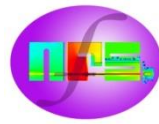


NFS facility at GANIL/Spiral2

Scientific program, technical solutions and operation

X. Ledoux on behalf of the NFS collaboration

1. The NFS facility
2. First neutron spectra measured at NFS
3. First experiments



NFS is one of the experimental areas of SPIRAL-2 at GANIL (Caen)

Physics case

- Fundamental physics
- Astrophysics
- New generation of reactor
- Fusion technology
- Radioisotopes production for medical applications
- Biology (cells irradiation..)
- Development and characterization of new detectors
- Study of the single-event upsets

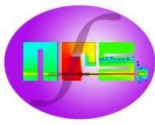
International collaboration

50 physicists

15 laboratories

8 partners



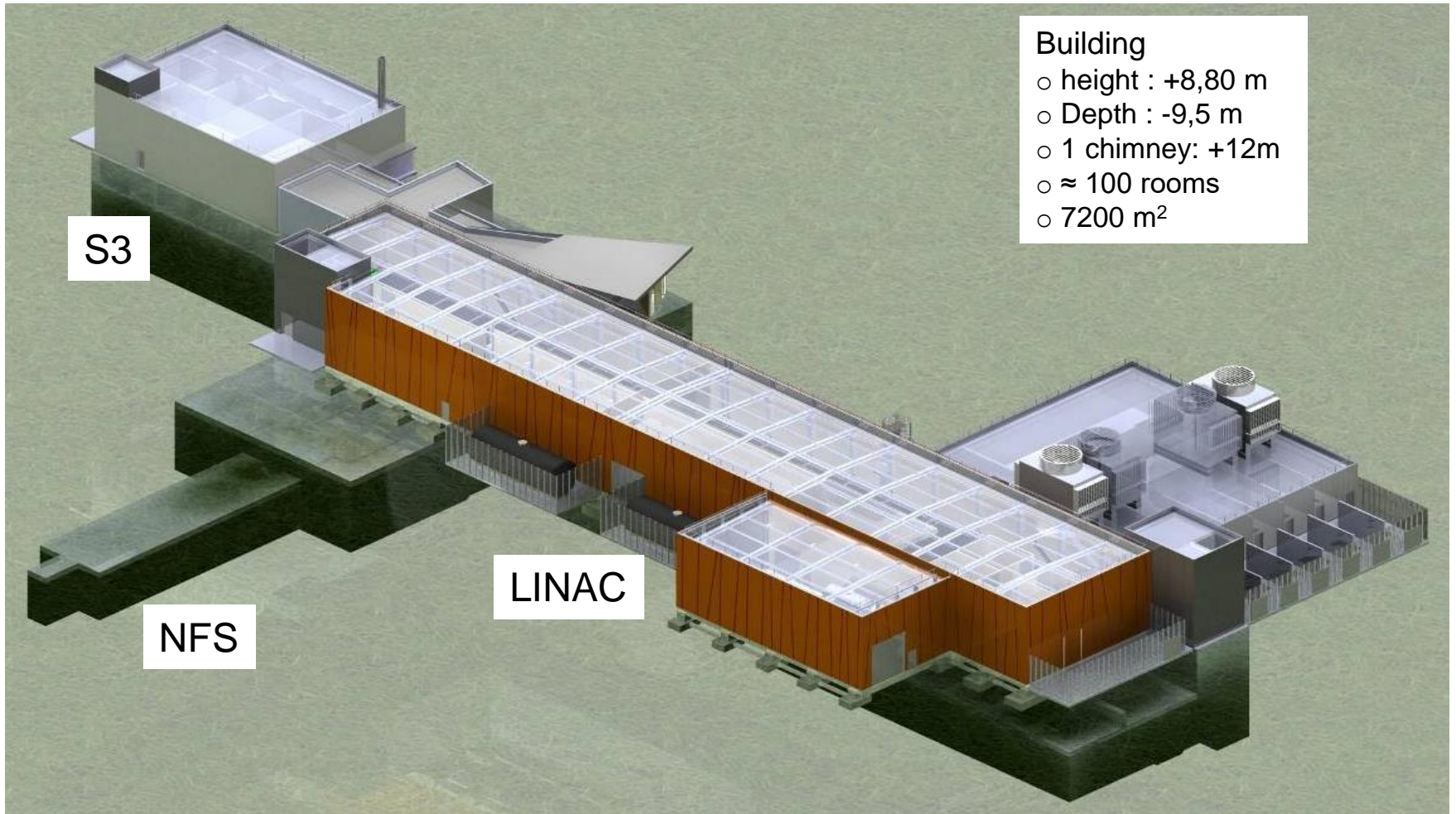
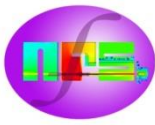


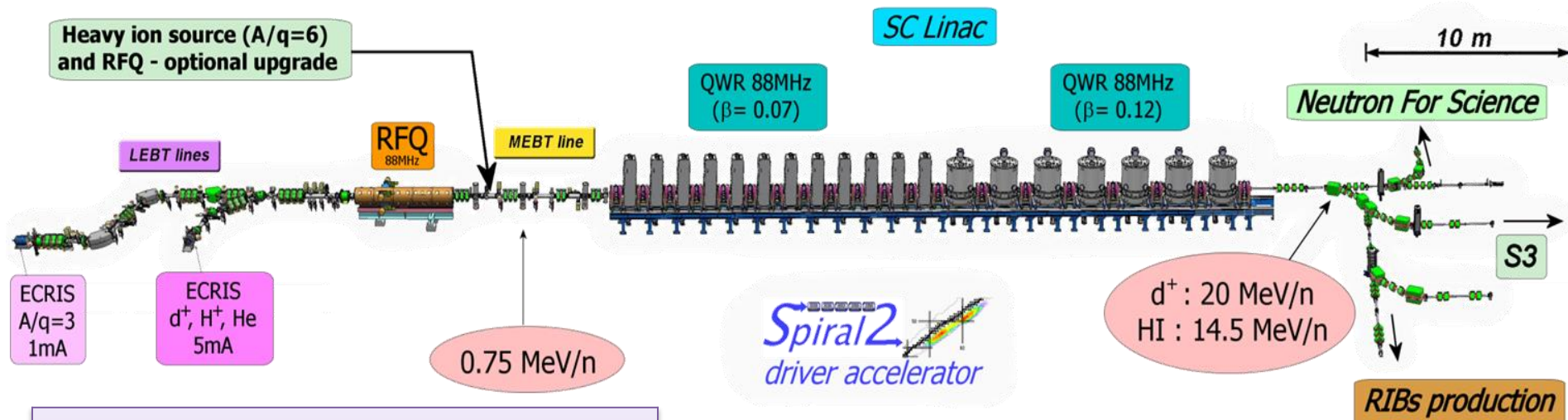
- ❑ Well collimated pulsed neutron beam
 - $F < 1$ MHz
 - Burst duration 1 ns
 - Flight path from 4 to 30 m → Good energy resolution

- ❑ Energy spectra :
 - Continuous up to 40 MeV (d + thick converter)
 - Quasi mono-energetic up to 31 MeV (p + thin lithium converter)

- ❑ Irradiation station
 - Neutron induced reaction
 - Ion induced reaction

- ❑ Ion beam delivered by the LINAC of SPIRAL-2
 - Proton : 2 – 33 MeV
 - Deuteron and Helium : 2 – 20 MeV/u
 - $I = 5$ mA



