Neutron Facilities

X. Ledoux

Ganil, Caen, France

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Ganil, Caen, France

Very Wide subject :

≈ 250 research reactors are operational

≈ 164 accelerators in the IAEA database

IAEA data base http://nucleus.iaea.org/sites/accelerators

Research reactors around the world

RR application-oriented functions of RRDB

Application	Number of RR involved	Involved / Operational, %	Number of countries
Education & Training	161	67	51
Neutron Activation Analysis	122	51	54
Radioisotope production	90	37	44
Neutron radiography	68	28	40
Material/fuel testing/irradiations	60	25	25
Neutron scattering	48	21	32
Nuclear Data Measurements	42	18	20
Gem coloration	36	15	22
Si doping	35	15	22
Geochronology	26	11	21
Neutron Therapy	20	8	13
Other	95	40	29

IAEA **Indispensable to define priorities and plan our activities!**

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Contact: D.Ridikas@iaea.org

Characteristics of a neutron facility

- Energy domain
- Flux
- Energy spectrum : mono-energetic, continuous, quasi-mono-energetic
- Neutron production mode
- Time structure : pulsed or continuous

    -Energy range

    -Energy resolution

- Number and size of experimental areas
- Use of radioactive samples (actinide for fission studies)

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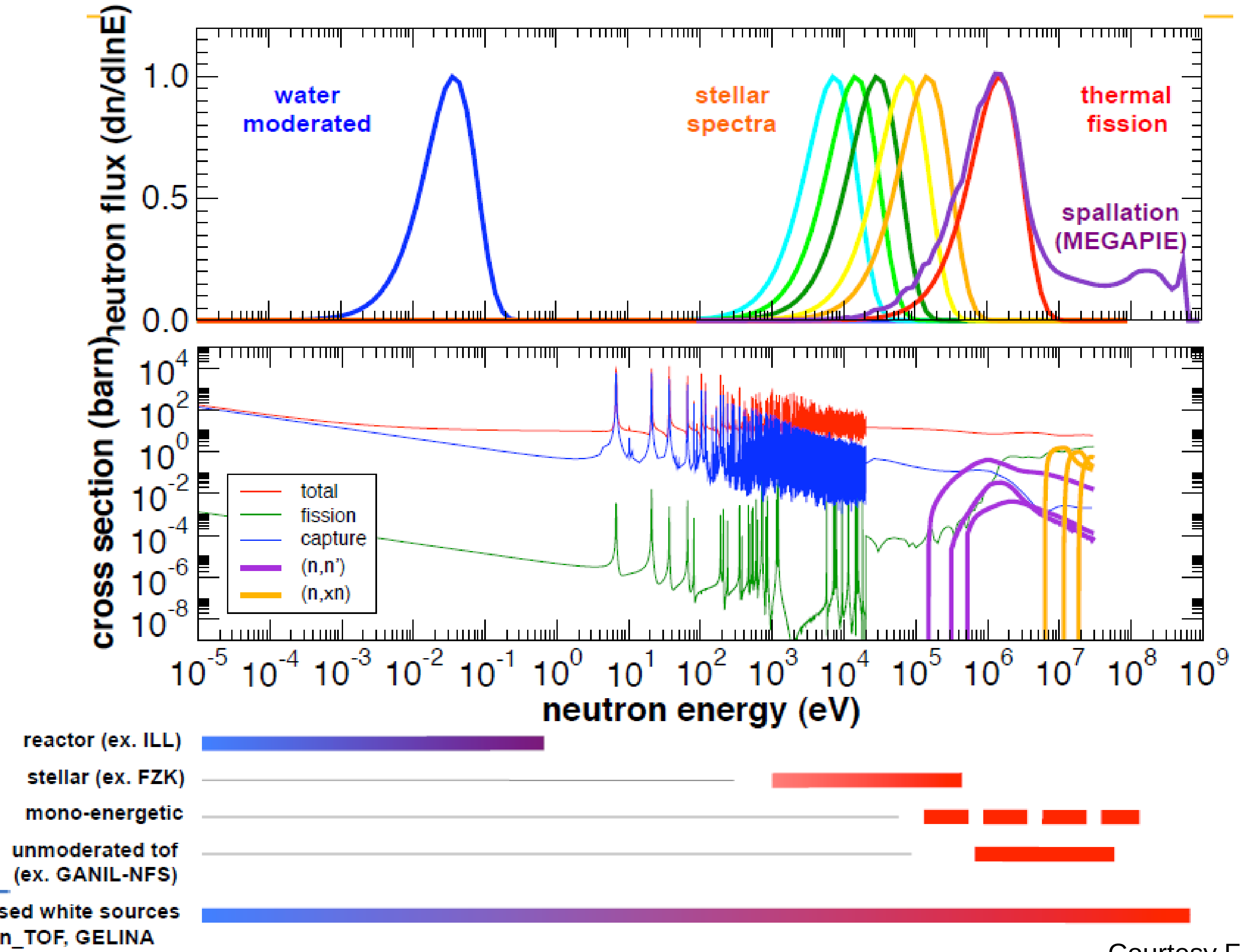
- Sort by neutron production mode
- Facilities involved in nuclear data measurements (no integral measurement)
- List not exhaustive, focus on some recent or new facilities

Neutron fluxes and cross-sections



Courtesy F. Gunsing

OUTLINE

- REACTORS
- ELECTRON ACCELERATOR BASED FACILITIES
- MONOENERGETIC NEUTRON FIELDS
- INTERMEDIATE ENERGY REACTIONS
- SPALLATION REACTIONS

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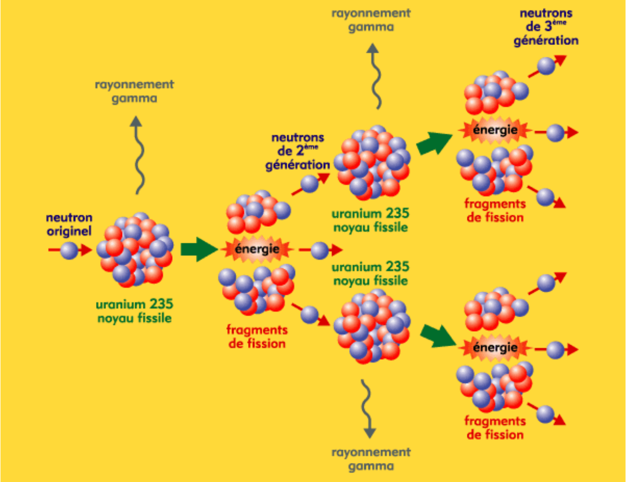
Reactor based facilities

- Neutron fission
- High flux
- No time spectrum
- Energy limited to 10 MeV
- Construction and exploitation very expensive
- Energy spectrum :



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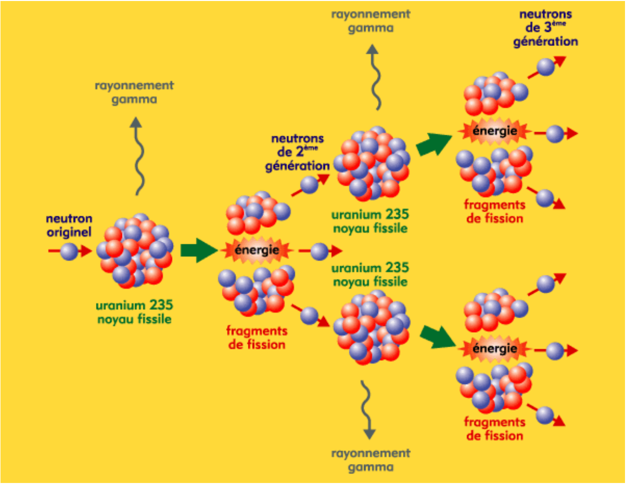
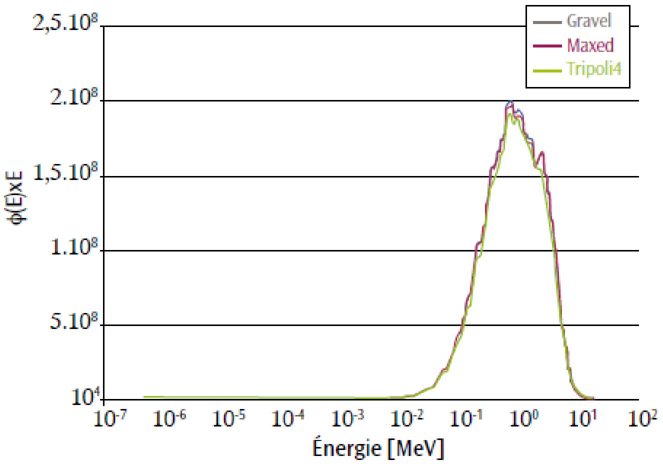


Fast neutrons



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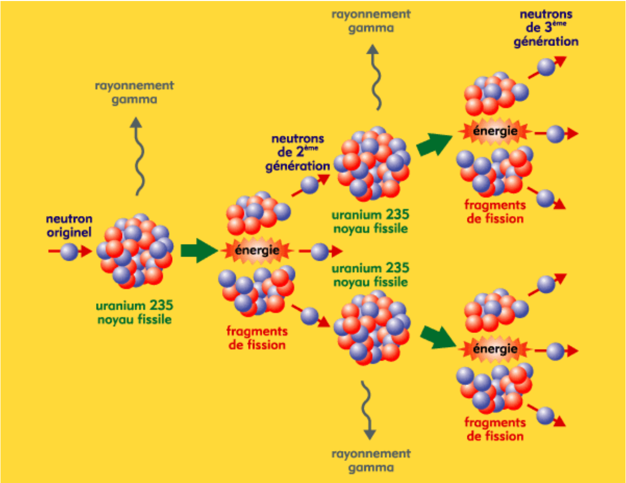

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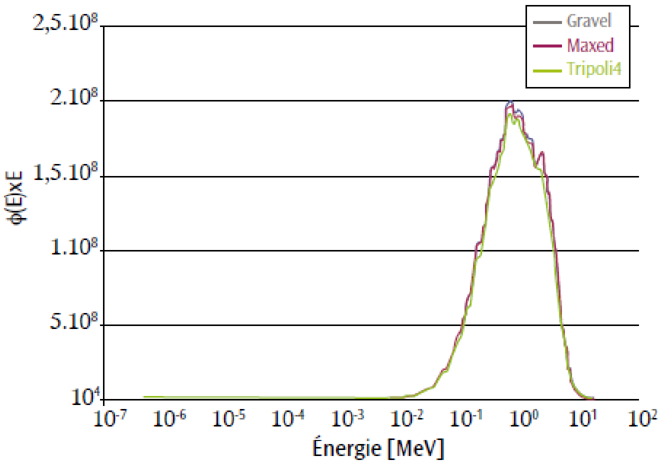
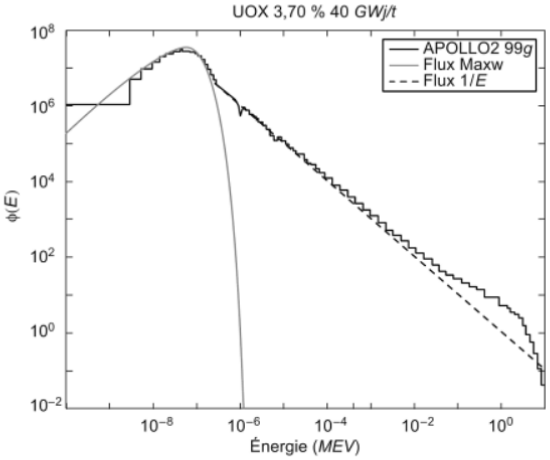


Thermal neutrons



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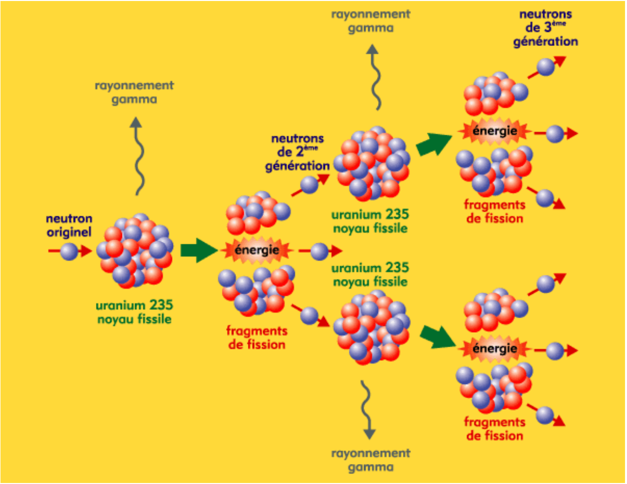

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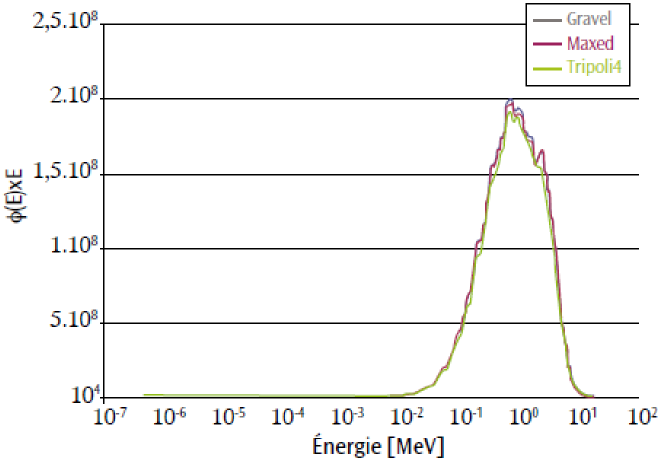

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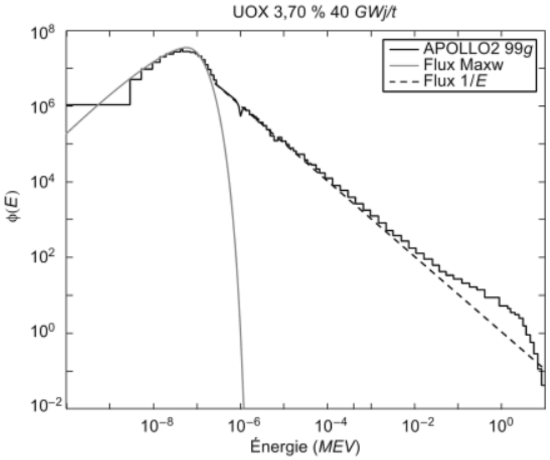
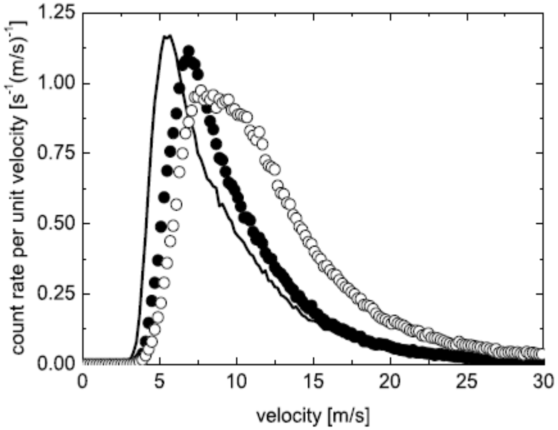
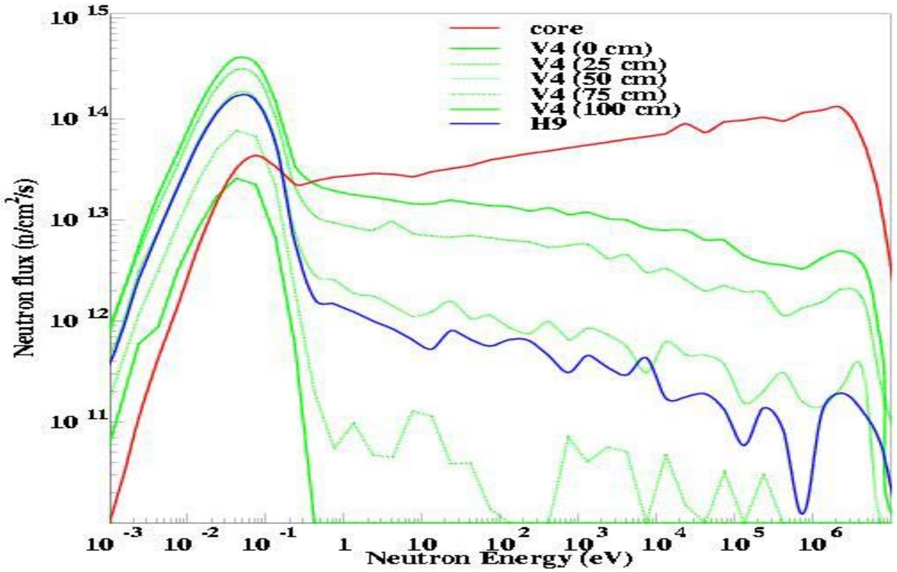


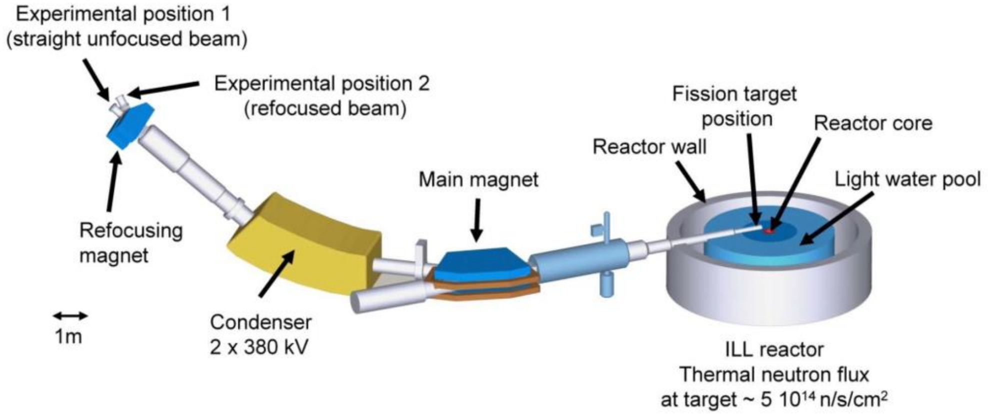
Ultra cold neutrons



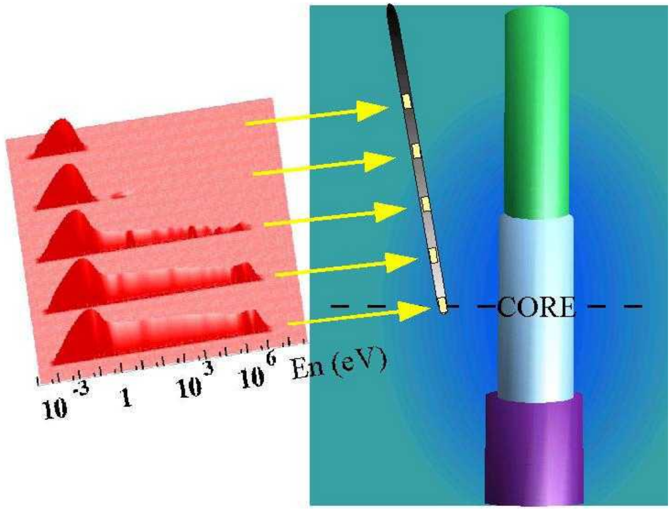
Institut Laue-Langevin (Grenoble, France)

58 MW, heavy water moderated 10^{15} n/cm^2/s



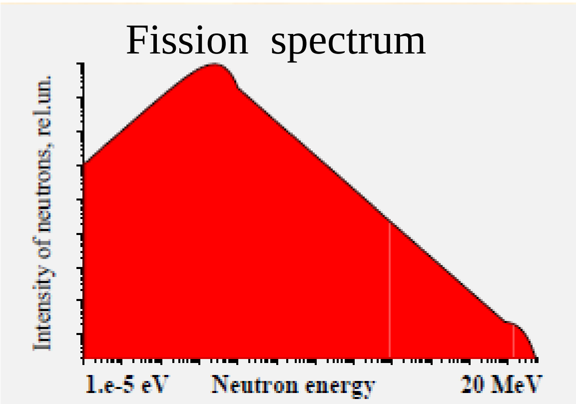


Lohengrin spectrometer : study of fission fragment yields

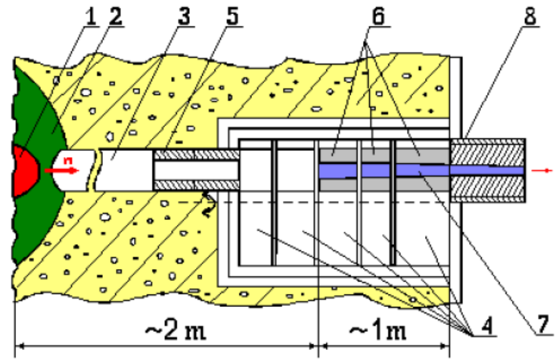


Channel with high neutron flux :
Measurement of actinide cross-section,
….

