Learning HISPANoS, a new Neutron Beam Facility at CNA

Detector and SEE experiments

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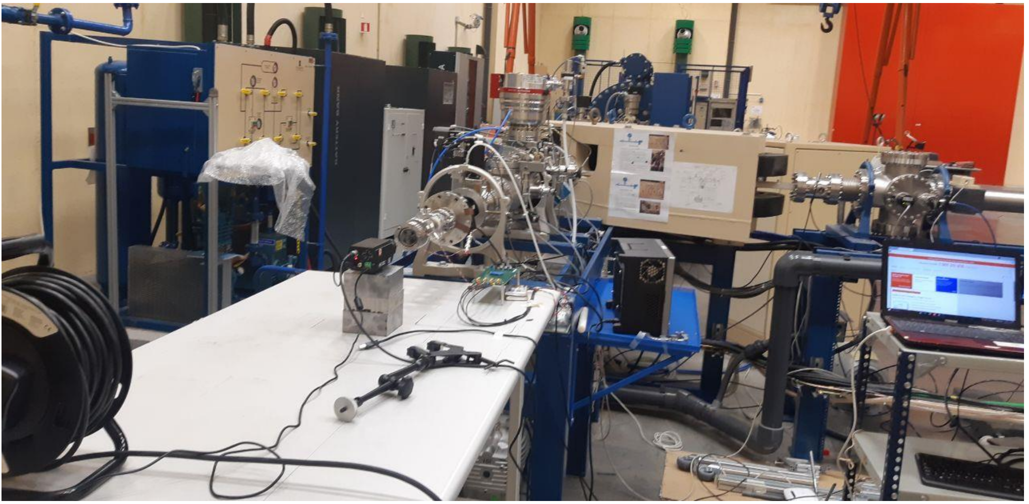
Centro Nacional de Aceleradores

https://indico.cern.ch/event/1334364/ 43rd RD50, Nov 28th to Dec 1st, CERN, 2023

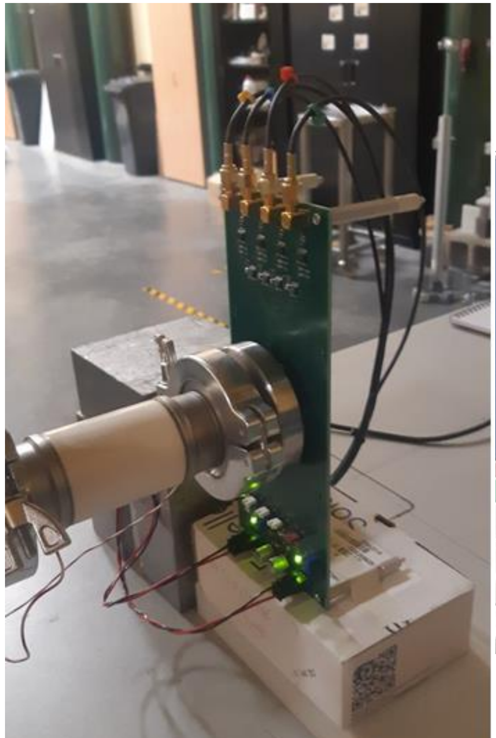
Learning HISPANoS, a new neutron beam facility at CNA

Introduction

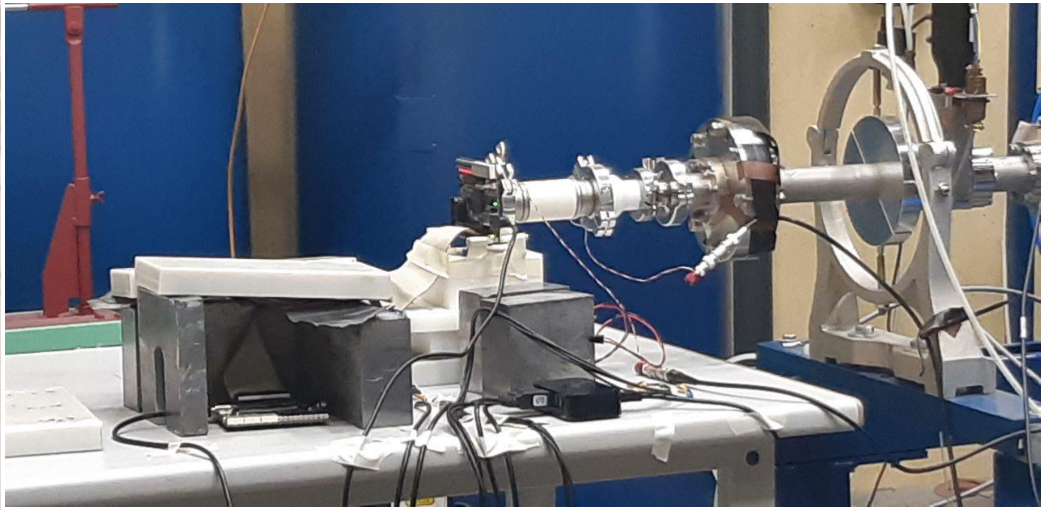
1. About the new HISPANoS neutron beam now open for experiments at the National Center of Accelerators, Sevilla, Spain
2. On a first experiment about detection of neutron induced nuclear reactions in silicon photodiodes and its intrincacies
3. Neutron induced Single Event Effects in an Intel MAX10 FPGA (55 nm)



Preparation of the Neutron Beam Line for the experiment



Photodiode Matrix Experiment



SEU FPGA experiment

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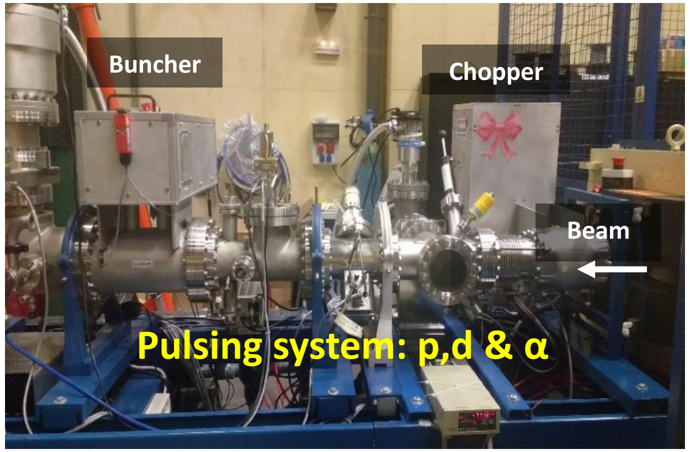
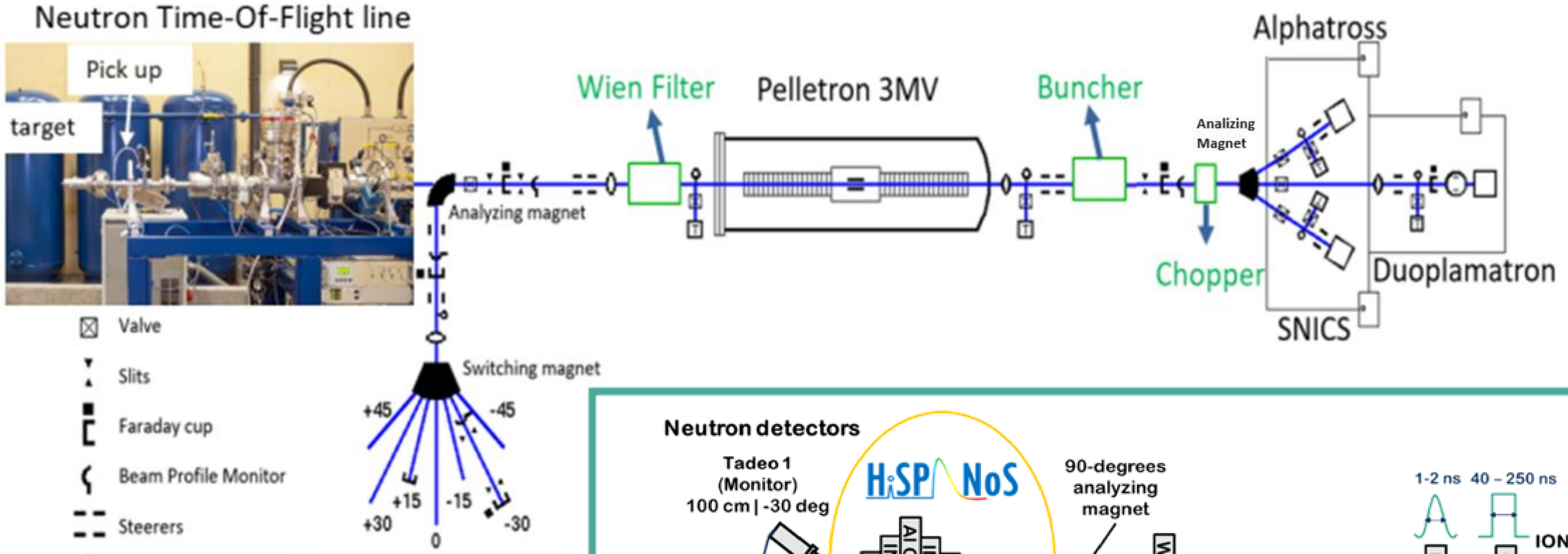


