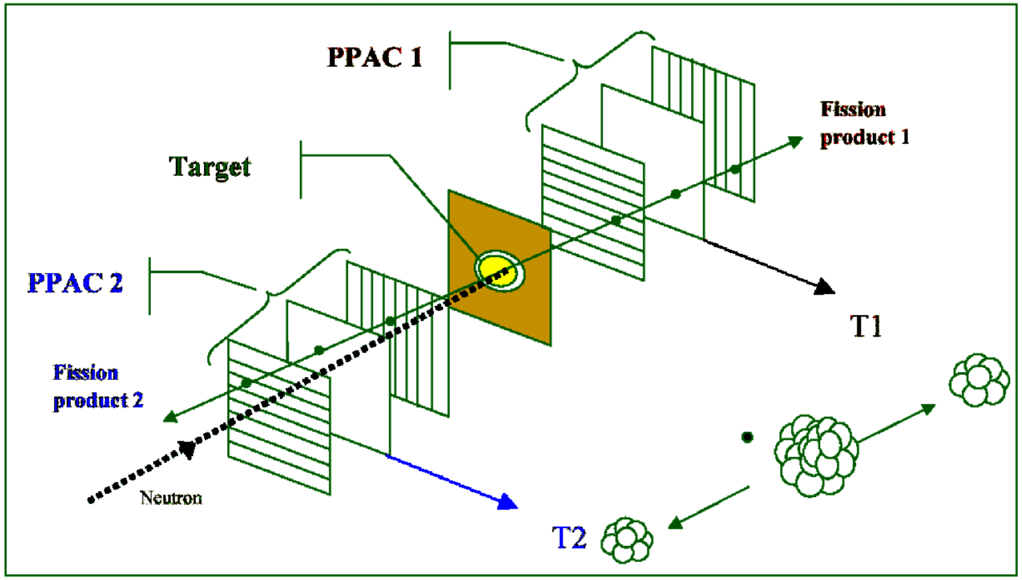
Micromegas chamber

- low-noice, high-gain, radiation-hard detector



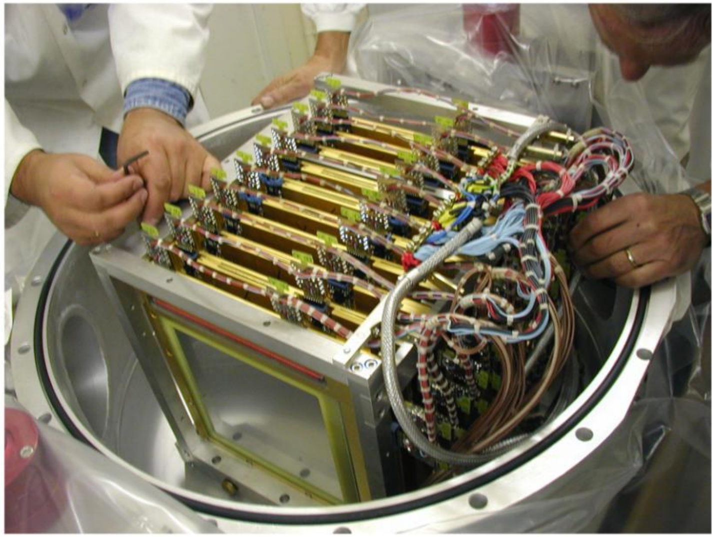


The coincidence method (PPAC)



Parallel Plate Avalanche Counters:

- both fission fragments detected, **in coincidence**
- very good **rejection** of alpha background
- fast timing (0.5 ns resolution)
- require **very thin samples** and **very thin backing**



Measured isotopes at n_TOF:

- **^{235}U, ^{238}U** (standard of measurement)
- **^{233,234}U, ^{232}Th** (Th/U fuel cycle)
- **^{237}Np** (transmutation and Gen IV fast reactors)
- **^{209}Bi, ^{nat}Pb** (spallation target)

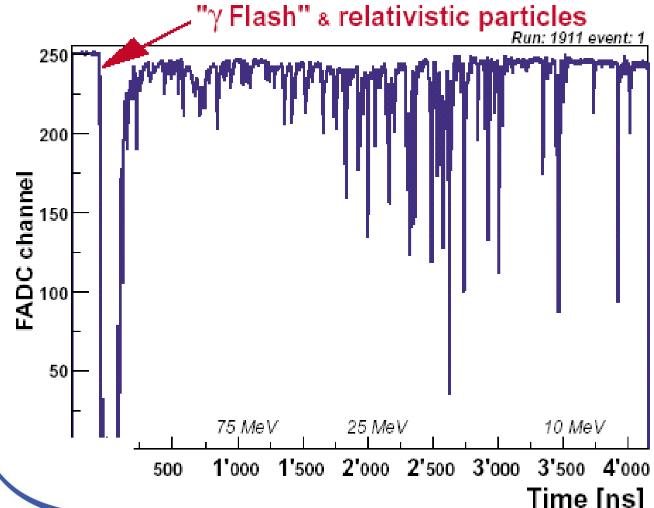
The n_TOF data acquisition system

High instantaneous neutron flux ➡ high probability of pile-up between signals

Standard DAQ methods are inadequate

n_TOF DAQ entirely based on Flash ADC

- Up to 1 GSample/s (500 MHz bandwidth), 16 MB buffer memory
- Software Zero suppression
- Commercially available in compact_PCI standard (from Acqiris and ETEP)



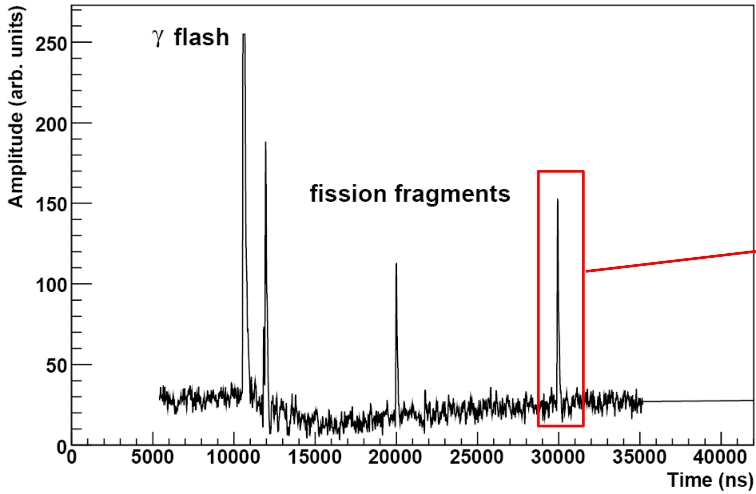
Offline signal reconstruction for time and charge information

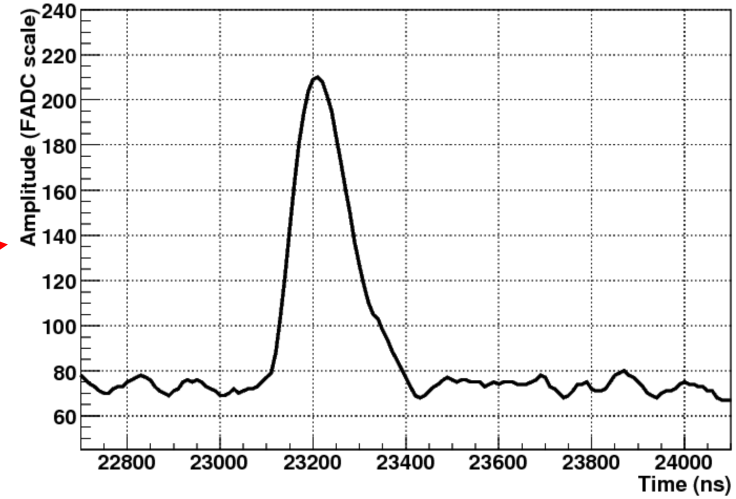
- Simple algorithm for a single signal
- Fitting procedure for pile-up events

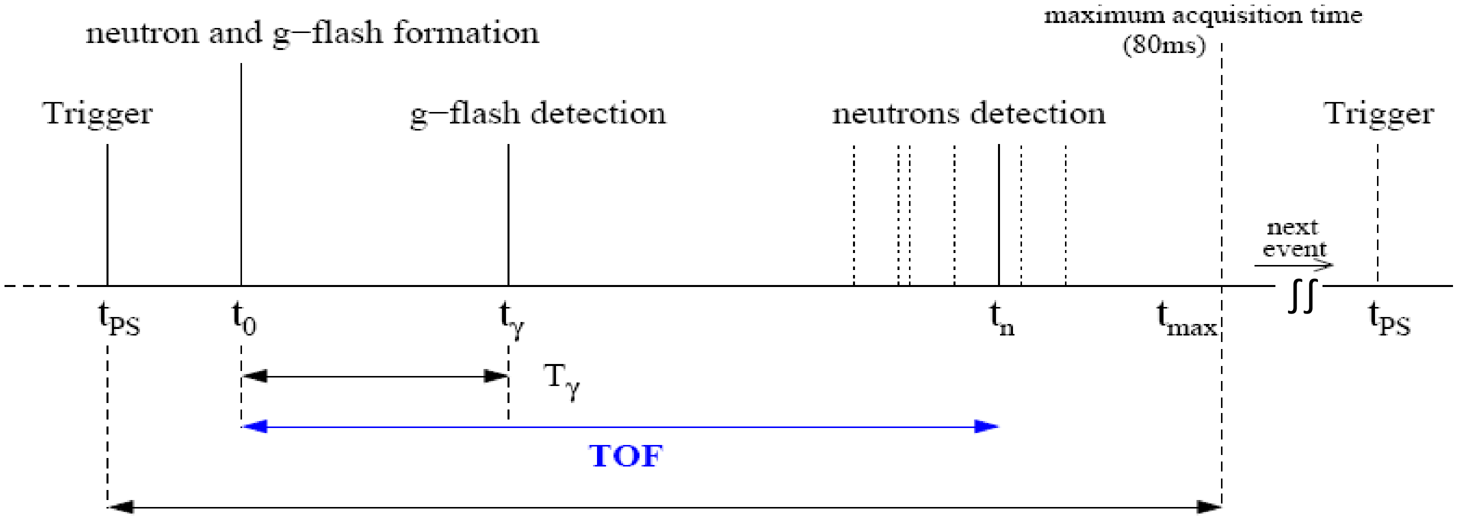
R.Plag et al., Nucl. Instr. And Meth. A538 (2005) 692

Data analysis

Time-of-flight reconstruction





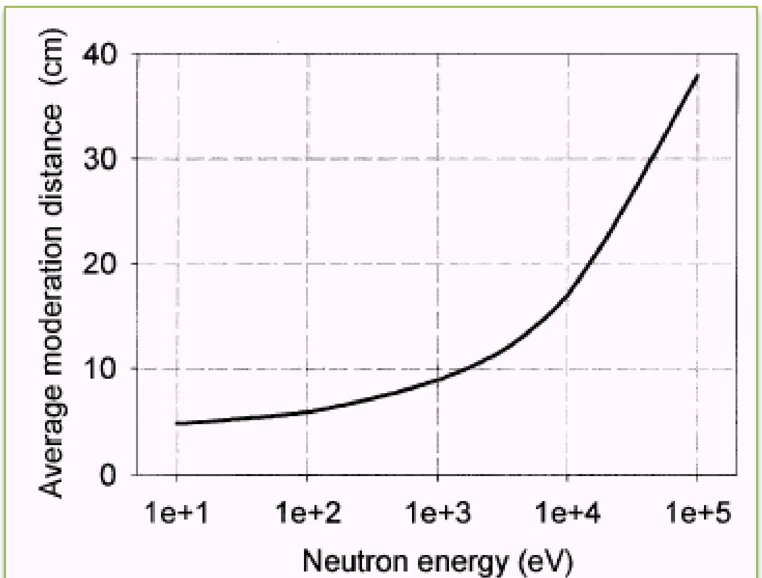


Calibration of neutron energy in ToF measurements

The neutron energy (at low energy) is determined from the time-of-flight according to:

$$E = \left(\frac{72.2977 \cdot L}{ToF - T_c} \right)^2$$

L = flight path length
ToF = time of flight
T_c=correction term



The "time-start" (or **physical reference** t_0) for the time-of-flight is typically given by a **"prompt flash"** (γ-rays, high-energy charged particles, etc…).

In **moderated** neutron beams, L does not coincide with the **geometric distance** from neutron source, since neutrons **travel** some distance inside the target/moderator.

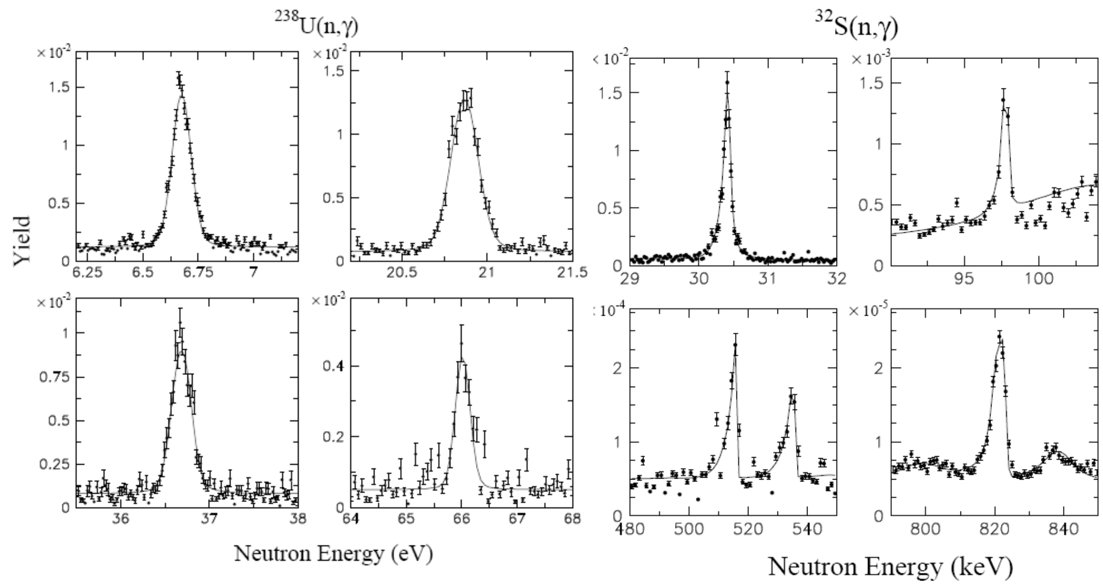
The "moderation distance" **v·t** depends on the neutron energy (t=moderation time).

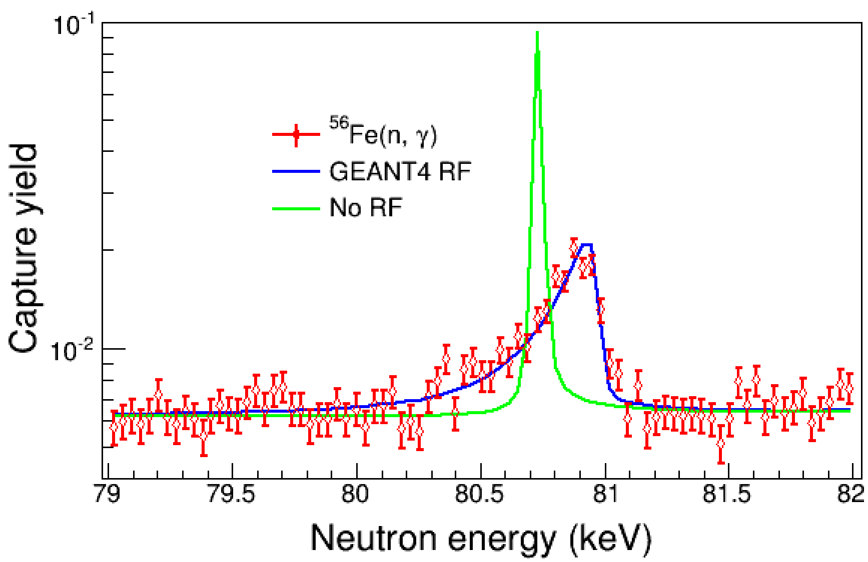
Necessary to calibratate the neutron energy with respect to energy standards

Time-to-energy calibration and Resolution Function

"To calibrate" the neutron energy from the time-of-flight means to find the **"effective flight path length"** (geometrical + moderation distance)

To this purpose, **resonances with well known energy** have to be used.



