HiSPAlis Neutron Source: línea de neutrones del CNA.

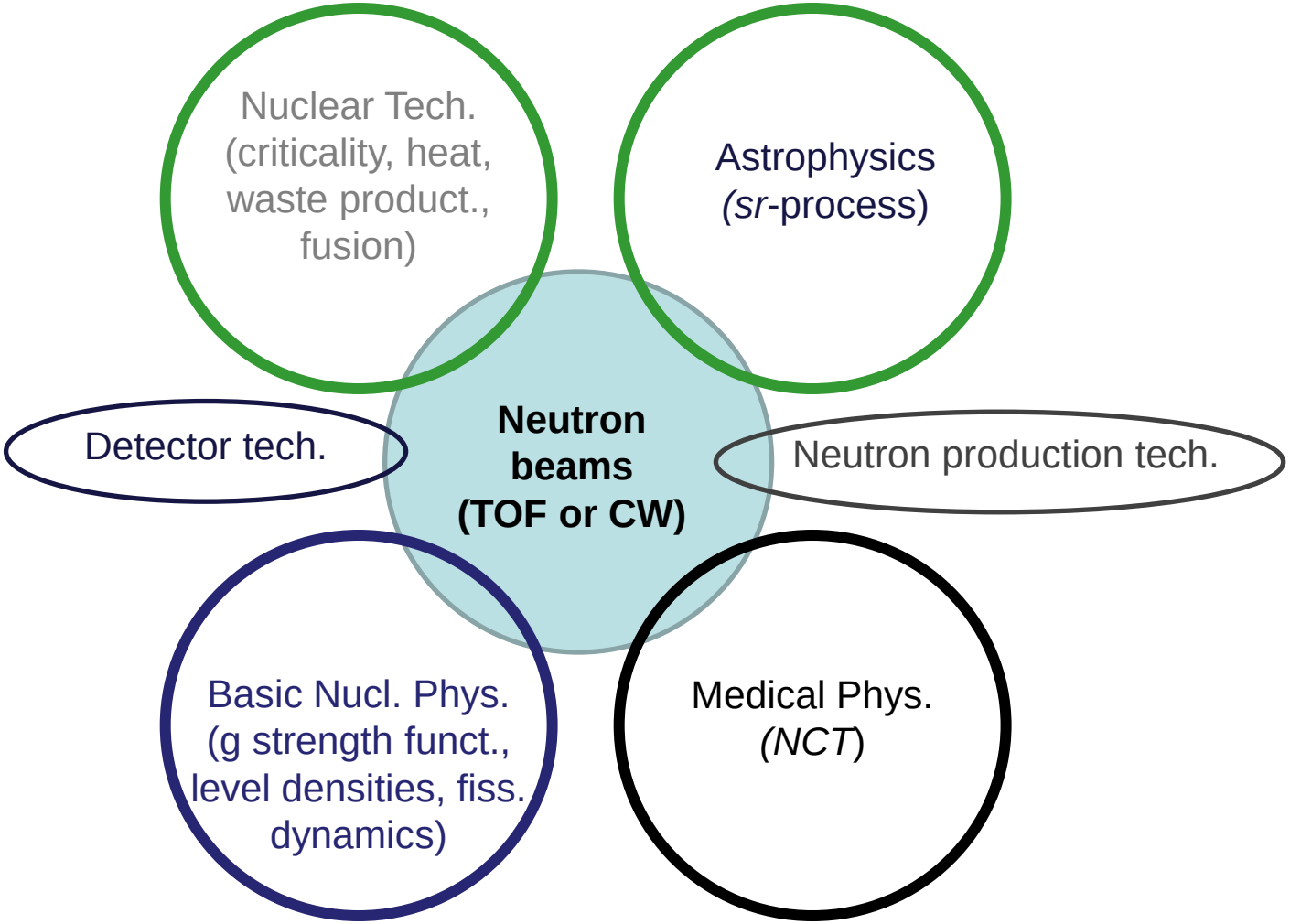
Javier Praena,

Begoña Fernández, Miguel Macías, Juan Ángel Labrador

Summary

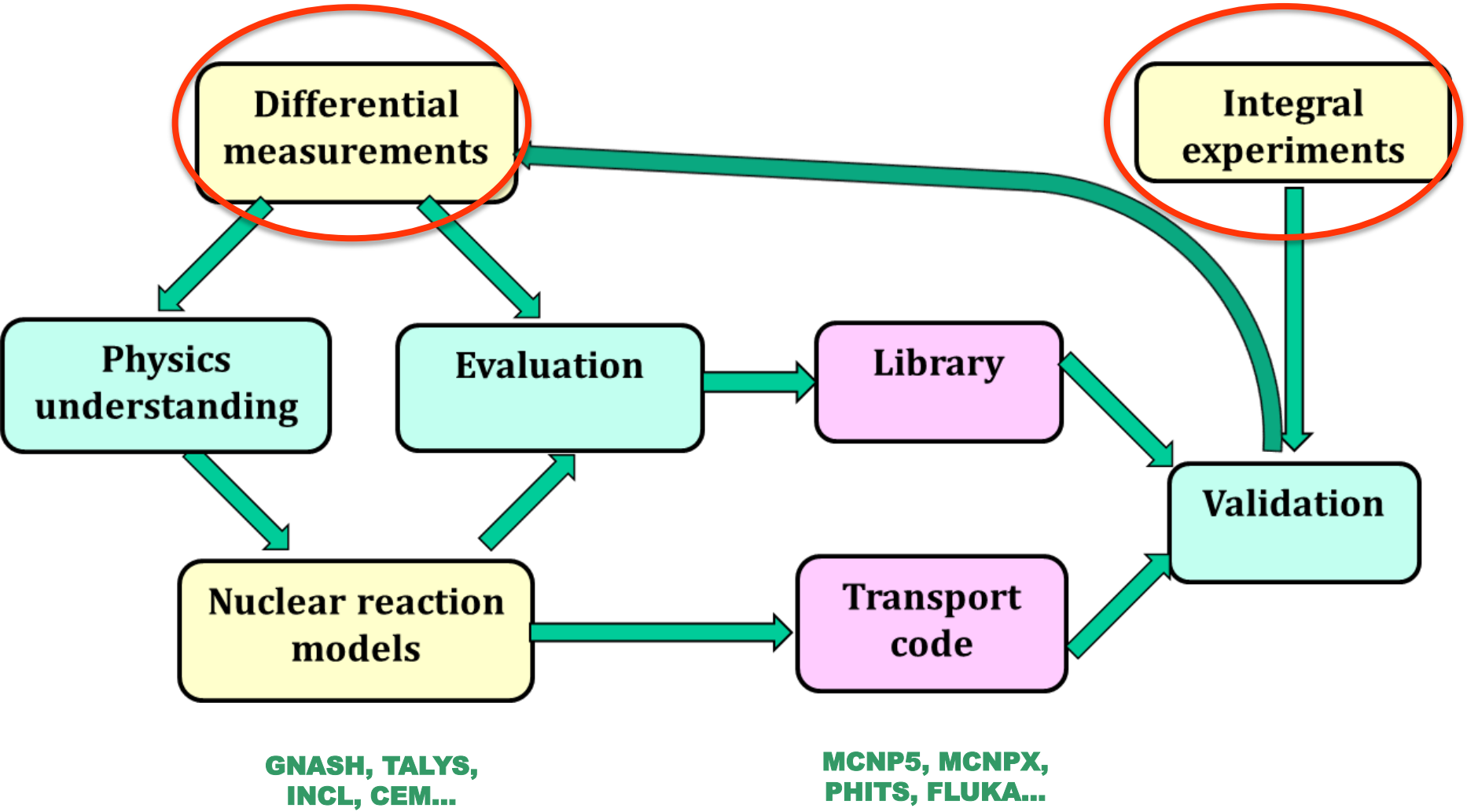
- **Motivations.**
- **Accelerator-based neutron sources: European and national framework.**
- **CNA as neutron facility from 2011-2015: continuous beam encompassing a large energy range and applications.**
- **CNA as neutron time-of-flight facility: 2016.**
- **Description of the CNA chopper/buncher for pulsing and time compression of the charge particle beam.**
- **Possible TOF measurements.**

