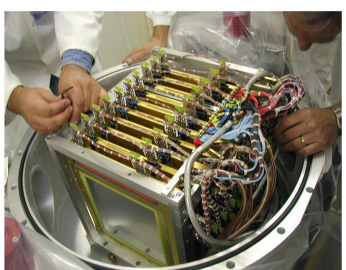
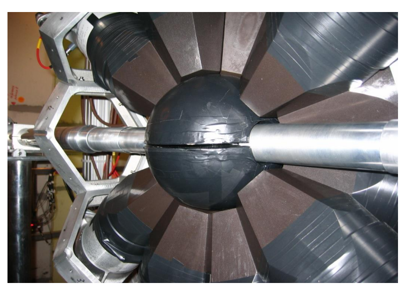
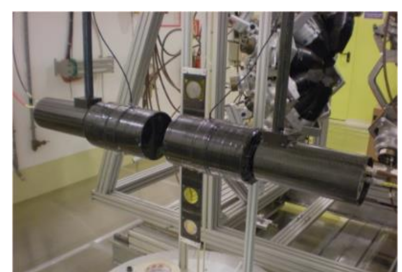
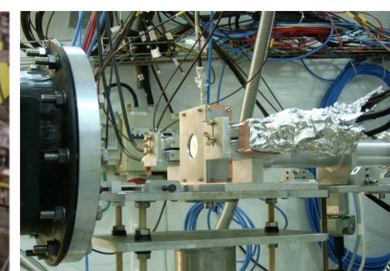
The n_TOF Collaboration, www.cern.ch/nTOF

Physics with neutron beams at the CERN n_TOF facility

Carlos GUERRERO

Applied Physics Fellow @CERN (PH/SME)

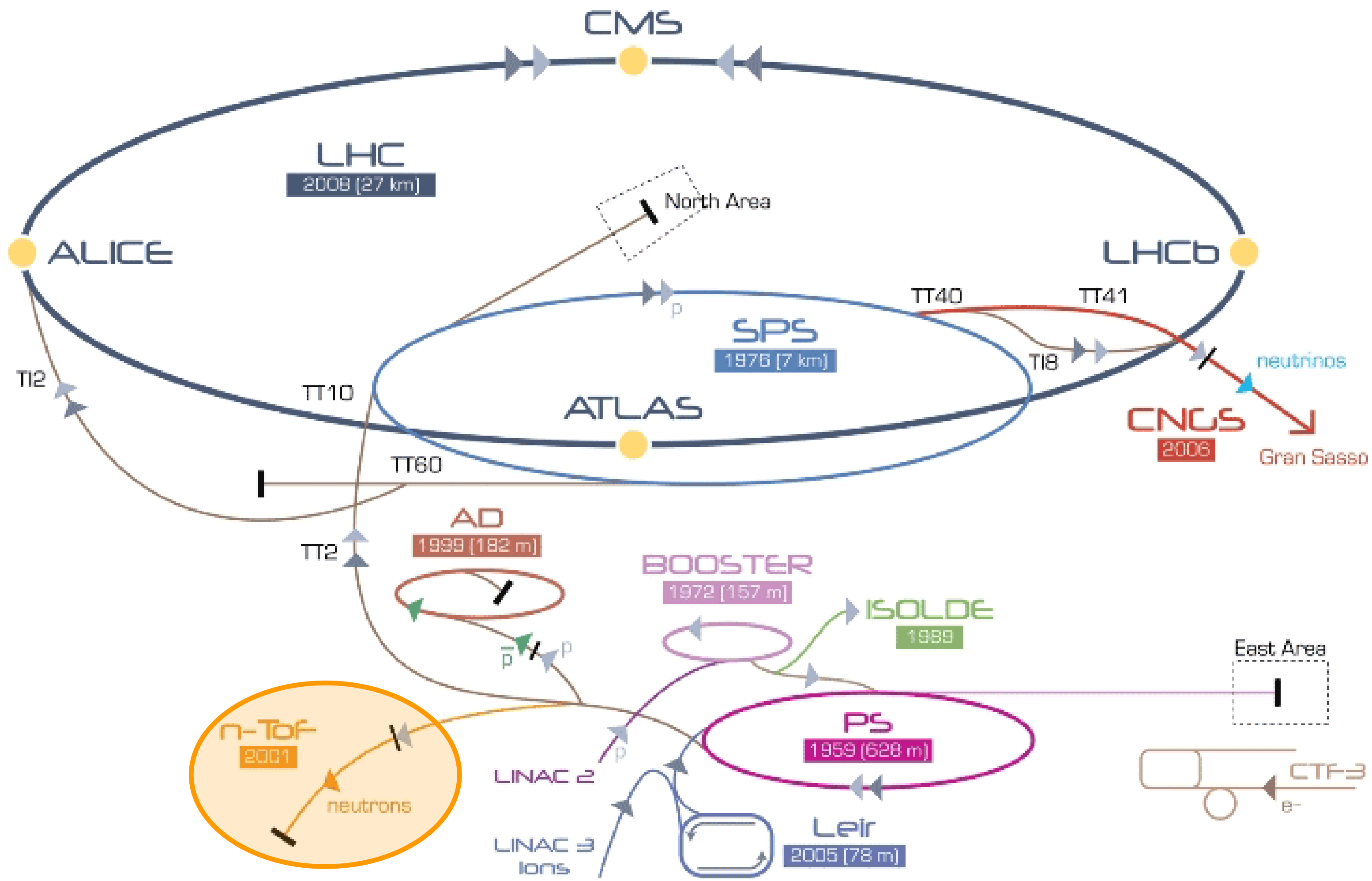
n_TOF Run and Analysis Coordinator

"In the early days of the Manhattan Project when an unknown cross section was needed, the procedure for obtaining a value for it was simple. You went and asked Fermi. Invariably he would refuse to hazard a guess. The next step, so the story goes, was to recite slowly a long string of numbers, and if one of the numbers produced a gleam in Fermi's eye - that was the value to use!"

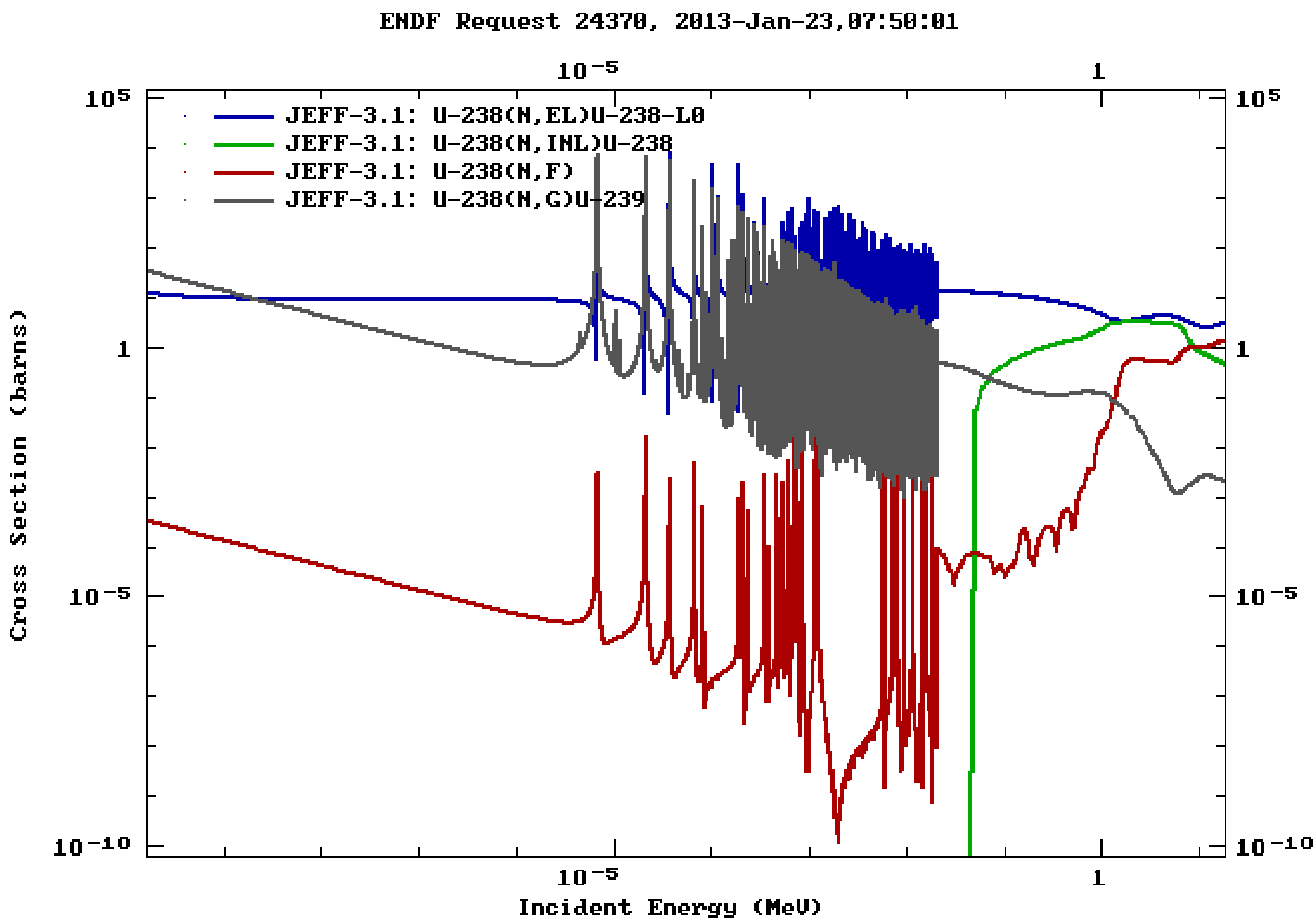
H. Goldstein (talk at Atomenergie, Sweden, September 1953)

n_TOF: A spallation neutron source using the PS 20 GeV/c prot. beam

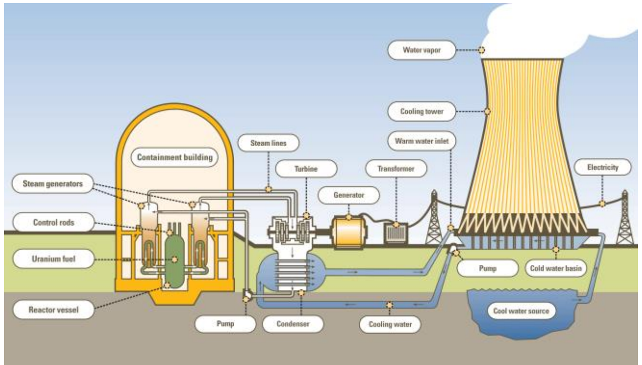


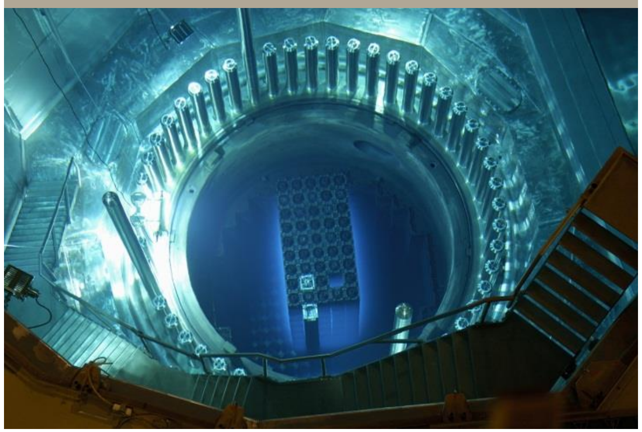
C. Rubbia et al., ***A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV***, CERN/LHC/98-02(EET) 1998.

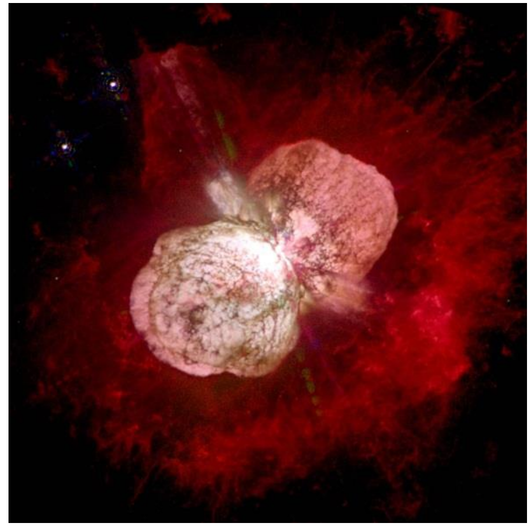
How does a neutron cross section look like?

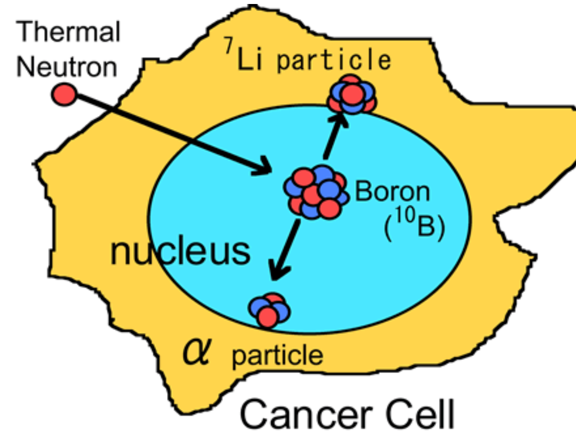


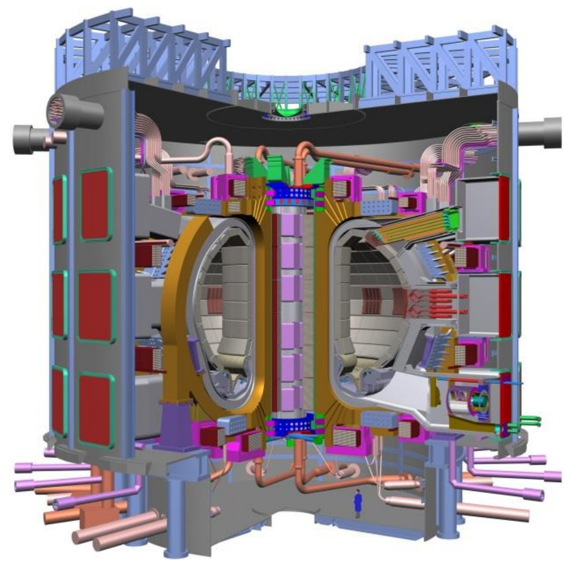
Neutrons in fission/fusion react., stars, cancer therapies, imaging,…

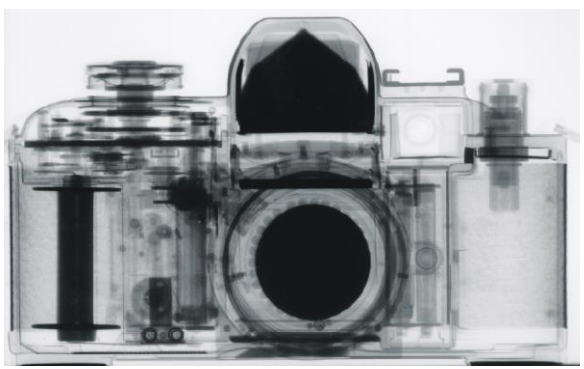






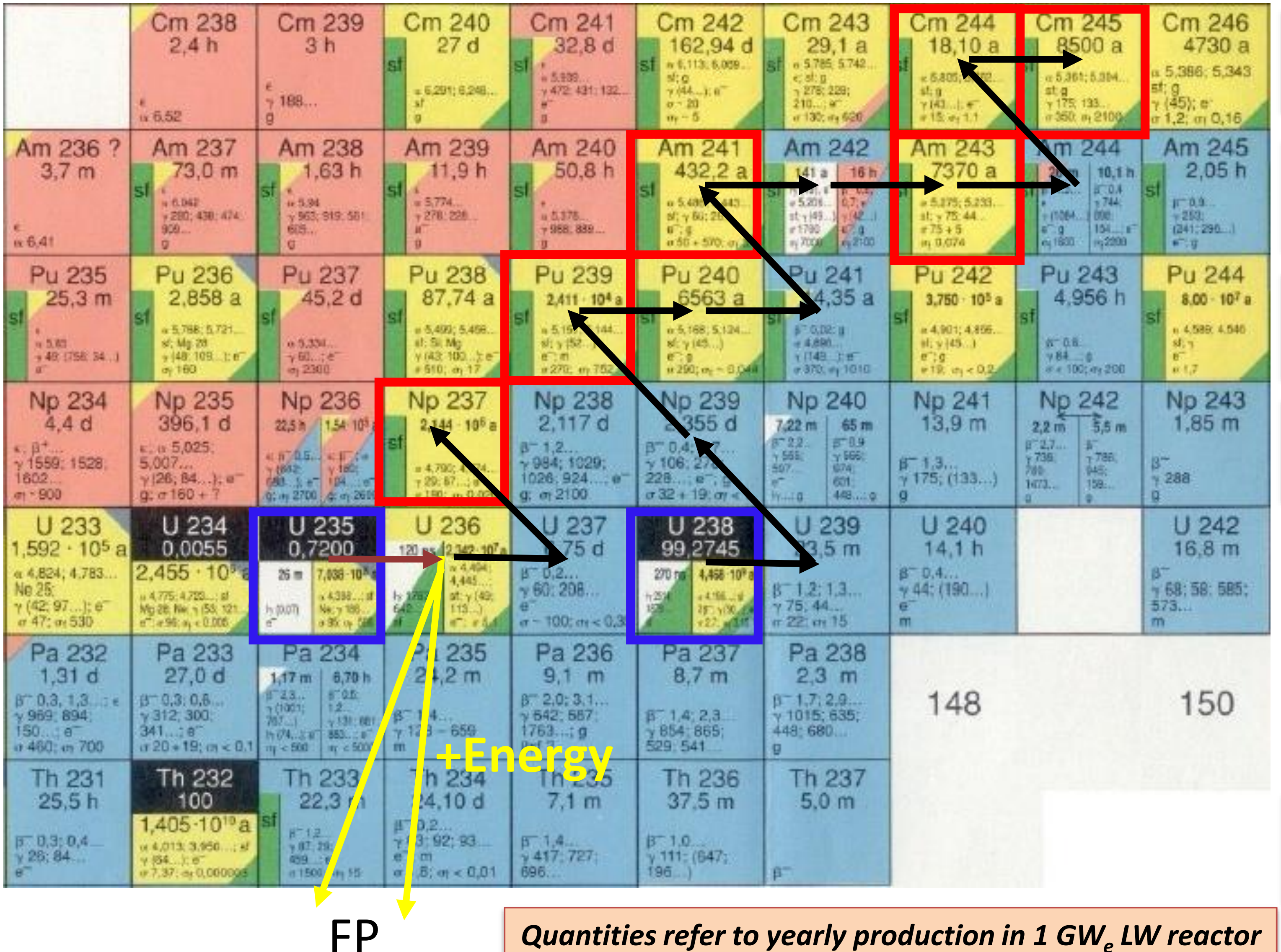






"Physics with neutron beams at the CERN n_TOF facility"
ISOLDE Seminar at CERN, January 23rd 2013

Neutrons and production of nuclear energy (& radioactive waste)



^{244,245}Cm
1.5 Kg/yr

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

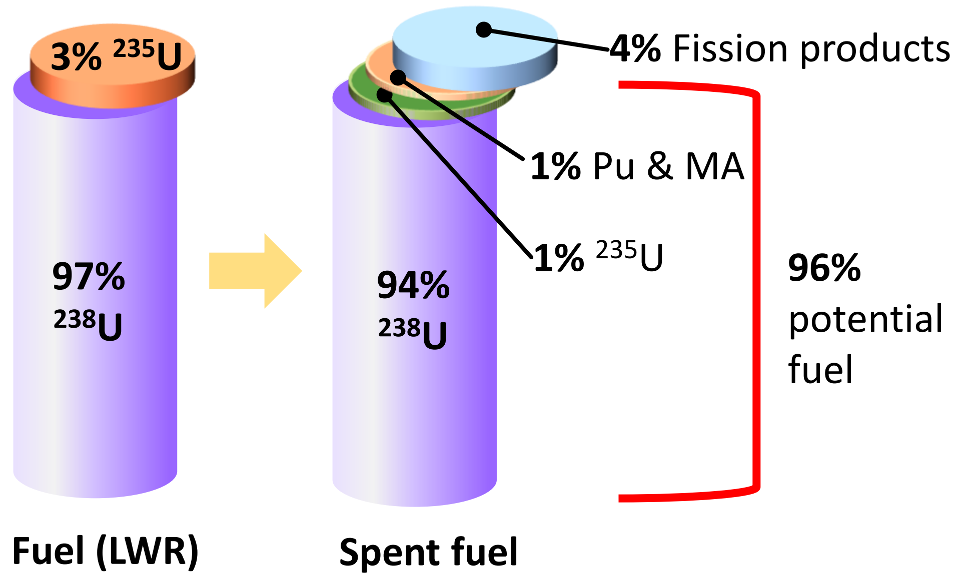
^{239}Pu: 125 Kg/yr

^{237}Np: 16 Kg/yr

LLFP
76.2 Kg/yr

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

Neutrons and production of nuclear energy (& radioactive waste)



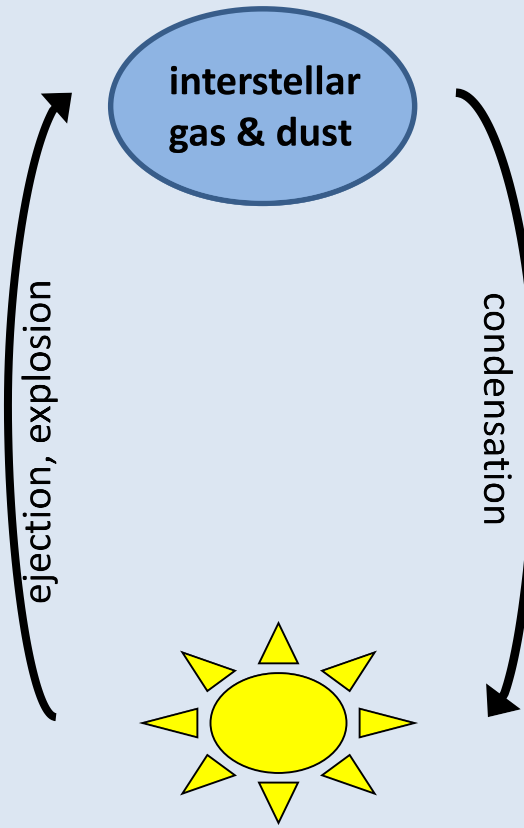
New nuclear reactor concepts:

a) Gen-IV: Fast reactors that can operate with fuels including U, Pu and MA
b) ADS (Accelerator Driven Systems): dedicated nuclear waste burners

New fuels composition and different neutron energy regime call for new reactions, whose cross sections are not known with the required accuracy.

