Pulsed and continuous neutron beams at the CNA HISPANOS facility

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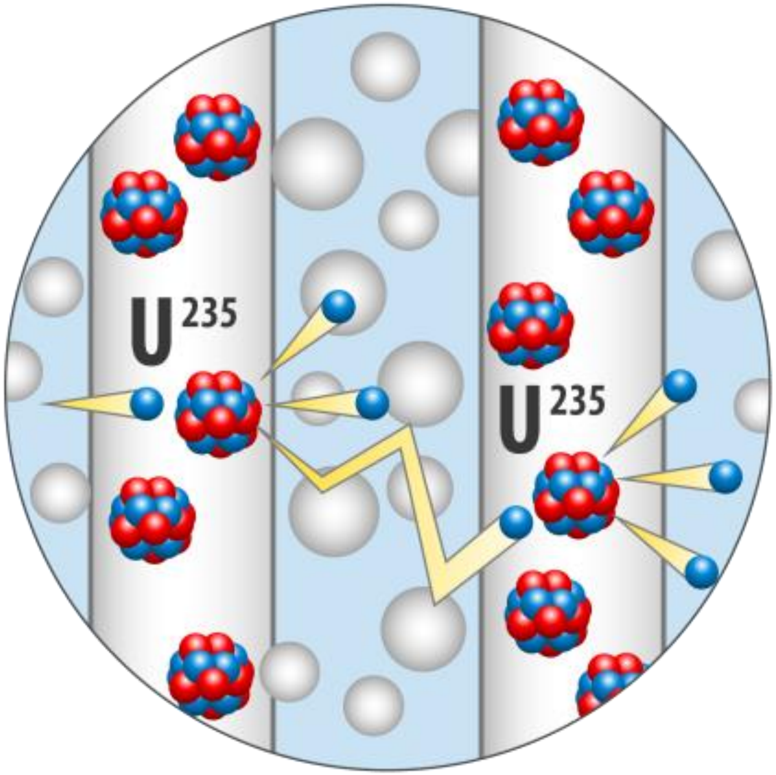
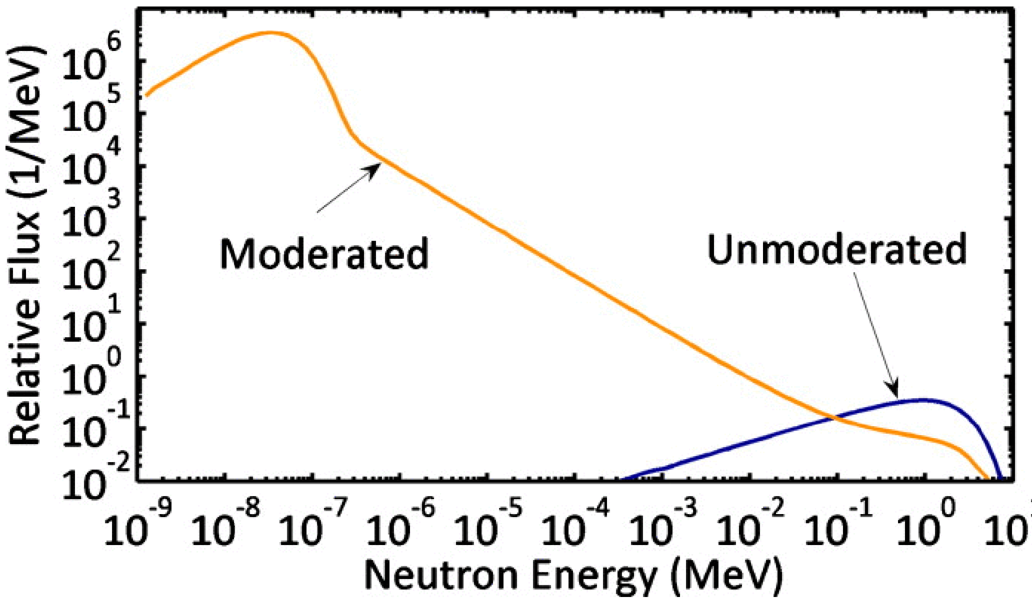
41st RD50 Workshop on Radiation hard semiconductor devices for very high luminosity colliders

Some general considerations

Neutron moderation process

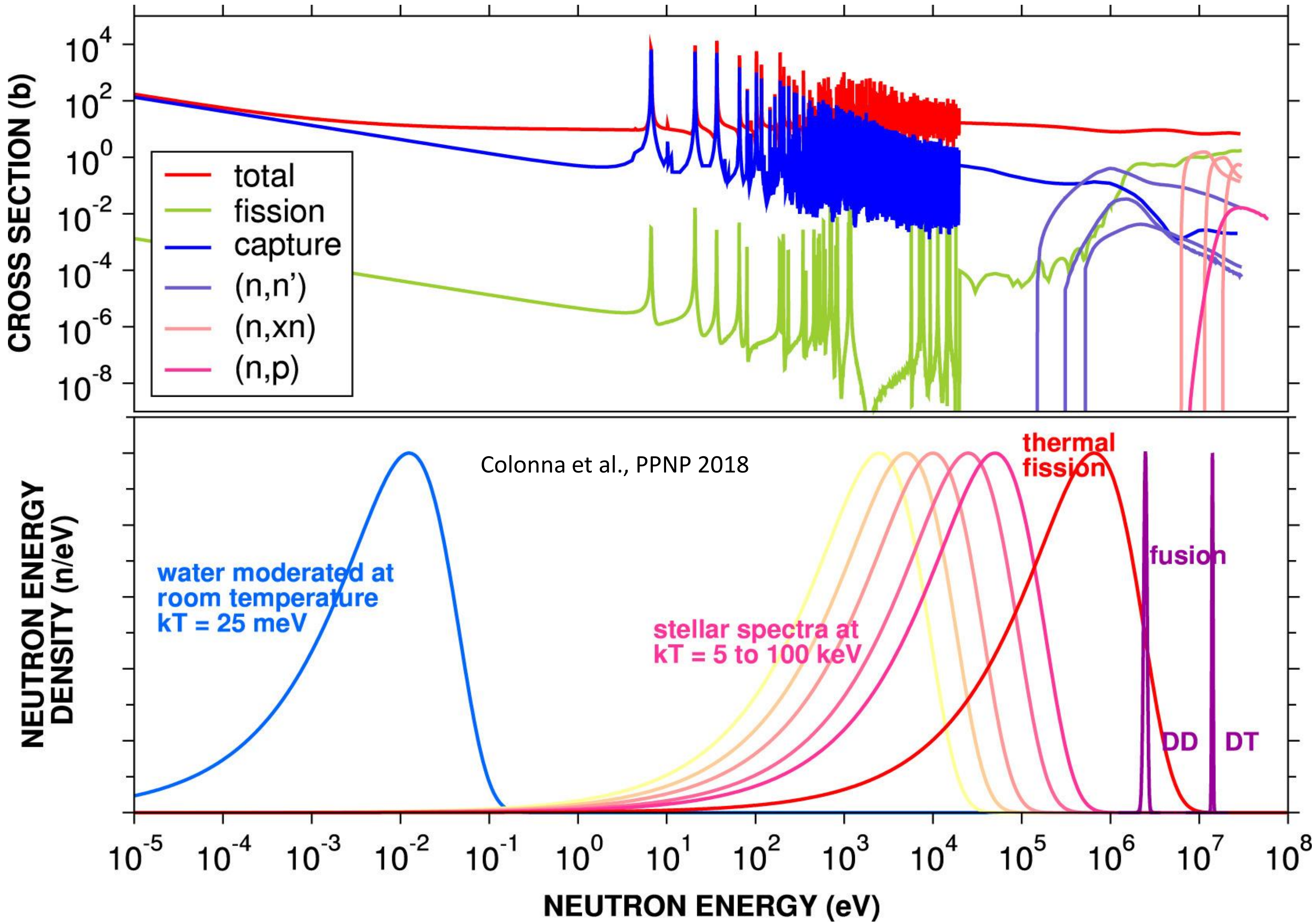




Continuous neutron scattering end up with the neutrons in thermal equilibrium with the medium:

MB distrib. with characteristic *k*T

Neutron energy ranges



Continuous vs. pulsed beams: time-of-flight

- Continuous: Neutrons of all energies "together":

  => integral effects (not a problem if spectrum adequate)

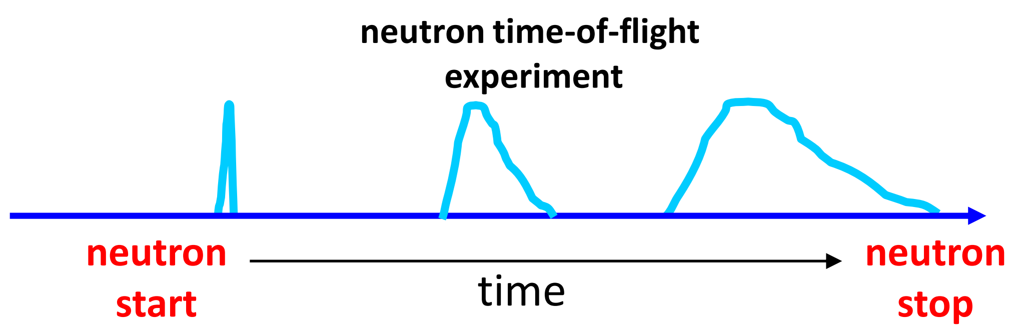
  Examples:

  - Irradiation (thermal, atmospheric, etc.)
  - Production of radioisotopes
  - Activation for a given spectrum

