Detection of neutron induced reactions in silicon photodiodes at the HISPANoS facility

Detector and SEE experiments

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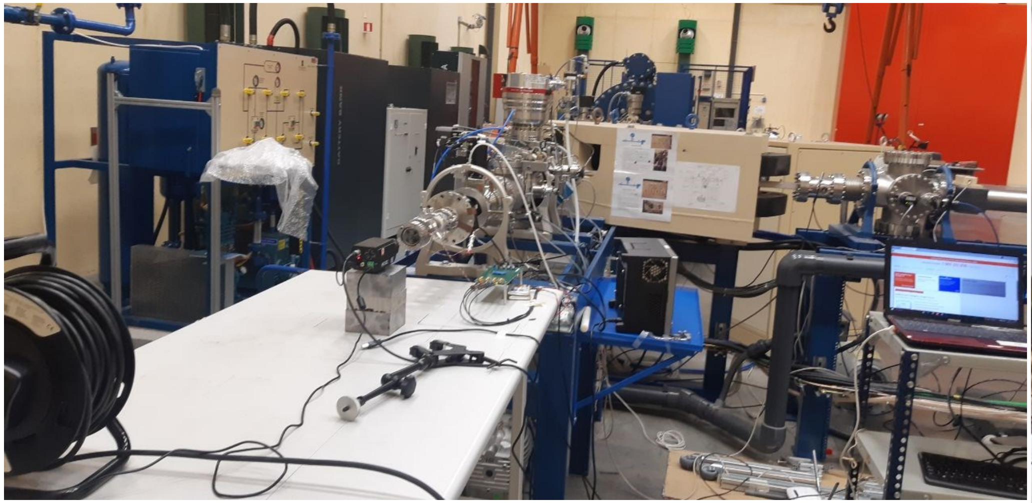
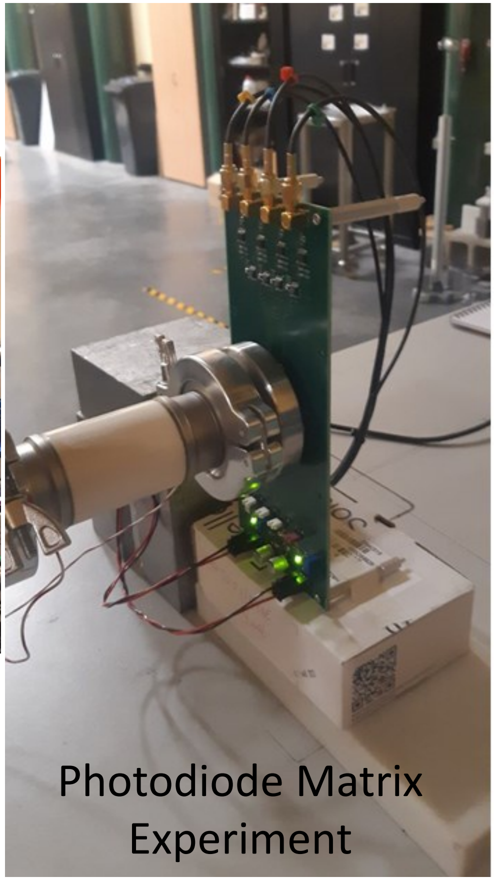
Introduction

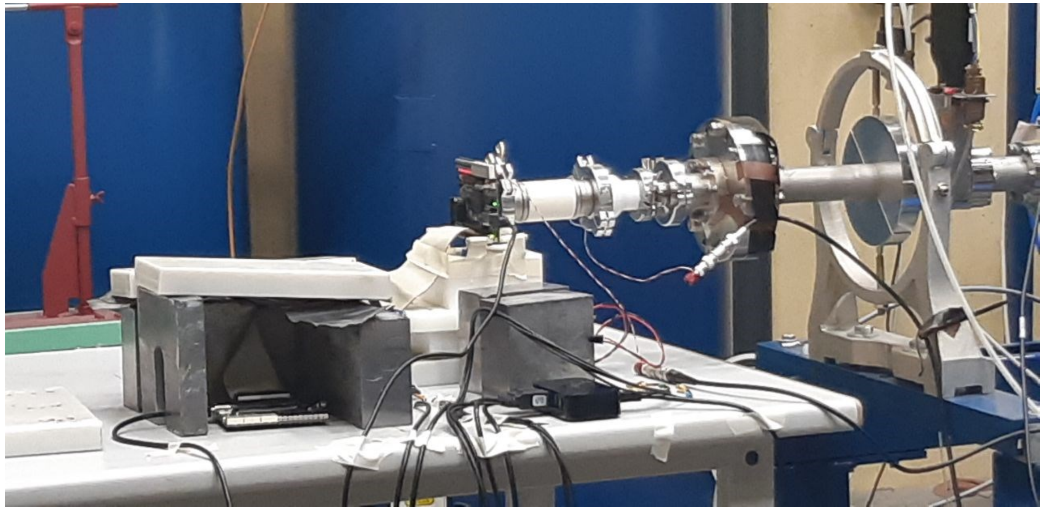
1. About the new HISPANoS neutron beam now open for experiments at the National Center of Accelerators, Sevilla, Spain
2. On a first experiment about detection of neutron induced nuclear reactions in silicon photodiodes and its intrincacies
3. Neutron induced Single Event Effects in an Intel MAX10 FPGA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