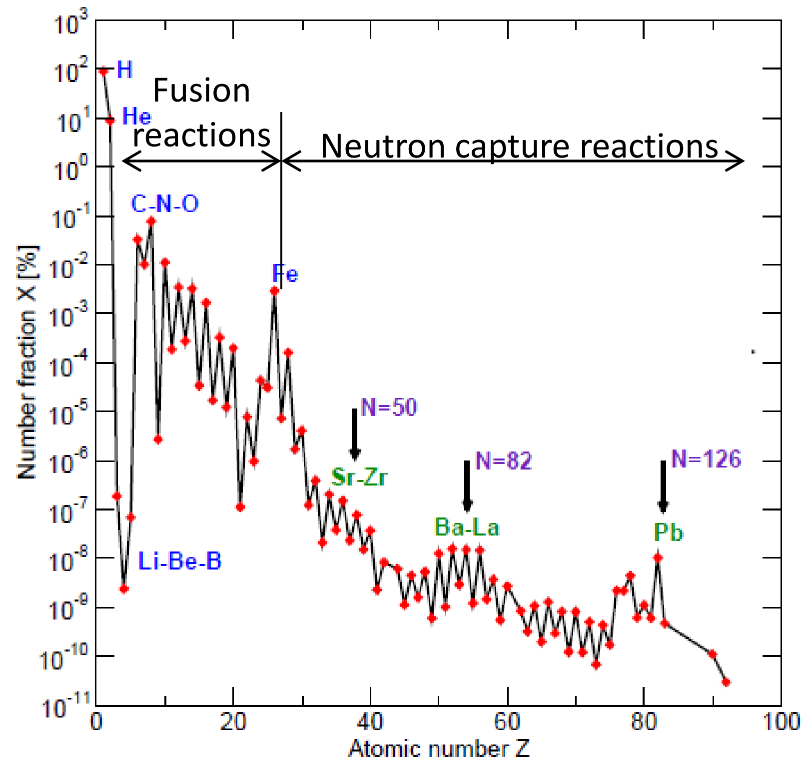
Neutrons and production of isotopes in stars: The *s*-process

Mixing
(abundance distribution)



Nuclear reactions:
- energy generation
- nucleosynthesis

Solar system elemental abundances

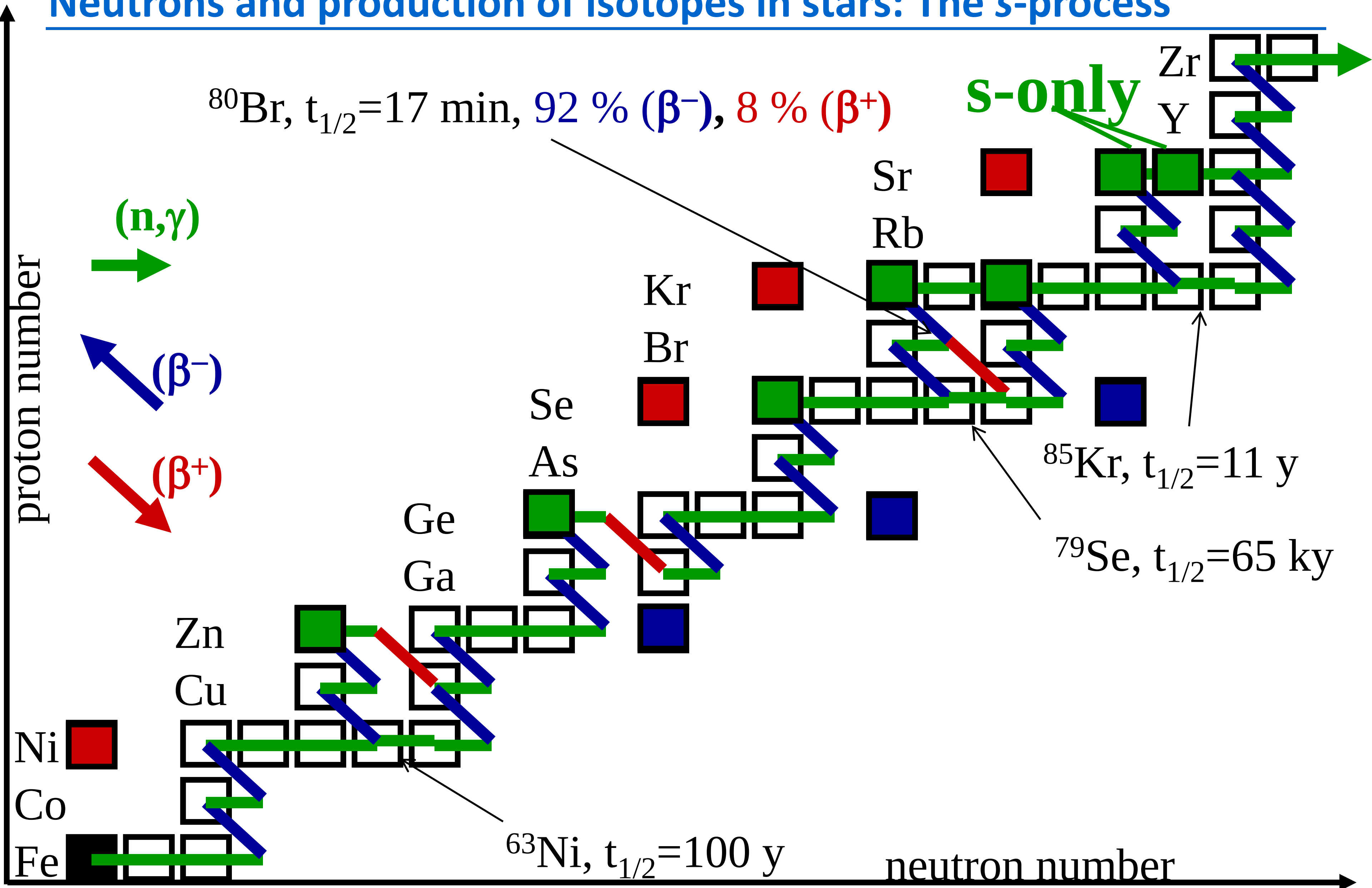


Chemical elements beyond Iron are synthesized via neutron capture reactions in stars:

~ ½ by the s-process (red giants)

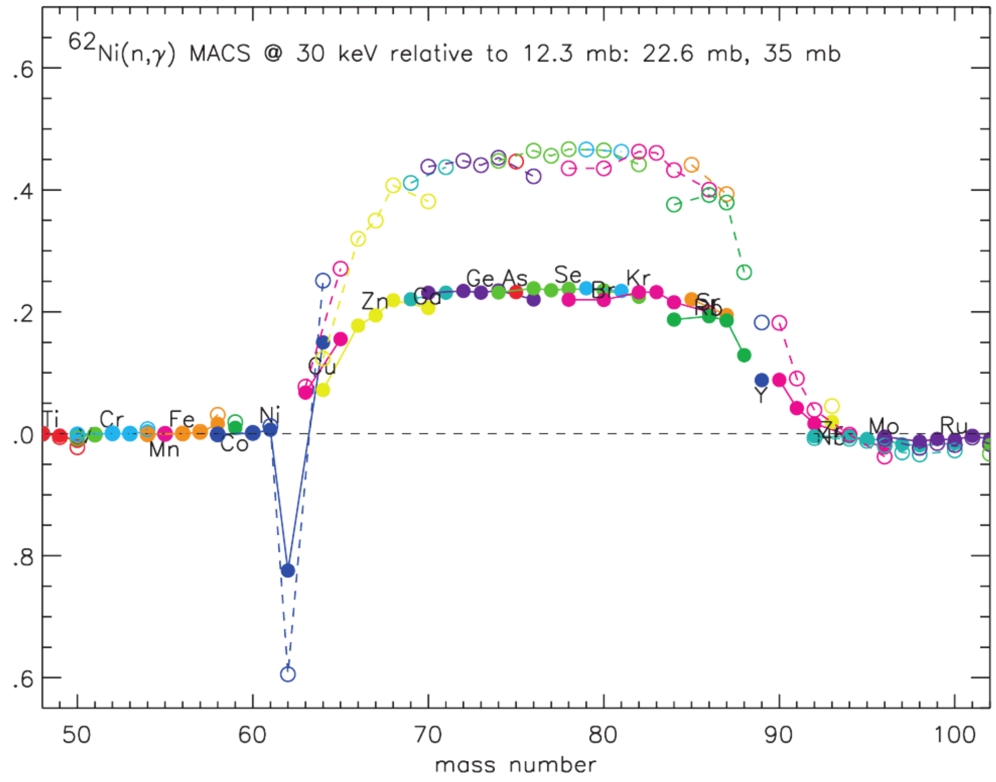
~ ½ by the r-process (explosive)

Neutrons and production of isotopes in stars: The *s*-process



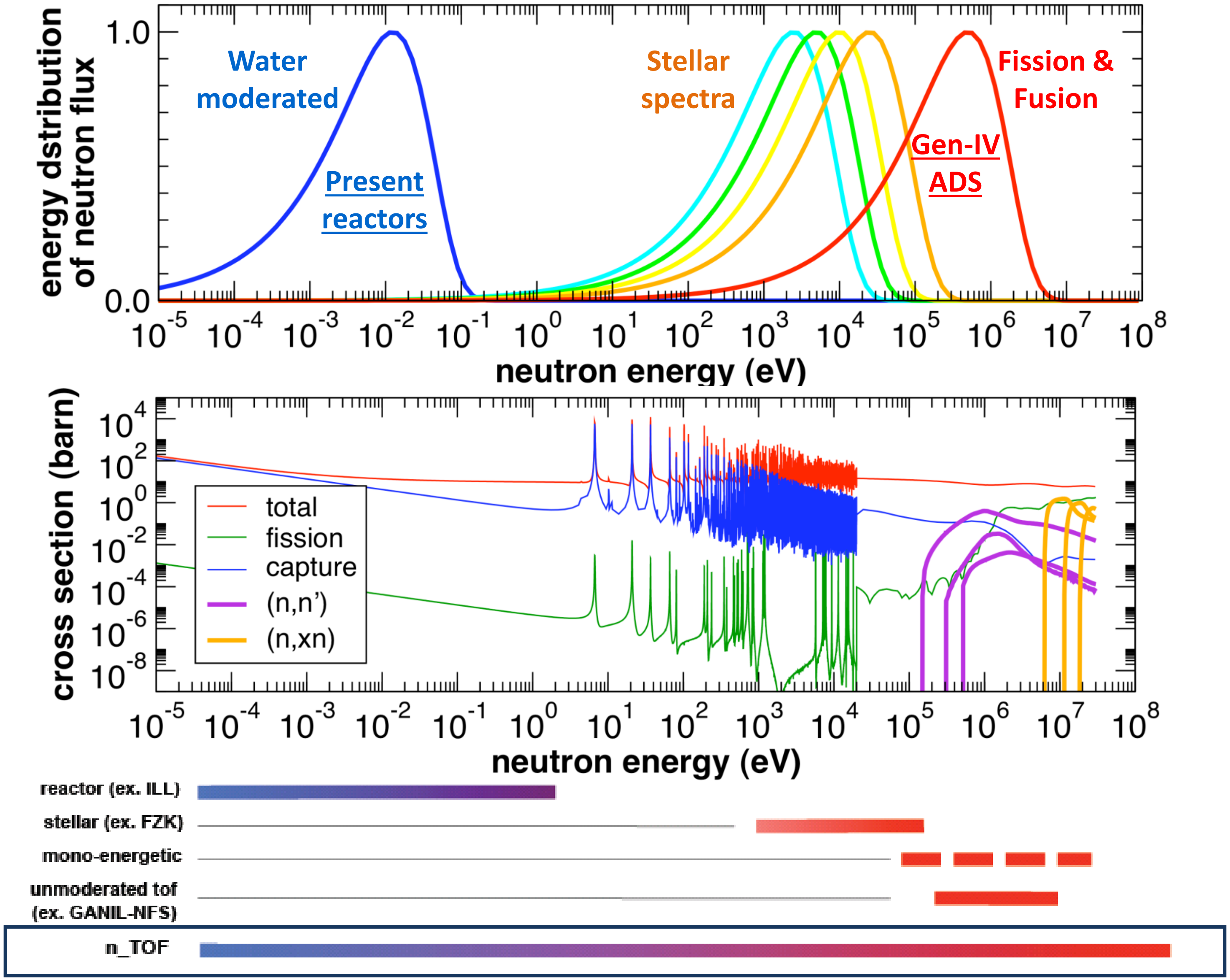
Neutrons and production of isotopes in stars: The *s*-process

In the weak s-process region the abundances of isotopes from Fe to Zr are highly affected by the knowledge of the cross section of every single isotopes:
Conclusions can be drawn only when ALL cross sections are known!



n_TOF campaign to measure all the available isotopes of Fe & Ni:
^{54,56,57,58}Fe // ^{58,60,61,62,63,64}Ni

Neutrons and cross sections: energy distributions



The n_TOF facility at CERN

The n_TOF Collaboration

The n_TOF Collaboration
30 Research Institutions from Europe, Asia and USA.
16 PhD students!

NUCLEAR ASTROPHYSICS: stellar nucleosynthesis

Neutron capture and (n,α) cross section of stable & unstable medium mass isotopes playing a role in the *s*- and *r*-processes (0.1-300 keV).

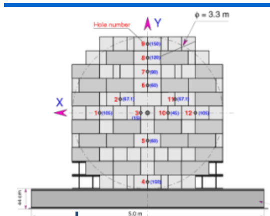
NUCLEAR TECHNOLOGIES: ADS, Gen-IV and Th/U fuel cycle

Neutron capture and fission cross sections of Actinides and Fission Fragments in the thermal (meV), epithermal (eV-keV) and fast (MeV) energy ranges.

BASIC NUCLEAR PHYSICS: levels densities, γ-ray strength functions and ang. distributions

Time-of-Flight measurements with dedicated detectors provide very valuable information on basic nuclear physics quantities.

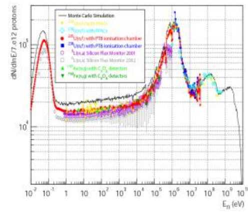
n_TOF Facility Timeline



1995-1997 **TARC** experiment

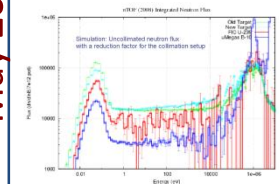
May 1998 **Feasibility** CERN/LHC/98-02+Add

2000 **Commissioning**

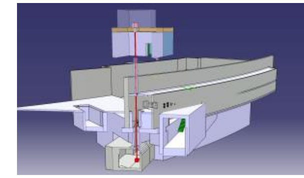


2008 **New Target** construction

May 2009 **Commissioning**



2011 **EAR2** design



2014 **EAR2** Commissioning

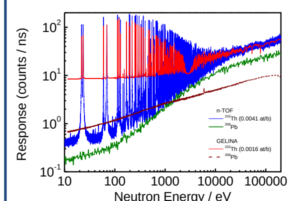
1996 — **2012**

V. Vlachoudis

1997 **Concept** by C.Rubbia CERN/ET/Int. Note 97-19

Aug 1998 **Proposal** submitted

1999 **Construction** started



2001-2004 **Phase I**
Isotopes
Capture: 25
Fission: 11
Papers: 43
Proc.: 51

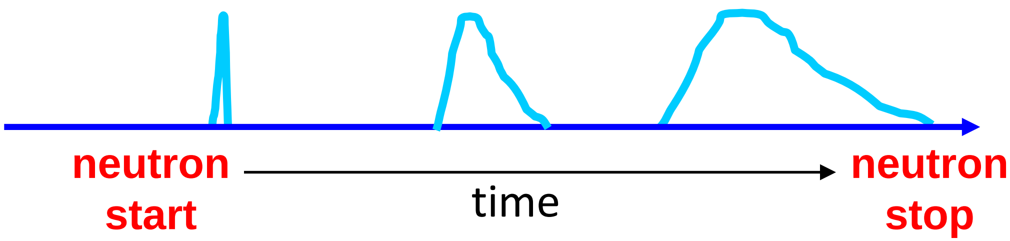
2004-2007 **Problem** Investigation

2009 **Phase II**

2010 **Upgrades:**
Borated-H_2O
Second Line
Class-A

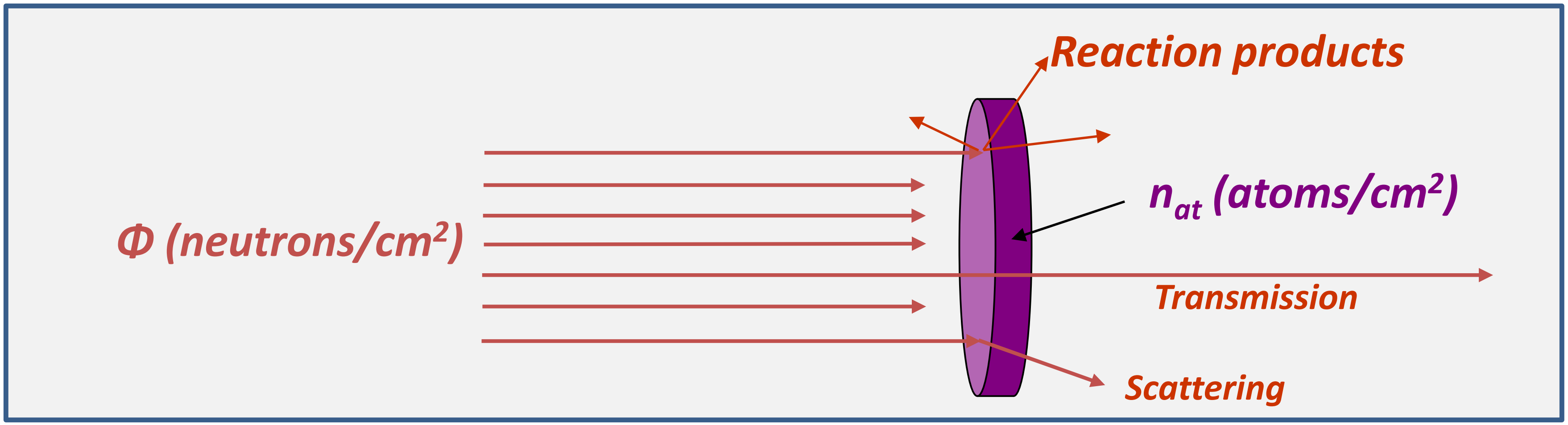
Measurement of neutron-induced cross sections: ToF technique

neutron time-of-flight experiment



Time-of-Flight to E_n relation (non-rel.):