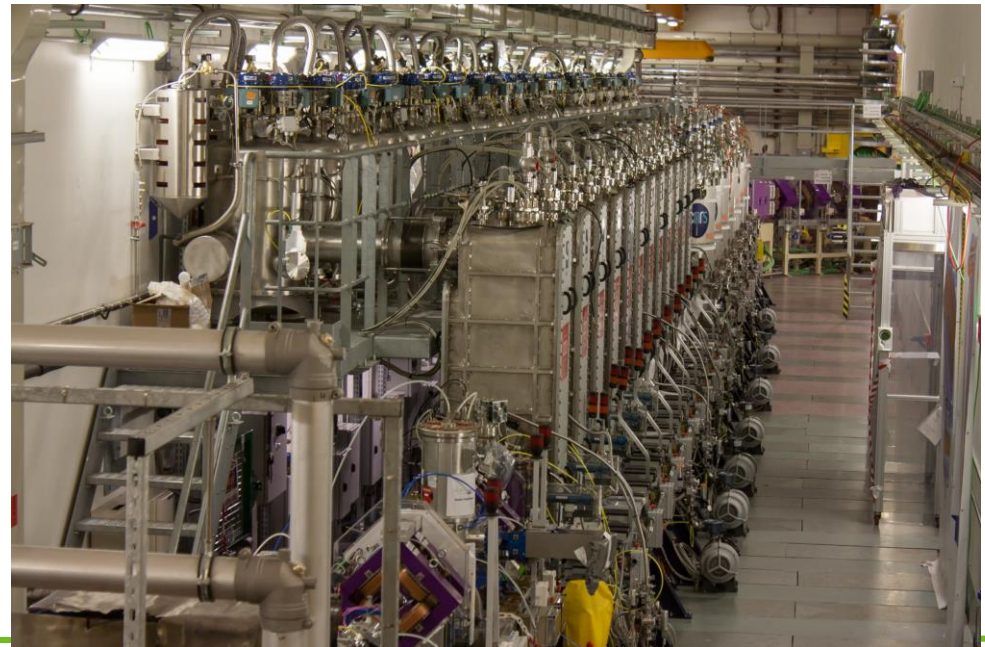


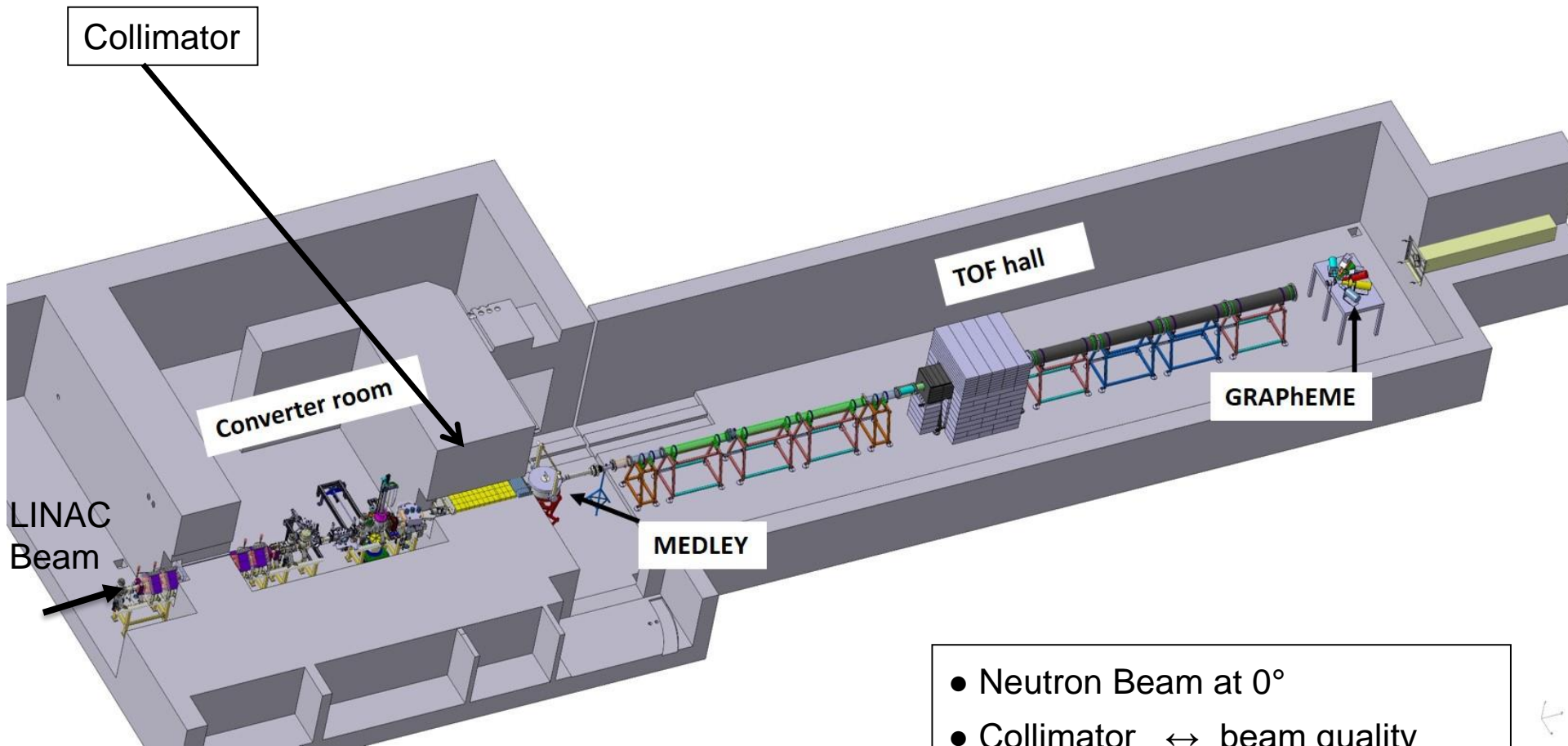
Total length: 65 m (without HE lines)

Slow (LEBT) and Fast Chopper (MEBT)
RFQ (1/1, 1/2, 1/3) & 3 re-bunchers

12 QWR beta 0.07 (12 cryomodules)
14 (+2) QWR beta 0.12 (7+1 cryomodules)
1.1 kW Helium Liquifier (4.5 K)
Room Temperature Quadrupoles
Solid State RF amplifiers (10 & 20 KW)

RFQ frequency $F = 88\text{MHz}$



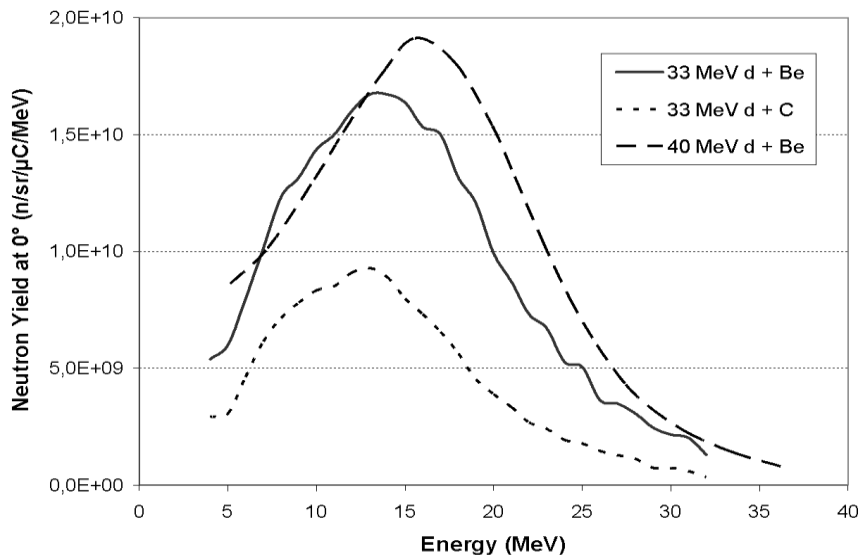


- Ion and neutron induced reactions
- Beam line extension
- Irradiation station (n, p, d)

- Neutron Beam at 0°
- Collimator ↔ beam quality
- Size (L x l) ≈ (28m x 6m)
 - **TOF measurements**
 - free flight path

Deuteron + thick converter (1cm)

$E_{\text{max}} = 40 \text{ MeV}$, $\langle E \rangle = 14 \text{ MeV}$



40 MeV d + Be at 50 μA

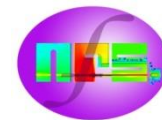
E MeV	Flux at 5 m
0-40	$8 \cdot 10^7 \text{ n/cm}^2/\text{s}$
5	$2 \cdot 10^6 \text{ n/cm}^2/\text{MeV/s}$
14	$5 \cdot 10^6 \text{ n/cm}^2/\text{MeV/s}$
30	$6 \cdot 10^5 \text{ n/cm}^2/\text{MeV/s}$



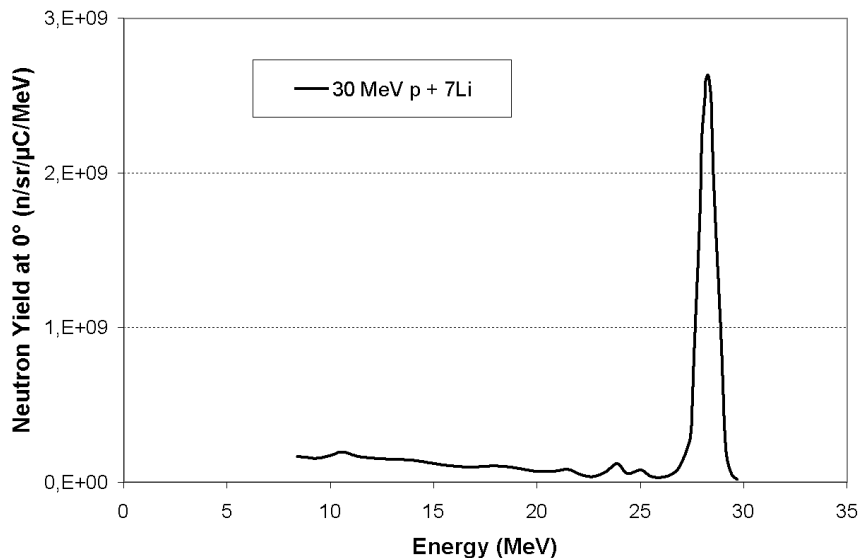
Rotating converter

- thick target C or Be
- $P < 2 \text{ kW}$





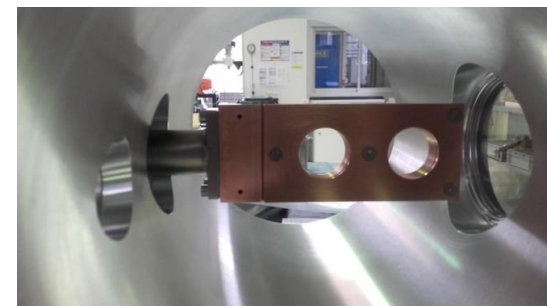
p + ⁷Li thin lithium target
 E_n = up to 31 MeV