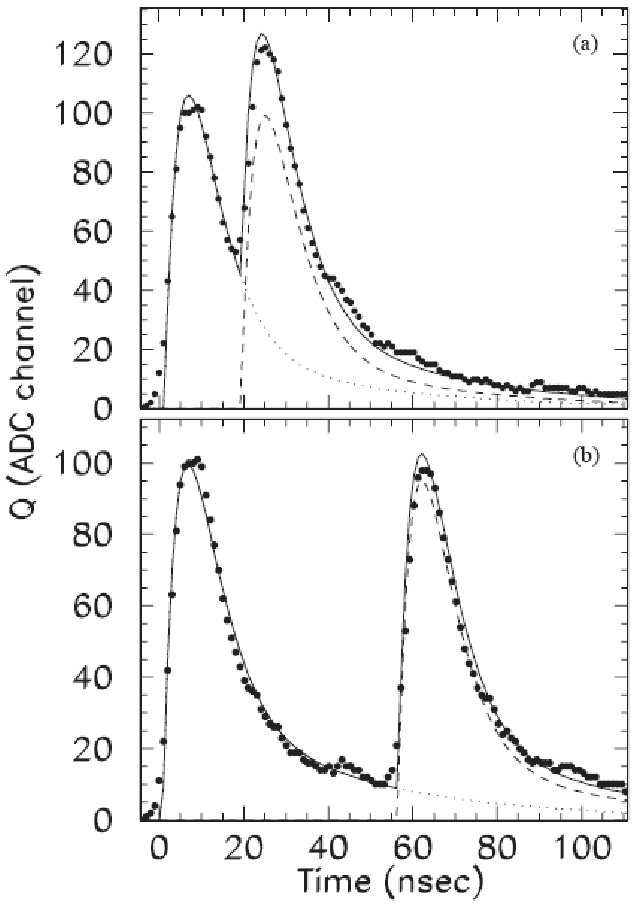


When analysing resonances, it is extremely important to take into account the **"resolution function"** of the neutron beam (as well as Doppler broadening).

Resolution function: **neutron energy distribution** for a given time-of-flight

Can be determined from **simulations of the spallation process**

Signal pile-up



Two signals close in time give **pile-up.**

If not minimized, pile-up may result in **loss of events** (one signal instead of two)

LOSS OF EFFICIENCY

Pile-up probability function of **count-rate.** It depends on:

- sample **thickness** and **cross-section**
- neutron flux
- detector **time-response**

Even in ratio measurements, a **correction** is needed (pile-up may be different for sample and reference, if different count-rate).

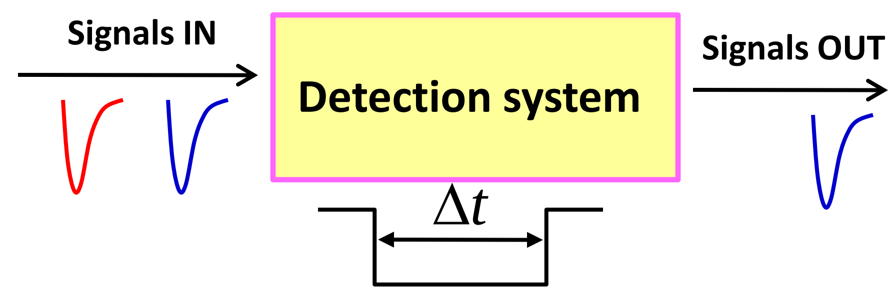
Problem minimized by using **Flash ADC**

The problem of dead-time

When the detector or **electronics or DAQ is busy** processing an event, if a new one occurs it is LOST

⇓

LOSS OF EFFICIENCY



The number of **events lost** depends on:

- count rate (C_m)
- dead-time (Δt)

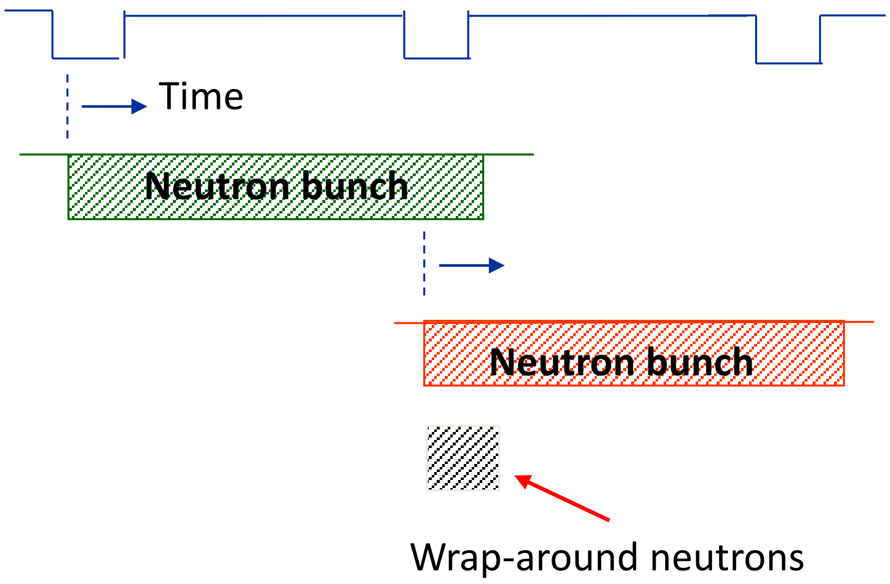
$$C_R = \frac{C_m}{1 - C_m \cdot \Delta t}$$

C_m measured count-rate
C_R true count-rate
ΔT dead-time

In traditional data acquisition systems, the **dead-time** is typically of the order of **μs** (or hundreds of μs). In new systems, based on Flash ADC, much smaller (**tens of ns**).

As for pile-up, the dead-time may be different for sample and reference (different count-rates) . A correction needs to be applied !!

Background due to wrap-around



Low energy neutrons from one pulse may arrive at the fission detector at the same time as high energy neutrons from the next pulse.

Pulse overlap causes background (important for some samples):

- high fission cross-section at low energy results in a large number of events contaminating the high-energy part

Two possibility:

- measurements **with filters** (to cut low-energy neutrons)
- **increase the spacing** between pulses (see n_TOF)
- determine the background with **"threshold" isotopes** (like ^{238}U)

Measurements of fission cross section: the ratio method

Number of counts at E_n

Background

$$\sigma_f(E_n) = \frac{C_{^AX}(E_n) - B_{^AX}(E_n)}{\Phi(E_n)\cdot N_{^AX}\cdot\varepsilon\cdot cf}$$

Neutron flux

Atoms/barn of the sample

Efficiency

Other correction factors (dead-time, …)

^AX sample being investigated

E_n neutron energy

$$ratio(E_n) = \frac{C_{^AX} - B_{^AX}}{\Phi(E_n)\cdot N_{^AX}\cdot\varepsilon_{^AX}\cdot cf_{^AX}} \Bigg/ \frac{C_{^{235}U} - B_{^{235}U}}{\Phi(E_n)\cdot N_{^{235}U}\cdot\varepsilon_{^{235}U}\cdot cf_{^{235}U}}$$

$$ratio(E_n) = \frac{C_{^AX} - B_{^AX}}{C_{^{235}U} - B_{^{235}U}} \cdot \frac{N_{^{235}U}\cdot\varepsilon_{^{235}U}\cdot cf_{^{235}U}}{N_{^AX}\cdot\varepsilon_{^AX}\cdot cf_{^AX}}$$

In the ratio, the neutron flux cancels out

“How to” in fission measurements

$$\sigma_f\left({}^{A}X, E_n\right) = \text{ratio}(E_n)\cdot\sigma_f\left({}^{235}U, E_n\right)$$

Standard cross-section used as reference (from evaluated data file)

Measured quantity

$$\text{ratio}(E_n) = \frac{C_{{}^{A}X} - B_{{}^{A}X}}{C_{{}^{235}U} - B_{{}^{235}U}} \cdot \frac{N_{{}^{235}U}\cdot\varepsilon_{{}^{235}U}\cdot cf_{{}^{235}U}}{N_{{}^{A}X}\cdot\varepsilon_{{}^{A}X}\cdot cf_{{}^{A}X}}$$

Calculated quantity: (areal density, efficiency, dead-time, anysotropy, …)

Things to **remember** about the use of ^{235}U (or ^{239}Pu) as reference samples:

- reference samples typically mounted inside the **same chamber** for same efficiency
- all samples with the **same area** to avoid correction for the flux interception
- if possible, **same thickness**, to minimize efficiency corrections (ε)
- approximately **same count-rate**, to minimize dead-time correction (cf)
- need to correct for **anysotropy** in angular distribution of fission fragments (particularly important at high energy). Included in the factor cf.

Source of uncertainties

Main **issues in fission** cross section measurements:

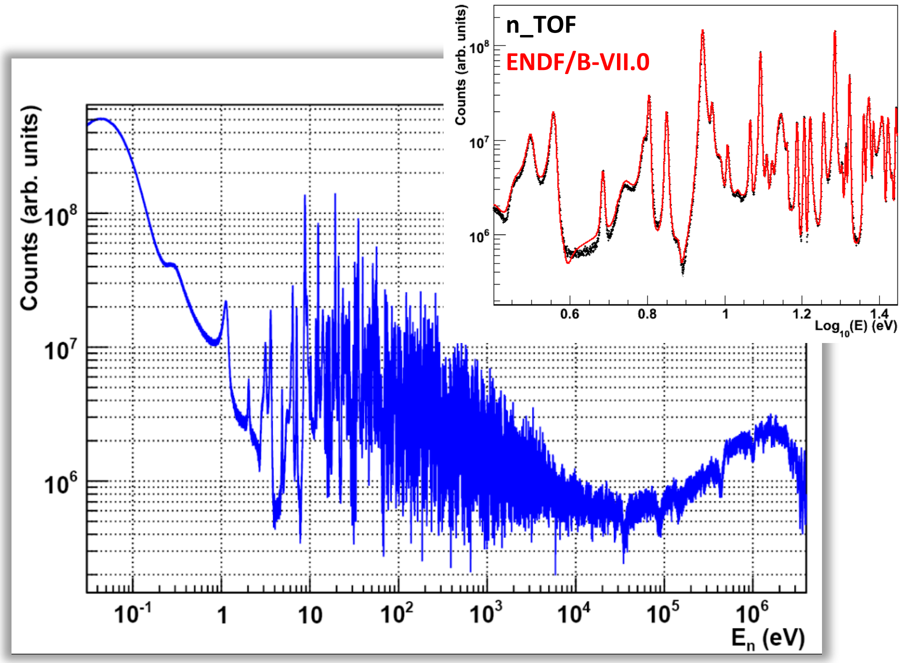
- **areal density** and **uniformity** of samples
- presence of **contaminants** in the sample
- **background** rejection and/or subtraction (*in particular* α*-background*)
- **efficiency** and **dead-time** corrections
- **wrap-around** neutrons (*not at n_TOF*)

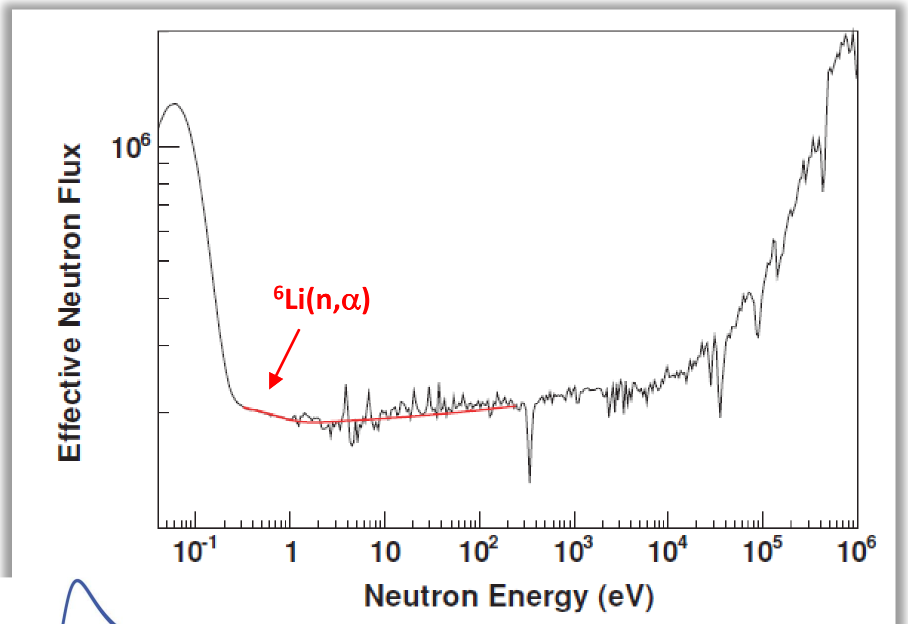
Ideally one needs (apart for a good quality neutron beam):

- samples with adequate mass, purity and uniformity
- fast detectors
- accurate knowledge of detection efficiency

The problem of the ^{235}U reference

Reaction	Energy range
^{3}He(n,p)	25.3 meV – 50 keV
^{6}Li(n,t)	25.3 meV – 1 MeV
^{10}B(n,α)	25.3 meV – 250 keV
Au(n,γ)	25.3 meV and 0.2 – 2.5 MeV
^{235}U(n,f)	**25.3 meV and 0.15 – 200 MeV**
^{238}U(n,f)	2 – 200 MeV





In the **Resolved Resonance Region** the ratio method cannot be applied.

Use the neutron flux determined with **^{6}Li(n,t)** or **^{10}B(n,α)** reactions (smooth cross sections)

Possible sources of background

Several sources of background may affect the measurements of fission cross-sections:

- electronic noise ………………………………………………………
- α-particle from radioactive decay of samples ……………
- spontaneous fission …………………………………………………
- ambient neutrons ……………………………………………………………………………
- neutrons scattered from the detector and surrounding material ……
- wrap-around neutrons ………………………………………………… **measured with filters**
- resolution function …………………………………………………… **simulations (mainly)**

(electronic noise, α-particle from radioactive decay of samples, spontaneous fission: **runs with no beam**)

(ambient neutrons, neutrons scattered from the detector and surrounding material: **sample outside beam**)

It is preferable to try and **minimize** all possibile sources of background, to increase signal-to-background ratio and minimize uncertainty on background subtraction:

- **high neutron flux** (to minimize ambient background and natural radioactivity)
- minimize **mass** of the detector and surrounding material (for neutron scattering)

Uncertainty analysis

When extracting the fission cross-sections with ratio method, **uncertainties** related to:

• **mass** of the sample and of the reference	typically, 1 %
• presence of other isotopes (**contaminants**) in the samples	depends on the sample
• **background** subtraction	depends on the sample
• **wrap-around** neutrons	depends on the facility
• **efficiency** and **dead-time** corrections	depends on detector
• neutron beam **attenuation**	depends on set-up
• **evaluated cross-sections** used as reference	typically, 1-3 %

In addition, other possible sources of uncertainty are:

- sample **non-uniformity** (combined with beam non-uniformity)
- **misallignement** between sample and reference (don't intercept the same neutron flux)

