THE NEUTRONS FOR SCIENCE FACILITY AT SPIRAL-2

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The Neutrons For Science facility

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

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

OUTLINE

- GANIL/SPIRAL-2
- NFS
- Firsts experiments

- GANIL/SPIRAL-2
- NFS
- Firsts experiments

GANIL

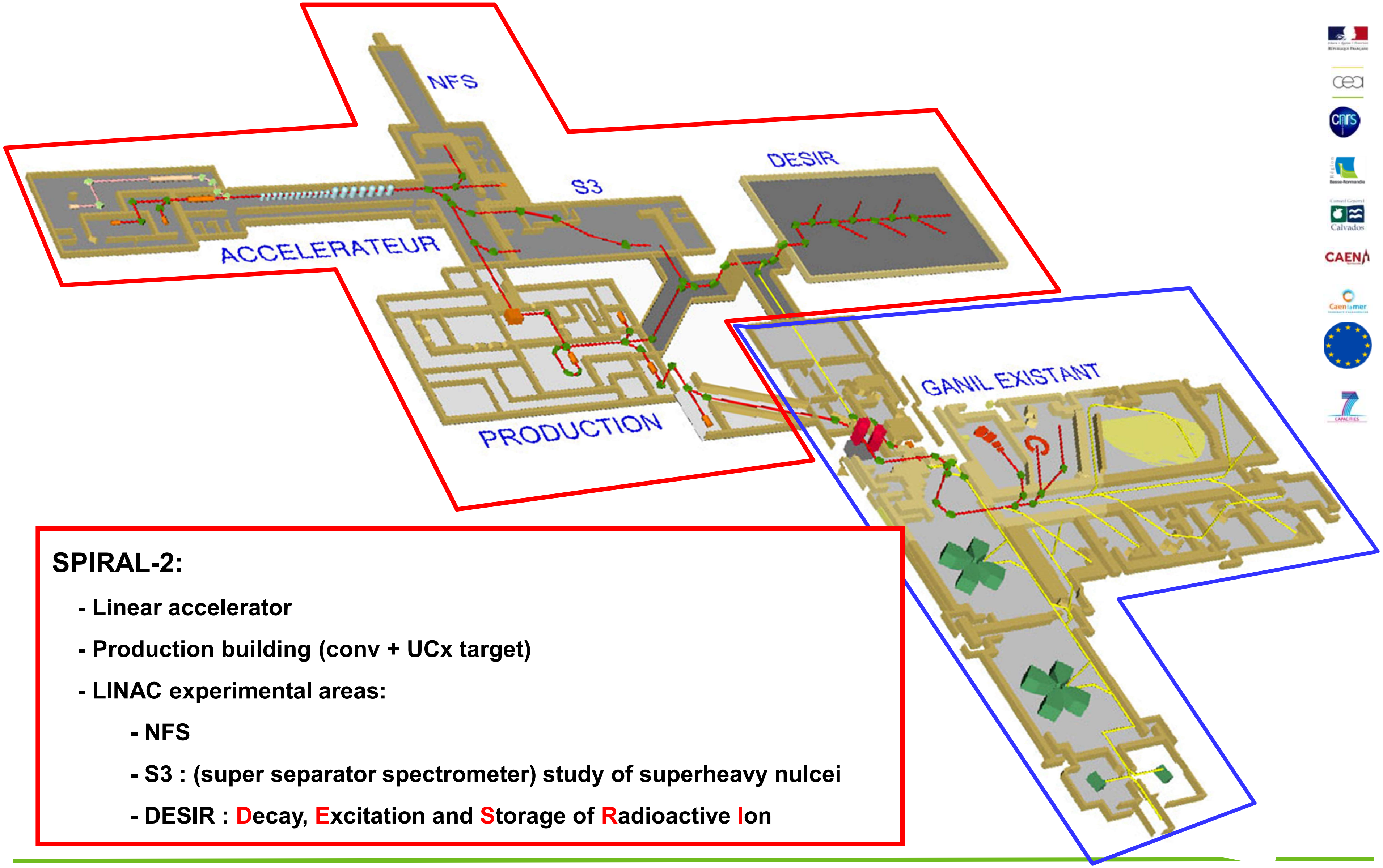
Grand Accélérateur National d'Ions Lourds

- National Facility, located at Caen, France
- First beam in 1983
- 250 permanent people (≈25 nuclear physicists)
- 700 scientific visitors per year

Fundamental physics

Industrial applications

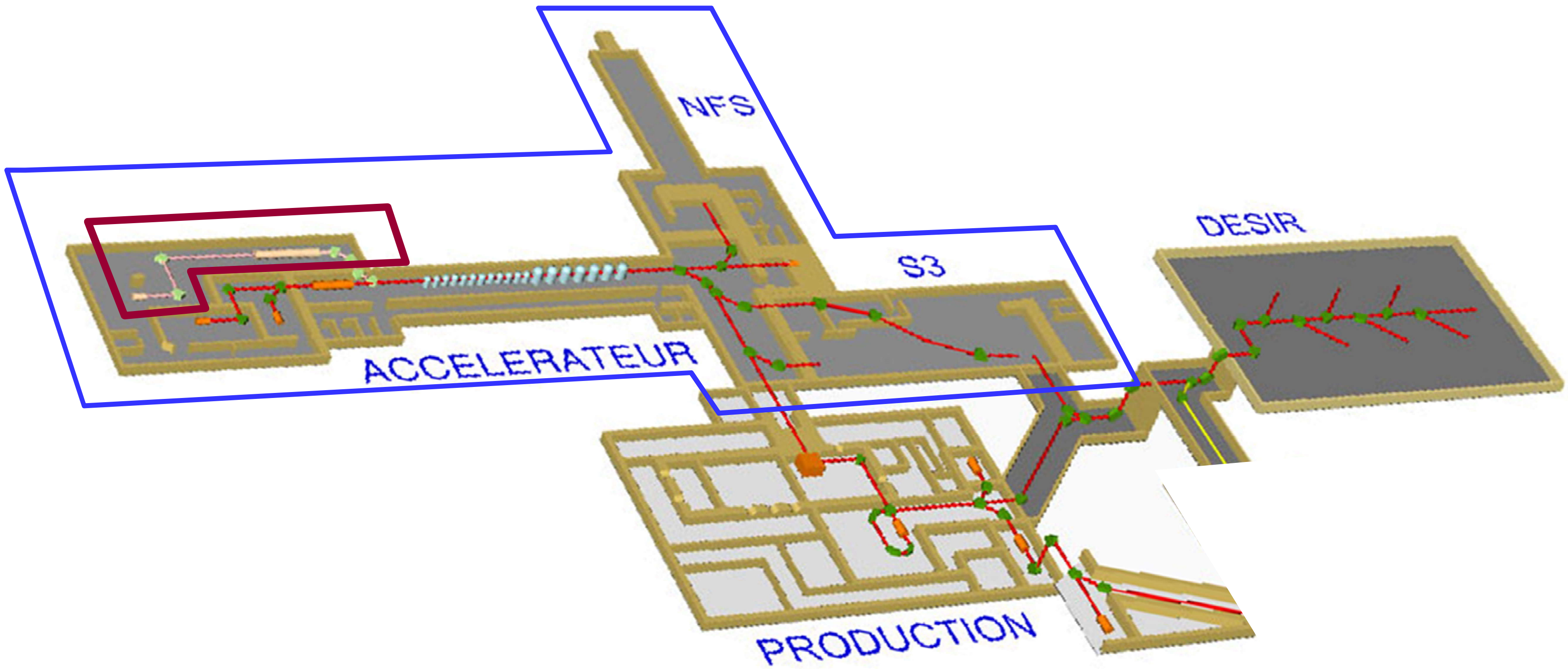
GANIL/SPIRAL 2 facility



SPIRAL-2:

- **Linear accelerator**
- **Production building (conv + UCx target)**
- **LINAC experimental areas:**
  - **NFS**
  - **S3 : (super separator spectrometer) study of superheavy nulcei**
  - **DESIR : Decay, Excitation and Storage of Radioactive Ion**

SPIRAL 2 construction phases

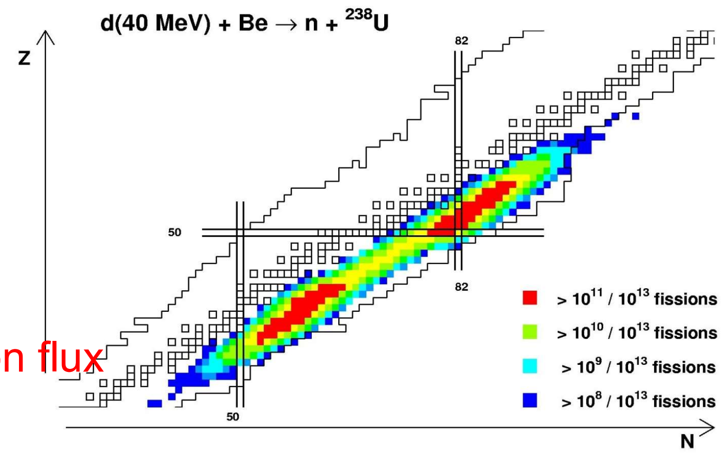


Phase 1 : LINAC + NFS + S3 **Built**

The SPIRAL-2 project

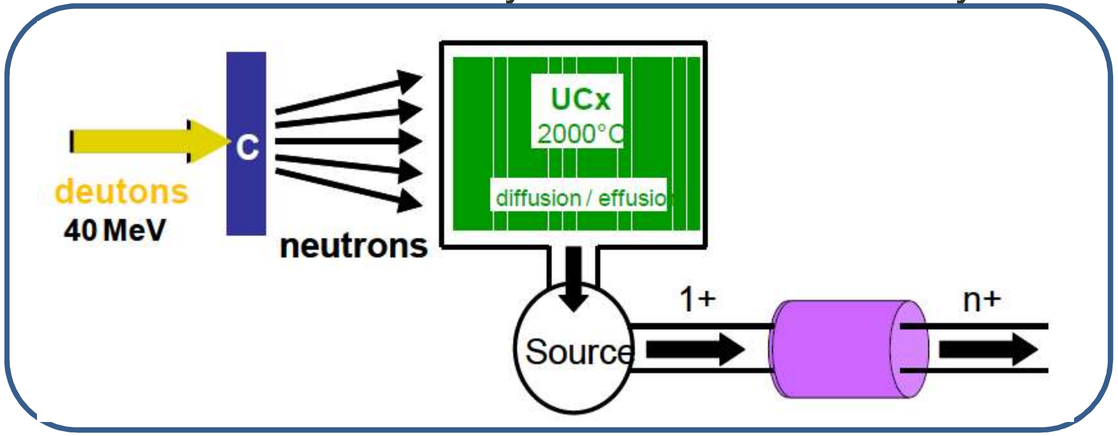
Main objectives:

- Increasing the RIB production by a factor 10 to 1000
- Extend the range of beams nuclei Z>40 A>80