Thin converter

- Li or Be
- Static target

Deflecting magnet for proton beam



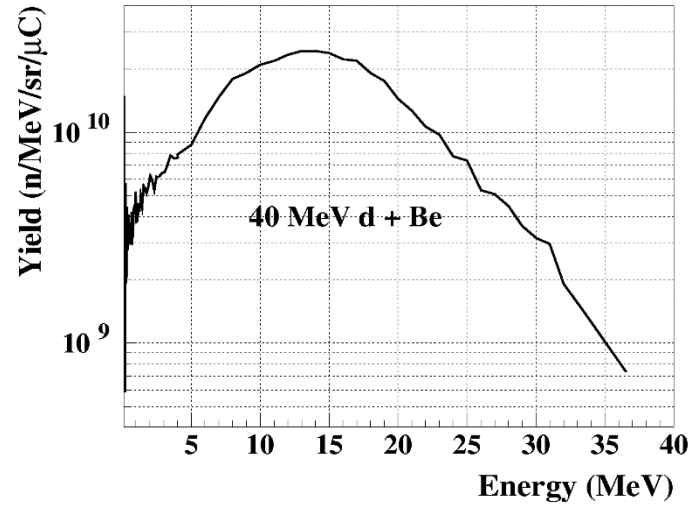
p + Li at 20 μA

Li thickness ↔ Δep=1MeV

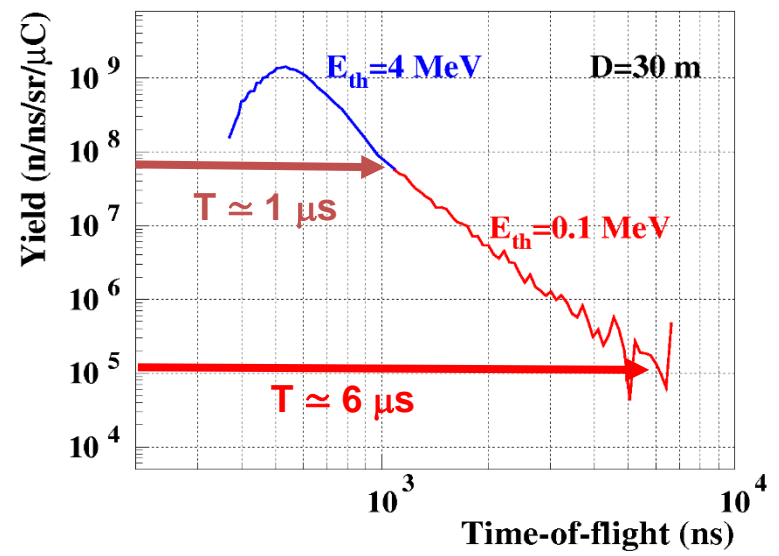
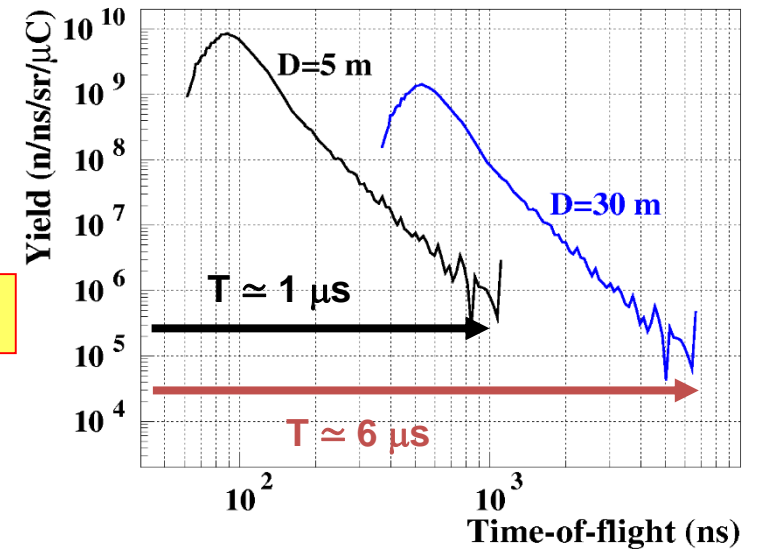
E MeV	Flux at 5 m
5	1,7.10 ⁴ n/cm ² /MeV/s
10	5.10 ³ n/cm ² /MeV/s
20	2,3.10 ⁴ n/cm ² /MeV/s
30	1,2.10 ⁵ n/cm ² /MeV/s



Identification between 2 neutrons with time of flight **t** et **t+T**

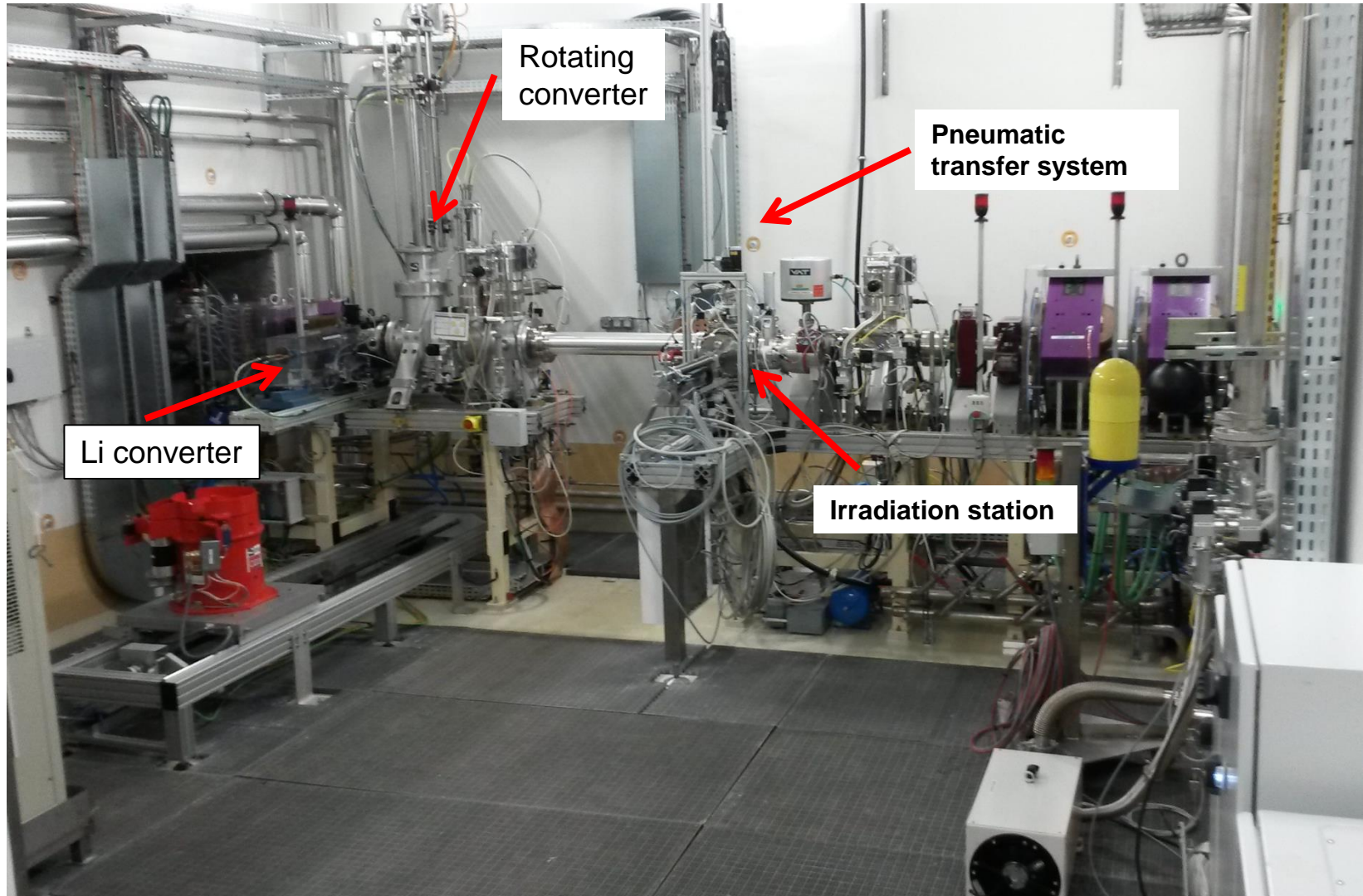
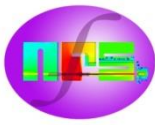