- Pulsed: allows for time-of-flight

  => time of arrival provides neutron kinetic energy

  => differential experiments => $X(E_n)$



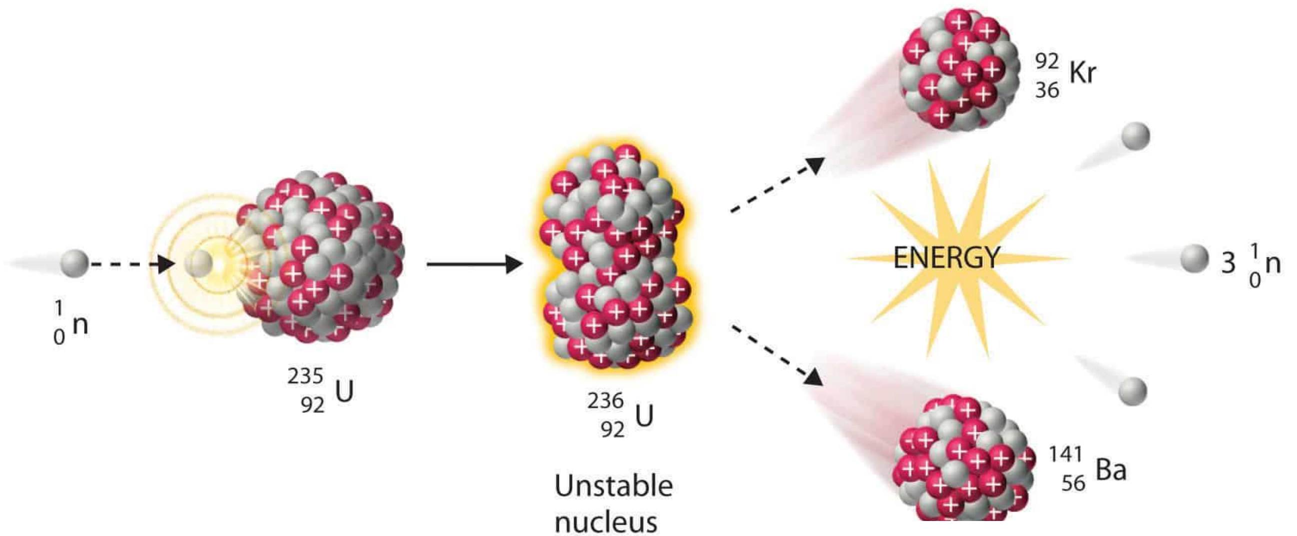
Time-of-Flight to E_n relation (non-rel.):

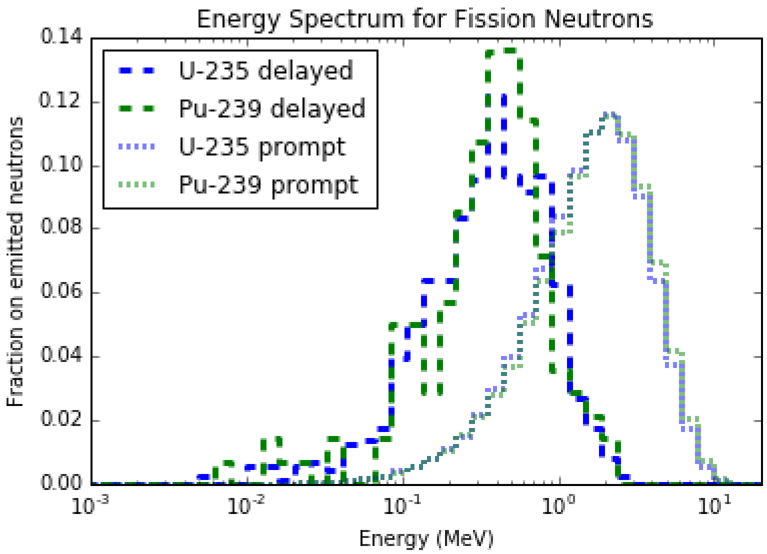
$$ToF \propto \frac{L}{\sqrt{E_n}}$$

=> E_n resolution increases with L

Neutron production

Neutrons produced by fission

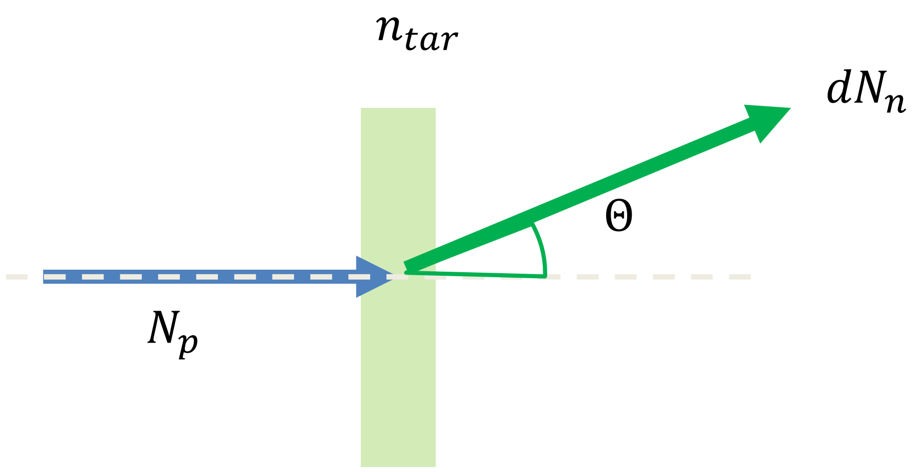




ILL (France): 10^{15} n/cm^2/s @core (~meV)

Neutron producing nuclear reactions (I)

- In two-body reactions monoenergetic neutrons can be produced, e.g. DT-reaction: $T(D,n)^4He$, $Q = 17.16$ MeV
- Kinematics determines the angular distribution and energy spectrum
- The yield (neutrons /primary particles) is determined by the differential cross section $\frac{d\sigma}{d\Omega}(E_{proyectile}, \Theta)$
- Realistic yield determination by integration over the target thickness and angular range (slowing down of the beam in the target material)

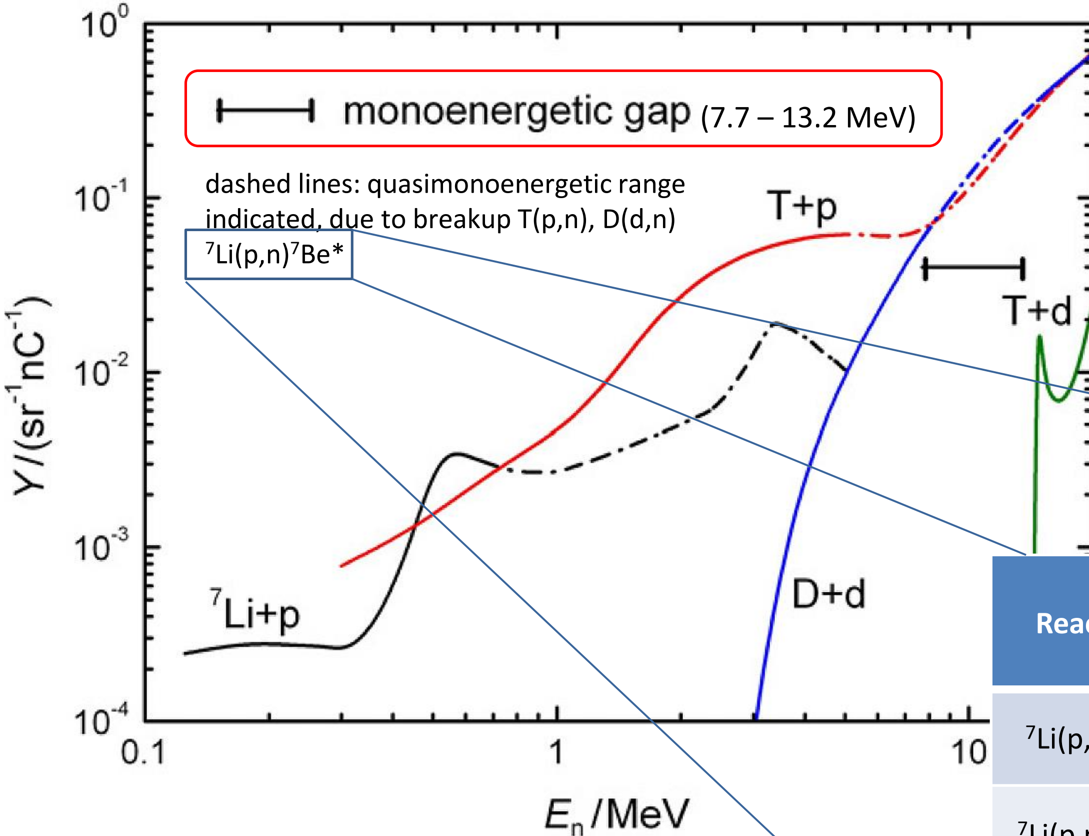


Neutron producing nuclear reactions (II)

Table 2 Common nuclear reactions particle accelerators use to produce neutrons.