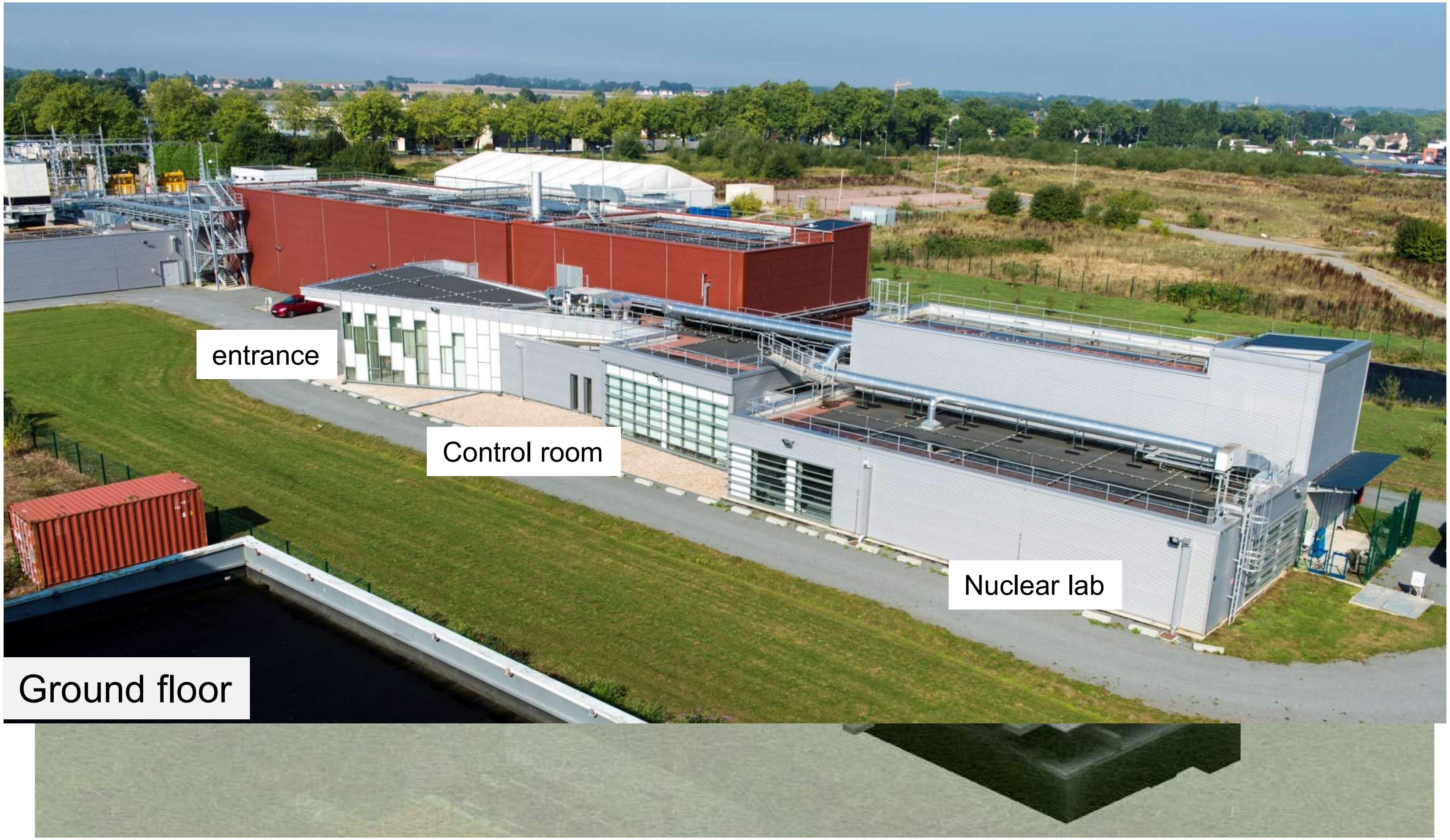
Technique :

- Primary beam of high intensity to produce high neutron flux
- Neutron induced fission of 238U
- UCx target
- Post-Acceleration of secondary beam with the CIME cyclotron



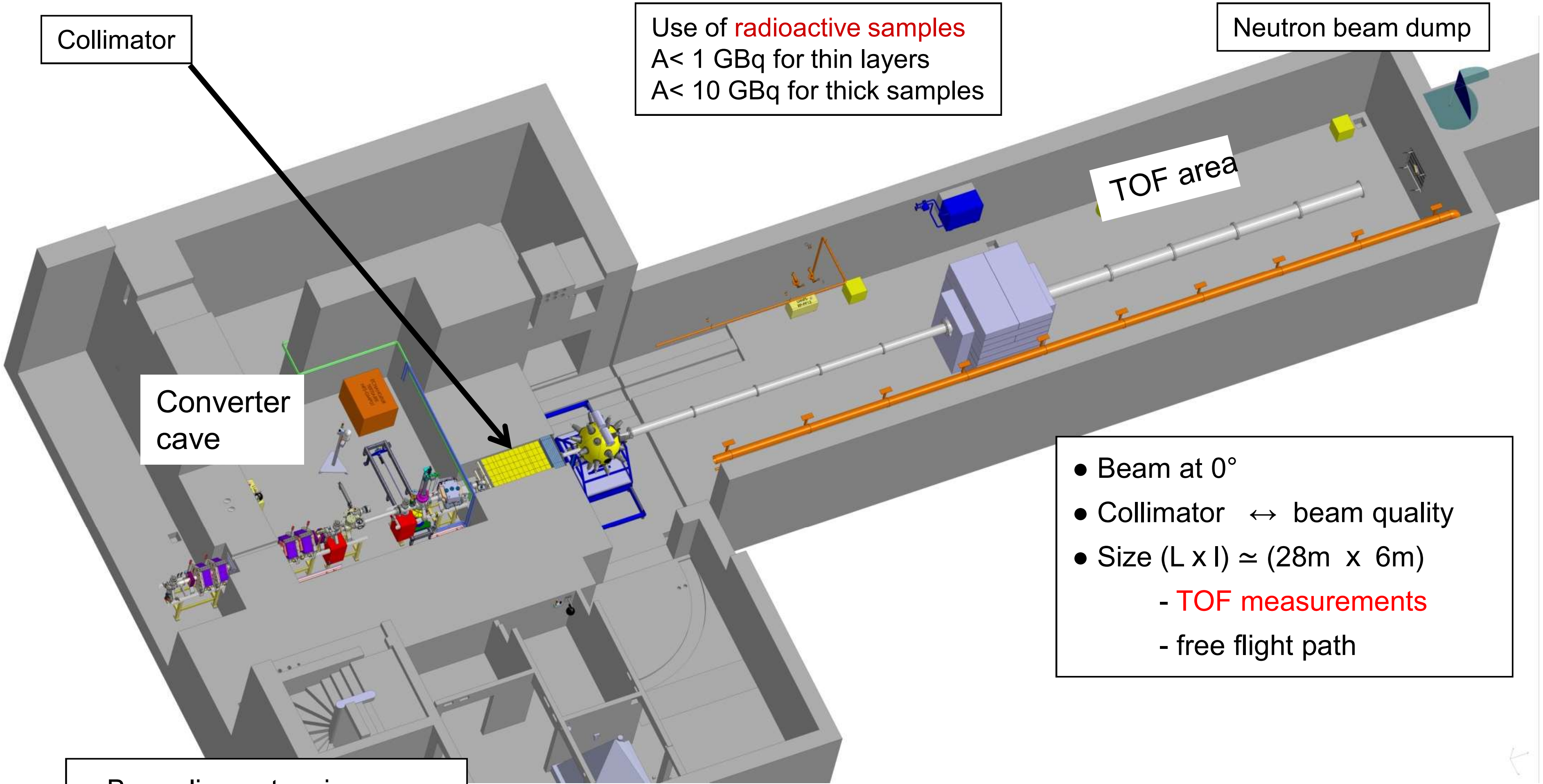
Linear accelerator: p and d up to 5mA, HI up to 14,5 MeV/A

SPIRAL-2 phase 1 building



- ❑ GANIL/SPIRAL-2
- ❑ NFS
- ❑ Firsts experiments

NFS layout



Use of radioactive samples
A< 1 GBq for thin layers
A< 10 GBq for thick samples

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

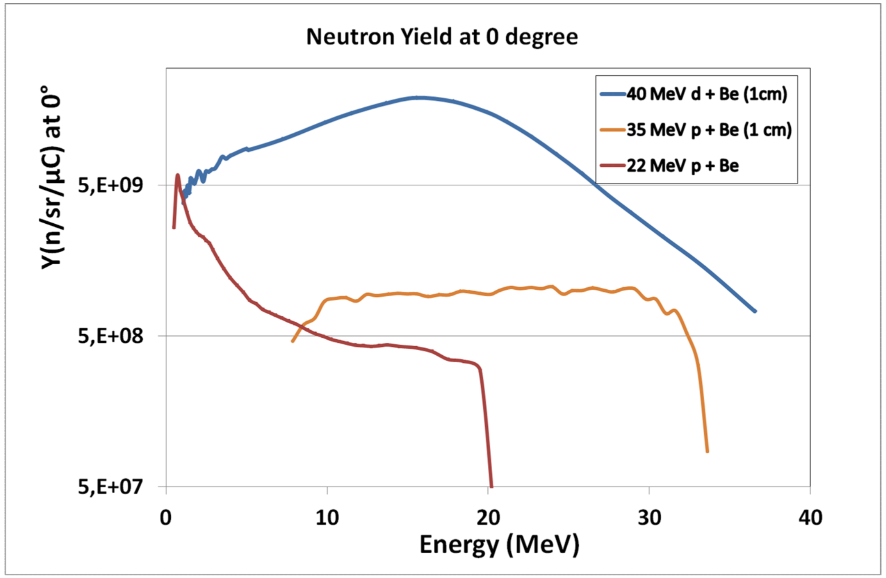
- Beam line extension
- Converter
- Magnet and beam dump
- Irradiation station (n, p, d)