Different applications depending on the neutron beam



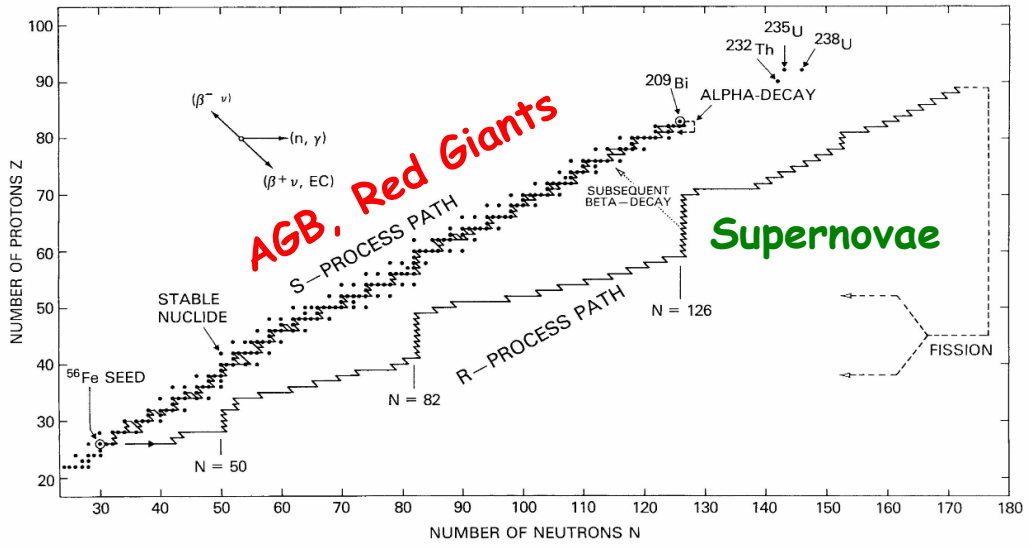
HiSPANoS can deliver neutron beams that encompasses all these fields.

Why TOF and Integral measurements? Nuclear Data.

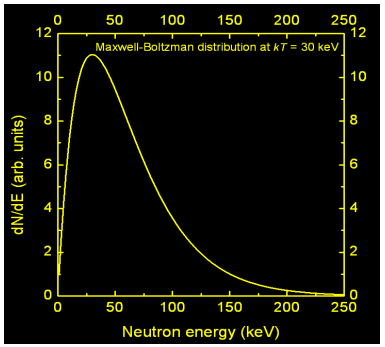


International Atomic Energy Agency
Nuclear Data Services
Секция Ядерных Данных МАГАТЭ

Why TOF and Integral measurements? Astrophysics.



The stellar neutron spectrum follows a Maxwell-Boltzmann distribution of velocities with its maximum at kT (in E) corresponding to the temperature of the shell of the star

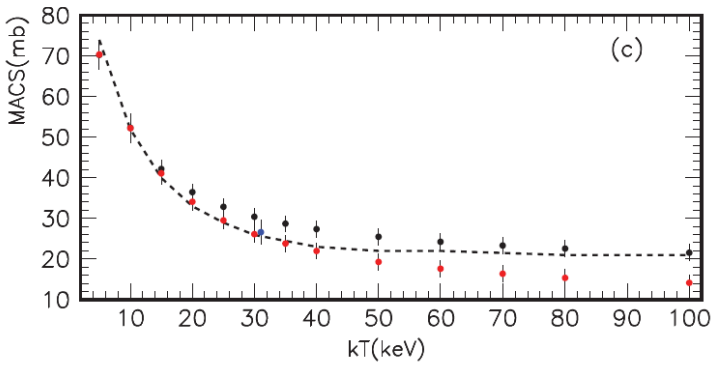


$$MACS \equiv \langle \sigma \rangle = \frac{\langle \sigma \cdot v \rangle_A}{v_T}$$

MACS is the important cross-section

PHYSICAL REVIEW C **84**, 015801 (2011)

Neutron capture on ^{94}Zr: Resonance parameters and Maxwellian-averaged cross sections



Time-of-flight:

The differential measurement allows obtaining the MACS as function of the kT.

Integral (CW):

The integral measurement allows obtaining the MACS at a certain kT in case the neutron spectrum could be corrected to a maxwellian.

Accelerator-based neutron sources: Europe.

3.1. MONOENERGETIC AND MAXWELL SPECTRUM NEUTRON BEAMS (< 5 MEV)

Joint Research Centre, European Commission	Nuclear Research with Mono-Energetic NEUTRONS AT the JRC MONNET Facility	→ **TOF and CW. Decommissioned (New Tandem 2018)** Fission, inelastic scattering, calibration, spectrometry.
Physikalisch-Technische Bundesanstalt, Germany	Neutron beams and neutron metrology at the PTB ion accelerator facility PIAF and at the IThemba LABS neutron beam facility	→ **TOF and CW. Decommissioned (VdG)** Cyclotron with high energy spread
National Technical University of Athens, Greece	The neutron facility at the Athens Tandem Accelerator NCSR "Demokritos" and NTUA Research Activities	→ Fission. D(d,n) and T(d,n) reactions. Li(p,n) coming. **No TOF**, only CW.
EURATOM, U.K.	Nuclear Data Capabilities at the ASP Neutron Generator	→ 14 MeV T(d,n) reaction. Ed=300 keV **No TOF**, only CW.

3.2. ION-INDUCED QUASI-MONOENERGETIC AND WHITE NEUTRON BEAMS

Uppsala University, Sweden	High-energy Neutron Beam Facilities and Nuclear Data Measurements at The Svedberg Laboratory	→ Cyclotron 20-180 MeV proton beam. TOF. QMN (quasi monoenergetic neutron beam) Anita (Atmospheric-like Neutrons from thIck Target)
Nuclear Physics Institute of ASCR PRI, Czech Republic	Fast neutron generators at Nuclear Physics Institute Řež	→ Cyclotron 6-38 MeV. **No TOF**, only CW. Quasi monoenergetic neutron beams.

3.3. ELECTRON-INDUCED WHITE SPECTRUM NEUTRON BEAMS

Joint Research Centre, European Commission	Nuclear Data Measurements at GELINA	→ 10 TOF beam lines. From thermal to fast neutrons.
Institute of Radiation Physics, Germany	The NELBE Neutron Time-of-Flight Facility	→ TOF. 0.2-10 MeV neutrons. Nuclear transmutation.

IAEA International Atomic Energy Agency **IAEA-TECDOC-1743, 2014**

Accelerator-based neutron sources: Europe.

