THE NEUTRONS FOR SCIENCE FACILITY AT SPIRAL-2

X. Ledoux and the NFS collaboration

- Motivations
- Description of NFS
- Firsts experiments
- Organization and status

The NFS project

- **Part of the SPIRAL-2 project built on the GANIL site, Caen, France**
- **NFS is one of the two facilities of the LINAG Experimental Area**
  - **Neutron beam between 100 keV and 40 MeV**
  - **Irradiation station for n, p, d and ions induced reactions**
- **Scientific collaboration: 50 physicists, 15 laboratories**

CEA/DAM/DIF, F-91297, Arpajon, France
CEA/DSM/IRFU/SPhN, Saclay, France
CENBG, Gradignan, France
LPC, Caen, France
IPHC, Strasbourg, France
NPI, Řež, Czech Republic
Uppsala University, Uppsala, Sweden
KIT, Karlsruhe, Germany
GANIL, Caen, France
NIPNE, Bucharest, Romania
JRC/IRMM, Geel, Belgium
CEA/DEN, Cadarache, France
IPNO, Orsay, France
CIMAP, Caen, France
Culham Centre for Fusion Energy, United Kingdom

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Physics case

Domains where high energy neutrons play a role

- **Fundamental physics**
  - Astrophysics
  - NN interaction
  - Production of RIB
- **Energy production**
  - New generation of reactor
  - Fusion technology
  - Accelerator Driven System
- **Nuclear medicine**
  - Radioisotopes production for medical applications
  - Neutron therapy
  - Biology (cells irradiation..)
- **Development and characterization of new detectors**
- **Study of the single-event upsets**

Needs for the new generation of reactor

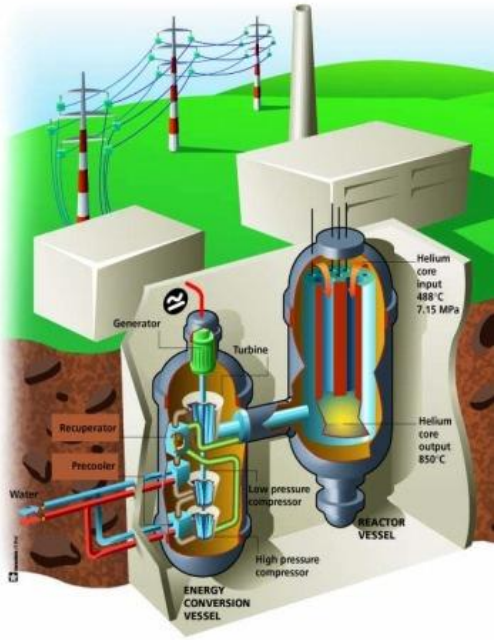
GENIV reactors and ADS need nuclear data development (evaluated data and measurements):

- **Fast neutron**
- **Transmutation and target design in ADS**
- **High burn-up systems.**
- **Structural materials and coolants**

Cross sections (fission, capture, scattering)
Fission neutron spectra, Nu-bar
Gamma source term, Spent fuel inventories,
Decay heat, and dose rates

A High Priority Request List (Short list) :

- fission cross sections of ^{234}U, ^{237}Np, $^{238,240-242}$Pu, ^{241,242m,243}Am, $^{242-246}$Cm
- fission nu-bar of ^{238,240}Pu, ^{241}Am and ^{244}Cm
- capture of ^{235,238}U, ^{237}Np, $^{238-242}$Pu, ^{241,242m,243}Am, ^{244}Cm
- inelastic scattering of ^{238}U, ^{239,240,242}Pu, ^{241,243}Am, C, O, Na, ^{56}Fe, Pb, Bi, ^{90}Zr
- neutron removal of ^{10}B, C, O, Na, Si, Fe, Ni, Pb
- elastic scattering of ^{238}U, C, ^{15}N, O, ^{52}Cr, ^{56}Fe, Pb



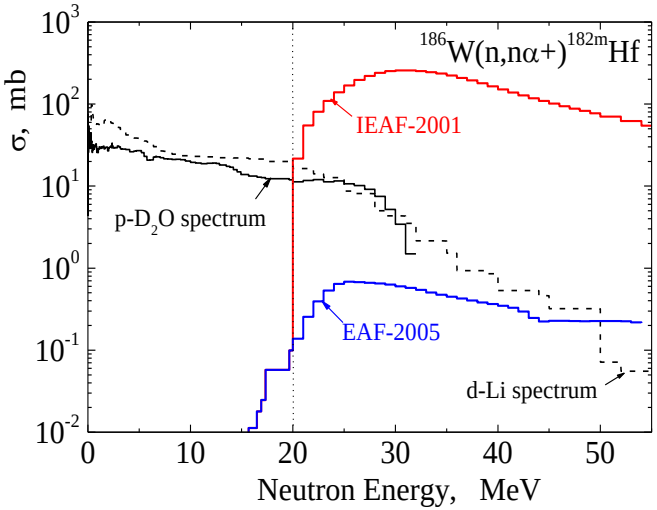
And
- Prompt neutrons and gamma fission spectra
- Delayed neutrons and gamma yield

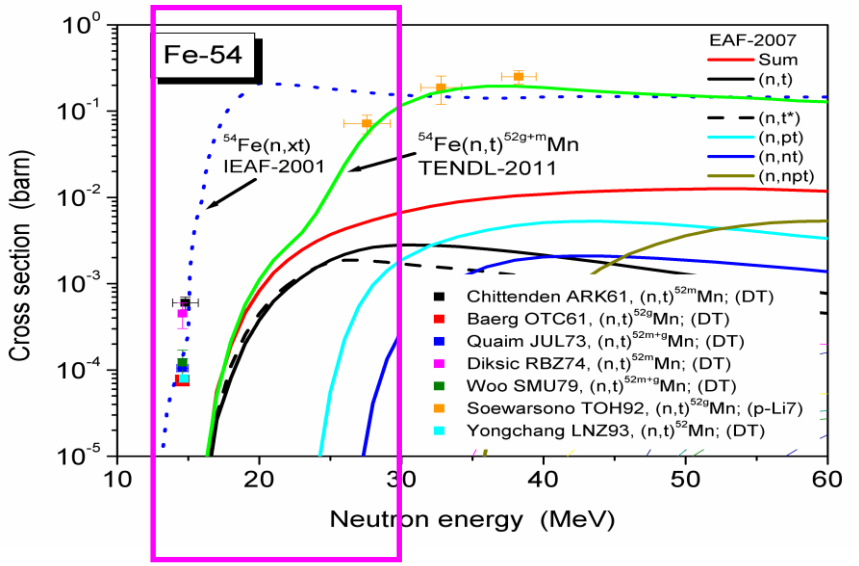
Need of accurate measurements of neutron induced reactions

Needs for the fusion technology

IFMIF : International Fusion Material Irradiation Facility needs neutron and deuteron induced reactions cross-section for flux monitoring and activation evaluation.

- **Data scarce or not existing**
- **Large discrepancies between data base**





IFMIF: Tritium production on iron

Evaluated data libraries and available experimental data

Material to be studied for IFMIF :

Al, Fe, Cr, Cu, Nb for cavities and beam transport elements

Be, C, O, N, Na, K, S, Ca, Fe, Cr, Ni for Li loop

Need of measurements in n, p and d induced reactions up to 40 MeV

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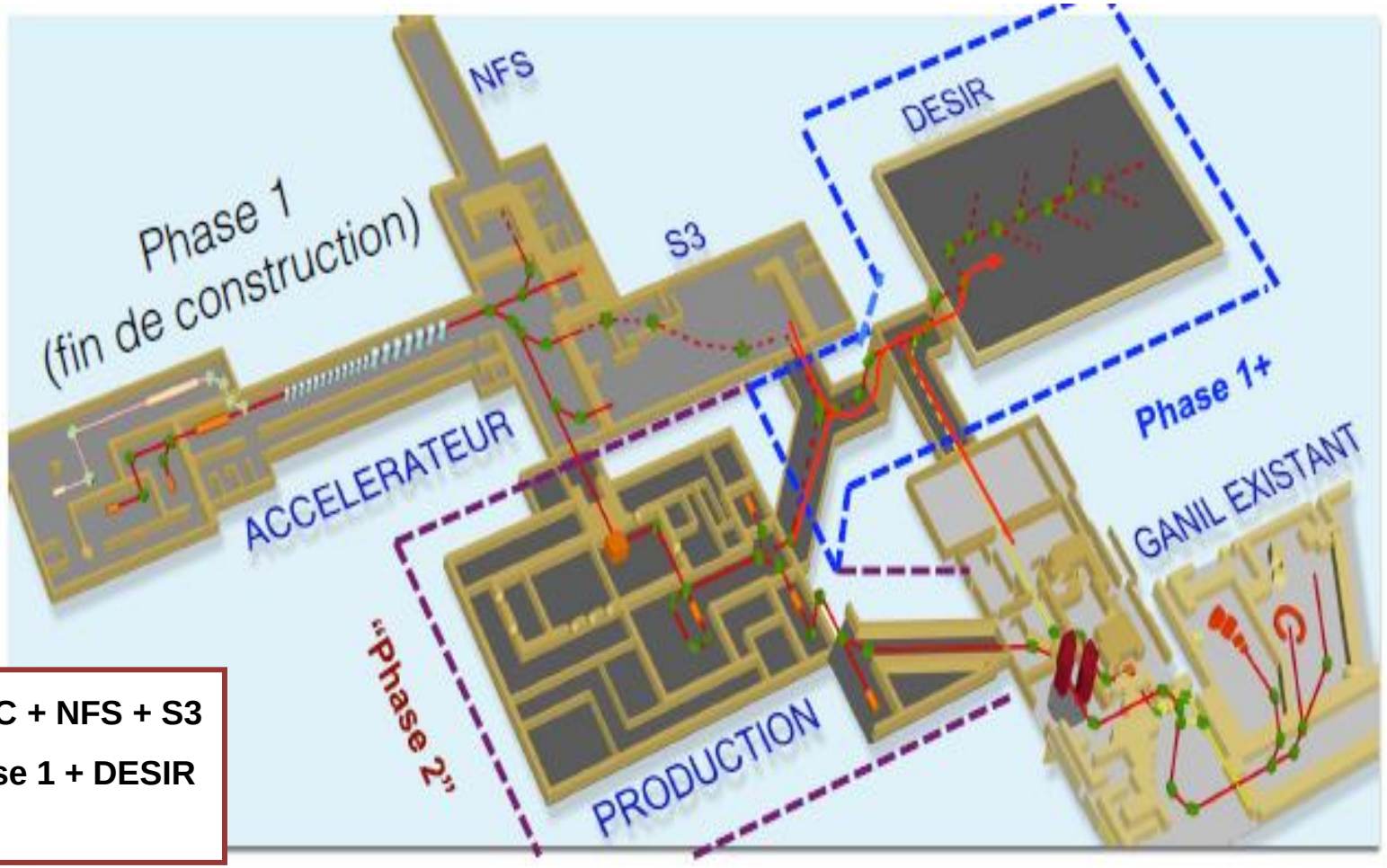
SPIRAL-2