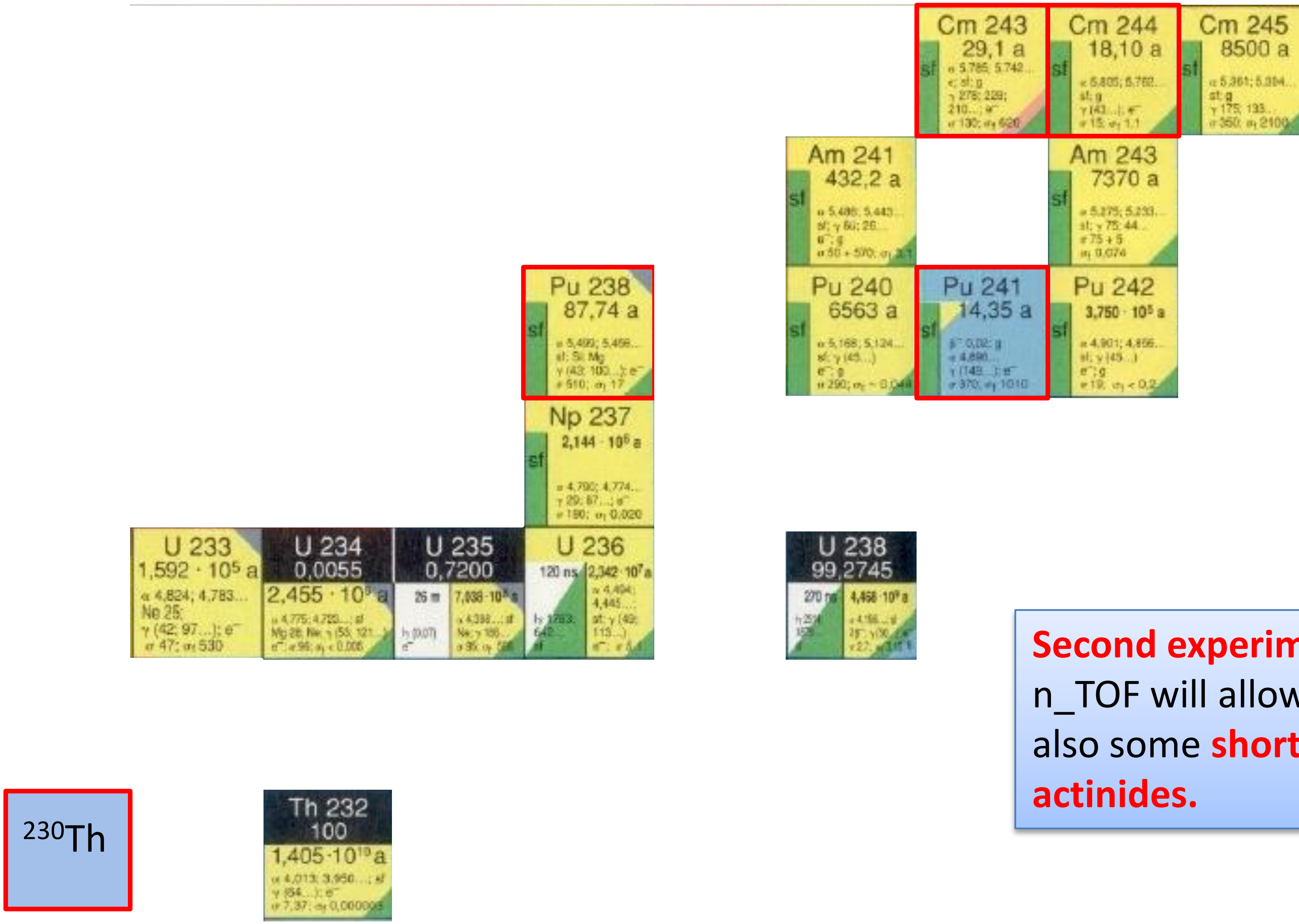
Results

Measured fission reactions

In the two experimental campaigns, measured capture and fission cross sections for **most long-lived actinides** (432 y and above).

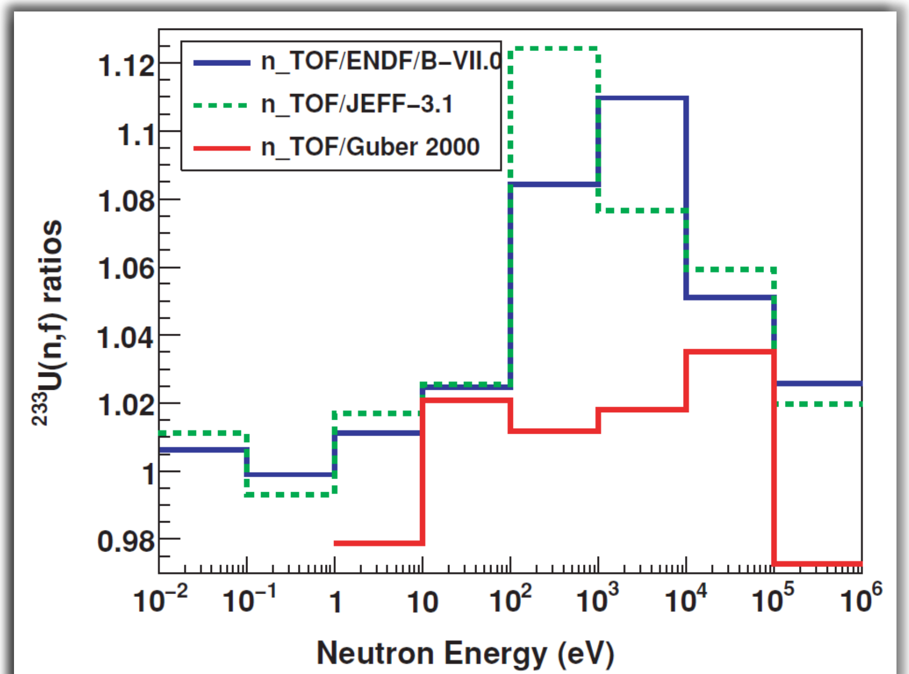
For some of them, measured FF anysotropy as well.

More to be measured



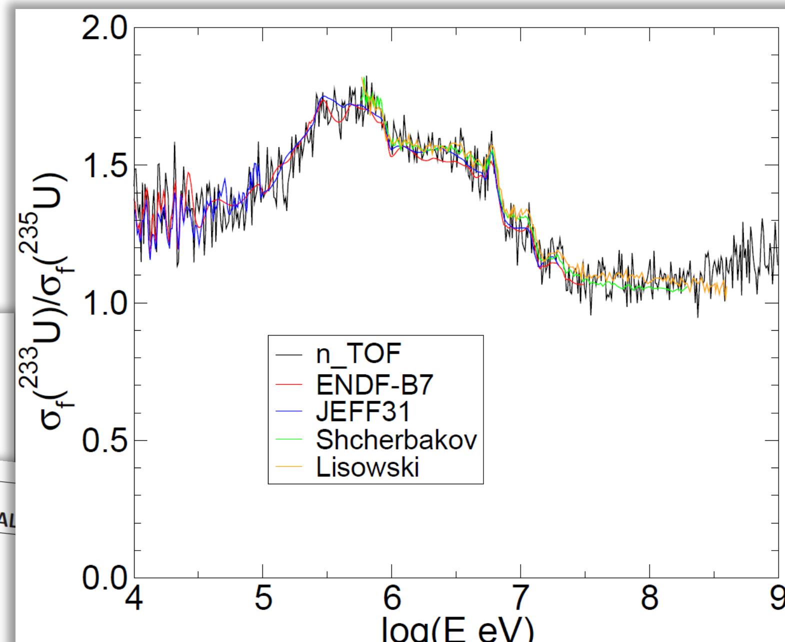
Second experimental area at n_TOF will allow to measure also some **short-lived actinides.**

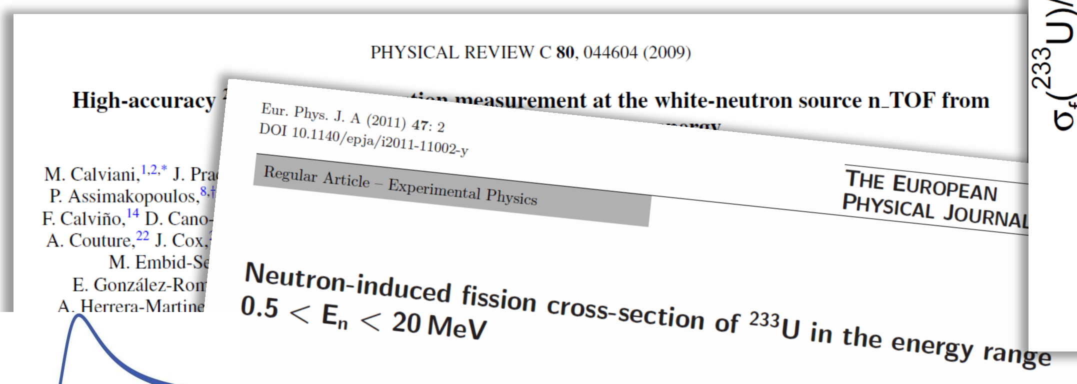
The ^{233}U(n,f) cross section



Half-life: **1.59x10^5 y**
Sample: **29 mg (/4)**
Activity: **2.6 MBq** (each sample)

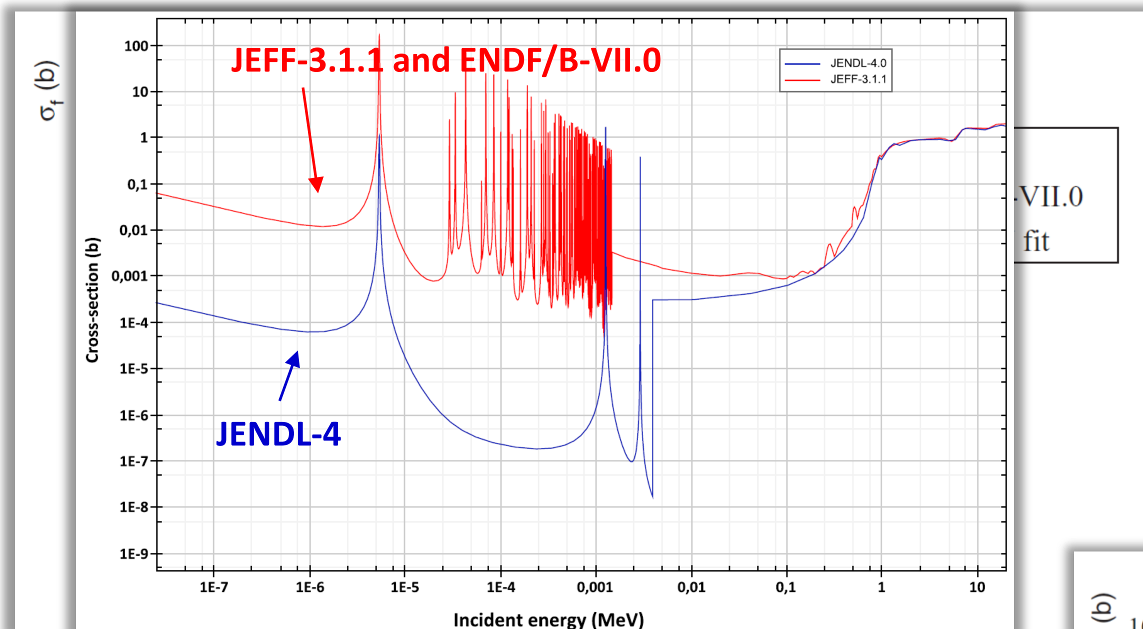
Fission cross-section on ^{233}U measured in a single measurement from thermal to 20 MeV, with **5 % accuracy, and high resolution**.





nTOF

The fission cross-section of ^{236}U



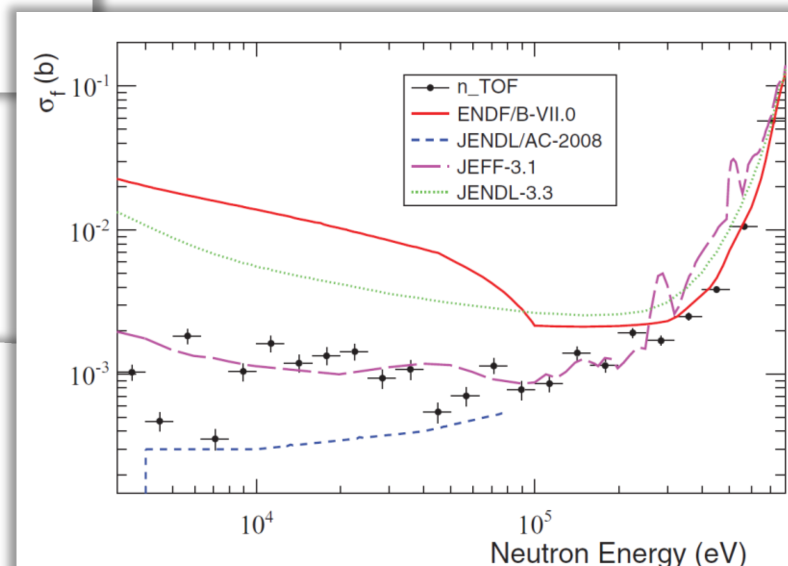
Half-life: **2.34x10^7 y**
Sample: **21.4 mg (/4)**
Activity: **13 kBq** (each sample)
Contamination of **^{235}U 0.05%**

n_TOF data **confirm** results from GELINA (C. Wagemans et al.).

Below a few keV, **ENDF and JEFF overestimate** cross section (x100).

Resonances in ENDF and JEFF are **from ^{235}U** !!

JENDL-4 is (mostly) correct



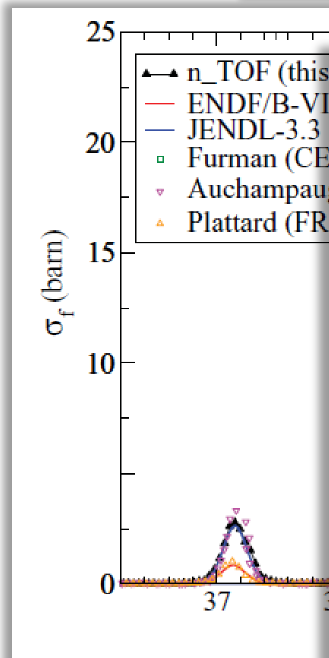
PHYSICAL REVIEW C **84**, 044618 (2011)

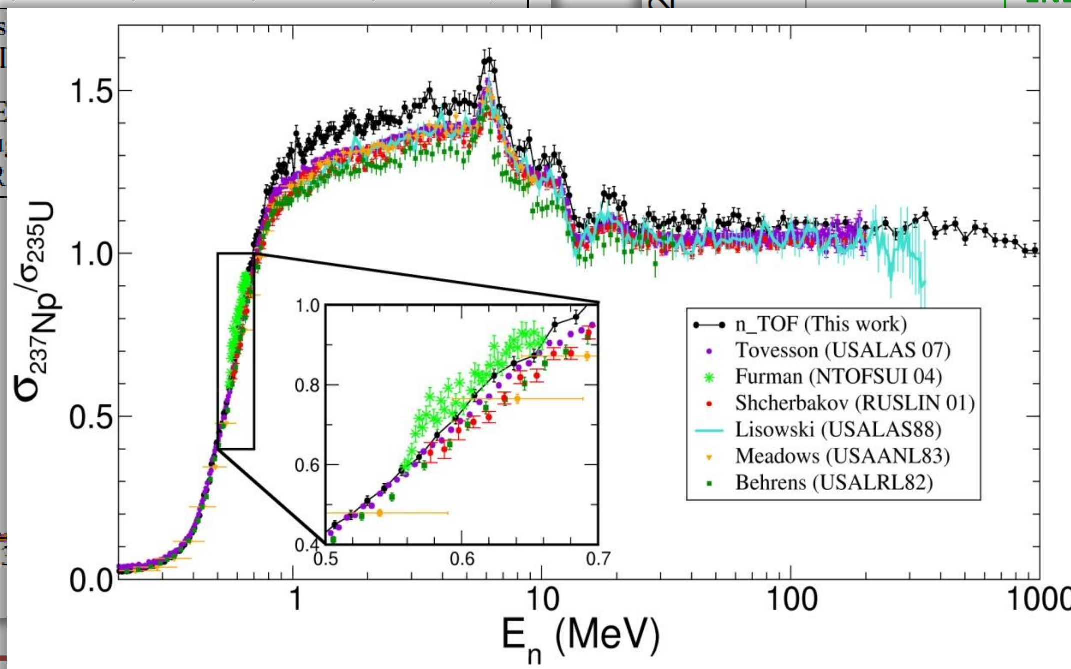
Measurement of the ^{236}U(n,f) cross section from 170 meV to 2 MeV at the CERN n_TOF facility