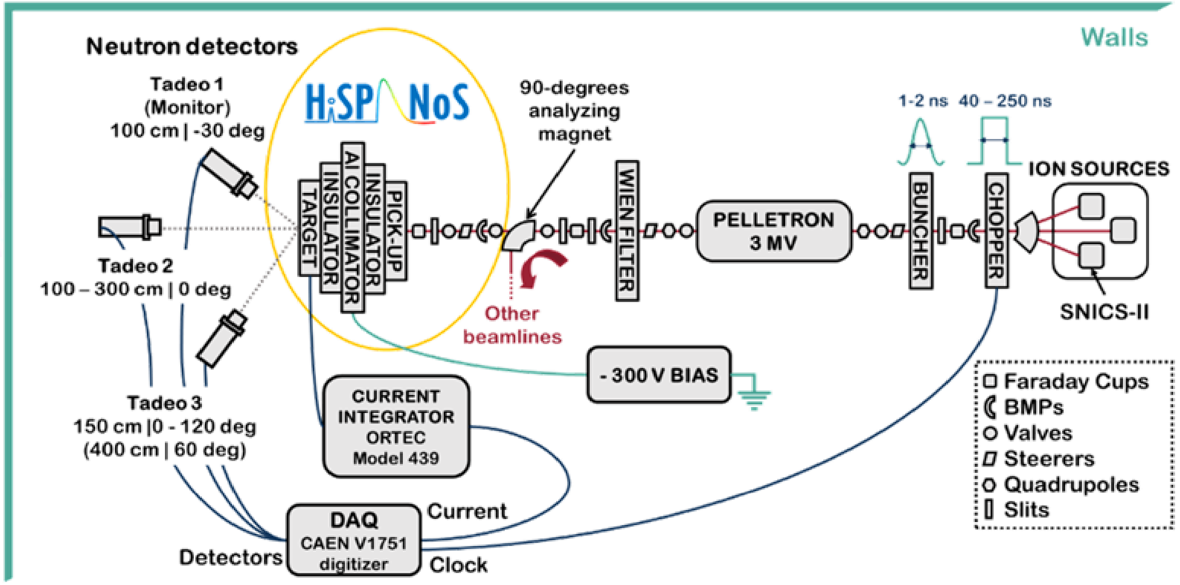


$$E = E_{I.S.} + (n+1)\,\Delta V$$

Buncher:
Needs tuning (delay & power) for synchronization

Chopper:

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



HiSPANoS is the first Accelerator-based neutron source in Spain and it is installed at the 3 MV Tandem Accelerator. Operates since 2013 in continuous mode and since 2018 in pulsed mode.

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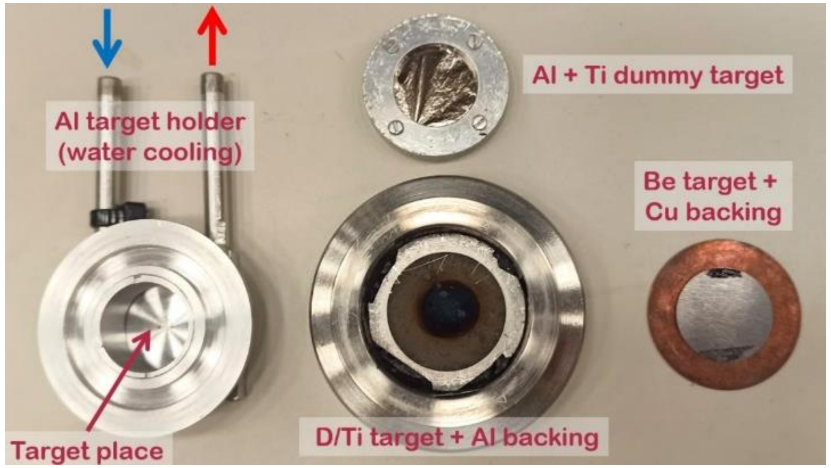
Neutron production targets/mechanisms

For our experiments we choose Fast Neutrons between up to 10 MeV, ^{2}H on ^{9}Be target ($^{9}Be(d,n)^{10}B$)



Monoenergetic and broad energy neutron beams

Reaction	Q-value (MeV)	Eth (MeV)	Target			Neutron spectra
			Material	Thickness	Diameter	
$^{2}H(d,n)^{3}He$	3,27	0,0	D/Ti	546 μg/cm^2	30 mm	Quasi-monoenergetic 2,2 – 6,1 MeV
$^{9}Be(p,n)^{9}B$	-1,85	2,06	Be	500 μm	25 mm	Continuum up to 4 MeV
$^{9}Be(d,n)^{10}B$	4,36	0,0				Continuum up to10 MeV
$^{7}Li(p,n)^{7}Be$	-1,64	1,88	Li	500 μm	25 mm	Continuum up to 4 MeV
$^{7}Li(d,n)^{8}Be$	15,03	0,0				Continuum up to 20 MeV

Projectiles

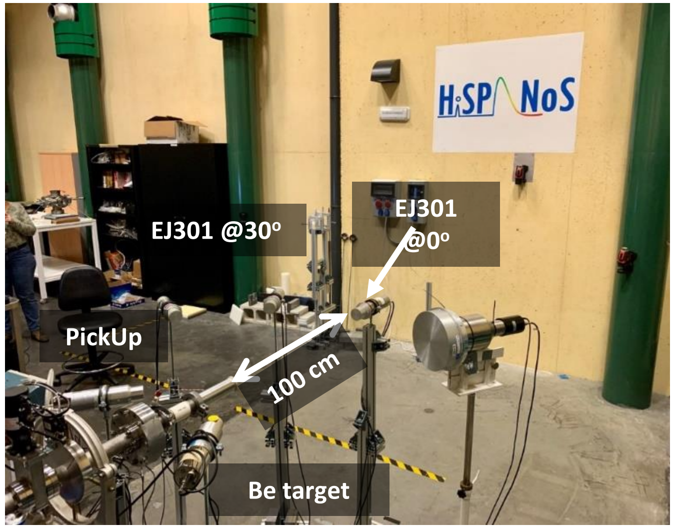
- ^{1}H, ^{2}H up to 6 MeV
- ^{4}He up to 6 MeV