Reaction	Shorthand	Q Value [MeV]	Threshold Energy [MeV]	Minimum Product Energies [MeV]
$^{2}H + ^{2}H \rightarrow ^{3}He + n$	$^{2}H(d,n)^{3}He$	+3.269	NA	^{3}He: 0.82 n: 2.45 *
$^{2}H + ^{3}H \rightarrow ^{4}He + n$	$^{3}H(d,n)^{4}He$	+17.589	NA	^{4}He: 3.54 n: 14.05
$^{1}H + ^{7}Li \rightarrow ^{7}Be + n$	$^{7}Li(p,n)^{7}Be^{\dagger}$	-1.644	1.880	^{7}Be: 0.21 n: 0.03
	$^{1}H(^{7}Li,n)^{7}Be^{\dagger}$	-1.644	13.094	^{7}Be: 10.0 n: 1.44
$^{2}H + ^{7}Li \rightarrow ^{8}Be + n$	$^{7}Li(d,n)^{8}Be$	+15.031	NA	^{8}Be: 1.68 n: 13.35
$^{1}H + ^{9}Be \rightarrow ^{9}B + n$	$^{9}Be(p,n)^{9}B$	-1.850	2.057	^{9}B: 0.18 n: 0.023
$^{2}H + ^{9}Be \rightarrow ^{10}Be + n$	$^{9}Be(d,n)^{10}B$	+4.361	NA	^{10}B: 0.40 n: 3.96

Monoenergetic (& quasi) neutron beams

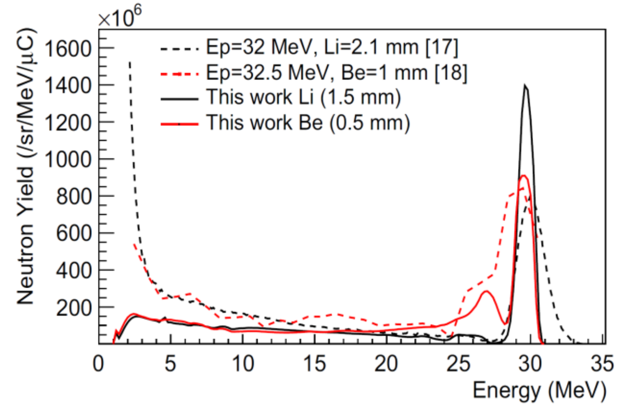


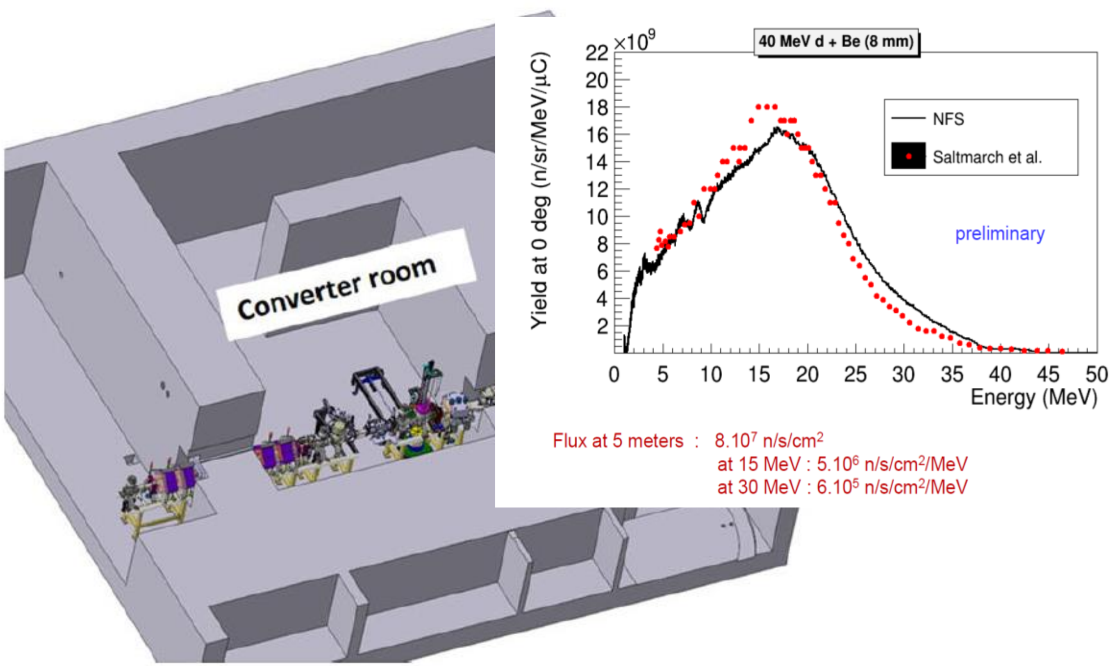
Reaction	^{7}Be* Exc. Energy (MeV)	Q-value (MeV)	Threshold (MeV)
^{7}Li(p,n)^{7}Be	0	-1.644	1.881 forward 1.920 backward
^{7}Li(p,n)^{7}Be*	0.429	-2.073	2.371 forward 2.421 backward
^{7}Li(p,n^{3}He)^{4}He	break-up	-3.229	3.692
^{7}Li(p,n)^{7}Be**	4.57	-6.214	7.110 forward 7.260 backward

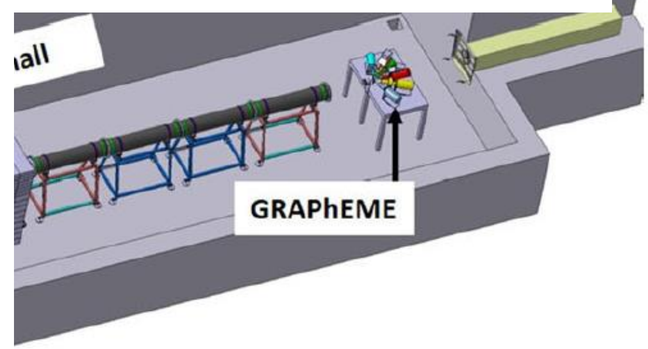
Nuclear reactions with high energy ions

GANIL's SPIRAL-2, a Superconducting Linear Accelerator:

- 40 MeV deuteron and 33 MeV protons
- Beam current 5 mA, i.e. rotating target
- Flight path 5 to 10 meters
- Frequency=0.25-1 MHz



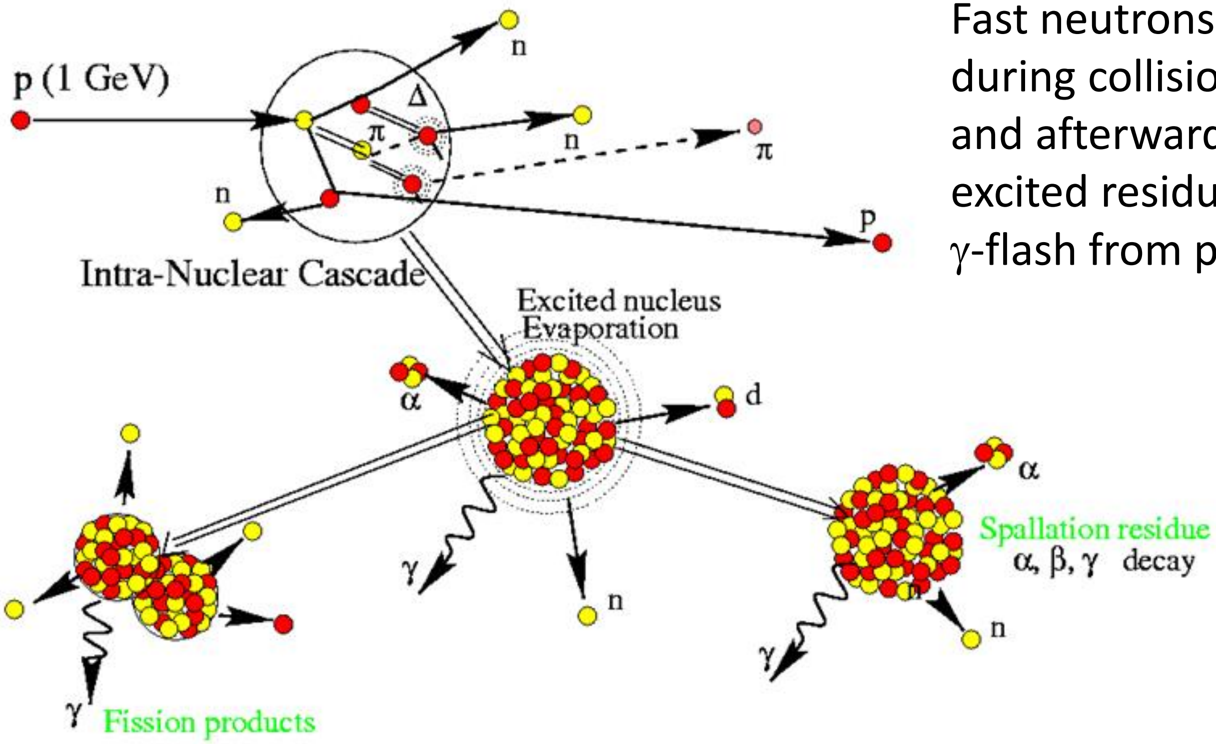




Flight path: 5 – 30 m
Energy range: 0.1- 40 MeV
Low γ-flash background
Low instantaneous flux
High repetition rates