3.4. SPALLATION PROTON-INDUCED (> 200 MEV) WHITE SPECTRUM NEUTRON BEAMS

CERN, Switzerland	Nuclear Data experimental program at CERN for reactor physics

→ **2 TOF beam lines. From thermal to fast neutrons. Capture and fission measurements, (n,alpha).**

3.5. NEUTRON BEAMS FROM INVERSE KINEMATIC REACTIONS

Joint Research Centre, European Commission	Nuclear Research with Quasi Mono-Energetic Neutrons at the IPNO LICORNE Facility

Decommissioned (New Tandem 2018)

LENOS (Legnaro Neutron Source)
Laboratori Nazionali di Legnaro (INFN, Padova)

→ **CN accelerator -> VdG 7 MV**
Recently developed TOF system based on a former pulsing/bunching system at 3 MHz

The AMANDE facility

("Accelerator for metrology and neutron applications for external dosimetry"), commissioned in 2005, produces monoenergetic neutron reference fields, with two objectives:

1) define national fluence references (i.e. in terms of the number of neutrons per surface area unit) or dose equivalents references (ambient or personal) related to neutrons,
2) perform various types of calibration on radiation protection instruments (routine calibration, calibration in "realistic" fields, determination of the energy variation with neutron energy).

IAEA International Atomic Energy Agency **IAEA-TECDOC-1743, 2014**

Spanish neutron community at CERN.

The Spanish neutron community focused on nuclear data for nuclear technology applications belongs to the n_TOF-CERN collaboration and also performed experiments in other facilities

There are 5+1 Spanish n_TOF-CERN groups: CIETMAT, IFIC, USC, UPC, US and recently UGR.

In 2009, US-CNA had the purpose to develop a neutron source at CNA.

Centro Nacional Aceleradores: Tandem Pelletron 3MV.

- High stabiblity of the accelerator for V>500 keV.
- Continuous Wave mode funtioning (integral measurements)
- 3 sources: Alphatross, Duoplasmatron and SNICS-II.
- SNICS-II can deliver whatever ion beam.
- For neutron production, SINCS-II can deliver protons and deuterons with a current higher of 50 uA at source.
- Only 10% of the current is lost from tank transmission, analyzing magnet and swithcing magnet. CNA staff has performed a good job in beam optics.

What have we done since 2009 at HisPANoS?

- We have performed a radioprotection study by means of MNCPX simulations in order to check the possible activation or damage of the other beam lines and instruments.

- We have carried out experiments that cover a large energy range:
  - Thermal neutrons (meV) : ^{7}Li(p,n) at Ep=1912 keV and moderation.
  - Epithermal neutrons (keV): ^{7}Li(p,n).
  - Fast neutrons (<8MeV): D(d,n).

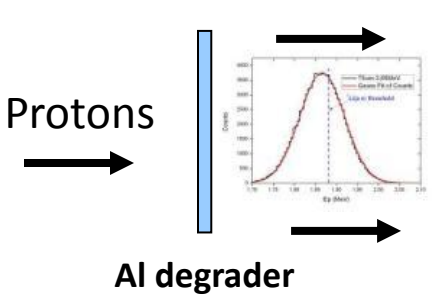
- We have developed a system for neutron motorization based on the dosimetry history of the produced neutrons and the current history of the charge particle beam on the neutron target production.

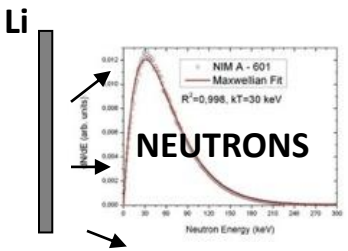
- We have developed a system (HPGe) for neutron flux determination based on the activation of foils of elements with well-known cross-section and the Be7 production.

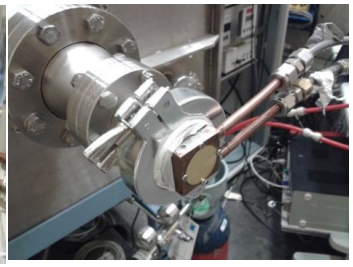
Epithermal neutrons (keV): astrofísica. ^{7}Li(p,n) reaction.

At CNA we generate neutron spectra following a maxwellian distribution, therefore the MACS can be directly measurement by activation.

Other methods need to correct for the neutron spectrum and for this correction the assumption of the cross-section is mandatory.







Measurement of the MACS of ^{159}Tb(n,γ) at $kT = 30$ keV by Activation

J. Praena,[1,2,*] P.F. Mastinu,[3] M. Pignatari,[4] J.M. Quesada,[1] R. Capote,[5] and Y. Morilla[1,2]

TABLE I. Summary of corrections and uncertainties (upper panel). The MACS of ^{159}Tb(n,γ) at $kT = 30$ keV vs experimental data and selected evaluations (lower panel).

Corrections	Value ± Uncertainty(%)
Counting statistics	– ± 0.1
Au self-absorption [9],[23]	0.988 ± 0.2
Tb self-absorption [24]	0.956 ± 0.4
I_γ (Au) [25]	95.6 ± 0.2
I_γ (Tb) [26]	26.6 ± 0.2
Efficiency HPGe	– ± 5.8
$T_{1/2}$ Au (days) [25]	2.6947 ± 0.1
$T_{1/2}$ Tb (days) [26]	72.3 ± 0.1
Fluence ratio	1.02 ± 0.2
MACS Au reference [11]	(582 ± 1.5) mb
Fitting procedure	– ± 0.1
Total	– ± 8.3
	MACS (mb) at $kT = 30$ keV
This work	2166 ± 181
Bokhovko 1992 [19]	1471 ± 66
Mizumoto 1978 [20]	1800 ± 100
Lépine 1972 [27]	1850 ± 250
Allen 1971 [16]	2200 ± 200
KADoNiS [5]	1580 ± 150
ENDF/B-VII.1 [17, 18]	2080 ± 250

The neutron capture on Tb159 may affect the production of other species as Dy, Ho during the nucleosynthesis in AGB stars.

Especially during the radiative C-13 pocket.

The impact of the measured Tb(n,g) MACS was studied in C-13 pocket conditions, 3Mo star, Z=0.01.

The variation of the MACS only affects the Tb production.

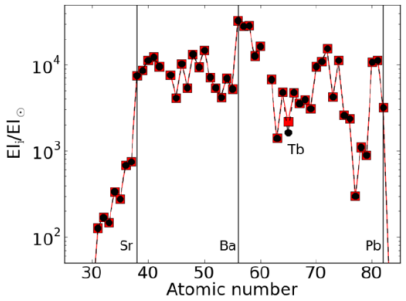


FIG. 3. The *s*-process abundance distributions in the radiative C13-pocket layers of a 3M$_\odot$ star, Z=0.01 [22], after the 5th Third Dredge-Up. The results using our new ^{159}Tb(n,γ) cross section (black circles) are shown in comparison with the results using the previous MACS (red squares).