Reference beam: 40 MeV d + Be (8mm) @ 40 MeV

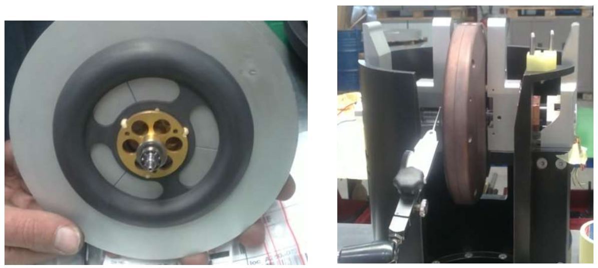
Neutron spectra provided at NFS

Continuous spectrum

40 MeV d+ Be (6 mm)

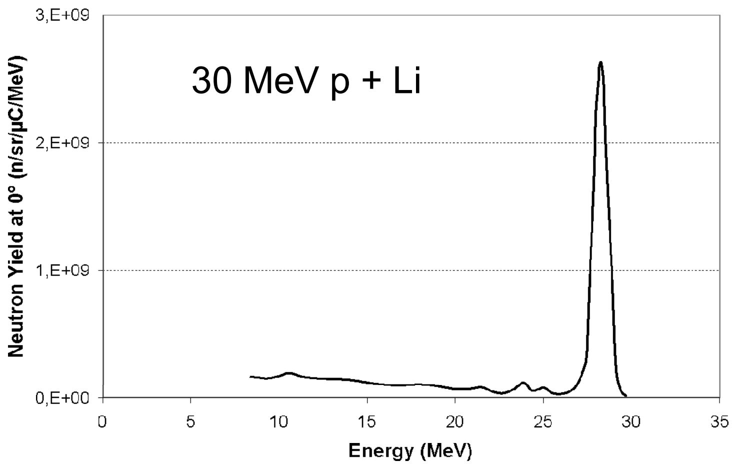


Rotating thick converter



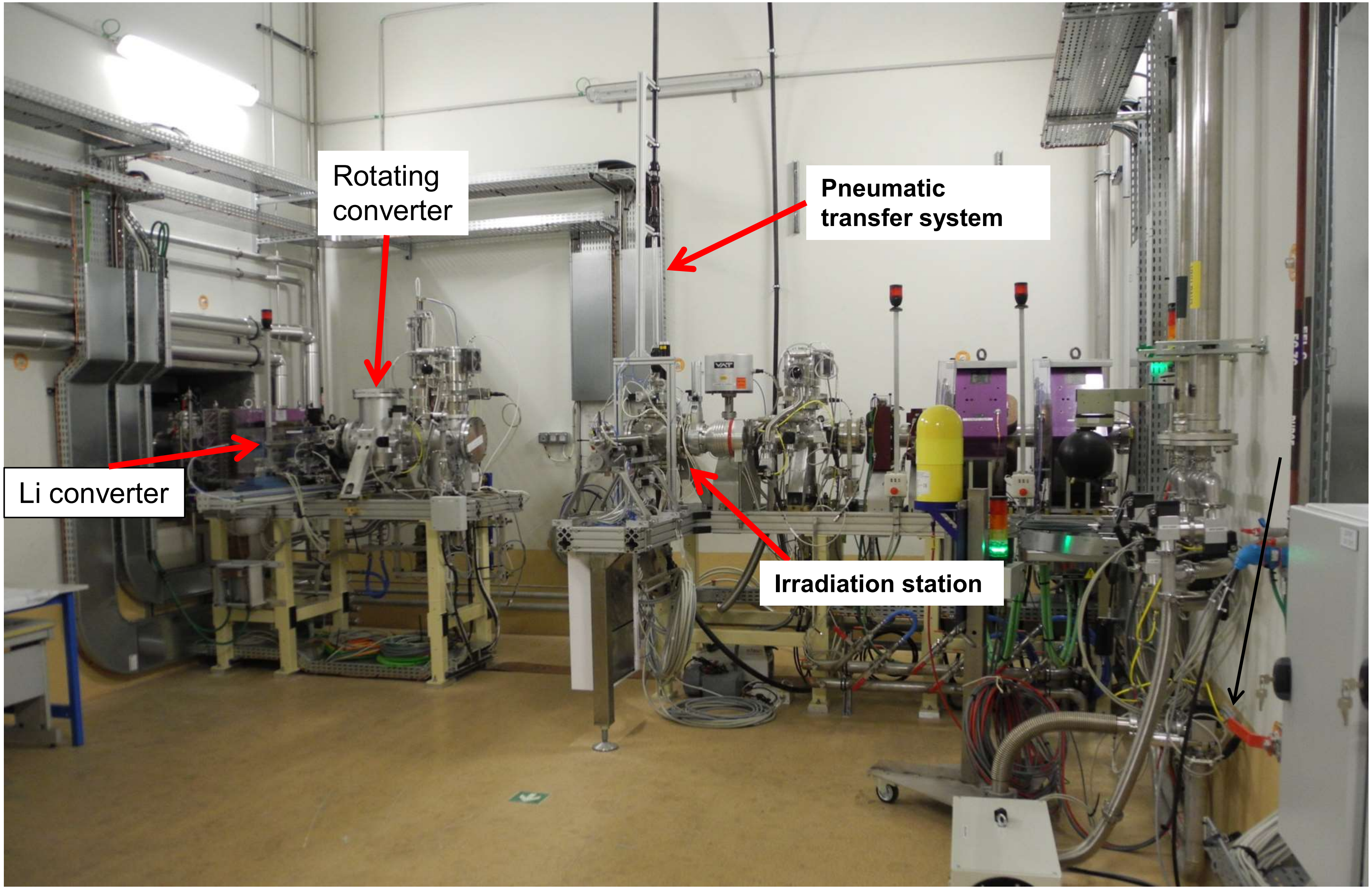
Quasi-mono-energetic spectrum

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



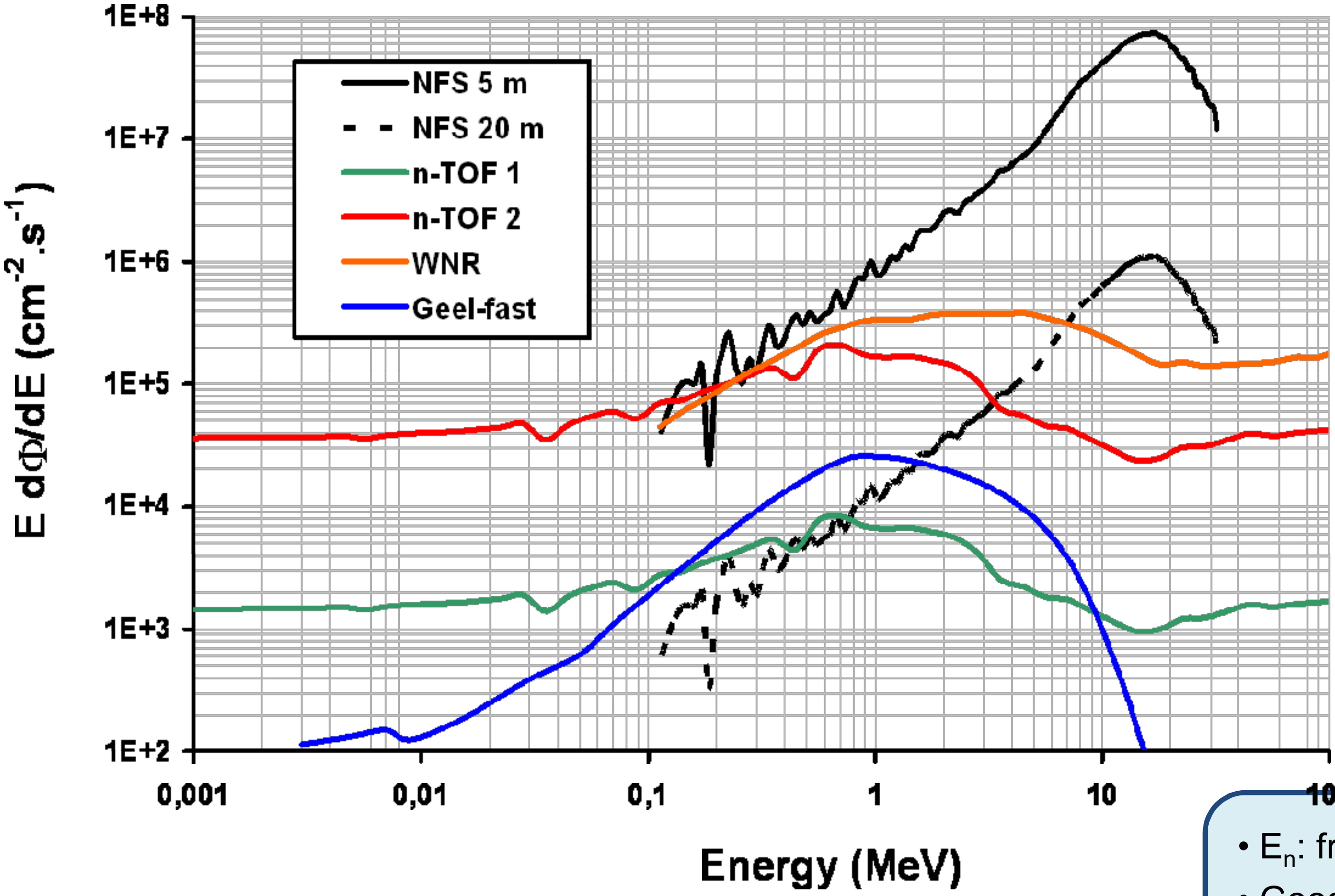
Thin converter

NFS: The converter room



NFS: The TOF area

Comparison with other Neutron TOF facilities



NFS : 40 MeV d + Be

WNR : Los Alamos

n-TOF 2 : CERN

n-TOF 1 : CERN

GELINA : Geel

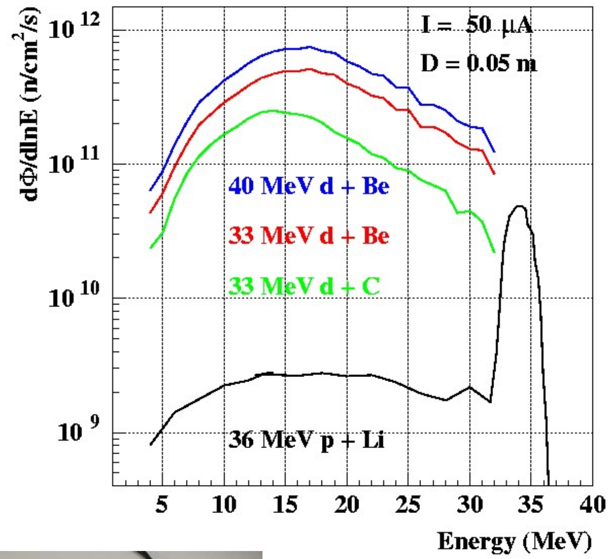
- E_n: from 0,1 MeV to 40 MeV
- Good energy resolution
- Reduced γ flash
- Low instantaneous flux

Complementary to the existing facilities

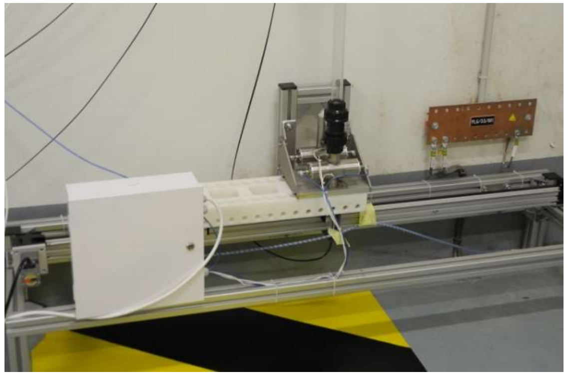
Measurement by activation method

1- Sample irradiation in the converter room

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

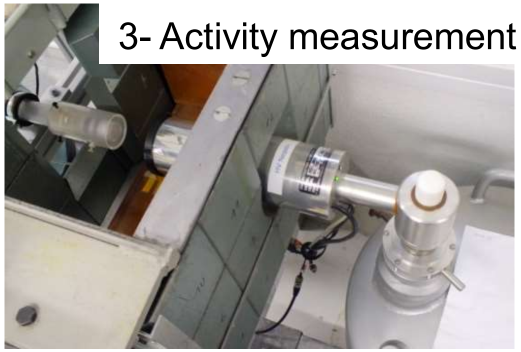


2- Sample transfer system



See J. Mrazek's talk

3- Activity measurement



Cross-section measurements by activation method
Study of radioisotope production

Ion induced reactions

- All ions accelerated by the LINAC can be used at NFS
- In the converter room only
- Experiment type:
  - Activation technique
  - Vacuum chamber + detector
- Energy domain
- Imax :
  - P< 2 kW in any case (thermal constrains only)
  - P> 2 kW to be studied case by case (thermal and radiological constrains)

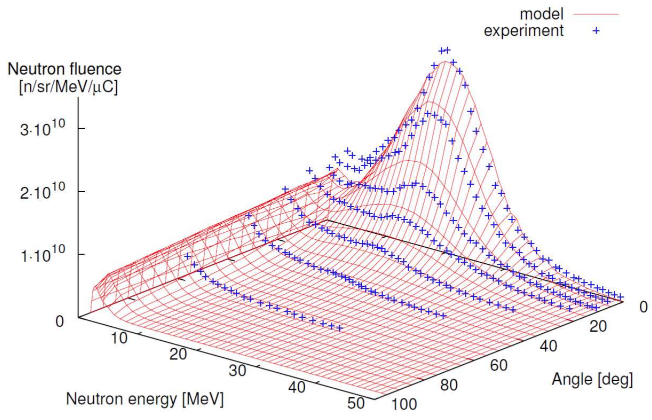
	Protons H^+	deutons $^2H^{1+}$ alpha He^{2+}	Heavy ions	
	q/A=1	q/A=1/2	q/A≥1/3	q/A≥1/6
E_{min} (MeV/A)	2	2	2	2
E_{max} (MeV/A)	33	20	15	9

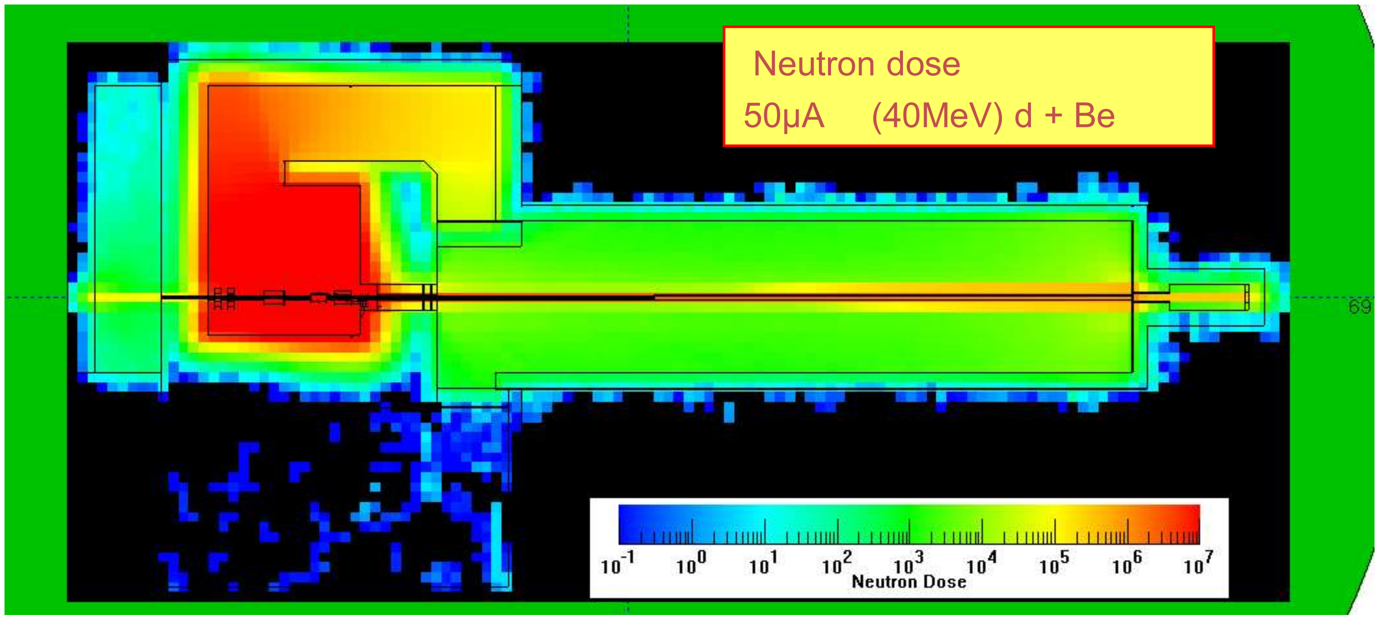
Irradiation station connected to the pneumatic transfer system

See J. Mrazek's talk

Neutron transport simulations

- Neutron transport simulations are needed for :
  - Safety purpose
  - Background evaluation
- Simulations characteristics :
  - MCNPX neutron code
  - Neutron source d+Be and p+^{7}Li
  - Faithful geometry of the buildings