Preparation of the Neutron Beam Line for the experiment



Photodiode Matrix Experiment



SEU FPGA experiment

Detection of neutron induced reactions in silicon photodiodes at the HISPANoS facility

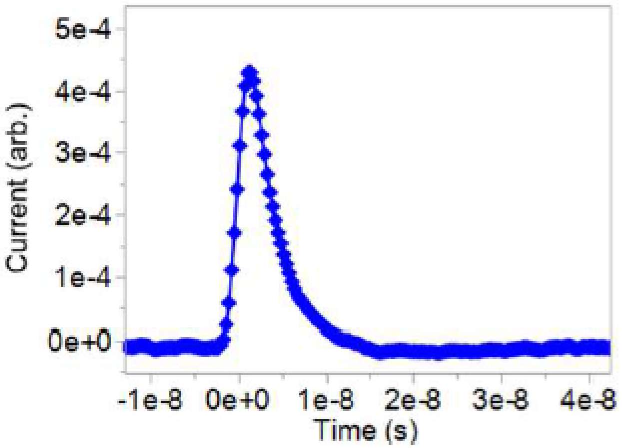
Motivation:

1. Neutron irradiation of semiconductors generates ions (^{28}Si elastic scattering, $^{28}Si(n,\alpha)^{25}Mg$, $^{28}Si(n,p)^{27}Al$ mainly) in the semiconductor bulk. Those secondary ions have a short flight range in the device, generating **internal localized ionization volumes**.
2. Solid State Detectors give a **signal proportional** to the amount of **electron-holes generated in the ionization volume**.
3. It is posible to generate **photoionization localized volumes** inside a semiconductor detector using **lasers** with wavelength λ>1200 nm (**Two Photon Absorption**). Ultrashort laser pulses (<<1 ps) mimic the secondary ion flight lapse.

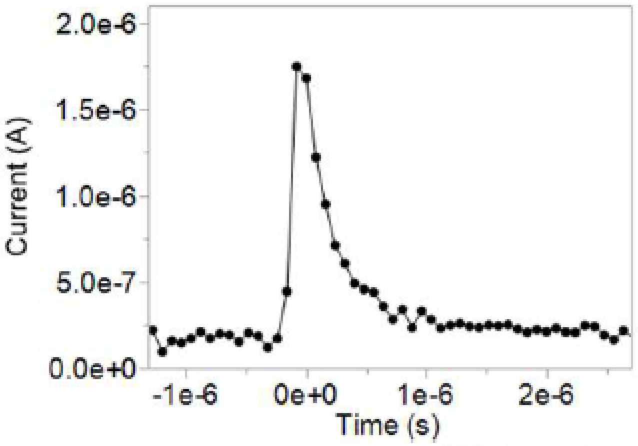
We want to record a signal dataset from neutrón interaction inside a photodiode. We generated a second signal dataset illuminating the photodiode with a femtosecond pulsed laser with a wavelength λ>1200 nm (Two Photon Absorption regime) (Intel Labs). **The purpose is to cross calibrate neutron signals with laser signals. Ultrashort pulsed lasers are a simplest tool to analyze Single Event Effect in electronics.**

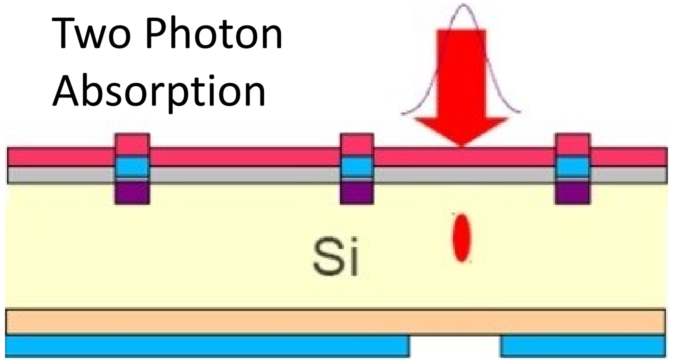
The photodiode experiment (small active region) in this presentation is related to the neutron reactions signal data set.