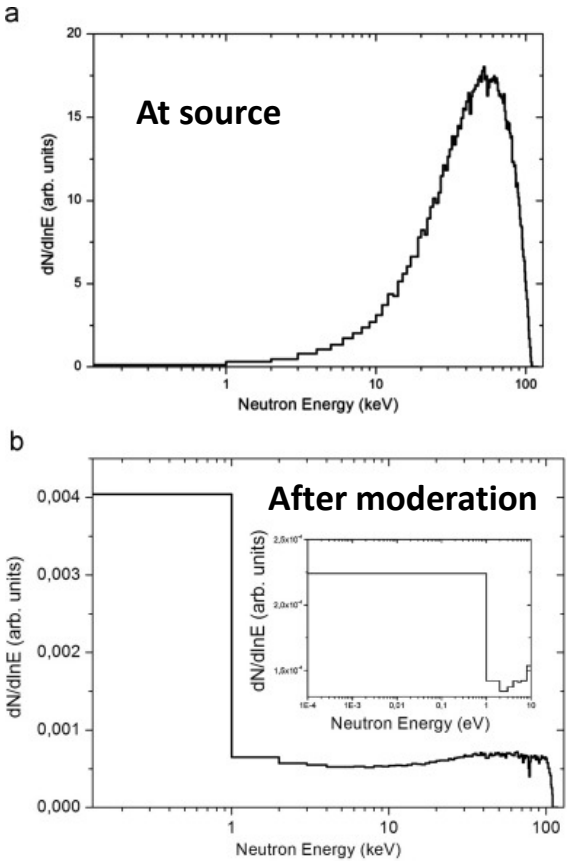
J. Praena *et al.*, NIM A, 727 1-6 (2013)
J. Praena *et al.*, NDS, 120 205-207 (2014).
P. Jiménez *et al.*, PoS (NIC XIII) 057 (2015).

Thermal neutrons (meV-eV): Li(p,n)+moderation

At CNA we generate well-characterized neutron spectrum with the ^{7}Li(p,n) reaction at Ep=1912 keV. Then these neutrons are moderated.

Characterization of the spectrum: MCNP simulations of the setup and the inclusion of the energy-angular neutron distributions from the ^{7}Li(p,n) reaction (experimental confirmation).

Neutron flux is determined by the activation of Au (IAEA standard).

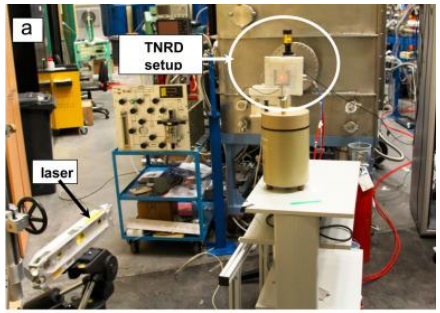


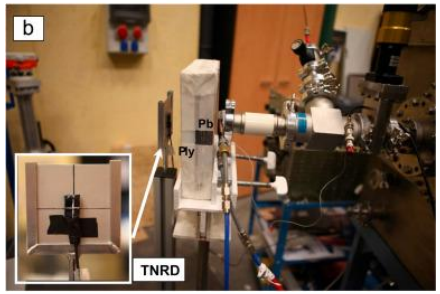
Using a Tandem Pelletron accelerator to produce a thermal neutron beam for detector testing purposes

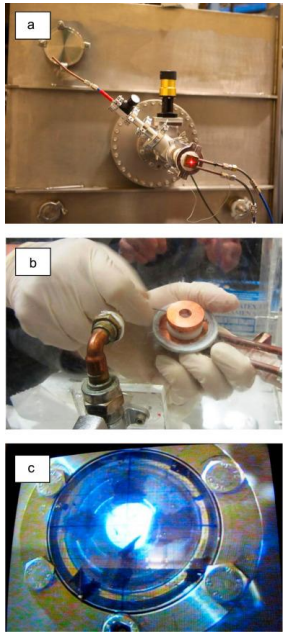
L. Irazola [a,b,*], J. Praena [c,d], B. Fernández [c], M. Macías [c], R. Bedogni [e], J.A. Terrón [b,a], B. Sánchez-Nieto [f], F. Arias de Saavedra [d], I. Porras [d], F. Sánchez-Doblado [a,b]

ESTRO European Society for RADIOTHERAPY & ONCOLOGY
Recommended by ESTRO

Fig. 1 One of the *TNRD* detectors (marked with a white box) and associated six electronics channels.







L. Irazola *et al.*, Applied Radiation and Isotopes 107 (2016) 330-334

Fast neutrons: D(d,n) up to En=8 MeV.

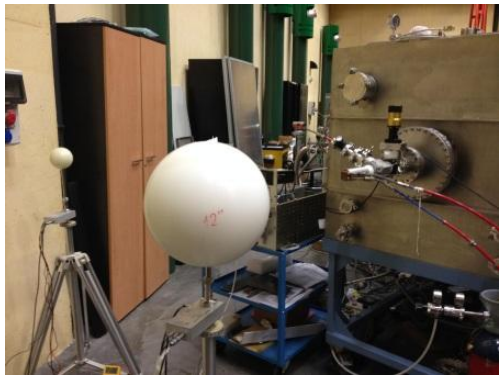
At CNA we generate fast neutron spectra at different energies by means of the d-d reaction.

Thin TiD_2 target is used for the generation of quasi-monoenergetic neutrons.

At present the neutron energy is determined by the well-known reaction kinematics.

Neutron flux can be determined with the activation of Al foils.

Bonner Spheres for neutron spectrometry
Work in progress (2014)
C. Domingo and F. Fernández, UAB



Single Event Upset has been studied for the SRAMs developed in U. Islas Baleares (TEC2011-25017)

S. Bota and D. Malagón

Work in progress (June 2015)

HiSPANoS: funds.

MINISTERIO
DE ECONOMÍA
Y COMPETITIVIDAD

Informe evaluación final — **SE Infraestructuras Científicas y Técnicas y Equipamiento 2013**

Referencia:	**UNSE13-1E-2023**	**Fecha:**	**02/10/2014 09:35:40**
Área:	**FI - Físicas y Ciencias del Espacio/Physics and Space Sci.**		
Sol. Principal:	**Gomez Camacho, Joaquin**		
Título:	**Línea de Neutrones en El Cna**		

Puntuación final

La nueva infraestructura propuesta por el CNA puede dar servicio a un amplio número de grupos de investigación en España (una lista más extensa de la propuesta en la memoria) y cubre una carencia notable dentro del panorama nacional. Por tanto, se apoya su financiación sin ningún atisbo de duda.

We have organized a committe for the follow up of the project: CIEMAT, IFIC, USC, UPB, US and CNA.

HiSPANoS: time-of-flight beam line, chopper and buncher.