Residual activation

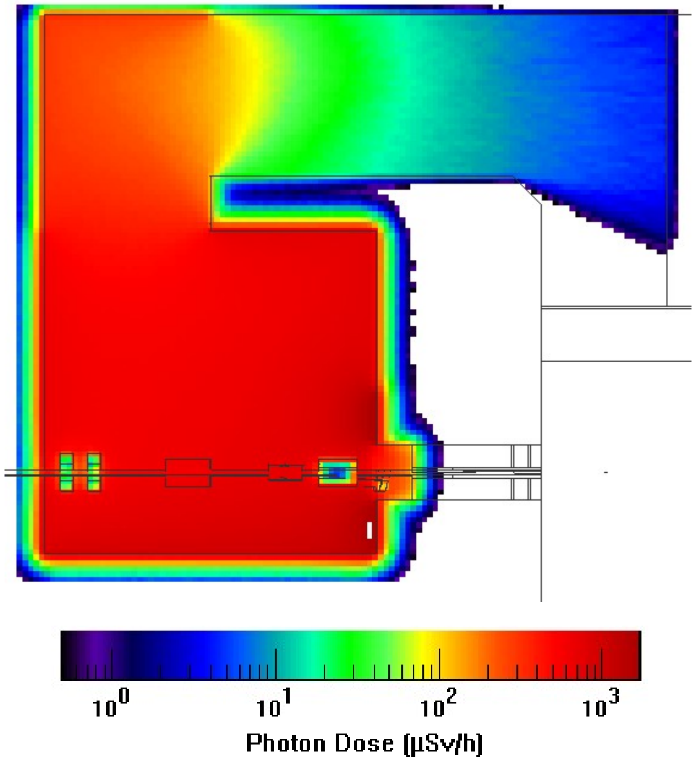
1- MCNPX → neutrons flux in all cells

2- FISPACT + scenario → Activity in each cell for several cooling times

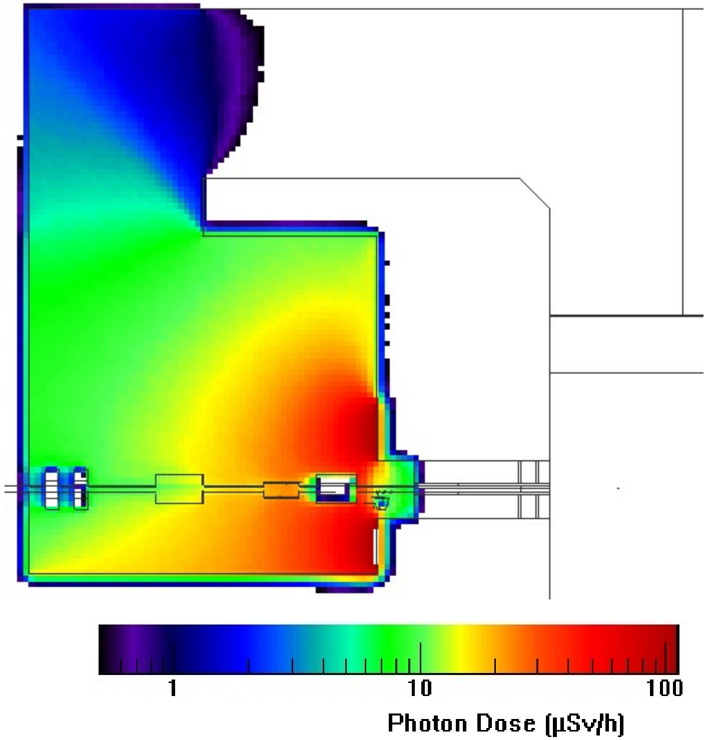
3- Creation of associated gamma sources

4- MCNPX → ambiance equivalent dose calculation

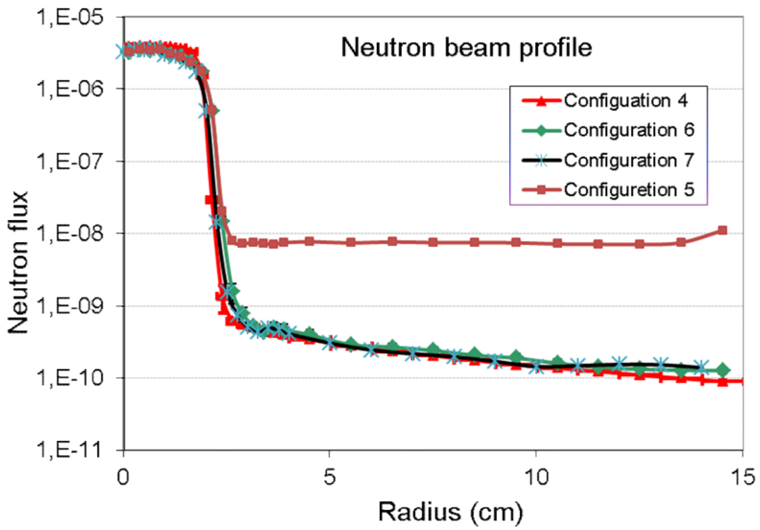
Cooling 1 day

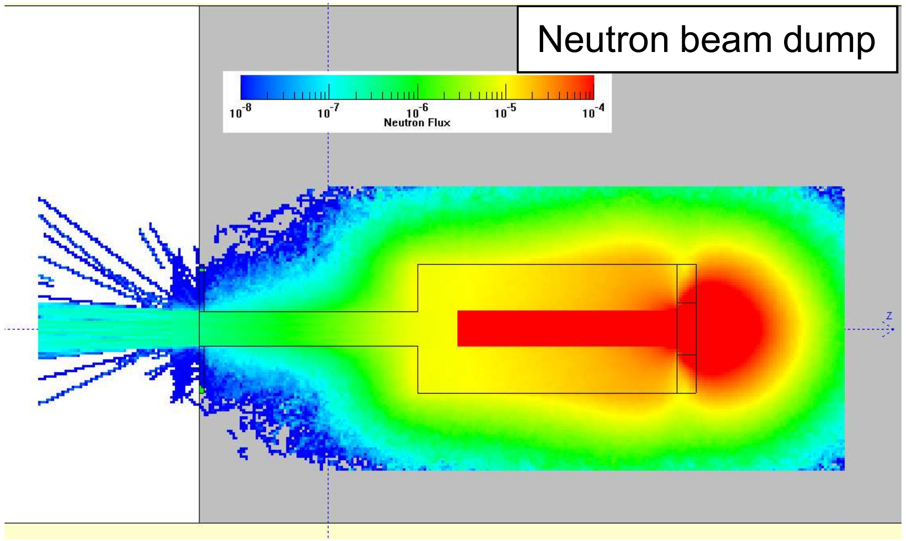


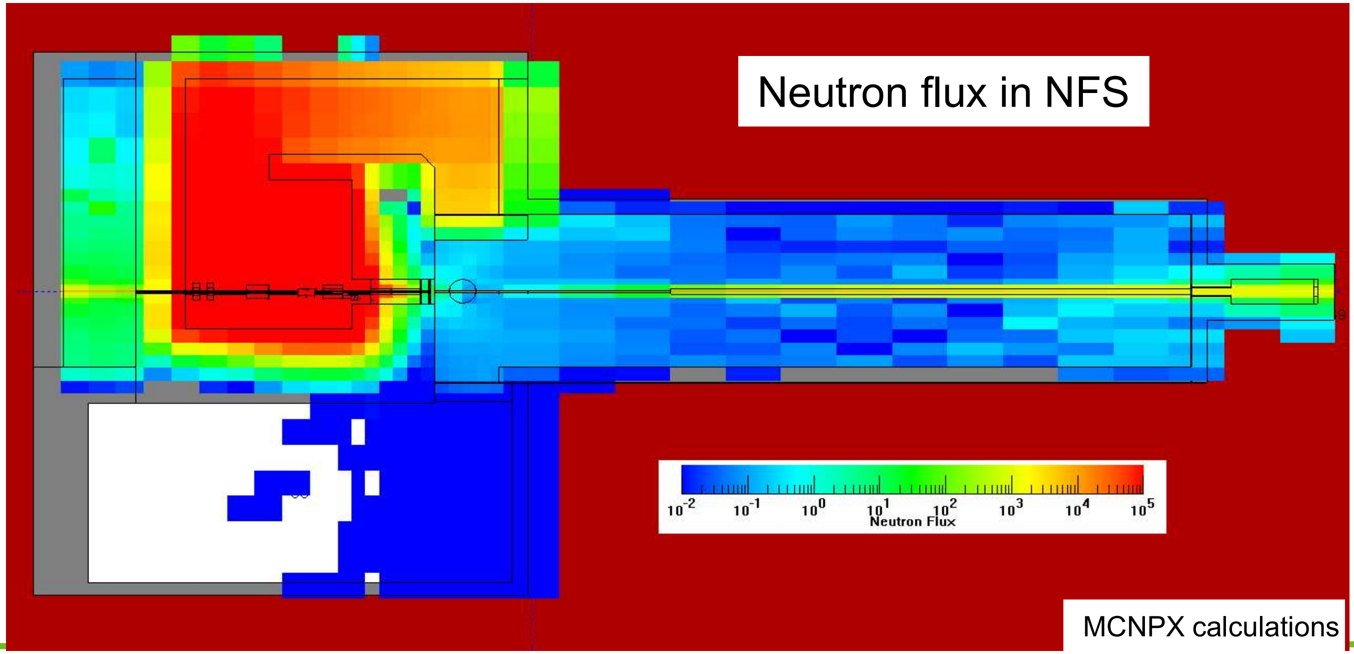
Cooling 10 days



Calculation for beam profile and neutron background

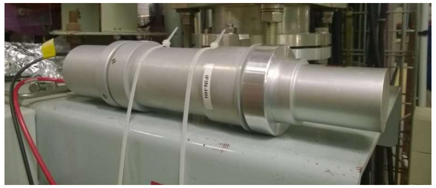




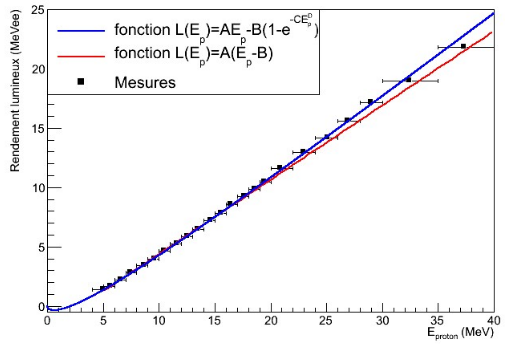


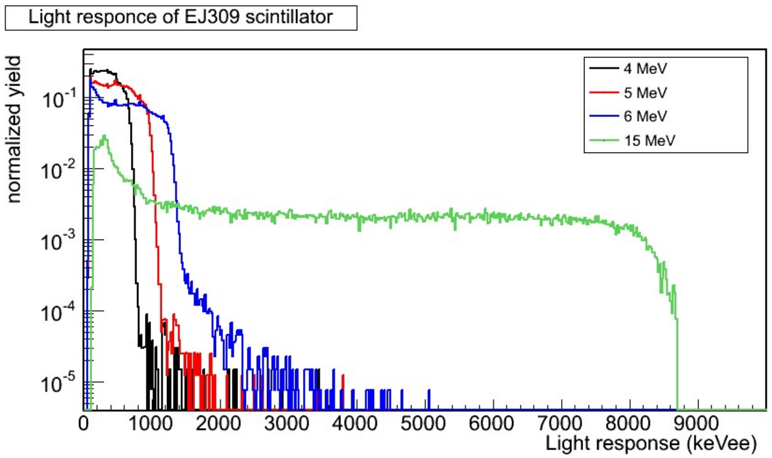
Neutron monitoring

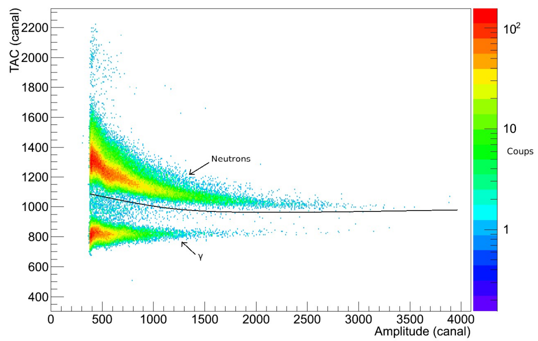
❑ Detector based on liquid scintillator EJ309



- Neutron spectrum and flux measurement by the TOF technique
- n-γ discrimination by pulse shape analysis
- Characterization
  - at Ganil reaction 10,5 MeV/A Kr + Cu
    - Light response between 5 and 30 MeV
  - at CEA/DIF
    - Mono-energetic neutrons at 4, 5, 6 and 15 MeV
    - Efficiency measurement







❑ Proton recoil telescope

- CH2 radiator + ΔE-ΔE-E Si telescope
- Prototype tested at GANIL

Status

❑ **Ready and installed:**

- Collimator
- Beam line in the converter room
- Vacuum
- Automation
- Irradiation station
- Pneumatic transfer system

❑ **Built but not yet fully installed :**

- Rotating converter
- Beam line in the TOF hall
- Single bunch selector
- Neutron beam dump