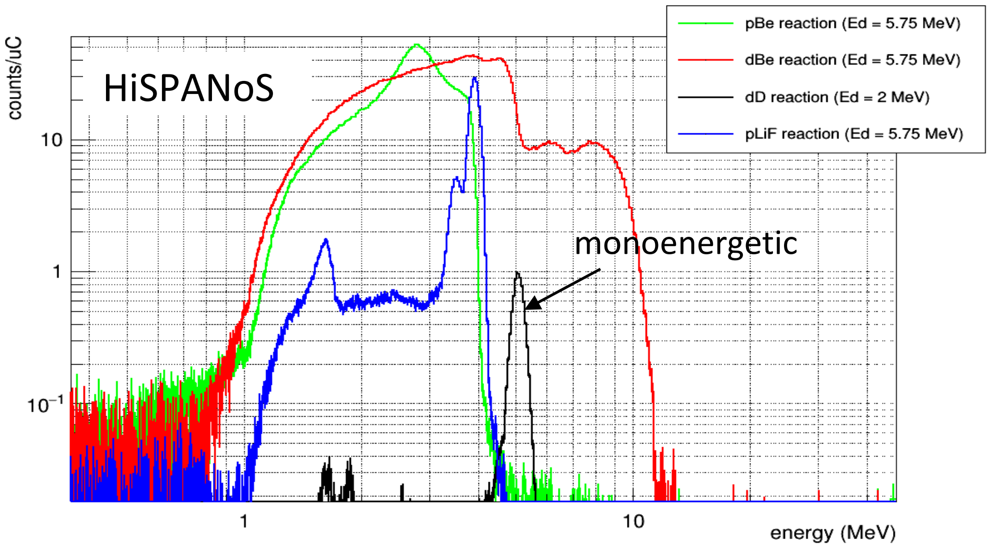
Continuous mode

- Up to 10 uA

Pulsed mode

- 1-2 ns pulse width
- 32,5 kHz - 2 MHz
- 1- 4 m flight path





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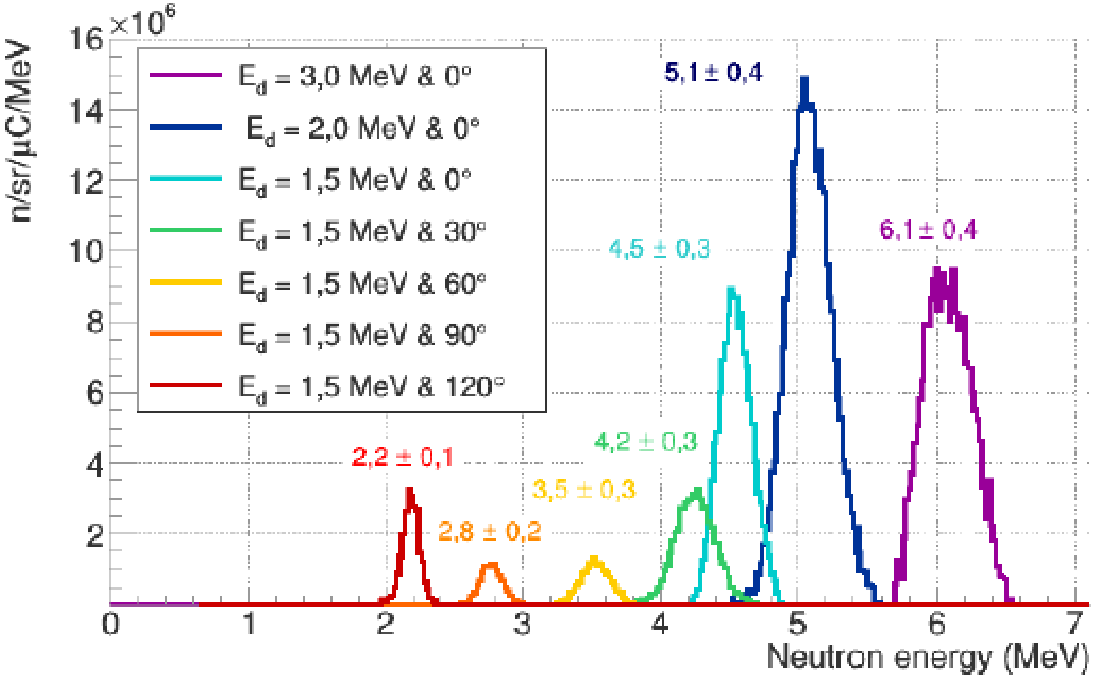
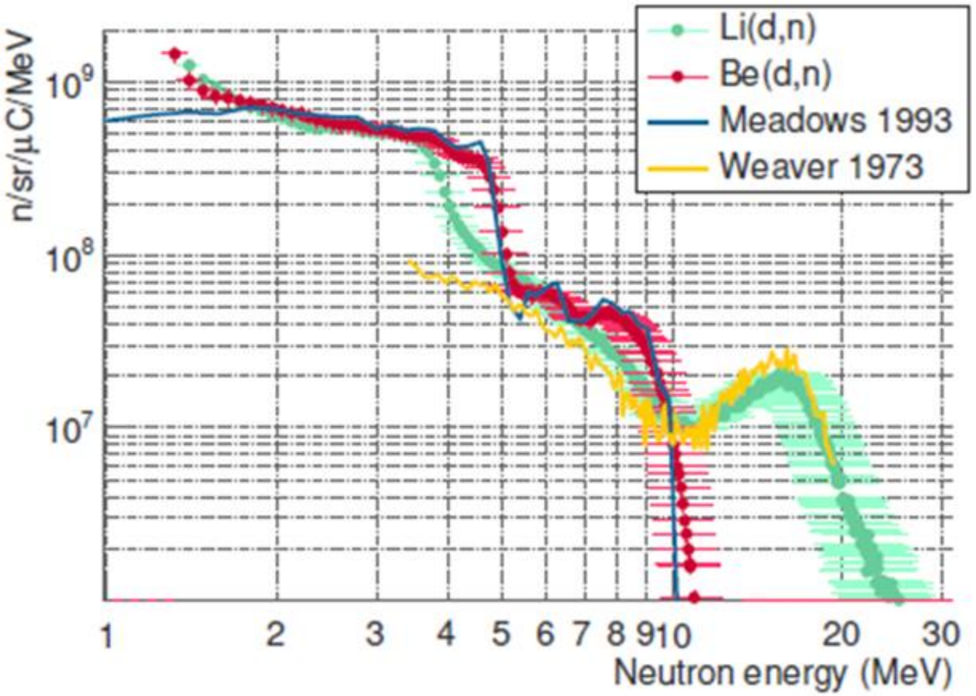
Monoenergetic and Broad Energy Neutron Beams



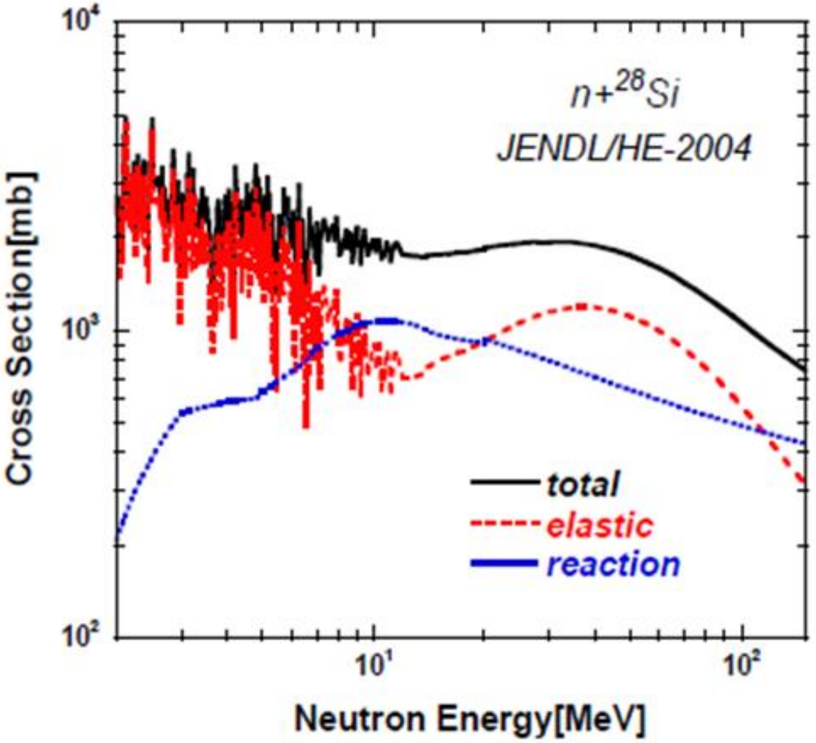


E_d (MeV)	θ (deg)	E_n (MeV)	ΔE/E	Φ_n ($n/sr/\mu C$)	Φ_n (n/cm²/s) *Continuous*	*Pulsed*
1,5	120	2,2	5%	4,5(0,4)·10^5	100(10)	4,0(0,4)
1,5	90	2,8	7%	2,7(0,3)·10^5	60(6)	2,4(0,2)
1,5	60	3,5	8%	4,1(0,4)·10^5	90(9)	3,6(0,4)
1,5	30	4,2	7%	1,2(0,1)·10^6	270(30)	11(1)
1,5	0	4,5	7%	2,6(0,2)·10^6	590(20)	23(2)
2,0	0	5,1	8%	3,1(0,3)·10^6	680(30)	27(3)
3,0	0	6,1	7%	3,7(0,4)·10^6	830(30)	33(3)