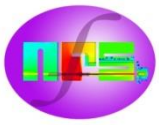
$T_{LINAG} = 11 \text{ ns}$

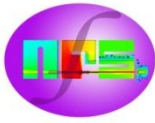


1 bunch over N ($f = F_0/N$)
 - "fast chopper"
 - $I = I_{max} / N, I_{max} = 5\text{mA}$

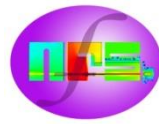
L(m)	E_{th} (MeV)	T(μs)	N	I_{max} (μA)
5	0.1	1	100	50
20	0.1	4	400	12
30	0.1	6	600	8





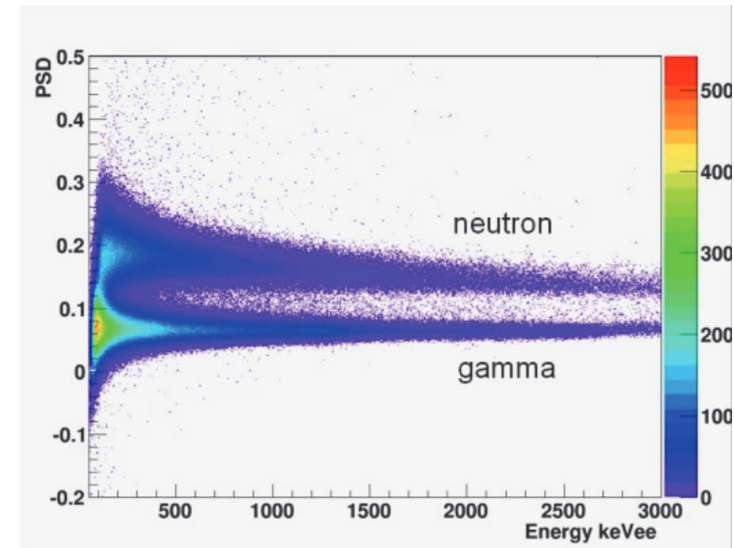
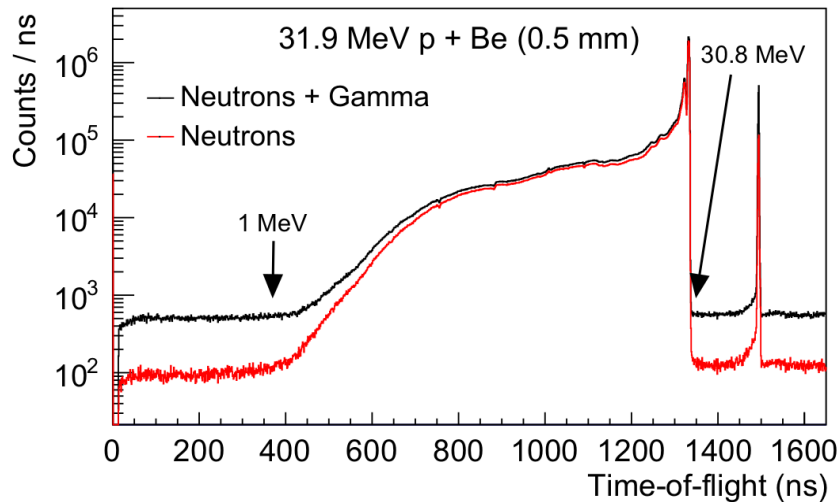
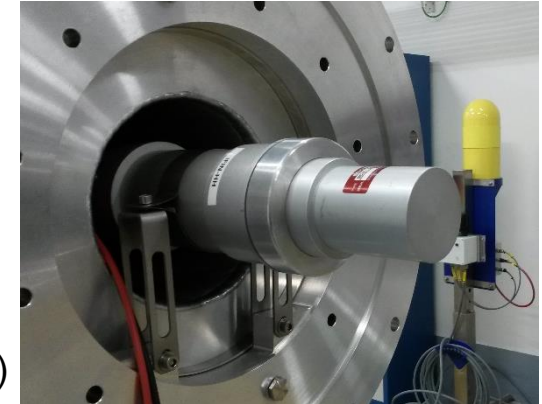


- ❑ December 2019 : **First proton beam at 33 MeV in the converter cave**
- ❑ September 2020 to December 2020: **First neutron beams**
 - First quasi-mono-energetic neutron beam: 33 MeV p + Li and Be
 - Continuous neutron beam 31,9 MeV p + Be (8 mm)
 - Flux and spectrum measurement
- ❑ July 2021: **First He-4 beam**
- ❑ September 2021: **First deuteron beam**
- ❑ September to December 2021: **First experiments**
 - E800 : LIONS
 - E811 : SCLAP
 - E807 : SCONE
 - E799 : Excitation function in proton induced reactions
 - Letters Of Intents 5 and 9

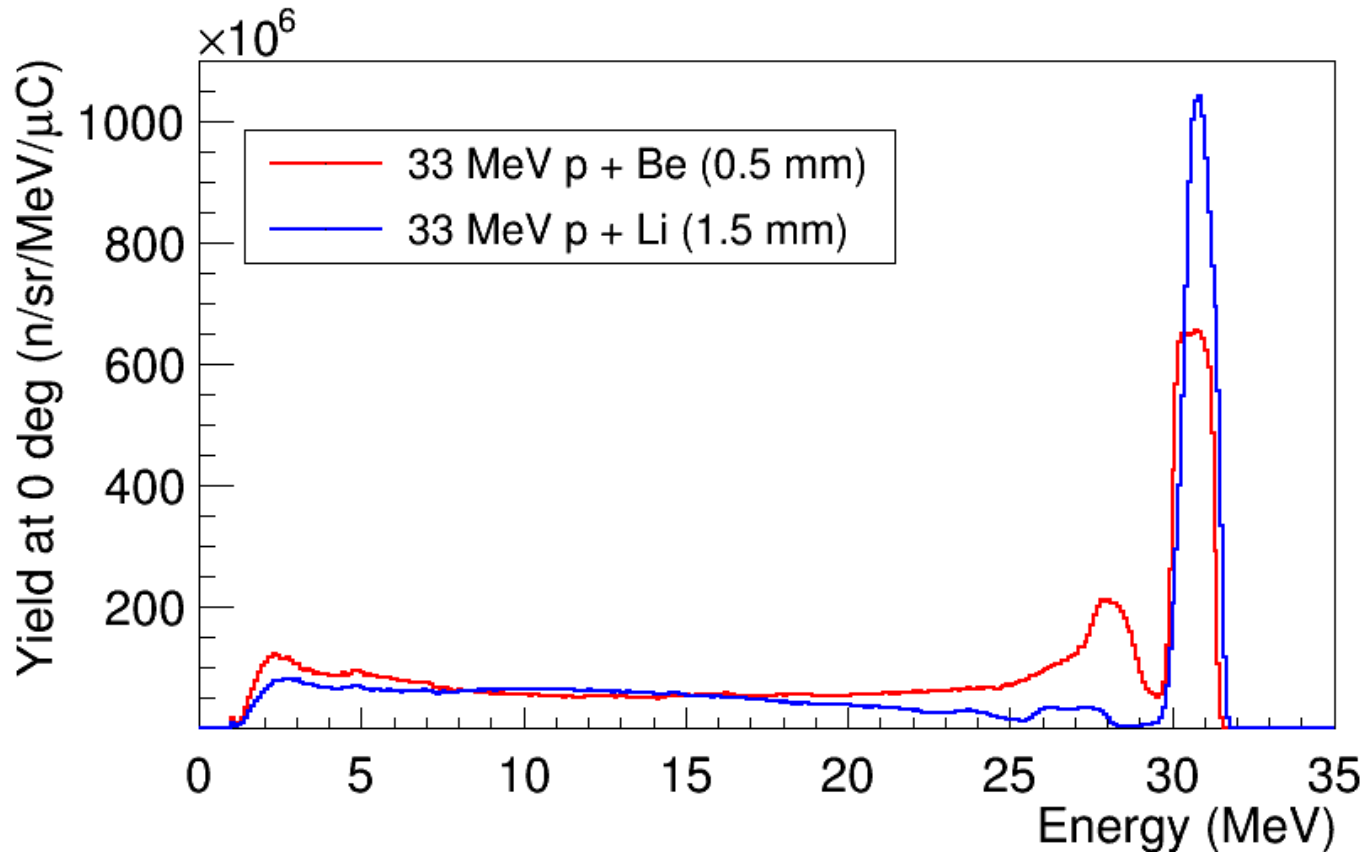


Detectors based on liquid scintillator EJ309

- ❑ Neutron spectrum and flux measurement by the TOF technique
- ❑ n-γ discrimination by pulse shape analysis
- ❑ EJ309 cell (2 inches in diameter, 3 inches in length)
- ❑ Placed in the beam pipe downstream of the rotating converter (15 to 30 m)