❑ **Not yet built**

- 2nd collimator : under conception (deliver by end of 2018)

Milestones

J1: Vacuum + interlock (30 Sep 2017)

J2: Irradiation station + pneumatic transfer system (31 Jan 2018)

J3: Rotating converter + SGAF (31 May 2018)

- ❑ GANIL/SPIRAL-2
- ❑ NFS
- ❑ Firsts experiments

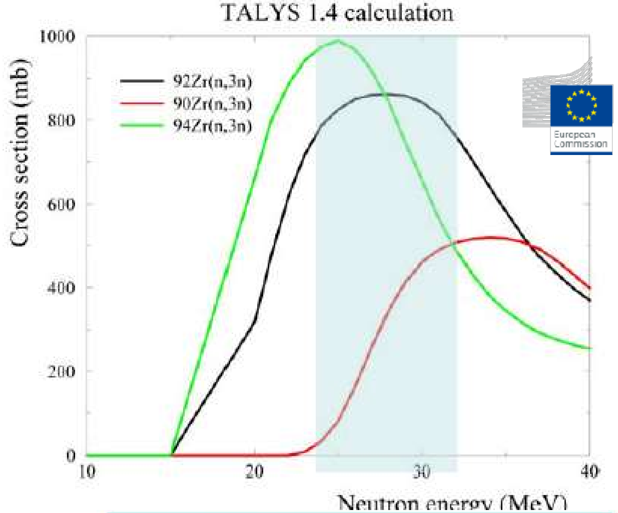
LoI and proposals for Day-One experiments at NFS

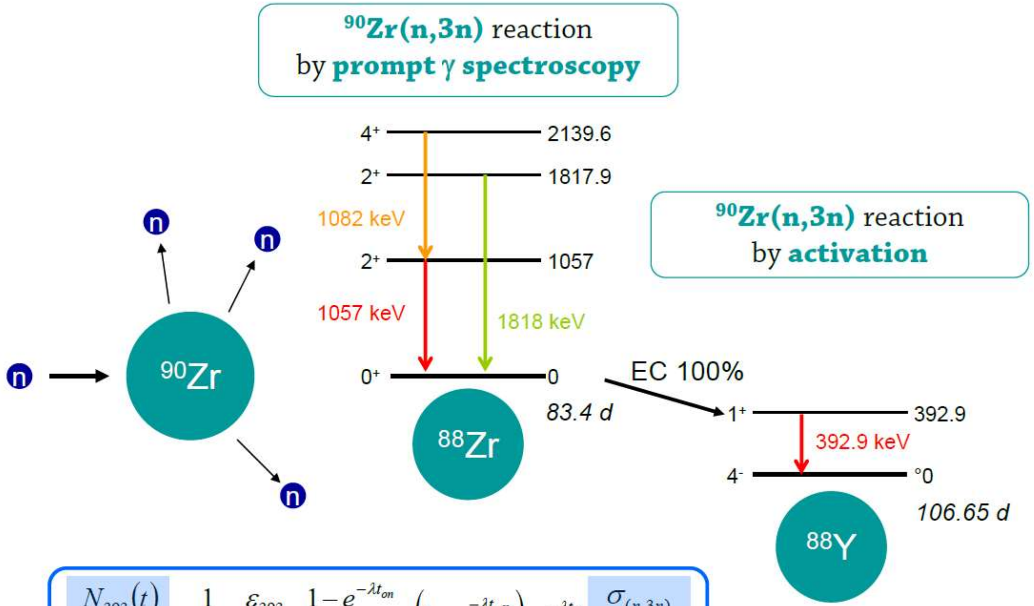
- Neutron induced reactions studies :
  - LoI_13 : Study of pre-equilibrium process in (n,xn) reaction, *X. Ledoux*
  - LoI_14 : Comparison between activation and prompt spectroscopy as means of (n,xn) cross section measurements, *M. Kerveno*
  - LoI_20 : Direct measurement of (n,xn) reaction cross sections on ^{239}Pu, *G. Bélier*
  - LoI_21 : Light-ion production studies with Medley, *S. Pomp*
  - SCALP - Scintillating ionization Chamber for ALpha particle Production in neutron induced reaction, G. Lehaut
- Fission :
  - LoI_15 : Fission fragment distributions and neutron multiplicities, D. Doré
  - LoI_22 : Fission fragment angular distribution and fission cross section measurements relative to elastic np scattering with Medley, S. Pomp
  - LoI_28 : Study of the fission process and fission cross-section measurements, G. Bélier
  - Measurements of prompt fission neutron energy spectra for fast neutron induced fission on major and minor actinides, A. Sardet
  - 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 :
  - LoI_16 : Proton and deuteron induced activation reactions, *P. Bem*
  - LoI_24 : Neutron-induced activations reactions, A. Klix
  - Measurement of cross-sections of deuteron-induced reactions on Ni and Zn, J. Grinyer
- Biology :
  - LoI_23 : Response of Mammalian cells to neutron exposure, *C. Hellweg*
  - R&D for the production of radioisotopes for medical applications at NFS, G. De France
  - Investigation of 211At and 64Cu medical radioisotope production at NFS, J. Grinyer
- Detector development :
  - LoI_29 : Neutron spectrometer characterization for LMJ project, *B. Rossé*
  - Characterization of neutron signal in Si-CsI telescope and measurement of the absolute neutron detection efficiency, E. Bonnet

(n,xnγ) cross section measurement at NFS (LoI-14)

The (n,xnγ) cross-section measurements are used to extract (n,xn) cross section-> need of theoretical model

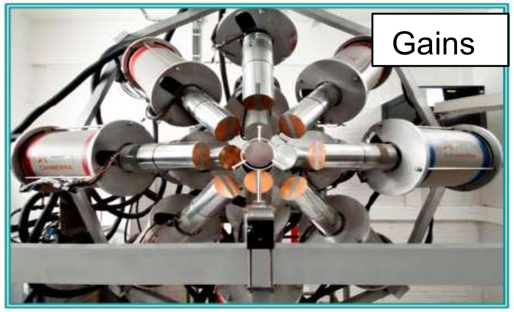
At NFS the $^{90}Zr(n,3n)$ cross-section can be measured by prompt γ spectroscopy and by activation technique at the same time →validation of the theoretical models

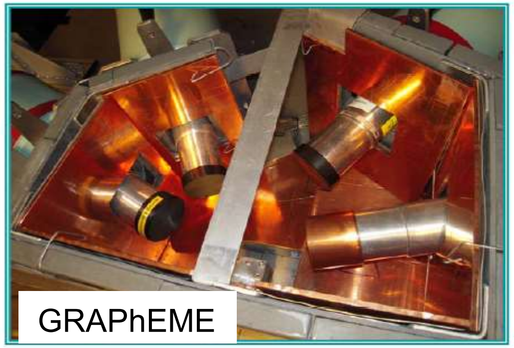




$$\frac{N_{393}(t)}{N_{1057}(t)} = \frac{1}{t_{on}} \cdot \frac{\varepsilon_{393}}{\varepsilon_{1057}} \cdot \frac{1-e^{-\lambda t_{on}}}{\lambda} \cdot \left(1-e^{-\lambda t_{off}}\right) \cdot e^{-\lambda t_d} \cdot \frac{\sigma_{(n,3n)}}{\sigma_{(n,3n\gamma)}}$$

Quasi-mono-energetic neutrons from 26 to 32 MeV





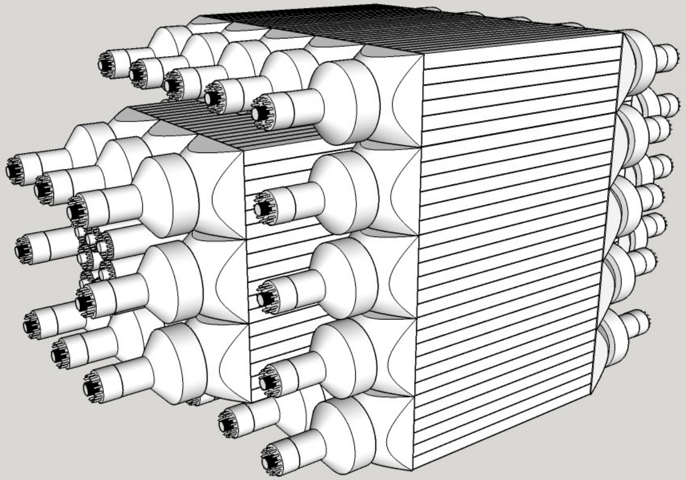
The other (n,xn) cross-sections will be measured in following experiments

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

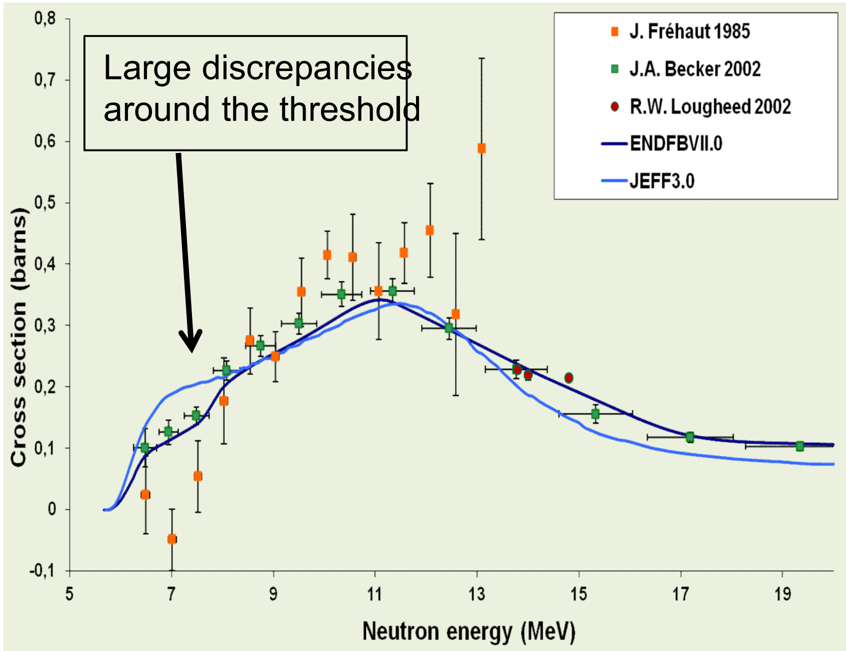
Spokesperson : G. Bélier, CEA-DAM-DIF

- (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)

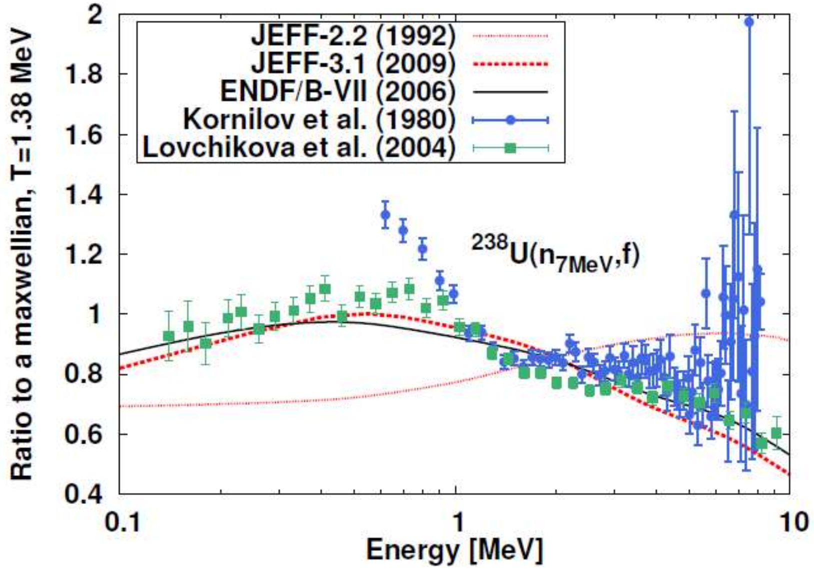


E713 :Prompt fission neutron spectra measurement in neutron induced fission reactions

Spokesperson : B. Laurent, CEA-DAM-DIF

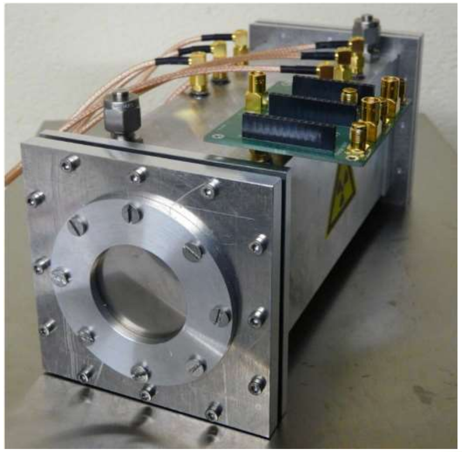
- Important in many applications :
  - -Understanding of the fission process
  - - Accuracy of nuclear criticality calculation (conventional and advance reactors, non-proliferation applications)
  - -Theoretical description of PFNS difficult
- Few experimental data
- Discrepancies between measurements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