CNA http://centro.us.es/cna/esquema_sala_tandem.htm

Neutron energy by Time-Of-Flight (TOF)

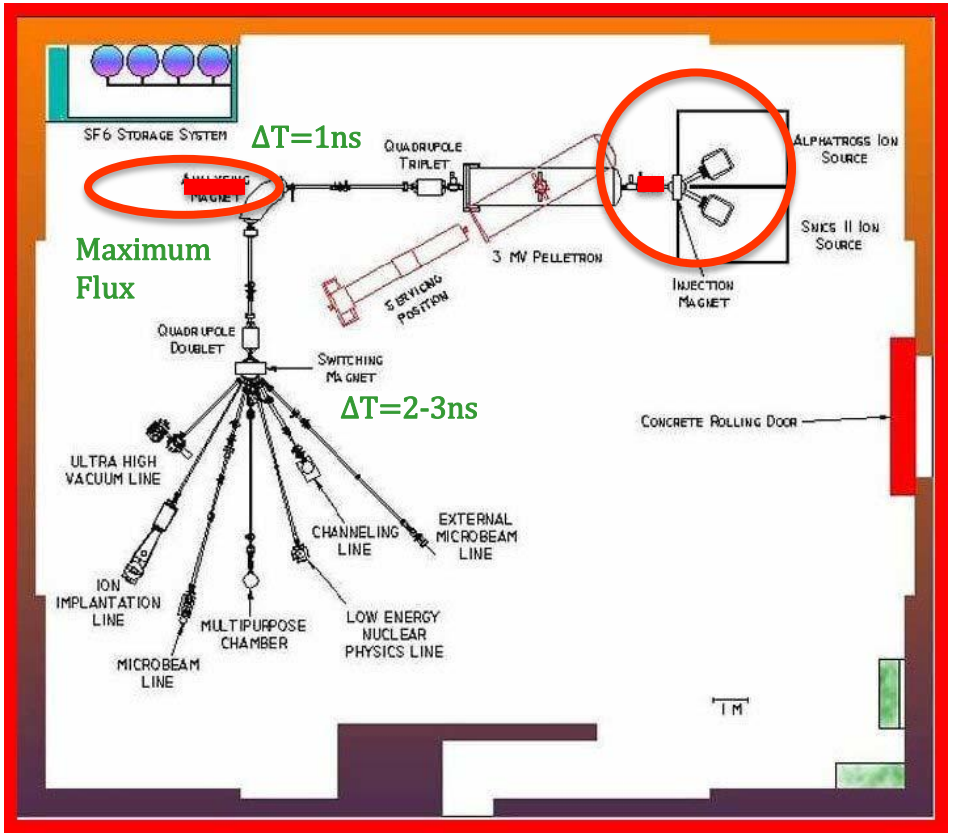
$$E_n = \frac{1}{2} m_n v_n^2 = \frac{1}{2} m_n \left(\frac{L}{t}\right)^2$$

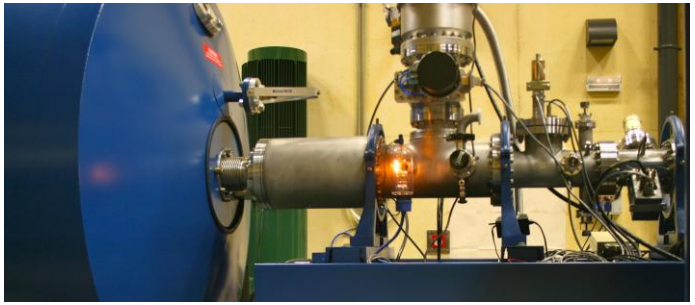
Neutron Flux $\Rightarrow$ L ↘

$$\varphi_n(L) \propto \frac{1}{L^2}$$

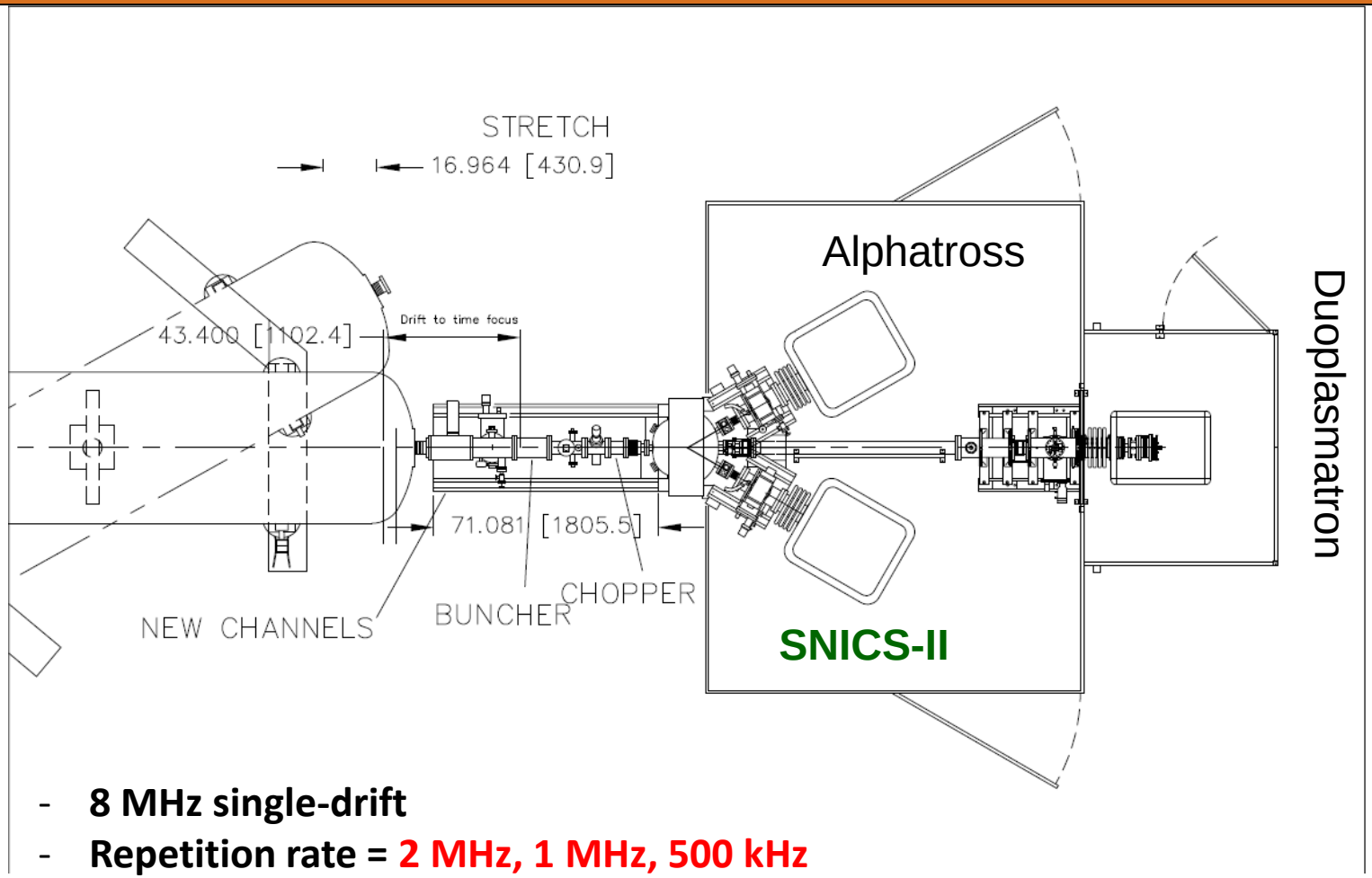
Resolution $\Rightarrow$ L ↗

$$\frac{\Delta E_n}{E_n} = \frac{1}{L}\sqrt{\frac{E_n \Delta T^2}{\alpha} + \Delta L^2}$$