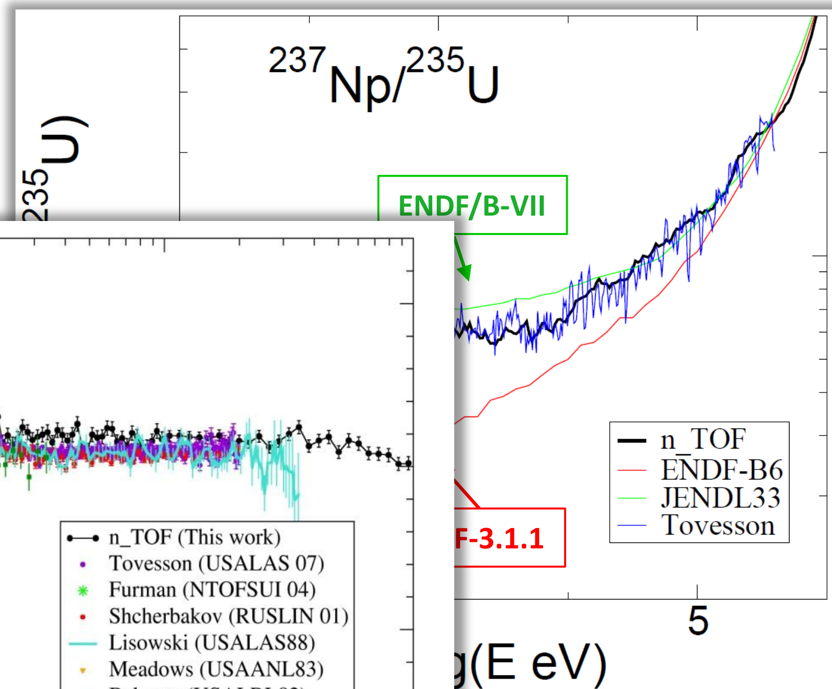
R. Sarmento,[1] M. Calviani,[2] J. Praena,[14] N. Colonna,[3] F. Belloni,[4] I. F. Gonçalves,[1] P. Vaz,[1] G. Aerts,[17] H. Alvarez,[26] F. Alvarez-Velarde,[5] S. Andriamonje,[2] J. Andrzejewski,[6] P. Assimakopoulos,[7] L. Audouin,[8] M. Barbagallo,[3] G. Badurek,[9] P. Baumann,[10] F. Becvar,[11] E. Berthoumieux,[17] F. Calvino,[12] D. Cano-Ott,[5] R. Capote,[13,14] C. Carrapiço,[1] A. Carrillo de Albornoz,[1] P. Cennini [15] V. Chepel,[16] E. Chiaveri,[2] G. Cortes,[18] A. Couture,[19] J. Cox,[19] M. Dahlfors,[15] S. David,[8] M. Diakaki,[34] ...,[21] C. Domingo-Pardo,[22] W. Dridi,[17] I. Duran,[26] C. Eleftheriadis,[23] L. Ferrant,[8] A. Ferrari [15] ...rais-Koelbl,[13] K. Fuji,[4] W. Furman,[24] E. Gonzalez-Romero,[5] ...ero,[5,2] E. Gunsing [17] ...

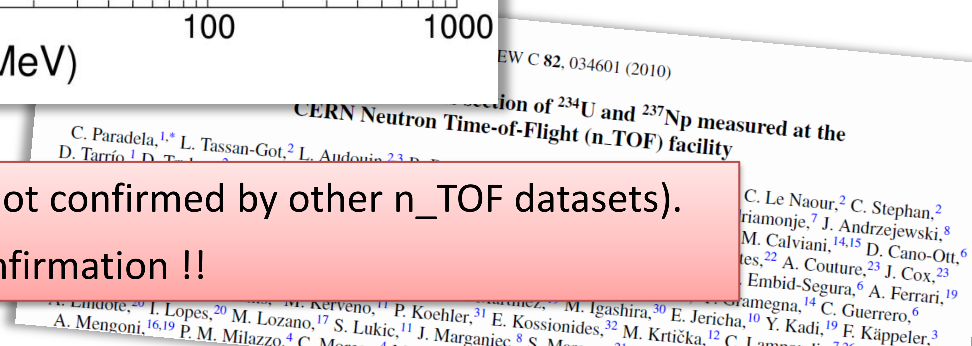
The ^{237}Np(n,f) reaction

Half-life: **2.14x10^6 y**
Sample: **63 mg (/4)**
Activity: **0.41 MBq** (each sample)









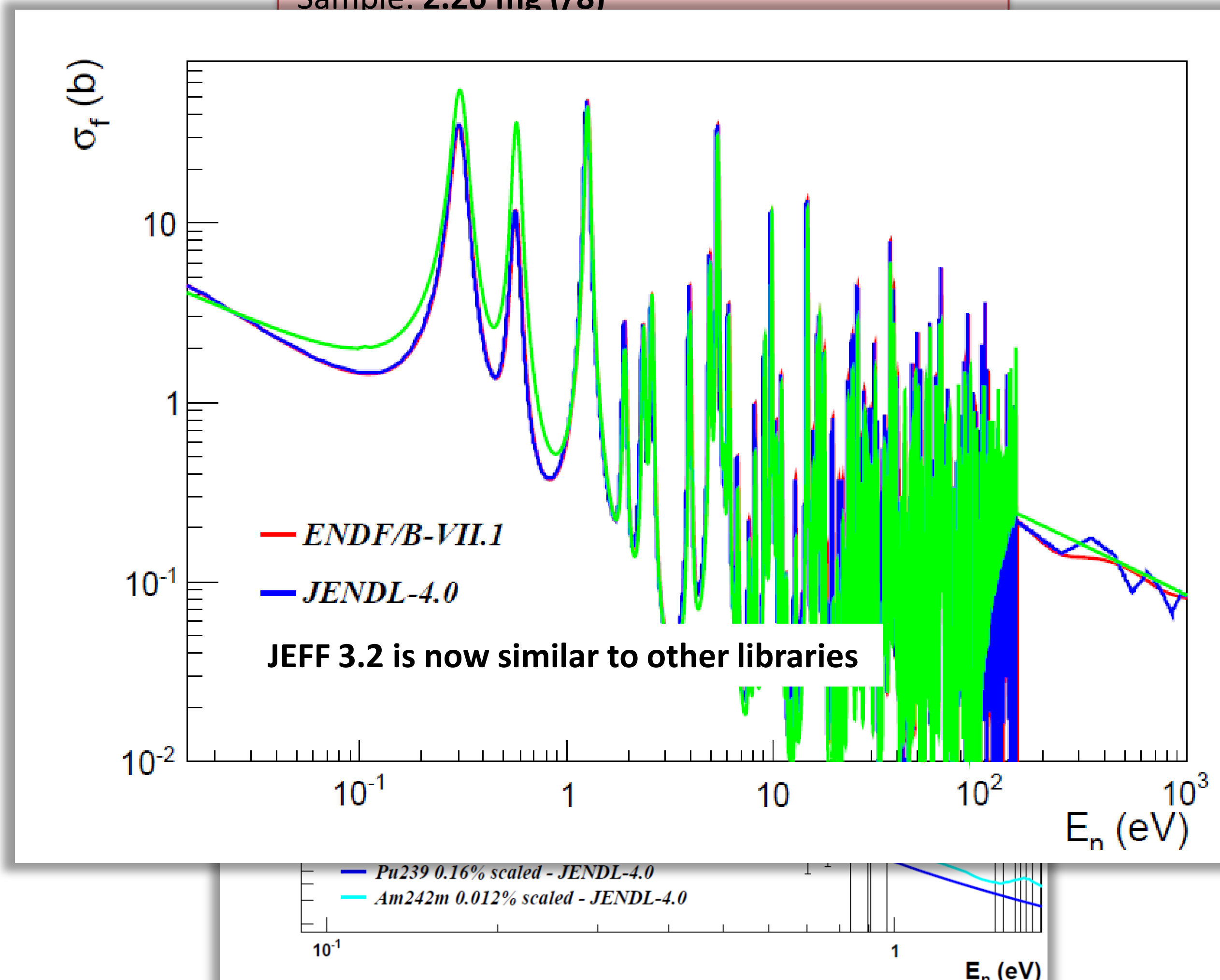
Below threshold, some corrections on current librari
recent

Controversial result, still being checked (not confirmed by other n_TOF datasets).

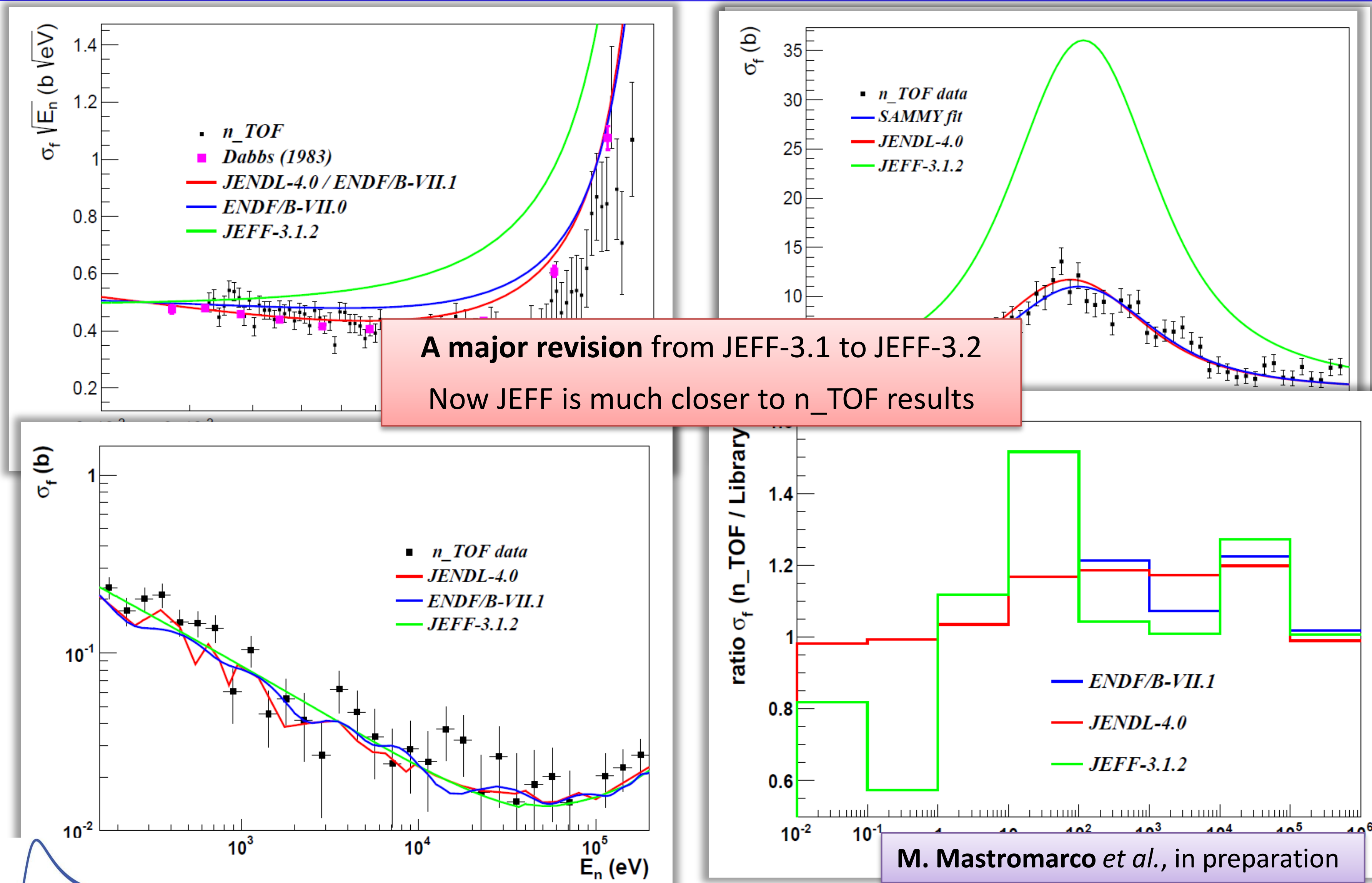
Still needs confirmation !!

The ^{241}Am(n,f) at n_TOF

Half-life: **432 y**
Sample: **2.26 mg (/8)**



The ^{241}Am(n,f) at n_TOF



A major revision from JEFF-3.1 to JEFF-3.2

Now JEFF is much closer to n_TOF results

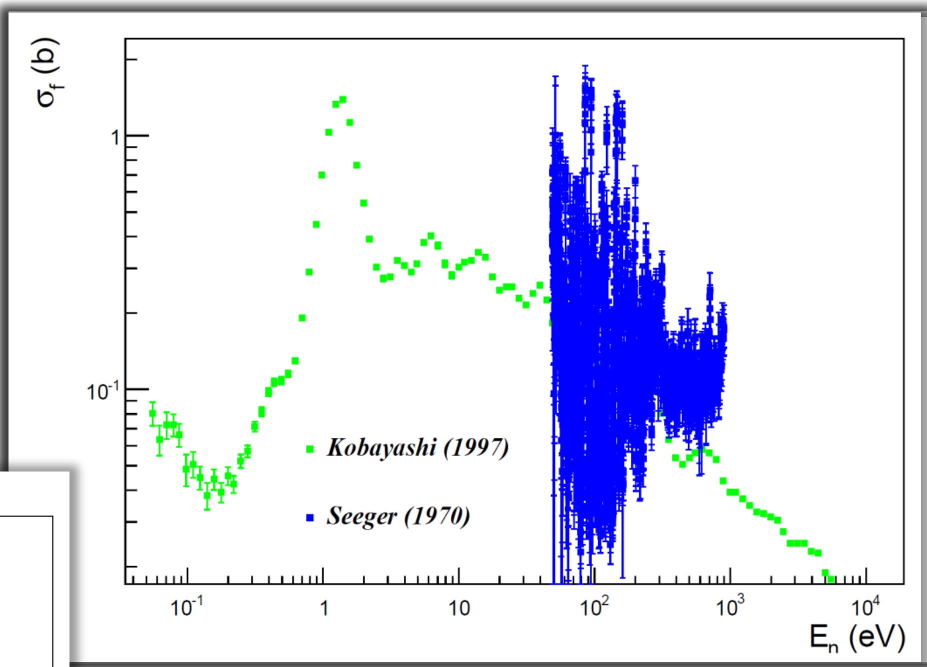
M. Mastromarco ***et al.***, in preparation

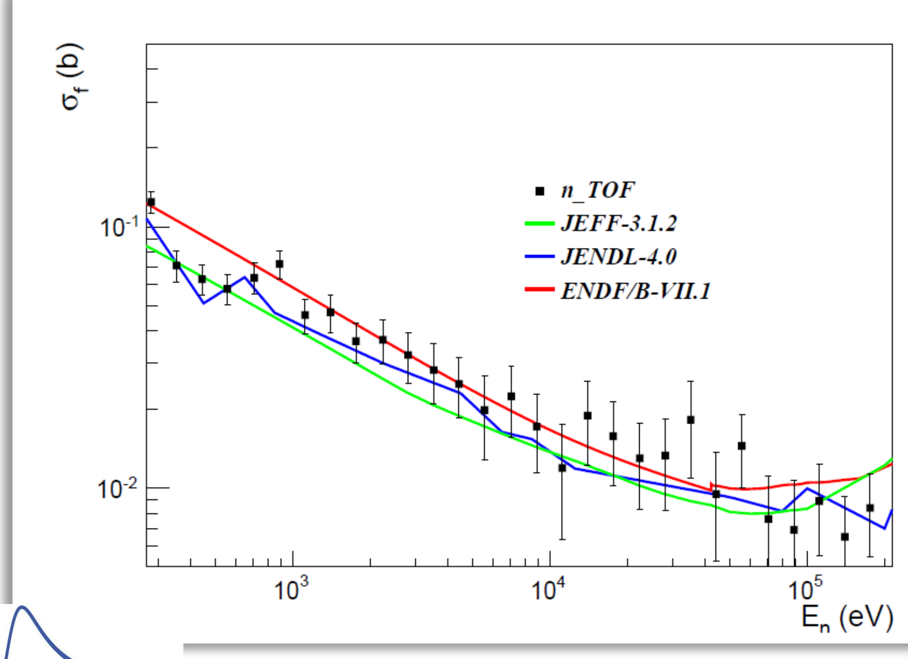
The $^{243}Am(n,f)$ at low energy

Half-life: **7370 y**
Sample: **4.8 mg (/8)**
Activity: **4.4 MBq** (each sample)
Contamination (declared): **^{241}Am 2.5%**
Contamination (undeclared): **^{239}Pu , ^{242m}Am**