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

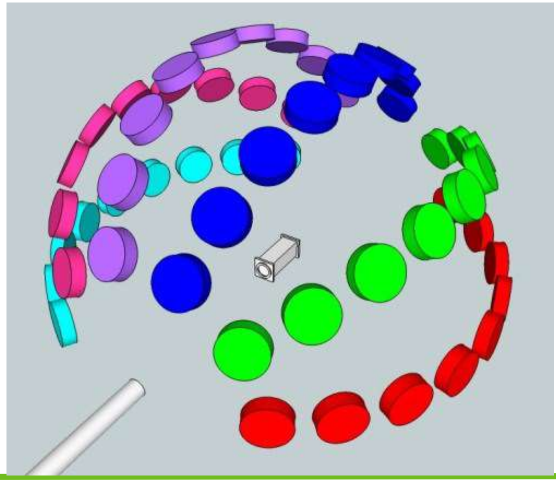


Experimental technique :

Fission chamber (370 mg of U238)



Array of 50 neutrons detectors



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

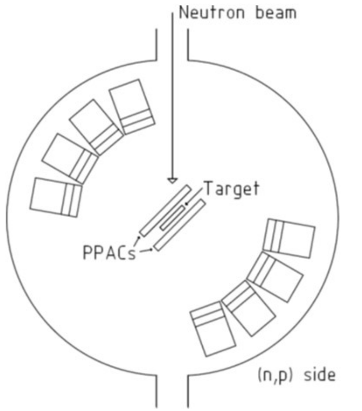
Next step :
n + ^{239}Pu
pulsed beam

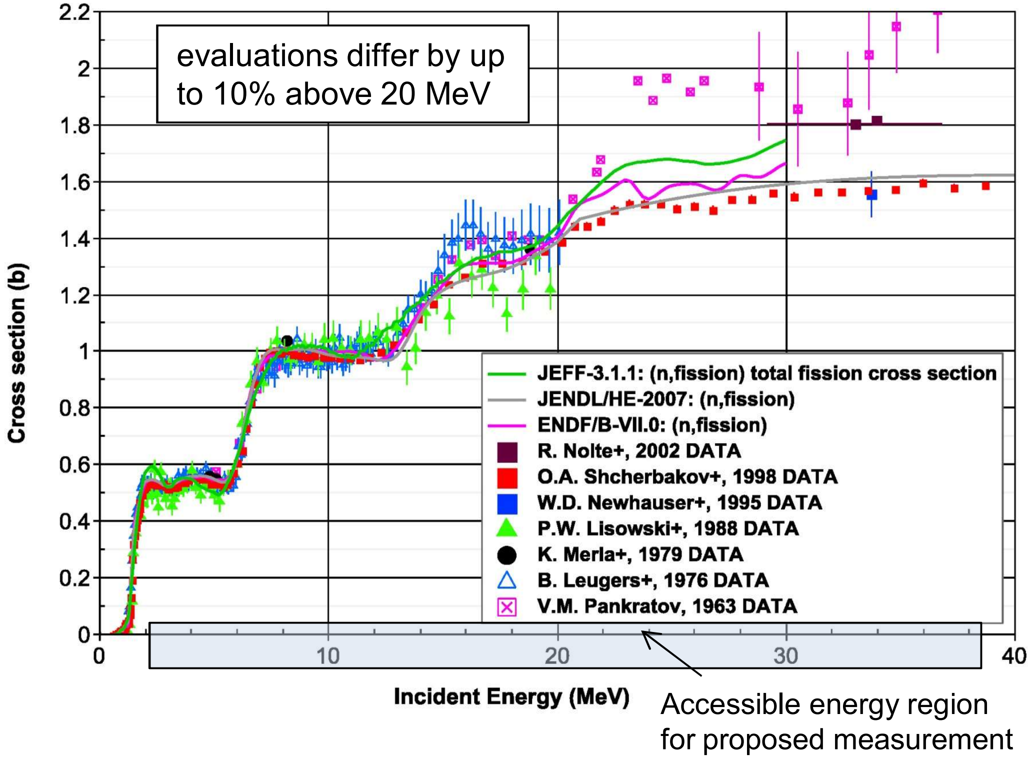
Fission fragment angular distribution and fission cross section measurements relative to elastic *np* scattering with Medley (LoI-21)

- Necessity of improving the quality of the standards (*A.D. Carlson, Metrologia **48**, S328, 2011*).
- Theoretical understanding of the fission process
- Measuring the behaviour of the anisotropy where (n,nf), (n,2nf) and (n,3nf) channels open up will allow to test model calculations for the transition states.

Proposed method:

Measurement of cross sections and angular distributions for ^{238}U(n,f) using recoil protons from the H(n,n) reaction for normalization.





- MEDLEY detector
- PPAC detectors for fast ToF timing for neutron energy measurement.
- Sandwich target: ^{238}U-CH_2-^{238}U for measurement relative to the *np* cross section.

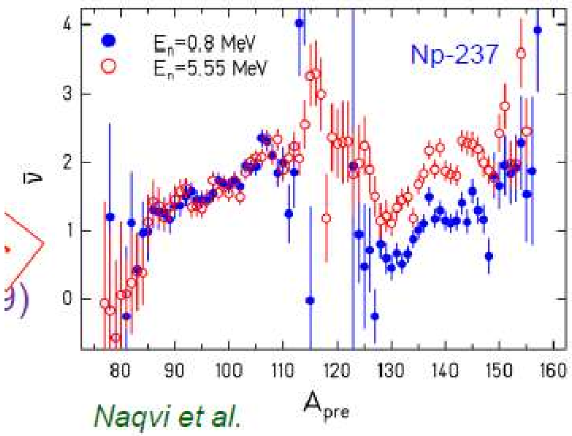
FALSTAFF (LoI 15)

Spokesperson: D. Doré (CEA/IRFU)

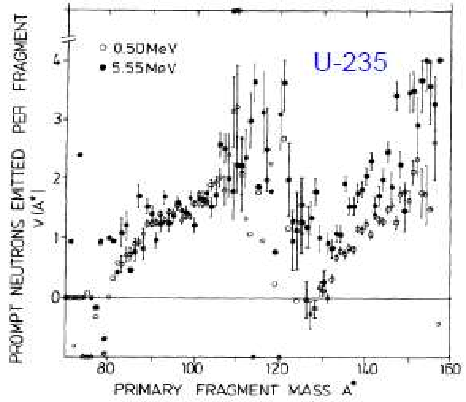
FALSTAFF : Four Arm cLover for the Study of Actinide Fission Fragments

Perform experiments in the fast domain to characterize actinide fission fragments

- Neutron Sawtooth Curve
- Important piece of information about scission
  - Excitation energy sharing
  - Shell effects
  - Energy balance



Naqvi et al.



Müeller et al.

Many models exist but not predictive enough

Actinides to study:
$^{235,238}U$, ^{239}Pu, ^{237}Np, ^{232}Th, ^{233}U

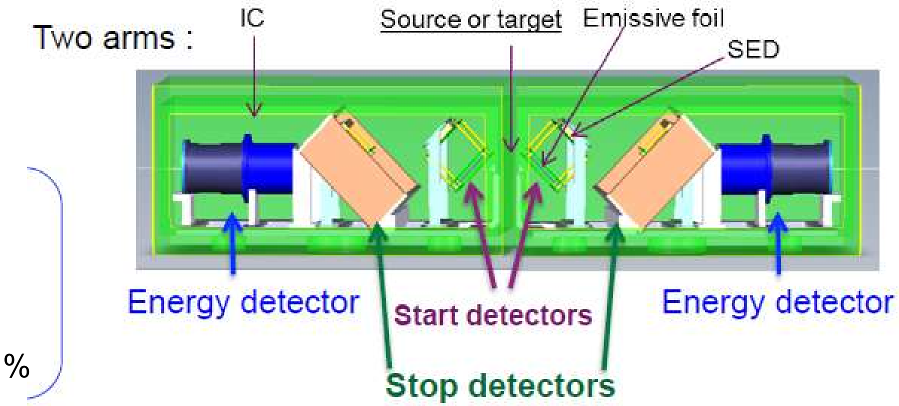
Detection of fragments in coincidence

Charge

Kinetic energy

Post-masses (after n evap) → EV method good energy resolution 1 %

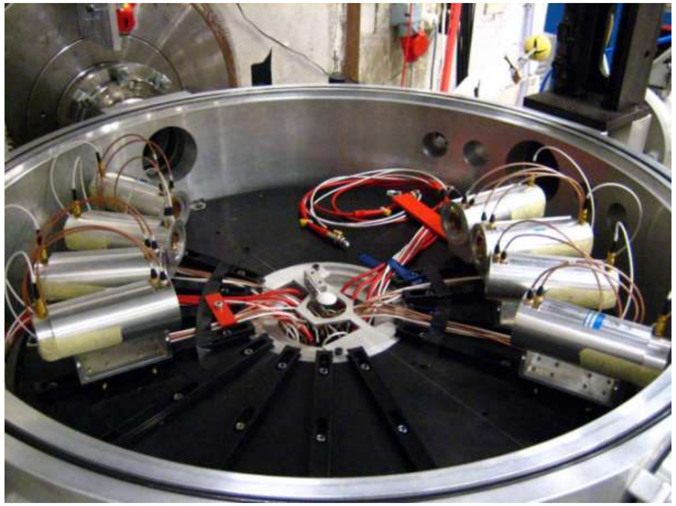
Pre-masses (before n evap) → 2V method TOF measurement time resolution < 150ps

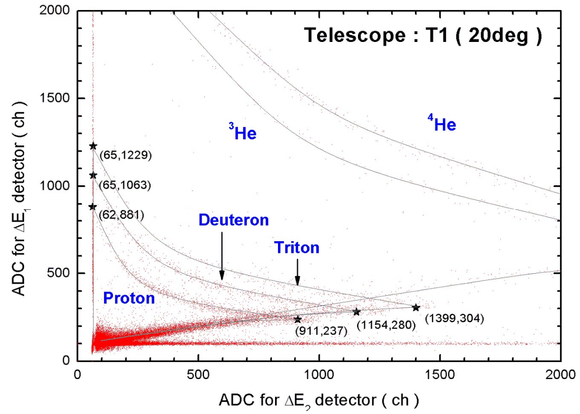


E721:LIONS - Light-Ion Production Studies with Medley at the NFS facility

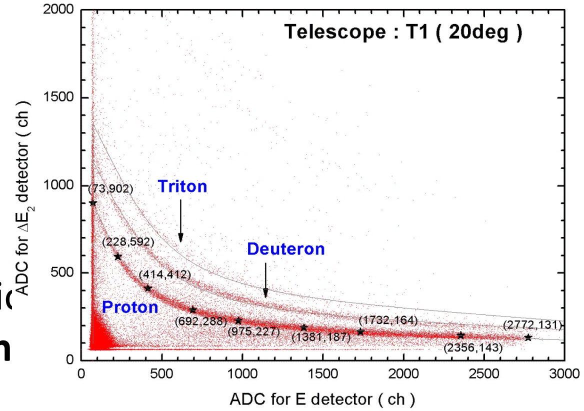
Spokesperson: A. Prokofiev (Uppsala university)

- 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 sectic
Can be used to measure **neutron**



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

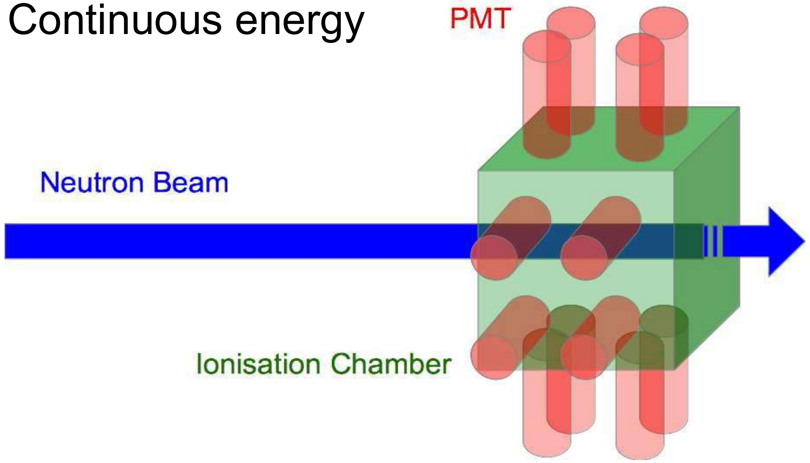
Cross section measurement of $^{16}O(n,\alpha)^{13}C$ Scintillating ionization Chamber for Alpha particle Production in neutron induced reactions.