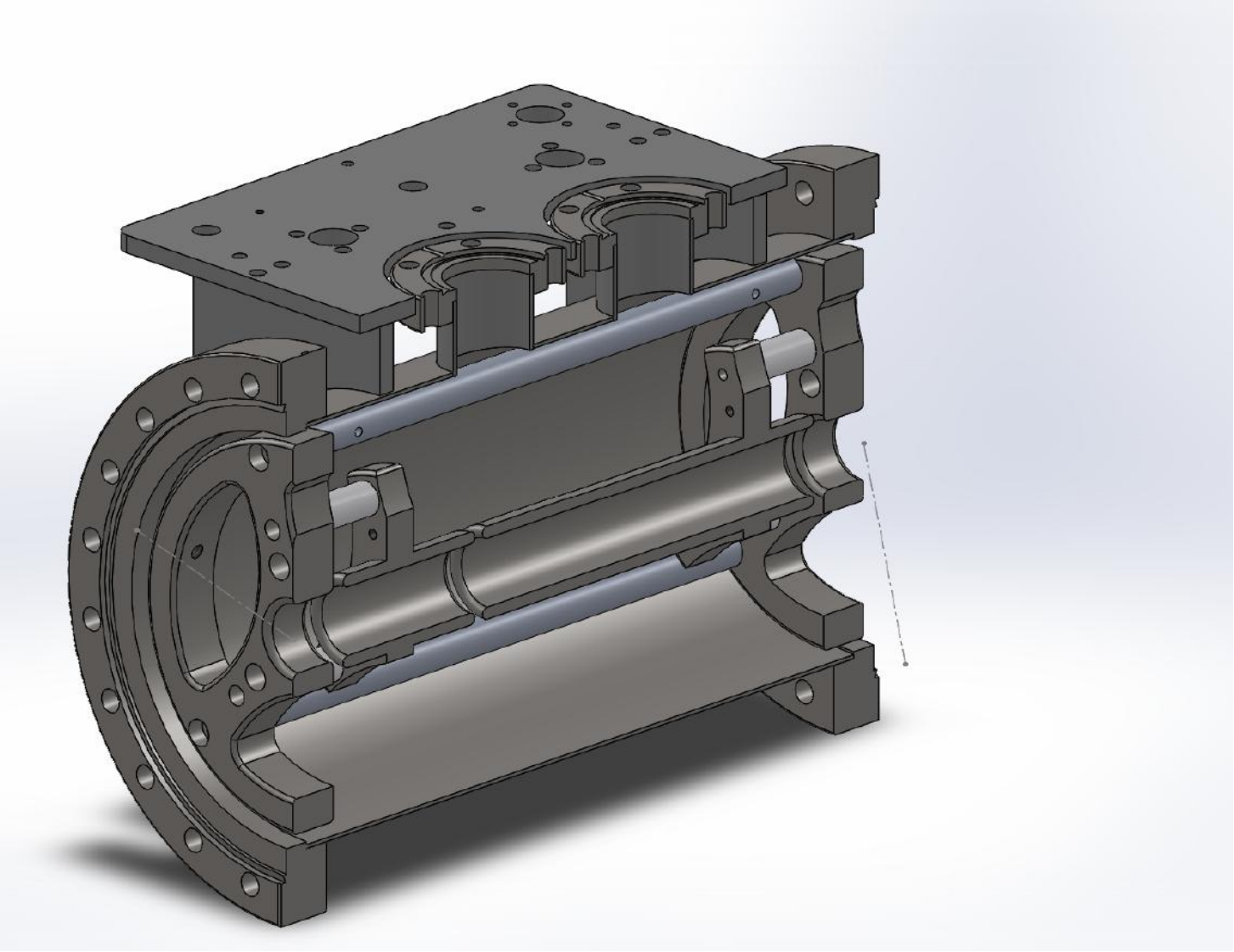


HiSPANoS: chopper and buncher upstream terminal.



- **8 MHz single-drift**
- **Repetition rate = 2 MHz, 1 MHz, 500 kHz**
- **Pulse width -> FWHM=1 ns tras el terminal (HE) y antes del analyzing magnet).**
- **Downstream the analyzing magnet ---> FWHM=2-3 ns.**
- **System will be ready to bunch protons and deuterons.**
- **Other ions need a previous study of the voltages.**
- **Summer 2016.**

HiSPANoS: buncher design.

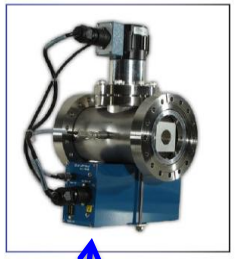


HiSPANoS: tof line, elements.

The Model FC18 is the highest power standard Faraday cup manufactured by NEC. The power rating is conservative at a continuous beam power density of 1000W into a 3mm diameter.

For a complete beam profile monitor system, the Model BPM80 is connected to an NEC controller, Model FP3A, SS5A or SS6. In addition, a display oscilloscope is required.

Minimum Detectable
Beam Current/ Density: 1nA or 10 nA/cm^2

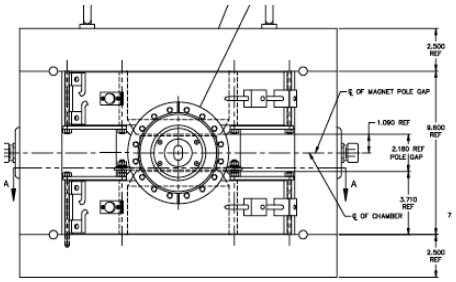


Model BPM80 beam profile monitor with NEC flanges, complete with preamplifier.

Cooling: Radiation

Element Material: Tantalum
Aperture Material: Tantalum

The Model BDS8 slit assembly has a conservative continuous beam power rating of 50W.



Neutrons

Valve2

Fadaray Cup

BPM

Steerers

Slit Motor

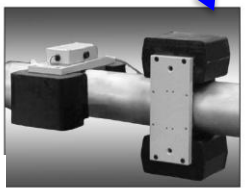
Slit Mec

Valve1

Pickup

Wien Filter.

TERMINAL



The NEC magnetic ion beam steerer for use on nominal 4" stainless steel beam tube.

The maximum magnetic field at the center of the steerer is 365 Gauss. At this maxiumum field, the strength is 65 Gauss-meters which will bend 2 MeV protons by 32.5 milli radians.

HiSPANoS tof line: proton current comparison.

The less favorable case in terms of current (therefore neutron flux) will be an experiment at 500 kHz. As conservative example, we consider 20 uA at the source (NEC claims that SNICS-II source can work at 50-70 µA during a day without problems):

20 uA * 0.25 (8 MHz) *0.075 (500kHz) *0,9 (Tank Transmission) = **330 nA @ 500 kHz**.

For comparison, the other facilities in Europe of the same characteristics:

- **JRC-IRMM** (Belgium, EU) ➔ 100 nA @ 600 kHz (recently decommisioned)
- **LNL-INFN** (Padova, Italy) ➔ 20 nA @ 600 kHz.
- **PTB** (Germany) ➔ 750 nA @ 625 kHz. VdG?
- **AMANDE** (France) ➔ Neutron fluence seem to be lower for Li(p,n)

ERINDA Scientific Results: Transnational Access Activities and Scientific Visits

Franz-Josef Hambsch[1]
[1]EC-JRC-IRMM, Retieseweg 111, B-2440 Geel, Belgium

Abstract
This paper gives an overview of the Transnational Access Activities and Scientific visits within the FP7 project ERINDA (European Research Infrastructures for Nuclear Data). It highlights the fact that nearly 3200 data-taking hours for external users were made available in the partner installations and 104 man weeks for scientific visits to partner institutes. This is much more than the 2500 beam hours and 80 weeks promised in the Description of Work of the project.