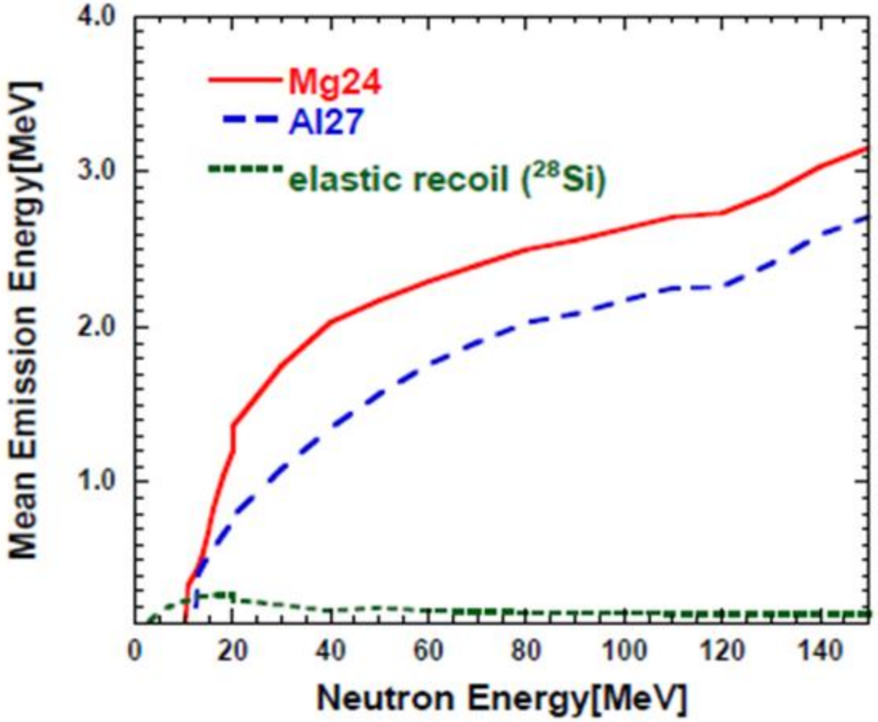
Reaction	E_d (MeV)	Max. E_n (MeV)	Φ_n ($n/sr/\mu C$)	Φ_n (n/cm²/s) *Continuous*	*Pulsed*
Li(d,n)	5,75	~ 20	2,2(0,2)·10^{10}	5,0(0,5)·10^6	2,0(0,2)·10^5
Be(d,n)	5,75	~ 10	2,5(0,3)·10^{10}	5,4(0,5)·10^6	2,2(0,2)·10^5

Expected Nuclear reactions in silicon

Reaction	Threshold (MeV)
$^{28}Si(n,n)^{28}Si$	<keV
$^{28}Si(n,\alpha)\,^{25}Mg$	2.75
$^{28}Si(n,p)\,^{28}Al$	4.00
$^{28}Si(n,n,\alpha)^{24}Mg$ Off limits	10.34 Off limits



Neutron total, elastic and reaction cross-section of ^{28}Si from JENDL/HE-2004

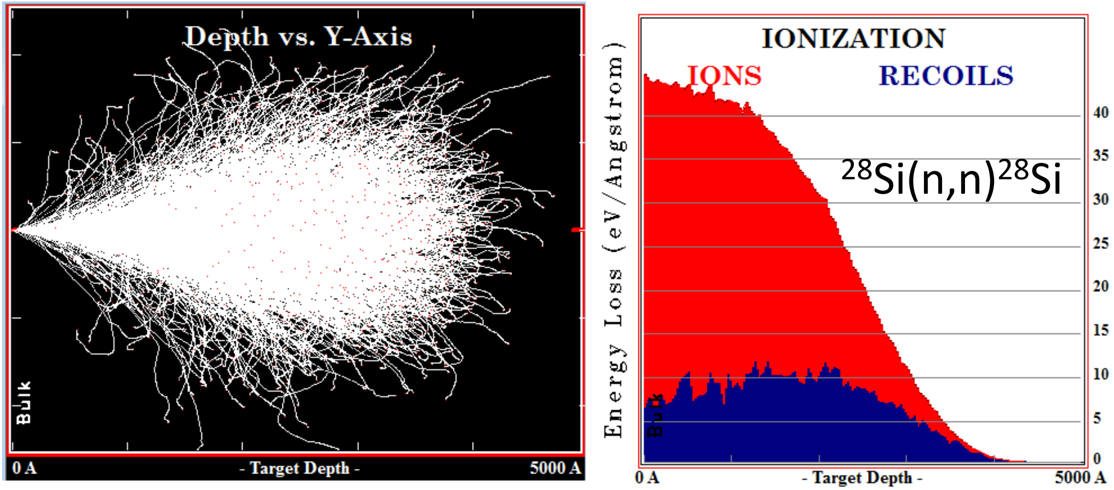


Averaged emission energy for elastic recoil $^{28}Si(n,n)^{28}Si$ and main nuclear reactions $^{28}Si(n,p)^{27}Al$, $^{28}Si(n,\alpha)^{24}Mg$

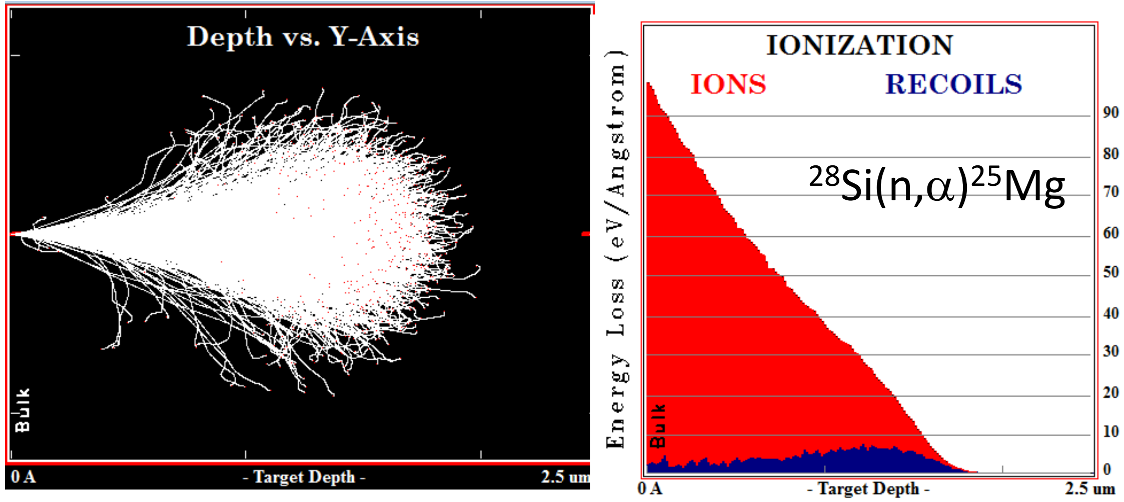
Nuclear data relevant to single event upsets in semiconductor memories induced by cosmic-ray neutrons and protons, Y. Watanabe, H. Nakashima, Proc. of 2006 Symposium on Nuclear Data, Jan 25-26, 2007, SND2006-III.03
Incidence of multiparticle events on soft error rates caused by n-Si Nuclear Reactions, F.Wrobel et al, IEEE TNS 47(6), 2000

Expected Nuclear reactions in silicon

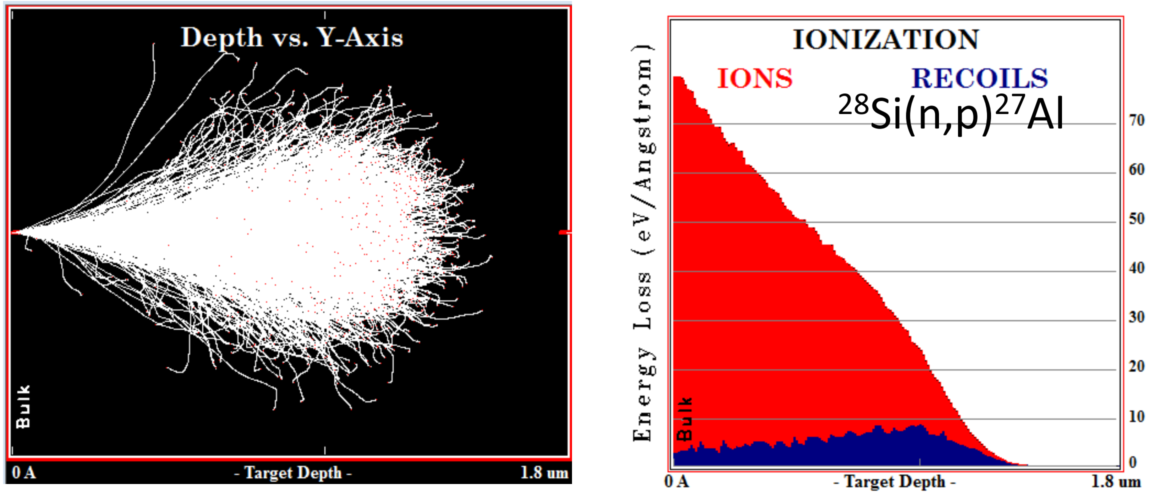
SRIM simulations for Si, Mg and Al ions at different possible kinetic energies from a nuclear reaction gives a hint about LET (minimum) and range in the Silicon Detector Bulk: the ion gives all its energy to the bulk and is trapped.