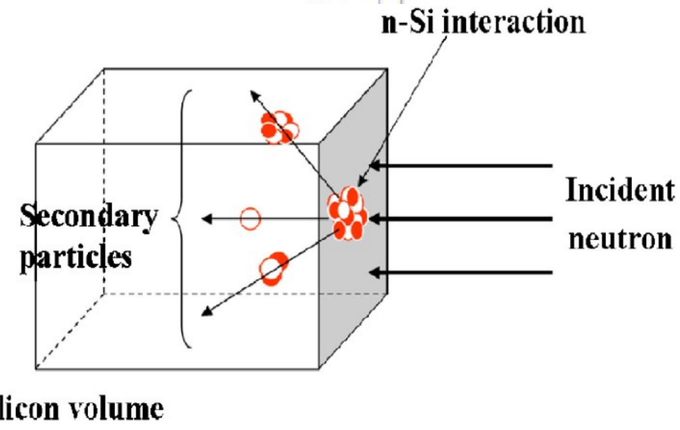
Laser pulse on a photodiode



Neutron collision on a photodiode







M.Wiehe; M.Fernández García; M.Moll; R.Montero; F.R.Palomo, I.Vila, H.Muñoz Marco, V.Otgón, P.Pérez-Millán; Development of a Tabletop Setup for the Transient Current Technique Using Two-Photon Absorption in Silicon Particle Detectors; *IEEE Transactions on Nuclear Science* **68 (2),** (2021)

H. Chabane; J. R. Vaillé; T. Mérelle; F. Saigné; L. Dusseau; M. Dumas; J. M. Palau; B. Barelaud; J. L. Decossas; F. Wrobel; N. Buard; M. C. Palau; Determination of the deposited energy in a silicon volume by n-Si interaction *Journal of Applied Physics* **99,** 124916 (2006)

Related approaches: Y.Chiang et al.;Investigate the equivalence of neutrons and protons in single event effects testing: A Geant4 Study, Applied Science,10, 3234 (2020) , M.A.Clemens et al.: The effects of neutron energy and high-Z materials on single event upsets and multiple cell upsets, IEEE Trans.Nucl.Sci., 58(6),(2011)