ERINDA-Host	Duration (weeks)
JRC-IRMM	6
CENBG	2
JYFL	6
JRC-IRMM	8
JRC-IRMM	8
JRC-IRMM	8
JRC-IRMM	6
CENBG	2
PTB	2
JRC-IRMM	4
JRC-IRMM	6
JRC-IRMM	4
JRC-IRMM	8
JRC-IRMM	8
CENBG	2
JRC-IRMM	8
JRC-IRMM	8
JRC-IRMM	8

HiSPANoS tof line: ΔE/E energy resolution comparison.

Neutron Energy	HiSPANoS	HiSPANoS	N_TOF EAR-1 (188m)	N_TOF EAR-2 (20m)
	ΔE/E (1ns – 0.5m)	ΔE/E (1ns – 1m)	ΔE/E	ΔE/E
1 keV	$8{,}8 \cdot 10^{-4}$	$4{,}4 \cdot 10^{-4}$	$5{,}4 \cdot 10^{-4}$	$8{,}5 \cdot 10^{-3}$
1 MeV	$2{,}8 \cdot 10^{-2}$	$1{,}4 \cdot 10^{-2}$	$3{,}6 \cdot 10^{-3}$	$4{,}1 \cdot 10^{-2}$

HiSPANoS TOF: neutron flux comparison, $^{7}Li(p,n)$ E_p=2 MeV

Energy interval	HiSPANoS TOF line, $^{7}Li(p,n)$ Ep=2 MeV	n_TOF-CERN EAR-1 (188m)	n_TOF-CERN EAR-2 (20m)
	n/(cm²·s) (1ns - 1m)	**n/(cm²·s)**	**n/(cm²·s)**
1 keV 100 keV	$2,8 \cdot 10^{5}$	$1,2 \cdot 10^{5}$	$2,6 \cdot 10^{6}$
100-300 keV (HiSPANoS) 1 MeV (n_TOF)	$1,3 \cdot 10^{4}$	$4,2 \cdot 10^{5}$	$7,3 \cdot 10^{6}$

HiSPANoS TOF line: possible measurements.

- In the first phase, CNA group will be focused on the installation of the chopper/buncher system and background studies.
- In a second phase, CNA group will perform neutron spectrometry measurements in the epithermal energy range.
- We will setup an adquisition system for Li-glass detectors.
- In parallel, the most important objective of the CNA group is to collaborate to users and to provide suitable neutron beams for their measurements.

- HiSPANoS tof line will be (summer 2016) a very versatile facility since different neutron beams can be generated: d-d, Li(p,n), Be(p,n)… for thin and thick targets.
- Neutron spectra measurements
- Neutron capture cross-section measurements, (n,γ).
- Neutron-induced cross-section measurements, (n,f).

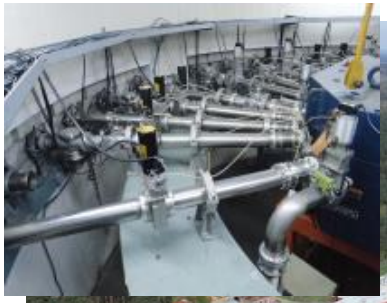
- Transmutation of nuclear waste, High temperatures reactors, Development of ADS systems, Th-U fuel cycle, U-Pu fuel cycle, Development of nuclear standards.
- Astrophysics.
- Neutron capture therapy.

Gracias por la atención

jpraena@ugr.es

JRC-IRMM (EU): GELINA.

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre



- Pulsed white neutron source
  (1 meV < E_n < 20 MeV)
- Neutron energy by Time-Of-Flight (TOF)

$$E_n = \frac{1}{2} m_n v_n^2 = \frac{1}{2} m_n \left(\frac{L}{t}\right)^2$$

- Multi-user facility
- 12 Flight Paths with varying L (8 - 400 m)
- The measurement stations have special equipment to perform:
  - Total cross section measurements
  - Partial cross section measurements

Normal Operation Parameters

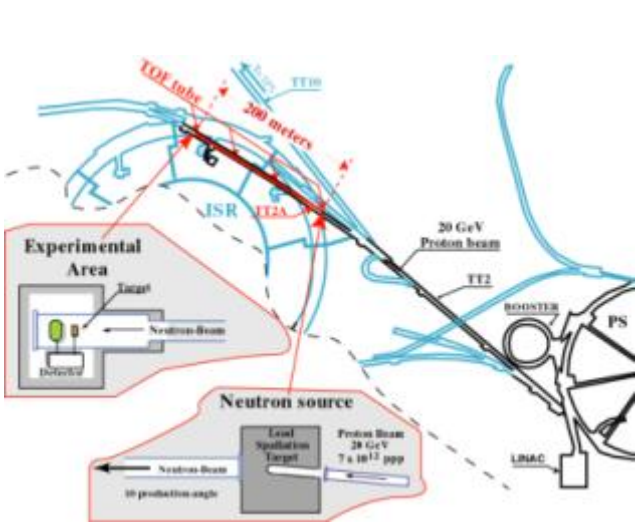
Average Current	: 75 μA	Frequency	: 800 Hz
Average Electron Energy	: 100 MeV	Pulse Width	: 1 ns
Mean Power	: 7.5 kW	Neutron Intensity	: 2.5 x 10^{13} n/s

Transmutation of nuclear waste.
High temperatures reactors.
Development of ADS systems.
Th-U fuel cycle.
U-Pu fuel cycle
NRCA for authenticity of artefacts.
Development of nuclear standards.

- Transmutation of nuclear waste
  - RP for ^{99}Tc, ^{129}I, ^{237}Np, ^{241}Am
- High Temperature Reactors
  - ^{240,242}Pu – Doppler effect
- Development of ADS systems
  - ^{209}Bi-branching
  - ^{206,207,208}Pb and ^{209}Bi (n,tot), (n,γ), (n,n'γ)
- Th-U fuel cycle
  - ^{234,236}U(n,f)
  - RP for ^{232}Th (RRR + URR)
- U-Pu fuel cycle
  - Fission products
  - ^{55}Mn

Funds from FP7

CERN: neutron_time-of-flight (n_TOF).

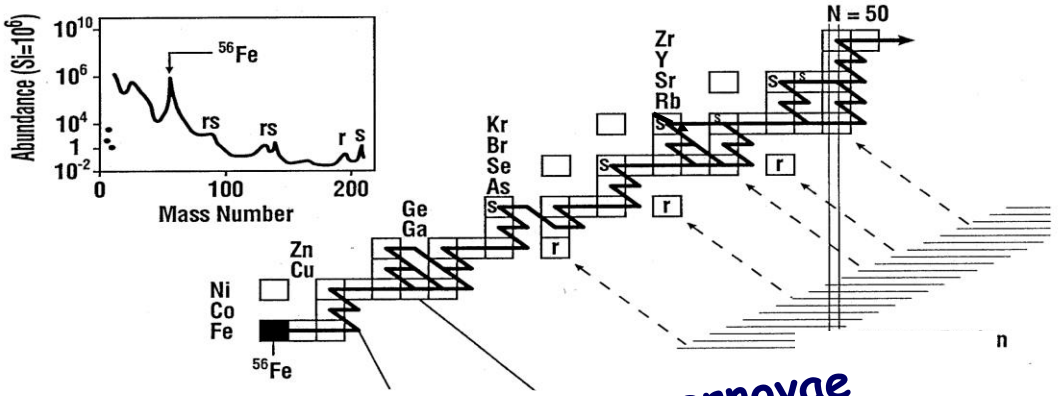


Neutron energy range	0.1 eV to 1 GeV
Intensity (dedicated)	7 x 10^{12} p/pulse
Repetition frequency	1 pulse/2.4 s
Pulse width	6 ns (rms)
n/p	300
Lead target dimensions	80x80x60 cm^3
Cooling & moderation	Borated H_2O
Moderator thickness in the exit face	5 cm

Nuclear technology

Funds from FP7

Nuclear Astrophysics



Red Giants
(s-process)
kT=8,30,90 keV

supernovae
(r-process)
kT=500 keV

JRC-IRMM (EU): 7 MV VdG accelerator.