SRIM range/straggling simulation, IEL, NIEL ^{28}Si 200 keV in silicon bulk



SRIM range/straggling simulation, IEL, NIEL ^{25}Mg 1 MeV in silicon bulk



SRIM range/straggling simulation, IEL, NIEL ^{27}Al 750 keV in silicon bulk

Ion	IEL (eV/Å)	LET (MeV/cm^2-mg)	Mean Range Long./Lateral (µm)
^{28}Si (elastic recoil)	~30	~1.3	~0.27/0.06
^{25}Mg (from ^{28}Si(n,a)^{25}Mg)	~50	~2.1	~1.4/0.3
^{27}Al (from ^{28}Si(n,p)^{27}Al)	~40	~1.7	~1.1/0.2

Ionizing Energy Loss, IEL. Non-Ionizing Energy Loss, NIEL

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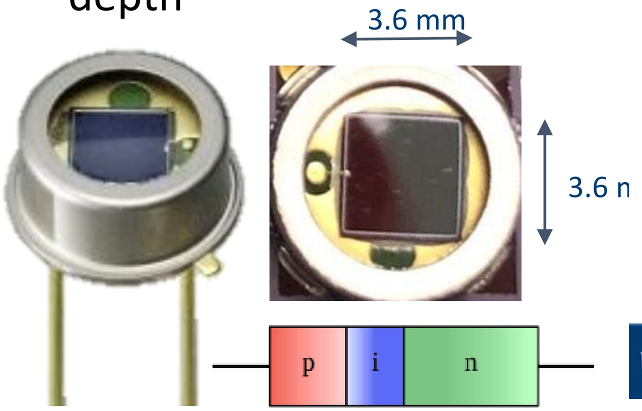
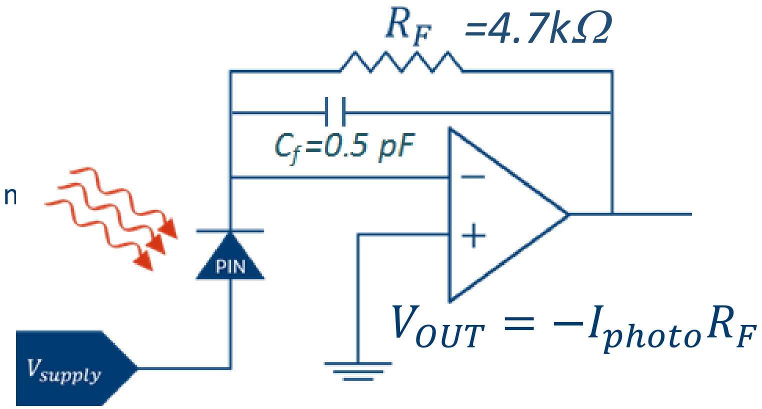
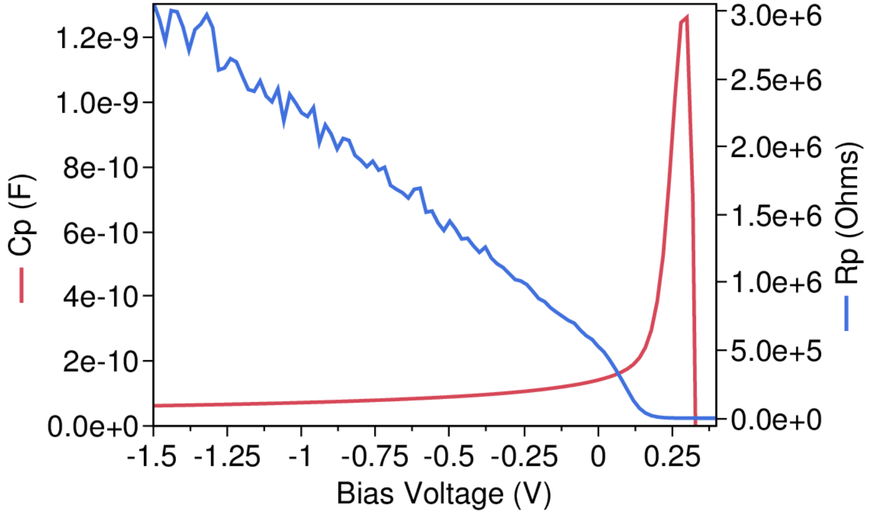
Photodiode Experiment

- Key to successful result is to achieve a very low noise, high speed pre-amplifier.
    - Battery-powered pre-amp board (remove AC noise).
    - Single trans-impedance amplifier, 500MHz BW, femtoA input bias, femtoF input cap (from Analog Devices Inc.).
    - VREF-filtered voltage regulators for low noise (uV) high ripple rejection (68dB).
    - Custom board layout to minimize parasitic capacitances
- Multiple diodes to maximize exposed cross section/oscilloscope channel usage.
- Hamamatsu S1336 series PIN detectors, 20 μm depletion depth

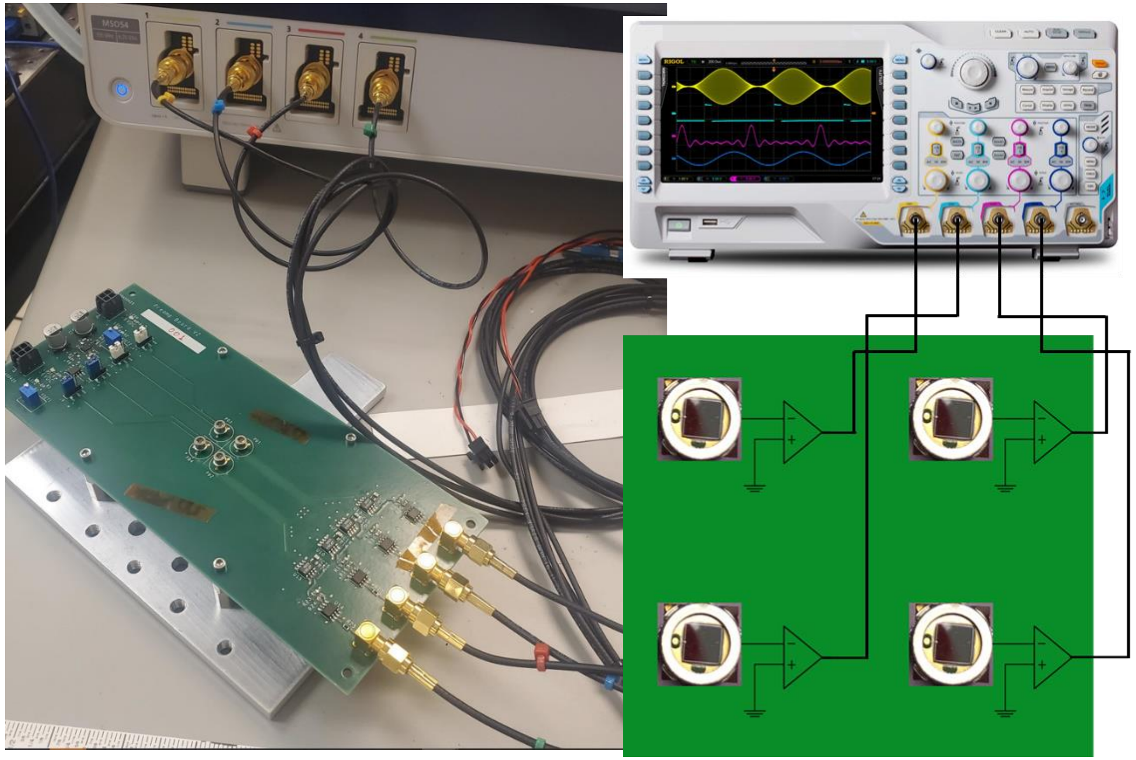






$$d = \frac{\epsilon A}{C}$$

At bias=-1.5 V we calculate depletion depth from the Capacitance Formula, d=20 μm



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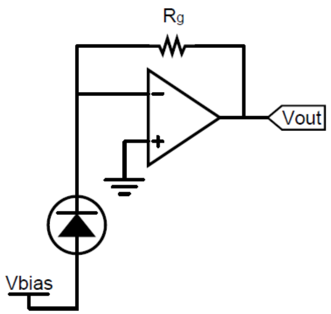
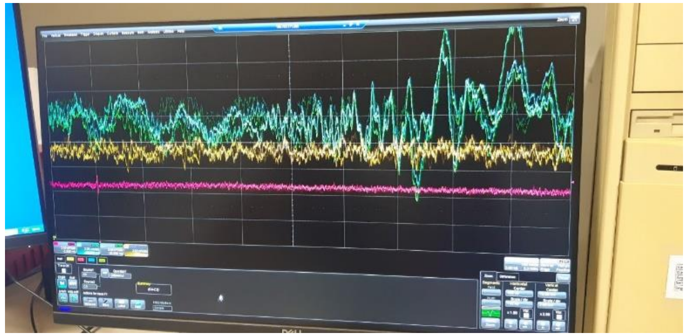
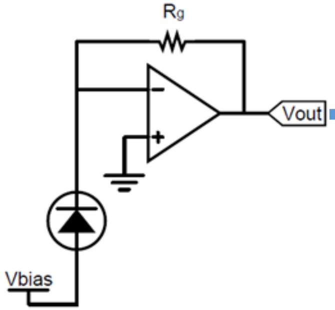
Photodiode Experiment





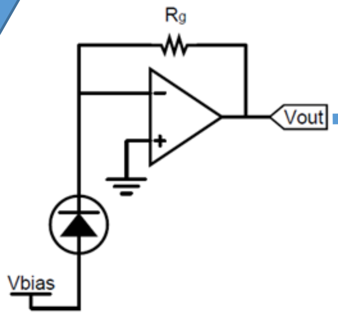
Direct measurement (Trans Impedance Amplifiers) is useful to get signals in a straight manner but it is very sensitive to Electro Magnetic Interference. There is plenty of EMI in the accelerator room, with an amplitude no less than 30 mV. The EMI signal is the same in both detectors but the ionization signal, at an instant, happens in only one.