- The final goal of SPIRAL-2 is to produce intense Radioactive Ions Beams
  - Radioactive ions are produced by $^{238}U(n,f)$ with fast neutrons
  - Neutrons are produced by 40MeV d + C using a LINAC delivering 5mA



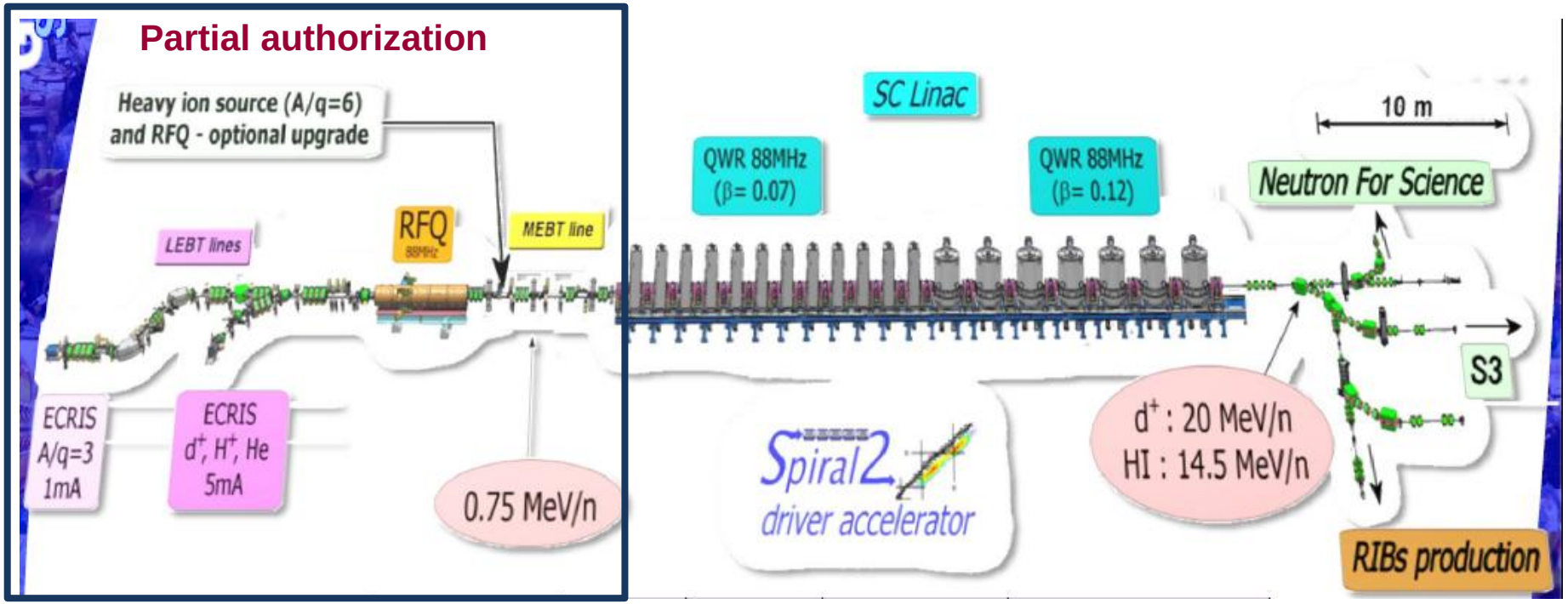
- LINAC Experi
  - S3 (Super
  - NFS
- DESIR facility

- Phase 1 : LINAC + NFS + S3

- Phase 1⁺ : Phase 1 + DESIR

- Phase 2 : RIB

The Accelerator

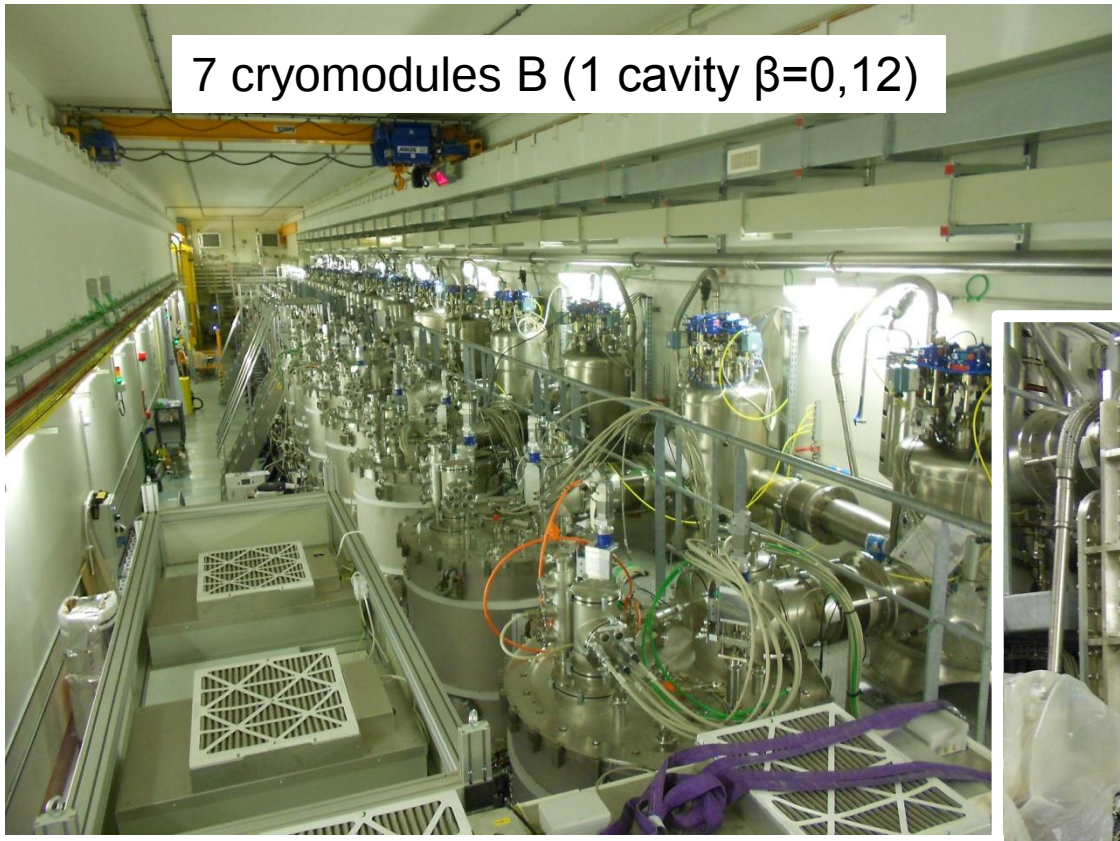


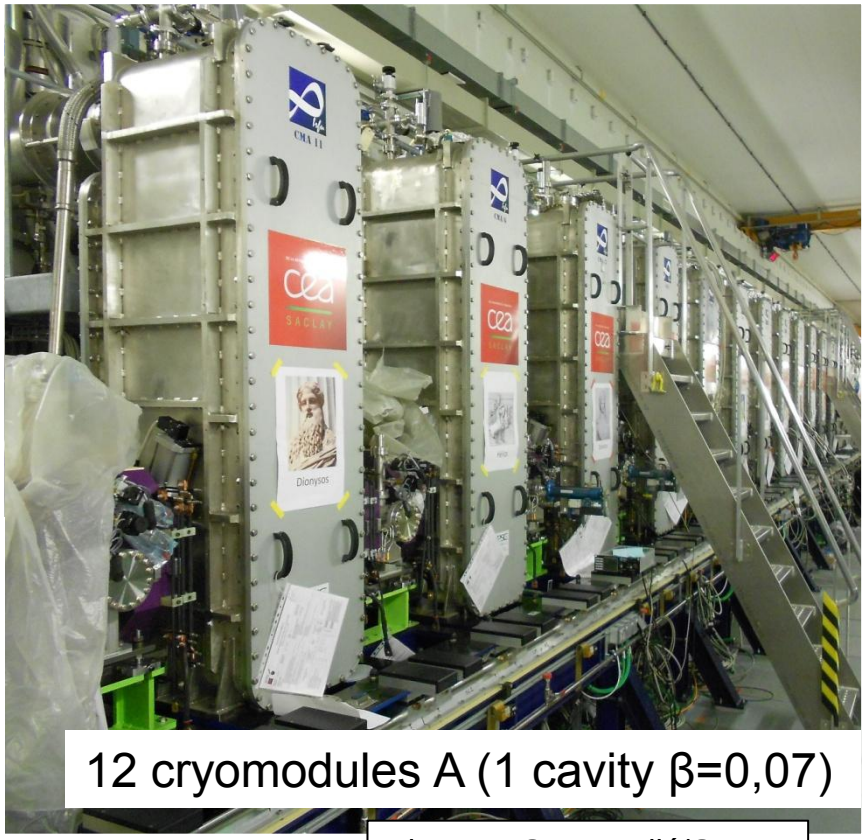
RFQ frequency F = 88MHz

For NFS burst divider → F/100

	Q/A	I (mA)	Energy (Mev/u)	CW max beam Power (KW)
Protons	1/1	5	2 - 33	165
Deuterons	1/2	5	2 - 20	200
Ions	1/3	1	2 - 14.5	45
Ions (option)	*1/6*	*1*	*2 - 8*	*48*