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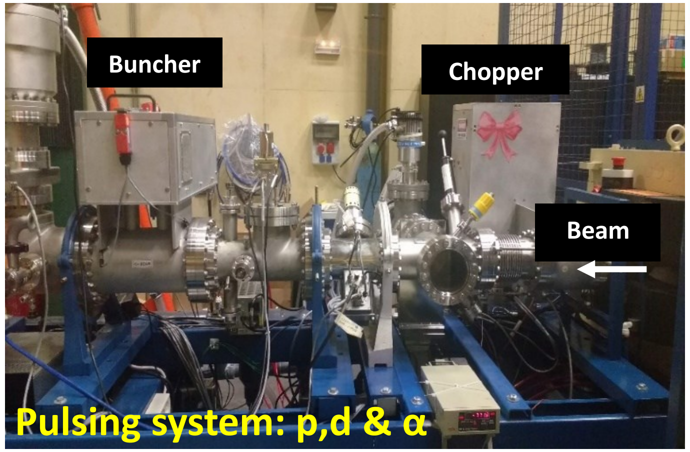
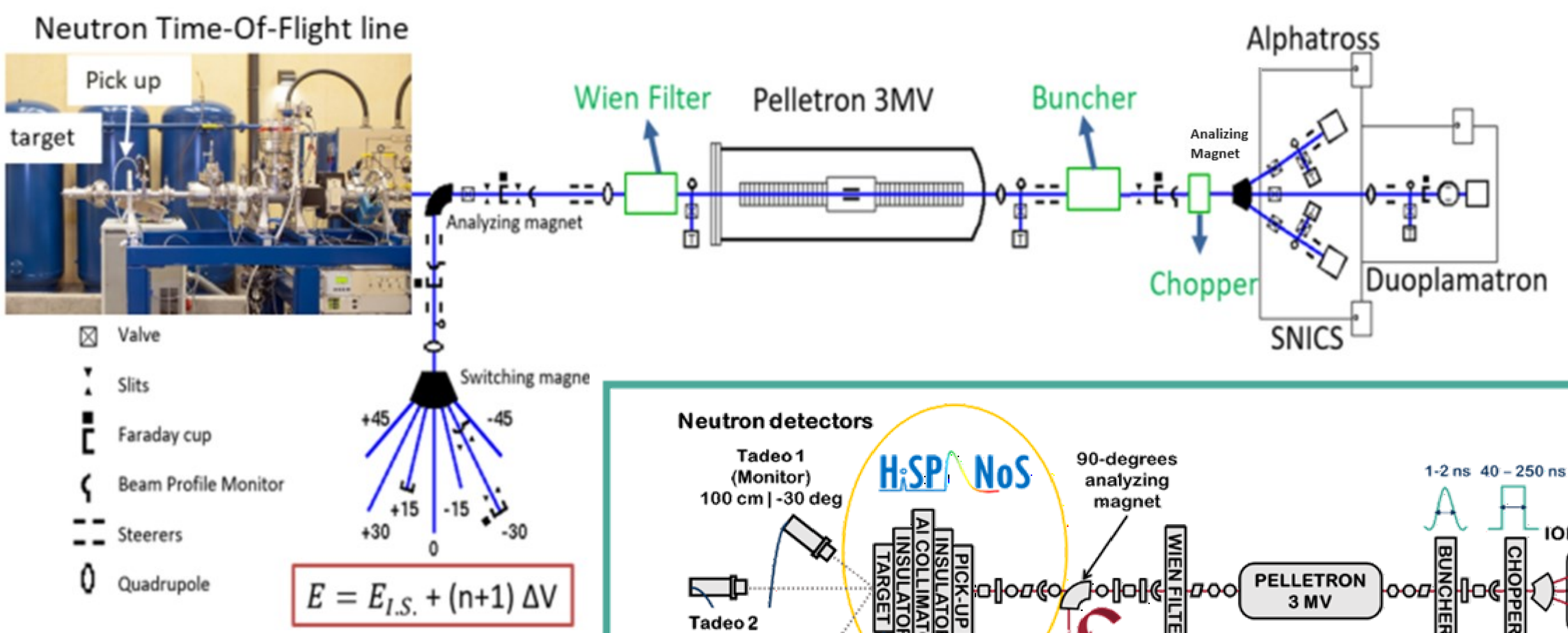
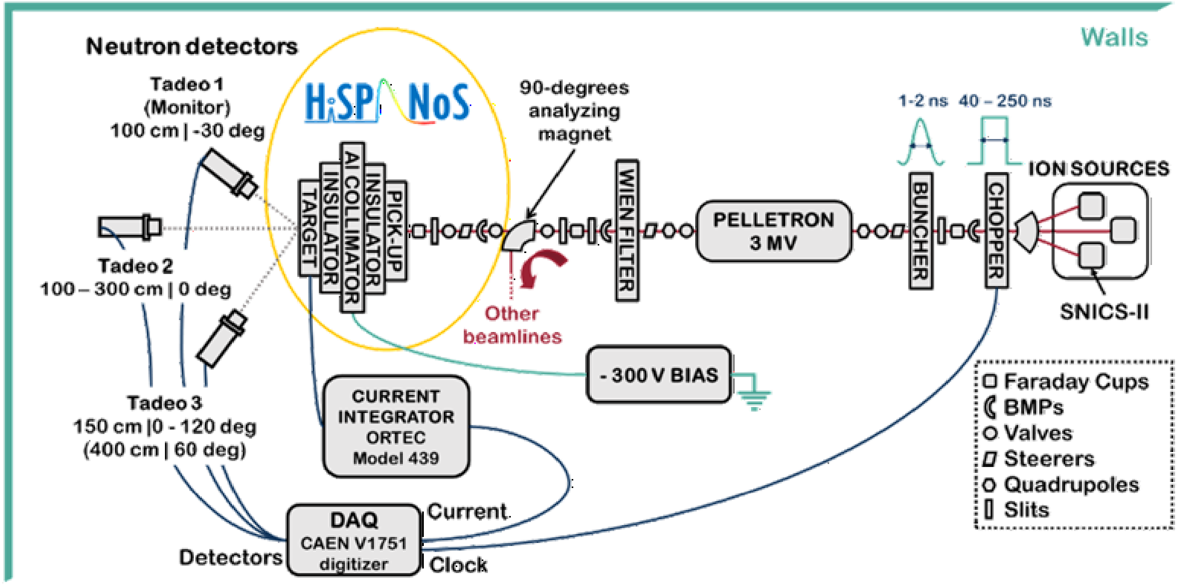