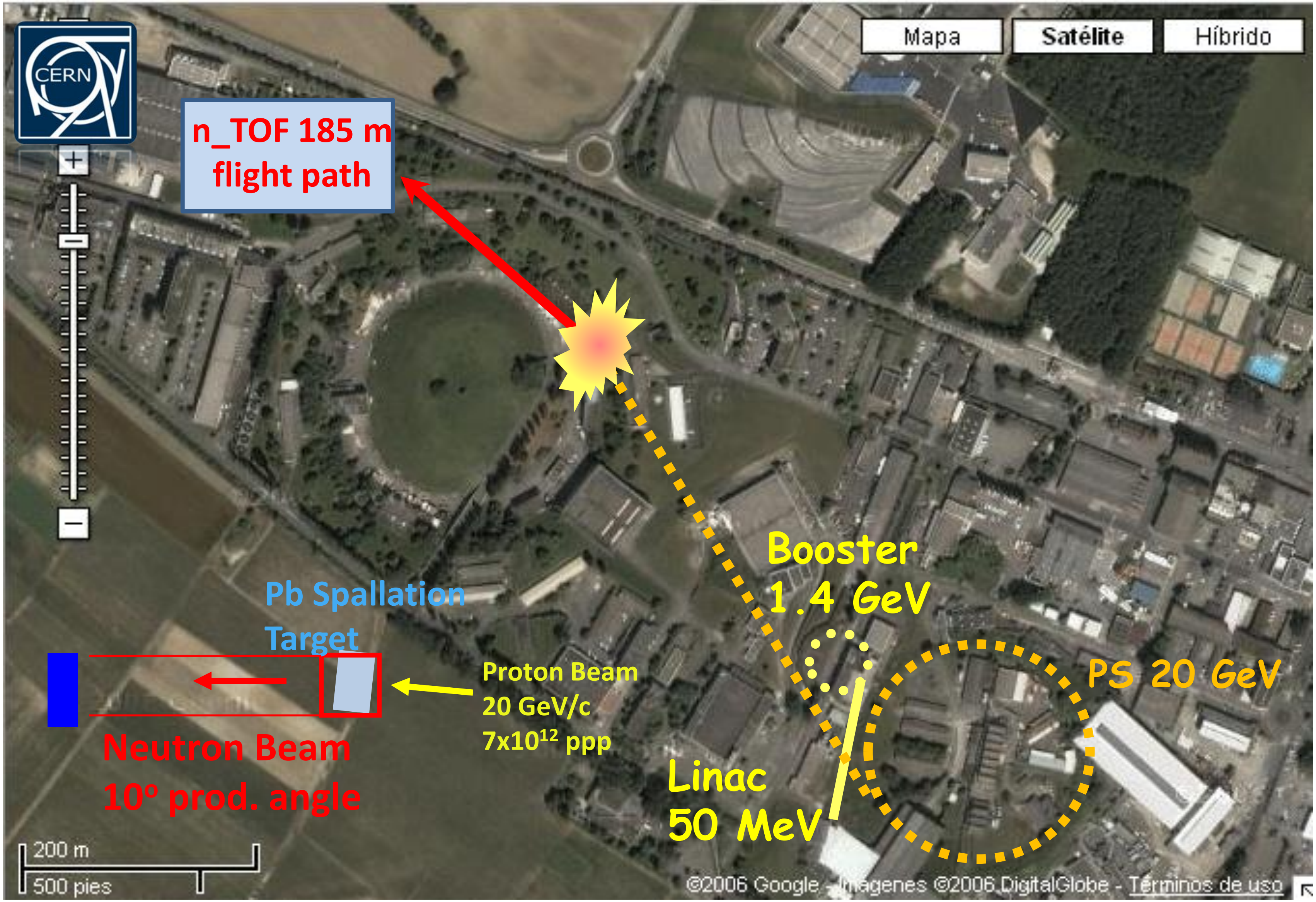
$$ToF \propto \frac{L}{\sqrt{E_n}}$$



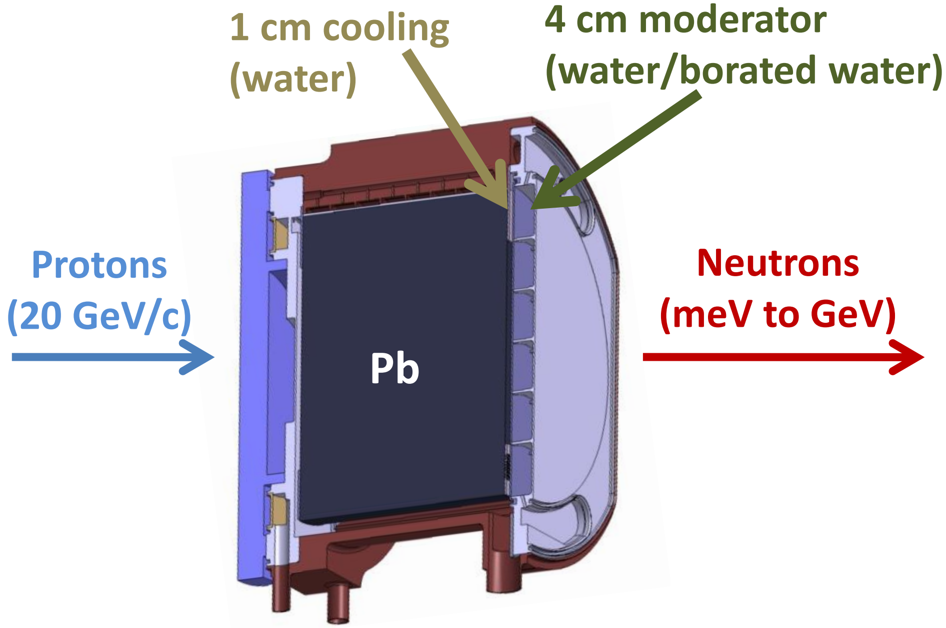
Measuring the neutron cross sections requires:

- A facility providing a neutron beam (The n_TOF facility).
- A detection system for counting the reactions
- A highly pure sample.
- A theoretical framework to express the cross sections (*R*΄- matrix formalism).

The n_TOF Facility at CERN: a Google view



The n_TOF lead spallation target (from 2008 onwards)



1. Approx. 400 FAST (MeV-GeV) neutrons/proton (20 GeV/c) are generated @target
2. They are slowed-down (MODERATED) in 5 cm of water+^{10}B-water: meV to GeV
3. A fraction reaches the experimental hall after 185 meters of vacuum

ToF (GeV) ~ 630 ns

ToF (MeV) ~ 13 μs

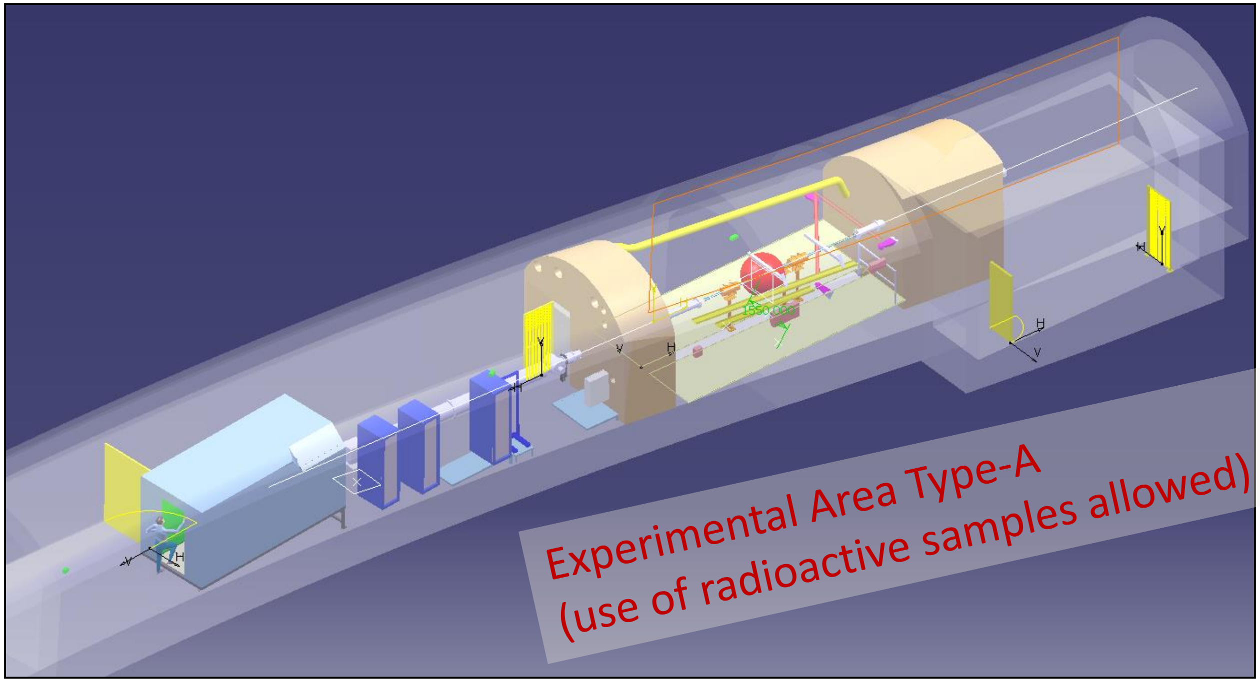
ToF (keV) ~ 420 μs

ToF (eV) ~ 13 ms

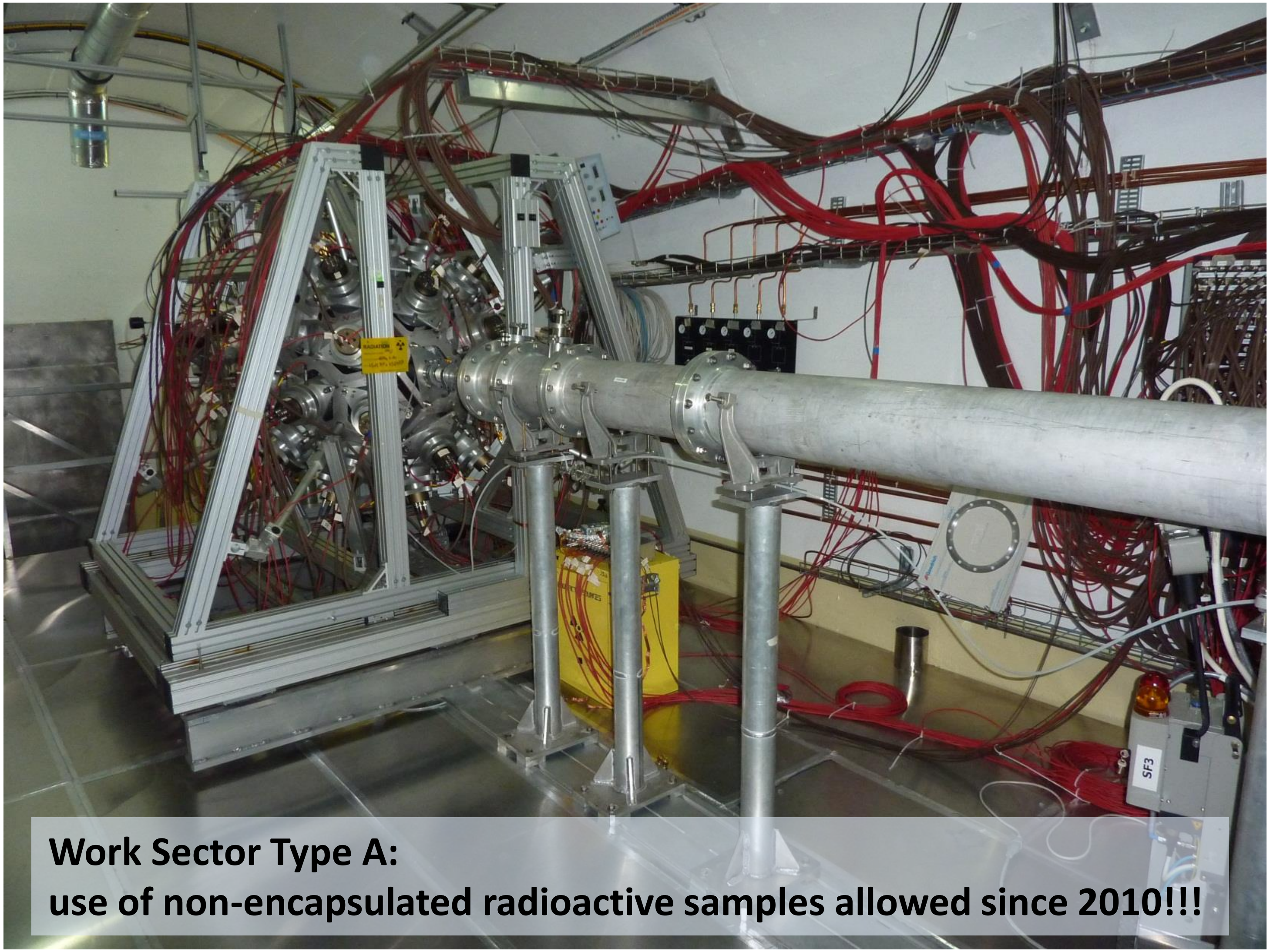
ToF (10 meV) ~ 133 ms

The n_TOF Facility in pictures



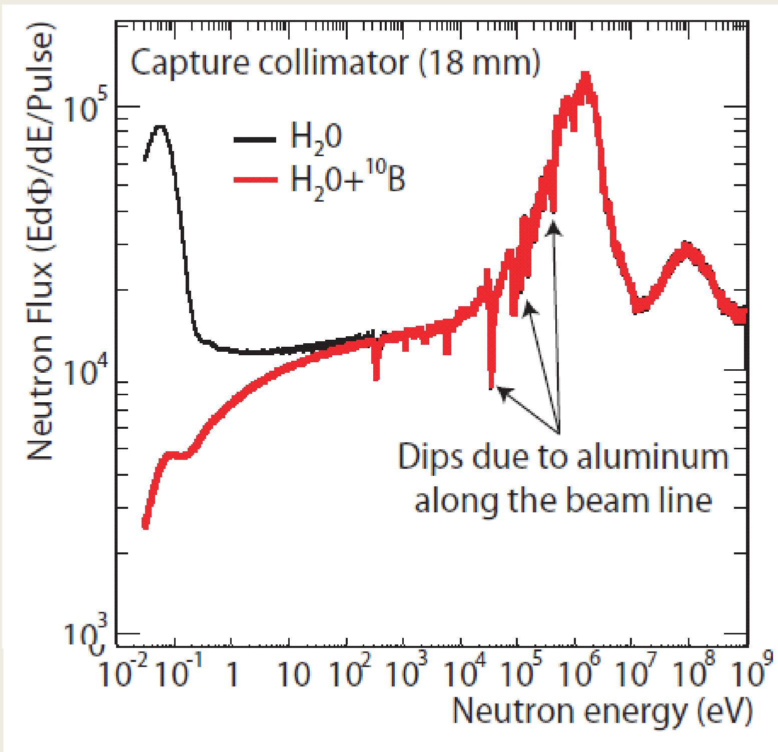
The n_TOF Facility in pictures



Work Sector Type A:
use of non-encapsulated radioactive samples allowed since 2010!!!

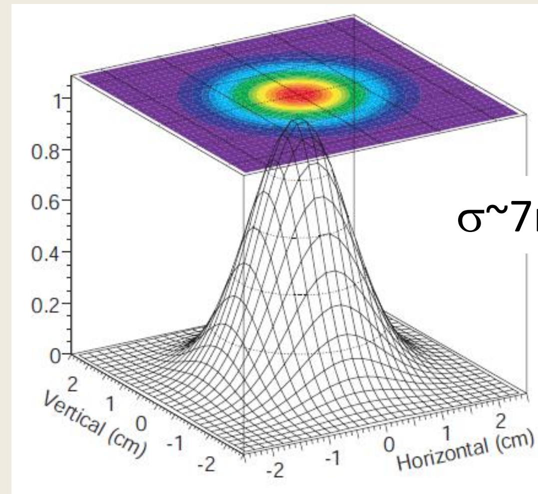
Main characteristics of the n_TOF neutron beam

NEUTRON FLUX



$0{,}6\cdot10^6$ neutrons/pulse (capture mode)
$12\cdot10^6$ neutrons/pulse (fission mode)

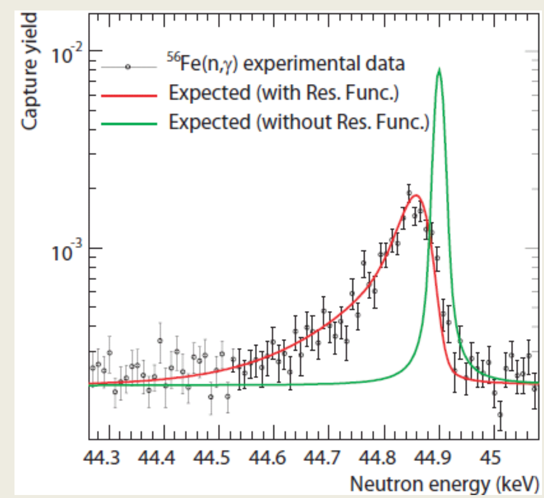
BEAM PROFILE



σ~7mm

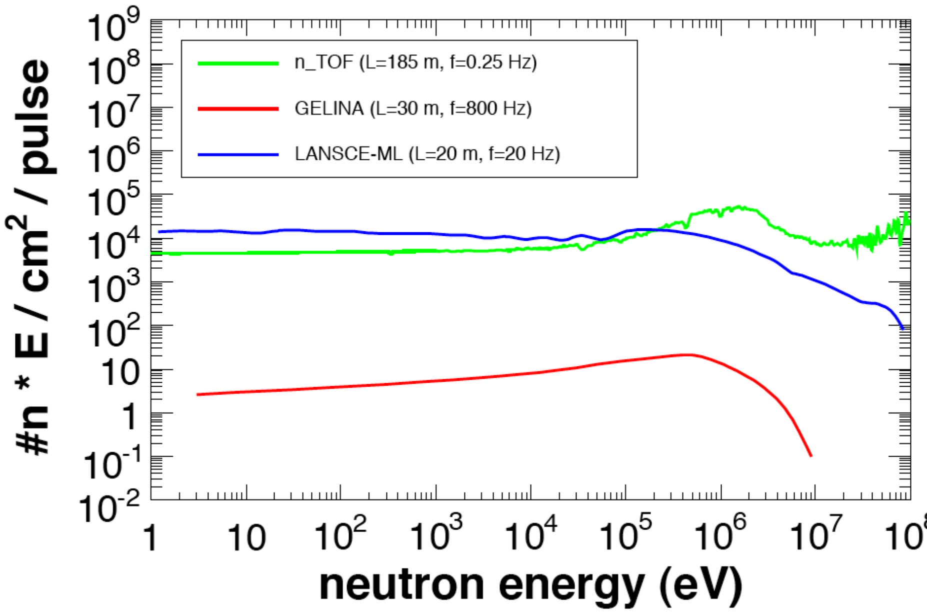
ENERGY RESOLUTION

E_n (eV)	$\Delta E_n/E_n$
1	$4.3\cdot10^{-4}$
10	$4.3\cdot10^{-4}$
10^2	$4.3\cdot10^{-4}$
10^3	$7.5\cdot10^{-4}$
10^4	$1.7\cdot10^{-3}$
10^5	$5.4\cdot10^{-3}$
10^6	$2.8\cdot10^{-3}$