The LINAC

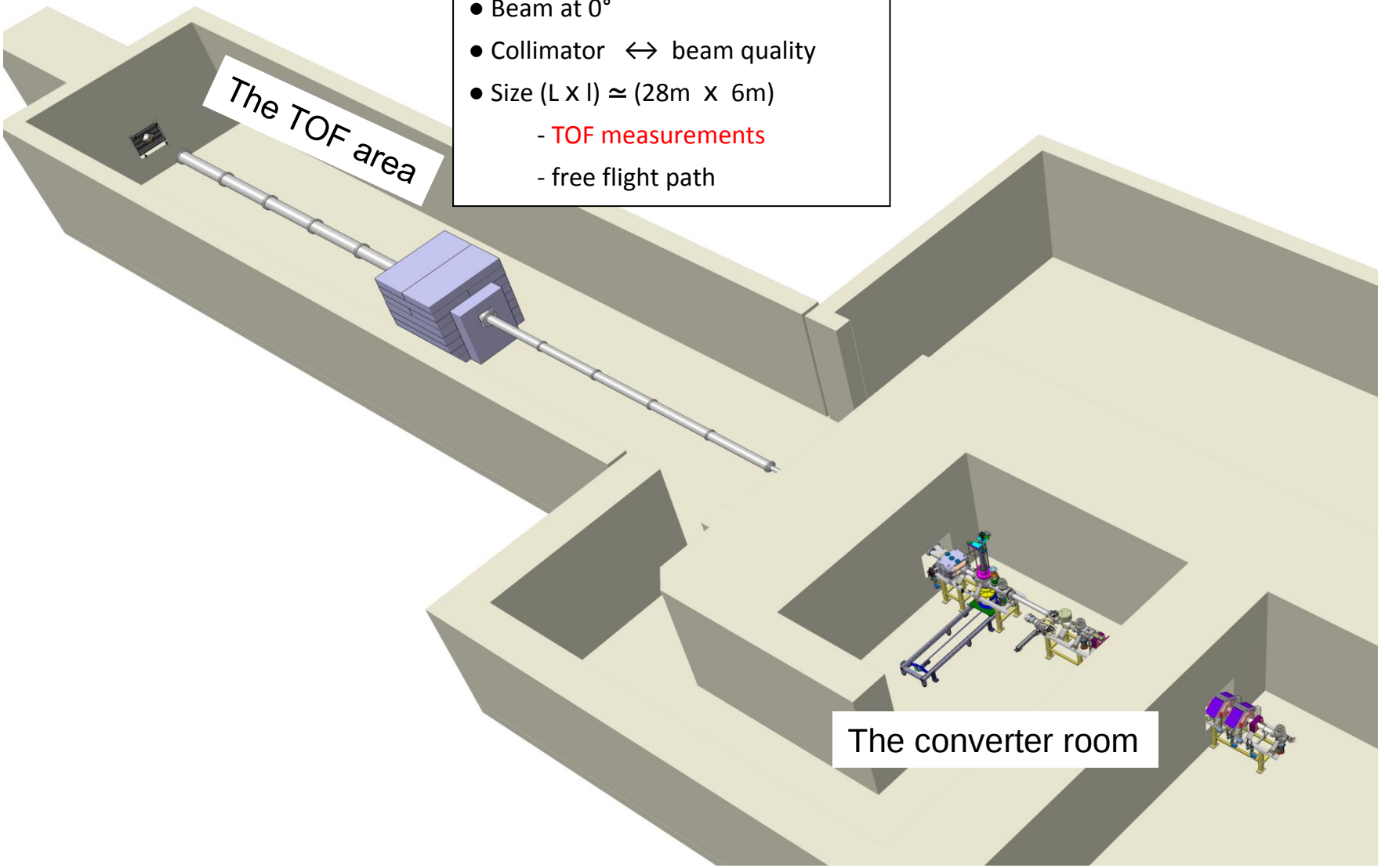




Pictures: G. Lescalié/GANIL

The NFS facility

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



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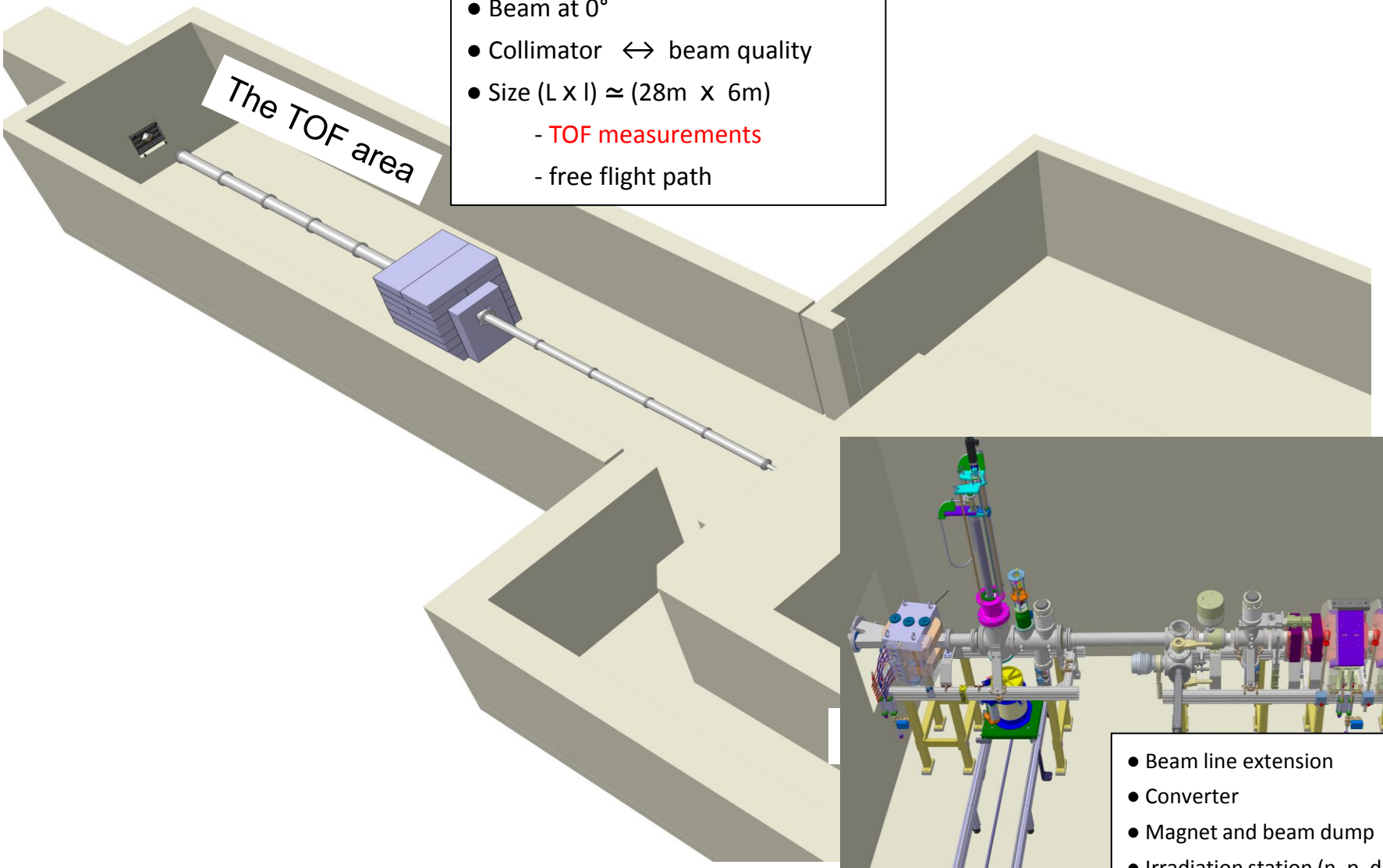
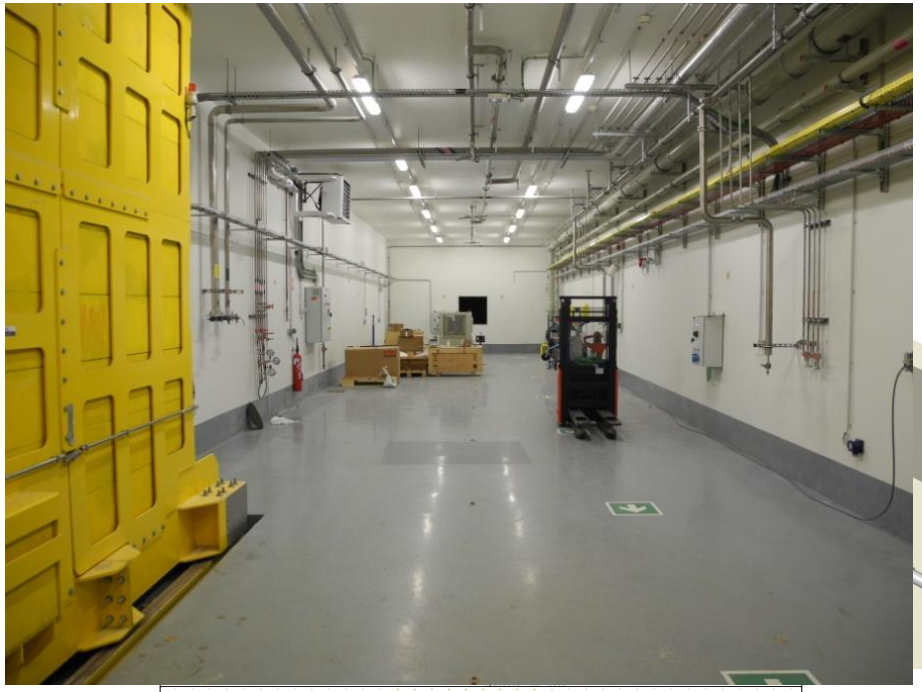
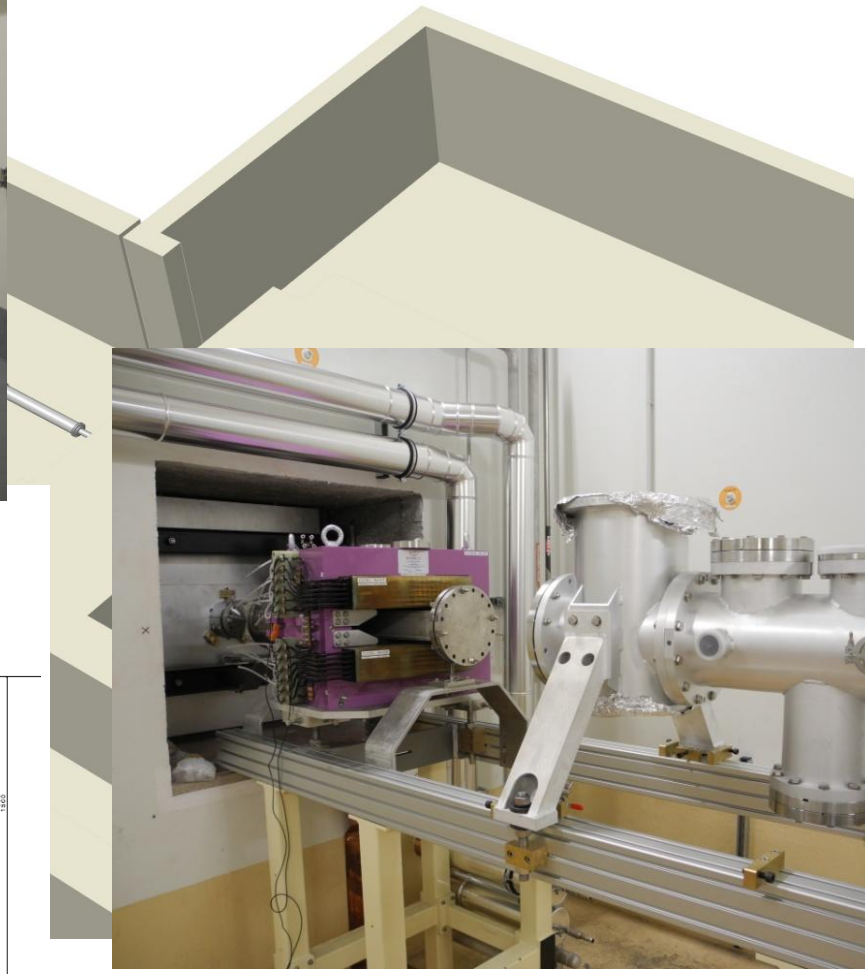
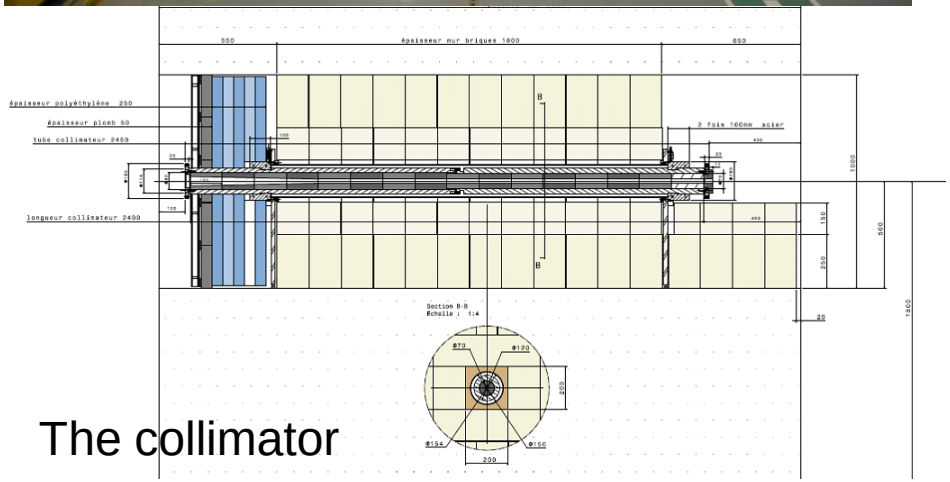