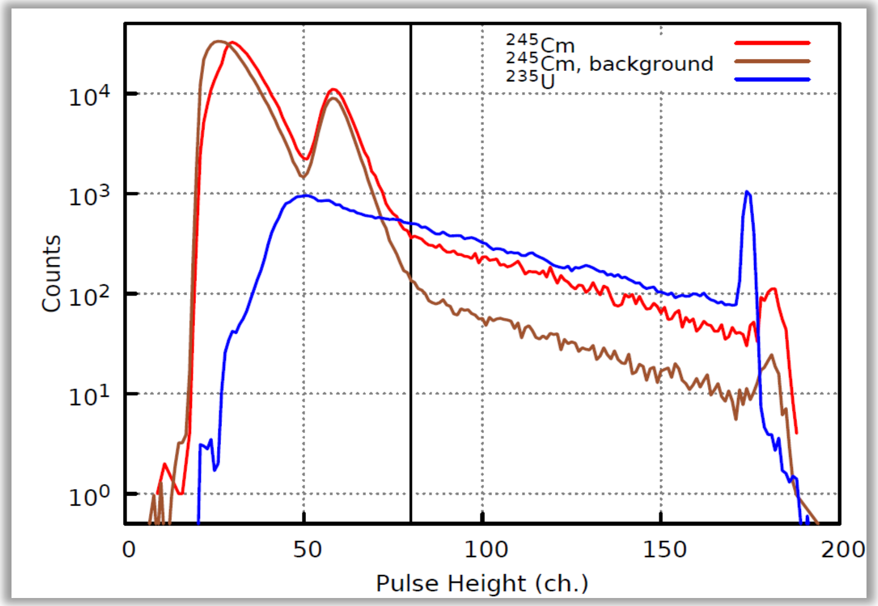
JEFF 3.2 same cross section as JENDL-4

ENDF/B-VII.1 differs in the first small resonance





The $^{245}Cm(n,f)$ reaction



Half-life: **8500 y (18.1 y)**
Sample: **1.71 mg (/4)**
Activity: **87 MBq** (each sample)
Contamination (declared): **^{244}Cm 6.6%**

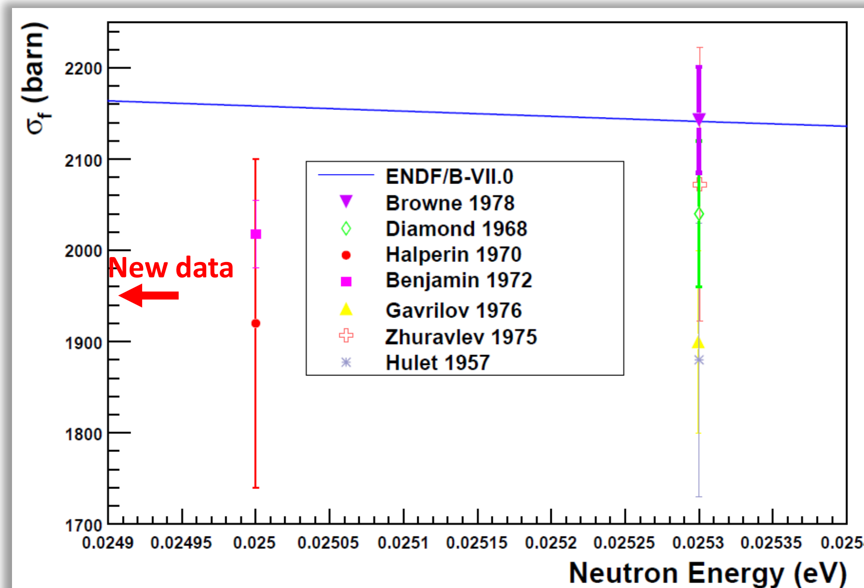
Very large α background (**0.1 GBq**)

High thresholds necessary (large uncertainty in efficiency corrections). Only cross section shape with good accuracy (3%).

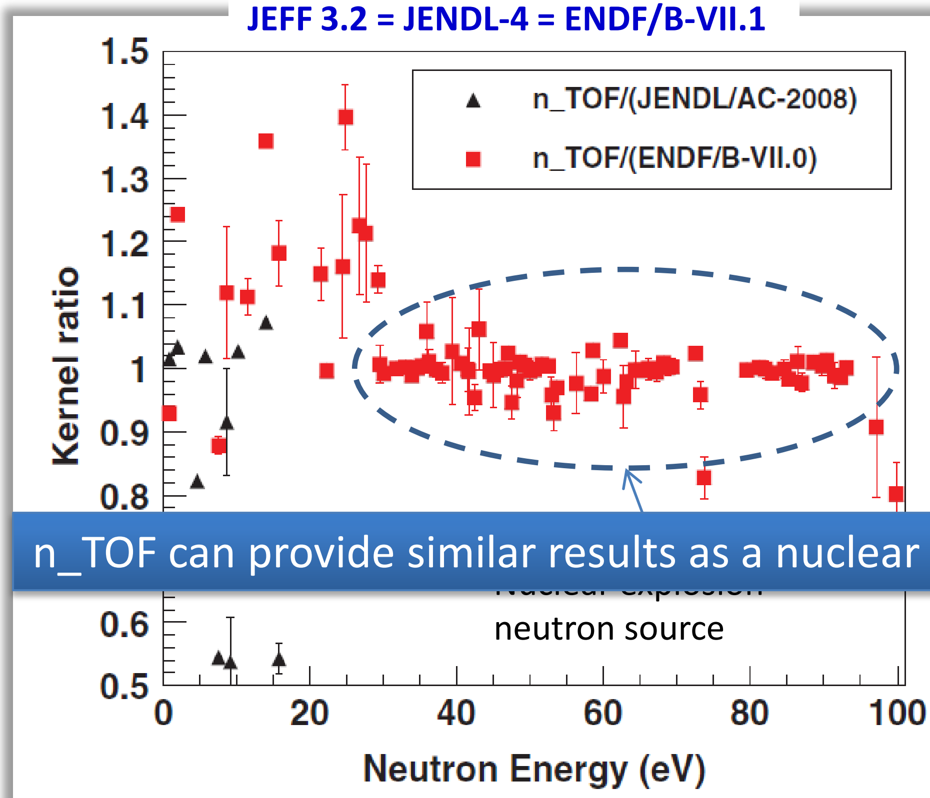
For absolute cross section, need to normalize to "recommended value" at thermal energy.

However, **large uncertainty (30%)** on thermal data.

Used two recent measurements of the thermal cross section (ILL and SCK-Mol) that agree within 5%.



The ^{245}Cm(n,f) reaction



Half-life: **8500 y**
Sample: **1.71 mg**
Activity: **87 MBq** (each sample)
Contamination (declared): **^{244}Cm 6.6% (18.1 y)**

Below 30 eV, two **(very old)** measurements exist, showing **large discrepancies**.

Above 30 MeV, **only one** measurement with neutrons from a **nuclear test**.

n_TOF can provide similar results as a nuclear explosion (but with fewer side effects …)

From thermal energy to 30 eV a **revision of the evaluations** is needed.

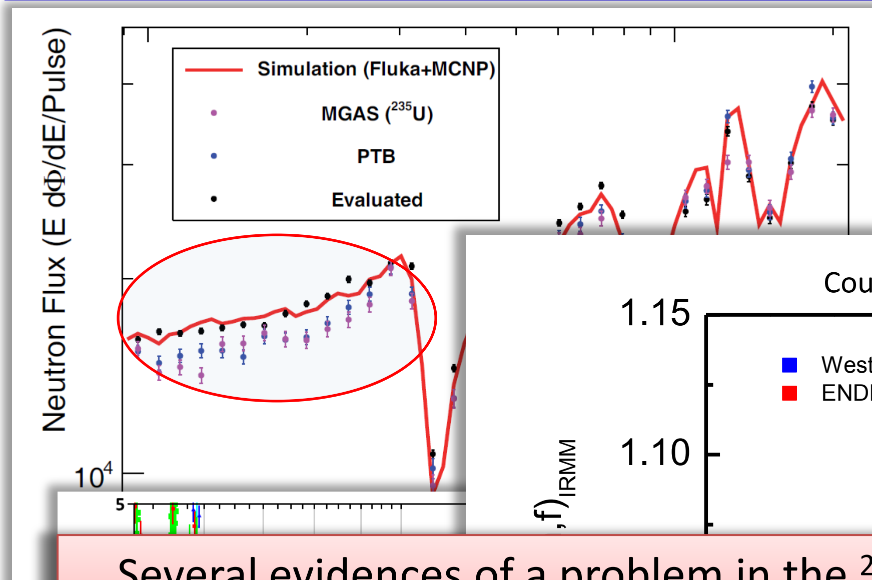
Above 30 eV, n_TOF confirm previous data and evaluations.

PHYSICAL REVIEW C **85**, 034616 (2012)

Neutron-induced fission cross section of ^{245}Cm: New results from data taken at the time-of-flight facility n_TOF

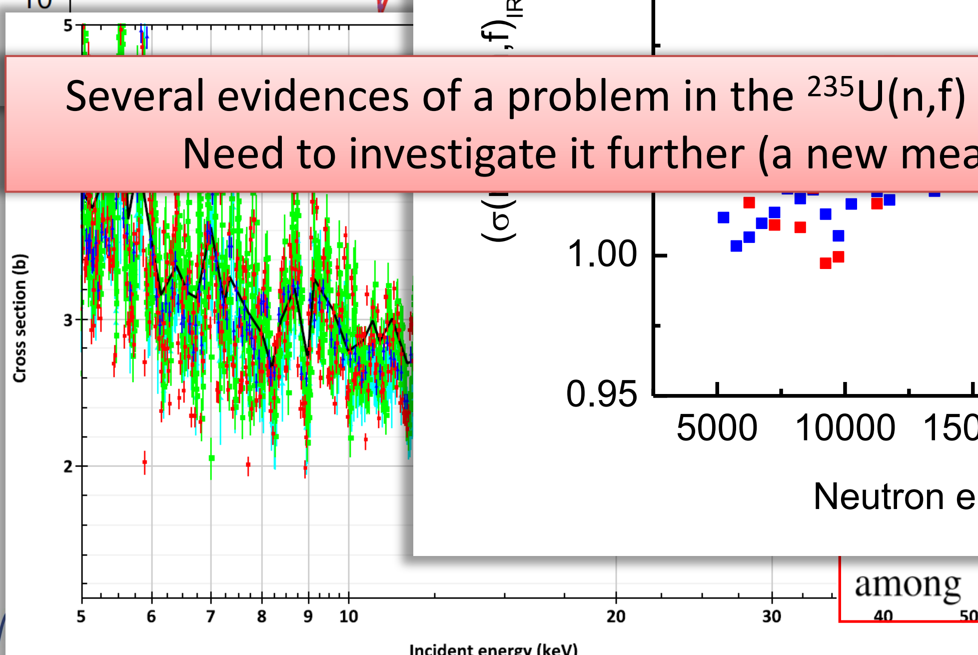
M. Calviani,[1,2,*] M. H. Meaze,[3,†] N. Colonna,[3] J. Praena,[4] U. Abbondanno,[5] G. Aerts,[6] H. Alvarez,[7] F. Alvarez-Velarde,[8] S. Andriamonje,[2,6] J. Andrzejewski,[9] P. Assimakopoulos,[10,‡] L. Audouin,[11] G. Badurek,[12] M. Barbagallo,[3] P. Baumann,[13] F. Bečvář,[14] F. Belloni,[5,6] B. Berthier,[11] E. Berthoumieux,[6] F. Calviño,[15] D. Cano-Ott,[16] R. Capote,[4,17] C. Carrapiço,[6,18] P. Cennini,[2] V. Chepel,[19] E. Chiaveri,[2] G. Cortes,[15] A. Couture,[19] J. Cox,[19] M. Dahlfors,[2] S. David,[11] I. Dillmann,[20] C. Domingo-Pardo,[21] W. Dridi,[6] I. Duran,[7] C. Eleftheriadis,[22] M. Embid-Segura,[8] L. Ferrant,[11,‡] A. Ferrari,[2]

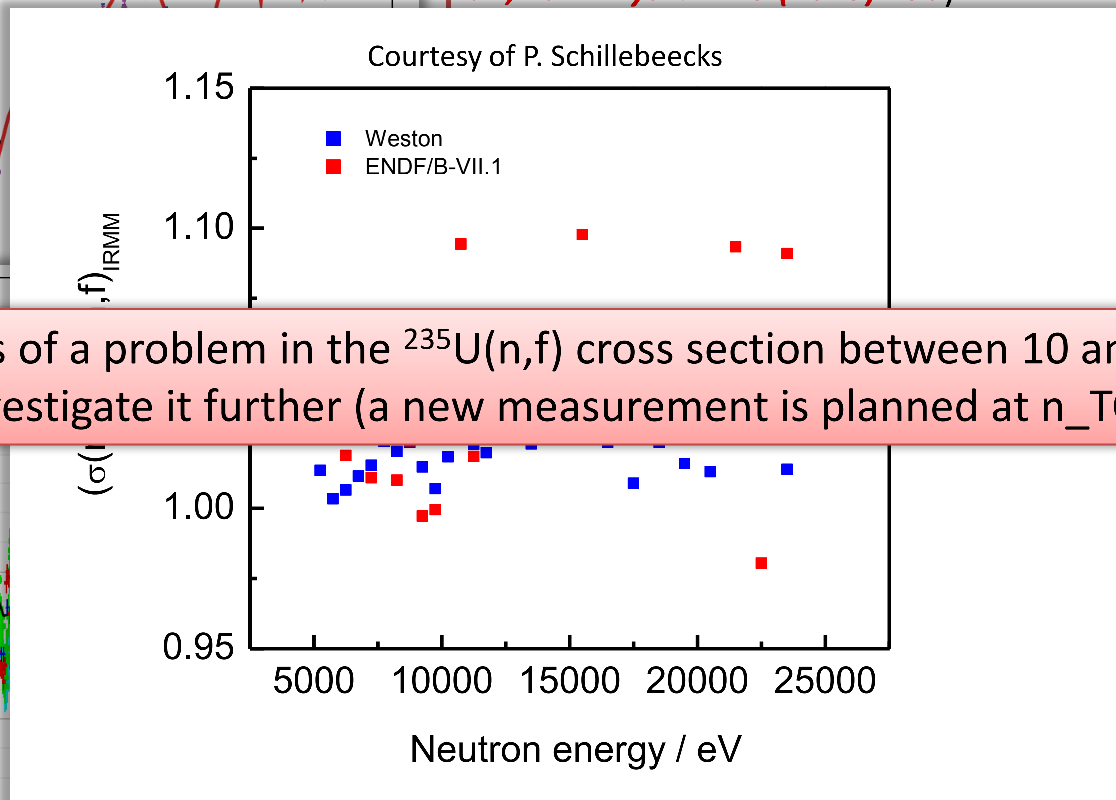
^{235}U(n,f) between 10 and 30 keV



The **flux** calculated on the basis of the ^{235}U(n,f) cross section **found systematically lower** than "expected" in the 10-30 keV range (***M. Barbagallo et al., Eur. Phys. J A 49 (2013) 156***).