Neutron filtering method

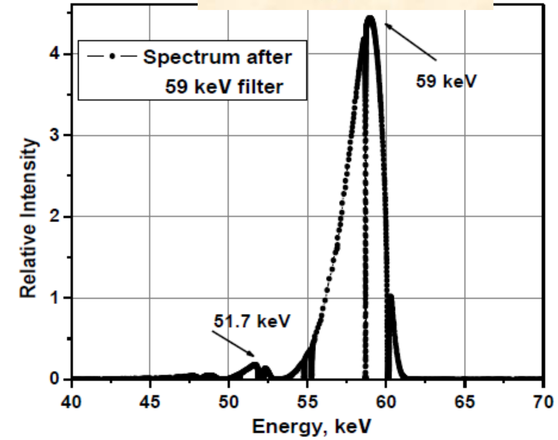


Set of filters



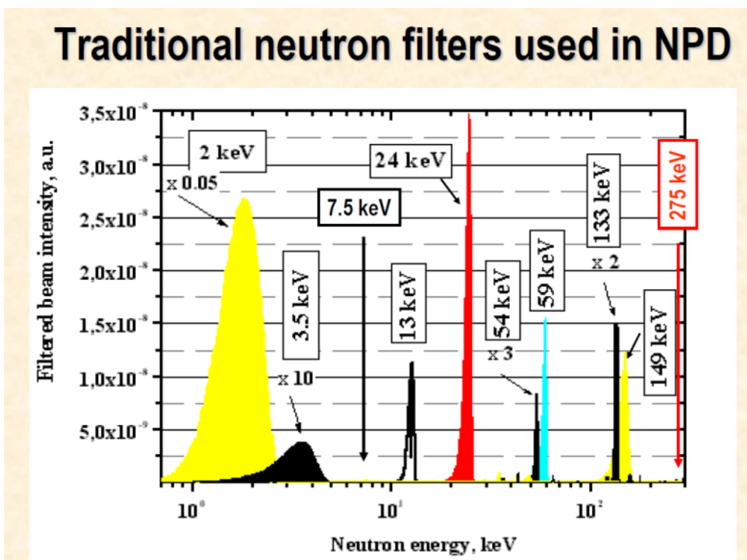
Elements	S	^{58}Ni	V	Al	^{10}B
Thickness, g/cm²	116.53	81.42	24.44	5.4	0.5

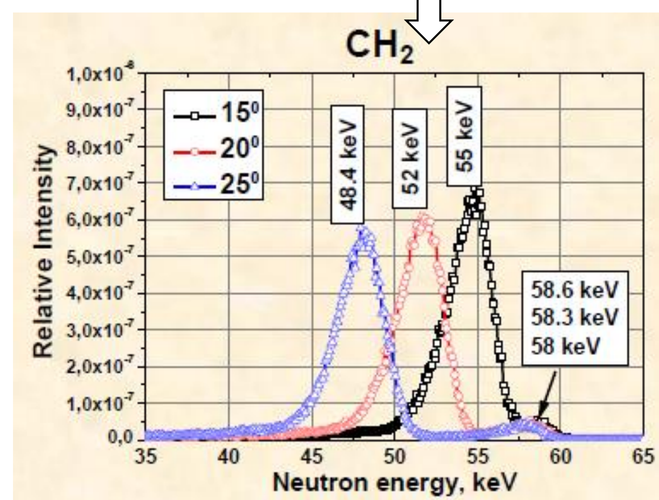
$$59 \pm^{1.2}_{6.7}\ keV$$



Transmitted neutron spectrum

Scattering angle on CH_2 to change the energy





Institute for Nuclear research Kiev, Ukraine

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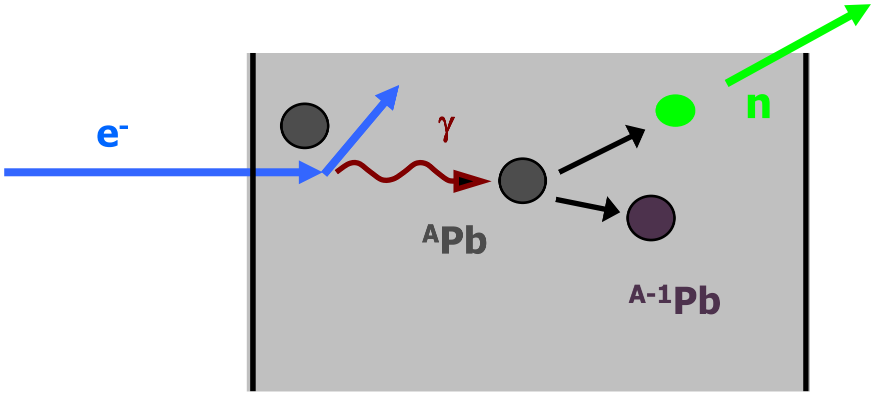
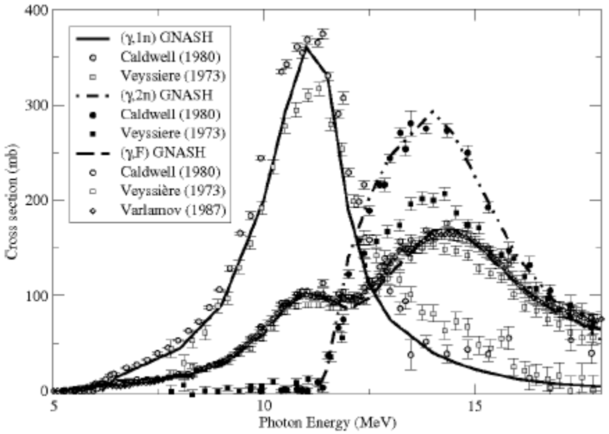
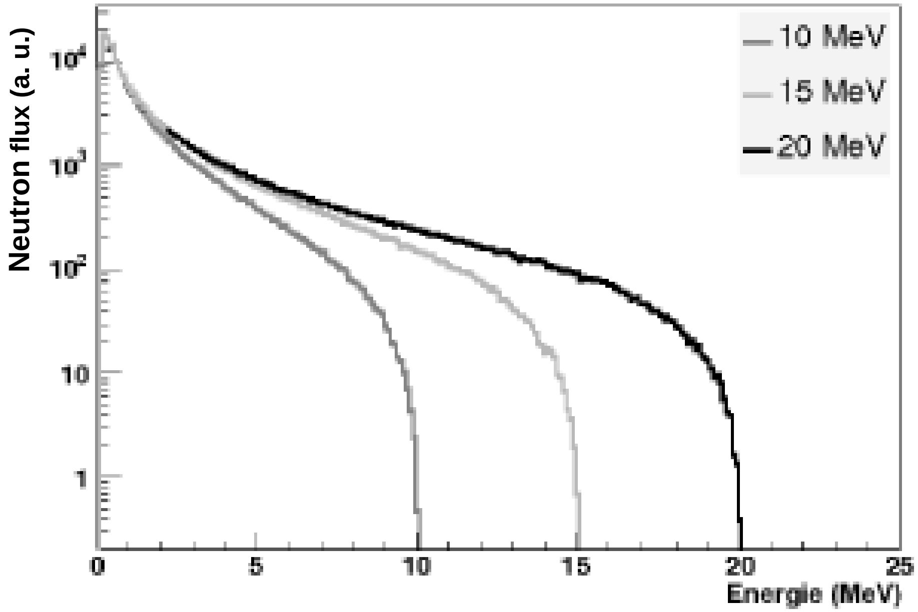
Photo production of neutrons with bremsstrahlung

- Electron beam
- Photon production by Bremsstrahlung
- Neutron production by (γ,xn) or (γ,f) reaction





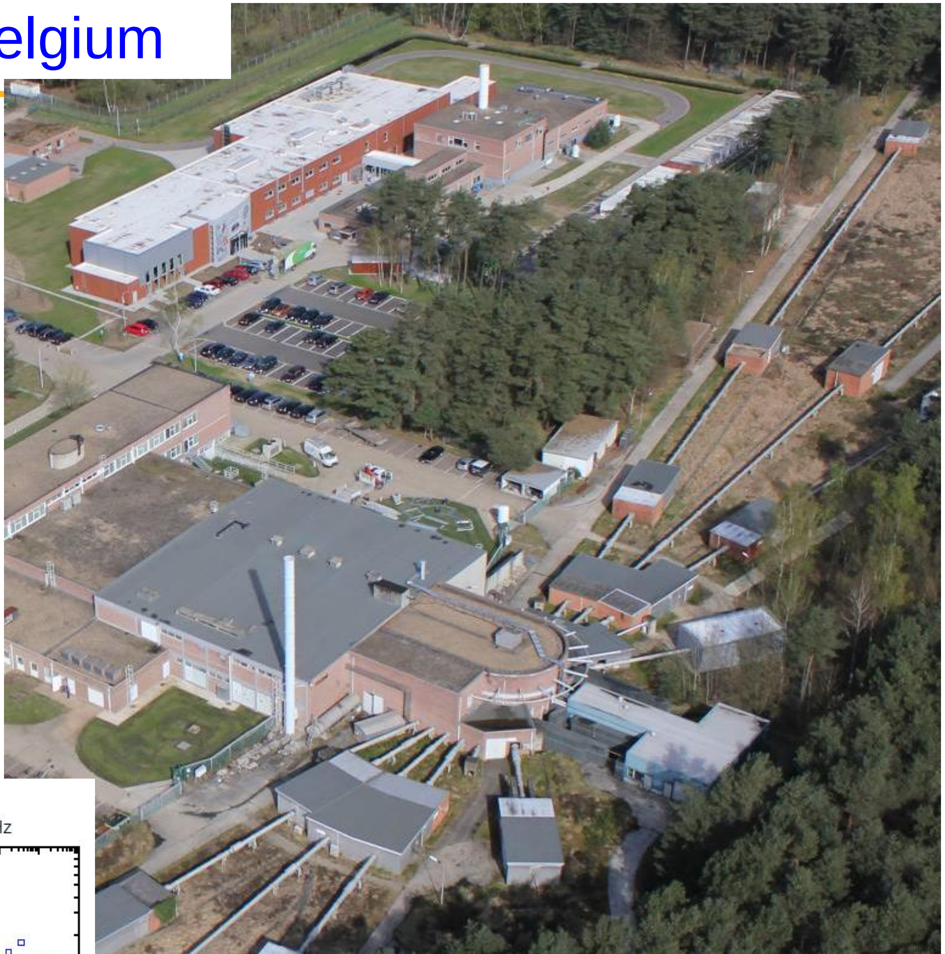


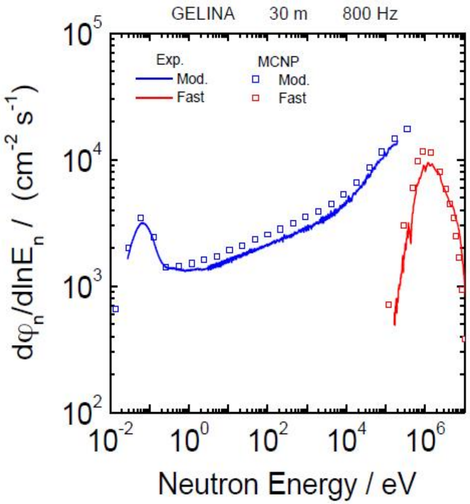
- Continuous neutron energy spectrum
- $0 < E_n < E_{e-}$
- LINAC accelerator
- High power accelerator

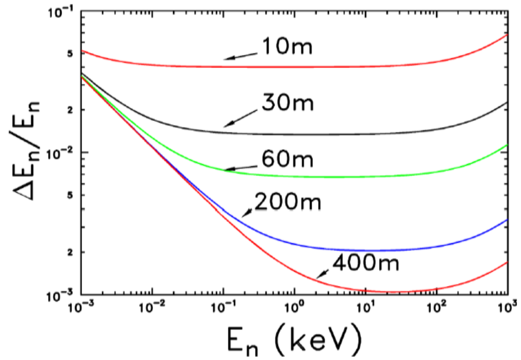
GELINA, IRMM, Geel Belgium

- *Electron energy: 140 MeV*
- *Pulse width: 1 ns*
- *12 A (peak), 100 μA (average)*
- *Pulse repetition @ 800 Hz*
- *$<\Phi_n> = 3.4 \times 10^{13}$ /s*
- *Sub-thermal to 20 MeV (1 - 2 MeV peak)*
- *Moderated neutron beam available*
- *Flight path: 10 – 400 m*

- *Transmission, capture and fission reactions*

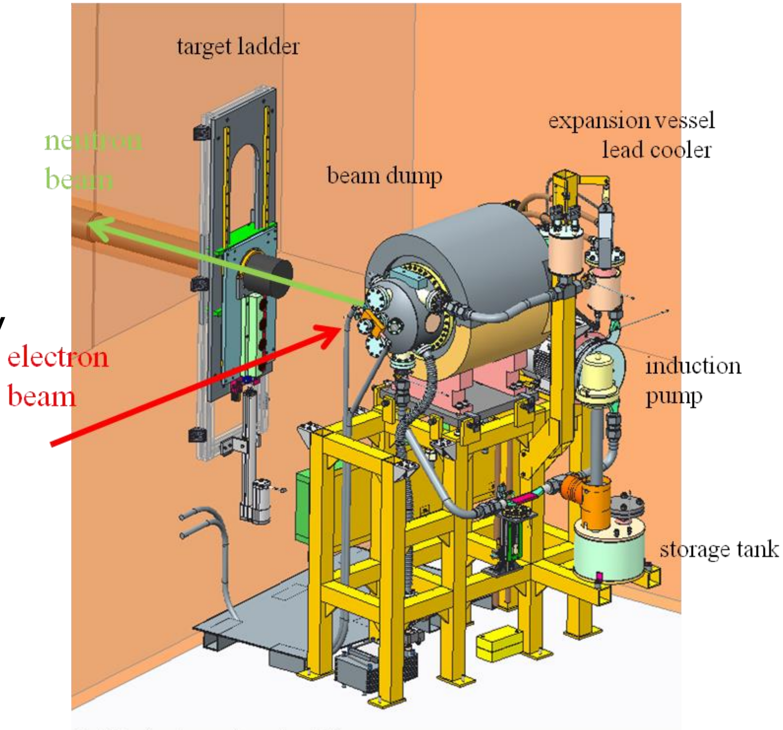






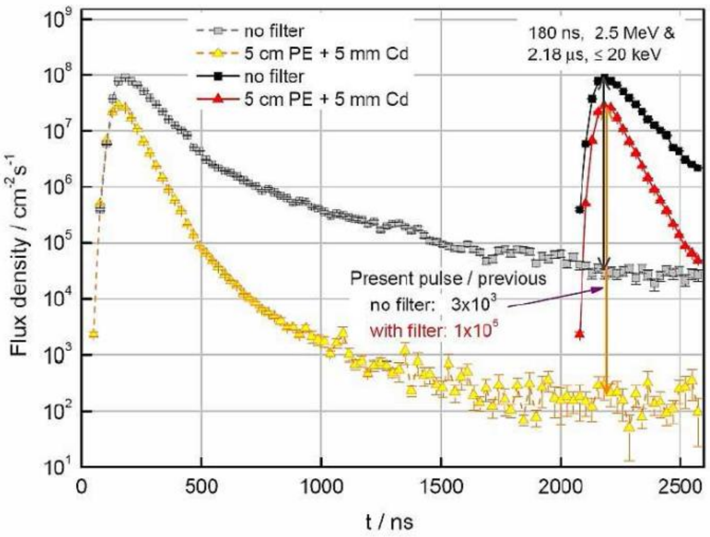
N-Elbe, Helmholtz-Zentrum Dresden-Rossendorf, Germany

- Liquid lead target (25kW/cm^3)
- E^- beam 30 MeV, I=1mA
- 10^{13} n/s, bunch duration 5 ps
- F=13 to 0,5MHz
- Flight path 7 m, overlap =20 keV, 100keV<En<10 MeV