Neutron production by spallation

Relativistic protons impinging on heavy target nuclei



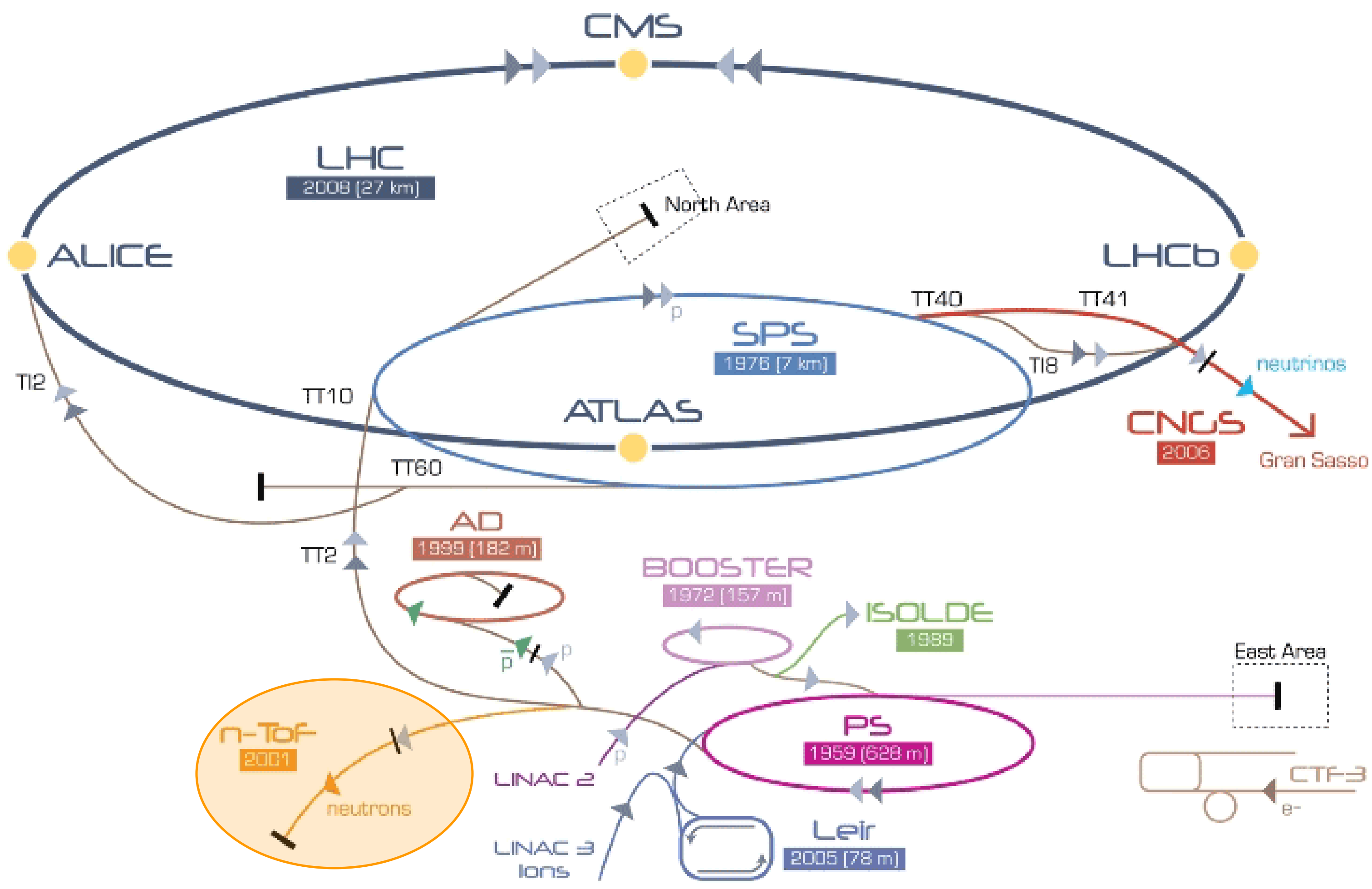
Fast neutrons emitted during collision
and afterwards from excited residual nuclei
γ-flash from pion decay

Nucleon-Nucleus collisions at relativistic energies

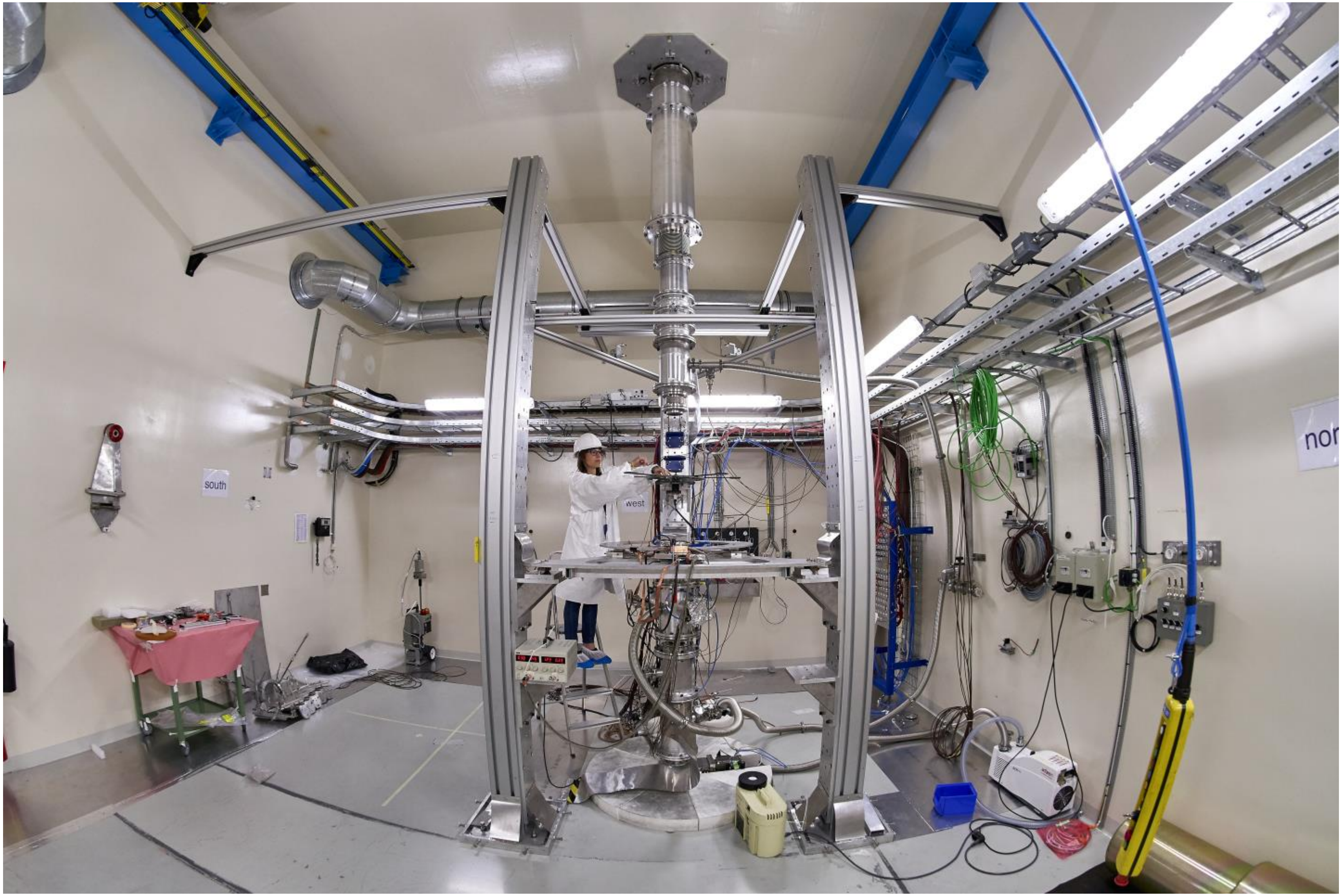
- $T_{coll} < 10^{-22}$s : Collisions of the projectile nucleon with nucleons in the target (Intranuclear Cascade, emission of **fast** particles π,**n**,p,…)
- $T_{equil} > 10^{-21}$s – 10^{-16}s Reorganisation of the residual nuclei, thermalization, **particle evaporation** (**n**,p,d,α,…), gamma ray emission

n_TOF at CERN

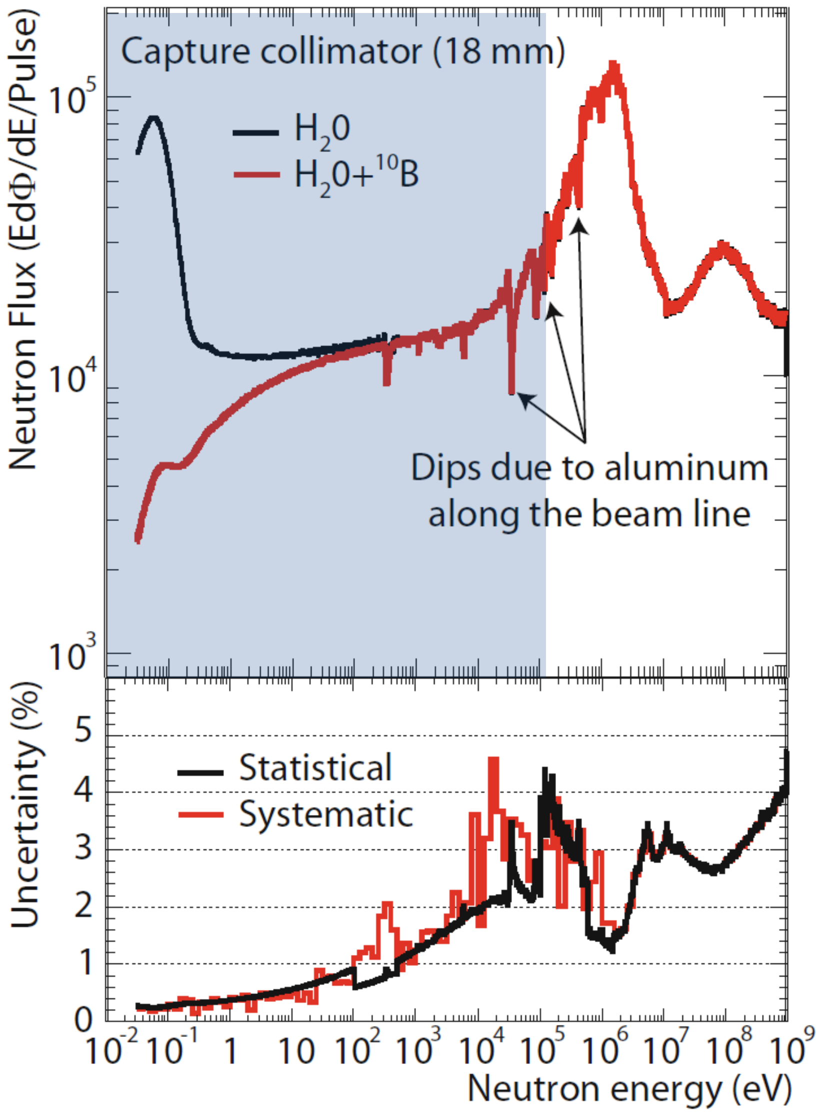
The n_TOF facility at CERN (I)