- Single-user facility
- 6 different beam lines
- 100h/w
- 0.1 - 10 & 13-21 MeV
- Li(p,n), T(p,n), D(d,n), T(d,n)

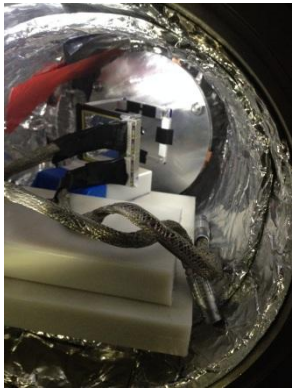
Pulse width of 2 ns and pulse repetition rates of 2.5, 1.25 or 0.625 MHz

Transmutation of nuclear waste.
High temperatures reactors.
Development of ADS systems.
Th-U fuel cycle.
U-Pu fuel cycle
Development of nuclear standards.

Measurement types

- Fission
- Activation measurements n ➔light charged particles
- Flux (BIPM)
- Inelastic scattering
- Calibration of detectors

Funds from FP7

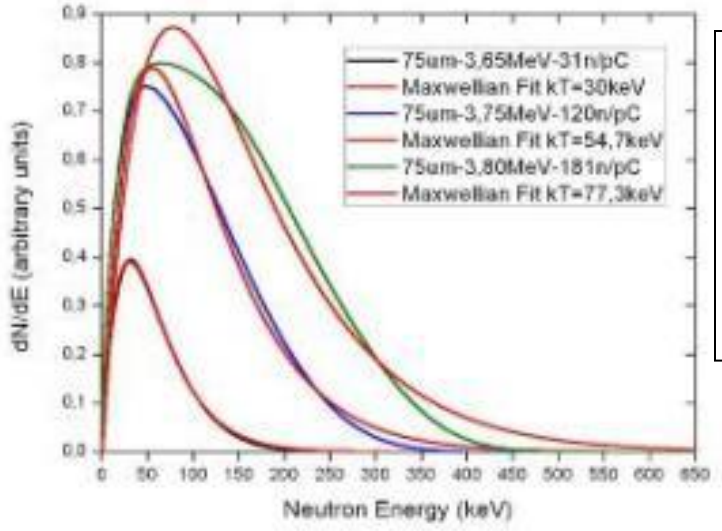


Setup characterization for ILL experiment

B. Fernández, M. Macías and J. Praena, US-CNA-UGR

Experiment performed at ILL in July 2015 (PF1B-10/2014)

En el CNA podemos proporcionar datos de MACS.



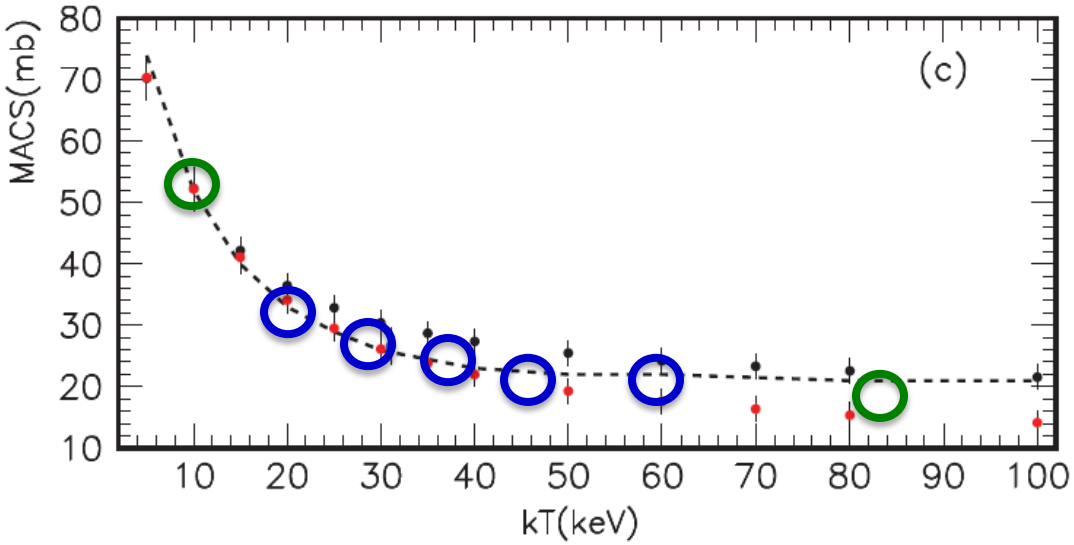
Podemos medir mediante activación la MACS en el CNA mediante activación desde kT=25 a 60 keV. Pero se trata de un método muy particular.

J. Praena, P. Mastinu, J.M. Quesada *et al.*, NIM A , 727, 1-6 (2013).

J. Praena, P. Mastinu, J.M. Quesada *et al.*, accepted Nuclear Data Sheetes6 (2013).

PHYSICAL REVIEW C **84**, 015801 (2011)

Neutron capture on ^{94}Zr: Resonance parameters and Maxwellian-averaged cross sections



Publicación típica n_TOF: Zr.

Doble interés, reactores y astrofísica nuclear

below 60 keV. (c) MACSs for the full energy range using the present results complemented above 60 keV by data of the JENDL-3.3 evaluation (black symbols) or by data of the JENDL-4.0 evaluation (red symbols). The 30 keV value from Ref. [31] (blue symbol) and the MACSs from the compilation of Ref. [11] (dashed line) are shown for comparison (to avoid the overlap of error bars the value from Ref. [31] was displaced along the abscissa from 30 to 31 keV).

Neutron Activation: validation of nuclear data.

Neutron integral experiments play a central role in validation of evaluated nuclear data [1][2][3].

Evaluated spectrum averaged cross-section in Maxwellian spectrum are being used for the validation of evaluated reactor dosimetry files [4].

[1] M.B. Chadwick *et al.* Nuclear Data Sheets 102, 2887 (2012).
[2] U. Fischer *et al.*, Fusion Engineering and Design 663,51 (2000)
[3] R.A. Forrest *et al.*, UKAEA FUS 467, 2001.
[4] International Reactor Dosimetry and Fusion File, IAEA, 2012.

International Atomic Energy Agency
Nuclear Data Services
Секция Ядерных Данных МАГАТЭ

For instance, experimental MACS can be used for the validation of nuclear data libraries in the 10-120 keV range that is important in the description of fast neutron systems (e.g. Gen-IV nuclear reactors).

The integral measurements with our method at CNA (and LNL) are of interest for the IAEA and it has been mentioned as one of the Actions in few IAEA Reports:

INDC (NDS)-0583. International Neutron Cross-Sections Standards: extending and updating. 2010.
INDC (NDS)-0639. Testing and Improving the International Reactor Dosimetry and Fusion File (IRDFF). 2013.
INDC (NDS)-0641. Toward a New Evaluation of Neutron Standards. 2013.