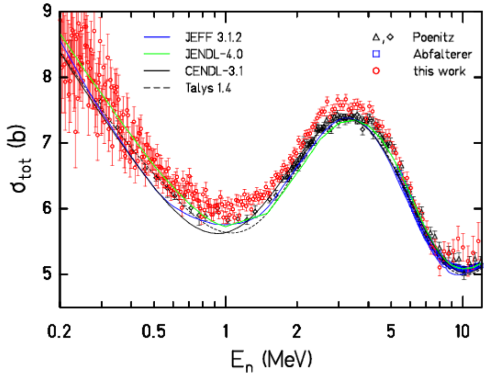


CAD design: Armin Winter

First beam with new Pb-loop: August 30, 2013



- Capture cross-sections
- Total cross-sections



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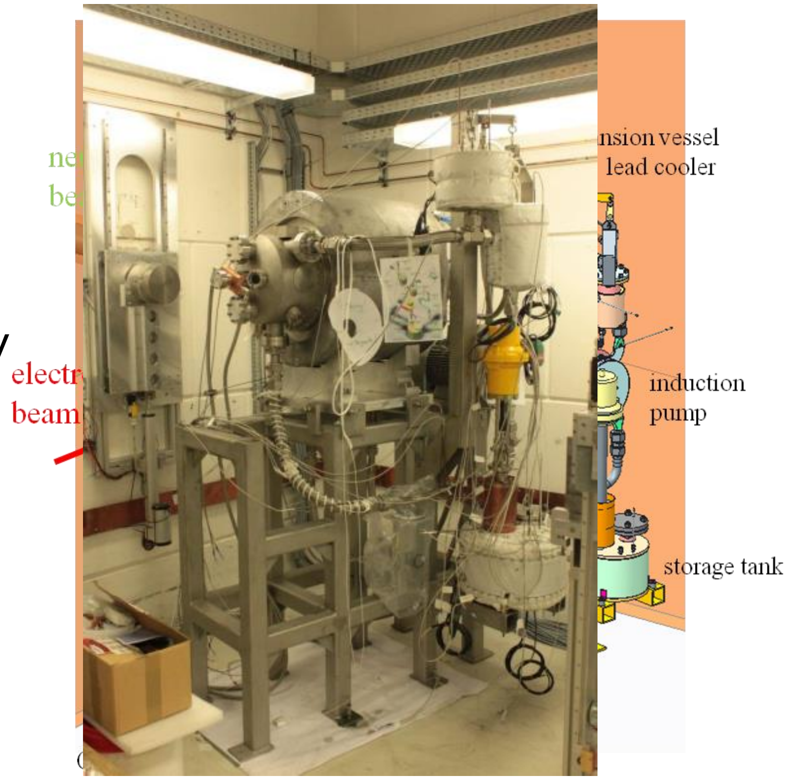

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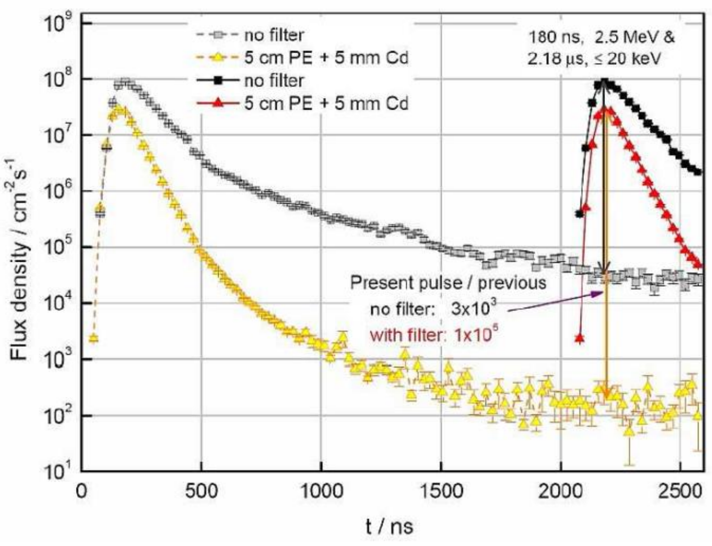

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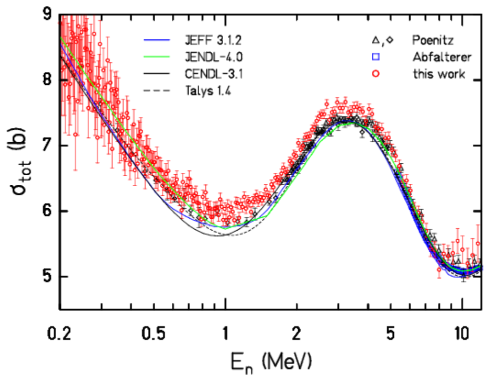

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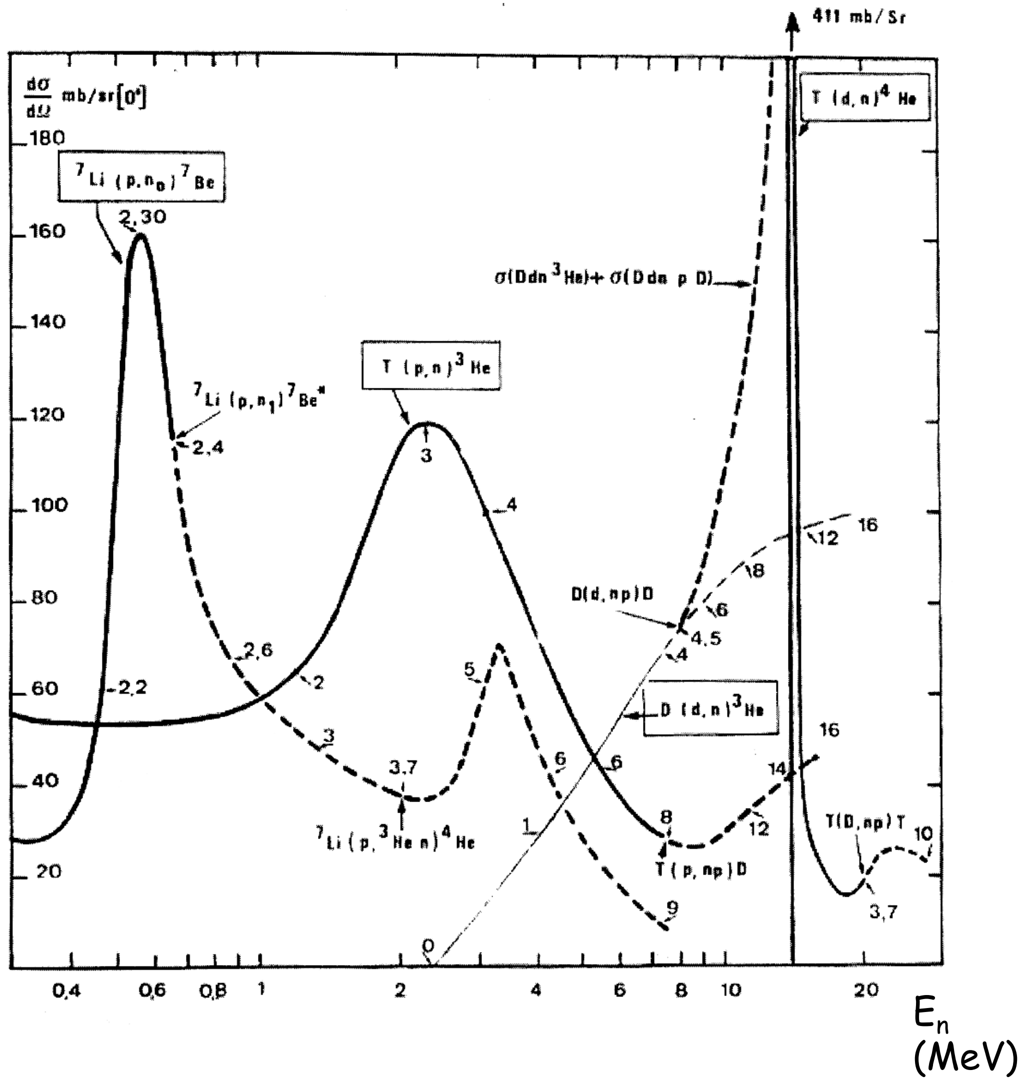
Reactions production

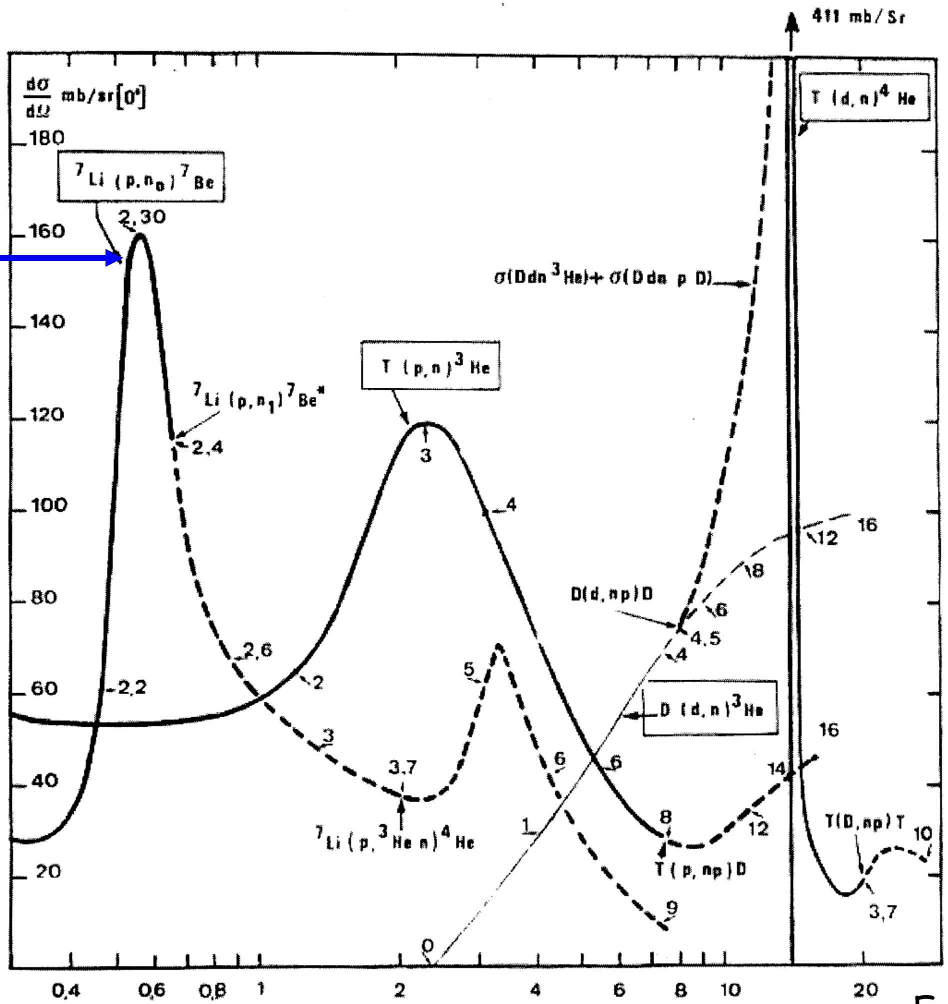


The big four

Reactions production

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

The big four



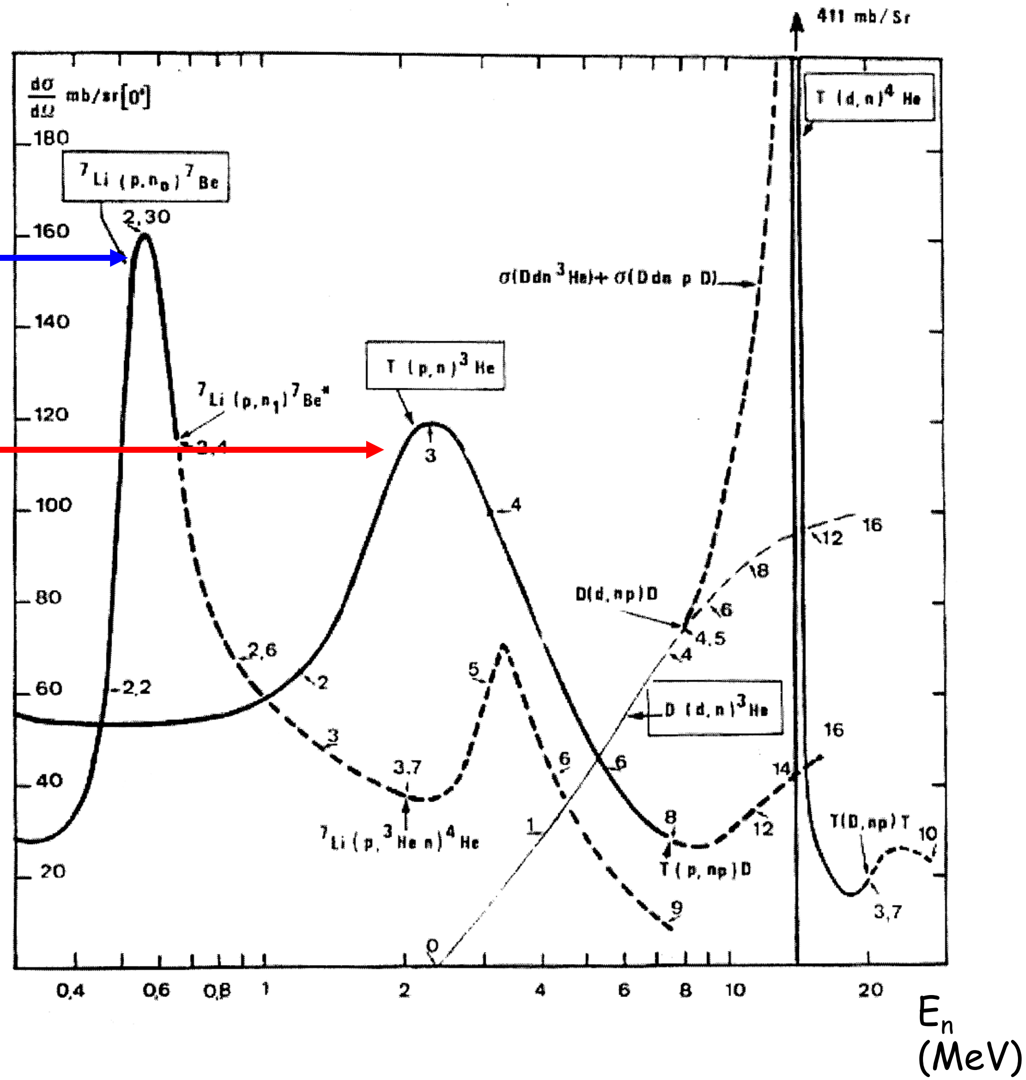
E_n (MeV)