RF Signals & Neutrons



4ns delay line

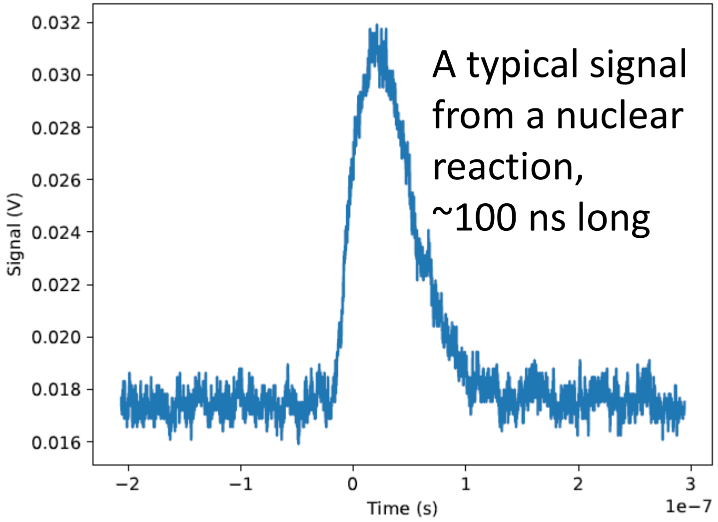
coax



Signal Inversion (delay = 4ns)

Difference Signal

The synchronous difference signal shows only the ionization pulse when a neutron arrives at one detector. Changing Level Trigger Sign selects pulses from one or the other detector



A typical signal from a nuclear reaction, ~100 ns long

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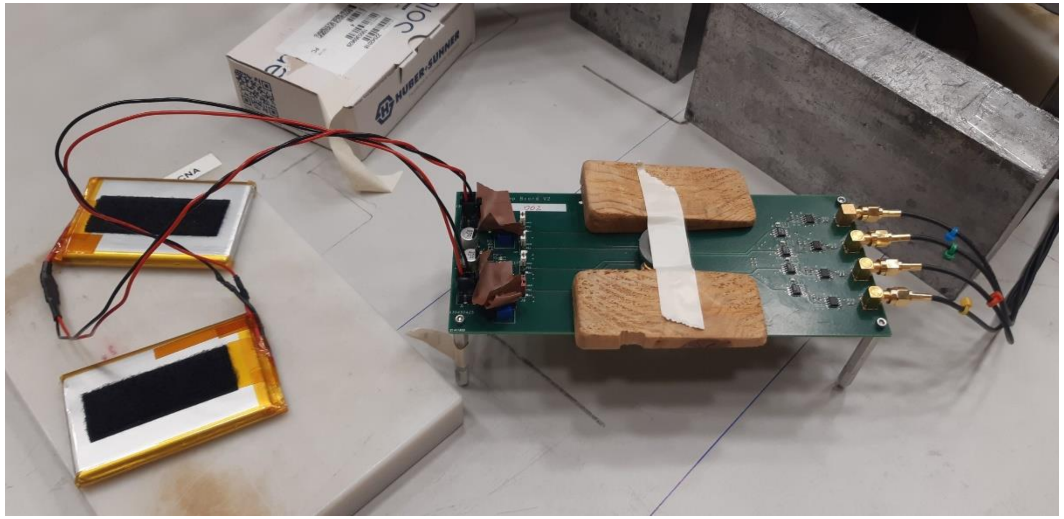
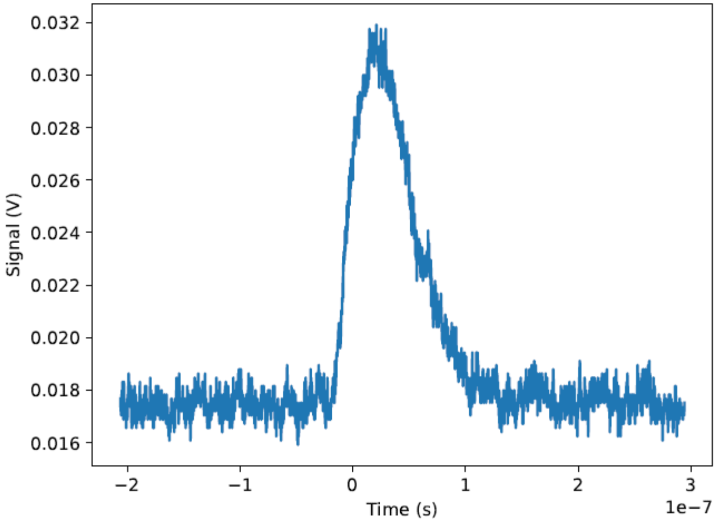
Photodiode Experiment

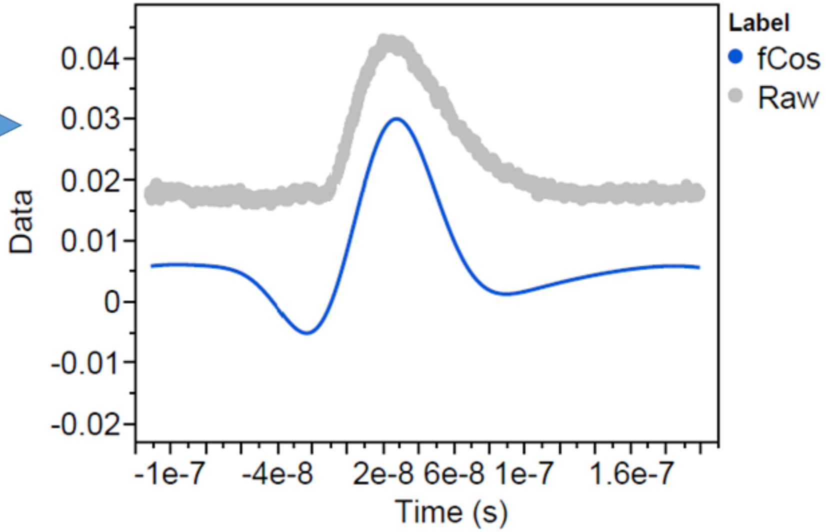
Just for calibration we put the same setup under gamma radiation from a Co60 source (accelerator shut off). We detect no spike from gamma photons so we concluded the dataset from the experiment with the accelerator on was due to neutron induced nuclear reactions in the photodetectors silicon bulk.

Digital Signal Processing of the data set showed the same conclusion:





Digital Data Processing (low pass convolution filter)



$$s(t) * k(t) = \int s(\tau)k(t-\tau)d\tau$$

$$k(t) = \frac{2}{w\sqrt{\pi}} e^{-2\left(\frac{t-w}{w}\right)^2} \cos\frac{2\pi t}{w}$$