…ge potentially





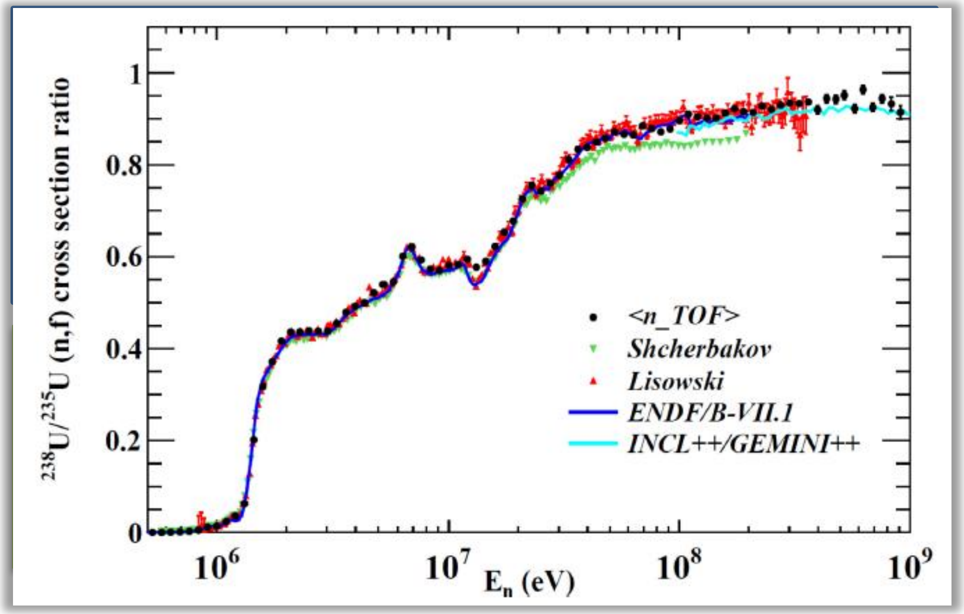
week ending
16 NOVEMBER 2012

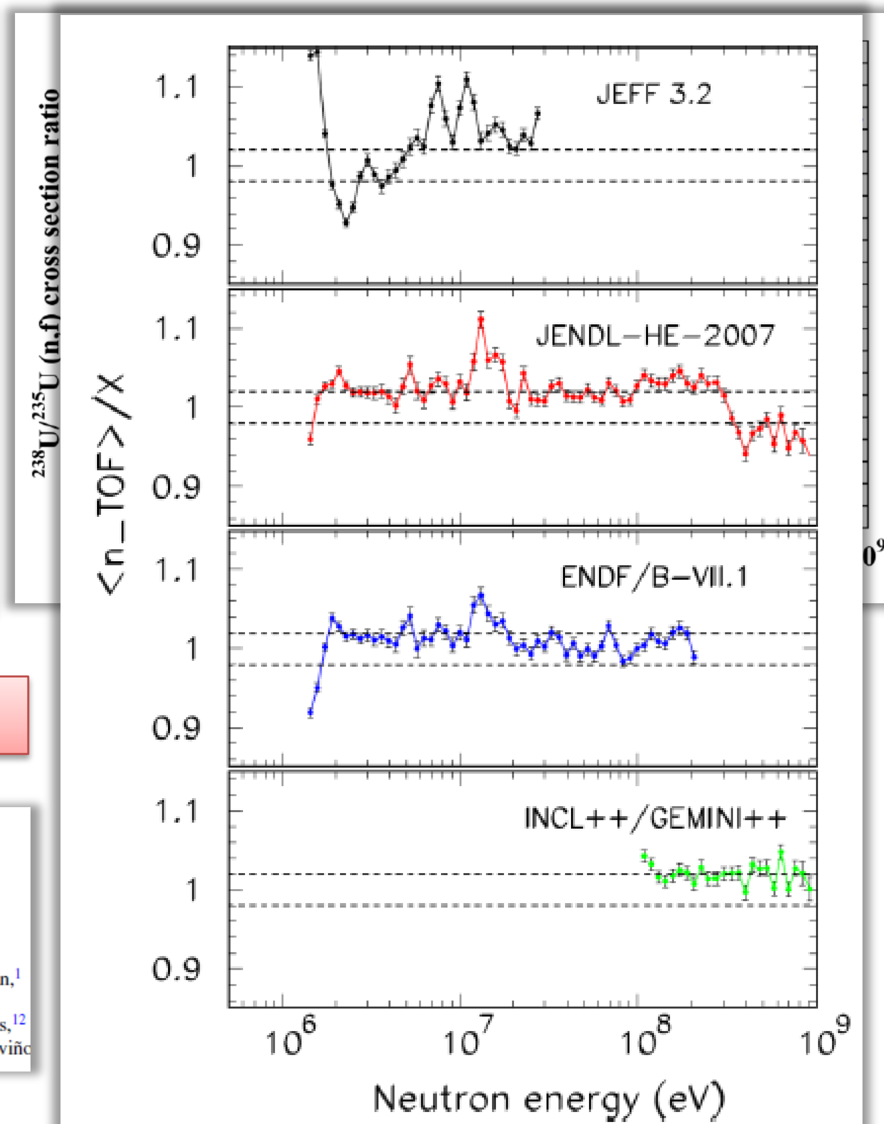
…, USA
…550, USA

…oss sections are …and JENDL-4.0 … are observed among other measurements [14–18]. Neutron flux at

Several evidences of a problem in the ^{235}U(n,f) cross section between 10 and 30 keV
Need to investigate it further (a new measurement is planned at n_TOF)

The $^{238/235}$U(n,f) cross section ratio





JEFF 3.2 needs a revision on this important ratio

PHYSICAL REVIEW C **00**, 004600 (2015)

High-accuracy determination of the ^{238}U/ ^{235}U fission cross section ratio up to ≈ 1 GeV at n_TOF at CERN

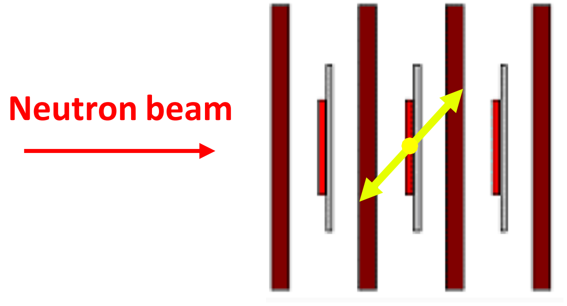
C. Paradela,[1,2] M. Calviani,[3] D. Tarrío,[1,4] E. Leal-Cidoncha,[1] L. S. Leong,[5,6] L. Tassan-Got,[5] C. Le Naour,[5] I. Duran,[1] N. Colonna,[7,*] L. Audouin,[5] M. Mastromarco,[7] S. Lo Meo,[8] A. Ventura,[9] G. Aerts,[10] S. Altstadt,[11] H. Álvarez,[1] F. Álvarez-Velarde,[12] S. Andriamonje,[10] J. Andrzejewski,[13] G. Badurek,[14] M. Barbagallo,[7] P. Baumann,[15] V. Bécares,[12] F. Bečvář,[16] F. Belloni,[2] B. Berthier,[5] E. Berthoumieux,[10] J. Billowes,[17] V. Boccone,[3] D. Bosnar,[18] M. Brugger,[3] F. Calviño

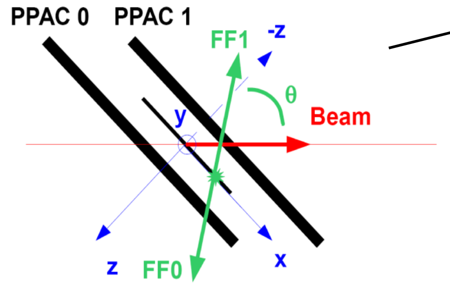
Angular distribution of FF

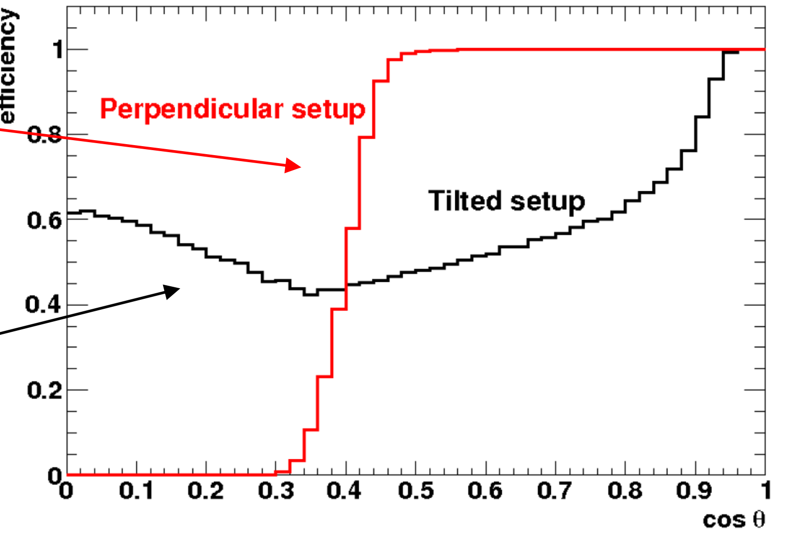
Fission Fragment angular distribution important to:

- obtain information on the state of the nucleus at saddle point (spin, parity, …) and on the **fission dynamics**
- calculate more **reliable detection efficiency**, thus improving accuracy of cross sections.

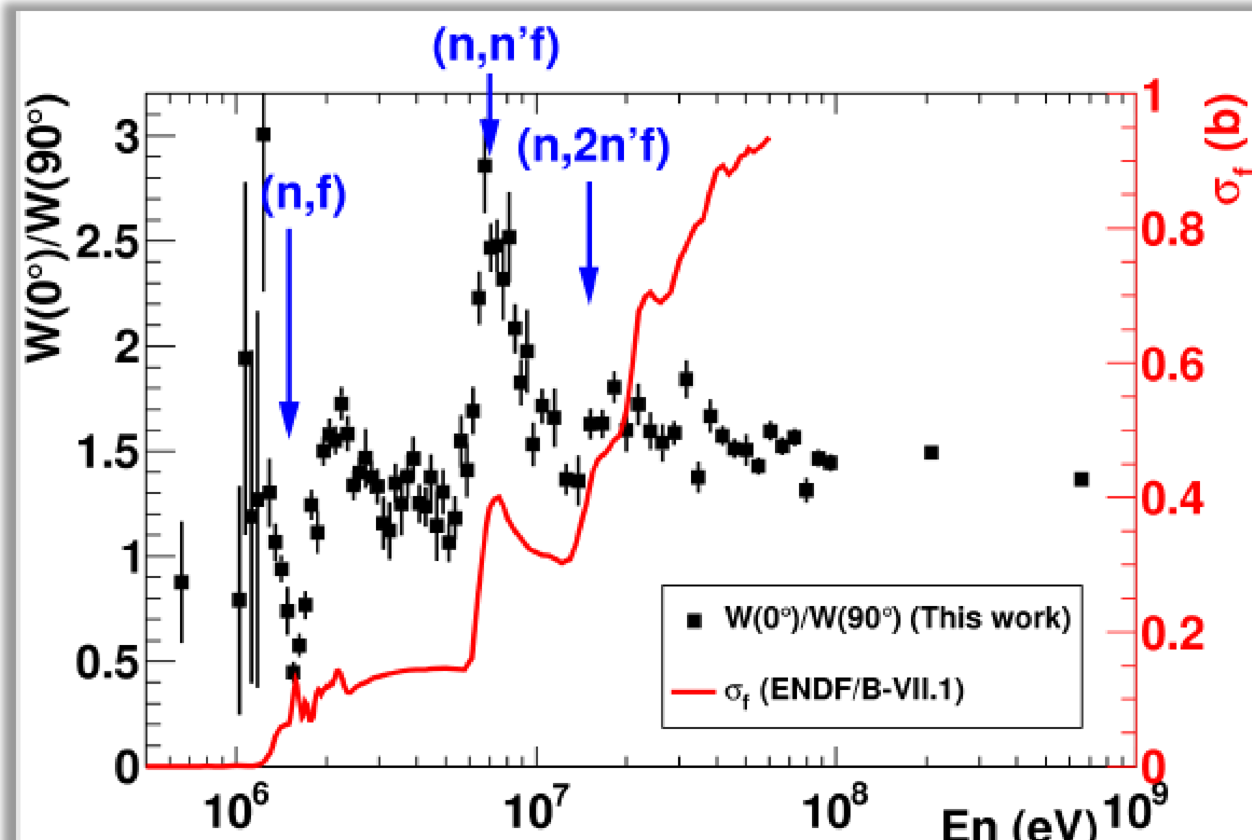
The effect on the cross section is particularly important **for coincidence technique (PPAC,** due to backing the angular acceptance is limited to 65º)





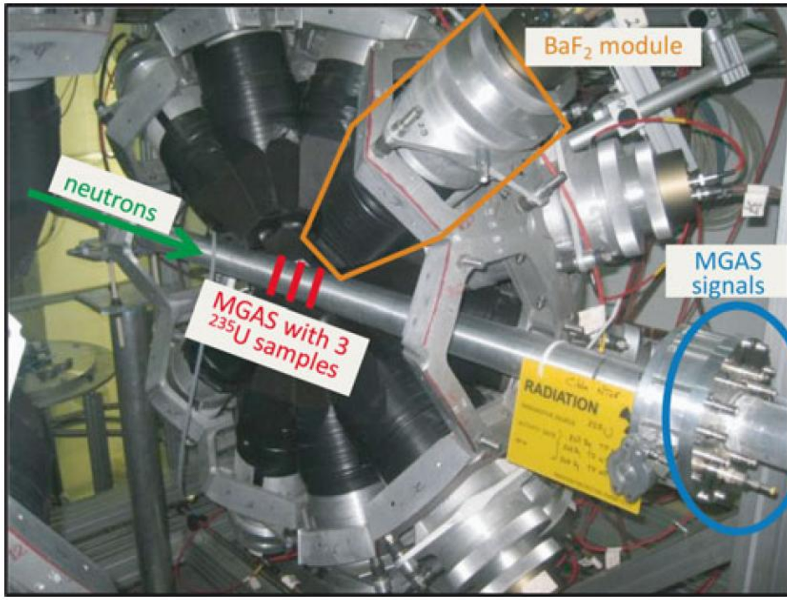


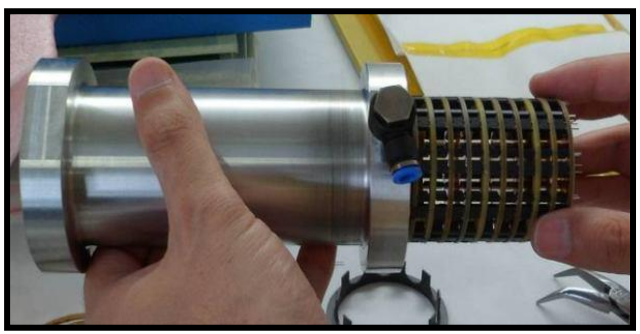
Angular anisotropy in ^{232}Th fission reaction

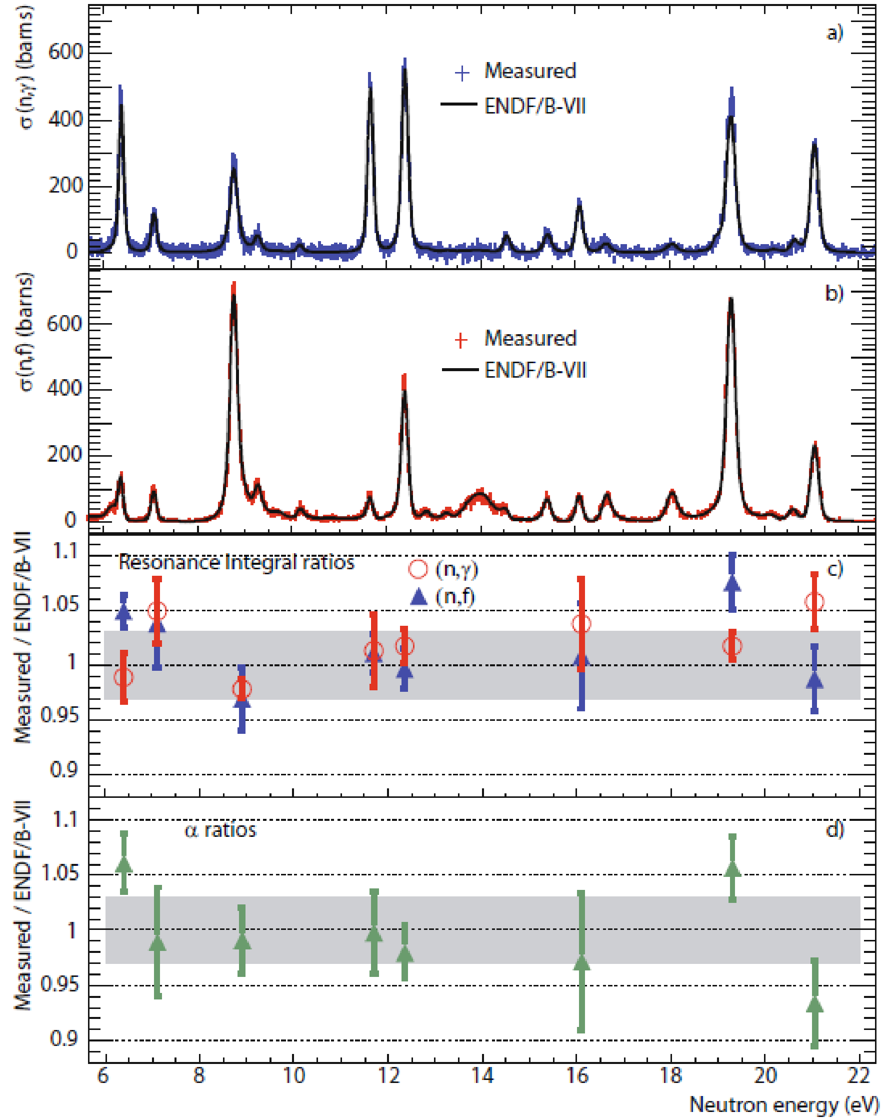


Measured anisotropy from fission threshold to 1 GeV !!!