- Beam line extension
- Converter
- Magnet and beam dump
- Irradiation station (n, p, d)

The NFS facility





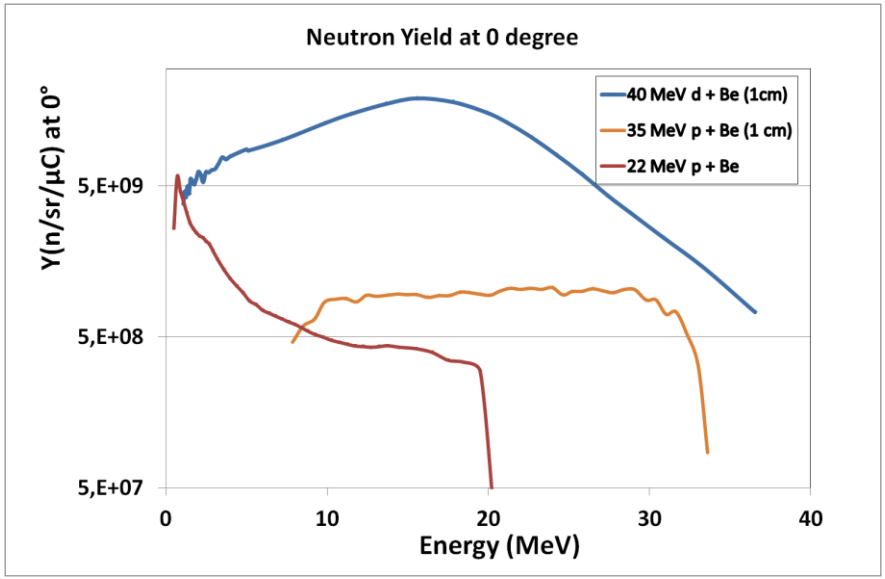


The collimator

Neutron spectra provided at NFS

Continuous spectrum

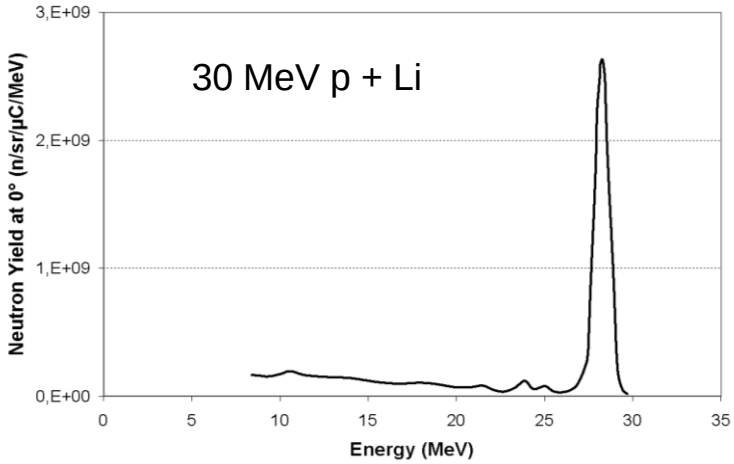
40 MeV d+ Be (6 mm)