$$E = E_{I.S.} + (n+1)\,\Delta V$$



Buncher:
Variable width: 1-2 ns
Needs tuning (delay & power) for synchronization

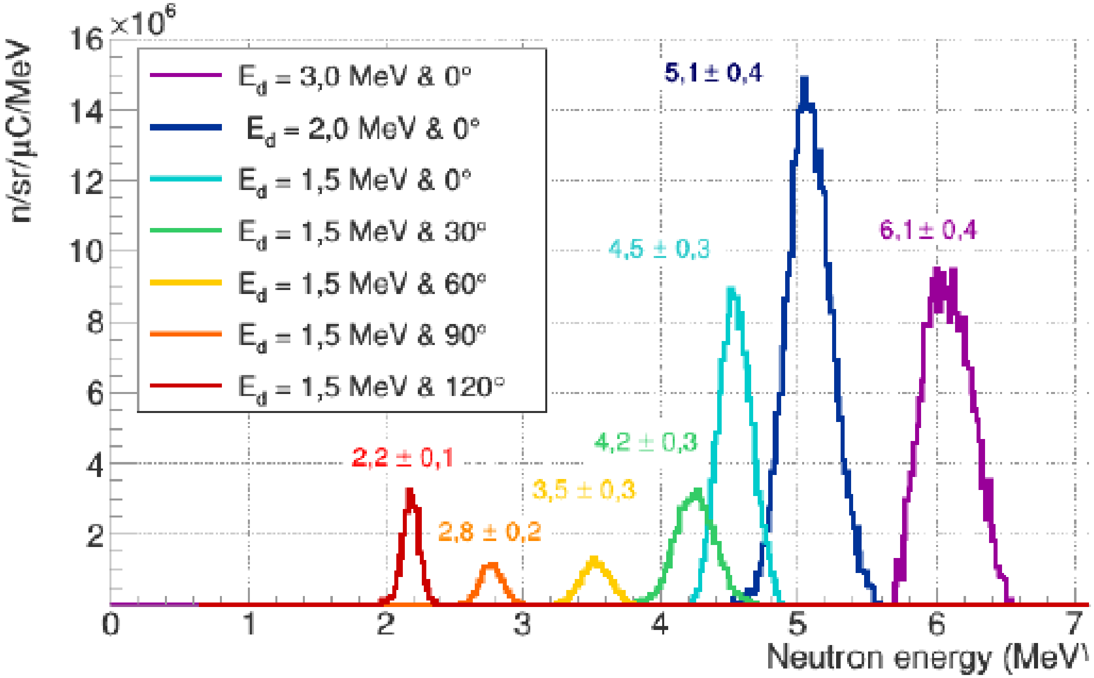
Chopper:

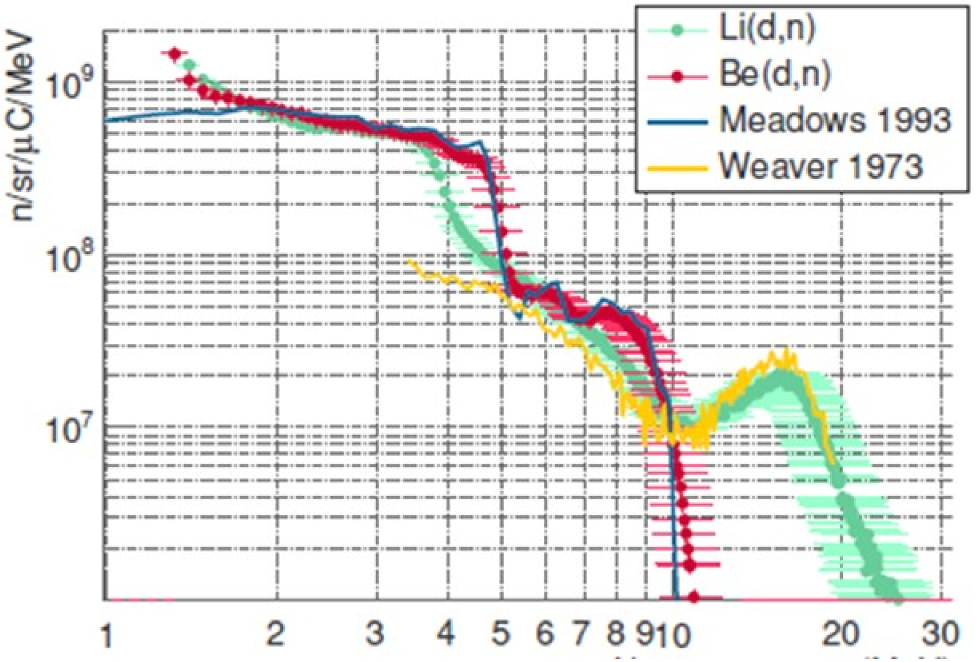
- Variable width: 40 ns-250 ns
- RR: 31.25 kHz-2MHz
- Switcher Voltage: 650 V

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.