The n_TOF Facility at CERN (II)



The n_TOF Facility at CERN (III)

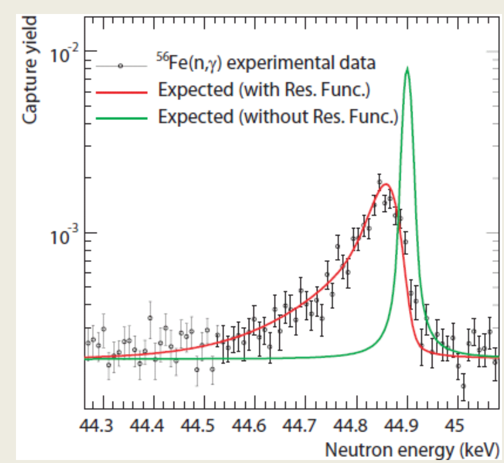


MeV to GeV range

Three pulsed beams available:
- EAR1 (185 m): ~ 10^6 -10^7 neutrons/pulse
- EAR2 (20 m): ~10^8 neutrons/pulse
- NEAR (3 m): expected 10^9 neutrons/pulse

ENERGY RESOLUTION

E_n (eV)	$\Delta E_n/E_n$
1	$4.3{\cdot}10^{-4}$
10	$4.3{\cdot}10^{-4}$
10^2	$4.3{\cdot}10^{-4}$
10^3	$7.5{\cdot}10^{-4}$
10^4	$1.7{\cdot}10^{-3}$
10^5	$5.4{\cdot}10^{-3}$
10^6	$2.8{\cdot}10^{-3}$

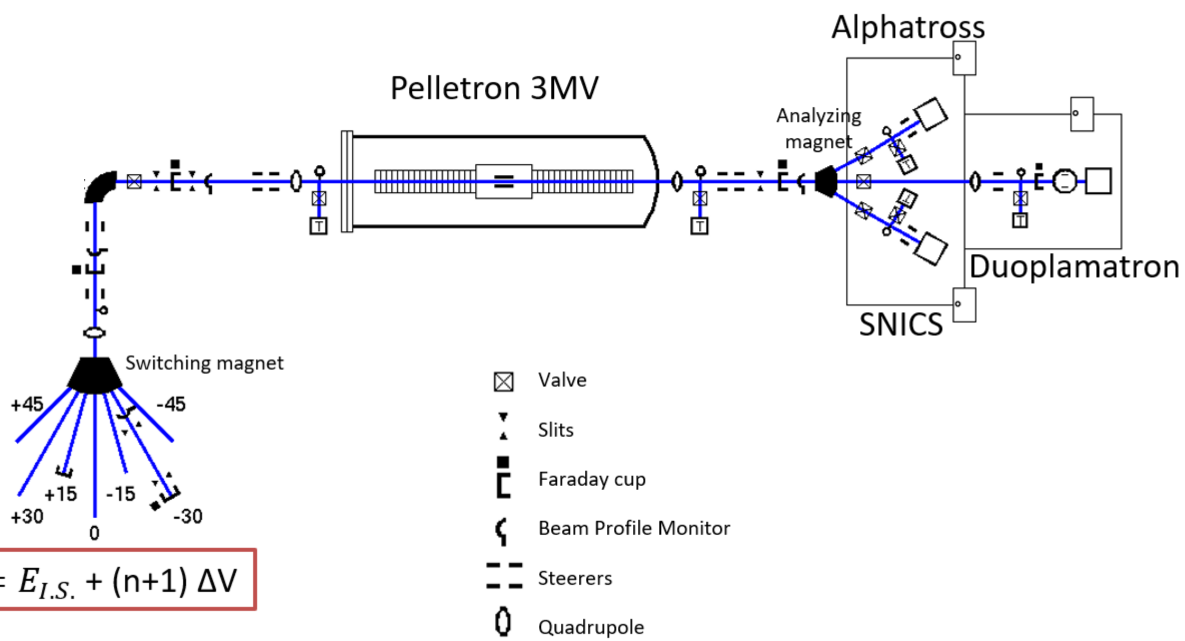


HISPANOS at CNA

HiSPANoS at the 3 MV Tandem Accelerator

HiSPANoS is the first Accelerator-based neutron source in Spain and it is installed at the the 3 MV Tandem Accelerator.

Continuous & Pulsed



$$E = E_{I.S.} + (n+1)\,\Delta V$$

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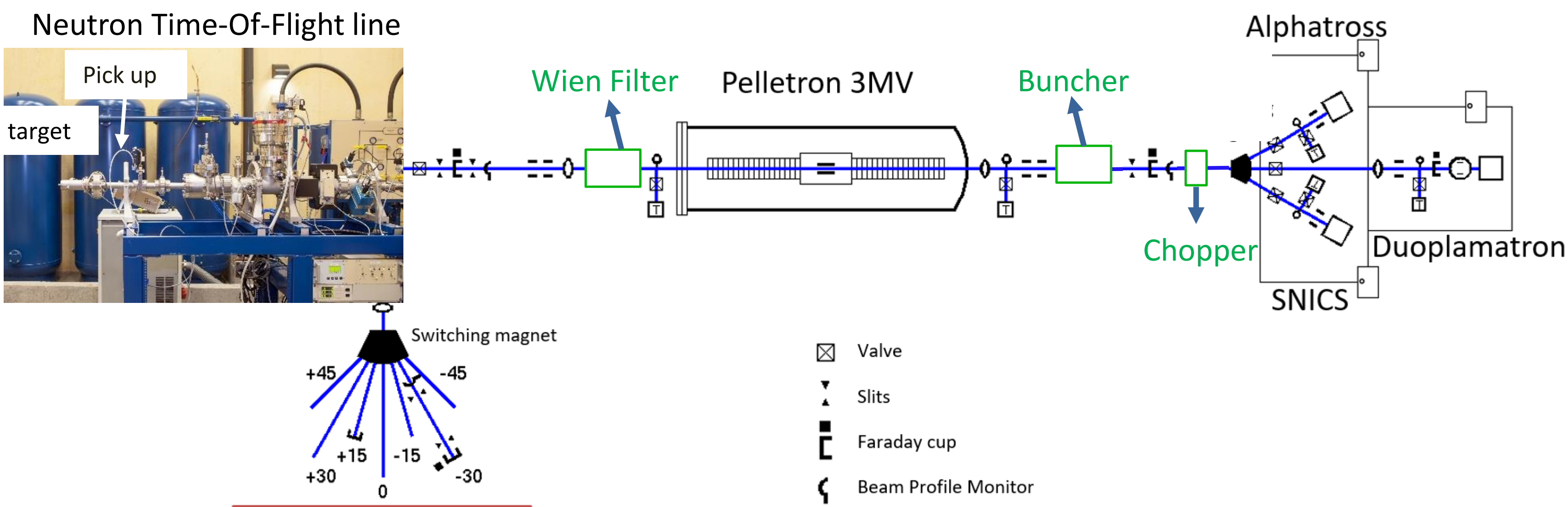
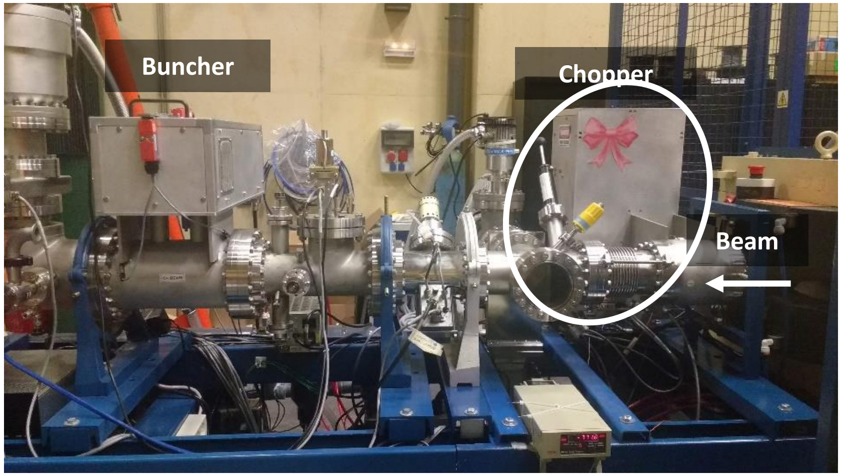