Reactions production

The big four

p + ^{7}Li → n + ^{7}Be

p + ^{3}H → n + ^{3}He



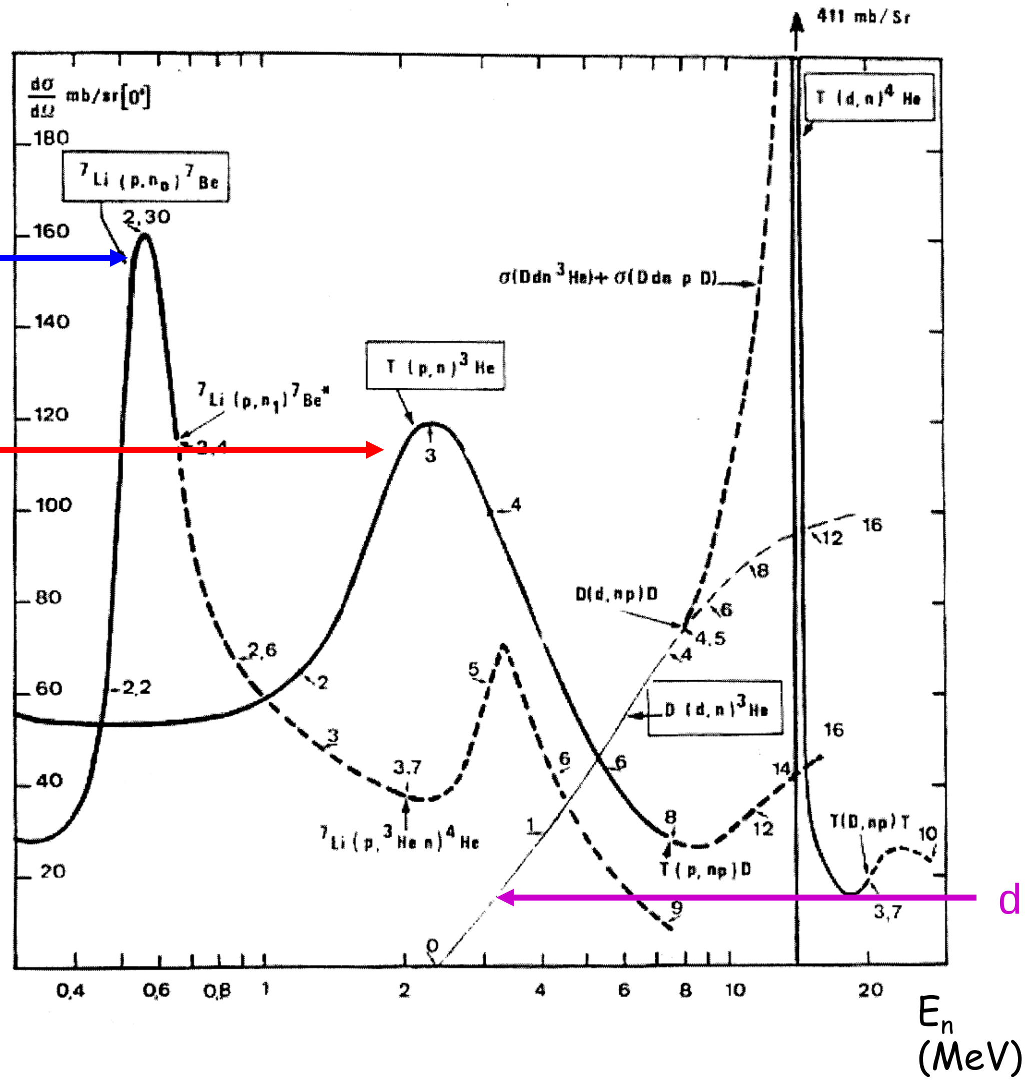
Reactions production

The big four

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

p + $^{3}H \rightarrow n + {}^{3}He$

d + $^{2}H \rightarrow n + {}^{3}He$



Reactions production

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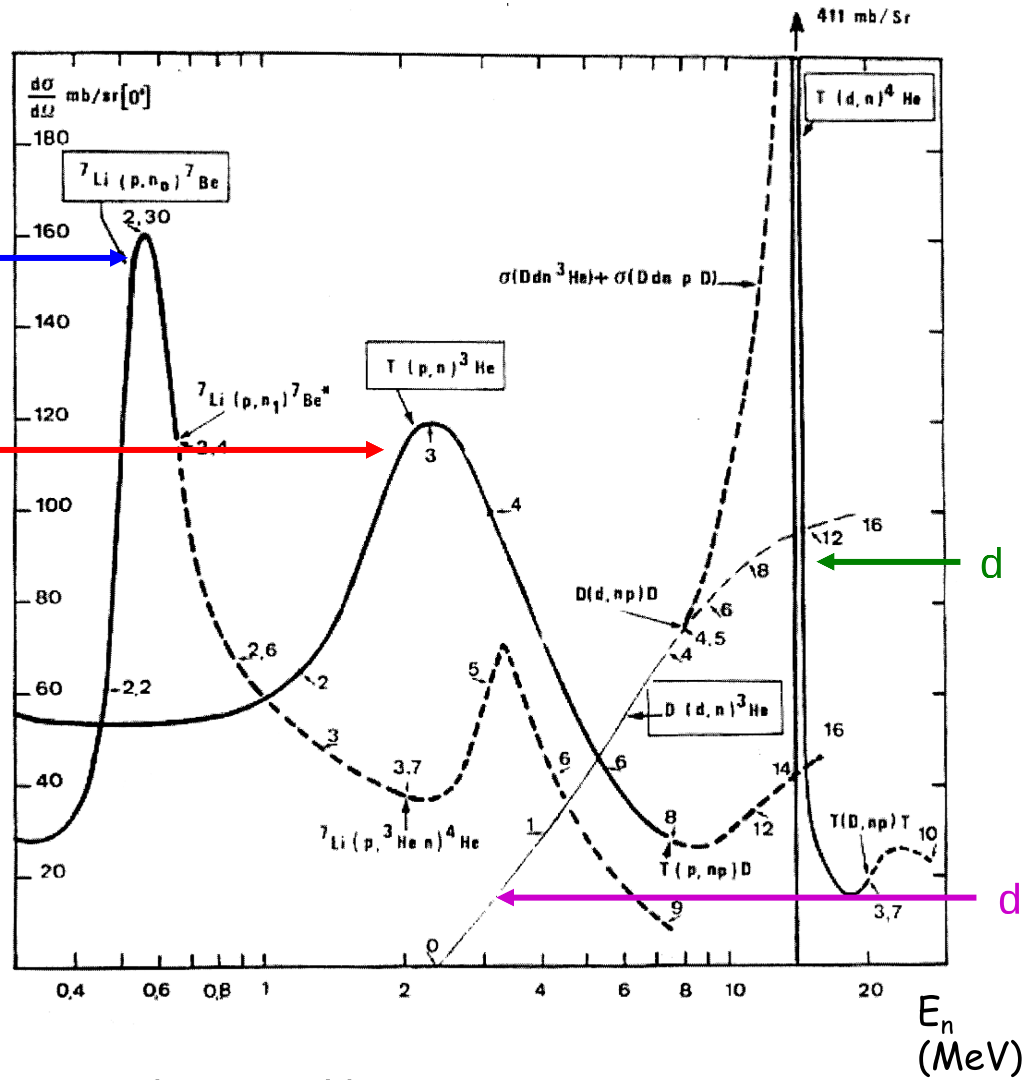


$d + {}^{3}H \rightarrow n + {}^{4}He$

$d + {}^{2}H \rightarrow n + {}^{3}He$

— monokinetic

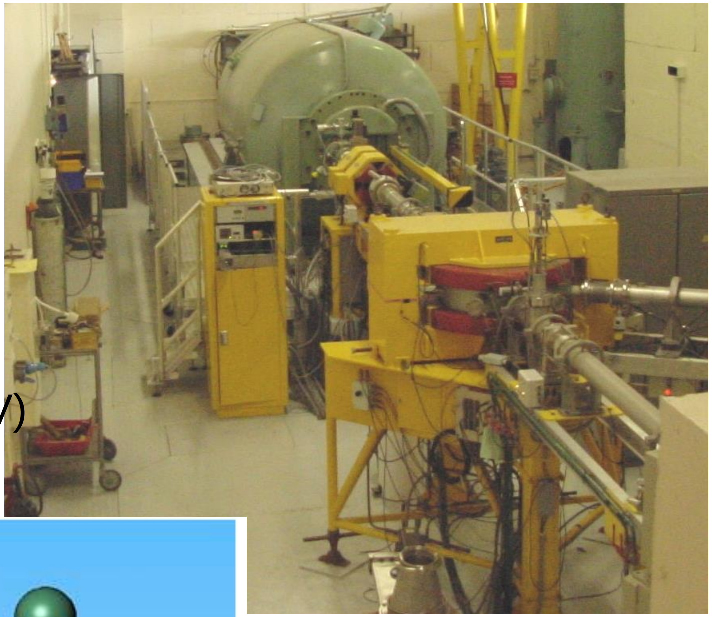
...... break-up component

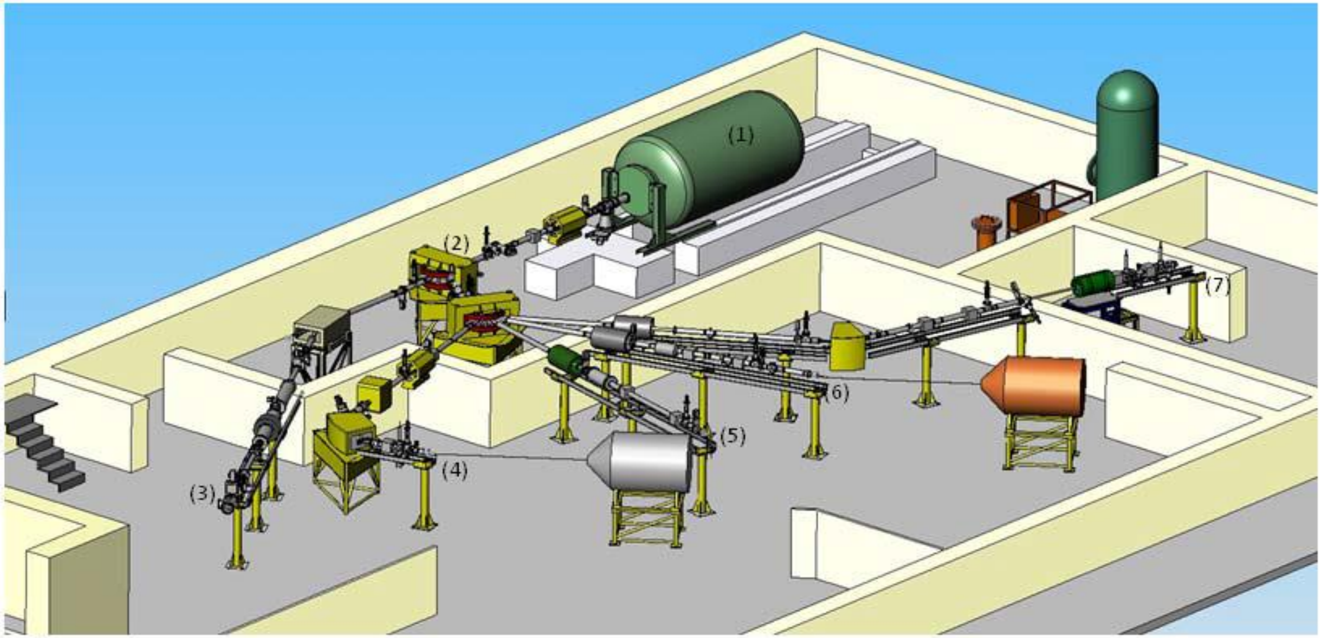
- Proton and deuteron beams with E< 4 MeV

- Purely mono-energetic neutrons up to 7 MeV and between 14 -17 MeV

Van de Graaff accelerators of CEA/DIF

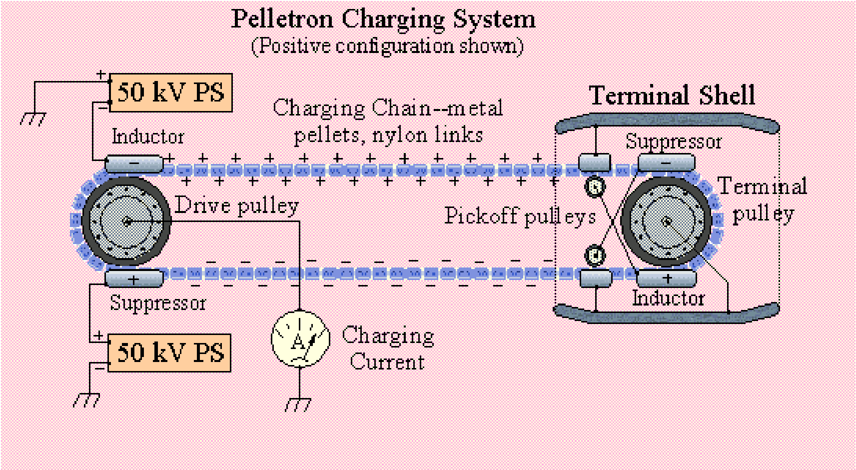
- 2 electrostatic accelerators
- **Van de Graaff 4MV** (0,4-4MV)
  - Light Ions beams : H, D, He
  - Ion energy from 0,4 to 4 MeV
  - « Mobley » line for neutron production
  - Nuclear microprobe
- **Van de Graaff tandem 7MV** (NENUPHAR 1,8MV-7MV)



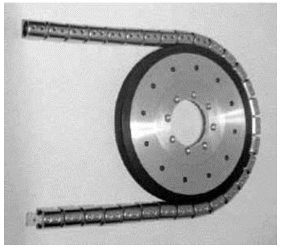


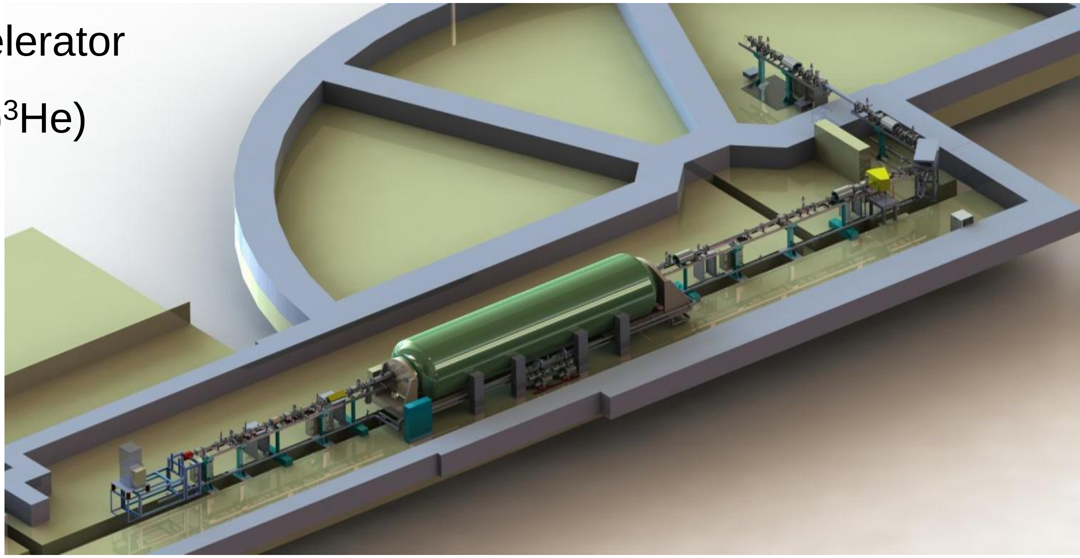
5 beam lines
2 experimental rooms

NENUPHAR, CEA, Bruyères-le-Châtel, France



- Refurbishment of the 7MV Tandem accelerator
- Neutron production up to 25 MeV $D(d,n)^3He$)
- The belt is replaced by a chain





Ready to accelerate the first beam as soon as the authorization is obtained

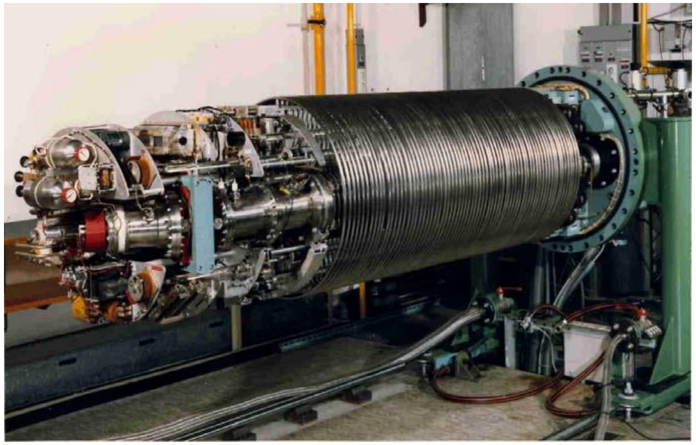
The PTB Facility, Braunschweig, Germany

TOF Spectrometer
Cyclotron CV 28

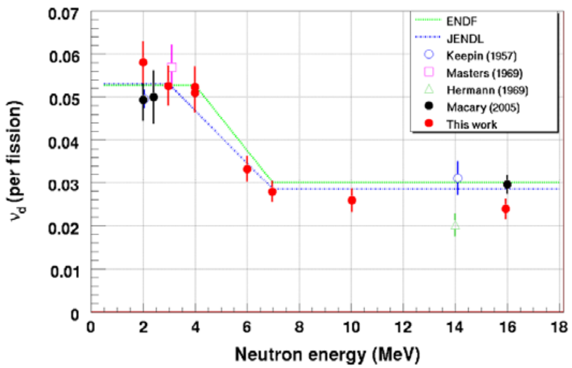
Monoenergetic fields :
- $^{7}Li(p,n)$: E_n= 144keV - 1MeV
- T(p,n) : En = 1MeV - 4 MeV
- D(d,n):En=5 MeV - 8MeV
- T(d,n) : E_n =14,8 MeV-17MeV

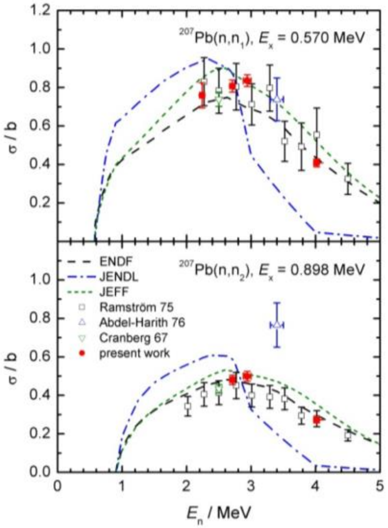
Quasi-monokinetic fields
- D(d,n): E_n =8MeV - 15 MeV
- T(d,n): E_n =17MeV - 23 MeV

Low scatter hall
VDG and CV 28



- **Metrology**
- **Study of the neutron source $^{15}N(p,n)^{15}O$**
- **Inelastic scattering on $^{206,207}Pb$, ^{209}Bi**
- **β-delayed neutrons from ^{232}Th and ^{237}Np**

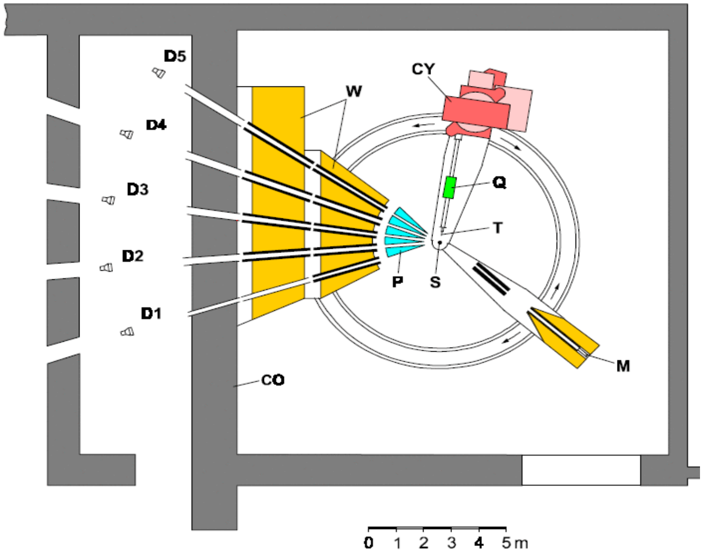




Upgrade : The VDG will be replaced by a TANDETRON

The PTB Facility, Braunschweig, Germany

TOF Spectrometer
Cyclotron CV 28



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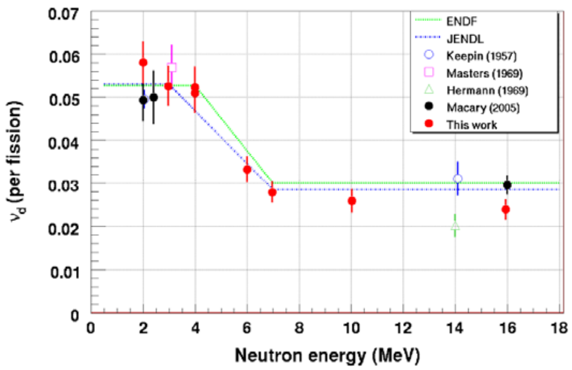
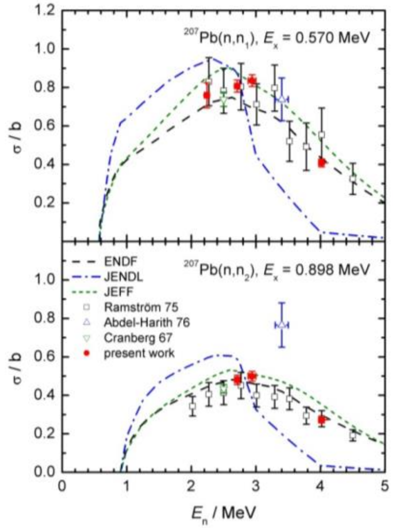