Detection of neutron induced reactions in silicon photodiodes at the HISPANoS facility

Monoenergetic and Broad Energy Neutron Beams available at HISPANoS





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)

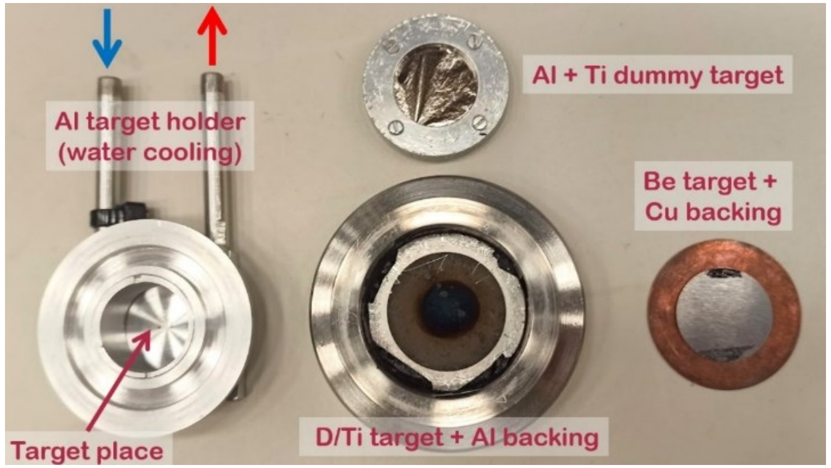
Reaction	E_d (MeV)	Max. E_n (MeV)	Φ_n ($n/sr/\mu C$)	Φ_n ($n/cm^2/s$) *Continuous*	*Pulsed*
Li(d,n)	5,75	~ 20	2,2(0,2)·10^{10}	5,0(0,5)·10^6	2,0(0,2)·10^5
Be(d,n)	5,75	~ 10	2,5(0,3)·10^{10}	5,4(0,5)·10^6	2,2(0,2)·10^5

More details at "Continuous and pulsed fast neutron beams at the CNA HiSPANoS facility", M.A.Millán-Callado et al., Radiation Physics and Chemistry, 217 (2024) 111464

Detection of neutron induced reactions in silicon photodiodes at the HISPANoS facility

Neutron production targets/mechanisms

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



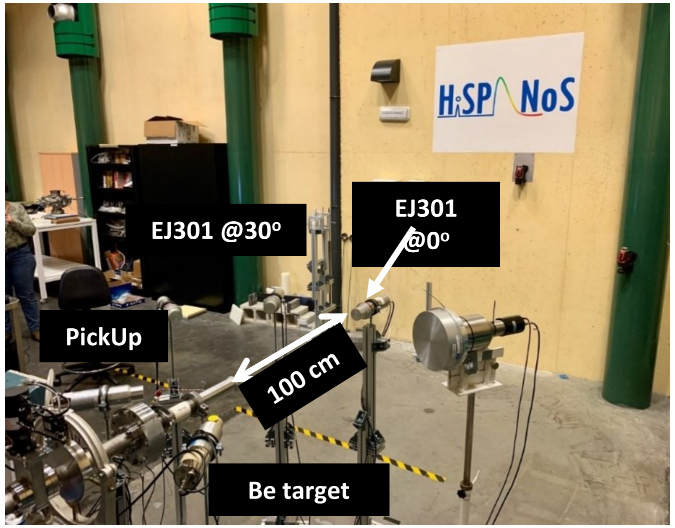
Projectiles
- ^{1}H, ^{2}H up to 6 MeV
- ^{4}He up to 6 MeV