Main characteristics of the n_TOF neutron beam

- Proton **intensity** — *$8x10^{12}$ p/pulse*
- Proton beam **momentum** — *20 GeV/c*
- Proton **pulse width** — *6 ns (rms)*
- high **instantaneous n flux** — *10^5 n/cm^2/pulse*
- wide energy **spectrum** — *25 meV<E_n<1GeV*
- low **repetition** rate — *< 0.25 Hz*
- good energy **resolution** — *$\Delta E/E = 10^{-4}$*

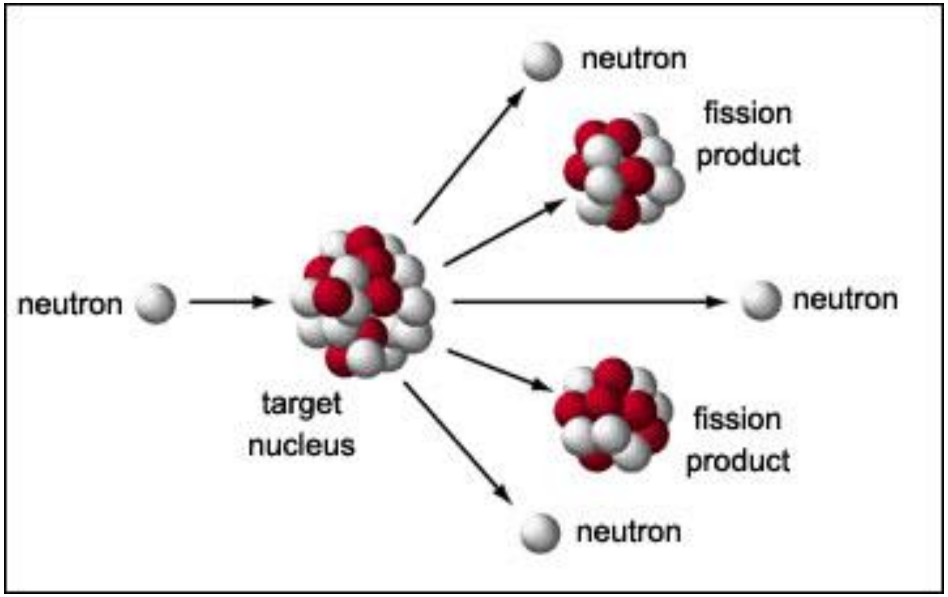


Neutron beam + state-of-the-art detectors and acquisition systems make n_TOF **UNIQUE** for:

- measuring **radioactive isotopes**, in particular **actinides**
- identifying and studying **resonances** (at energies higher than before)
- extending **energy range** for fission (up to 1 GeV !).

Measurements at n_TOF

Detection of neutron induced fission reactions



The most easy and clean method for measuring fission reactions is based in the **detection of at least one of the fission fragments**: ionization chambers!

Detection of neutron induced fission reactions

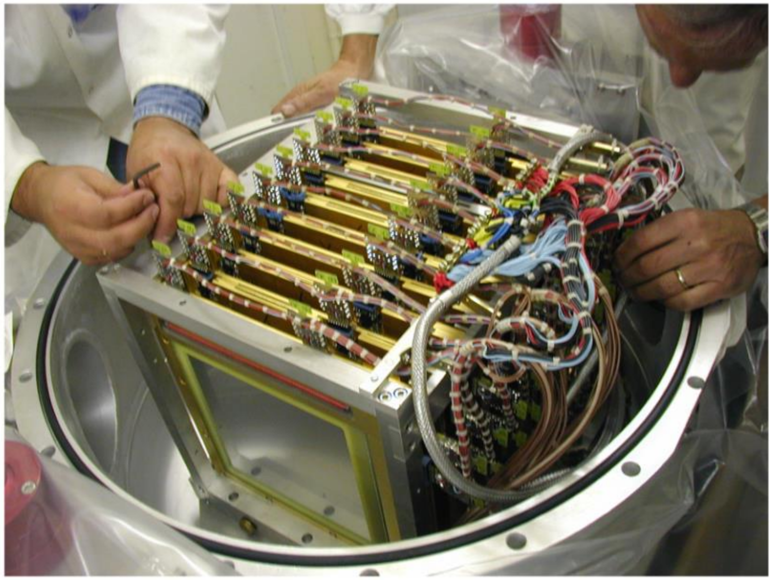
The main problem in fission measurements is the **background** due to **α-decay**.
At n_TOF the background minimized by the very **high instantaneous** neutron flux.

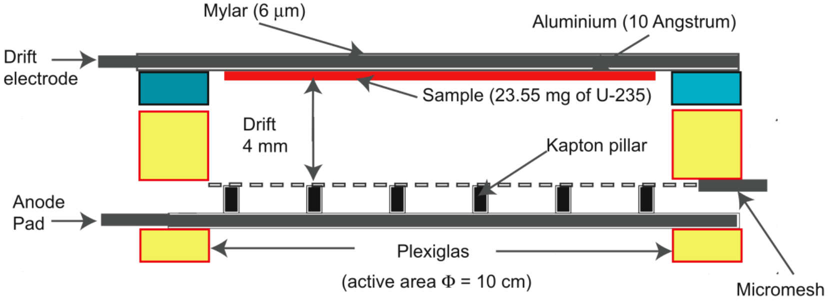
Micromegas (MGAS) detectors

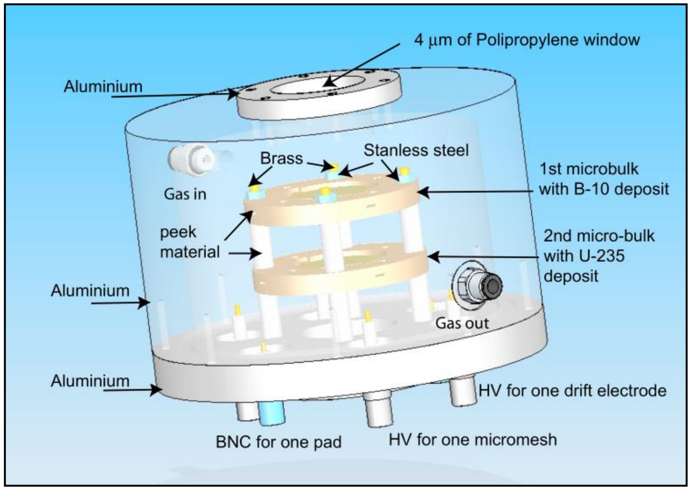
- low-noise, high-gain, radiation-hard detector

Parallel Plate Avalanche Counters (PPAC)

- Fission fragments detected **in coincidence**
- Very good rejection of α-background
- Provide info on angular distr. of fission fragments





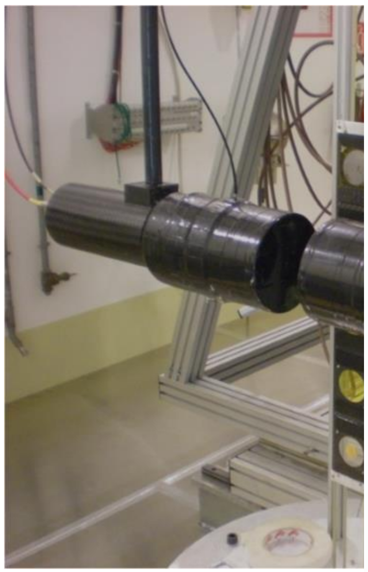


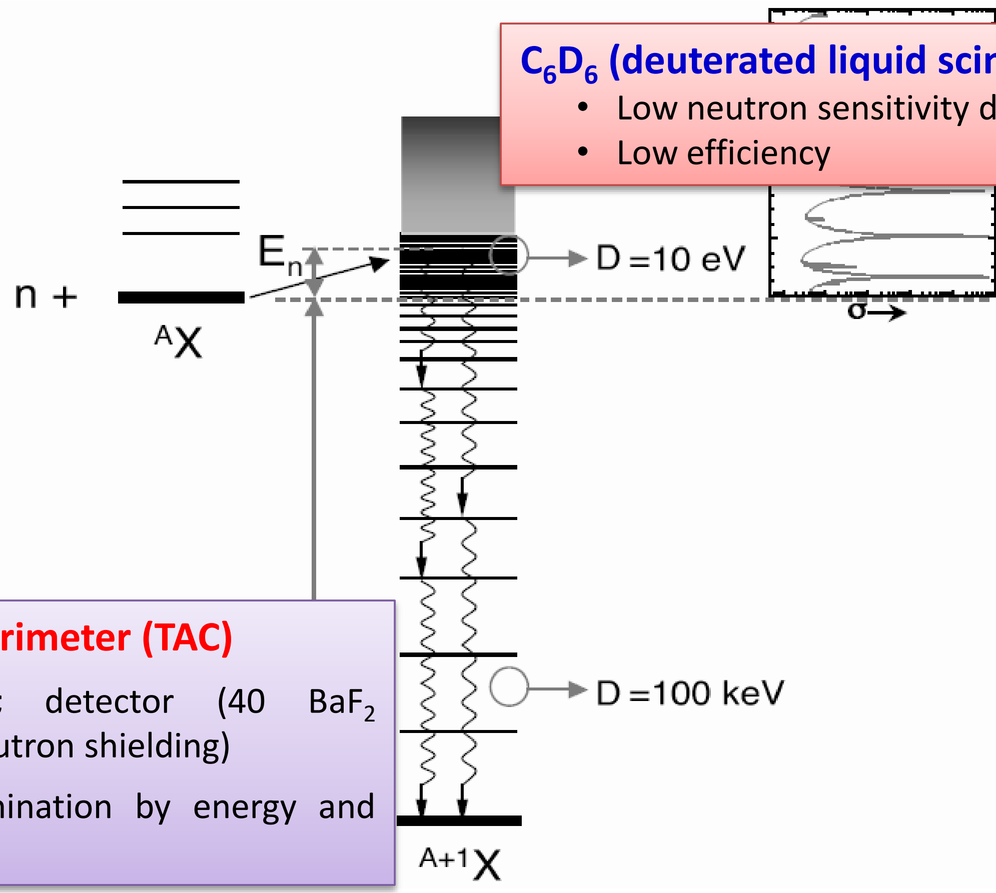
Detection of neutron capture reactions

Neutron capture reactions are measured by:

<u>detecting the γ-rays emitted in the de-excitation process</u>.

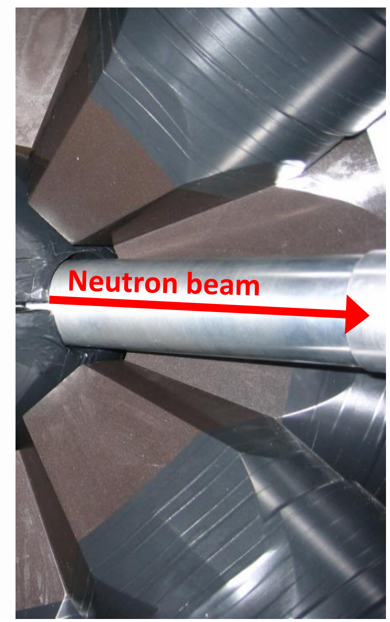
At n_TOF two different systems are available to minimize different types of background





C_6D_6 (deuterated liquid scintillators)

- Low neutron sensitivity device
- Low efficiency



Total Absorption Calorimeter (TAC)

- High-efficiency **4π** detector (40 BaF_2 scintillators with neutron shielding)
- Background discrimination by energy and multiplicity

Detection of (n,α) reactions

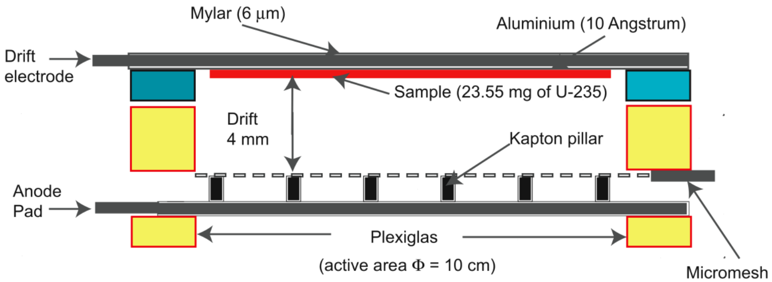
The main problem in (n,α) measurements is the background from other reactions in the sample, or in the detectors (gas recoils, etc.)

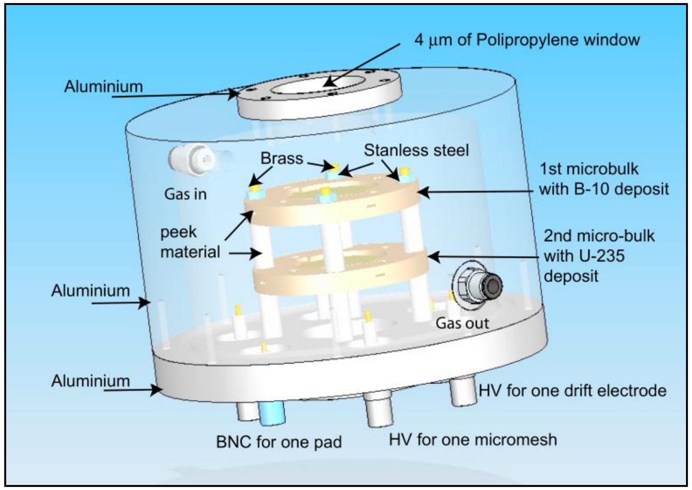
Micromegas chamber (MGAS)

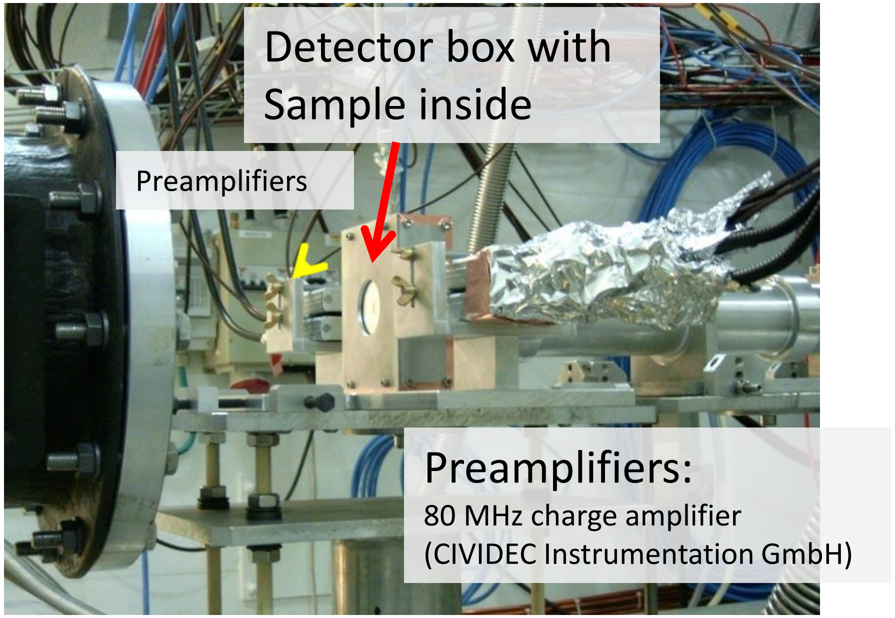
- low-noise, high-gain
- Several samples in parallel

Diamond (pCVD or sCVD)

- Background reactions only above 1 Mev
- Very fast response
- Particle discrimination (if sCVD or charge collection distance > 300 μm)







The neutron beam dump as neutron irradiation testing facility

Measurement of fast neutrons with a triple GEM
S. Puddu (CERN/RP) and F. Murtas (LNF-IFNN, Italy)

Test of a medipix device for neutron detection
C. Tecla (CERN/RP)

First test of a 3D silicon detector with fast neutrons
R. Palomo (U. Sevilla, Spain), I. Vila (CSIC, Spain) et al.

Diamond detectors response function to quasi-monochromatic high-energy neutrons
E. Perelli, M. Rebai, A. Pietropaolo et al. (CNR, Italy)

On the use of FBG optic fibers as neutron dosimeters
R. Palomo (U. Sevilla, Spain), I. Vila (CSIC, Spain) et al.

SELECTED MEASUREMENTS
(just four)

n_TOF Phase2 (2009-2012)

Nuclear technologies

Nuclear Astrophysics

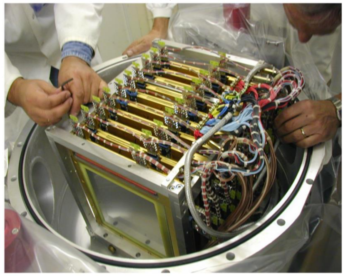
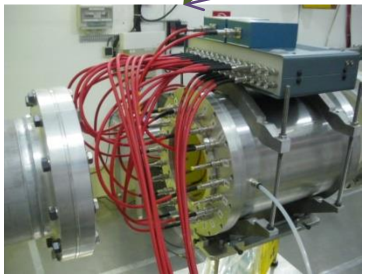
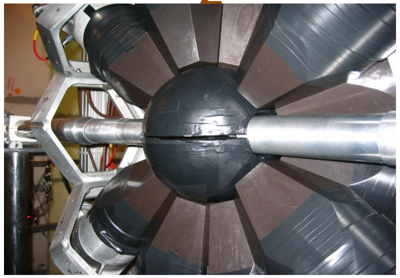
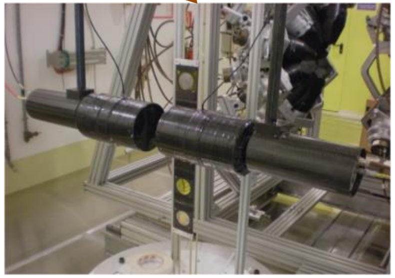
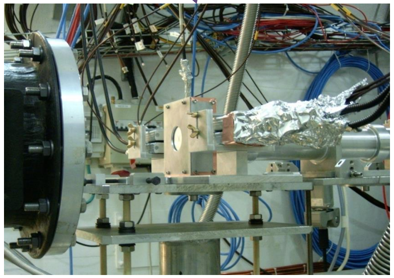
Medical applications

Ang. Distrib. FF
^{232}Th, ^{237}Np, ^{235,236,238}U

Fission
^{240,242}Pu, <u>^{235}U</u>

Neutron capture
^{54,56,57}Fe, ^{58,60,62,}<u>^{63}Ni</u>, ^{25}Mg,
^{93}Zr, <u>235</u>, ^{236,238}<u>U</u>, ^{241}Am