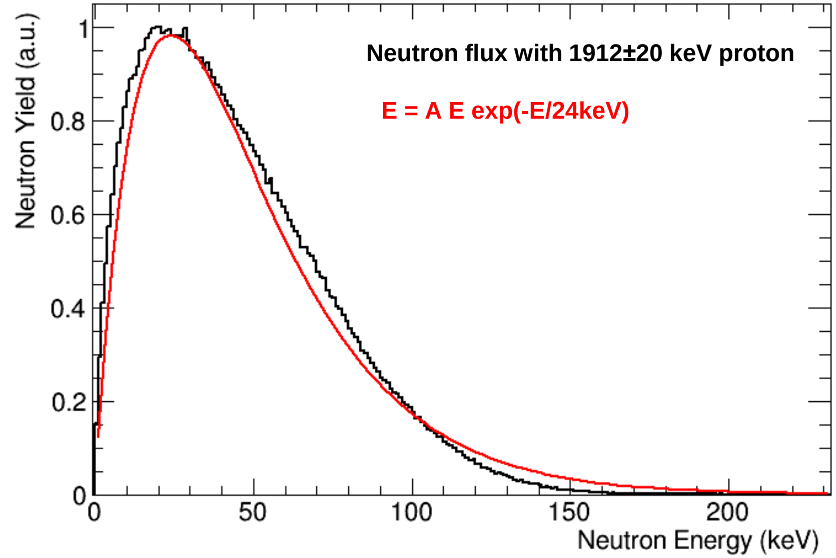
Upgrade : The VDG will be replaced by a TANDETRON

FRANZ, Frankfurt, Germany

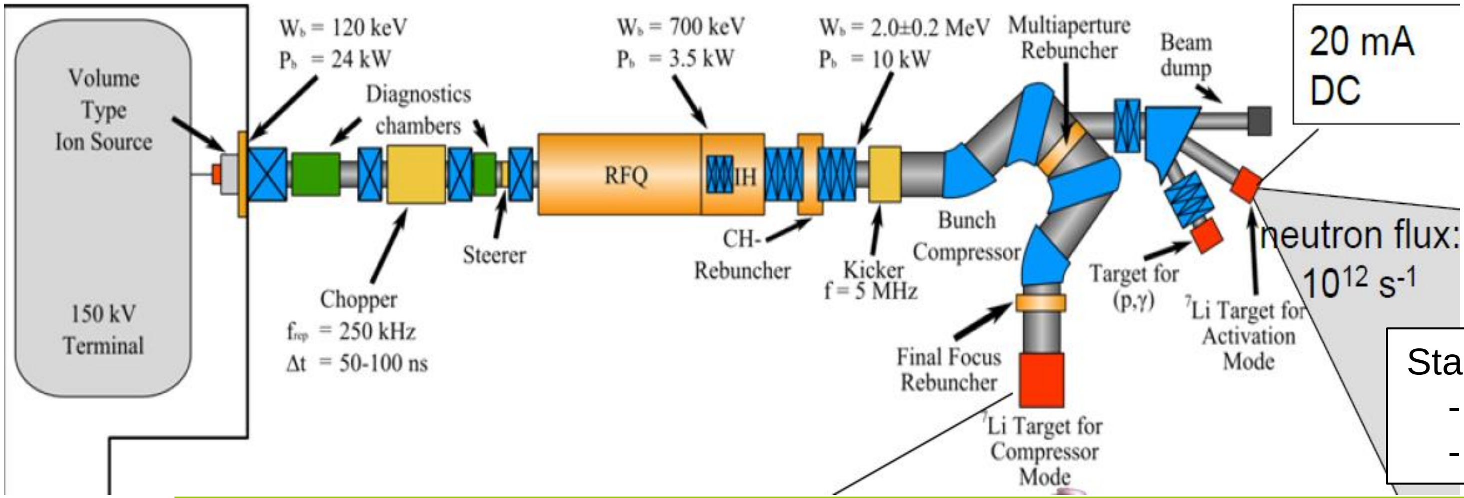
The main nuclear physics input to calculate abundances produced in the s process are Maxwellian Average Cross Sections (MCAS)

- Capture reactions in astrophysics
- ^{7}Li (p,n) reaction, Q=-1,8 MeV
- Neutrons emission cone
- Reproduction of a stellar energy spectrum

$$<\sigma>=\frac{2}{\sqrt{\pi}}\frac{1}{(k_BT)^2}\int_0^\infty \sigma(E)E\exp(-\frac{E}{k_BT})dE,$$



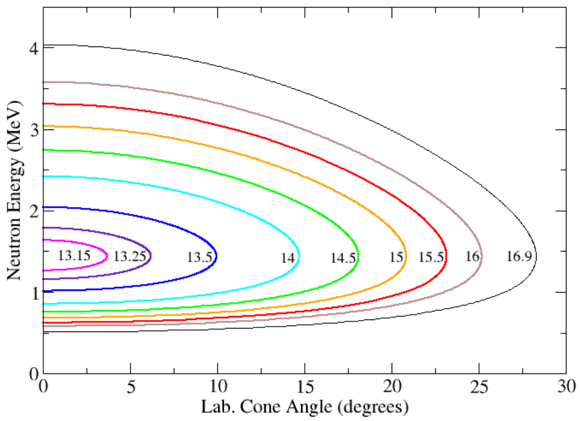
FRANZ (University of Frankfurt)



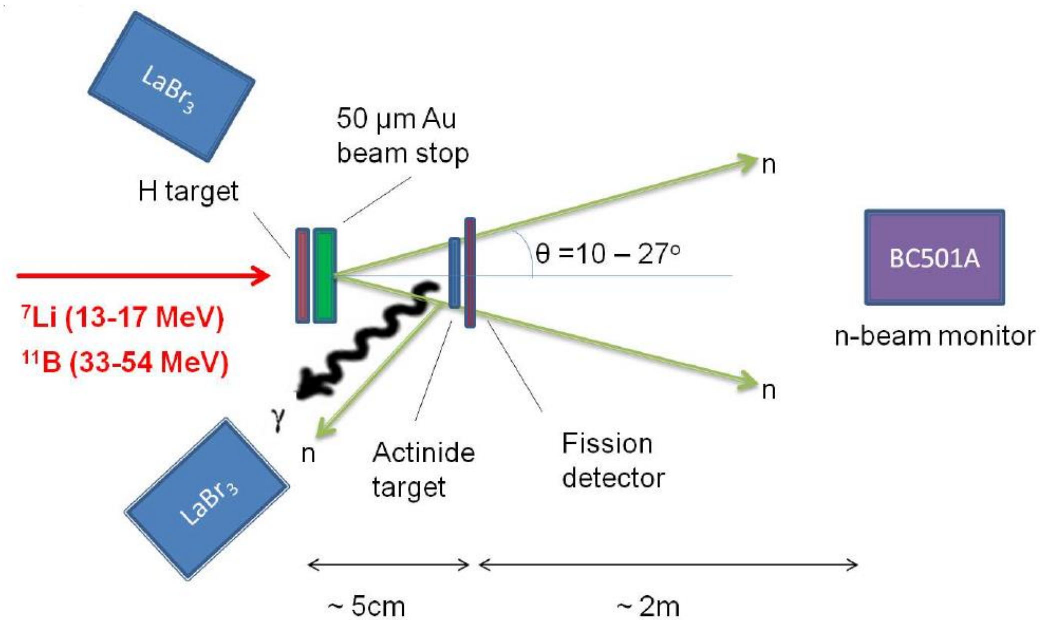
Starting intensities ~ 1 mA
- 10^7n/cm^2/s @ 1 m
- 10^9n/cm^2/s @ 10 cm

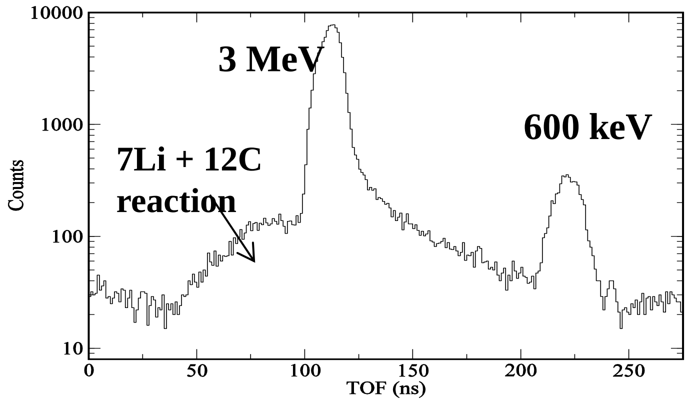
Lithium Inverse Cinematiques ORsay Neutron source

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



- Neutron production in inverse kinematic (1- 4 MeV)
- Neutrons are emitted in the forward direction:
  - Less lost neutrons
  - Detectors can be placed "outside" of the neutron flux





Fission studies

See talk of S. Oberstedt

M. Lebois et al., NIMA 735 (2014) p145-151

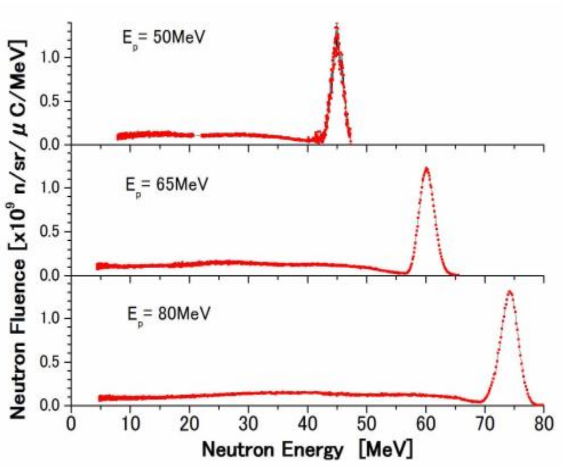
OUTLINE

- REACTORS
- ELECTRON ACCELERATOR BASED FACILITIES
- MONOENERGETIC NEUTRON FIELDS
- INTERMEDIATE ENERGY REACTIONS
- SPALLATION REACTIONS

Intermediate energy 20-200MeV

Quasi-mono-energetic spectrum:

- Proton beam on thin ^{7}Li converter
- ^{7}Li(p,n)^{7}Be reaction Q= -1,64 MeV → at 0° En ≈ Ep - 2 MeV
- Forward peak
- Limitations :
  - Spectrum not purely mono-energetic -> pulsed beam
  - Low melting point of Lithium (limited intensity) -> liquid target
  - Target highly activated (^{7}Be)



Intermediate energy 20-200MeV

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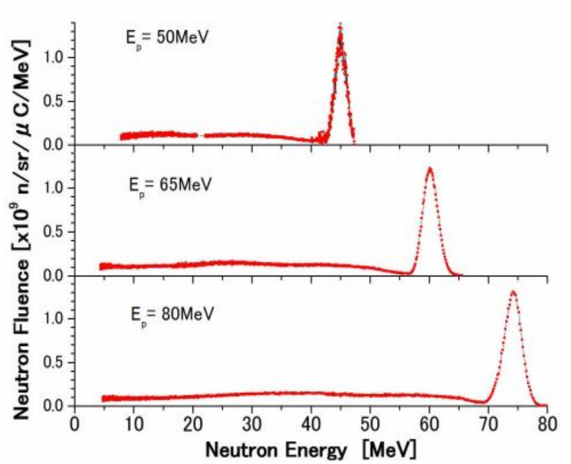
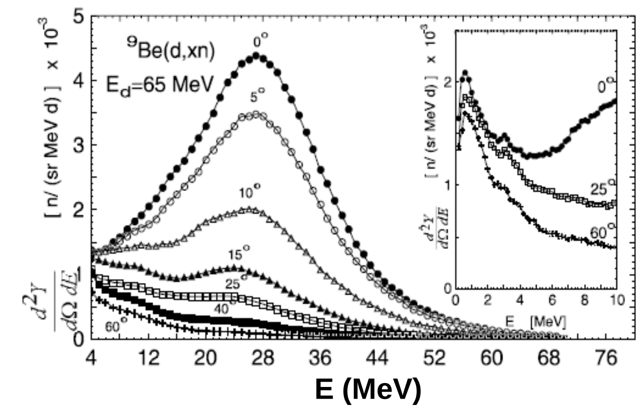
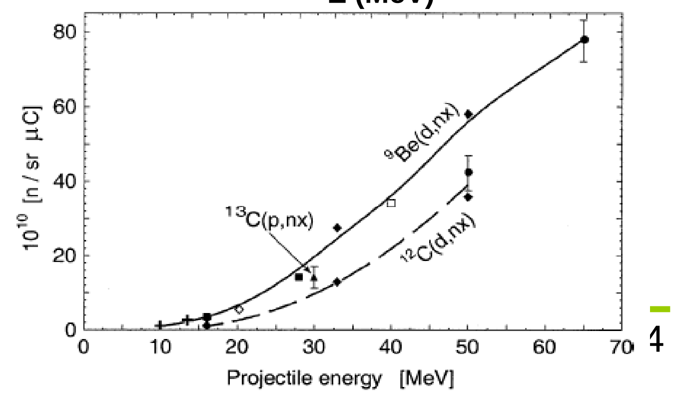


Continuous spectrum:

- Proton or deuteron beam on thick converter Be or C
- Continuous spectrum up to beam energy
- Flux increasing with energy
  - The beam stops in the converter
  - Large power deposition → cooling is challenging

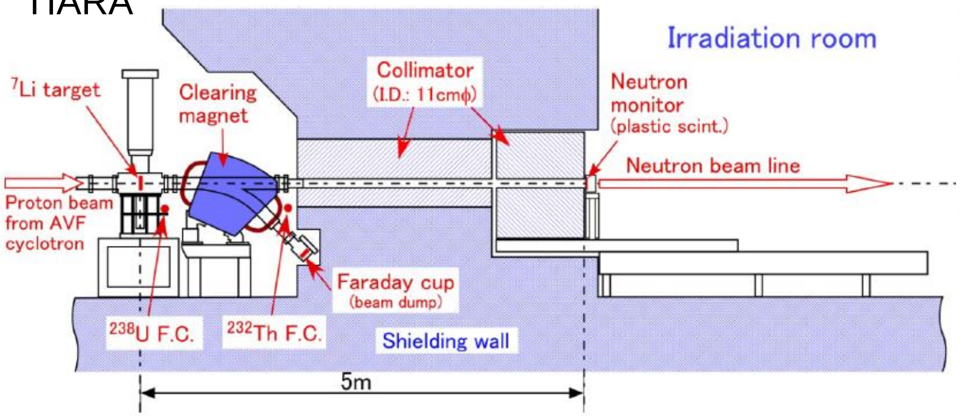




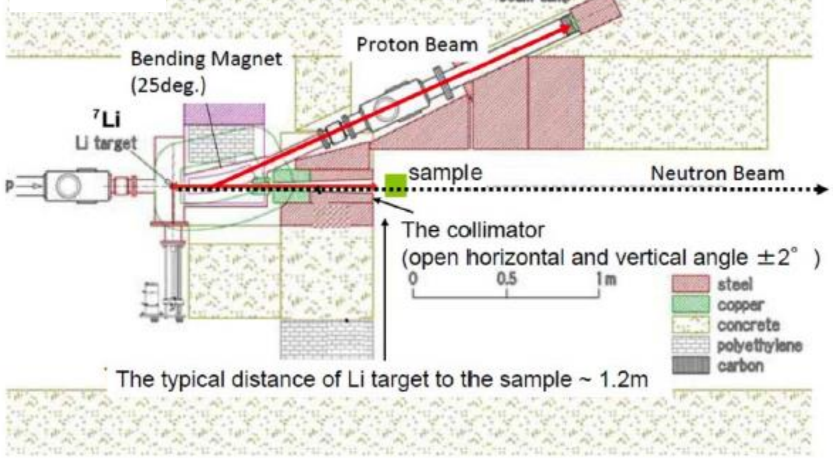
Several facilities proposes both types of spectra