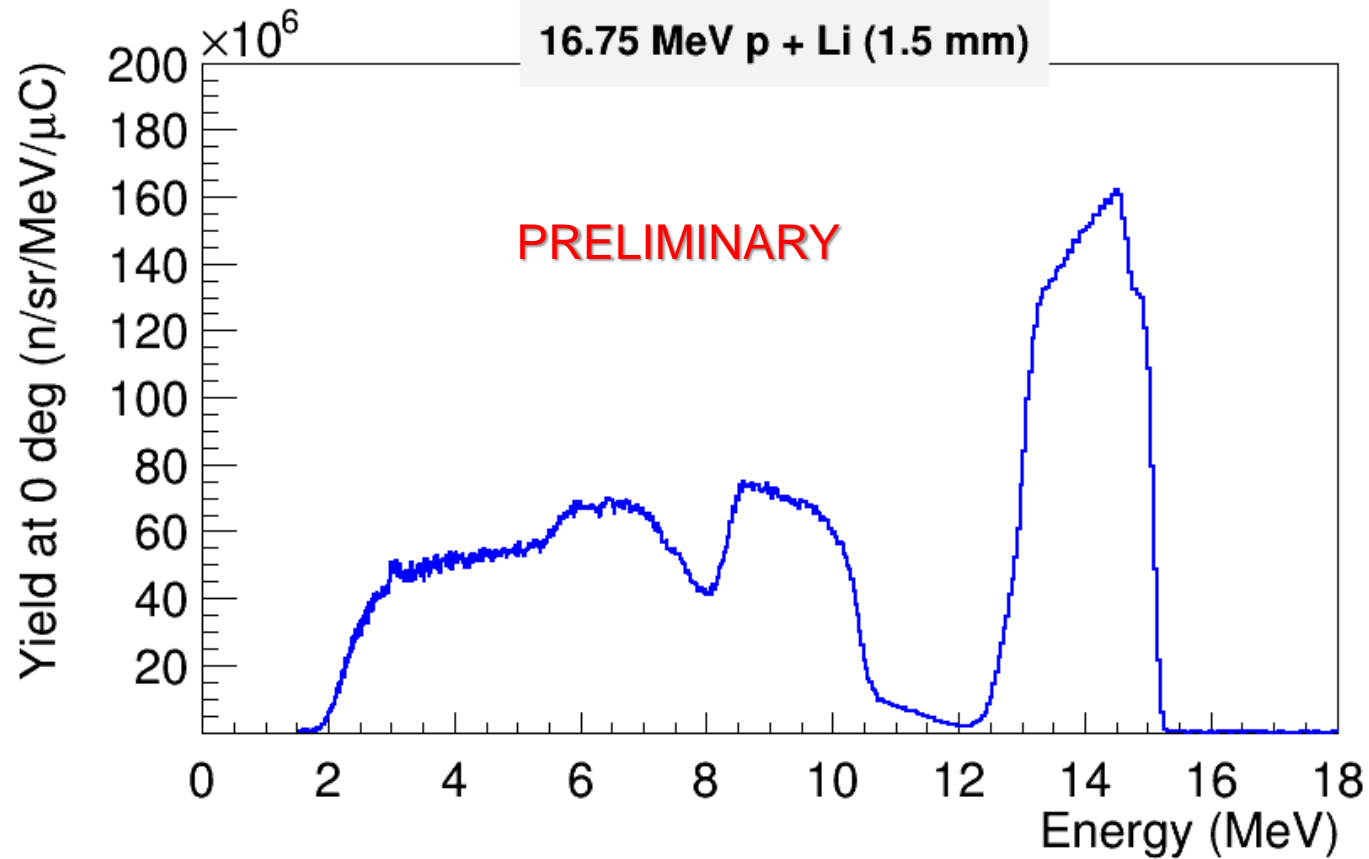
- ❑ Adaptation of the SCINFUL code:
 - Light response of EJ309 included
 - Efficiency determination



33 MeV p + Li (1,5 mm)

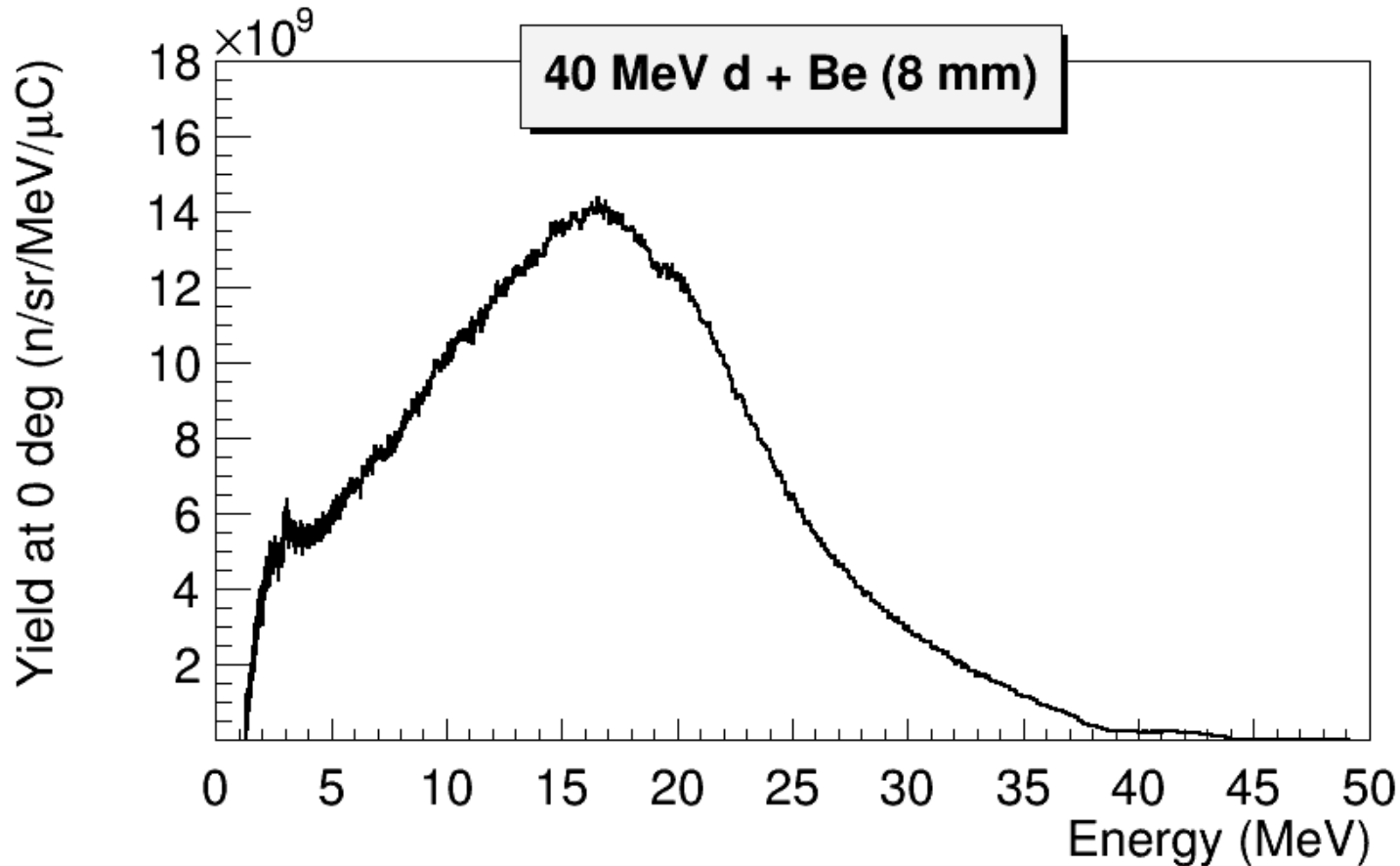
Neutron yield in the mono-energetic peak $1,2 \cdot 10^9$ n/sr/ μC