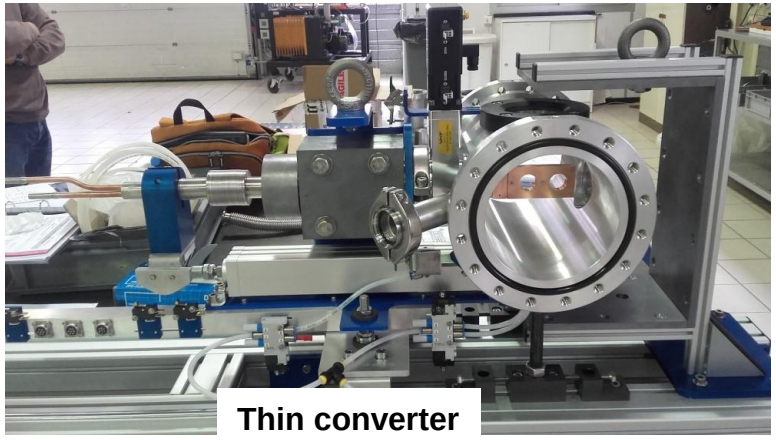


Rotating thick converter

Quasi-mono-energetic spectrum

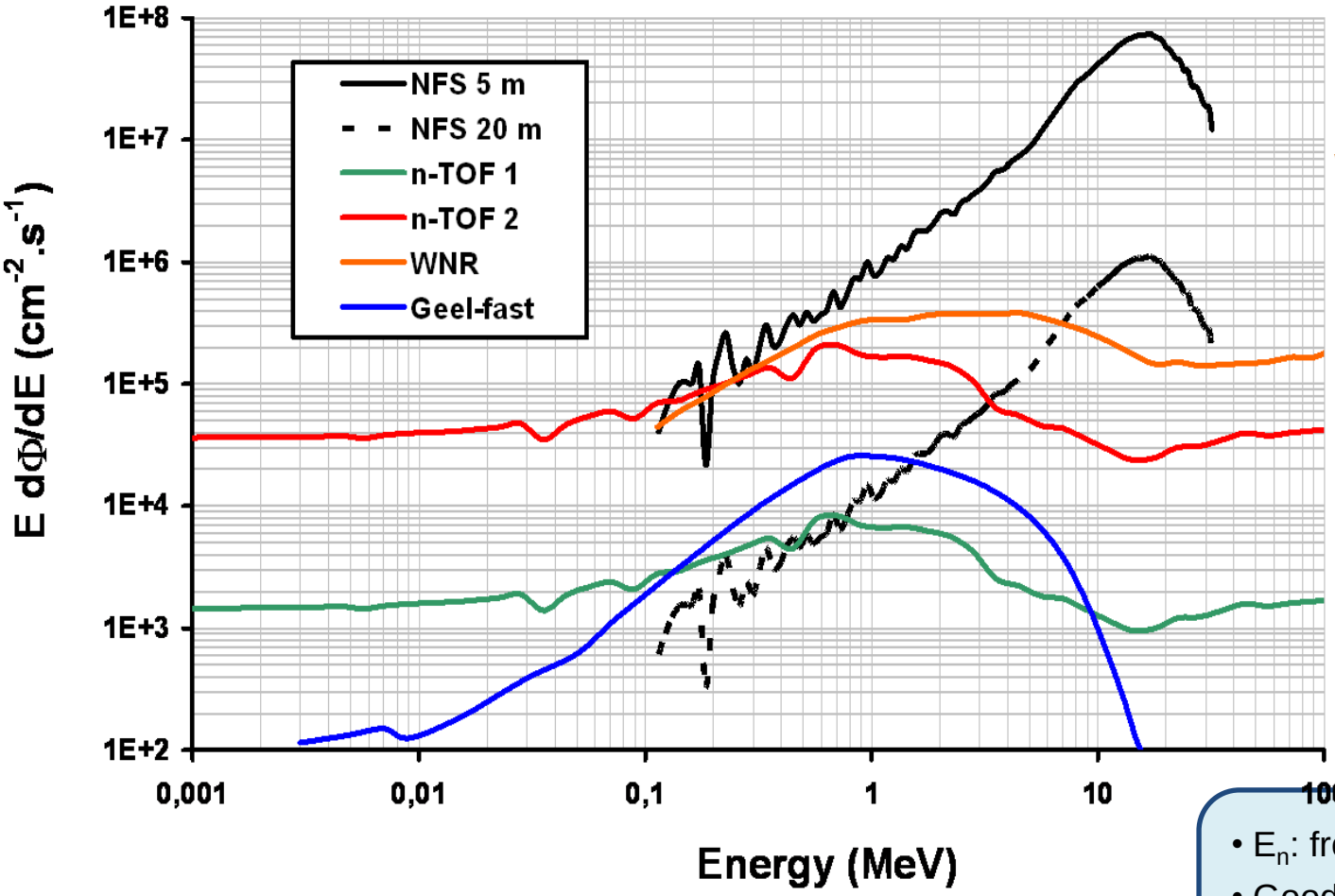
$p+^{7}Li \rightarrow n + {}^{7}Be \quad Q = -1.64$ MeV





Thin converter

Comparison with other Neutron TOF facilities



NFS : 40 MeV d + Be

WNR : Los Alamos

n-TOF 2 : CERN

n-TOF 1 : CERN

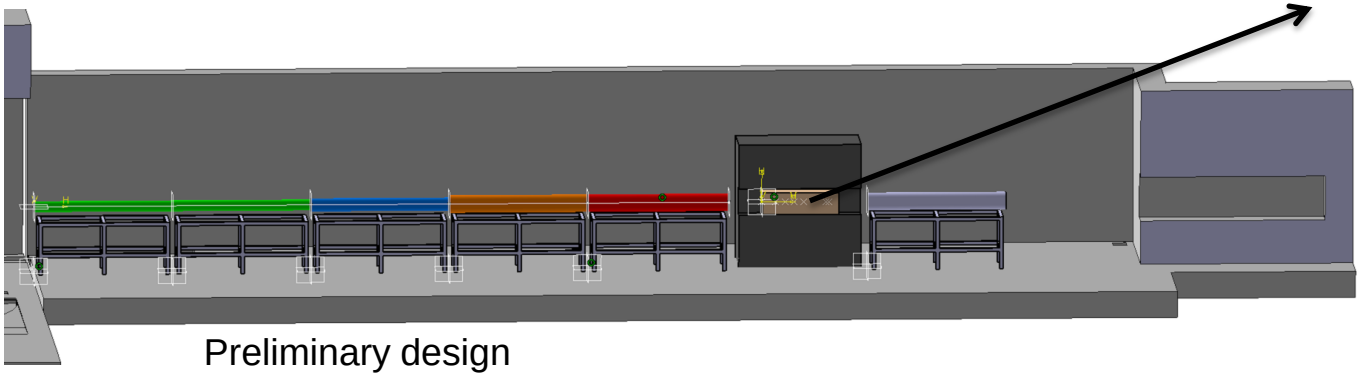
GELINA : Geel

- E_n: from 0,1 MeV to 40 MeV
- Good energy resolution
- Reduced γ flash
- Low instantaneous flux

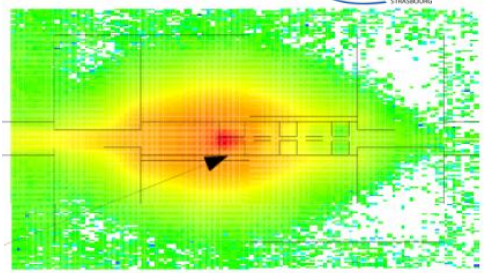
Complementary to the existing facilities

The second collimator

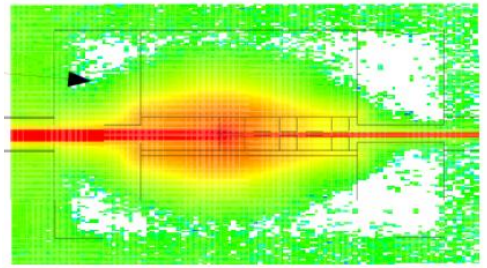
- For experiment at long distance, a 2ND collimator is needed for:
  - resizing the neutron beam
  - shielding detectors from background
- Study performed with MCNPX



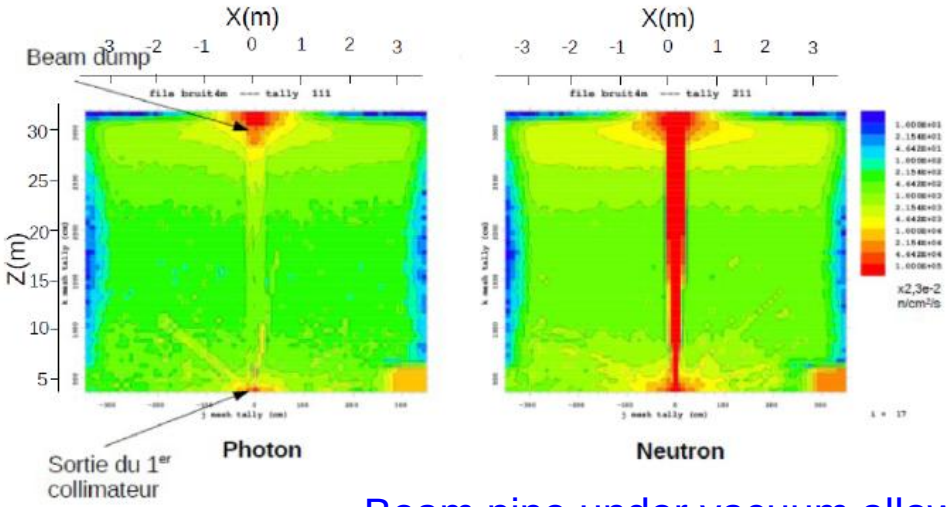
Preliminary design



Photon



Neutron



Beam on air

Beam on under vacuum

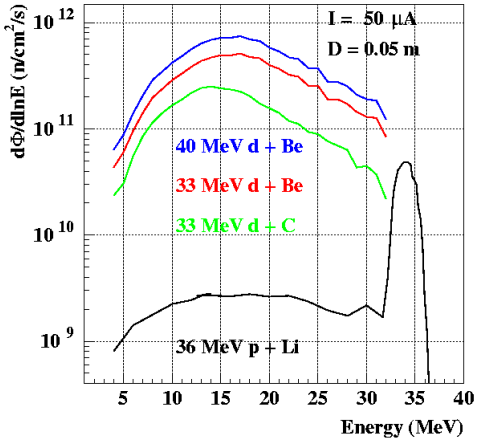
Beam pipe under vacuum allows reducing neutron and photon background

Measurement by activation method

1- Sample irradiation in the converter room

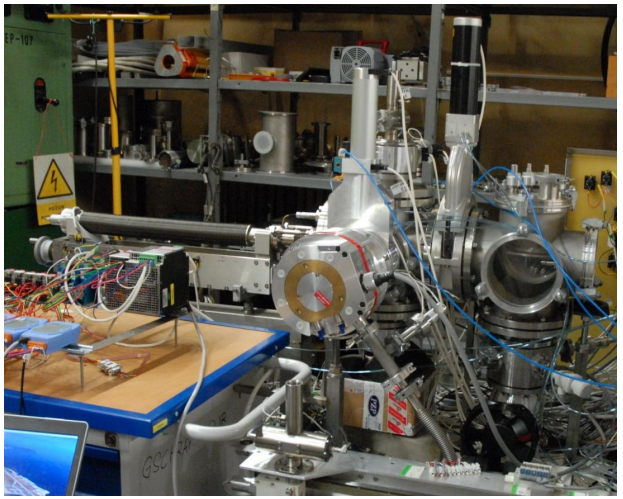
Neutron irradiation

- Spectrum similar to IFMIF
- $\Phi > 10^{11}$ n/s/cm^2

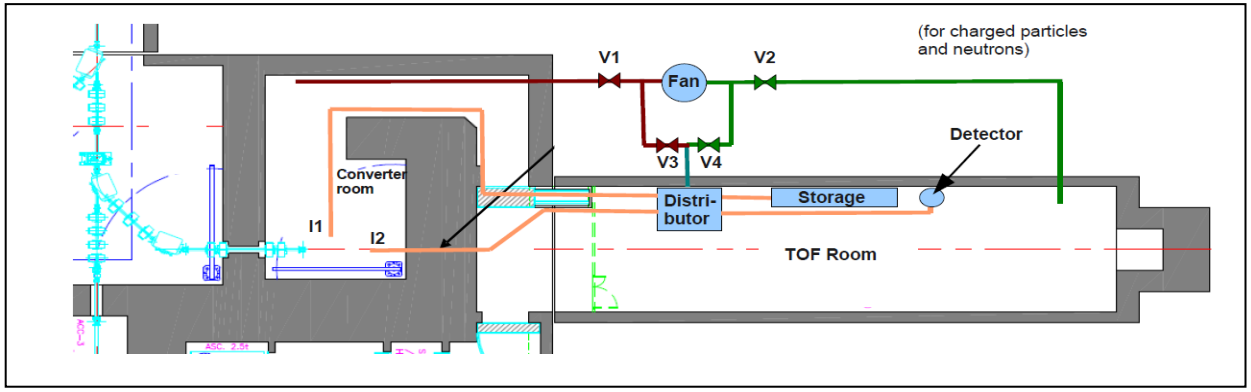


or

ion induced reactions



2- Transfer of sample to TOF room



3- Activity measurement

Cross-section measurements by activation method
Study of radioisotope production

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Letters Of Intent for experiments at NFS