Some Quasi-Monoenergetic facilities

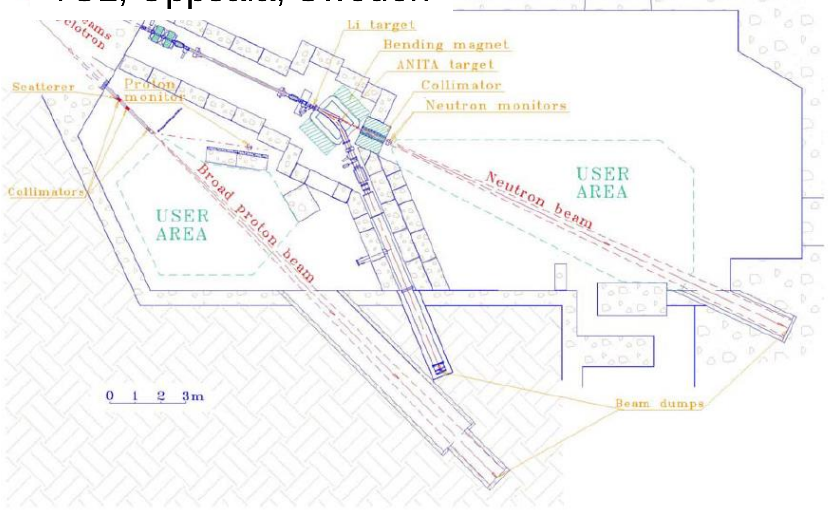
TIARA



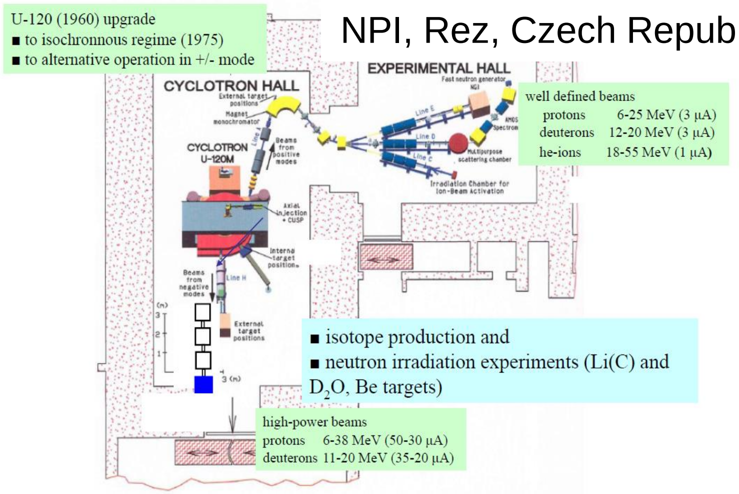
CYRIC



TSL, Uppsala, Sweden



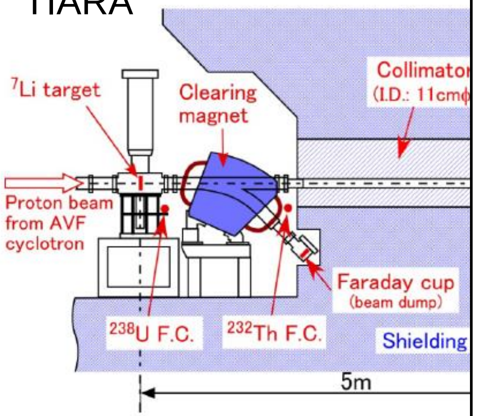
NPI, Rez, Czech Republic

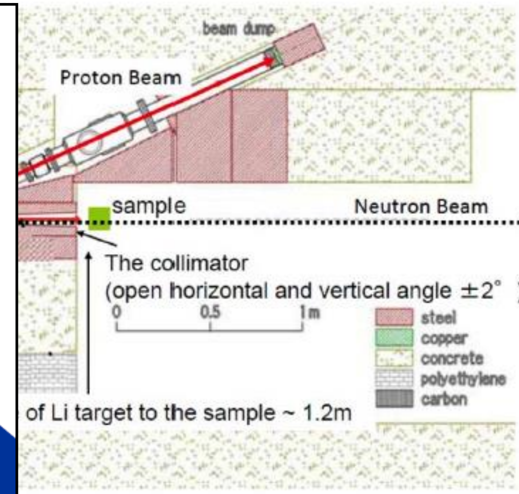


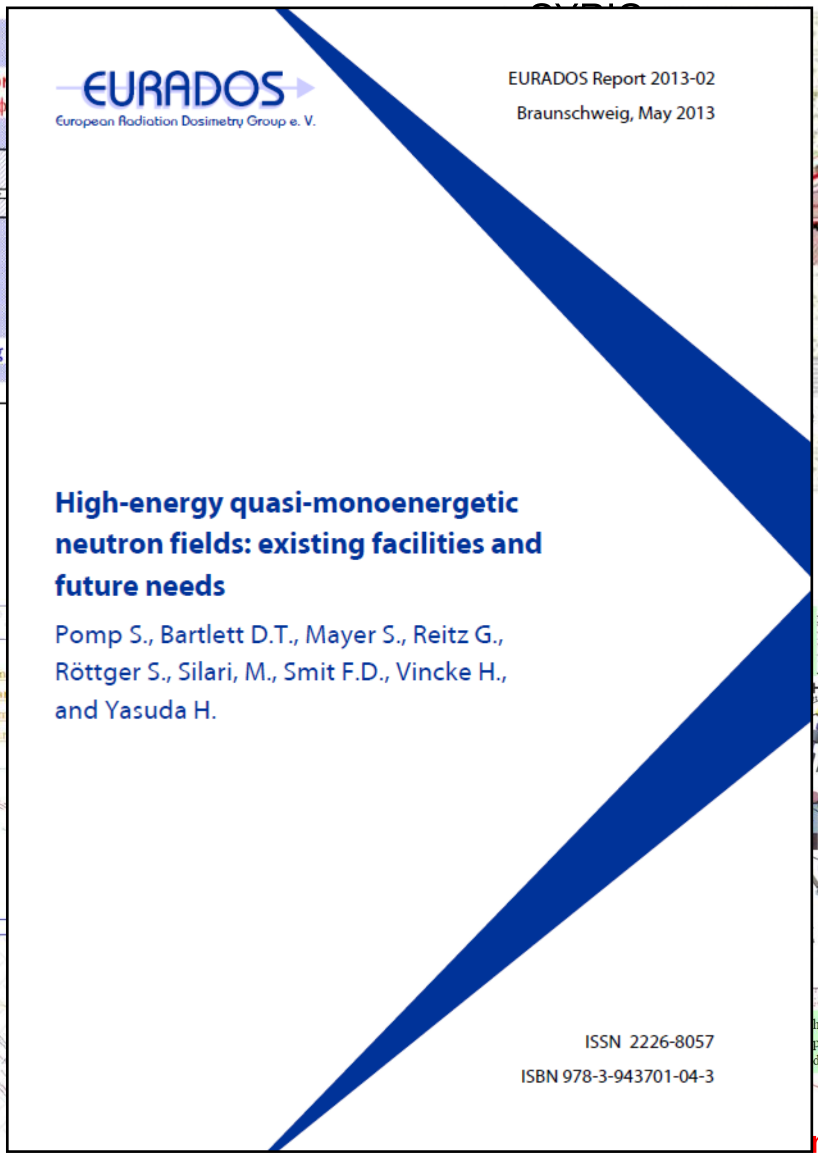
neutron flux up to 3 *10^8 n/cm^2/s

Some Quasi-Monoenergetic facilities

TIARA






EURADOS
European Radiation Dosimetry Group e. V.

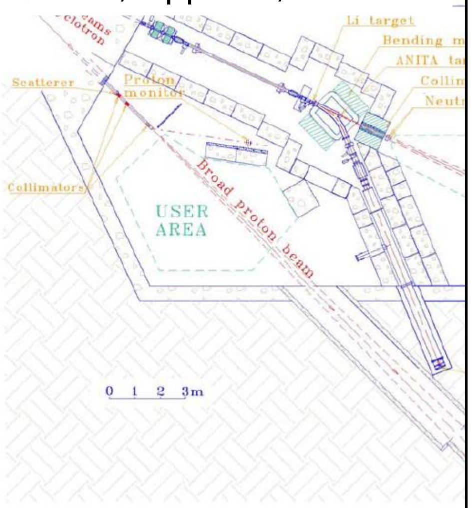
EURADOS Report 2013-02
Braunschweig, May 2013

High-energy quasi-monoenergetic neutron fields: existing facilities and future needs

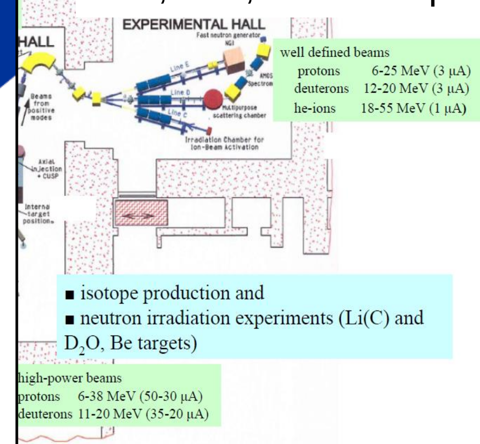
Pomp S., Bartlett D.T., Mayer S., Reitz G., Röttger S., Silari, M., Smit F.D., Vincke H., and Yasuda H.

ISSN 2226-8057
ISBN 978-3-943701-04-3

TSL, Uppsala, Sweden



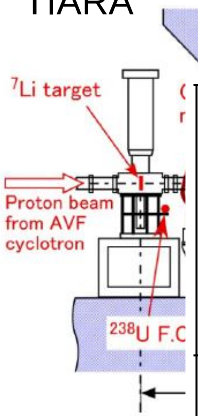
NPI, Rez, Czech Republic

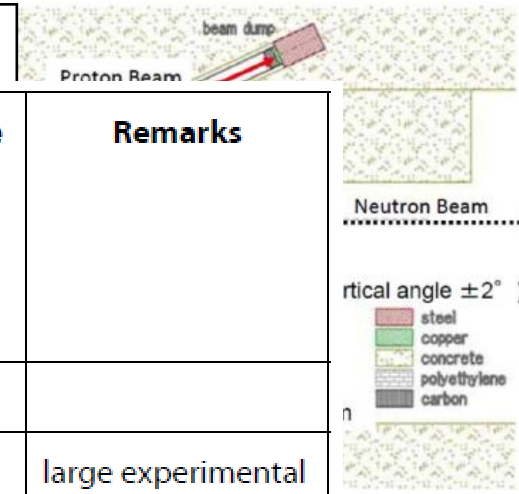


neutron flux up to 3 *10^8 n/cm^2/s

Some Quasi-Monoenergetic facilities

TIARA

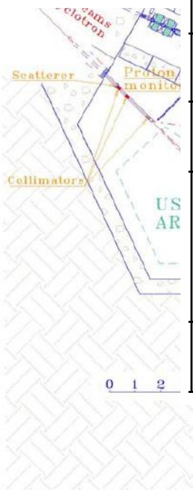




EURADOS Report 2013-02

Facility	Energy range [MeV]	Peak neutron fluence rate at standard irradiation position [$cm^{-2}s^{-1}$]	Beam angle relative to primary beam	Remarks
iThemba[a]	35 – 200	10^4	0°, 4°, 8°, 12°, 16°	
TSL[b]	11 – 175	10^6 for E_p < 100 MeV 10^5 for E_p > 100 MeV	0°	large experimental area
TIARA[c]	40-90	10^4	0°	large irradiation room
CYRIC[d]	20-90	10^6	0°	
RCNP[e]	100 - 400	10^5	0° - 30°	up to 100 m ToF
NPI[f]	18 – 36	Up to 10^9	0°	Standard irradiation very close to source
NFS[g]	20 – 33	n.a. yet	0°	Start late 2014

TSL, Up



ch Republic

d beams
6-25 MeV (3 μA)
12-20 MeV (3 μA)
18-55 MeV (1 μA)

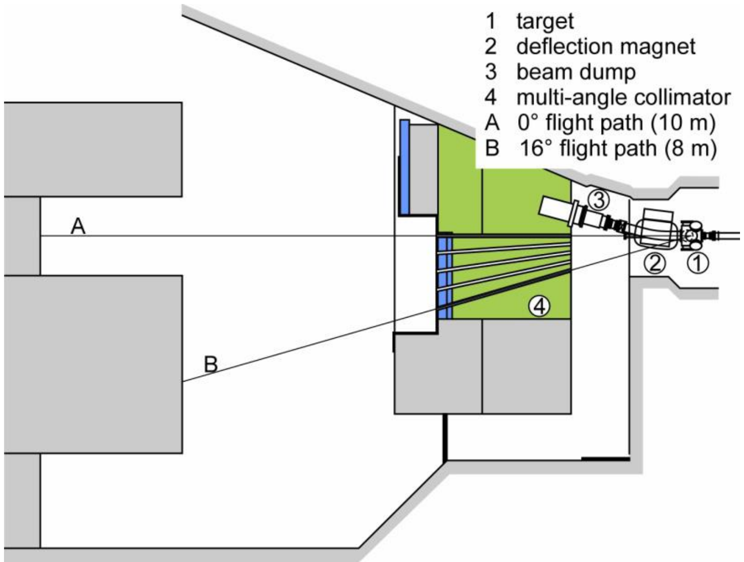
Li(C) and

deuterons 11-20 MeV (35-20 μA)

ISBN 978-3-943701-04-3

neutron flux up to 3 *10^8 n/cm^2/s

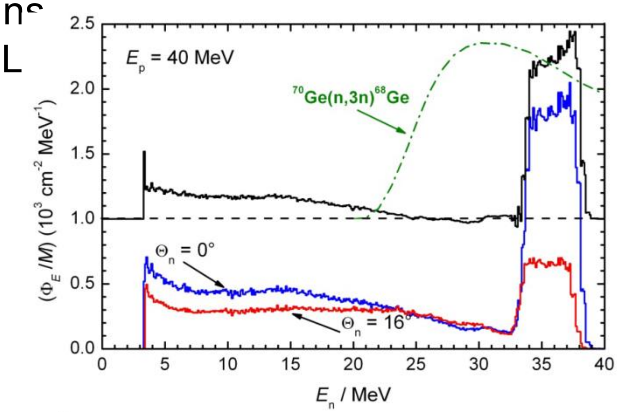
The iThemba LABS Neutron Beam Facility (Cape Town, SA)



Targets:
- Li, Be: quasi-monoenergetic
- C: quasi-white ('grey')

- Beam currents
  - 3-5 µA (*Ep < 100 MeV)*
  - 300 nA (*Ep = 200 MeV)*
- Pulse selection: 1/1 – 1/7
- Time resolution: ≈ 1 n
- Fluence rate (1 mm L
- Flight paths:
  - 10 m (0°)
  - 8 m (16°)

E_0 (MeV)	current (µA)	$d\Phi/dt$ ($cm^{-2}\ s^{-1}$)
66	3.0	4.7×10^4
100	3.0	3.4×10^4
150	2.0	2.8×10^4
200	0.3	4.6×10^3



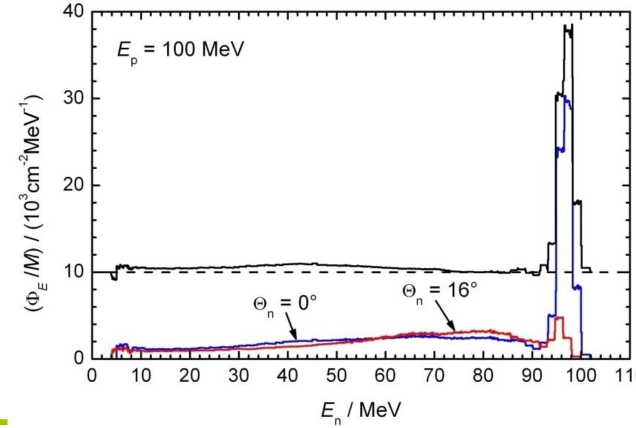
Reduction of the break-up continuum:

$(\Phi_E/Q)(0°) – f\cdot(\Phi_E/Q)(16°)$

- Activation cross sections:

$f = A_{cont}(0°)/A_{cont}(16°)$

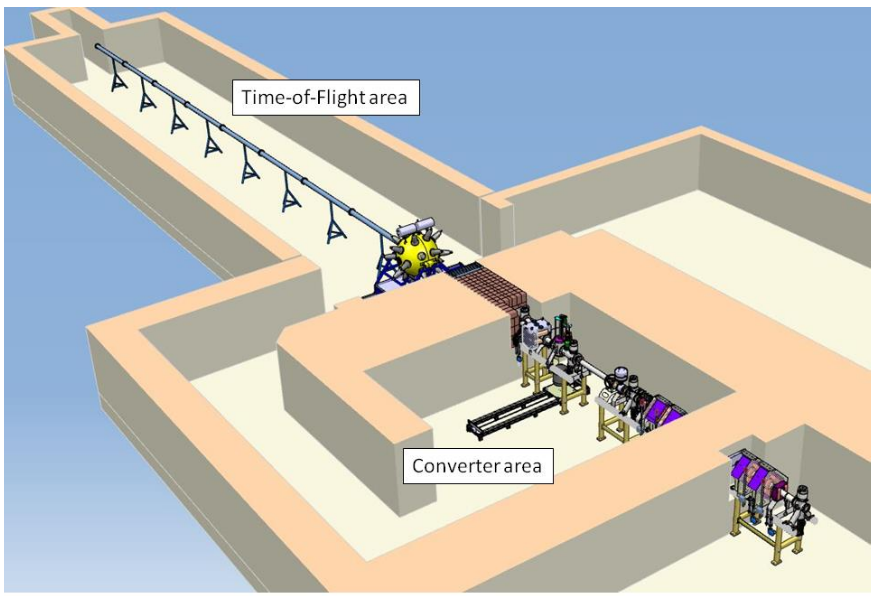
for a priori cross section σ(*E*)

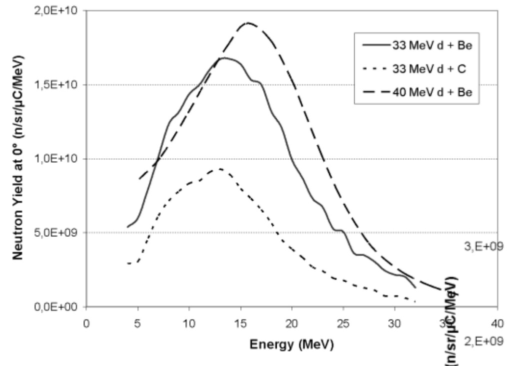


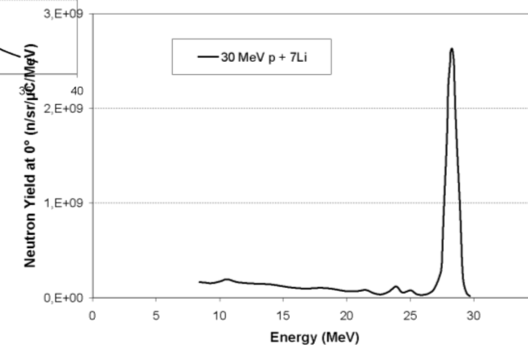
Neutrons For Science, CAEN, France

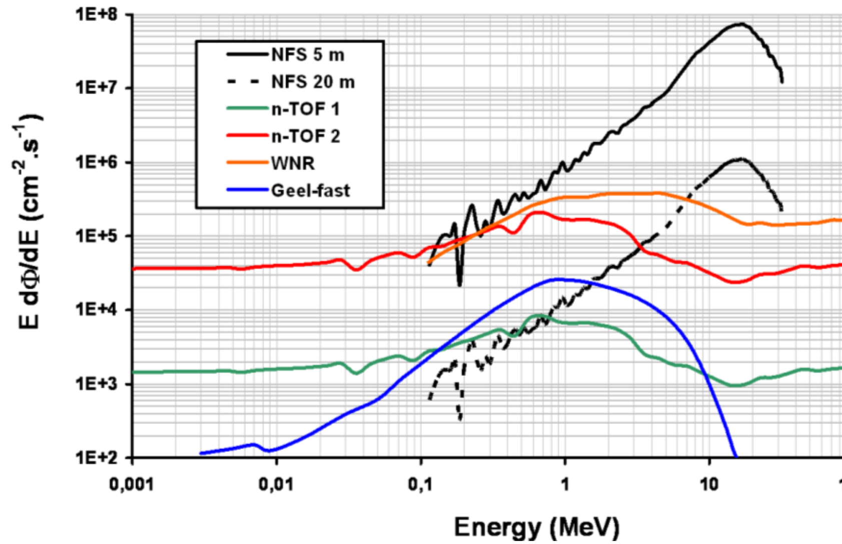
High intensity proton and deuteron beams of the Linar accelerator of SPIRAL-2

- Pulsed neutron beam
- Continuous spectrum : d + thick converter
- QMN spectra : p + thin converter
- Neutron energy range 0,1-40 MeV
- Measurements by activation method