(n,α)
^{10}B, ^{33}S, <u>^{59}Ni</u>

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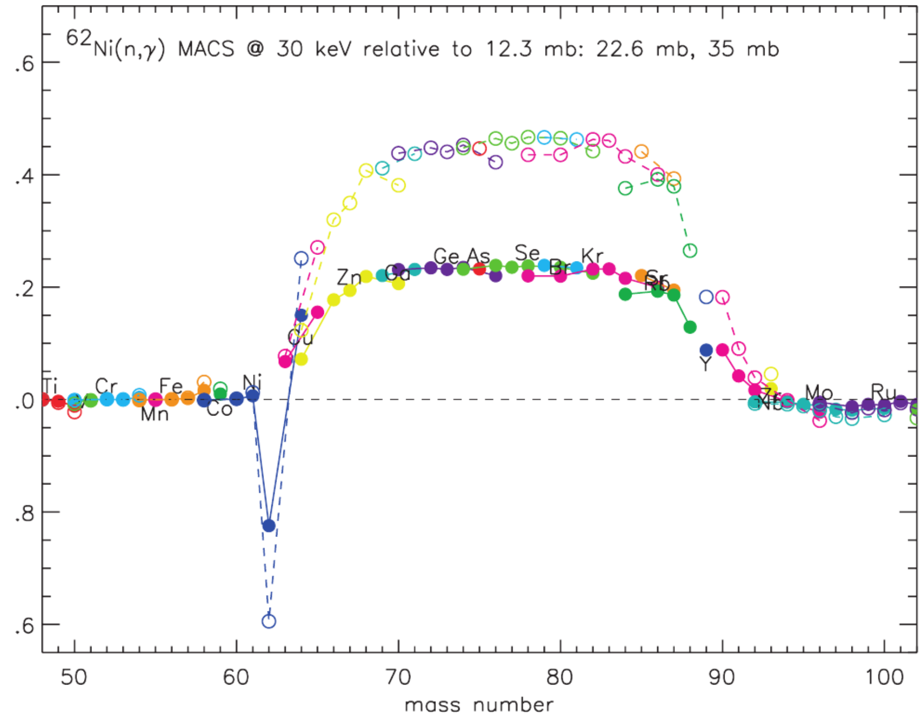
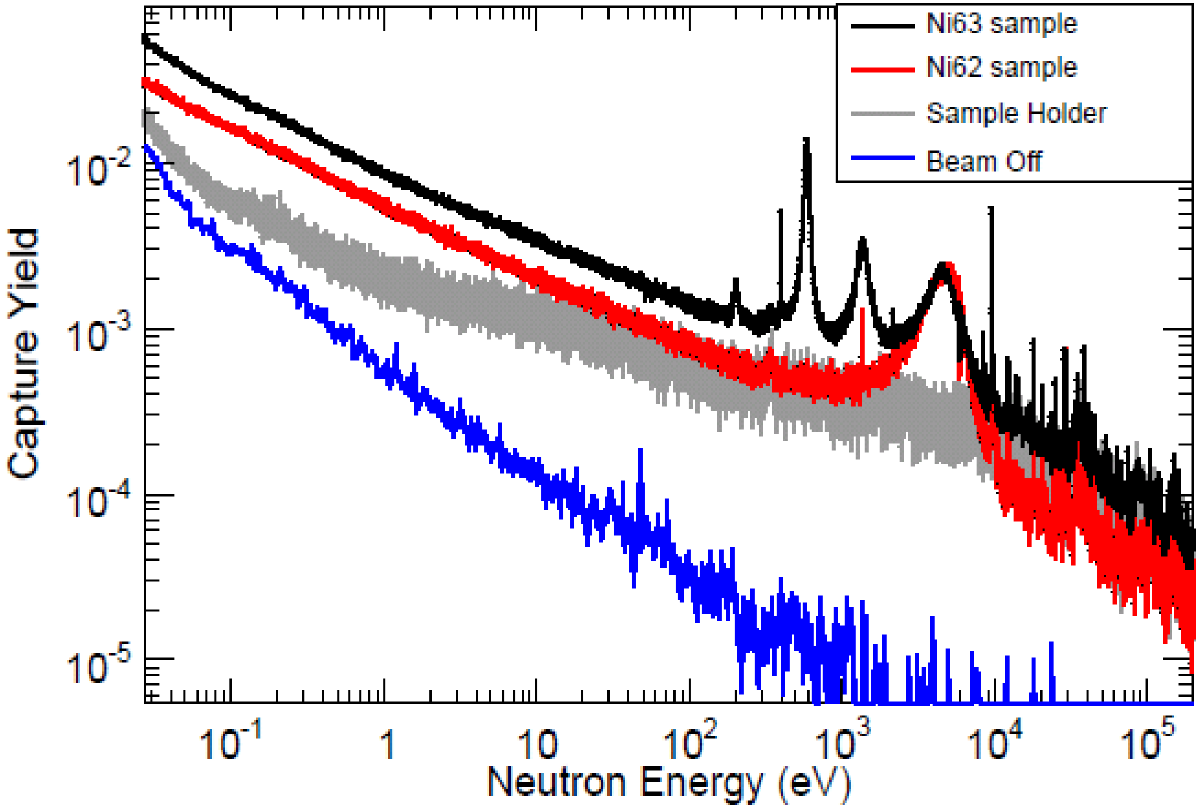


n_TOF campaign to measure the σ(n,γ) of all the key isotopes of Fe and Ni:

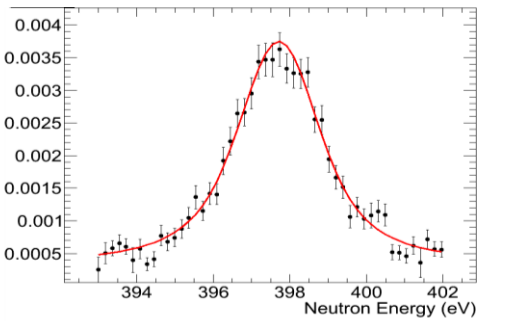
$^{54,56,57,58}Fe$ // $^{58,60,61,62,63,64}Ni$

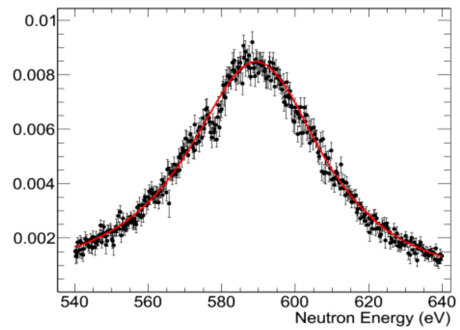
Unstable ^{63}Ni produced by irradiation for years of ^{62}Ni in nuclear reactor: ~100 mg of ^{63}NiO powder

First RRR measurement ever



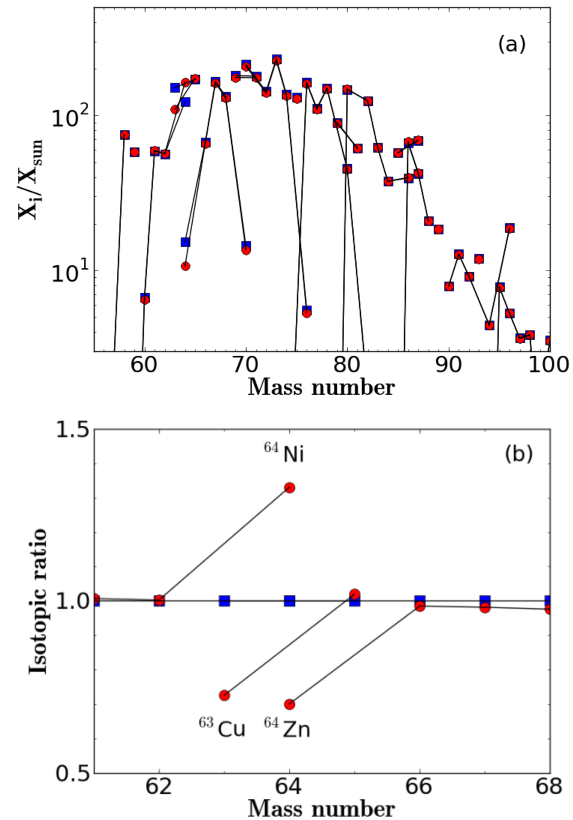
The neutron capture cross section of the s-process branch point isotope ^{63}Ni





E_r (eV)	A_γ (meV)	E_r	A_γ (meV)
397.96 ± 0.04	5.7 ± 0.4	9776 ± 3	100 ± 10
$587.25 \pm 0.09^*$	340 ± 20	13984 ± 3	131 ± 45
$1366 \pm 1^*$	810 ± 40	17127 ± 4	108 ± 59
8634 ± 2	45 ± 9	19561 ± 6	130 ± 20
8981 ± 3	50 ± 10	32330 ± 10	500 ± 200
9154 ± 4	43 ± 9	54750 ± 30	700 ± 200

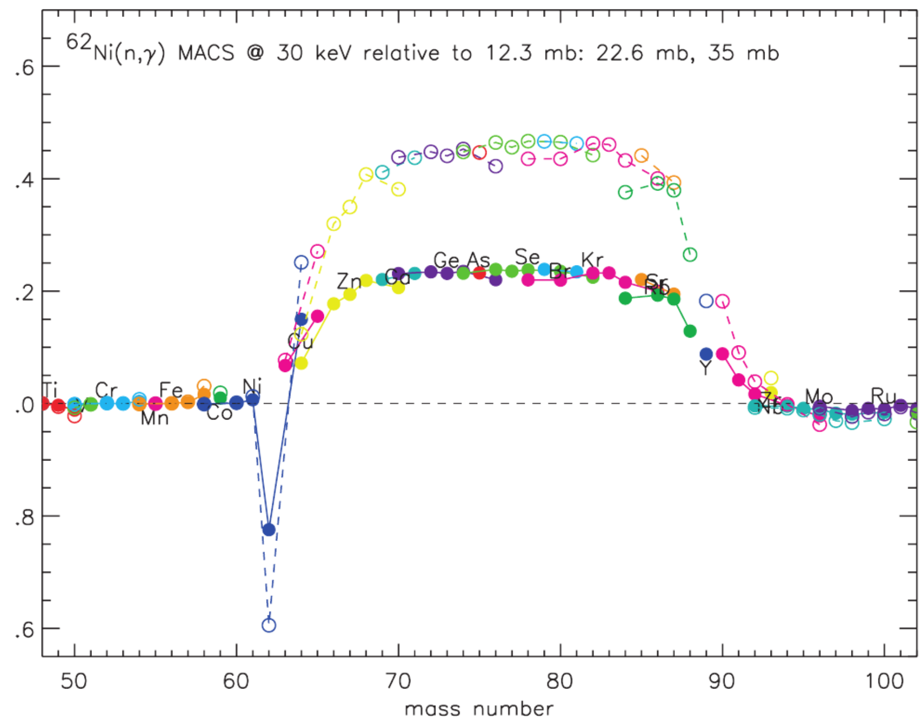
Measured MACS 2-2.5 higher than the model calculated values:
some isotopic stellar abundances (^{64}Ni, ^{63}Cu, ^{64}Zn) change up to ~40%.



C. Lederer et al., Phys. Rev. Lett. **110** (2013) 022501

In the weak s-process region the abundances of isotopes from Fe to Zr are highly affected by the knowledge of the cross section of every single isotopes:

Conclusions can be drawn only when ALL cross sections are known!

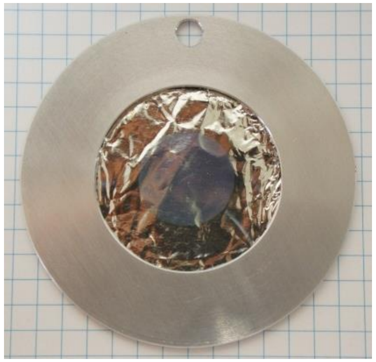


C. Weiss PhD work

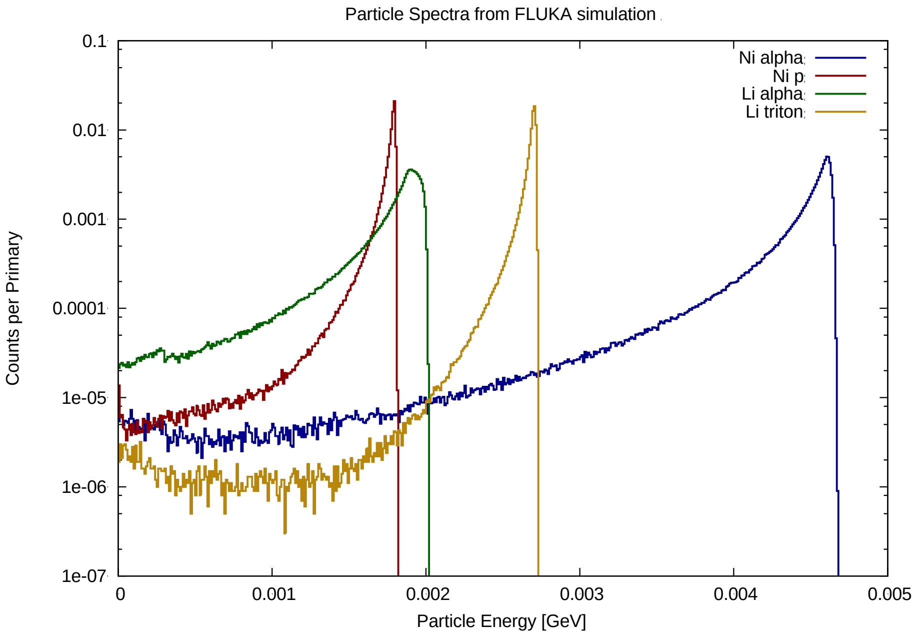
Sample from ORNL:

(180 ± 5) µg metallic Ni: 95% ^{59}Ni => 516 kBq (thickness = 102 nm)

(205 ± 5) µg LiF: 95% ^{6}Li (thickness = 394 nm)

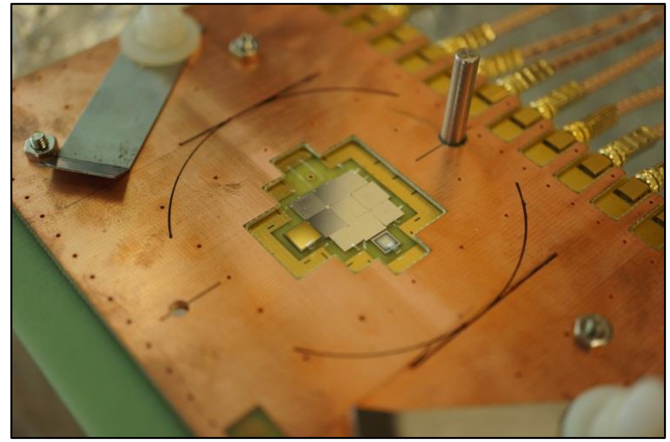


Reaction	Particle	E_{max} [MeV]
$^{59}Ni(n,\alpha)^{56}Fe$	α	4.76
$^{59}Ni(n,p)^{59}Co$	p	1.82
$^{6}Li(n,\alpha)^{3}H$	α	2.06
$^{6}Li(n,\alpha)^{3}H$	t	2.73

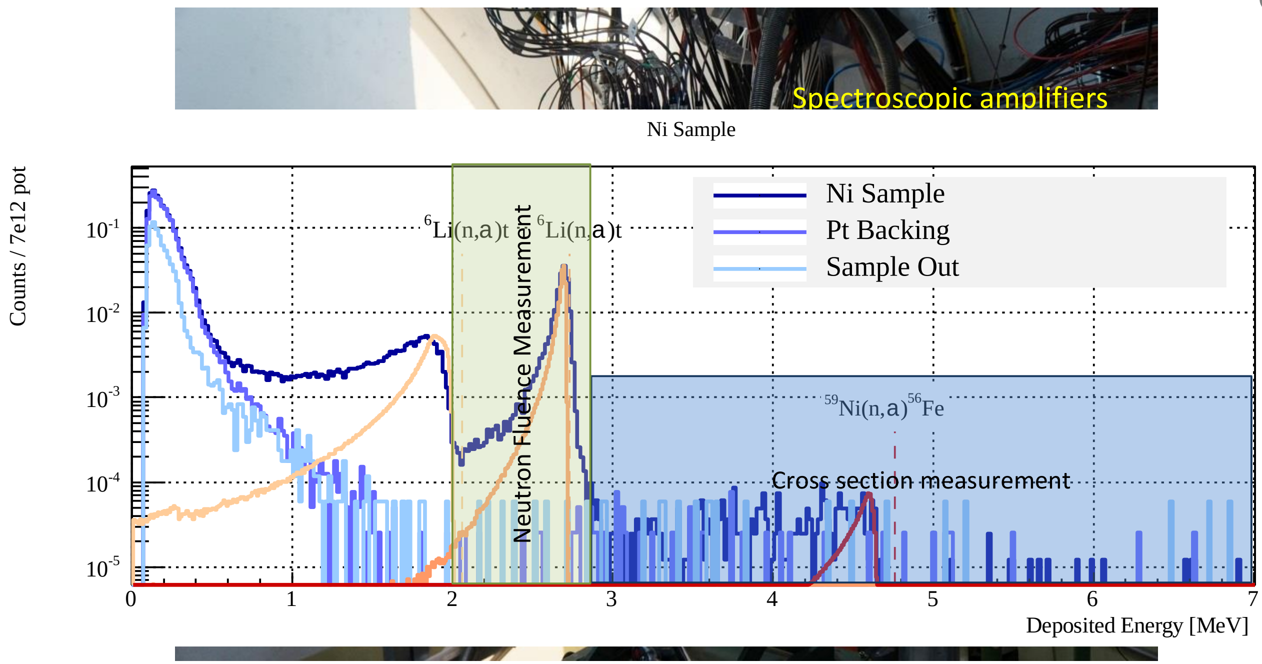


C. Weiss PhD work

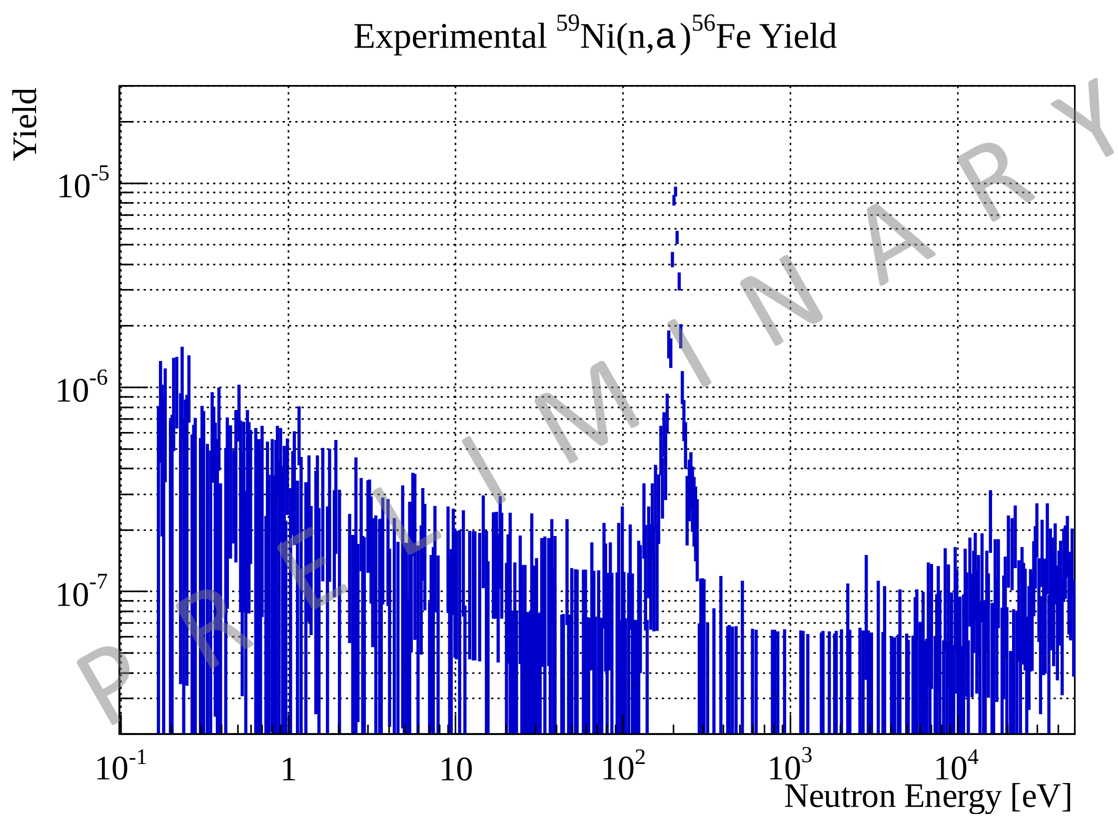
- 8 sCVD + 1 DOI diamond diodes:
  1. Thickness: 150 μm
  2. Electrodes: 200 nm Al