low pass filter kernel

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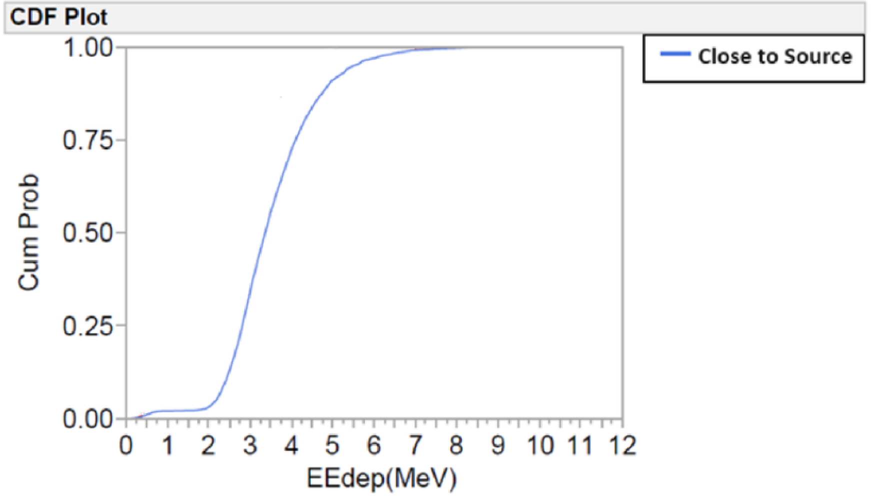
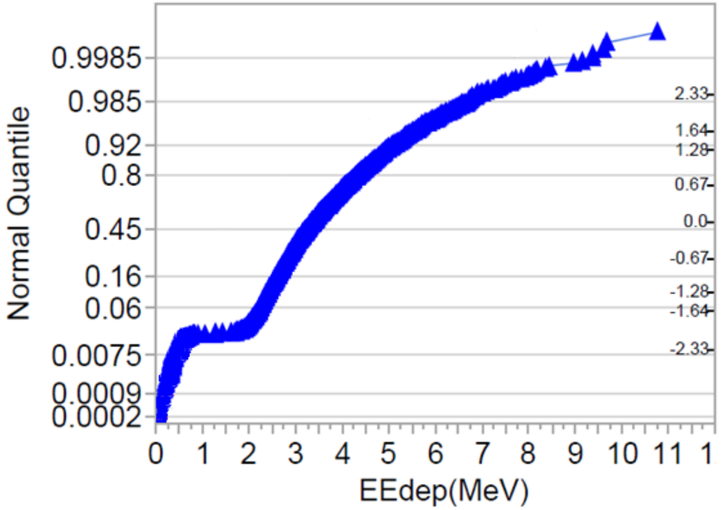
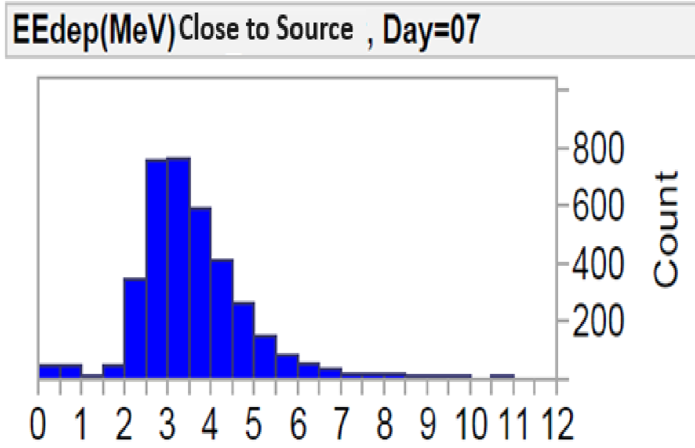
Photodiode Experiment

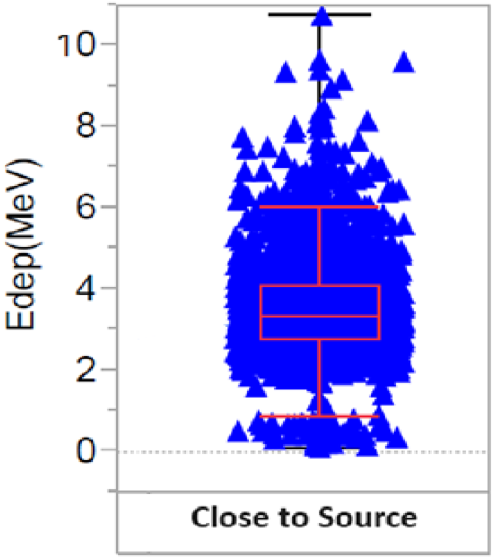




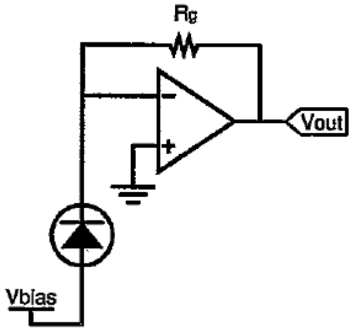
blue: close to neutron source



Summary Statistics	
Mean	3.5234581
Std Dev	1.1329032
N	3499
Minimum	0.0875928
Maximum	10.764085



Event distribution of captured events



$$Q = \int I dt = \int \frac{V_{out}}{R_g} I dt$$

$$E_{dep} = \frac{Q}{e}(3.6\ eV)$$

The analyzed data is consistent with the hypothesis that signals come from ions generated by neutron induced nuclear reactions in Silicon, as expected.

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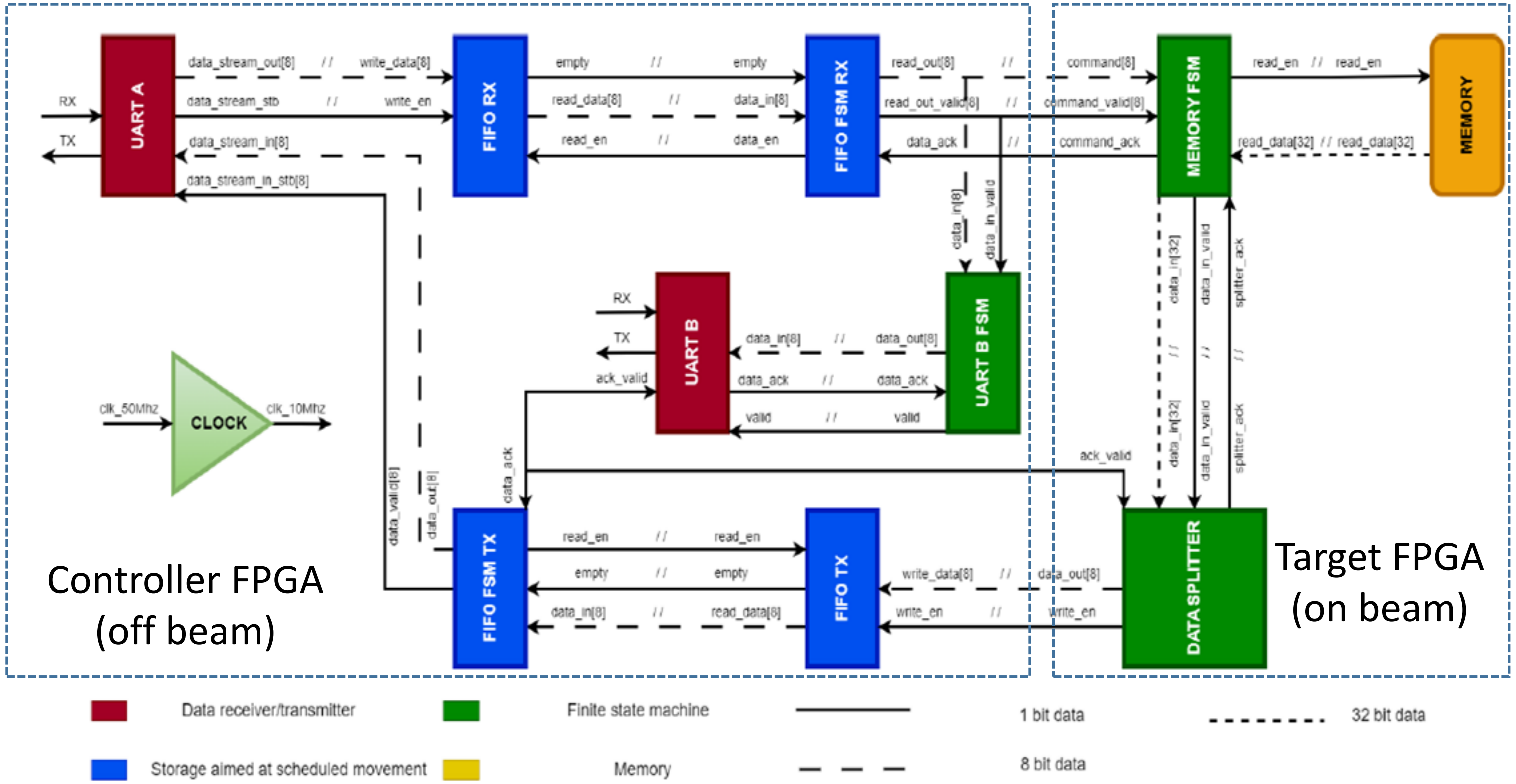
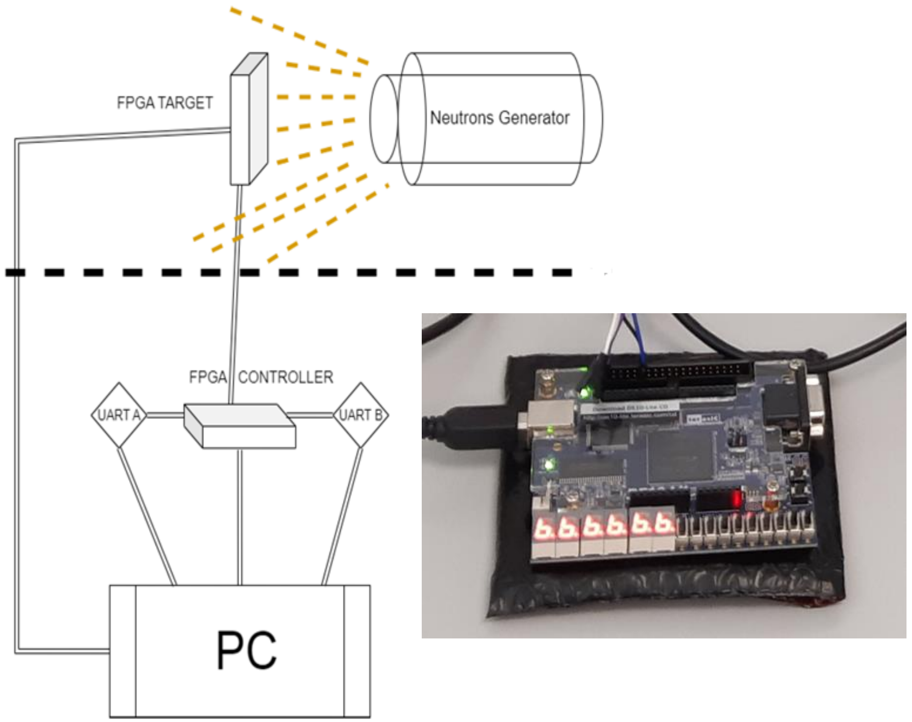
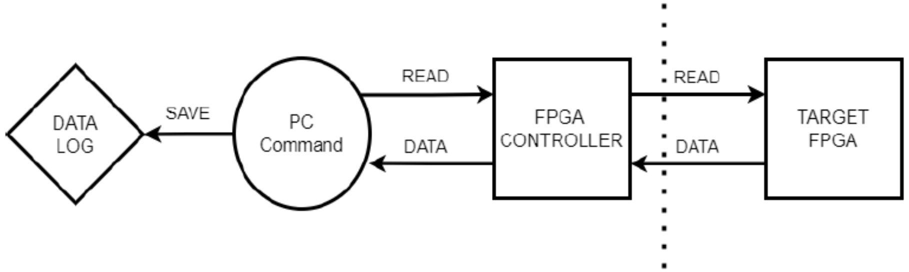
FPGA Experiment