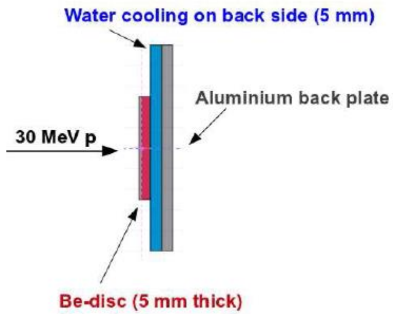


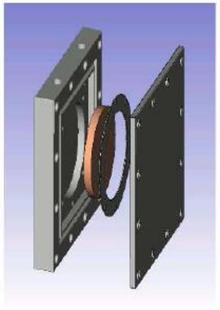


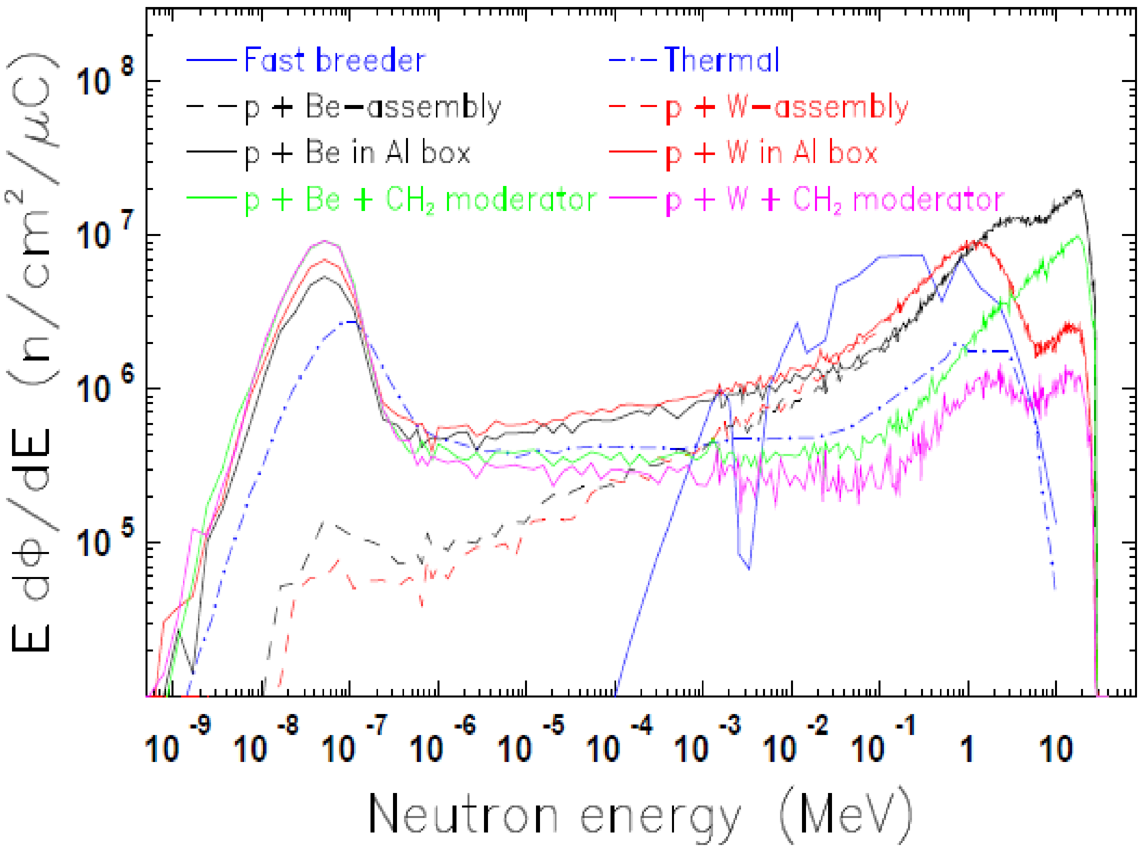
- High average flux in the 1-40 MeV range
- Good energy resolution

Jyväskylä, Finland

- High neutron flux by p induced reaction on thick converter
- Try to reproduce the fast reactor spectrum
- Study of fission yield







Goal 10^{12} n/s on the fission target

30 MeV proton up to 100 µA

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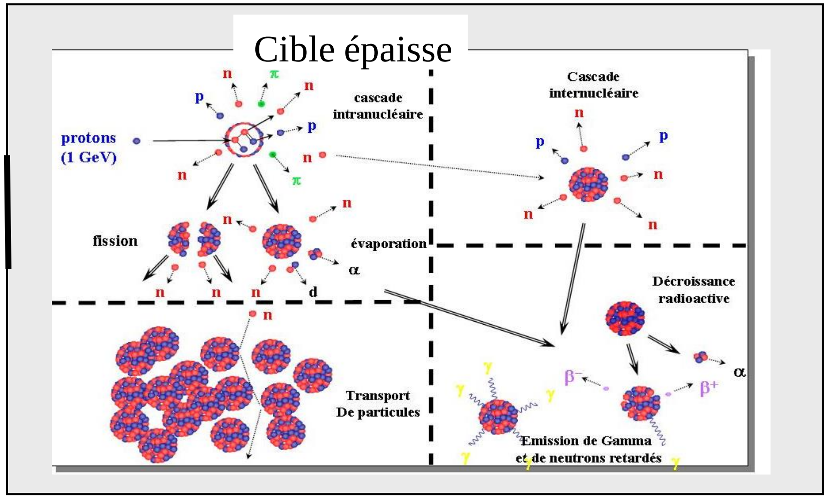
Spallation reaction

Proton beam with energy > 800MeV

Very intense neutrons source

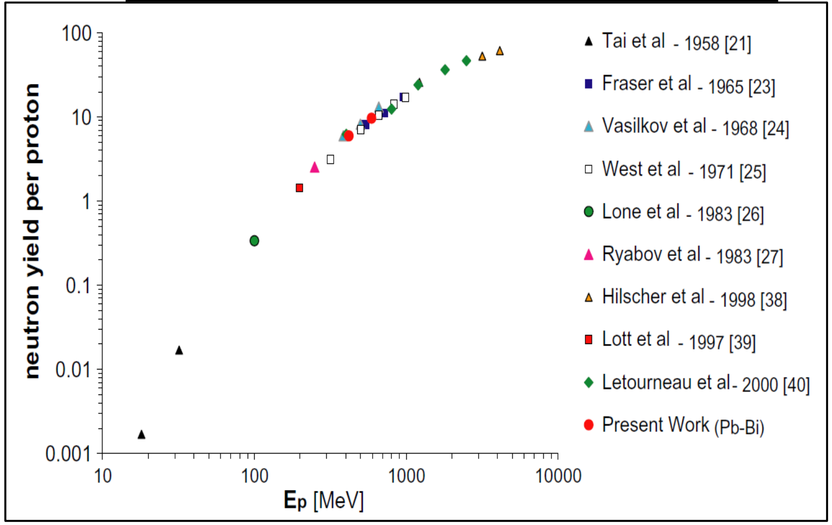
Proton accelerator 1 GeV x 1 mA = 1 MW

⇨ 10^{17} n/s



- Neutron production up to proton energy
- Use of moderator to increase neutrons flux at low energy thermal or cold
- Multipurpose Facilities :
  - Material studies
  - Radio element production for medicine
  - Small part in nuclear data measurement
- N-tof, WNR, SNS, ESS, JPARC

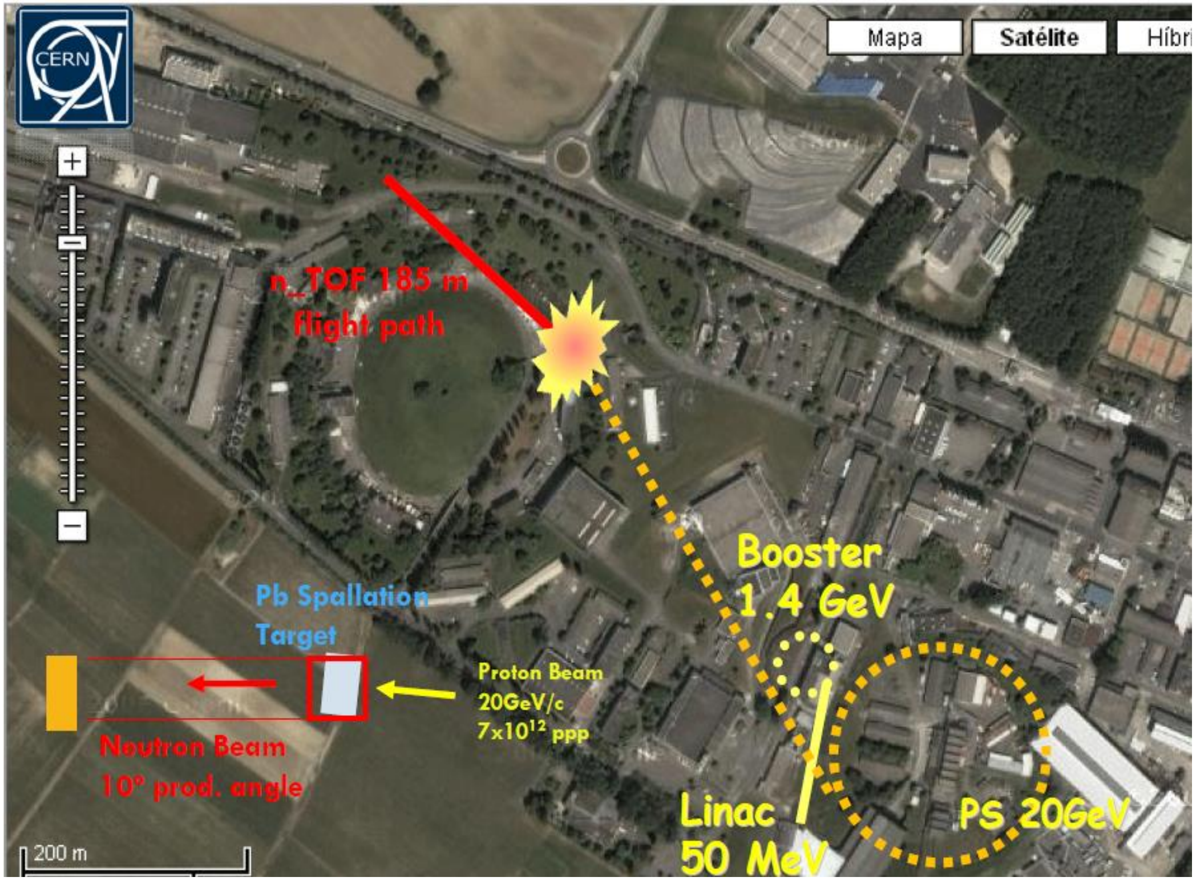
(1 GeV) p + Pb produces > 20 n/p



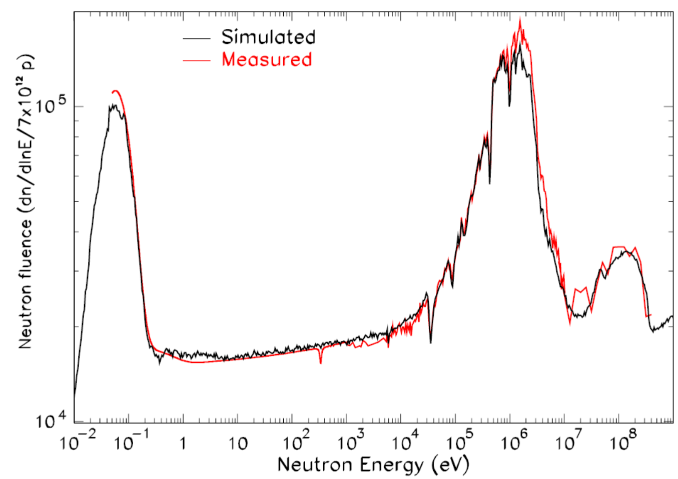
Challenges :

- High intensity accelerator
- Target power deposition
- Windows between accelerator and target

The n-tof, CERN, Switzerland



- 300 neutrons per proton at 20 GeV
- 185 m long flight path



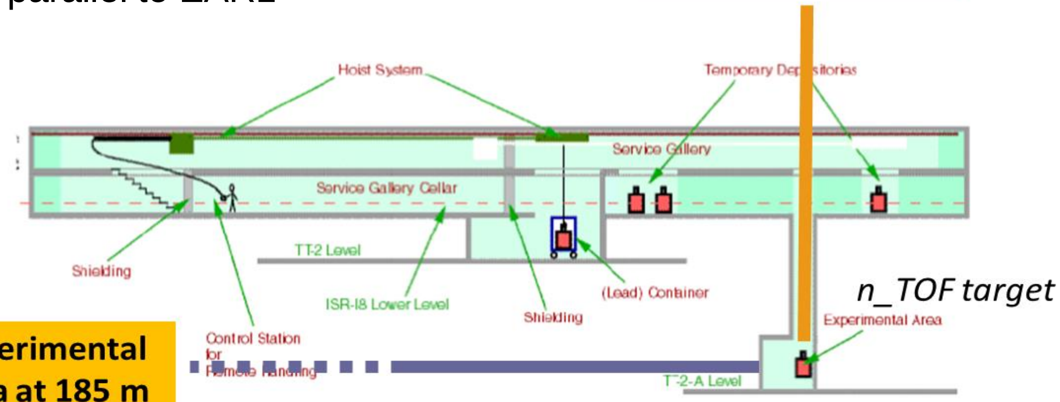
- Extremely high instantaneous neutron flux (10^5 n/cm^2/pulse)
- High resolution in energy (DE/E=10^{-4}) → study resonances
- Large energy range (25 meV<E_n<1 GeV)
- Low repetition rate (<0.8 Hz) → no wrap-around

The new n_TOF EAR-2 neutron beam line

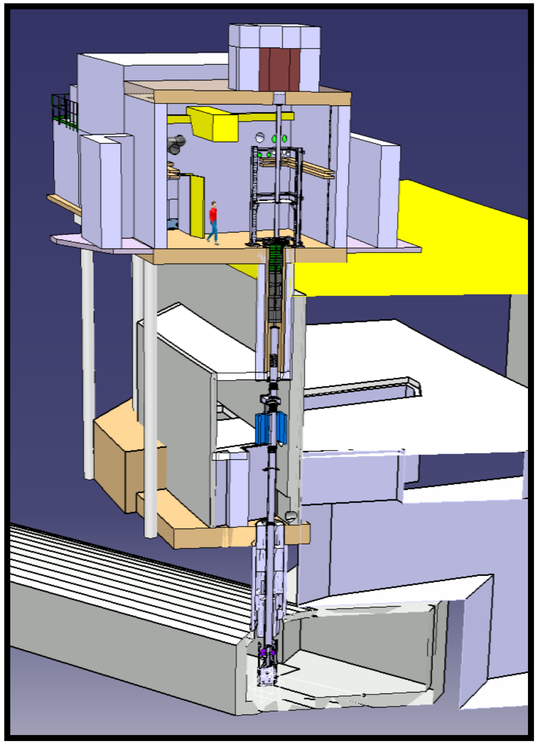
- 25 times higher flux (n/pulse) than EAR1
- Reduced energy resolution(no RR > ~10 keV)
- Runs in parallel to EAR1

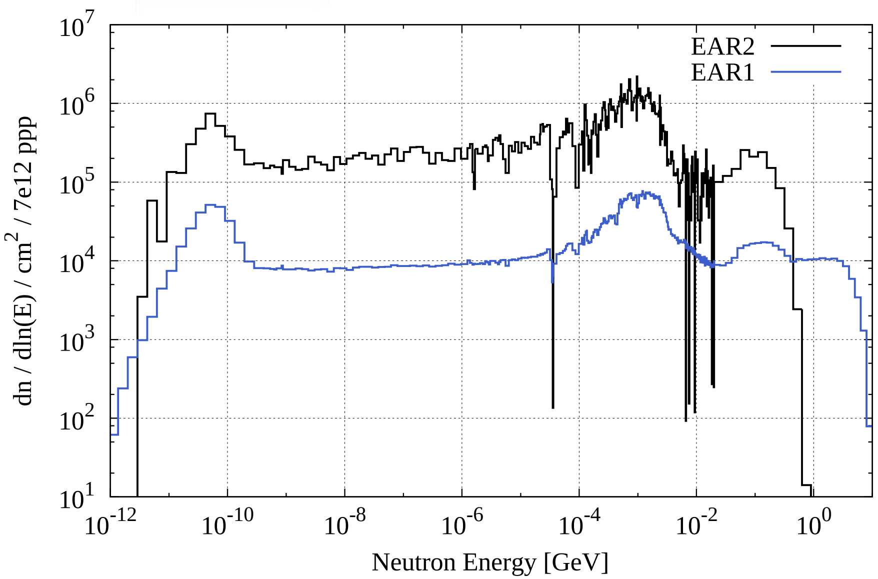
New experimental area at 19 m (EAR-2)

Under commissioning



Experimental area at 185 m





First physics experiments by end 2014:

- Capture on fissile isotopes
- Capture on small mass *s*-process branching points
- Fission spectroscopy and prompt g-rays with STEFF
- Elastic/inelastic reactions (HPGe or CsI+Si telescopes
- Fission on high activity samples (e.g. ^{240}Pu)
- Irradiation of electronic components (@1.5 m)
- …

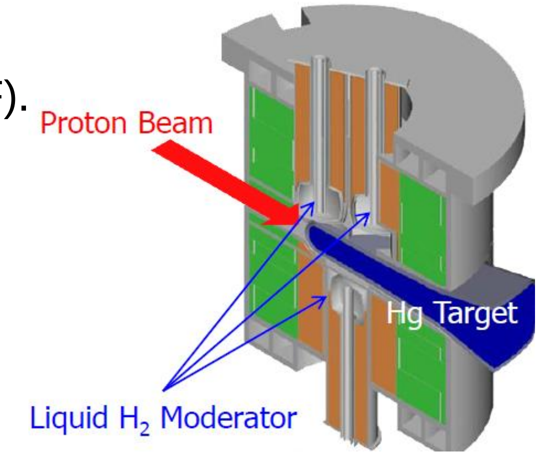
ANNRI, J-PARK, Japan

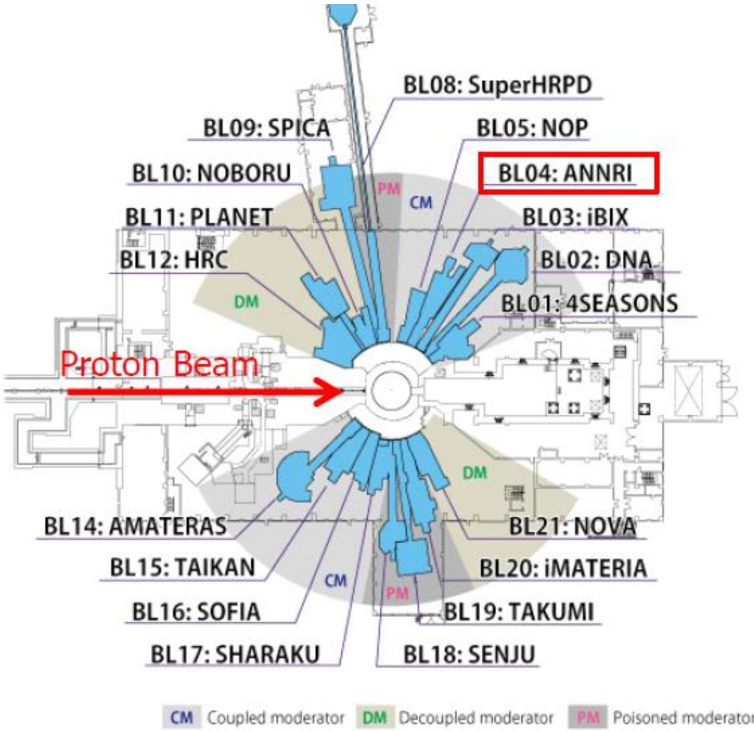
- Accurate Neutron Nucleus Reaction Measurement Instrument
- Two lines of the Materials and Life science experimental Facility (MLF).
- Two flight path (21 and 28 m)
- Neutrons produced by the Japanese Spallation Neutron Source