- Neutron induced reactions studies :
  - Study of pre-equilibrium process in (n,xn) reaction, *X. Ledoux*
  - Comparison between activation and prompt spectroscopy as means of (n,xn) cross section measurements, *M. Kerveno*
  - Scintillating ionization Chamber for ALpha particle Production in neutron induced reaction, *G. Lehaut* → **S133: Tuesday 15:4**

- Fission :
  - Fission fragment distributions and neutron multiplicities, D. Doré **→see talk R419: Thursday**
  - Study of the fission process and fission cross-section measurements, *G. Bélier*
  - Measurement of prompt fission gamma-ray spectra in fast neutron induced-fission of actinides, *J.M. Laborie*
  - Gamma-rays spectroscopy and lifetime measurements at NFS, *A. Dijon*

- Cross-section reaction measurements by activation technique :
  - Measurement of cross-sections of deuteron-induced reactions on Ni and Zn, J. Grinyer

- Biology :
  - Response of Mammalian cells to neutron exposure, *C. Hellweg*
  - Investigation of 211At and 64Cu medical radioisotope production at NFS, *J. Grinyer*

- Detector development :
  - Neutron spectrometer characterization for LMJ project, *B. Rossé*

First experiments

- 10 experiences submitted to the PAC of 9th and 10th of June 2016 -> 7 accepted

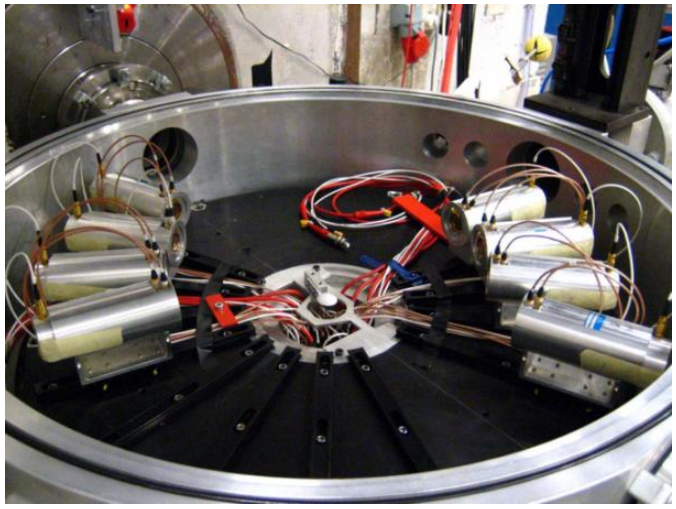
- For the first call :
  - no deuterons beam
  - no burst selector → limitation on realizable experiments

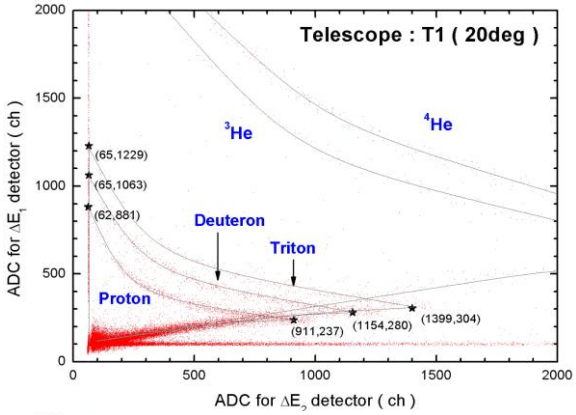
	NUM	Titre	Spokesperson	
Reaction model	E712	Measurement of (n,xn) reaction cross sections on U238	G. Bélier, CEA-DAM	
	E721	LIONS - Light-Ion Production Studies with Medley at the NFS facility	A.V. Prokofiev, Uppsala University	→R129
Fission	E713	Prompt fission neutron spectra measurement in neutron induced fission reactions	B. Laurent, CEA-DAM	→R247
	E718	Fission fragment angular distribution and fission cross section measurements relative to elastic NP scattering at 30 MeV	D. Tarrio, Uppsala University	→R129
Fusion		Excitation functions of short-lived isotopes in proton induced reactions on ^{nat}Fe	E. Simeckova, NPI, Rez	→R444
	E715	Neutron-induced activation reactions	A. Klix, KIT	
Radionuclei for medical applications		Alpha-induced reaction cross-section measurements on natural and enriched Zn	G. Grinyer, Ganil	
	E717	Measurements of the excitation function for the production of possible candidates for targeted alpha therapy at SPIRAL2	G. de France, Ganil	
Astrophysic	E719	Precise direct measurements of the ^{28}Si(p,γ)^{29}P and ^{29}Si(p,γ)^{30}P reaction rates to understand the origin of presolar nova grains	B. Bastin, Ganil	
Instrumentation	E720	Measurement of the absolute neutron detection efficiency of FAZIA telescopes	E. Bonnet, Ganil	

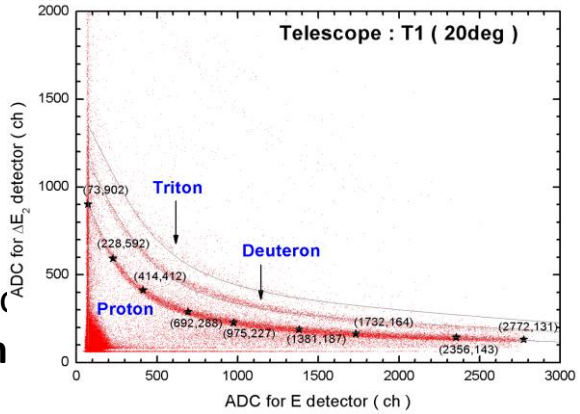
E721:LIONS - Light-Ion Production Studies with Medley at the NFS facility

Spokesperson: A. Prokofiev (Uppsala university)

- Cancer therapy and dosimetry (H, C, O, Ca, ...)
- Radiation effects in microelectronics (*SEU; single event upsets*) Si, O, ... **Silicon** and **oxygen** data is needed for:
- Energy applications (GenIV, fusion)
  - Construction material: Fe, Cr, …
  - Fuel: U, Th, …
  - Coolant: Pb, Bi, Na, …
  - $^{16}O(n,\alpha)$ reaction affect reactor reactivity, 25% of the helium production







Medley

Evacuated chamber

ΔE-ΔE-E technique + angles

⇒ double differential cross secti

Can be used to measure **neutron**

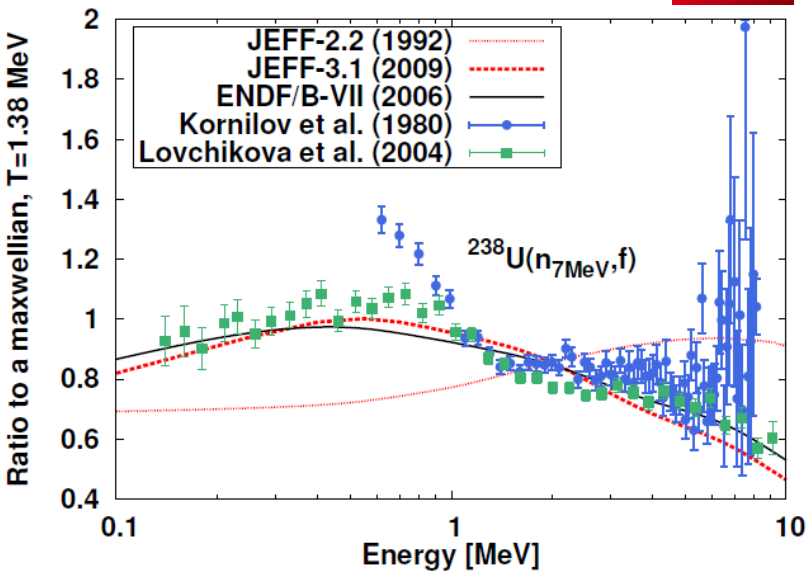
*Tippawan et al., Phys. Rev. C **79**, 064611 (2009).*

E713 :Prompt fission neutron spectra measurement in neutron induced fission reactions

Spokesperson : B. Laurent, CEA-DAM-DIF

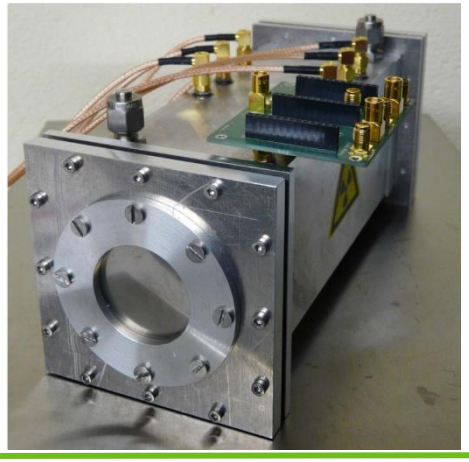
- Important in many applications :
  - -Understanding of the fission process
  - - Accuracy of nuclear criticality calculation (conventional and advance reactors, non-proliferation applications)
  - -Theoretical description of PFNS difficult
- Few experimental data
- Discrepancies between measurements and evaluations

→2009 international program aiming at improving the adequacy and the quality of PFNS launched by IAEA→INDC(NDS)-0541)

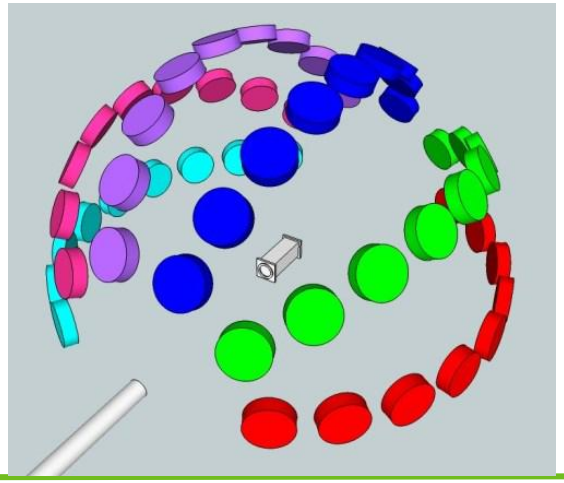


Experimental technique :