at 20 μA and $d=500\text{cm}$ $\rightarrow \Phi = 10^5$ n/s/ cm^2

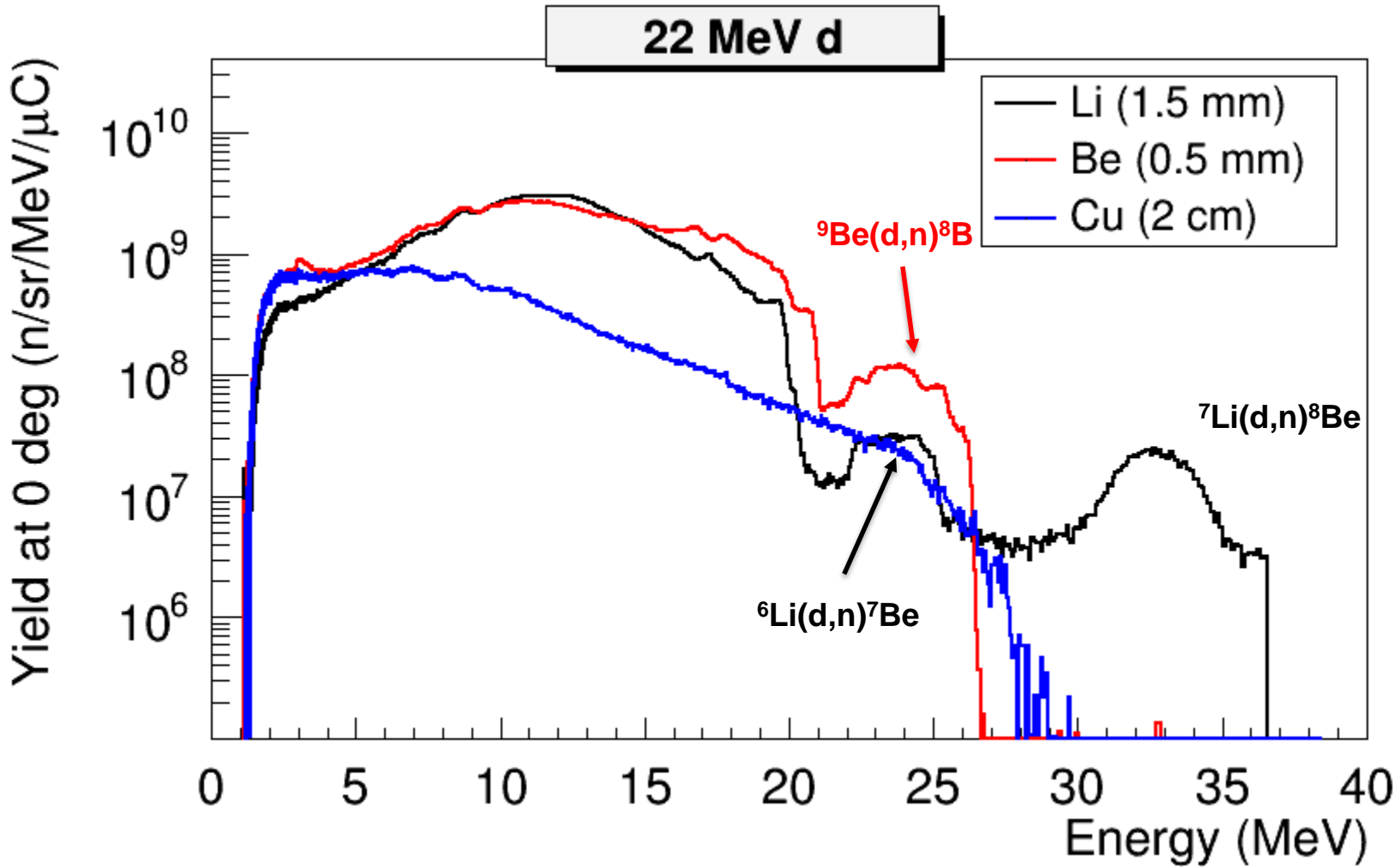


16,75 MeV p + Li (1,5 mm)

Neutron yield in the mono-energetic peak for $E > 12$ MeV $3,1 \cdot 10^8$ n/sr/μC

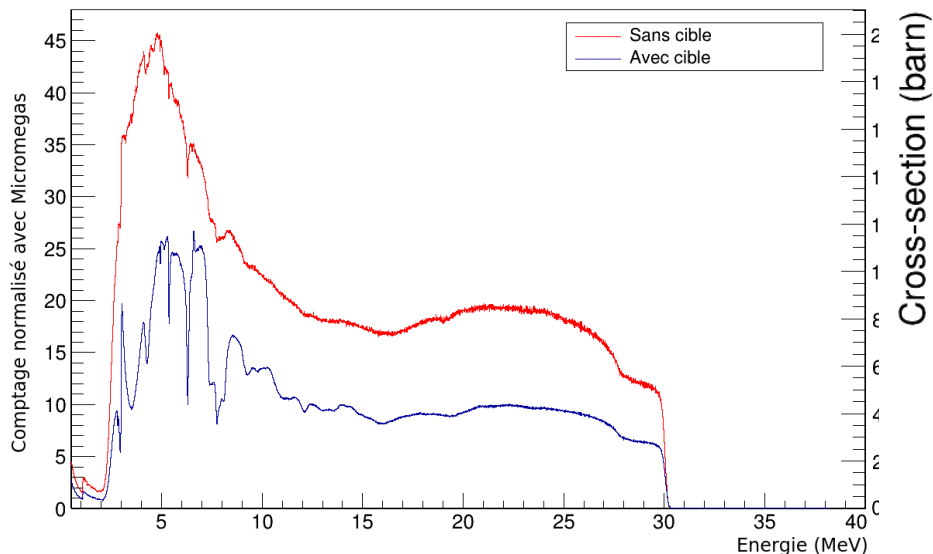


$I_{\max} = 50 \mu\text{A}$ \rightarrow $6 \cdot 10^7 \text{ n/cm}^2/\text{s}$ in TOF hall at 5 m
 $5 \cdot 10^{10} \text{ n/cm}^2/\text{s}$ for irradiation

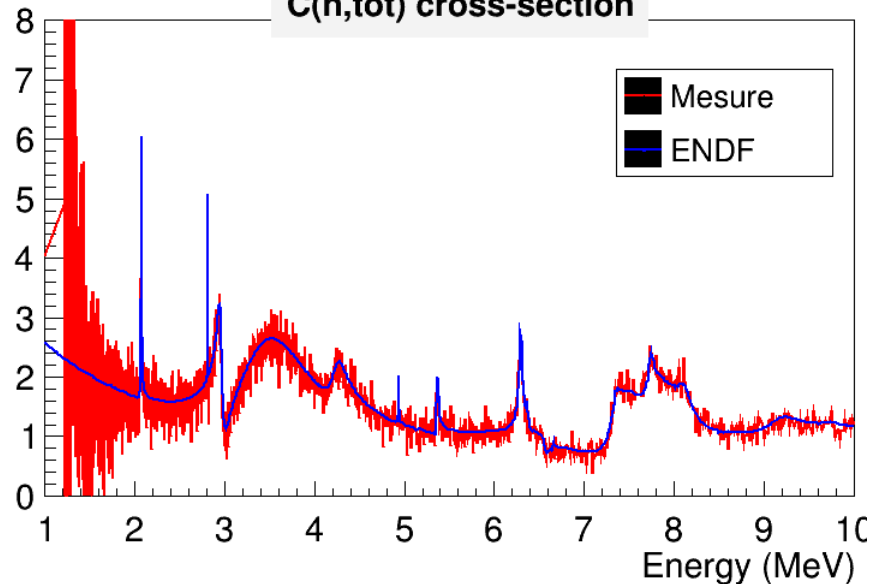


- ❑ Transmission measurement with Carbon samples (2, 4 and 6 cm thick)
- ❑ Total cross-section reaction measurement
- ❑ NFS Energy resolution estimation

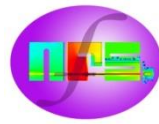
$$\sigma_T = -\frac{1}{nl} \ln \frac{R_i - B_i}{R_o - B_o}$$