CIVIDEC



C. Weiss PhD work

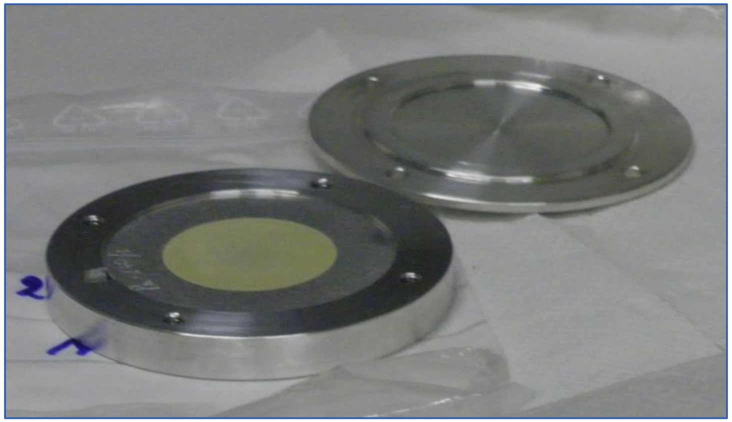


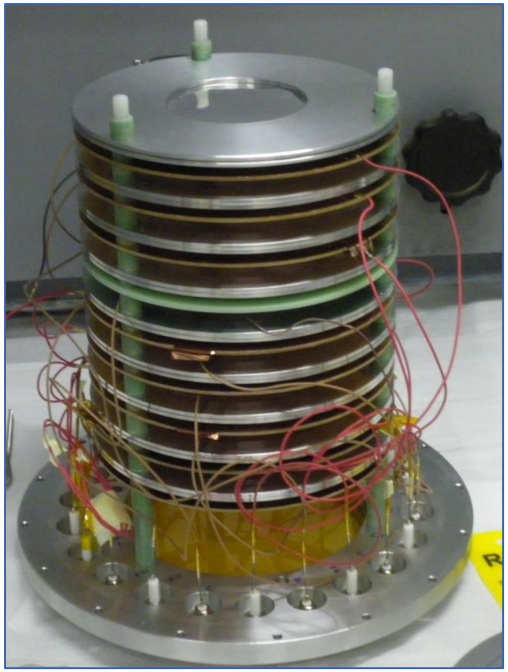
C. Weiss PhD work

Measurement of the fission cross-section of ^{240}Pu and ^{242}Pu at CERN's n_TOF Facility

^{242}Pu	
^{238}Pu	0.002719%
^{239}Pu	0.00435%
^{240}Pu	0.01924%
^{241}Pu	0.00814%
^{242}Pu	**99.96518%**
^{244}Pu	0.00036%
Mass	**3.0mg**
Activity	**1.2MBq**

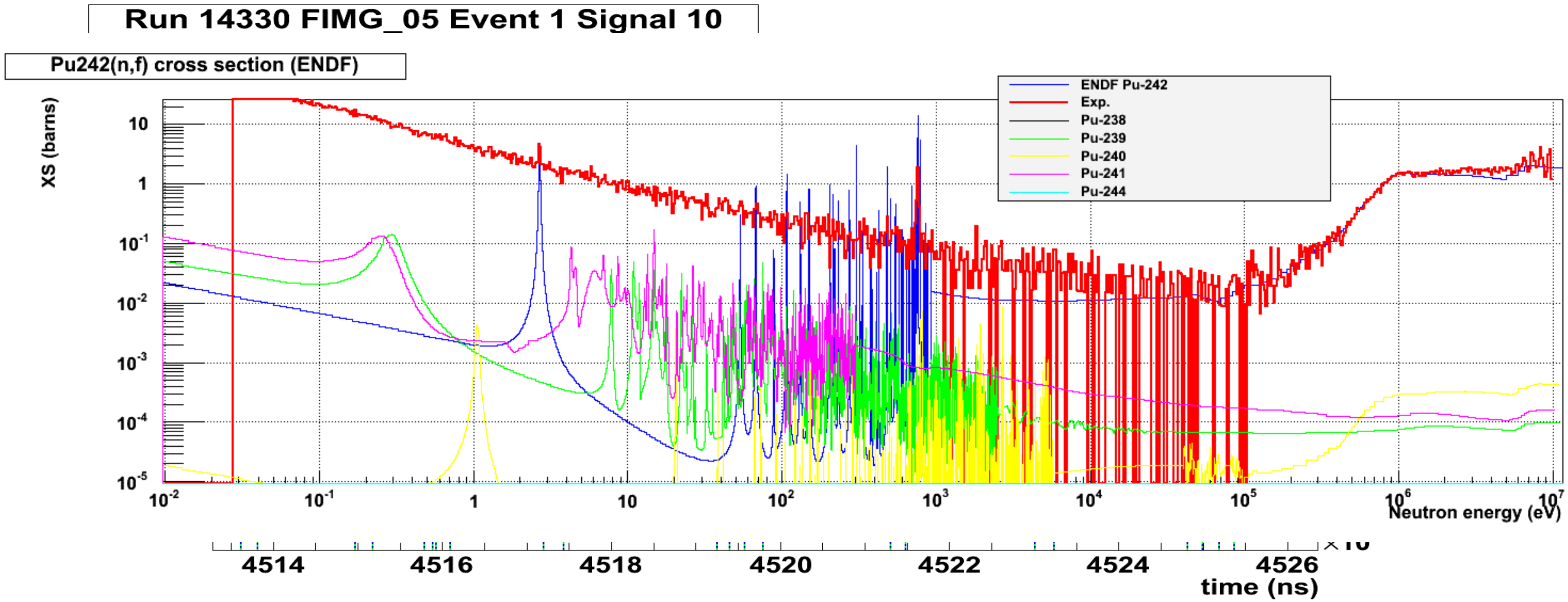
Also spontaneous fission!!





A. Tsinganis PhD work

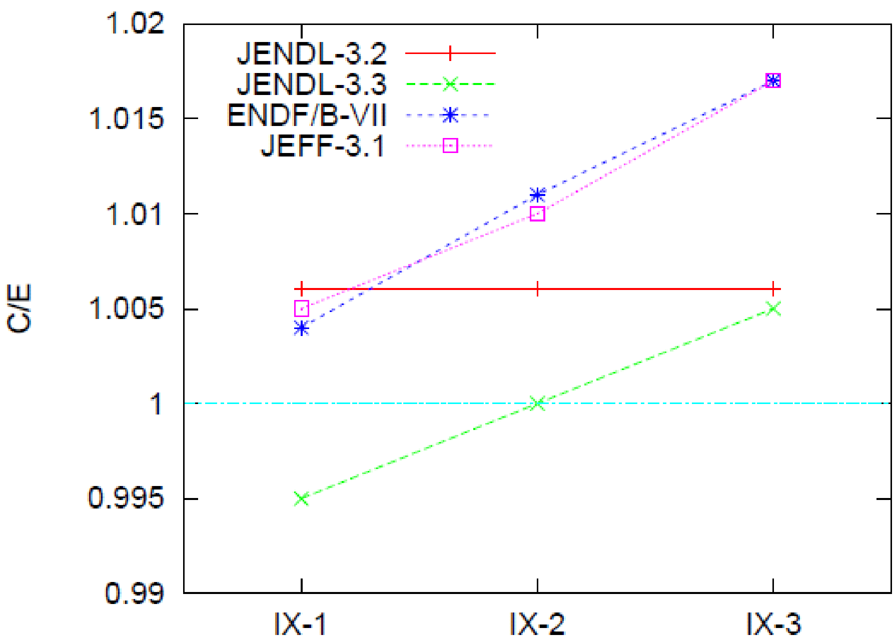
Measurement of the fission cross-section of ^{240}Pu and ^{242}Pu at CERN's n_TOF Facility



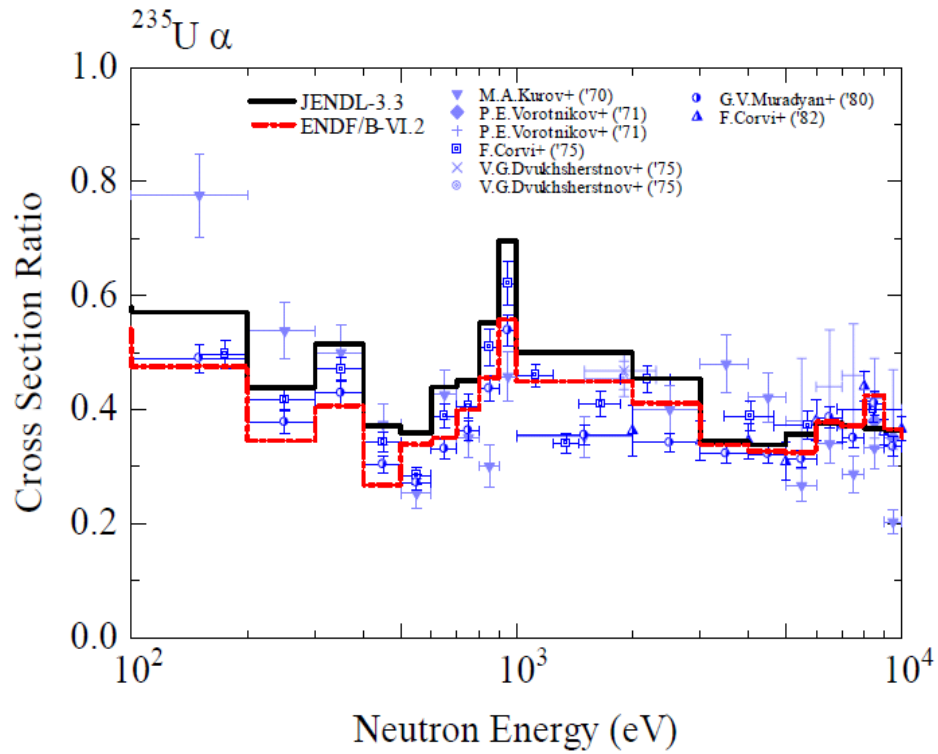
A. Tsinganis PhD work

Validation of simultaneous measurement of capture and fission reactions at n_TOF

The criticality of current and fast future reactors must be known within 0.3-0.5% for operation/safety.



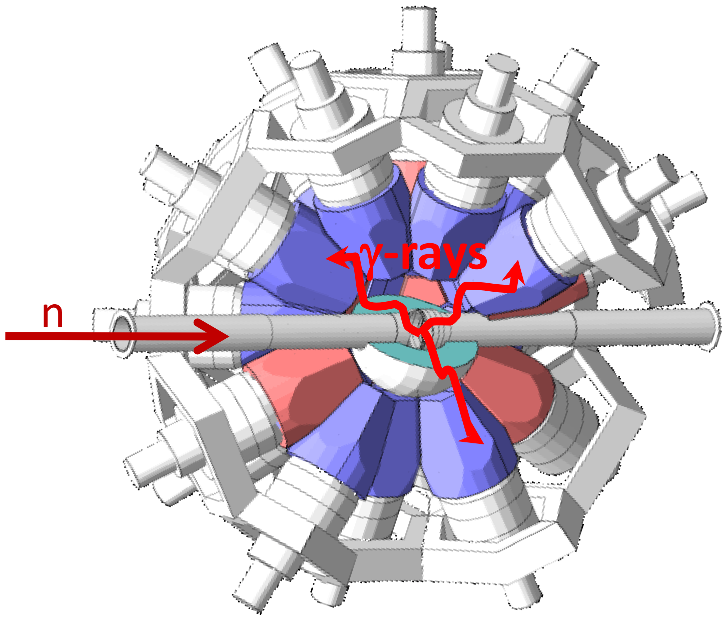
Sensitive mainly to the $^{235}U(n,\gamma)$ below 2.25 keV (RRR)



Validation of simultaneous measurement of capture and fission reactions at n_TOF

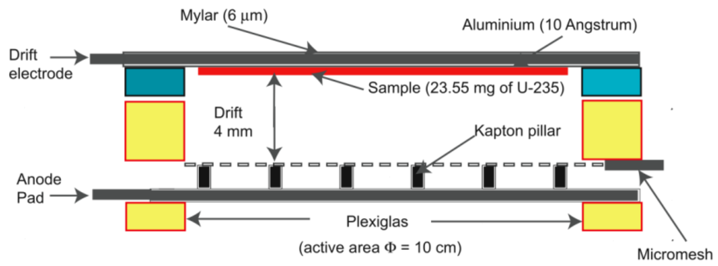
The n_TOF Total Absorption Calorimeter

- 4π geometry (high tot. absorption effic.)
- 40 BaF_2 crystals (segmentation)
- Good energy resolution (back. discrimin.)
- Used extensively for (n,γ) on actinides



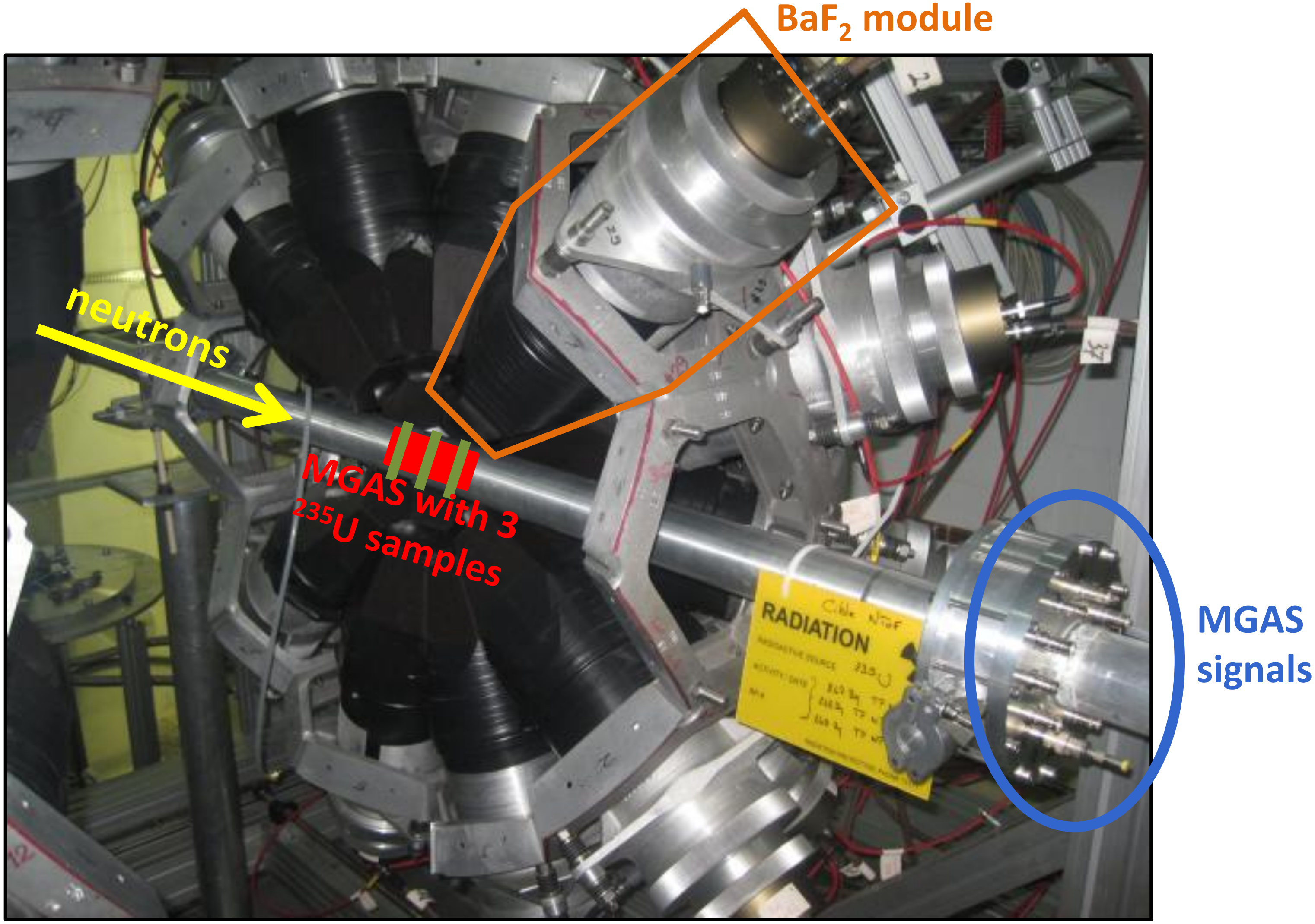
The n_TOF MicroMegas fission detector

-Two gas regions: conversion & amplification
- High gain and low noise
- Possibility for several samples in parallel.
- Used extensively for (n,f) and (n,α)



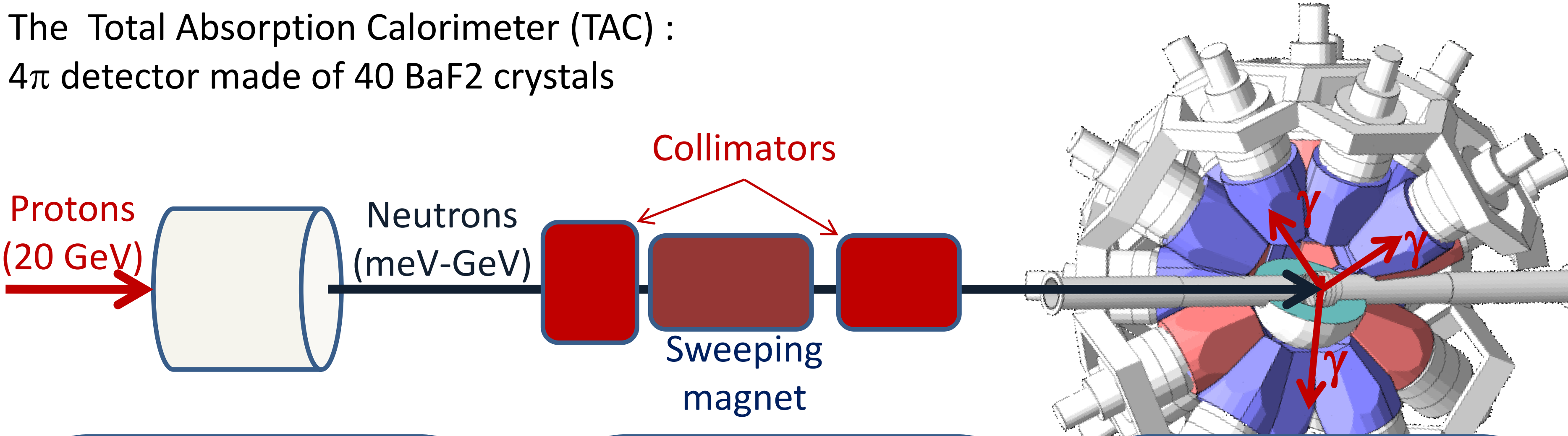
CERN-INTC-2010-037 / INTC-I-105
21/05/2010

Validation of simultaneous measurement of capture and fission reactions at n_TOF

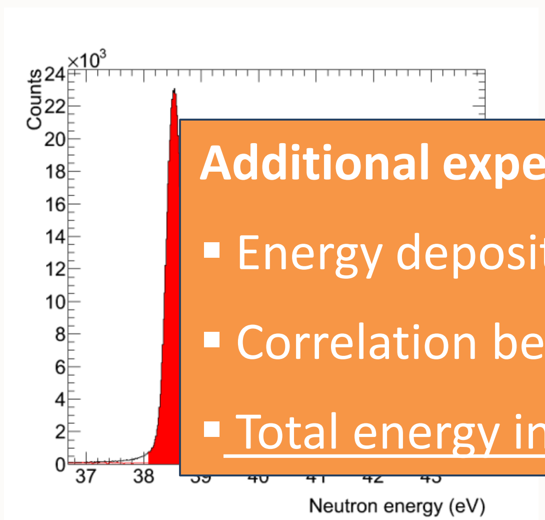


Information from (n,γ) cascades with the n_TOF/TAC

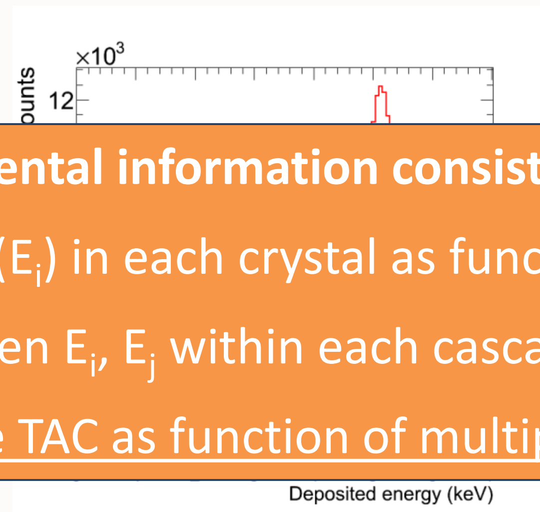
The Total Absorption Calorimeter (TAC) :
4π detector made of 40 BaF_2 crystals