Fission chamber (370 mg of U238)



Array of 50 neutrons detectors



First experiment :
6,5 MeV n + ^{238}U
quasi-mono energetic beam

Next step :
n + ^{239}Pu
pulsed beam

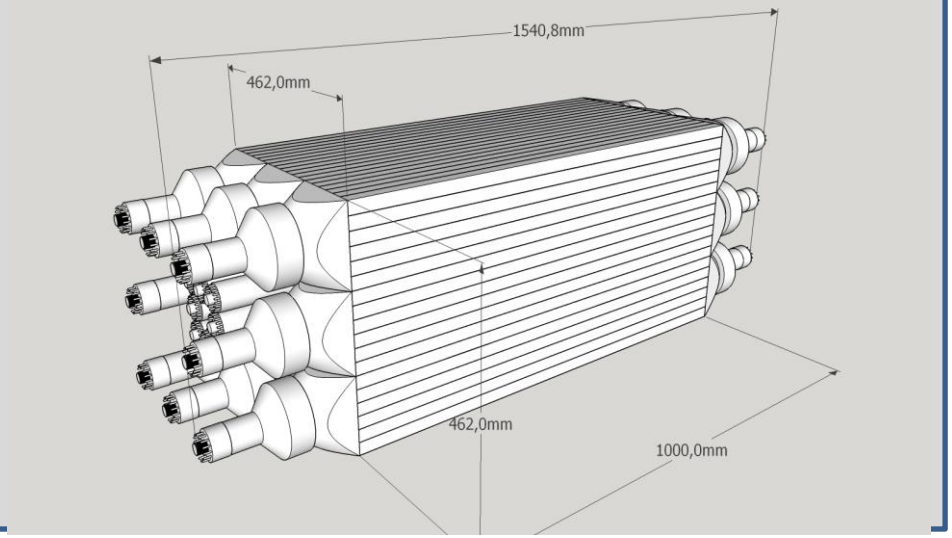
E712: Measurement of (n,xn) reaction cross sections on U238

Spokesperson : G. Bélier, CEA-DAM-DIF

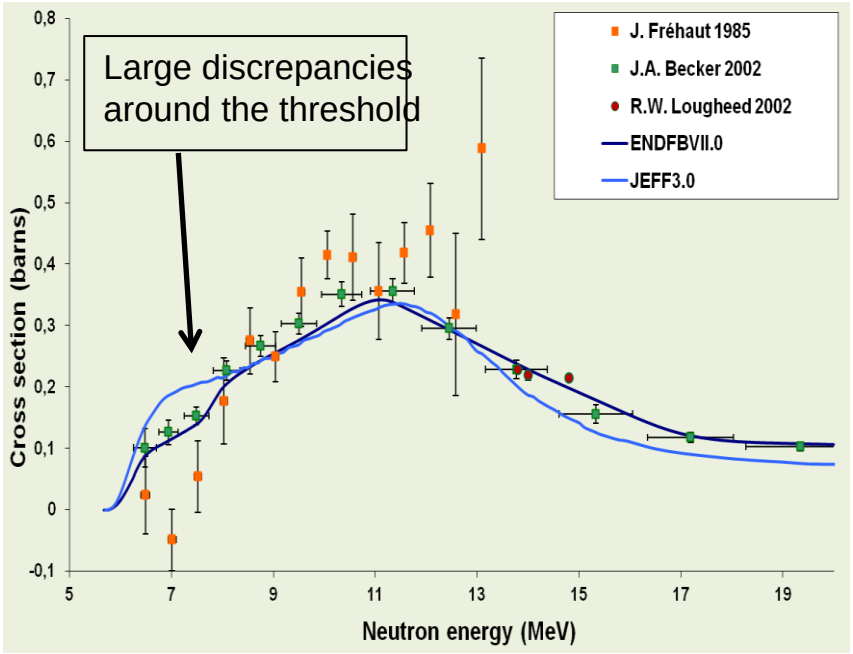
- (n,xn) reaction are important channels in the 5-50 MeV range
- (n,xn) cross-section measurement of actinide is very difficult:
  - radioactive sample
  - prompt neutron fission

Experimental technique :

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



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



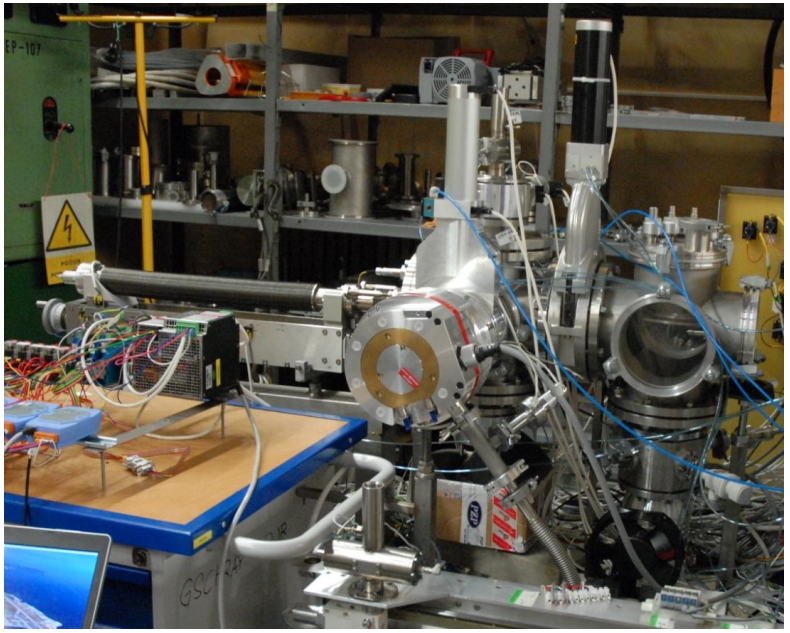
E714: Excitation functions of short-lived isotopes in proton-induced reactions on ^{nat}Fe

Spokesperson : E. Simeckova, NPI, Rez

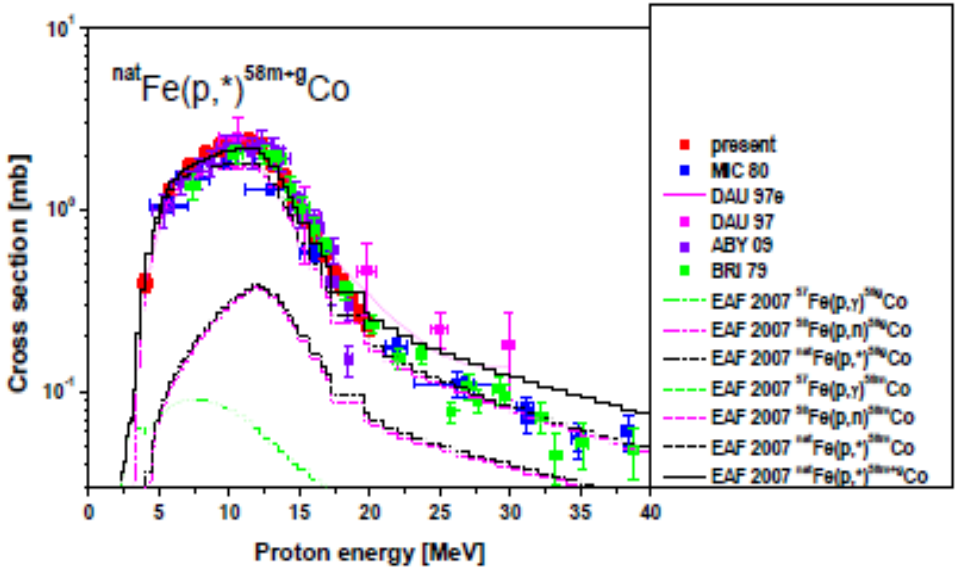
→see talk R444: Tuesday 17:10 Mozart

Measurement of reaction cross-sections by activation technique :

- data for IFMIF facility design
- improvement of reaction model
- Irradiation station + pneumatic transfer system
- proton at 33 and 25 MeV



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



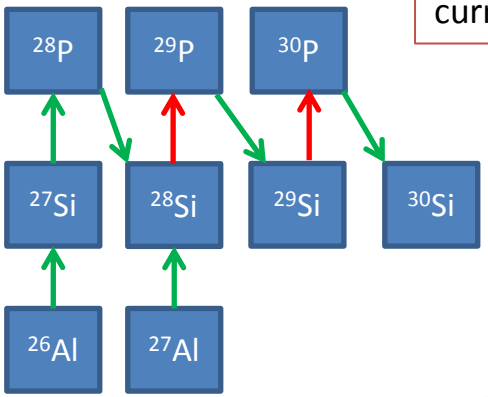
Other short-lived isotopes measured:

- ^{53m}Fe (2.58)
- ^{53}Fe (8.51)
- ^{54m}Co (1.48 min)
- ^{50m}Mn (1.75 min)
- ^{52m}Fe (45.9 s)

Precise direct measurements of the key $^{28}Si(p,\gamma)^{29}P$ and $^{29}Si(p,\gamma)^{30}P$ reaction rates to understand the origin of presolar nova grains