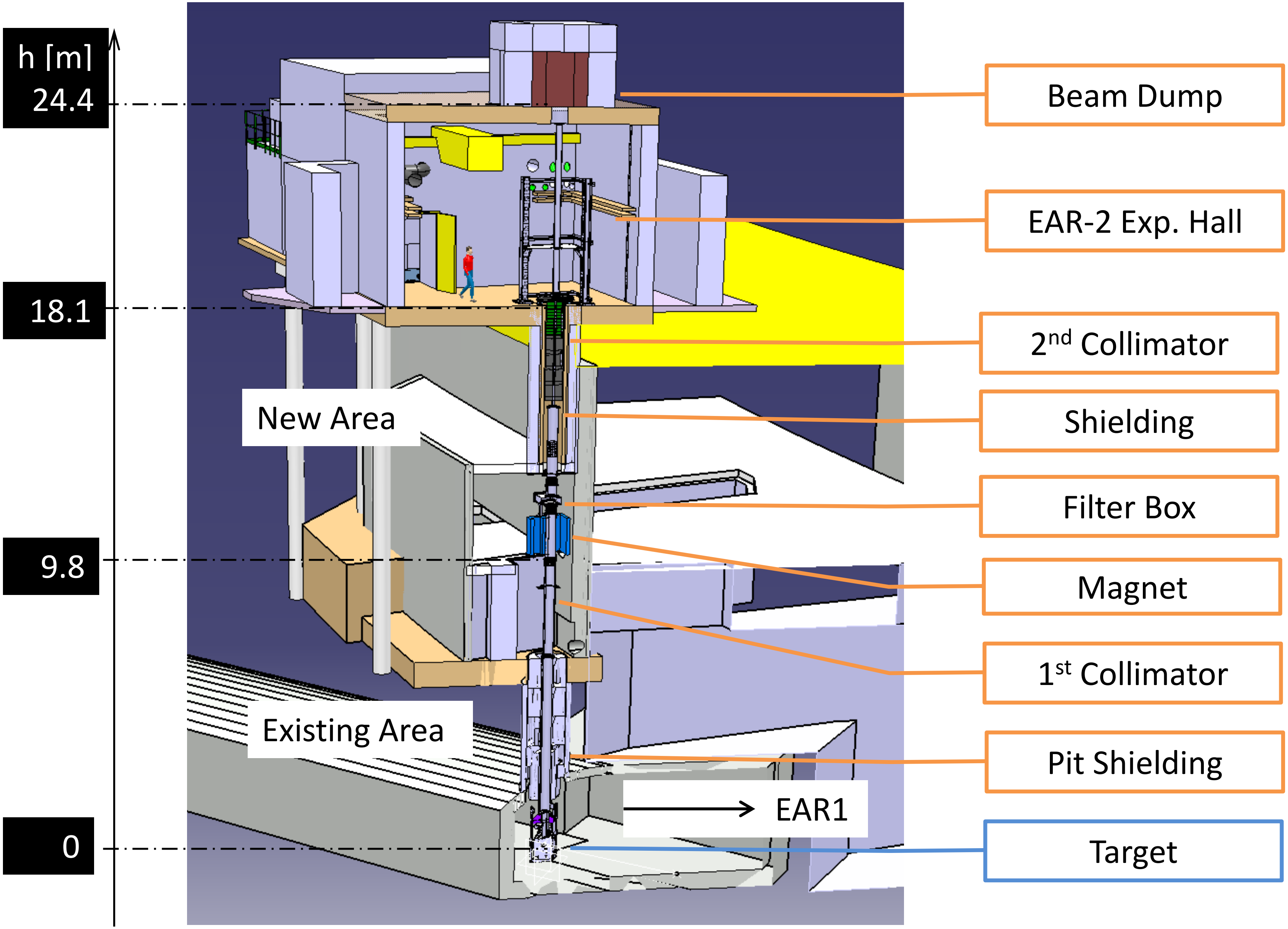
Simultaneous measurement of capture and fission cross section



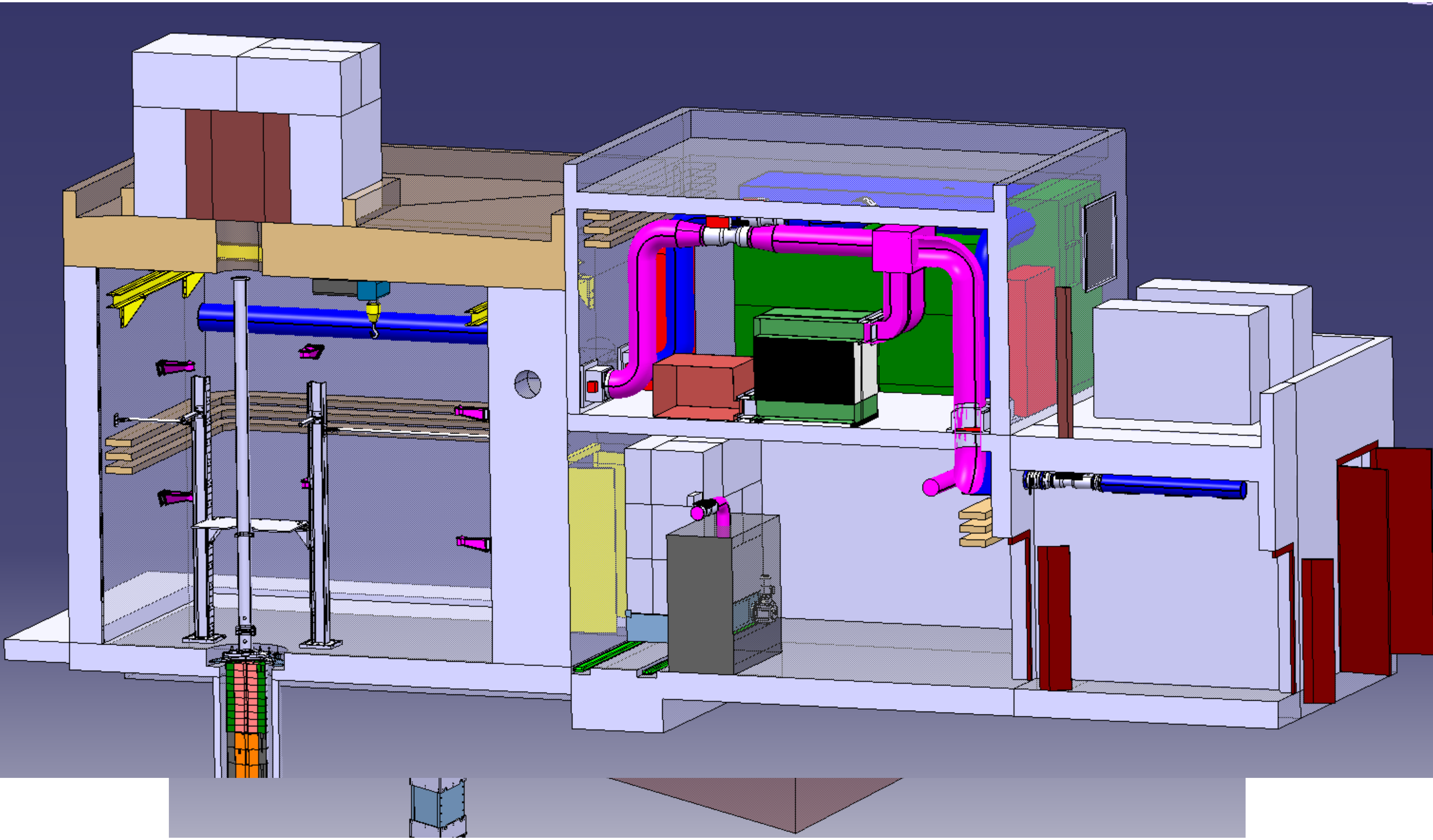




The second experimental area at n_TOF



h [m]
24.4
18.1
9.8
0
New Area
Existing Area
EAR1
Beam Dump
EAR-2 Exp. Hall
2nd Collimator
Shielding
Filter Box
Magnet
1st Collimator
Pit Shielding
Target



CER

32-34/2014 - Monday 4 August 2014
icles at: http://bulletin.cern.ch

THE FIRST
HITS EAR2

On 25 July 2014, about a
of CERN's neutron facilit
start its rich programme

The last part of the EAR2 beamlin
they hit the samples.

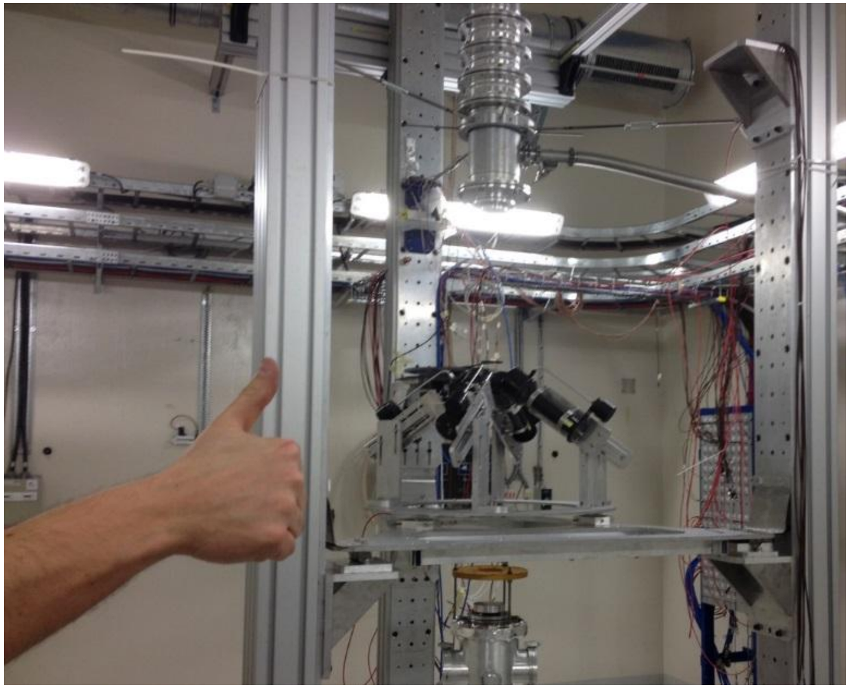
A word from the DG

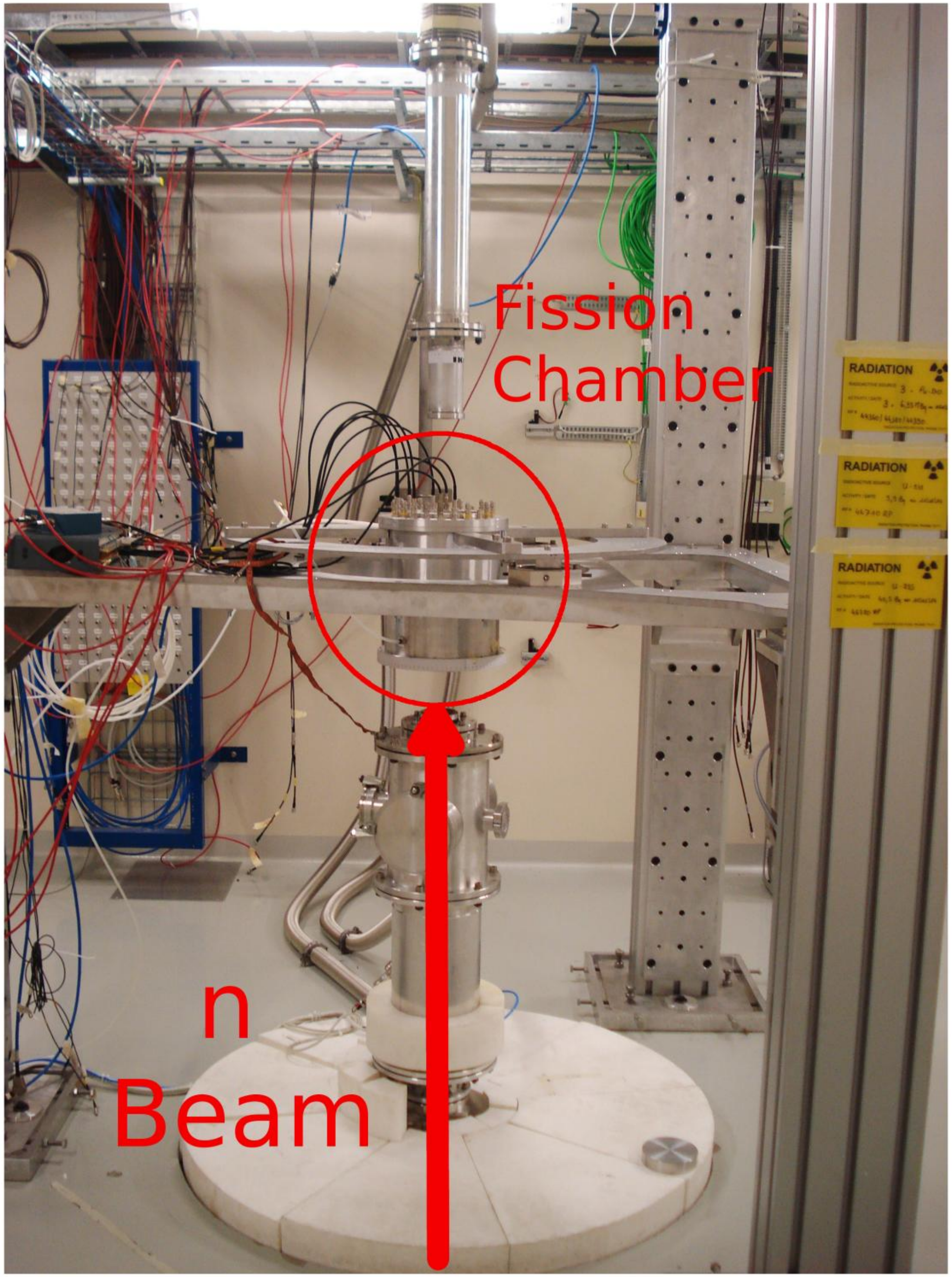
G TO KNOW INTERNATIONAL

nt years, CERN has been tightening with fellow organisations in vibrant international community.