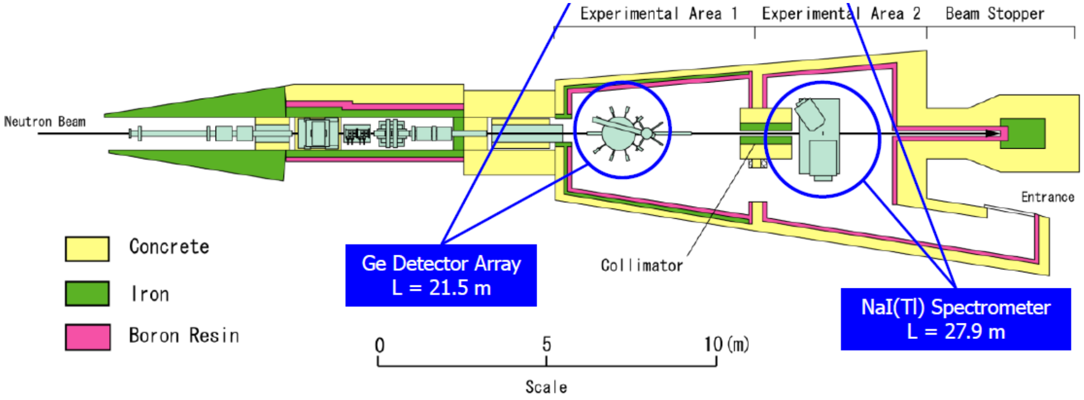
  -3 GeV proton beam on mercury target

  -1 MW beam power, 25 Hz repetition rate

→ **$1{,}5\ 10^{17}$ n/s**

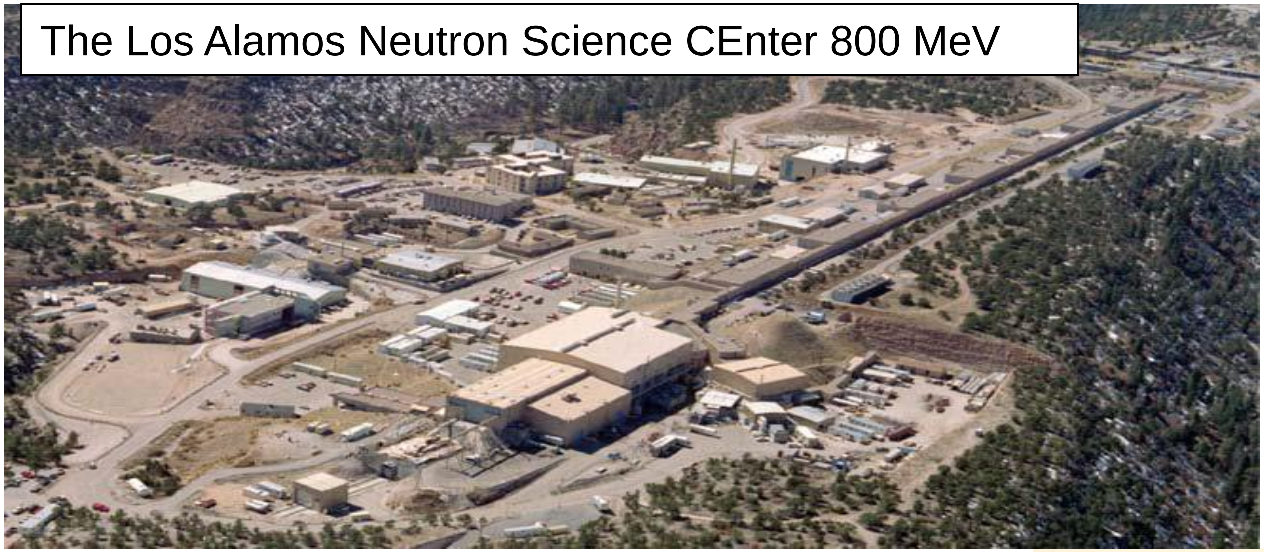






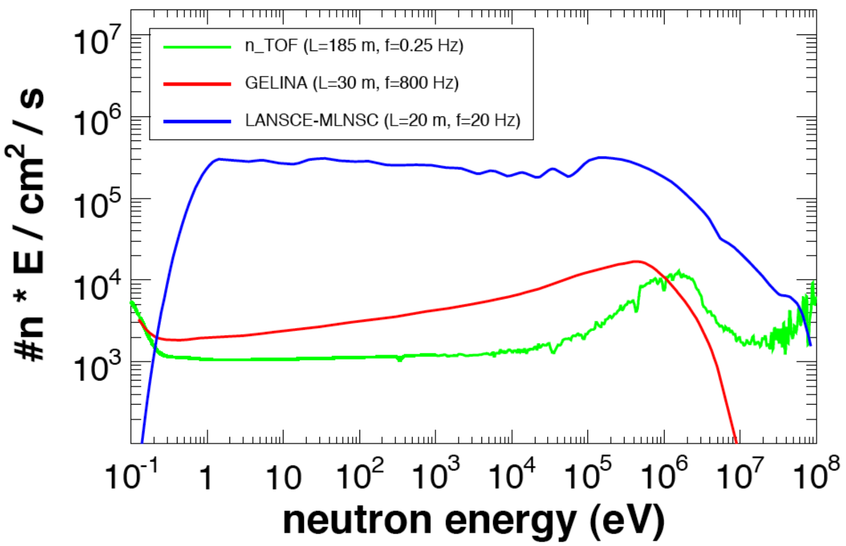
Neutron capture cross-section measurement of Minor Actinides and Long Live fission products for the study of transmutation of nuclear waste

Other multipuproses spallation neutron sources

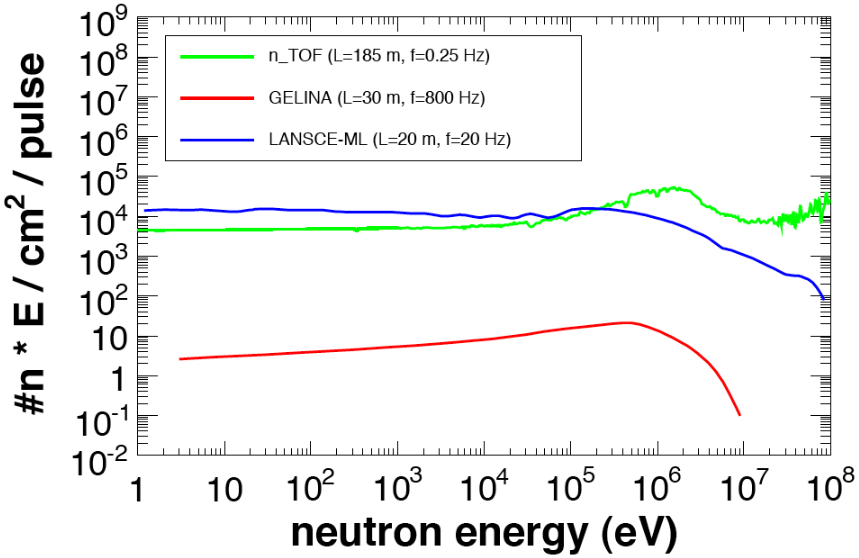


Flux comparison

Average flux

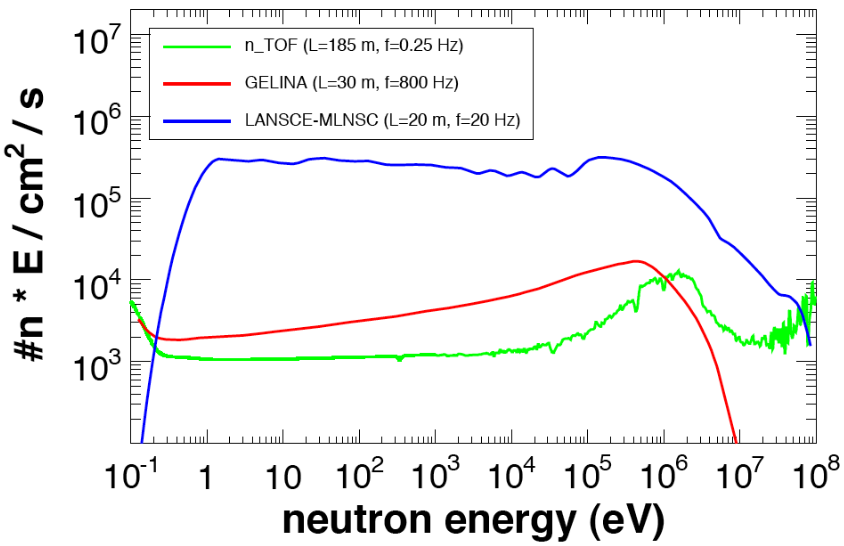


Instantaneous flux

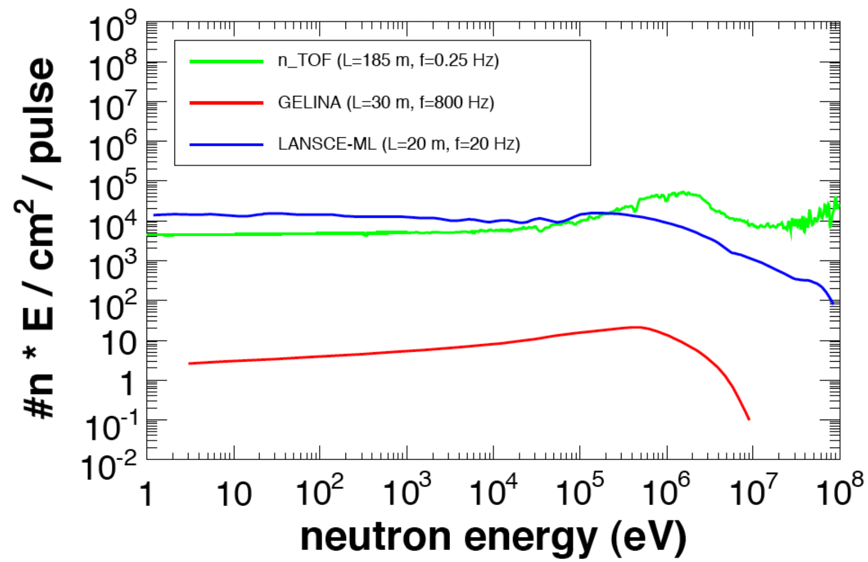


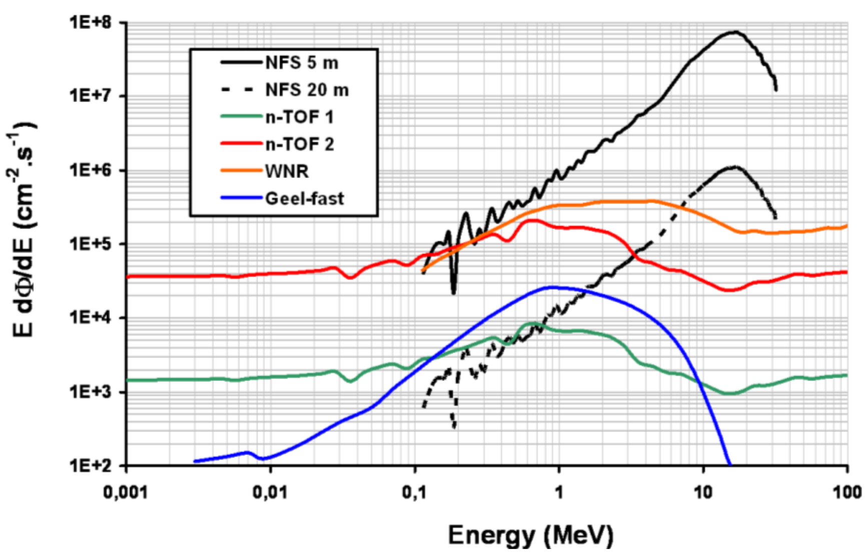
Flux comparison

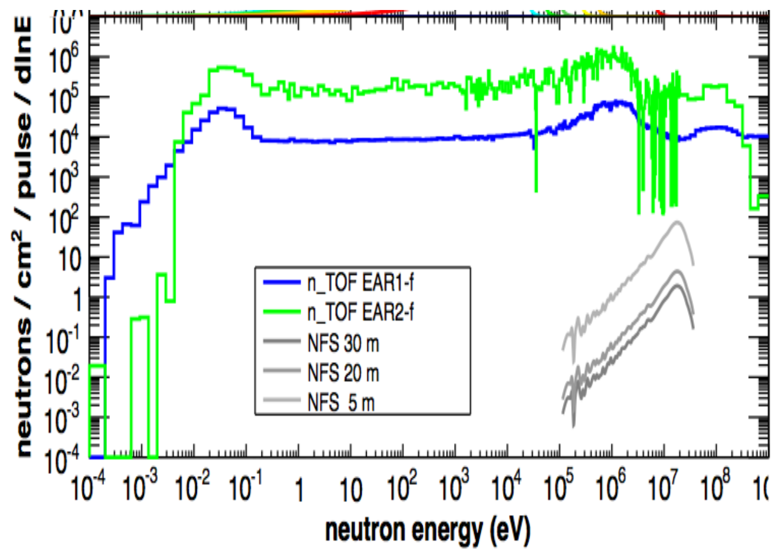
Average flux



Instantaneous flux







Summary

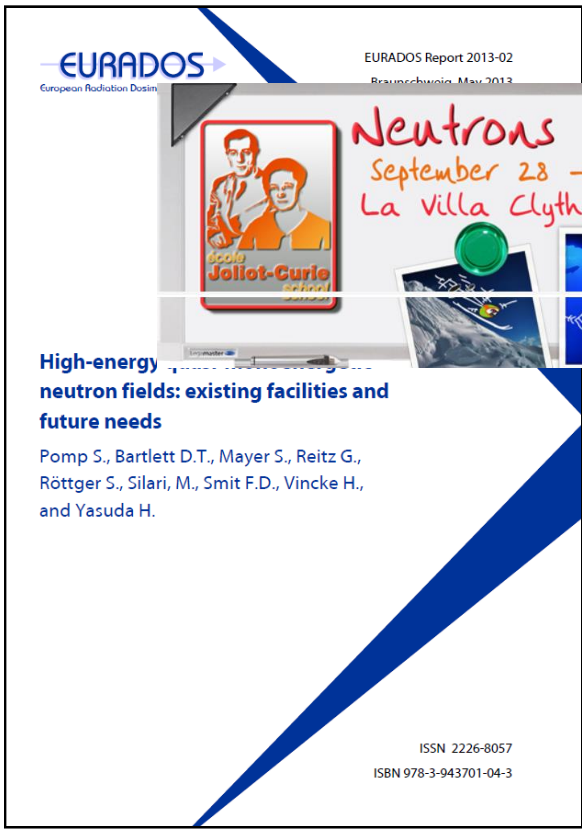
- Numerous neutron facilities exist
- Each energy domain has an adapted production mode
- The energy and flux are not the only characteristics to take into account
  - Time structure and energy resolution
  - Collimation
  - Background conditions
- Tendency for the next decade :
  - Increase the neutron flux :
    - Use of small samples (radioactive)
    - Multiple coincidence detection (low efficiency)
  - Most of the facilities are no more purely dedicated to nuclear data measurement
- But a facility is nothing without:
  - Detector(s)
  - Target
  - Physicists

References

•1st ERINDA Progress Meeting and Scientific Workshop, Prague, 16-18 January 2012

•**ERINDA,** Workshop, CERN, Geneva, Switzerland - 1-3 October 2013

•Joliot Curie School, “Neutron and Nuclei”, Fréjus, 28 Sep-3 Oct 2014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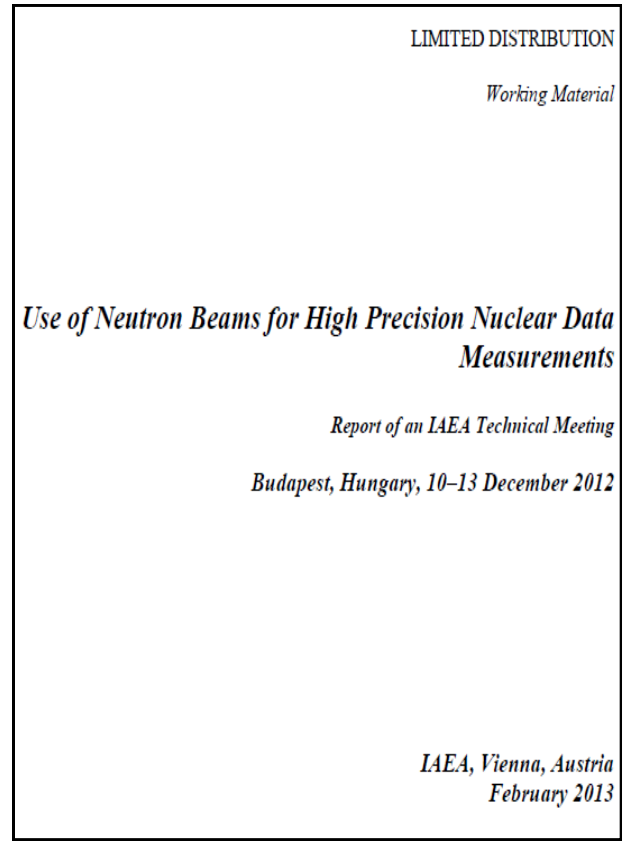
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Working Material

Use of Neutron Beams for High Precision Nuclear Data Measurements

Report of an IAEA Technical Meeting

Budapest, Hungary, 10–13 December 2012

IAEA, Vienna, Austria
February 2013