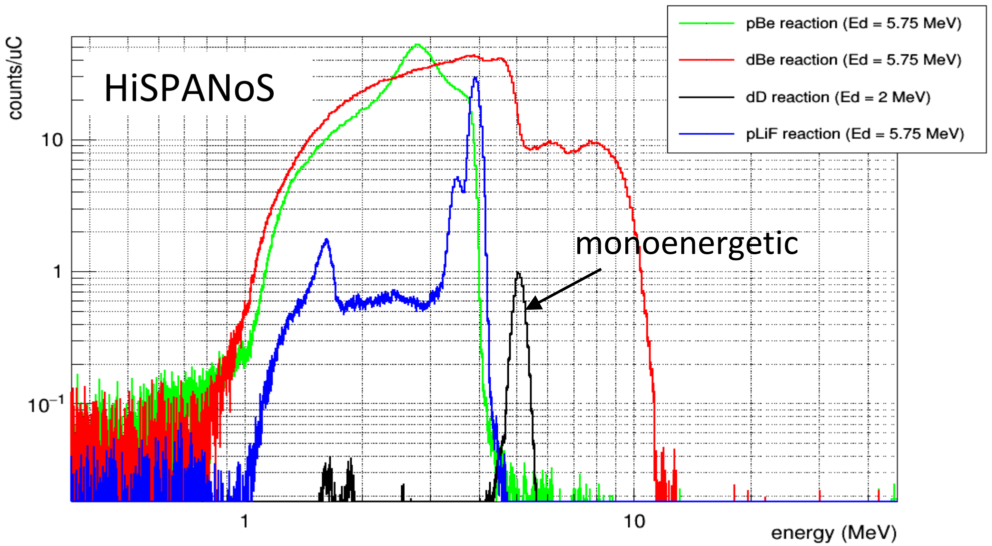
Continuous mode
- Up to 10 uA

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

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/cm²	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



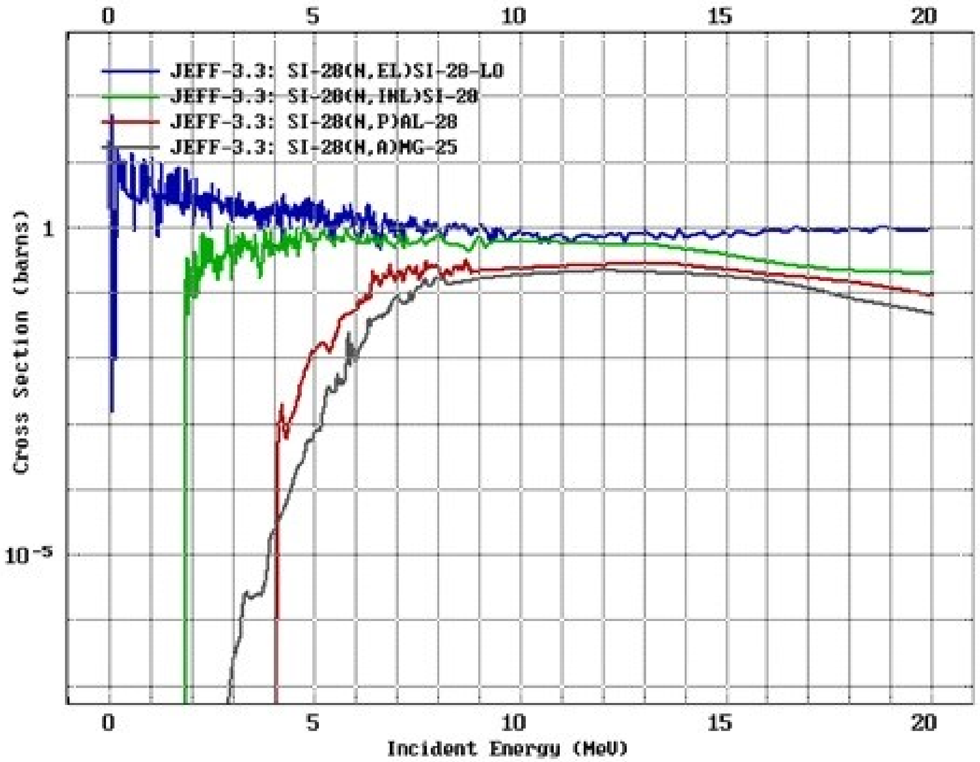


Detection of neutron induced reactions in silicon photodiodes at the HISPANoS facility