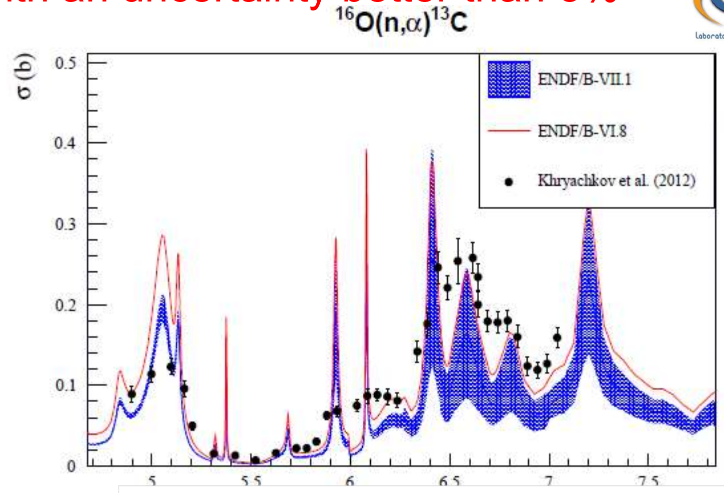
Goals : XS measurement in 7MeV-20MeV range with an uncertainty better than 5%

Active target

Scintillating Ionization chamber

Continuous energy





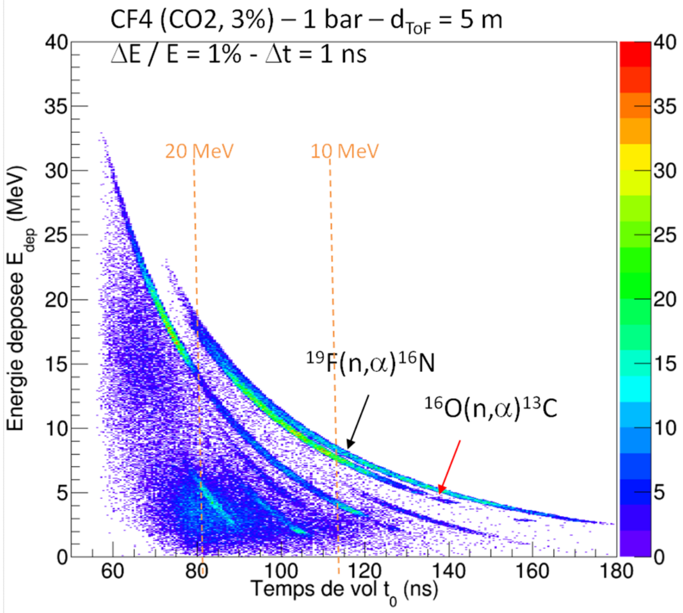
Target composition :

Oxygen → CO_2

Scintillation → CF_4

Normalization → ^3He

→ A lot of Channels to distinguish →

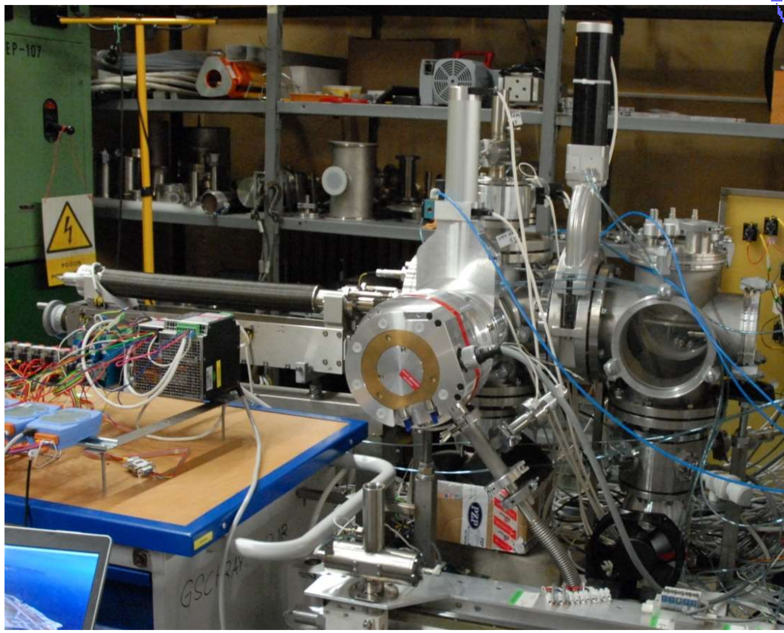


E714: Excitation functions of short-lived isotopes in proton-induced reactions on ^{nat}Fe

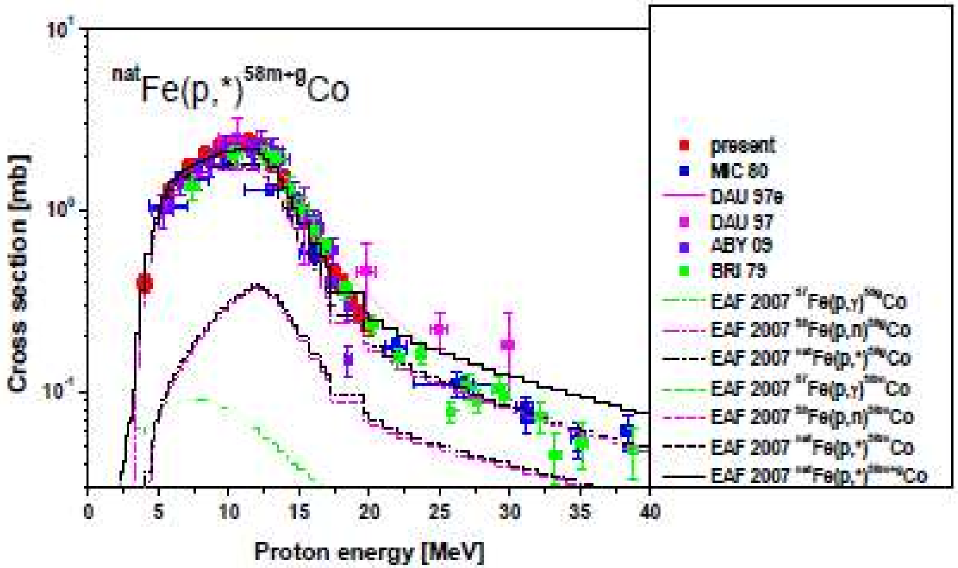
Spokesperson : E. Simeckova, NPI, Rez

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



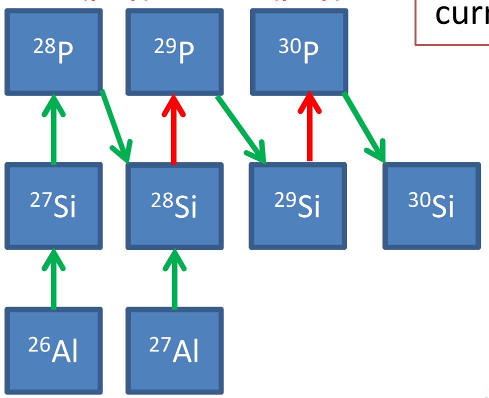
Other short-lived isotopes measured:

- ^{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

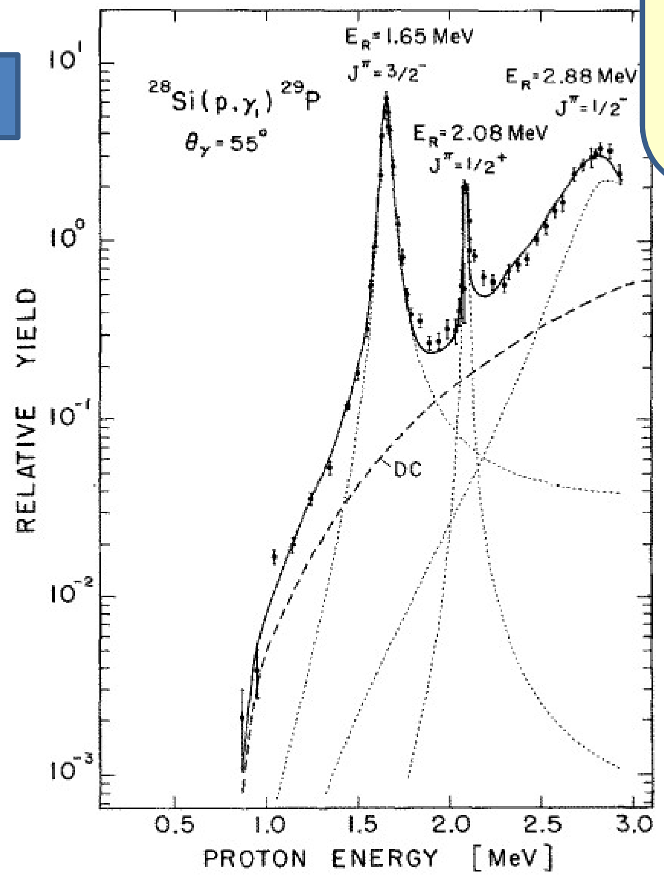
F. Boulay, B. Bastin, J. Mrazek, GANIL, IPN Orsay, CSNSM, IPN Lyon, JYFL, Instituto de Fisica Corpuscular (Valencia) , NCSR "Demokritos" and Subat

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



Hot CNO cycle

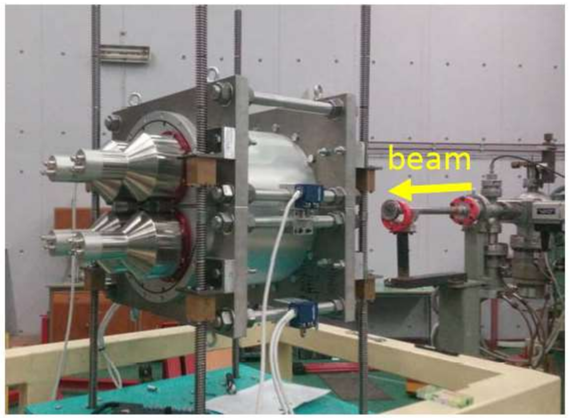
Necessity to constrain the reaction rates $^{28}Si(p,\gamma)^{29}P$ and $^{29}Si(p,\gamma)^{30}P$ which have currently 21 % and 30 % uncertainties.



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

Energy of interest :
Gamov window



Radioisotopes for medical applications

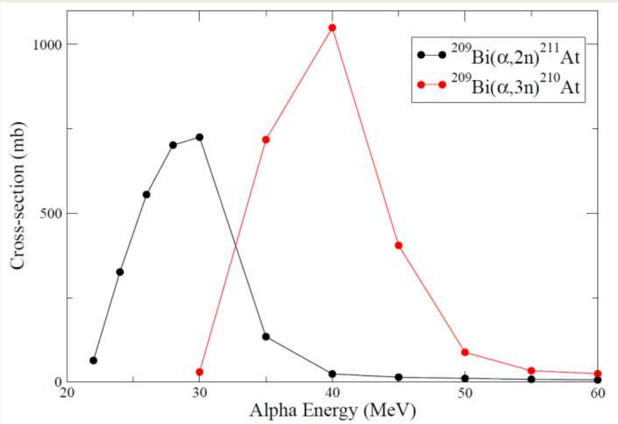
- Study of alternative route production of several radioisotopes used in medical applications
- SPIRAL-2 :
  - alpha, HI beams
  - tunable energy
- Production of alpha emitters

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

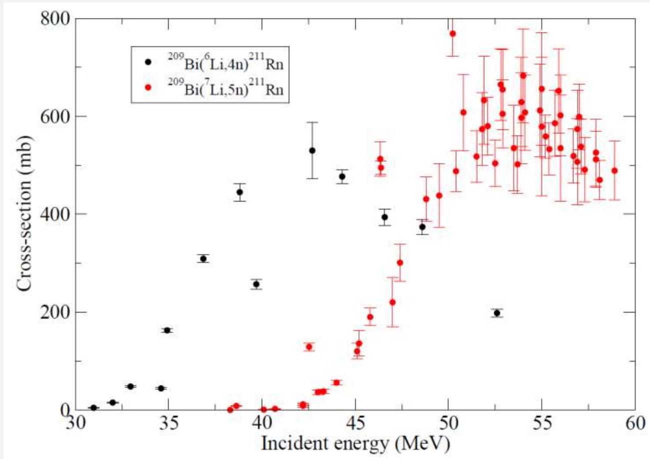


^{209}Bi(^{6}Li,4n)^{211}Rn or ^{209}Bi(^{7}Li,5n)^{211}Rn => Generator

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

Additional transportation/separation time

Less ^{210}Po

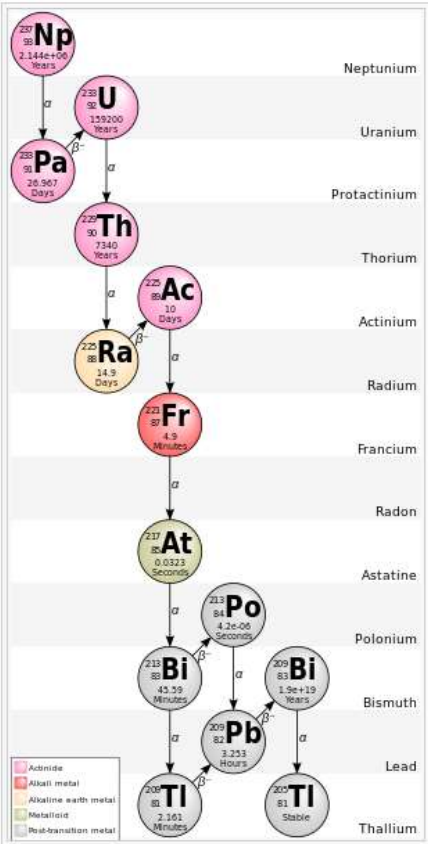


Collaboration Caen-Nantes (with ARRONAX)