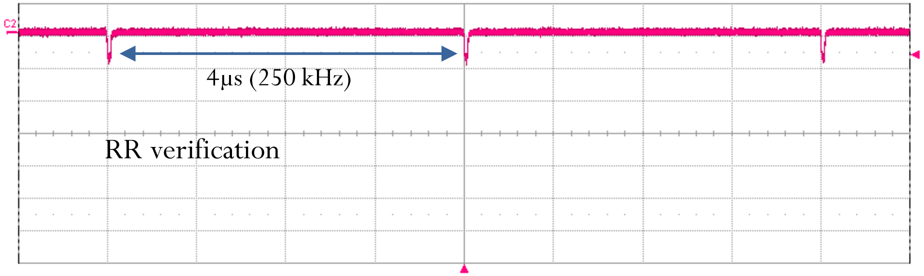
$E = E_{I.S.} + (n+1)\,\Delta V$

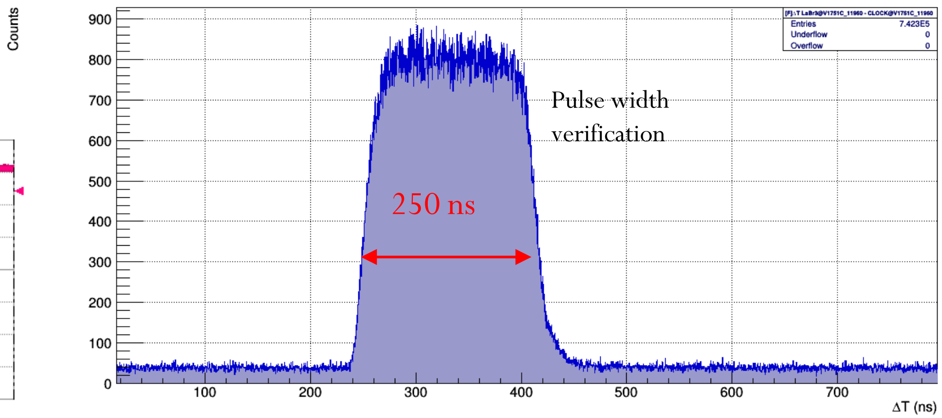
Pulsing system: p,d & α



Chopper:

- Variable width: 40 ns-250 ns
- RR: 31.25 kHz-2MHz
- Switcher Voltage: 650 V





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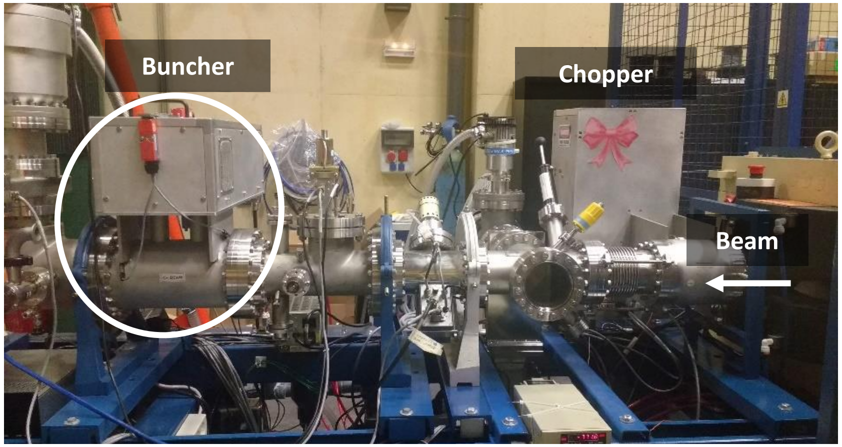
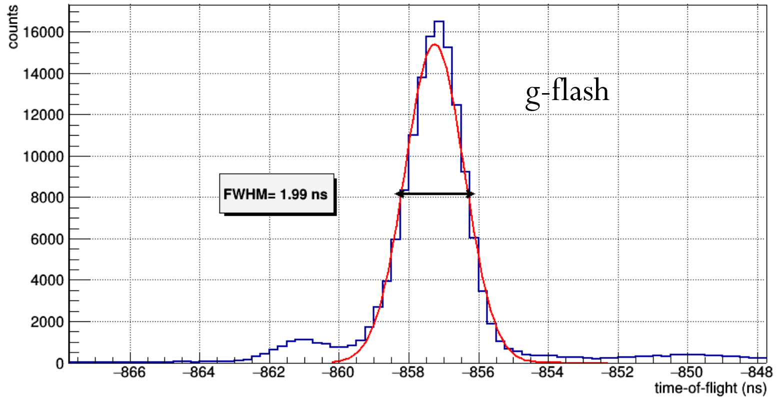
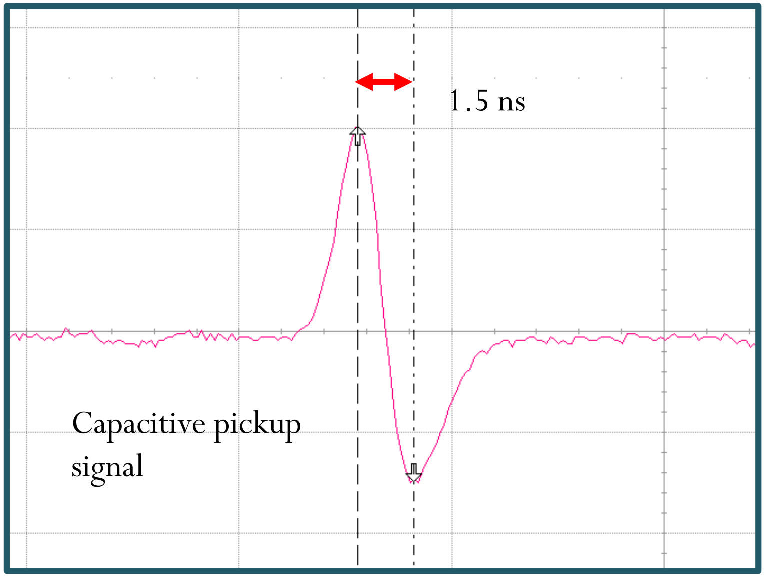
Pulsing system: p,d & α





Buncher:

Needs tuning (delay & power) for synchronization



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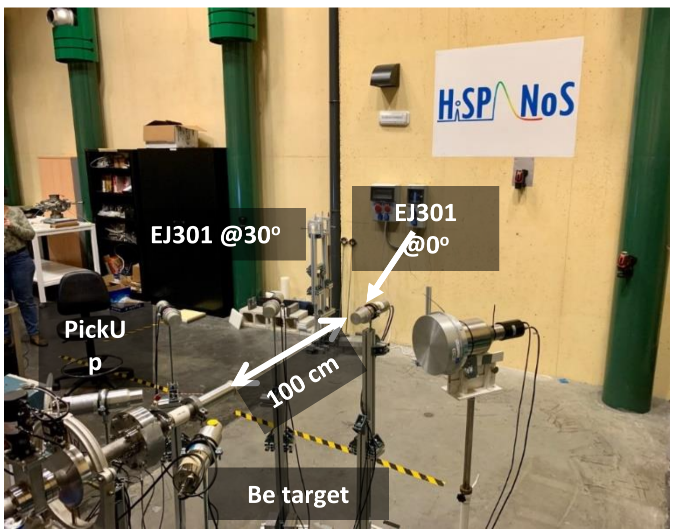
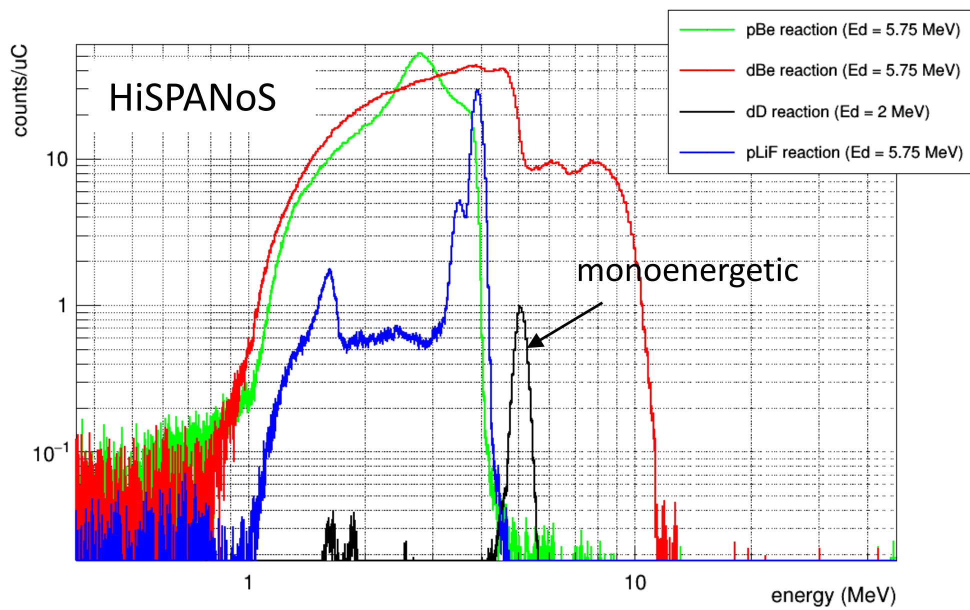
Neutron production targets/mechanism