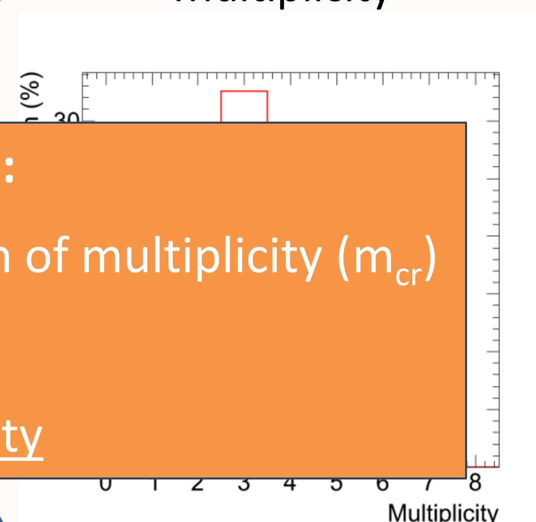
Neutron energy



Deposited energy



Multiplicity

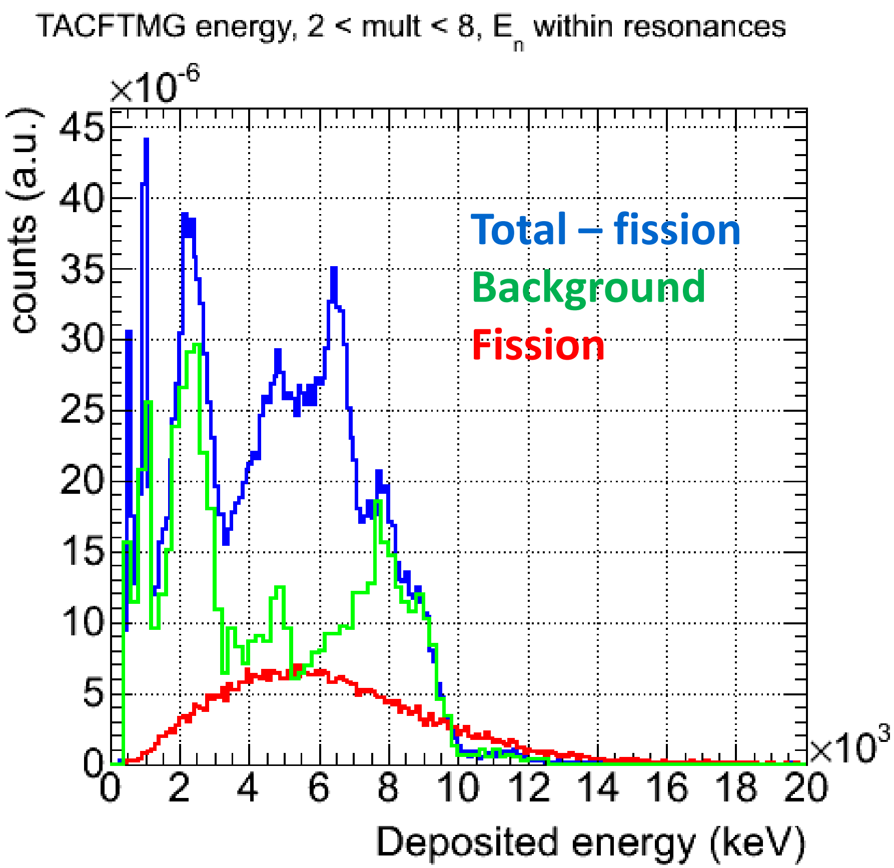


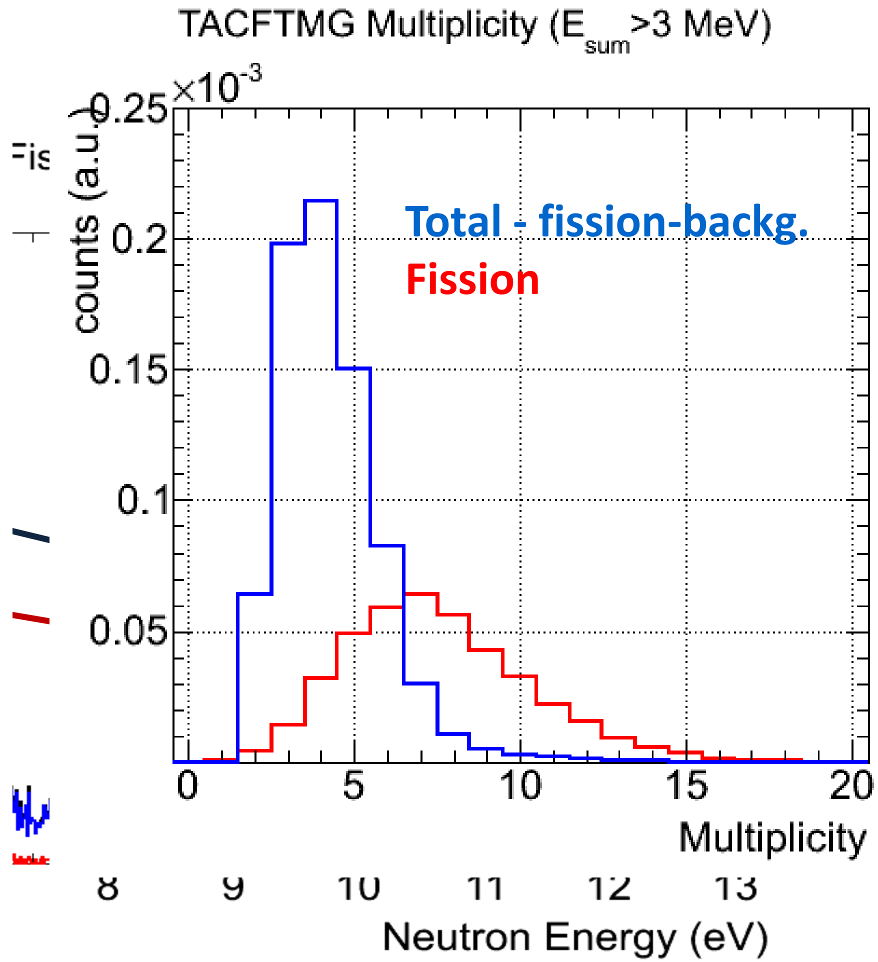
Additional experimental information consists in:

- Energy deposited (E_i) in each crystal as function of multiplicity (m_{cr})
- Correlation between E_i, E_j within each cascade
- Total energy in the TAC as function of multiplicity

CERN-INTC-2010-037 / INTC-I-105
21/05/2010

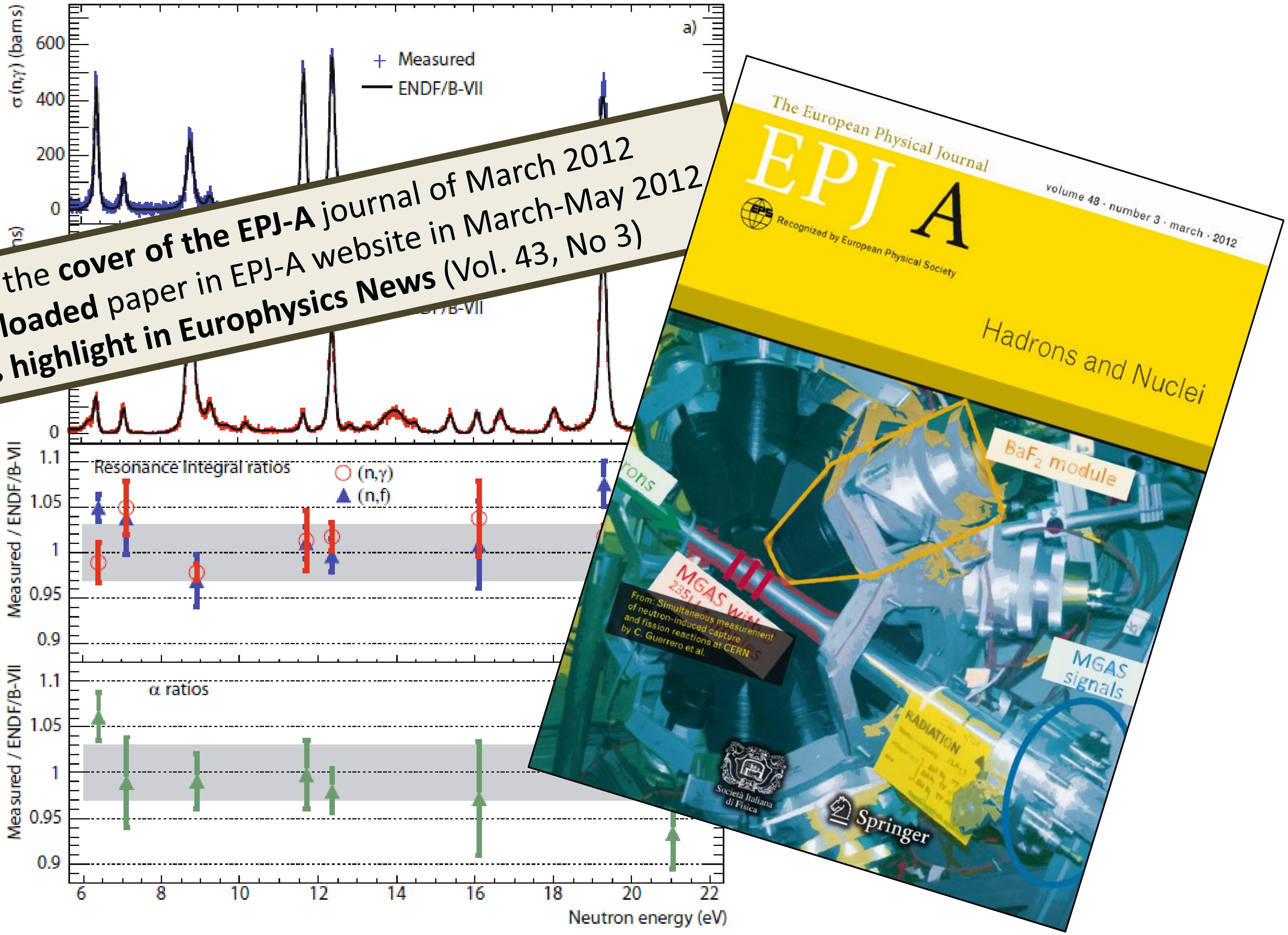
Validation of simultaneous measurement of capture and fission reactions at n_TOF





Validation of simultaneous measurement of capture and fission reactions at n_TOF

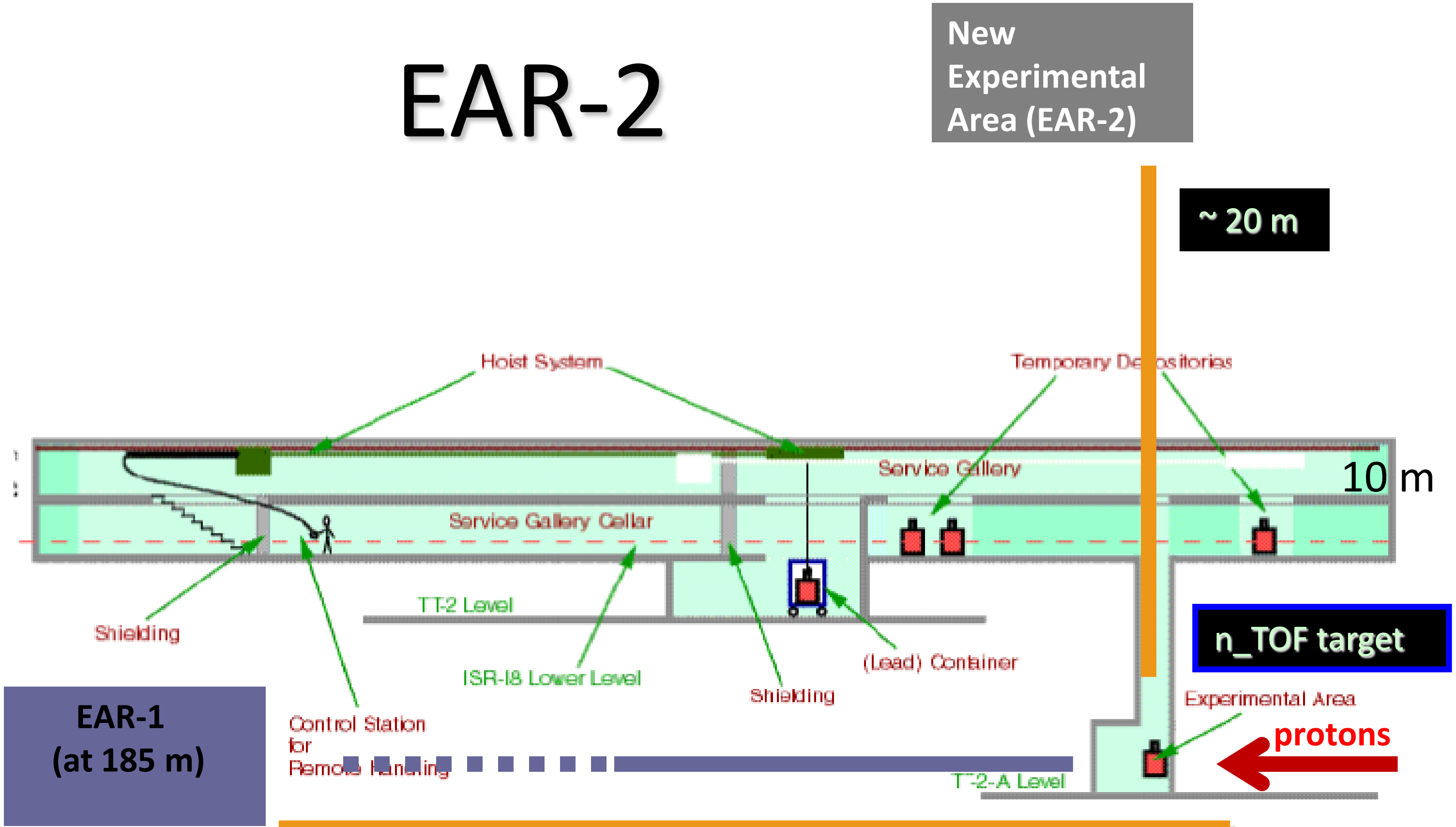
- Selected for the **cover of the EPJ-A** journal of March 2012
- **Most downloaded** paper in EPJ-A website in March-May 2012
- Selected as **highlight in Europhysics News** (Vol. 43, No 3)



THE FUTURE:
A VERTICAL NEUTRON BEAM LINE AT 20 M

n_TOF Phase 3: vertical flight path (20 m)

EAR-2



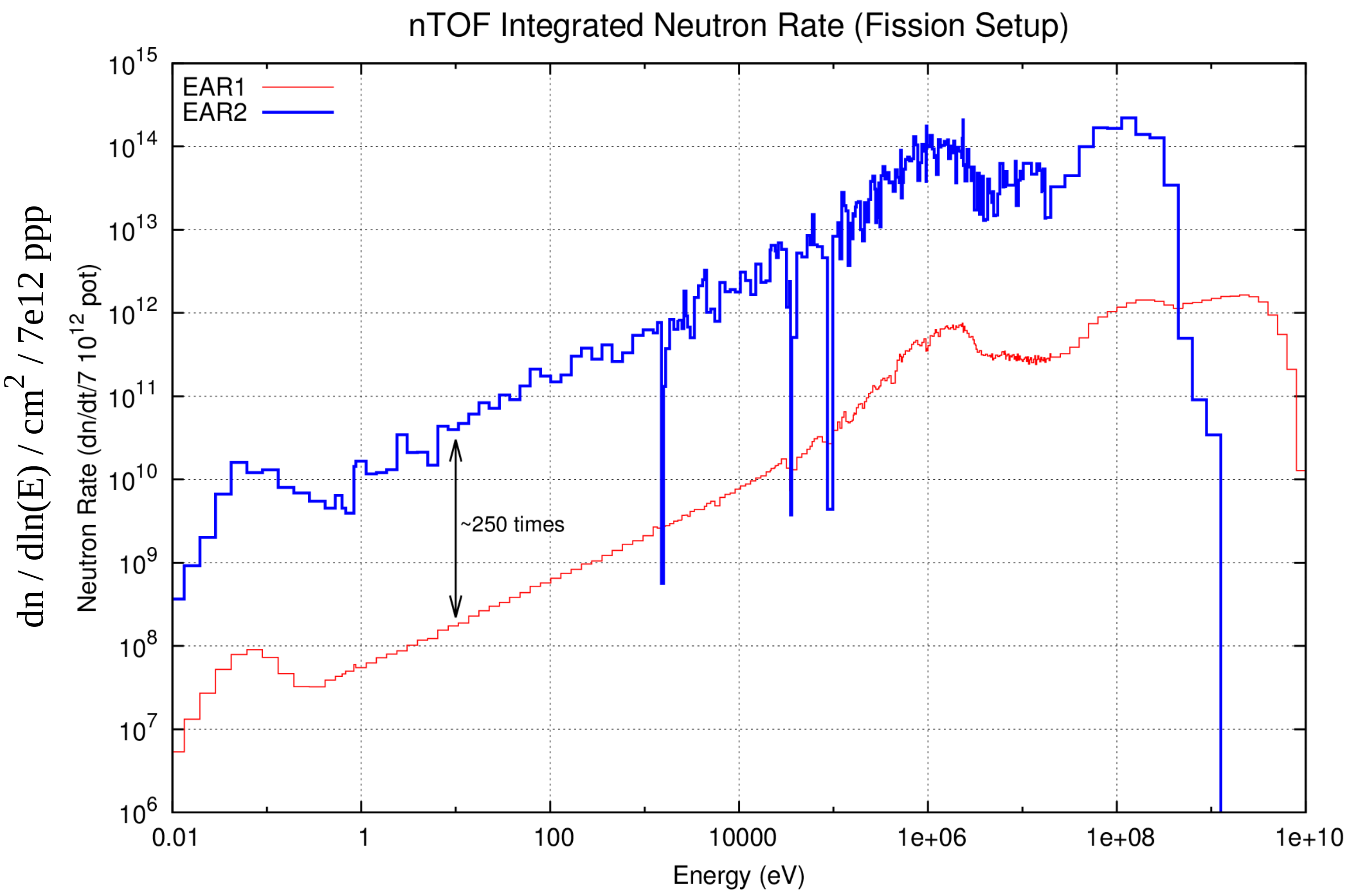
Flight-path length : ~20 m

at 90° respect to p-beam direction

expected neutron flux enhancement

drastic reduction of the t_0 flash

The future: n_TOF vertical flight path at 20 m



The future: n_TOF vertical flight path at 20 m

Experiments in EAR-2 can be performed :

i) on very small samples (reduce activity or used samples with limited availability)