^{213}Bi Production ways

^{213}Bi is in the decay chain of ^{225}Ac produced by various means:

- From aged ^{233}U (limited access)
- ^{226}Ra target irradiation
  - High flux reactor → large yield of ^{228}Th → shielding issue
  - Direct reactions (p,2n) or (γ,n)
  - Continuous production of ^{226}Ra = challenging
- ^{232}Th target irradiation by high energy protons → spallation reactions
- Exploration a new production method of ^{213}Bi via the α+^{232}Th reaction



Production yields estimations

- MCNPX+FISPACT II vs. PHITS

200 μAe 80 MeV α beam on ^{232}Th target
24 hours irradiation + 24 hours cooling time

  - **Huge** disagreement observed e.g. in specific activity of ^{224}Ra:

	MCNPX+FISPACT II	**PHITS**
^{224}Ra	3.56×10^{8} Bq/g	5.34×10^{6} Bq/g

  - Originating from input **cross sections** taken from **calculated** (TALYS) databases (complemented with data when available)
  - **No data** available for this mass region in α + ^{232}Th

⇨ **Production cross section** of several isotopes of potentially great interest for TAT (e.g. 213Bi via 225Ac and 225Ra routes)
⇨ Measure for the first time **cross-sections for nuclear data** purposes and check validity of calculated databases

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
Fission	E713	Prompt fission neutron spectra measurement in neutron induced fission reactions	B. Laurent, CEA-DAM
	E718	Fission fragment angular distribution and fission cross section measurements relative to elastic NP scattering at 30 MeV	D. Tarrio, Uppsala University
Fusion		Excitation functions of short-lived isotopes in proton induced reactions on ^{nat}Fe	E. Simeckova, NPI, Rez
	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 $^{28}Si(p,\gamma)^{29}P$ and $^{29}Si(p,\gamma)^{30}P$ 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

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

NFS – Scientific program definition

Memorandum of Understanding

Partners

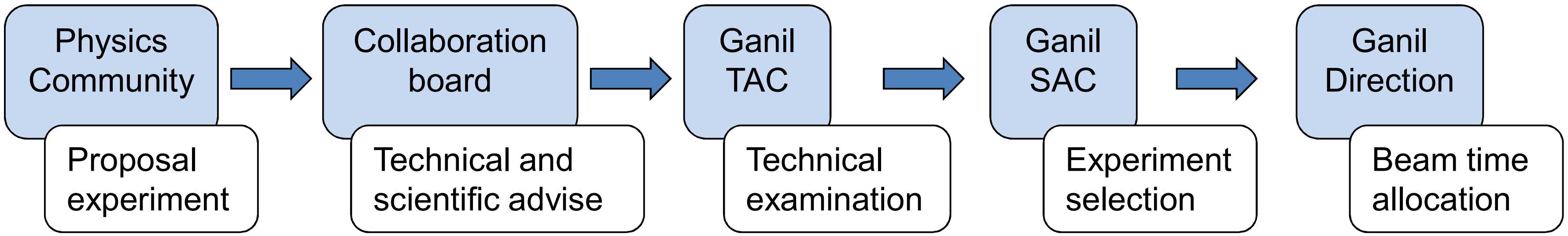
- CEA DAM DIF
- IN2P3
- Ganil
- CEA DSM IRFU
- CEA DEN
- NPI
- KIT
- Uppsala University

Steering committee :

- M. Lewitowicz (GANIL)
- F. Farget (CNRS/IN2P3)
- E. Bauge (CEA/DAM)
- F. Sabatié (CEA/DSM/Irfu)
- O. Serot (CEA/DEN)
- J. Mrazek (NPI)
- U. Fisher (KIT)
- A. Prokofiev (Uppsala University)

Collaboration board :

- X. Ledoux (GANIL
- P. Dessagne (CNRS/IN2P3)
- B. Bélier (CEA/DAM/DIF)
- D. Doré (CEA/DSM/Irfu)
- O. Sérot
- J. Mrazek (NPI)
- U. Fischer (KIT)
- S. Pomp (Uppsala University)



Summary

NFS:

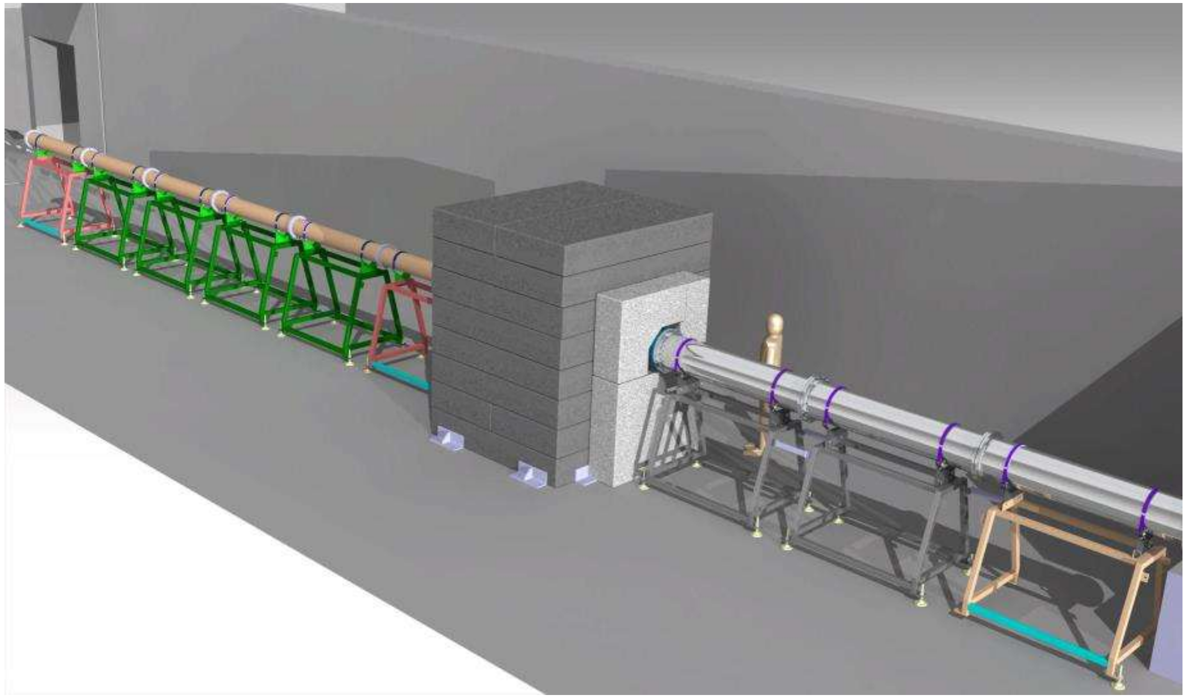
- White and quasi-monokinetic spectra in the 1-40 MeV range
- Neutron beams with high flux and good energy resolution
- Complementary to the existing n-tof facilities
- Measurements by activation reactions (n, p, d)

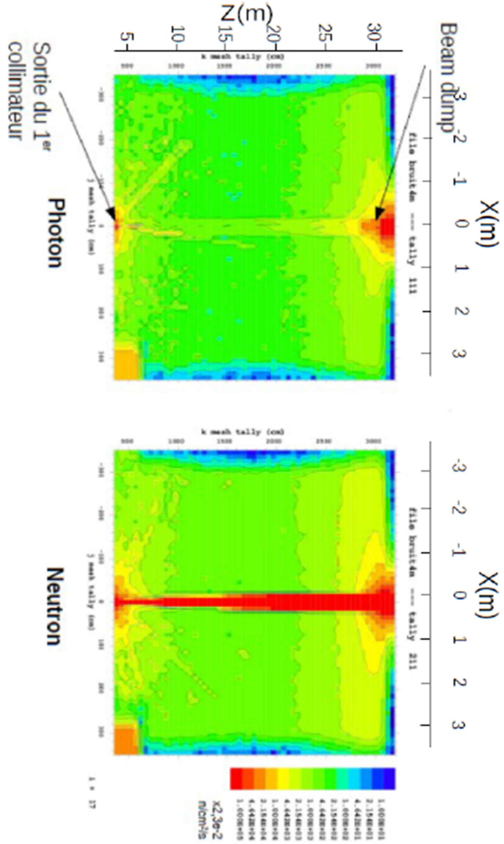
Day-One experiments:

- 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

The second collimator and the neutron beam line

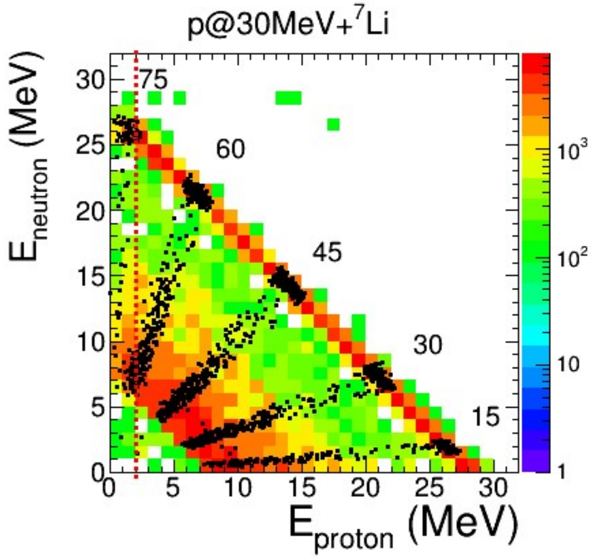
- For experiment at long distance, a 2ND collimator is needed for:
  - resizing the neutron beam
  - shielding detectors from background
- Beam line under construction at IPHC Strasbourg (Delivery in June 2017)
- Vacuum system delivered
- Collimator design and construction realized by IPHC Strasbourg





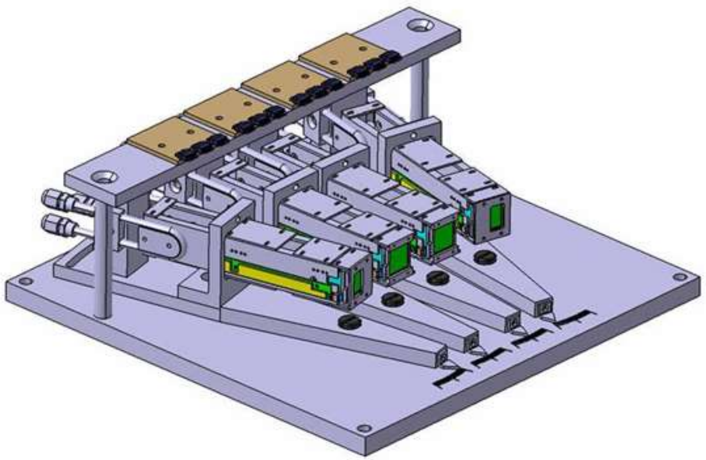
Spokespersons: E. Bonnet, N Le Neindre (LPC CAEN)

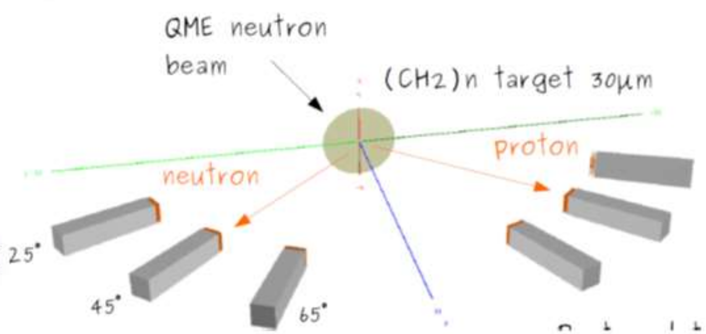
FAZIETO



Method : associated particle :

- absolute efficiency measurement
- no time structure required
- no flux measurement required





NFS configuration 2018