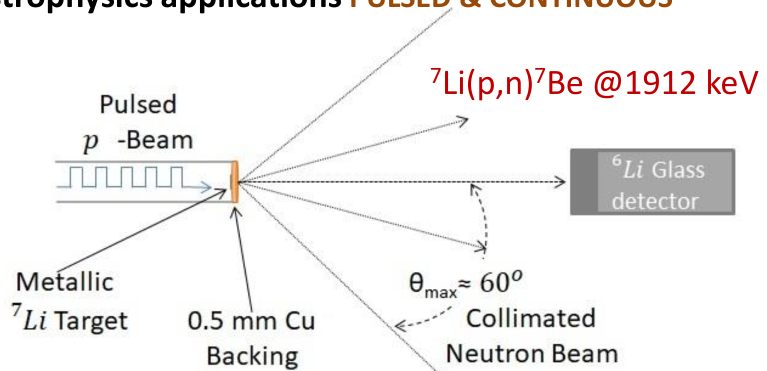
Target	Geometry	Reaction [Q value]	E_{beam} (MeV)	Neutron spectra
Li (metallic)	Ø 10 mm Thickness < 1mm	^{7}Li(p,n) [-1.7 MeV]	E_p=1.912	quasi-Maxwellian@kT=30keV Thermal by means of moderation
LiF (Evaporated on Cu)	Ø 30 mm Thickness: 16 μm			
D:Ti >1.5	Ø 30 mm D/Ti (500 μg/cm^2)	D(d,n) [3.3 MeV]	E_d=0.5-6	Quasi-monoenergetic between 3-9 MeV
Be	Square: 25 mm Thickness: 3 mm	^{9}Be(p,n) [-1.9 MeV]	E_p=2.1-6	Continium from keV to E_n~E_d-2.1MeV
		^{9}Be(d,n) [4.4 MeV]	E_d=0.5-6	Fast between 4 and 10 MeV





Neutron field and activation measurements for…

Astrophysics applications PULSED & CONTINUOUS



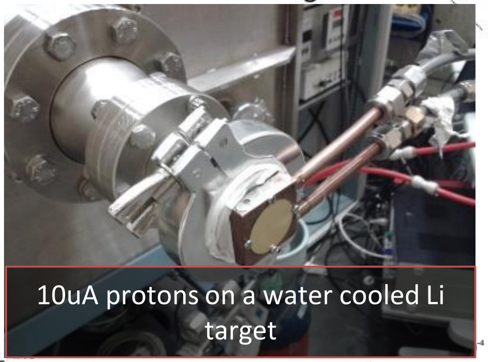
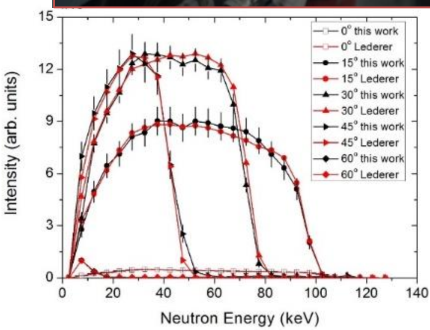
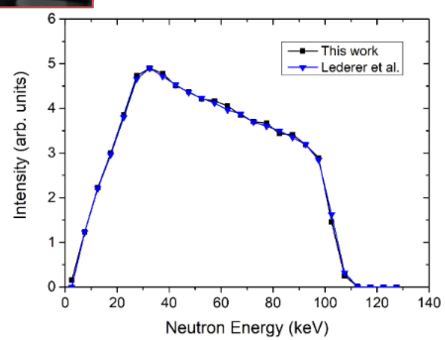

10uA protons on a water cooled Li target

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).

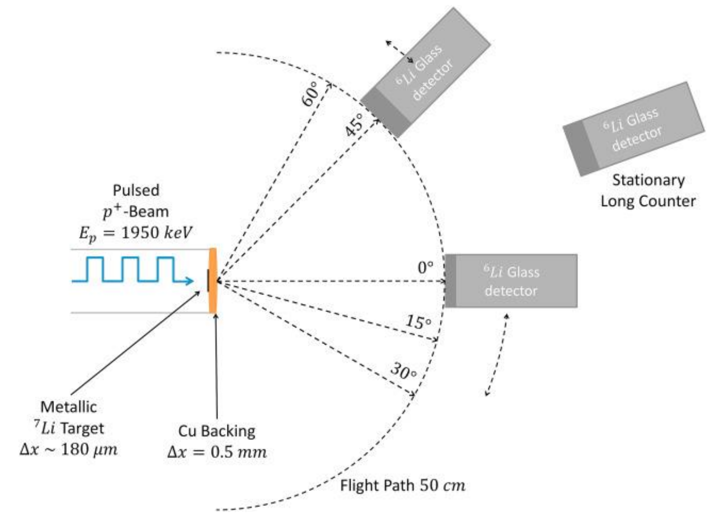
Corrections	Value ± Uncertainty(%)
Counting statistics	– ± 0.1
Au self-absorption [9],[23]	0.988 ± 0.2
Tb self-absorption [24]	0.956 ± 0.4
I_γ (Au) [25]	95.6 ± 0.2
I_γ (Tb) [26]	26.6 ± 0.2
Efficiency HPGe	– ± 5.8
$T_{1/2}$ Au (days) [25]	2.6947 ± 0.1
$T_{1/2}$ Tb (days) [26]	72.3 ± 0.1
Fluence ratio	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

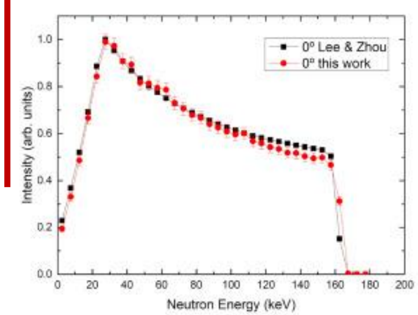


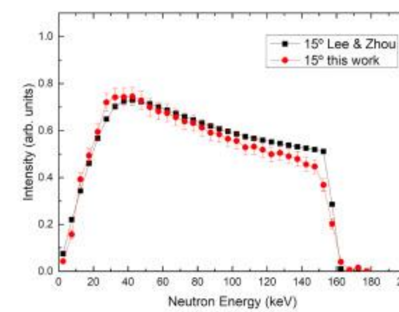


Medical Physics applications PULSED

^{7}Li(p,n) ^{7}Be@ 1950 keV for BNCT evaluation







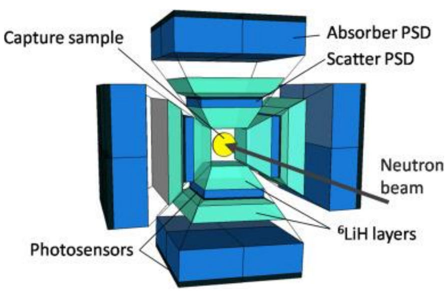
Detector characterization

Neutron sensitivity of i-TED for neutron capture at CERN n_TOF (with CSIC-IFIC) PULSED

+ CERN n_TOF: s(n,g) measurements by ToF
+ Scattered neutrons: main background

⇒ **Carachterization of detector response to epitermal neutrons**

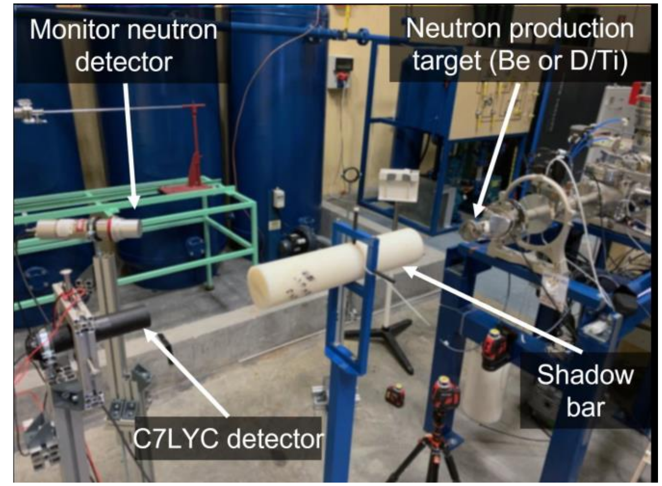
=> ^{7}Li(p,n) + time-of-flight



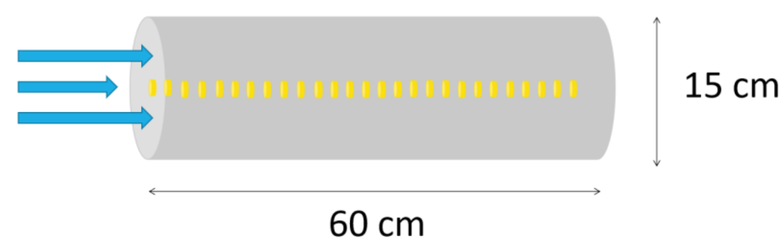
Characterization of C7LYC for fast (2,5 MeV) neutron diagnostic in fusion (with INFN-MIB) PULSED

@HISPANOS: Be(d,n) + time-of-flight

H2020-ARIEL TA => January 2022



Development of the ANTILOPE detector (with CIEMAT & n_TOF) CONTINUOUS

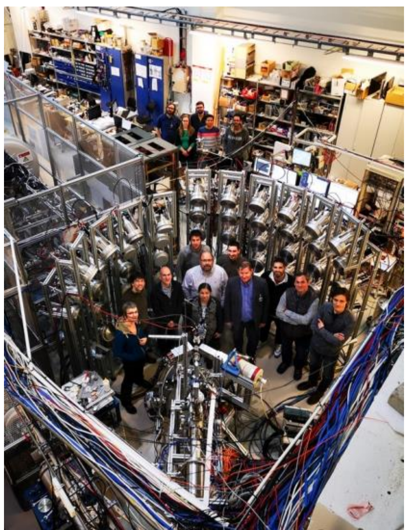


Cross sections measurements

Neutron production from (a,n) reactions for dark matter searches and astrophysics PULSED

(*The MANY Collaboration*: CNA, CMAM, CIEMAT, UPC, IFIC, UPM)