C(n,tot) cross-section

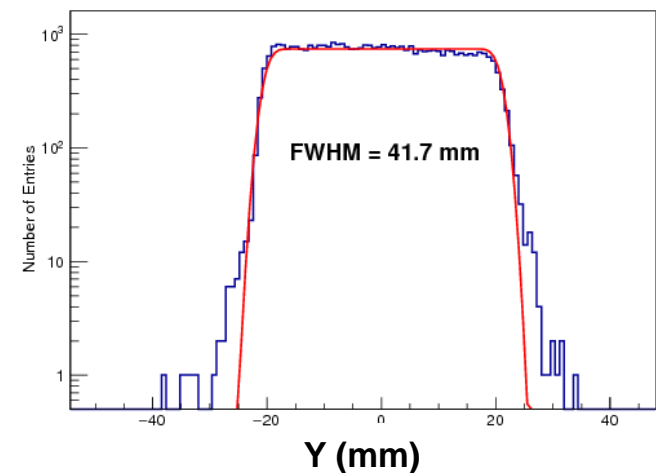
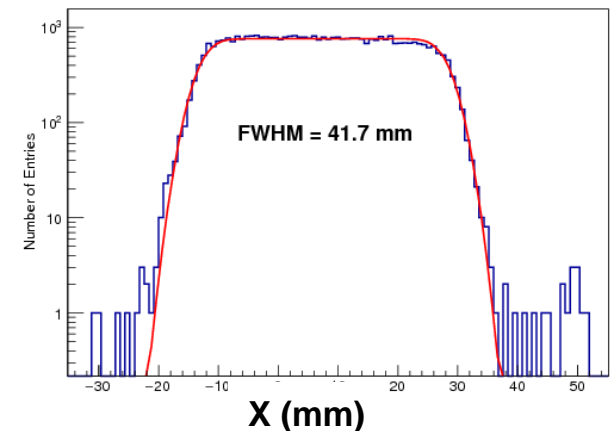
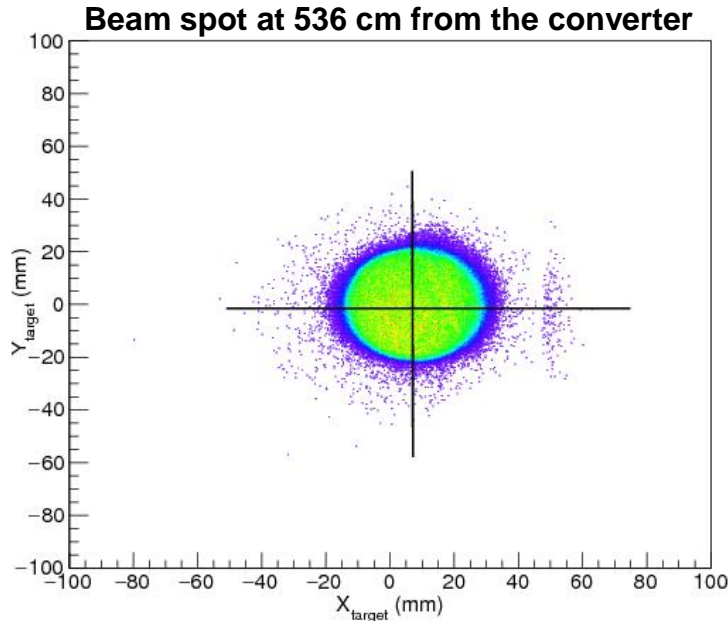


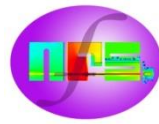
$$\frac{\Delta E}{E} = \gamma(\gamma + 1) \sqrt{\left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta L}{L}\right)^2}$$



- The beam has a conical shape :
 - $r=21$ mm at 5 m downstream from the collimator
 - $r=28$ mm at 29 m

- Beam profile measurement :
 - PPAC detector with U238 sample (IJCLab)
 - Graphchromic film at 29 m



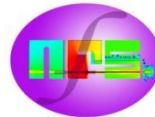


- Accepted experiments

NUM	Title	Spokesperson	UT Allocated
E799	Excitation functions of short-lived isotopes in proton induced reactions on ^{nat}Fe	E. Simeckova, NPI, Rez	5
E800	LIONS - Light-Ion Production Studies with Medley at the NFS facility	A.V. Prokofiev, Uppsala University	17
E802	GARIC - Gas production In Chromium by neutrons	A.V. Prokofiev, Uppsala University	21
E804	Measurement of fission cross sections standards relative to elastic n-p scattering at neutron energies 1- 40 MeV	D. Tarrío, Uppsala University	31
E807	Study of the (n,xn) and (n,f) reaction for U238	G. Bélier, CEA-DAM	12
E811	Study of the (n,alpha) reactions of interest for nuclear reactors - the SCALP Project	F. R. Lecolley, LPC Caen	12
E814	235U Fission fragment study with FALSTAFF at NFS	D. Doré, CEA/IRFU/DPhN	11
E832	Deuteron activation of ^{nat}Mo - focus on short-lived products	E. Simeckova, NPI, Rez	4
E833	Pygmy dipole resonance in ^{140}Ce using the (n,n'g) reaction at NFS	M. Vandebrouck, CEA Saclay	23
E835	Measurement of the neutron induced activation in materials	V. Bliëanu, CEA Saclay	3
E838	Shedding new light on the structure of ^{56}Ni using (n,3n) reaction at NFS	E. Clément, Ganil	22

- Letters of Intent

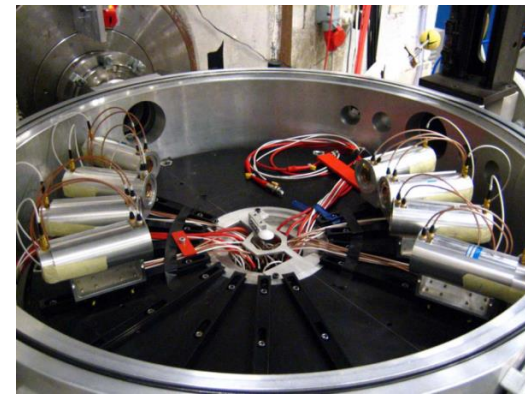
NUM	Title	Spokesperson
Loi 5	(n,n'g) reactions at NFS: a new probe to study the pygmy dipole resonance	M. Vandebrouck, CEA/IRFU/DPhN
Loi 7	New Judicious Experiments for Dark sectors Investigations at SPIRAL2	B. Bastin, GANIL
Loi 9	(n,xn g) reaction cross sections measurements for nuclear energy applications	M. Kerveno, CNRS/ PHC



Spokesperson : A. Prokofiev, Uppsala University

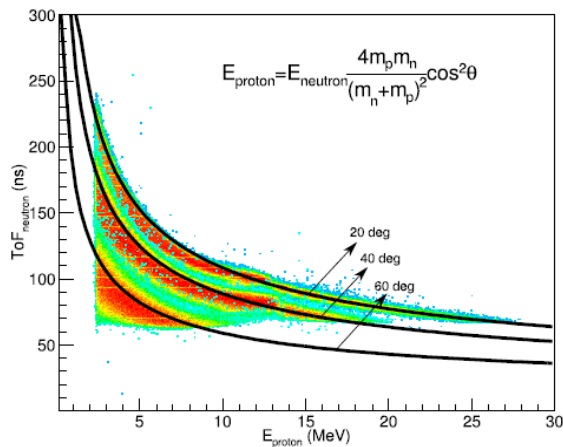
❑ Neutron-Induced Light charged particles emission with MEDLEY

- 8 Si-Si-CsI telescopes
- Double-differential **cross sections** :
- **Cancer therapy and dosimetry** (H,C,O, Ca...)
- **Radiation effects** in microelectronics (Si, O)
- Energy applications: **Gen-IV or fusion reactors** (building materials, fuel, coolants, etc)

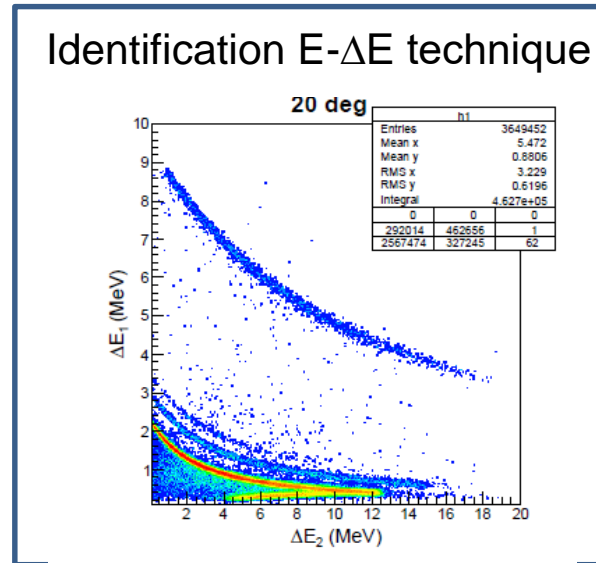


❑ Setup tested in fall 2020 and September 2021

- High **particle-identification capability**
- Simultaneous measurement of **charged-particles energy and neutron ToF** (digital



Identification E-ΔE technique



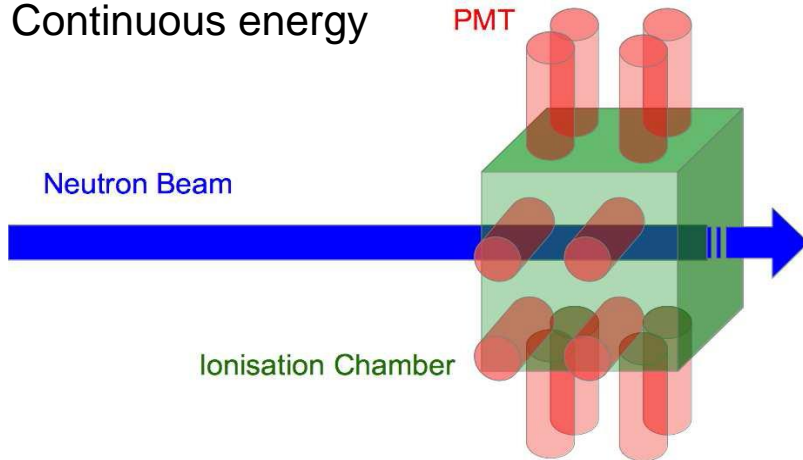
Spokesperson : J. F. Lecolley, LPC Caen

Goals : XS measurement in 7MeV-20MeV range with an uncertainty better than 5%

Active target

Scintillating Ionization chamber

Continuous energy



Target composition :