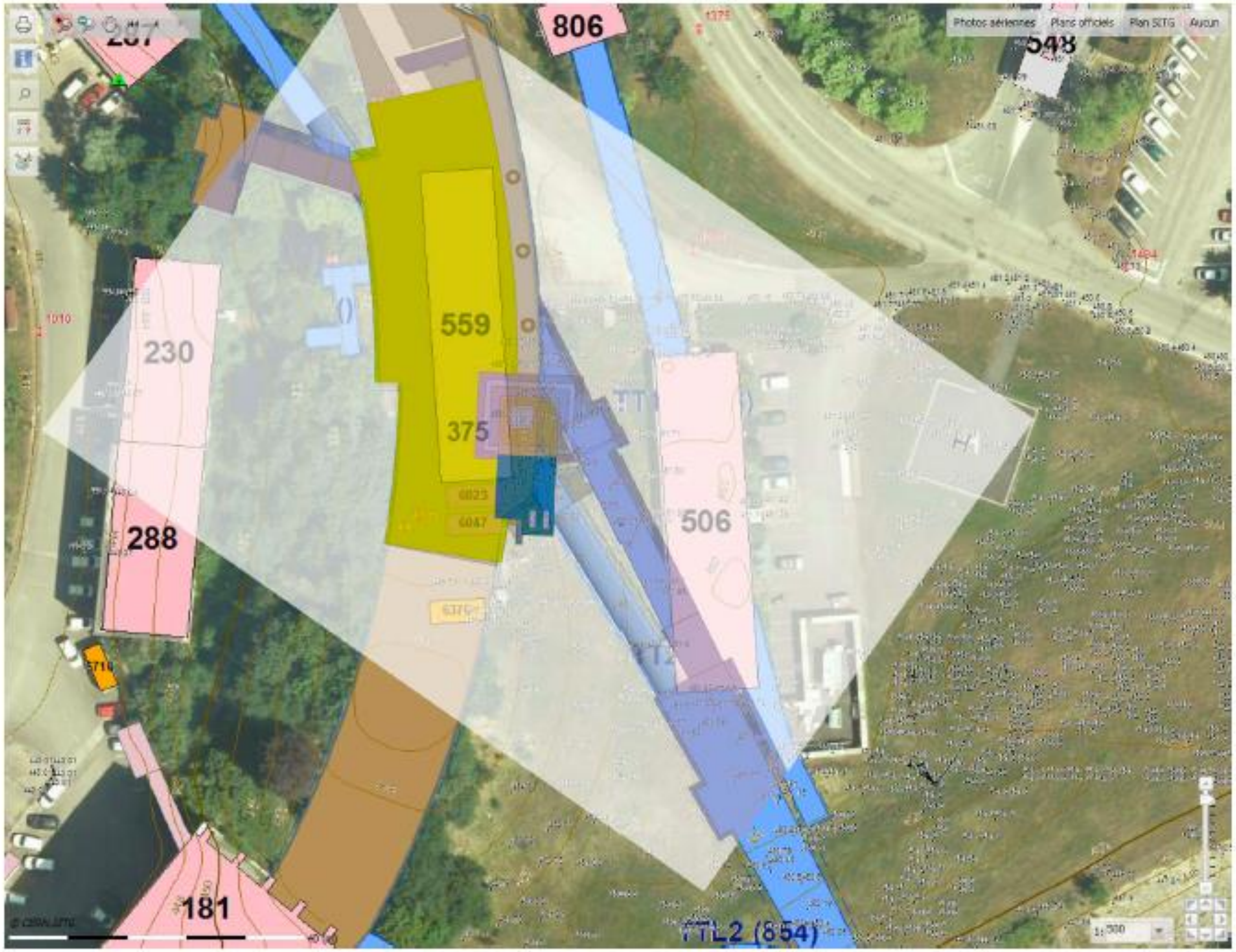
ii) on isotopes with very small cross sections (where signal/background ratio is crucial)

iii) in much shorter time (some meas. can be eventualy repeated to reduce systematic Δ)

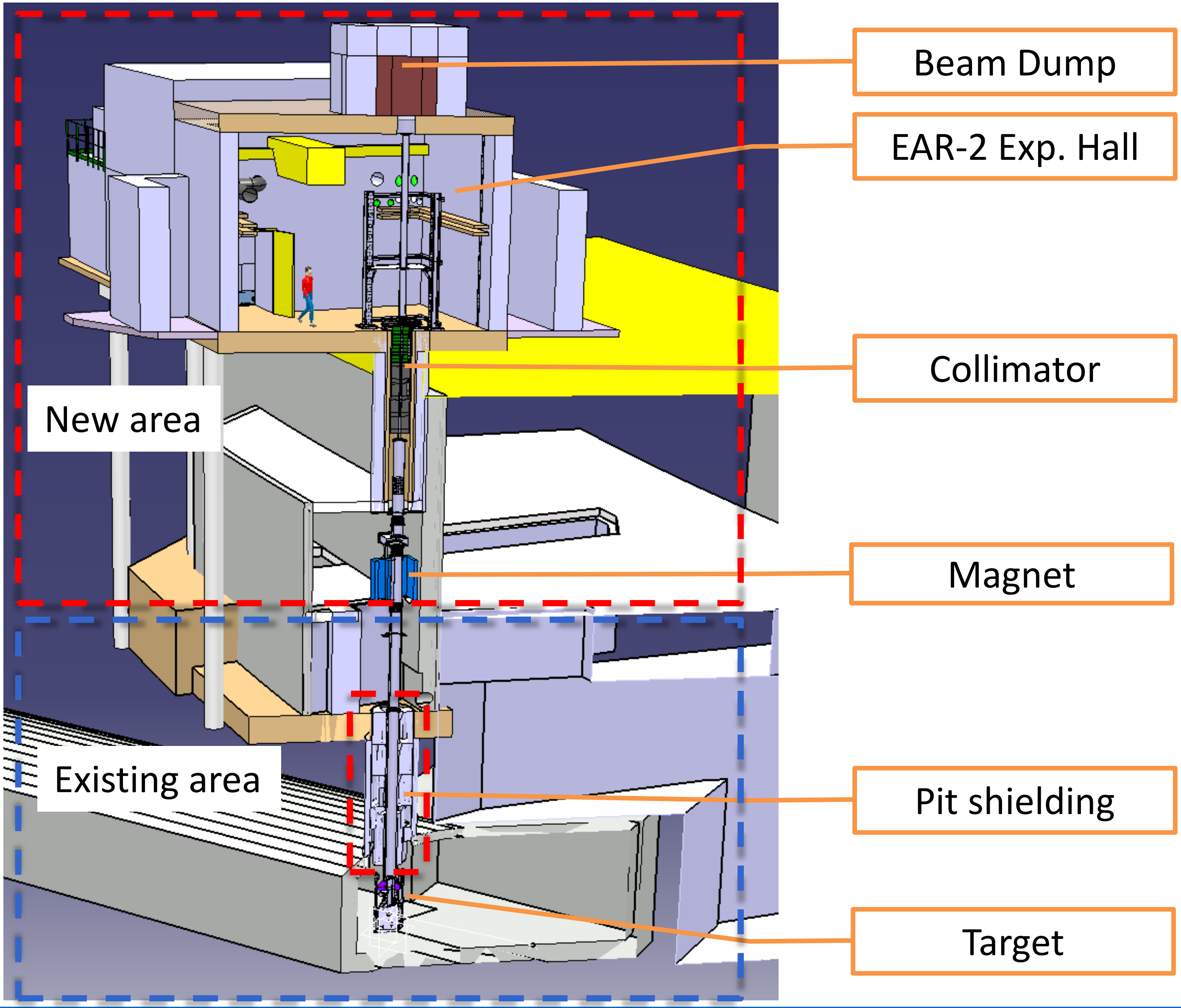
iv) on neutron-induced cross sections at high energies (E_n>10-100 MeV), which are not possible in the existing EAR-1, will benefit if the γ-flash is reduced.

v) possibility to bring a 'basket' with electronics component down to only 1.5 m from the target (10^{10} neutrons/pulse): irradiation facility (e.g. SEE)

The future: n_TOF vertical flight path at 20 m



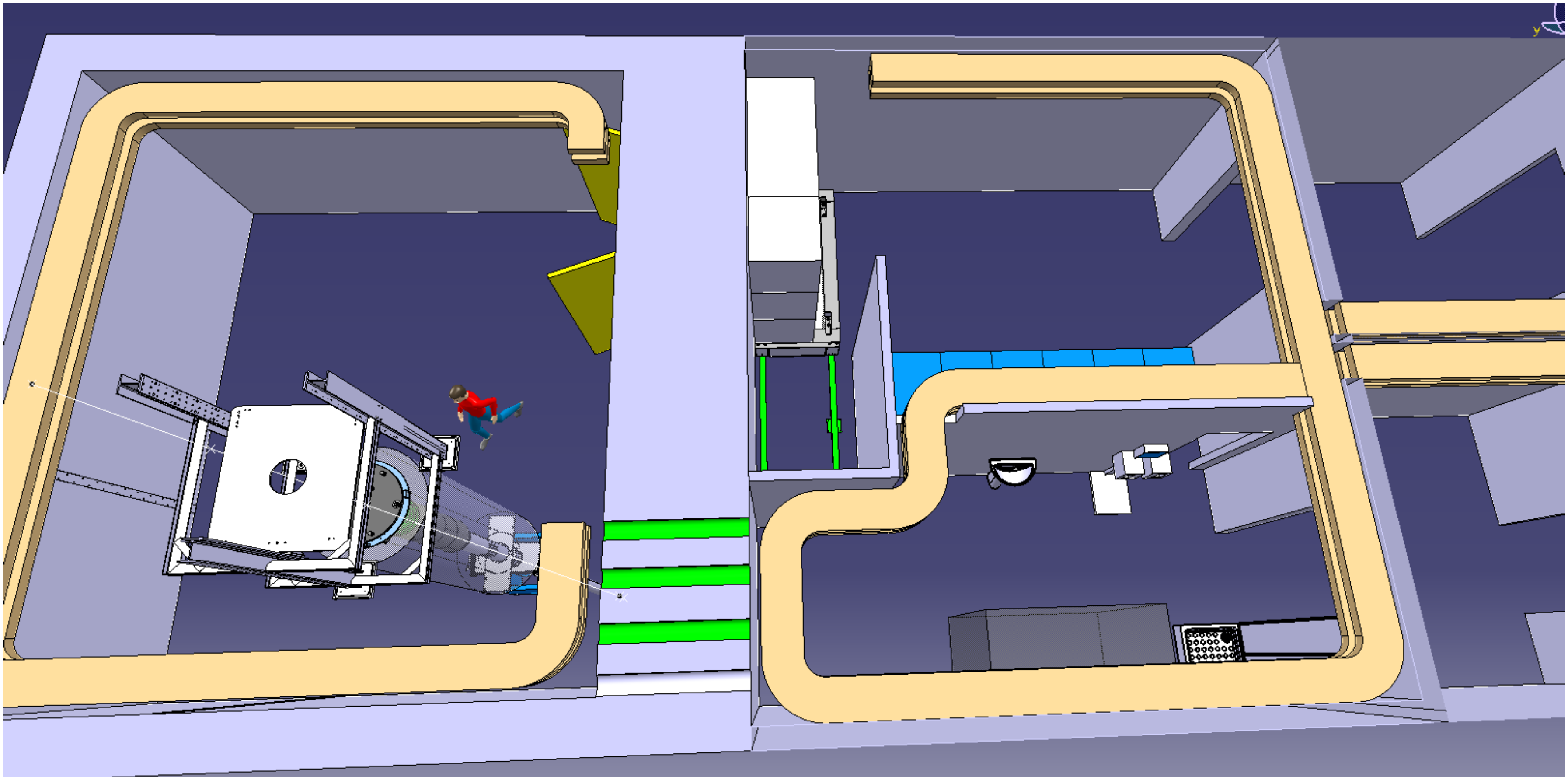
The future: n_TOF vertical flight path at 20 m



The future: n_TOF vertical flight path at 20 m (video 1)

The future: n_TOF vertical flight path at 20 m (video 2)

The future: n_TOF vertical flight path at 20 m



The future: n_TOF vertical flight path at 20 m

Main activities during the LS1

n_TOF@CERN

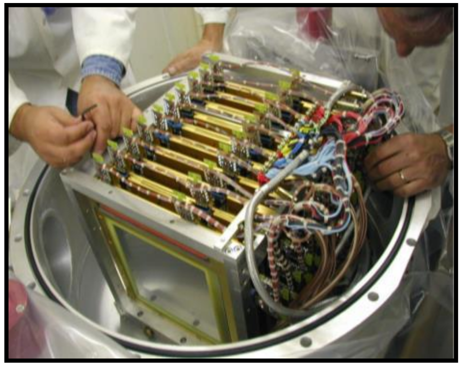
- ✓ Civil engineering work for building the bunker
- ✓ Optimize the design of the collimator and beam dump
- ✓ Making the bunker a Work Sector Type A

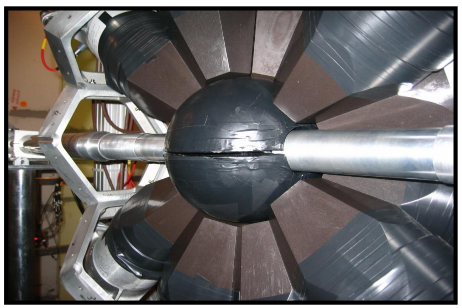
n_TOF Collaboration

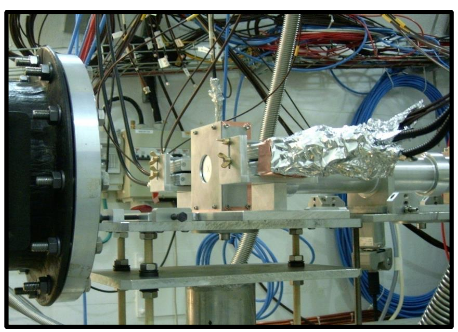
- ✓ Design new detectors optimized for the EAR-2 (very high counting rates)
- ✓ Upgrade the exisiting DAQ
- ✓ Find/prepare samples of exotic isotopes

Conclusions and perspectives

n_TOF@CERN is a world leading in the field of neutron induced reaction measurements







Operating since 2001 and upgraded in 2008

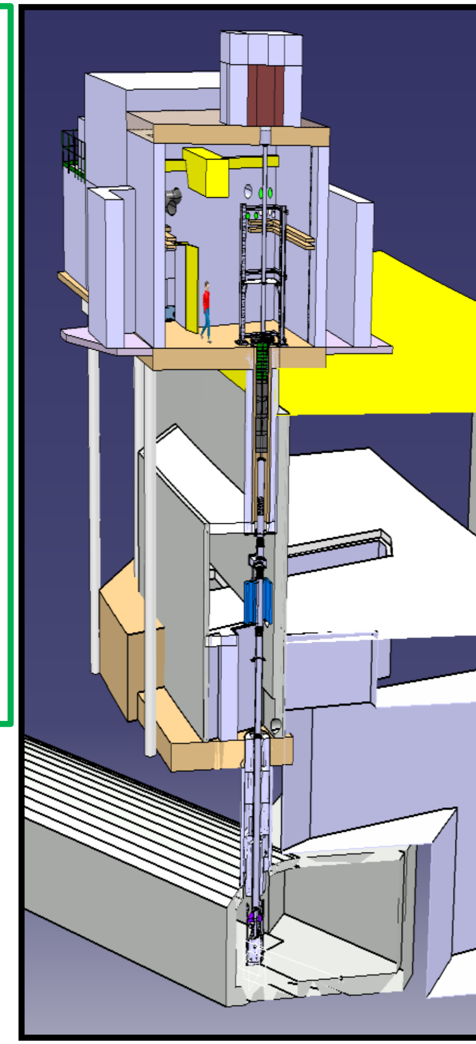
- ❑ Nucleosynthesis , Advanced Reactors and Basic Physics
- ❑ Mainly, but not only, (n,γ), (n,f) and (n,α)
- ❑ 40 capture measurements to date
- ❑ 15 fission measurements to date
- ❑ 16 PhD students at present

New neutron beam line to be ready in 2014

- ❑ 20 meters flight path
- ❑ 25 times higher neutron flux
- ❑ 250 times higher instantaneous intensity

The n_TOF team @CERN

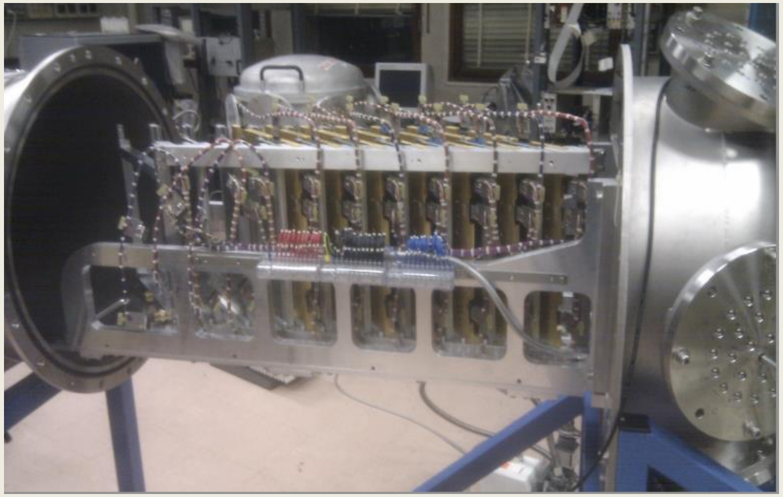
E. Berthoumieux, M. Calviani, E. Chiaveri, I. Bergstrom, C. Guerrero, A. Tsinganis, V. Vlachoudis and C. Weiss

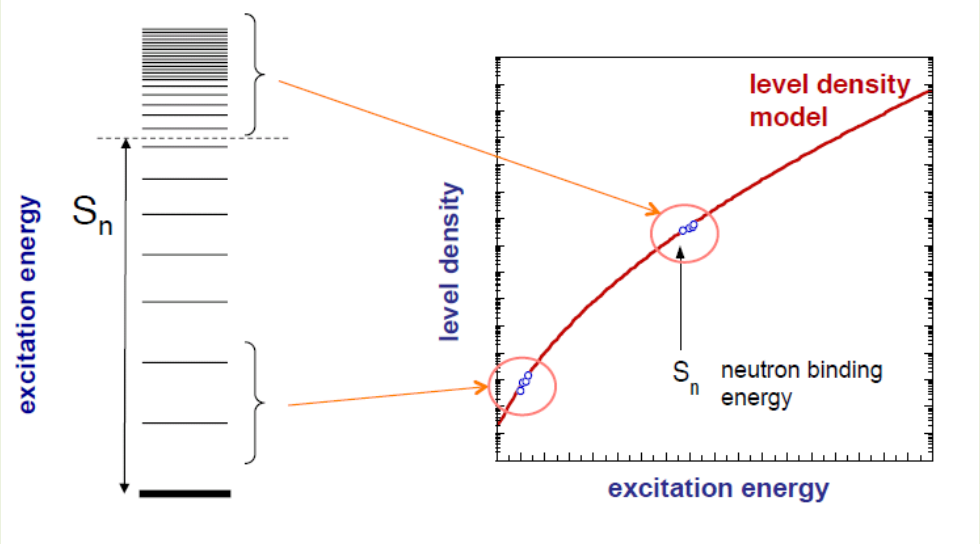


Basic nuclear physics measurements at n_TOF

Angular distribution of fission fragments:
Driven by the **dynamics of the fission process**
One can observe effects from 1st, 2nd,… chances

Use of position sensitive PPAC tilted 45º.





Spin assignments near S_n
Observe diff. in γ-ray decay from resonances of different spin
Fine tune/test of **level density models**

Use of 'segmented' TAC for γ cascades

(some) Neutron production mechanisms

Neutron 'radioactive sources':

$^{241}Am/^{9}Be$ using ^{241}Am α-decay: $\alpha + {}^{9}Be \rightarrow {}^{12}C + n$

(quasi)Mono-energetic sources (depending on Q-value, E_p and angle)

$p + {}^{9}Be \rightarrow {}^{9}B + n$

$p + {}^{7}Li \rightarrow {}^{7}Be + n$

$D + T \rightarrow {}^{4}He + n$ e.g. NFS@GANIL, ENEA-FNG

$D + D \rightarrow {}^{3}He + n$

Electron driven source:

$e^- + U \rightarrow$ Bremsstrahlung + U $\rightarrow$ photofission $_{(E_n < 20\ MeV)}$ e.g. GELINA, ORELA

Spallation sources:

p + Pb(W) $\rightarrow$ Spallation neutrons $_{(E_n < E_p)}$ e.g. n_TOF, LANSCE, J-PARC