The second experiment was oriented to evaluate the usefulness of HISPANoS for Single Event Upset experiments. The target was a MAX10 FPGA card, with another MAX10 FPGA out of beam as local controller. The MAX10 target had simple digital design: a memory controller and a RAM matrix, made with the flip-flop pool of the FPGA. A simple word (fff...) was recorded in the FPGA RAM memory. The memory controller readouts the RAM and send the data stream to the controller FPGA, from there to the control computer on a safe place. We used two uarts as a double check in the data transfer.







In this experiment the difficult part is at the digital design. Irradiation data analysis is very easy (just a disagreement in the fff... word received).

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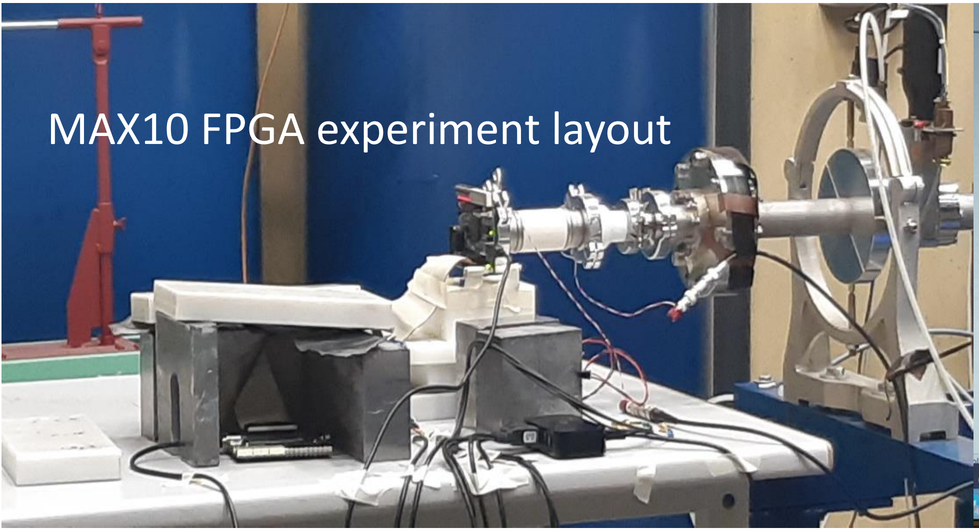
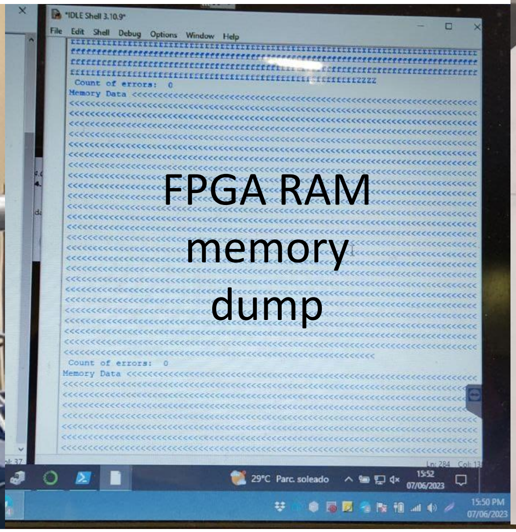
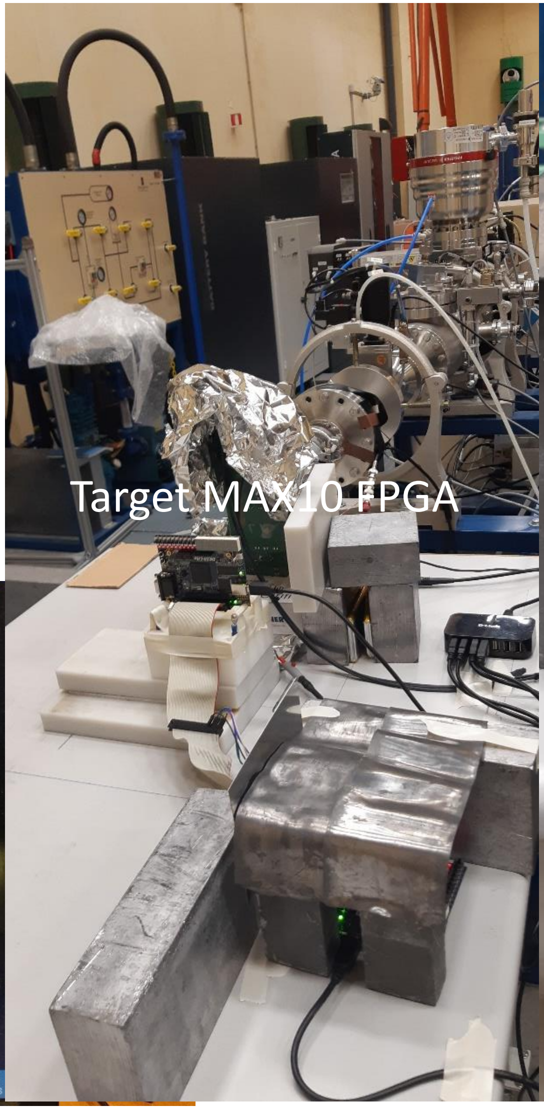
FPGA Experiment

With the Target FPGA close to the neutron source we detected SEUs at a rate of one every couple of minutes, sometimes even a total failure of the readout (an indication of SEU in the memory controller). No stuck bits in any case were seen, with the Target FPGA in pristine condition after scrubbing (or reconfiguration). For future experiments we will design a Shift Register structure in the Target FPGA, without the internal memory controller block, now possible because the MAX10 is insensitive to Single Event Effects Stuck Bits.







Conclusions

- We learned about how to make neutron detection experiments in the new HISPANoS neutron beam facility at CNA, Sevilla
- The photodiode experiment opens the way to more sophisticated detector experiments in the facility. As a plus, we got straight signals from neutron (up to 10 MeV) induced nuclear reactions in silicon.
- The MAX10 FPGA shows no stuck bits under neutron irradiation. New Neutron Single Event Effects experiments are planned.

Thanks to the funding programme H2020-ARIEL

Thanks for your attention!

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