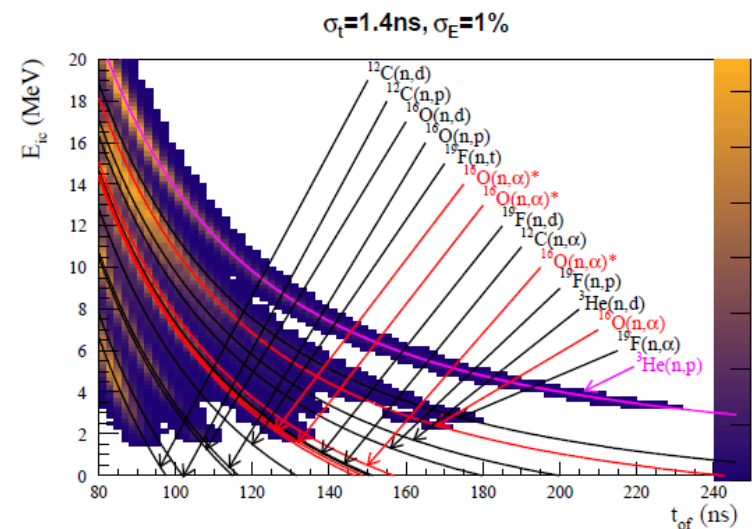
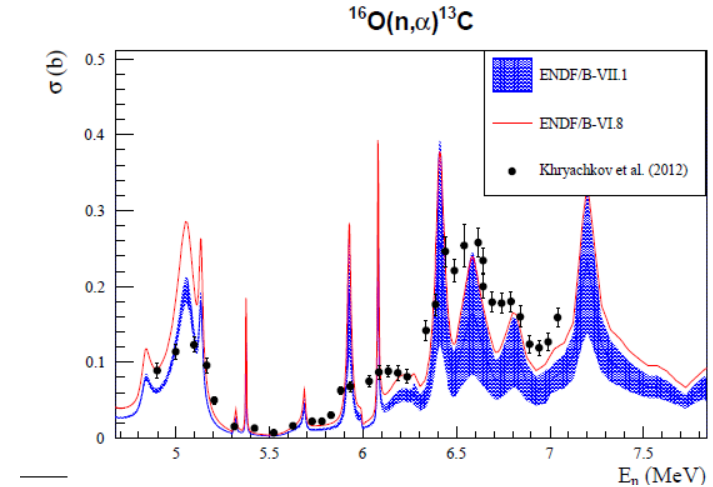
Oxygen \rightarrow CO₂

Scintillation \rightarrow CF₄

Normalization \rightarrow ³He

\rightarrow A lot of Channels to distinguish \rightarrow

Experiment scheduled by Oct 2021



Spokesperson : G. Bélier, CEA-DAM-DIF

- (n,xn) reaction are important channels in the 5-50 MeV range
- (n,xn) cross-section measurement of actinide is very difficult:
 - radioactive sample
 - prompt neutron fission

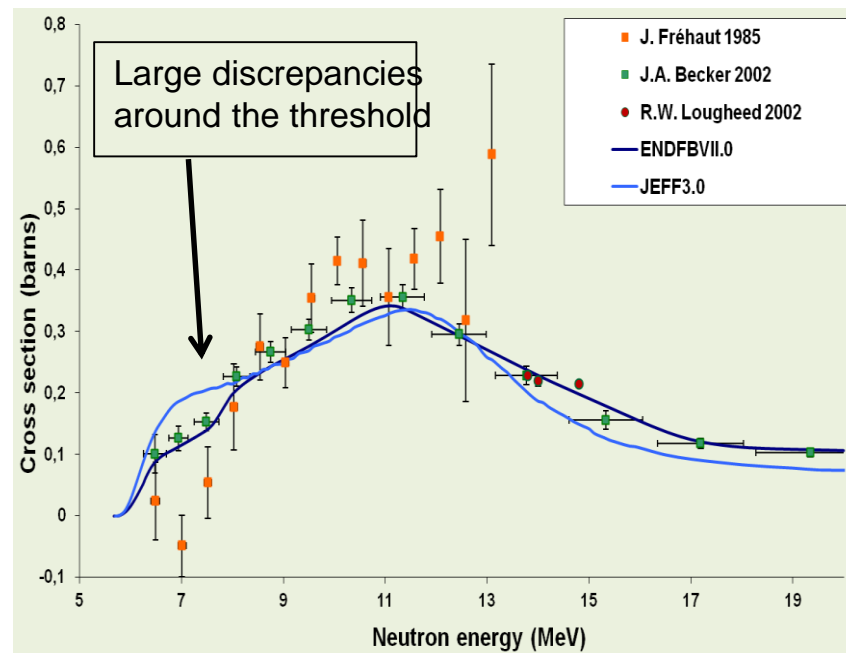


Experimental technique :

- Veto fission (fission chamber)
- 4π neutron detector SCONE
- 6 MeV < E_n < 20 MeV



Next Step : $^{239}\text{Pu}(n,2n)$



Spokesperson : E. Simeckova, NPI, Rez

Measurement of reaction cross-sections by activation technique :

- data for IFMIF facility design
- improvement of reaction model

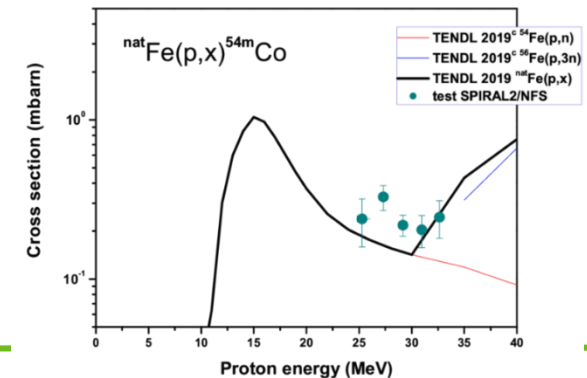
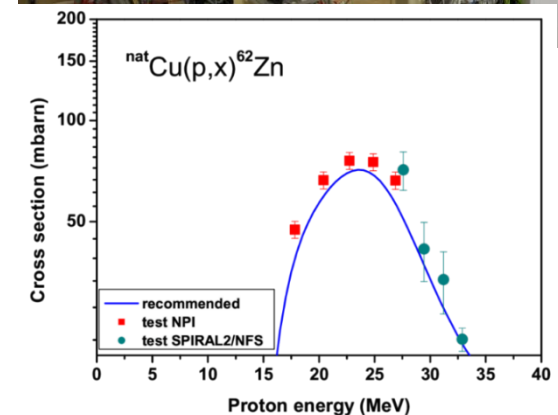
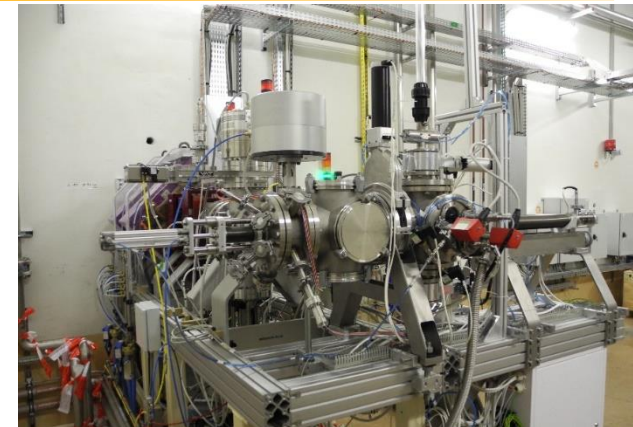
Goal: measure the ^{58m}Co and ^{58g}Co alimentionation

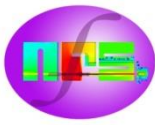
Commissioning : Irradiation station tested in December 2019

- **33 MeV proton beam**
- **80 nA beam intensity**
- **Fe and Cu samples irradiated**

• Good agreement between production cross section of ^{62}Zn and recommended values ->**proves the validity of the method in**

• **$^{nat}\text{Fe}(p,x)^{54m}\text{Co}$ measure for the first time the production cross section of the short-lived isomeric state of ^{54}Co**





- ❑ Neutrons for Science is now operational

- ❑ 4 Experiments and 2 tests have already been performed
 - Lcp particle production
 - Fission process
 - $n, xn\gamma$ reactions

- ❑ Everyone can propose an experiment
 - 1 PAC session per year; next PAC in November
 - GANIL web site “proposing an experiment” and contact me

- ❑ NFS is in the European Projects (Transnational Access):
 - ARIEL
 - RADNEXT