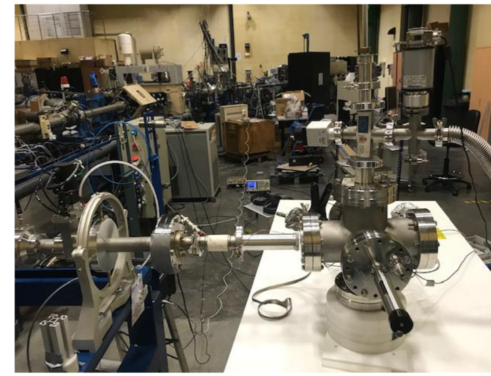
Measurements at CNA (cont.& pulsed) and CMAM (cont. only) with the detectors:
- miniBELEN
- MONSTER

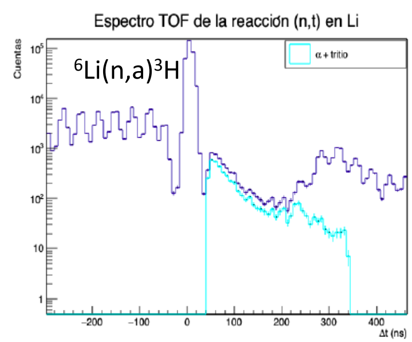


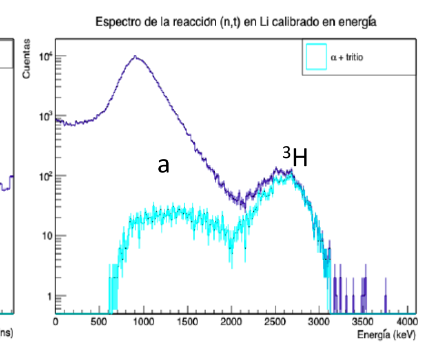
MONSTER@JYFL

MONSTER module@HISPANOS

Development of the capabilities to measure (n,cp) reactions by ToF PULSED

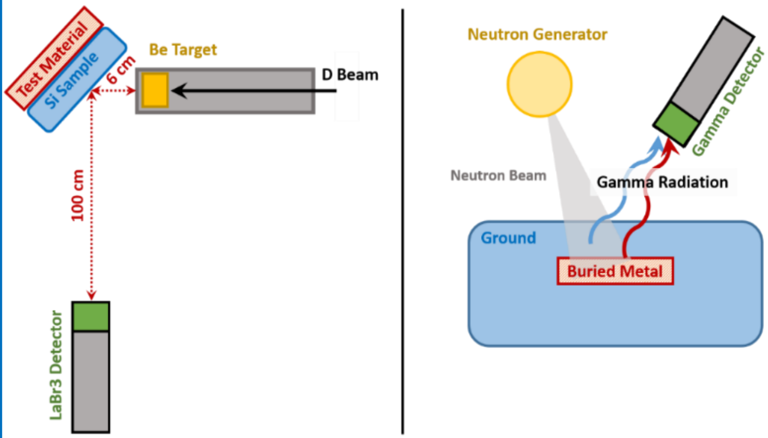


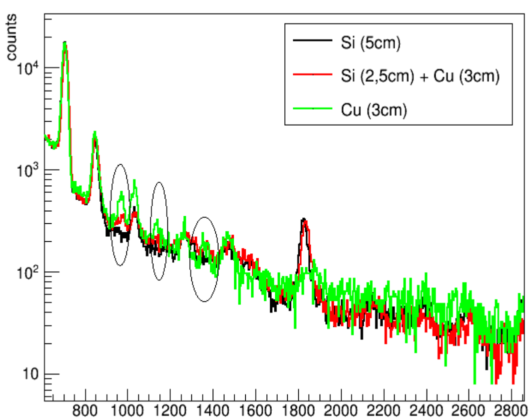




Imaging and material inspection

Identification of elements in large samples by PGA (with UPV & IDOM) CONTINUOUS





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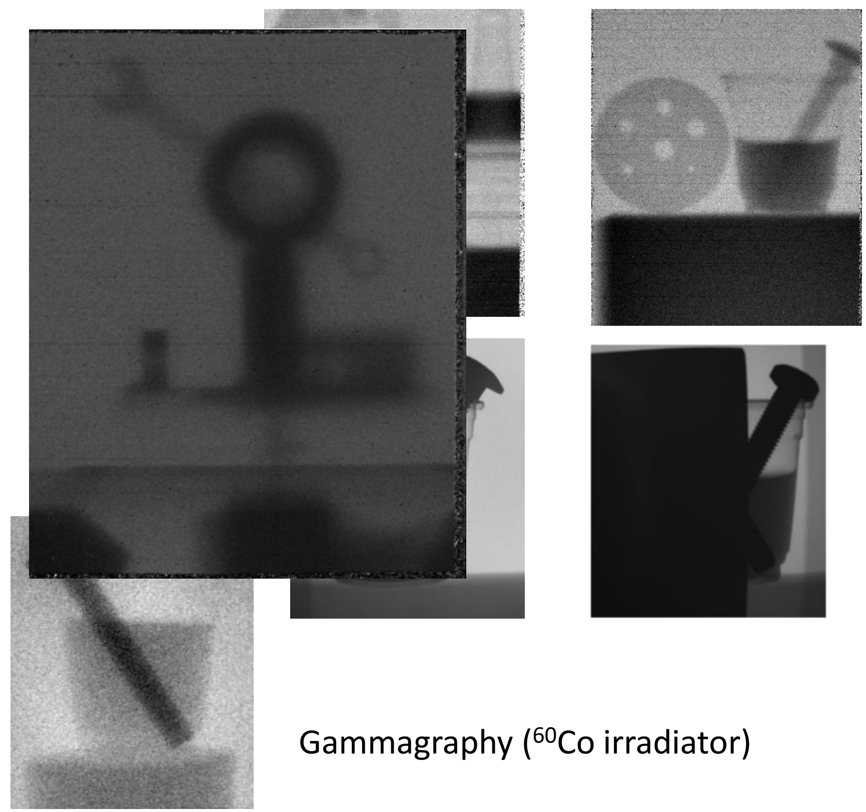
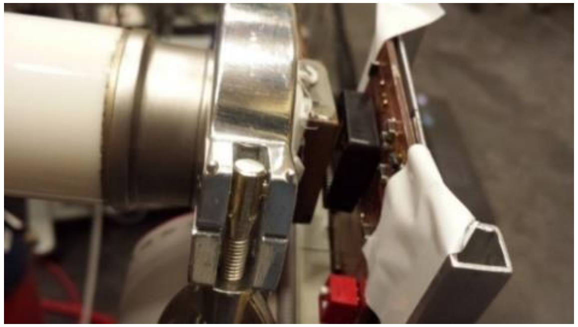
Neutron, gammas and x-ray imaging CONTINUOUS



Gammagraphy (^{60}Co irradiator)

Fast neutron irradiations & dosimetry

Electronic damage (soft error rate) by irradiation with protons and fast (MeV) neutrons CONTINUOUS



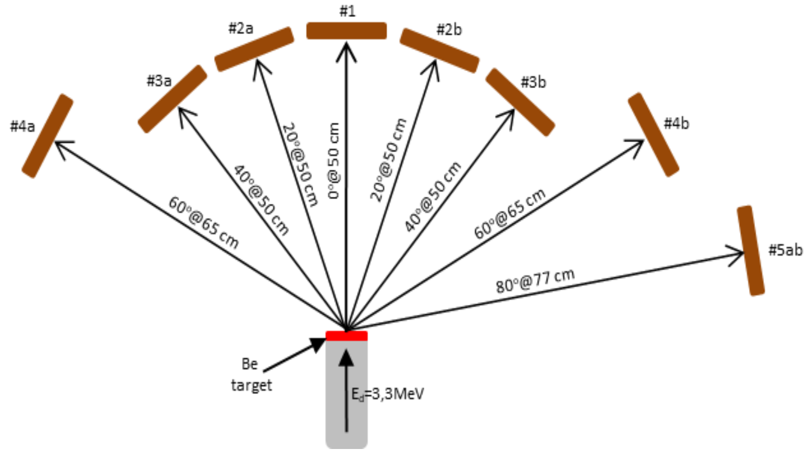
Dosimetric mapping & dosimeter intercomp. with fast (MeV) neutrons (with UPM) CONTINUOUS

@100 cm & 0º:
+ LUPIN (UPM): 77(1) mSv/h/μA
+ BIOREM (CNA): 88(1) mSv/h/μA

} 13% agreement

Buds irradiation with fast (MeV) neutrons

(Colab. ANECOOP & RadLab@CNA) CONTINUOUS



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HISPANOS for RD50?

A few examples found:

- Kaska et al., *Study on 150 um thick n- and p-type epitaxial silicon sensors irradiated with 24 GeV/c protons and 1 MeV neutrons*, NIM-A 612 (2010)
- Pacifico et al., *Characterization of proton and neutron irradiated low resistivity p-on-n magnetic Czochralski ministrip sensors and diodes*, NIM-A 658 (2011)
- Kramberger et al, *Modeling of electric field in silicon micro-strip detectors irradiated with neutrons and pions*, JINS 9 (2014)
- Gurimskaya et al., *Radiation damage in p-type EPI silicon pad diodes irradiated with protons and neutrons*, NIM-A 958 (2020)

Reactor neutrons (meV) from JSI in Slovenia, then normalized to 1 MeV neutron-equivalent values

Reminder: According to https://rd50.web.cern.ch/niel/, equivalent "**Displacement Damage in Silicon**" compared to 1 MeV neutrons is 0.001 for thermal neutrons and 2 for 5 MeV neutrons.

Fasts neutrons @HISPANOS => @ 10 cm with 10 uA

p+Li => 7×10^6 n/cm/s

p+Be => 5×10^6 n/cm/s

d+Be => 10^7 n/cm/s

Transnational Access via H2020-EuroLABS & H2020-ARIEL

(see Palomo's talk tomorrow)

THANK YOU