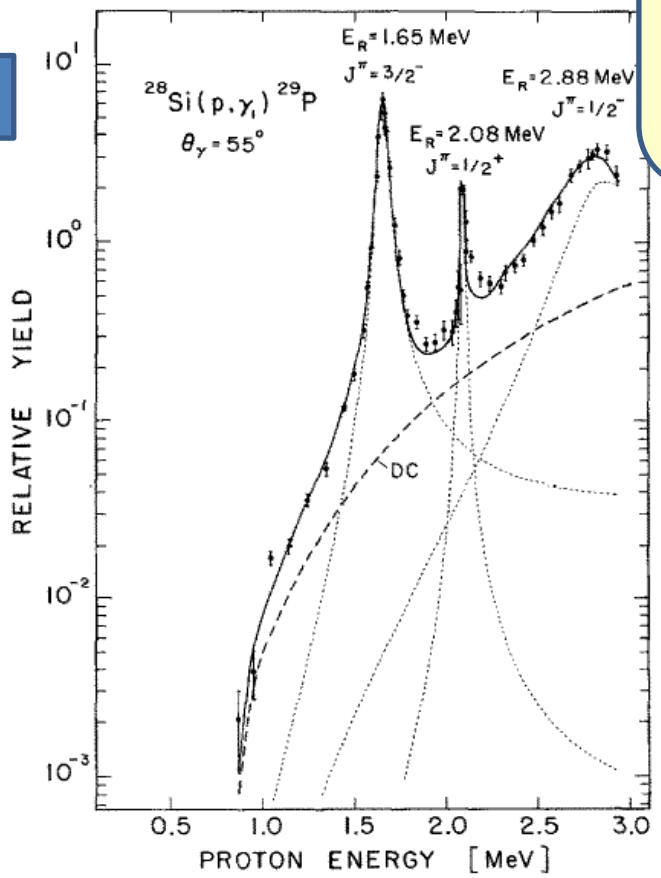
F. Boulay, B. Bastin, J. Mrazek, *GANIL, IPN Orsay, CSNSM, IPN Lyon, JYFL, Instituto de Fisica Corpuscular (Valencia) , NCSR "Demokritos" and Subat*

Destruction reactions
$^{28}Si(p,\gamma)^{29}P$, $^{29}Si(p,\gamma)^{30}P$



Hot CNO cycle

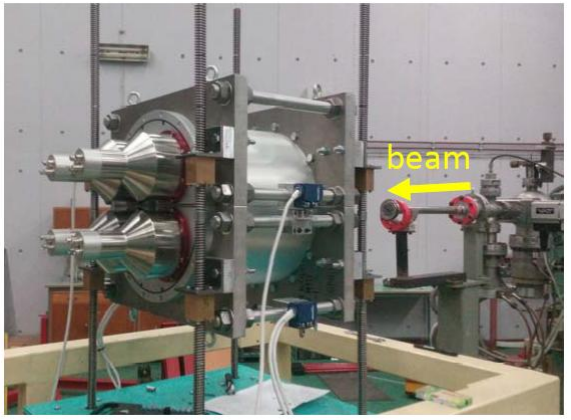
Necessity to constrain the reaction rates $^{28}Si(p,\gamma)^{29}P$ and $^{29}Si(p,\gamma)^{30}P$ which have currently 21 % and 30 % uncertainties.



Energy of interest :
Gamov window

Experiment at NFS:

- $^{28}Si(p,\gamma)^{29}P$ and $^{29}Si(p,\gamma)^{30}P$ reaction rates at 0.733 MeV
- Most intense proton beam in Europe
- 4π gamma summing technique
- Detector NeoPtolemos



Radioisotopes for medical applications

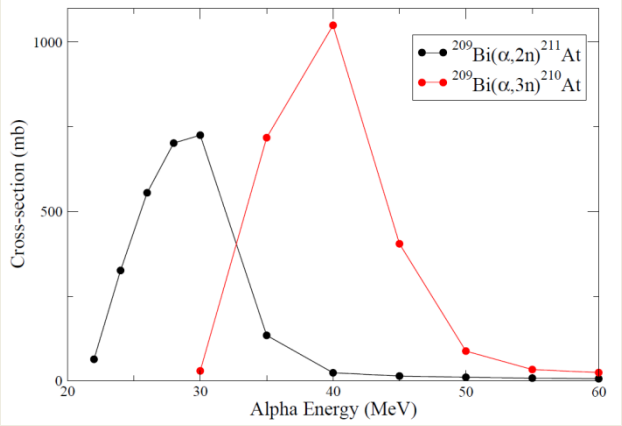
- Study of alternative route production of several radioisotopes used in medical applications
- SPIRAL-2 :
  - alpha, HI beams
  - tunable energy
- Production of alpha emitters

Example : production of ^{211}As (α emitter, $T_{1/2}$ = 7.2 h)

^{209}Bi(α,2n)^{211}At

Also produce ^{210}At (decays to ^{210}Po, $t_{1/2}$ = 138 d)

Reduce ^{210}At production if E_{alpha} <30 MeV

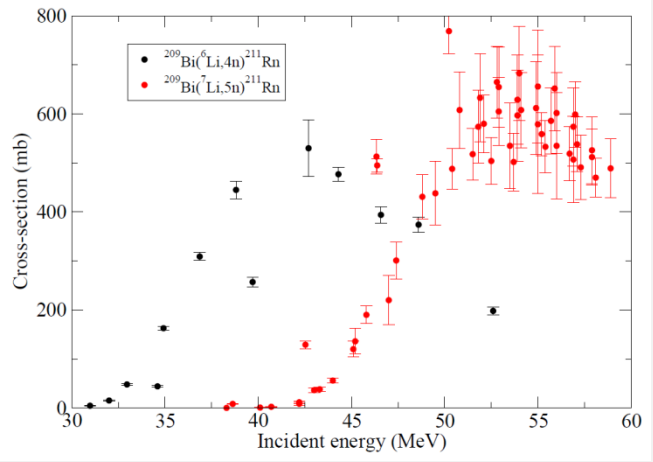


^{209}Bi(^{6}Li,4n)^{211}Rn or ^{209}Bi(^{7}Li,5n)^{211}Rn => Generator

^{211}Rn: EC decay (72.6%), $T_{1/2}$=14.6 h, to ^{211}At

Additional transportation/separation time

Less ^{210}Po



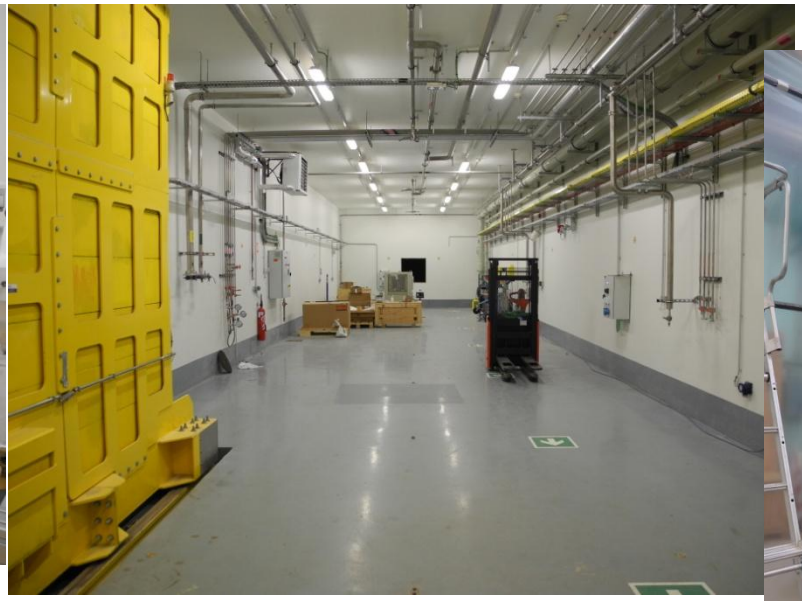
Collaboration Caen-Nantes (with ARRONAX)

OUTLINE

- Motivations
- Description of NFS
- Firsts experiments
- Organization and status

SPIRAL-2

NFS



Timeline

- 19th Dec 2014 : First proton beam delivered by the source
- 3th Dec 2015 : First beam accelerated through the RFQ
- 9th of June 2016 : NFS experiments @ GANIL PAC
- **end of 2016 : End of the installation of NFS :**
- **Final authorization (deuteron beam + LINAG) expected by December 2016**
- **Deuterons beam in the RFQ : T1 2017**
- **LINAC commissioning : T2 2017**
- **NFS commissioning : → as soon as the LINAG's beam is available**
- **First experiment : 2017**

NFS commissioning strategy

- Follows the accelerator commissioning strategy : proton, alpha, HI, deuterons
- Realize experiments ASAP

	E(MeV)	Converter	
Proton	33		Beam optic
			p induced reaction cross-section measurement
	0,73		$^{28}Si(p,\gamma)^{29}P$ cross-section
	33	Lithium	Commissioning
		Lithium	E720 + E721
	8,5	Lithium	Commissioning
		Lithium	PFNS
	8,5 to 25	Lithium	Commissioning
		Lithium	U238(n,2n) cross-section measurement
		Thick Be	Commissioning
alpha	80		Beam optic
			Reaction cross-section measurement

Collaboration and funds

- **Eight partners**
  - Have funded the main part of the process
  - Steering committee
  - Collaboration board.
- **NFS collaboration**
  - 15 labs
  - 50 physicists

Partners
GANIL, Caen
CEA/DAM/DIF, Arpajon
CEA/DSM/Irfu, Saclay,
IN_2P_3, France
CEA/DEN, Cadarache,
NPI, Řež, Czech
Uppsala University,
KIT, Karlsruhe

Other sources of funding

- **CHANDA :European contract:**
  - 190 k€ for manpower and investment
  - Transnational access
- **Bilateral cooperation between the Institute of Atomic Physics (IFA-Romania) and CEA**
  - Travel of Romanian physicists for experiment at NFS
  - Neutron detector monitoring and electronics
- **Soutien au RETOUR DES JEUNES CHERCHEURS partis à l'étranger : MENIR**
  - Help to the return of young scientists in Basse-Normandie
  - 3 years of Post-doctoral position

Summary

NFS:

- White and quasi-monokinetic spectra in the 0.1-40 MeV range
- Neutron beams with high flux and good energy resolution
- Complementary to the existing n-tof facilities
- Measurements by activation reactions (n, p, d)

Day-One experiments:

- 10 experiments submitted to the PAC
- Fission studies : σ, fragments, yields, neutron and gamma multiplicities
- (n,xn) and (n,lcp) reactions: σ and $d^2\sigma/dEd\Omega$
- Proton and alpha induced reactions
- Study of radioisotope production for medical application
- Detector development