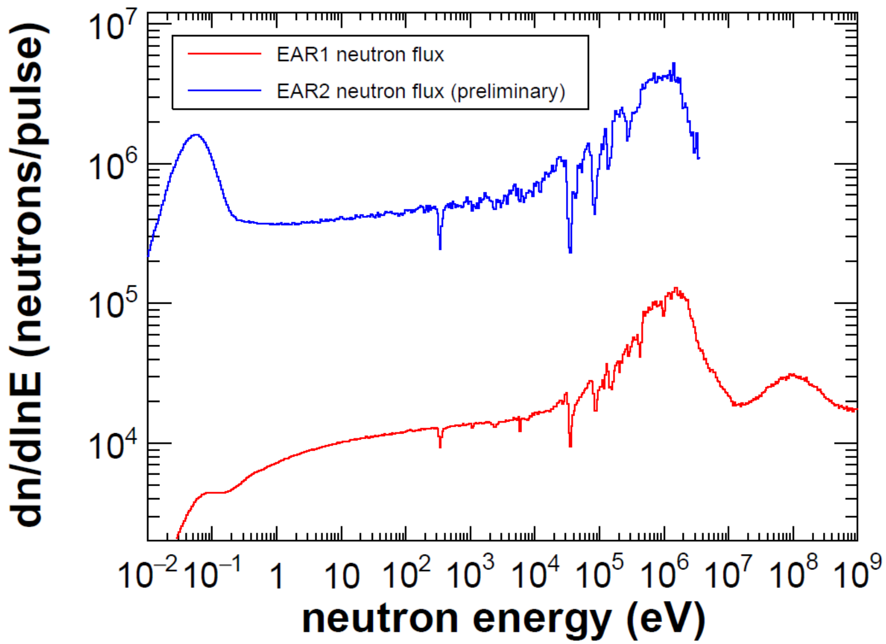
(Continued on page 2)

is issue




Fission
Chamber
n
Beam

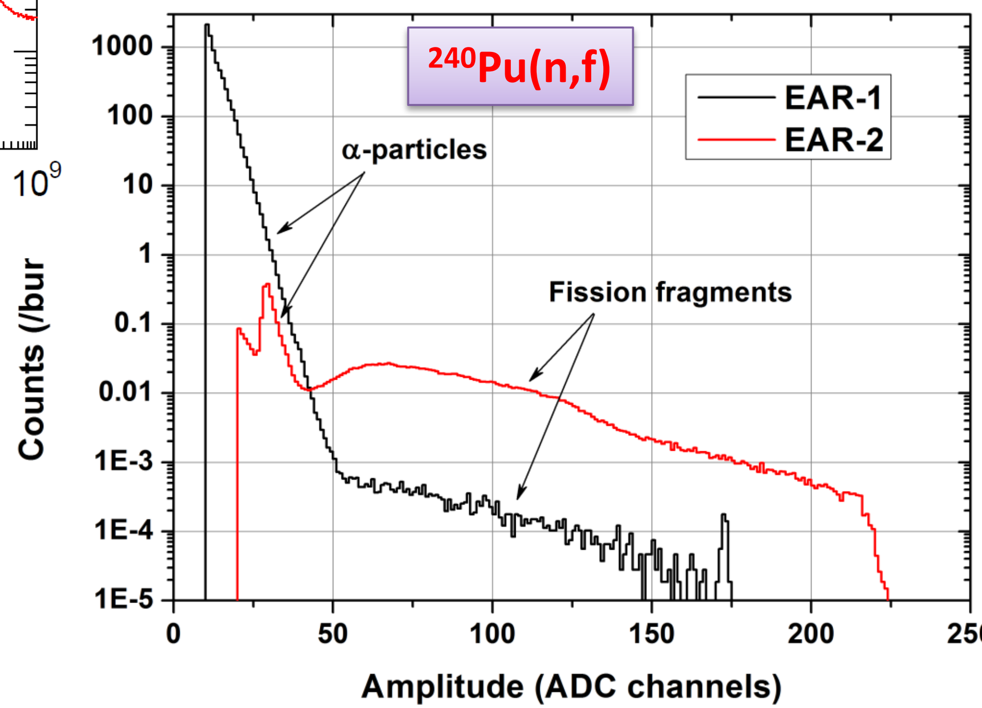
The main features of EAR 2



Flux in EAR2 **25 times** larger than in EAR1.

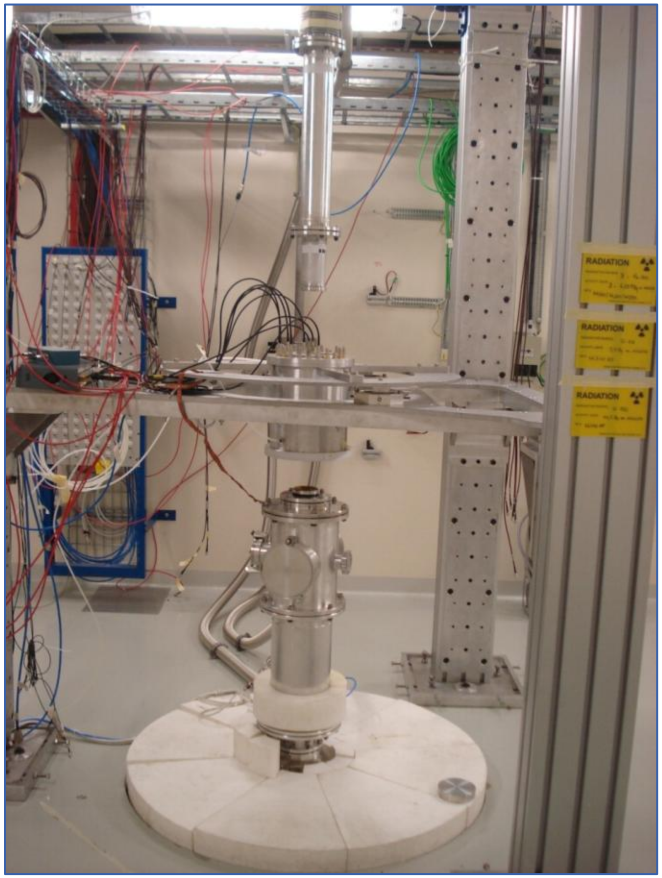
The **shorter flight path** implies a factor of 10 smaller time-of-flight.

Global gain relative to EAR1: **250 times** in neutron rate (thus **in signal/background ratio** for radioactive isotopes!)



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

^{240}Pu(n,f) in EAR2@n_TOF



See poster from A. Stomatopoulos

The experimental program in EAR2

The EAR2 will allow to:

- measure samples of **very small mass (<1 mg)**
- measure **short-lived radioisotopes** (down to a few years)
- collect data on a much **shorter time scale**
- **measure (n,charged particle)** reactions with **thin samples**

Fission measurements foreseen in EAR2:

- **^{238}Pu (87.7 y), ^{241}Pu(14.1 y), ^{244}Cm (18.1 y)**
- **^{232}U (70 y) - cross section and FF angular distribution**
- **^{230}Th (available in small amount)**

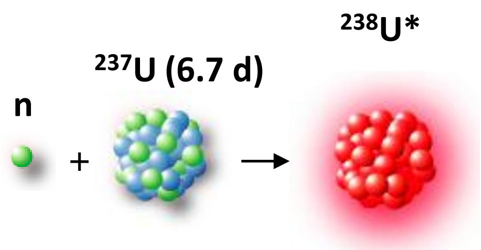
Other measurements in EAR2:

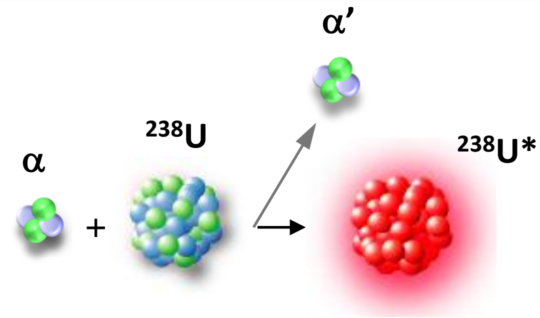
- **(n,p)** and **(n,α)** cross sections on **^{7}Be, ^{25}Mg, ^{26}Al**
- **Capture** cross section of **^{79}Se, ^{245}Cm**

The surrogate method

Neutron-induced reaction $^{237}U(n,f)$
(very difficult to measure)

Surrogate reaction $^{238}U(\alpha,\alpha')$
(easier to measure)





$$\sigma_{\alpha X}(E_\alpha)=\sum_{J,\pi}\sigma_\alpha^{CN}(E_{ex},J,\pi)\,G_X^{CN}(E_{ex},J,\pi).$$

Desired ($\sigma_{\alpha X}(E_\alpha)$) — **Calculated** ($\sigma_\alpha^{CN}$)

$$P_{\delta X}(E_{ex})=\sum_{J,\pi}F_\delta^{CN}(E_{ex},J,\pi)\,G_X^{CN}(E_{ex},J,\pi)$$

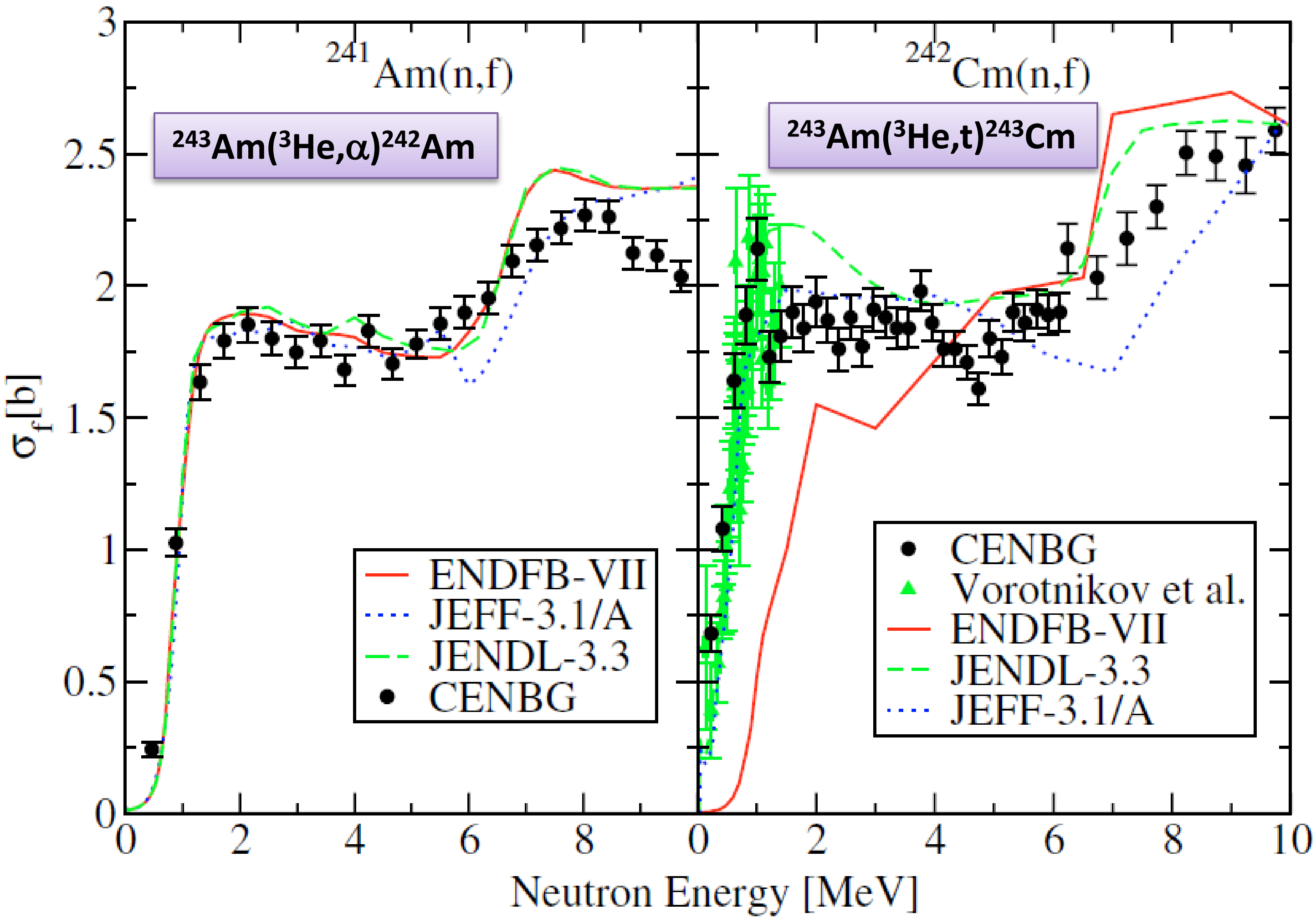
Measured ($P_{\delta X}(E_{ex})$) — **Calculated** (F_δ^{CN})

Surrogate reaction: reaction induced by light charged particles, leading to the **same Compound Nucleus** of the neutron-induced reaction.

Fission cross section extracted from a combination of experimental observation and modeling.

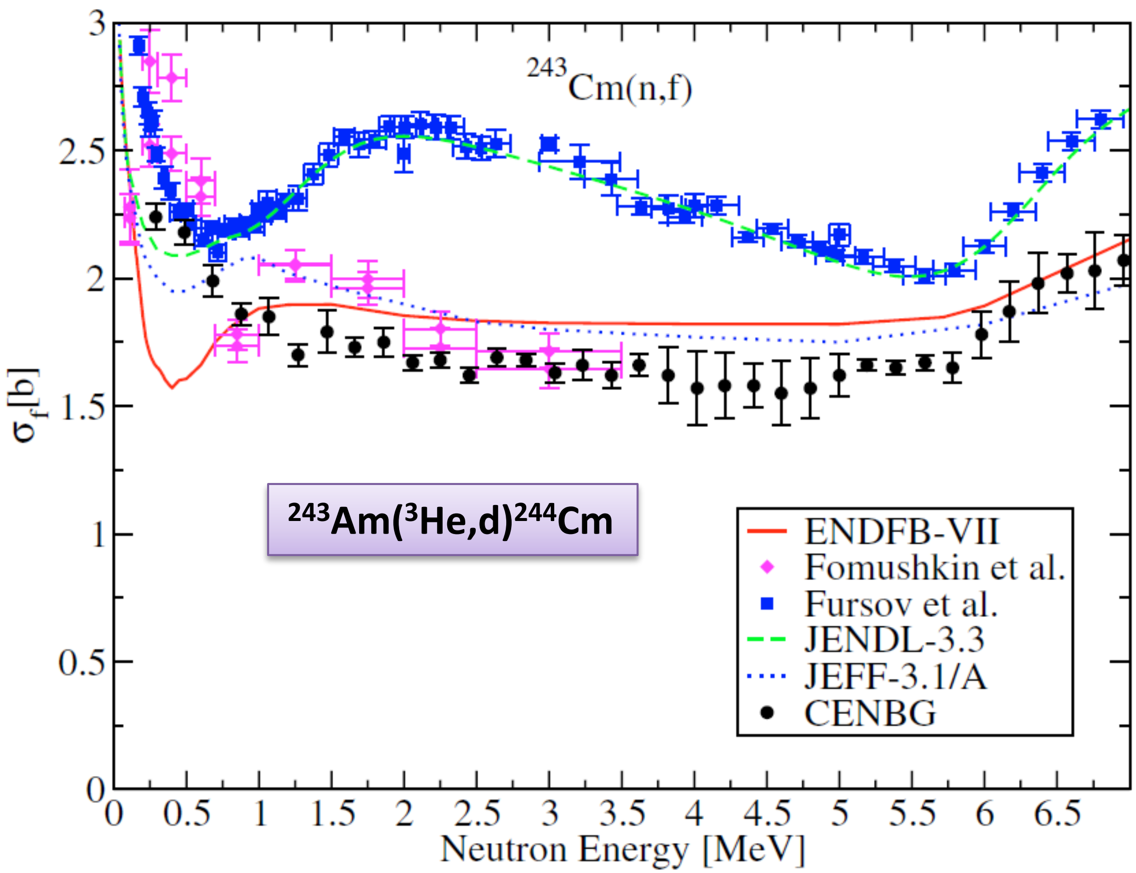
Advantage: can be used for very difficult measurements. Warning: relies on model calculations (need to check limitations).

The surrogate method



B. Jurado *et al.*, Int. Conf. Nucl. Data and Tech. 2007 DOI: 10.1051/ndata:07357

Open questions



^{243}Am(^{3}He,d)^{244}Cm

More reactions should be studied with the surrogate method:

^{244}Cm(n,f) ^{243}Am(^{3}He,p)^{245}Cm
^{238}Pu(n,f) ^{237}Np(^{3}He,p)^{239}Pu

B. Jurado *et al.*, Int. Conf. Nucl. Data and Tech. 2007 DOI: 10.1051/ndata:07357

Conclusions

- There is need of **accurate new data** on neutron-induced fission cross-sections for fundamental nuclear physics and **advanced nuclear technology.**
- Large effort in various neutron facilities around the world aimed at measuring fission (cross-section, neutron multiplicity, fragment mass distribution, delayed neutrons, etc…).
- Since 2001, **n_TOF@CERN** has provided an important contribution to the field, with several measurements on fission cross section of **long-lived actinides**.
- A second **experimental area at 20 m** has recently been built: higher flux (x30) and lower time-of-flight allows for a better signal-to-background ratio (x300).
- It will open **new perspectives** for frontier measurements on short-lived radionuclides, in particular minor actinides

WORK IN PROGRESS

Thank you