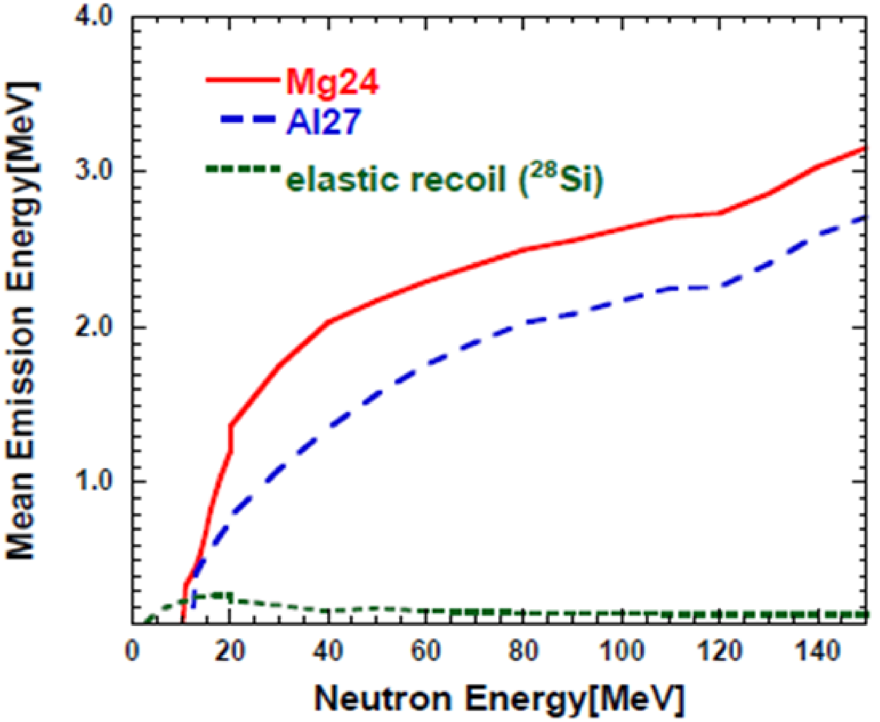
Expected Nuclear reactions in silicon

Reaction	Threshold (MeV)
$^{28}Si(n,n)^{28}Si$	-
$^{28}Si(n,\gamma)^{29}Si$	1,779
$^{28}Si(n,\alpha)\,^{25}Mg$	2.75
$^{28}Si(n,p)\,^{28}Al$	4.00
$^{28}Si(n,n,\alpha)^{24}Mg$ Off limits	10.34 Off limits

n up to 10 MeV (continuum) $^{9}Be(d,n)^{10}B$ production reaction



Reaction cross sections, ^{28}Si(n,elastic) in blue, ^{28}Si(n,inelastic) in green, $^{28}Si(n,a)^{25}Mg$ in dark grey, $^{28}Si(n,p)^{28}Al$ in red, requested from the Evaluated Nuclear Data File (ENDF) website, https://www.nndc.bnl.gov/endf



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

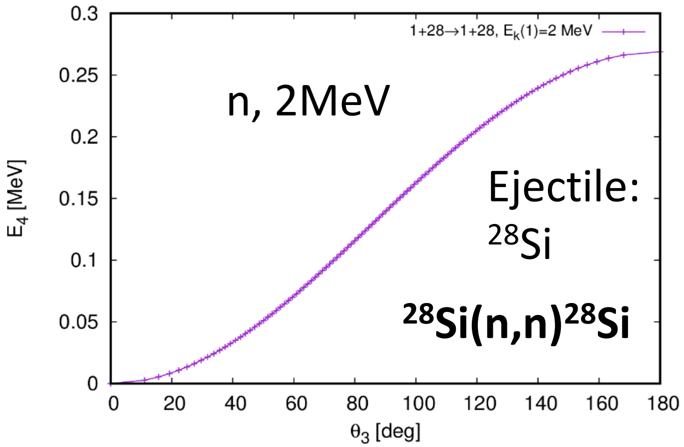
Detection of neutron induced reactions in silicon photodiodes at the HISPANoS facility

Kinematics analysis of typical nuclear reactions 28Si(n,x)X up to neutron 10 MeV to get an input to SRIM sims, for example:

Reaction summary for 1+28→1+28, $E_k(1)$=2 MeV

- The maximum 1 energy is 2 MeV. The minimum 1 energy is 1.731 MeV.
- The maximum 28 energy is 0.269 MeV. The minimum 28 energy is 0 MeV. The maximum 28 angle is 90 degrees.

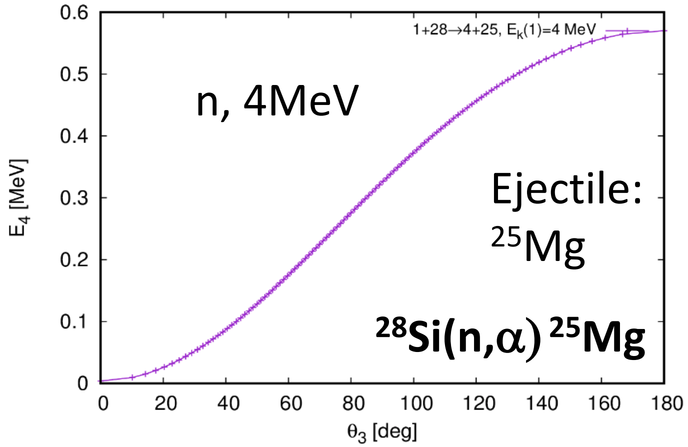
KE_4 as a function of θ_3:



Reaction summary for 1+28→4+25, $E_k(1)$=4 MeV

- The maximum 4 energy is 1.343 MeV. The minimum 4 energy is 0.777 MeV.
- The maximum 25 energy is 0.57 MeV. The minimum 25 energy is 0.004 MeV.

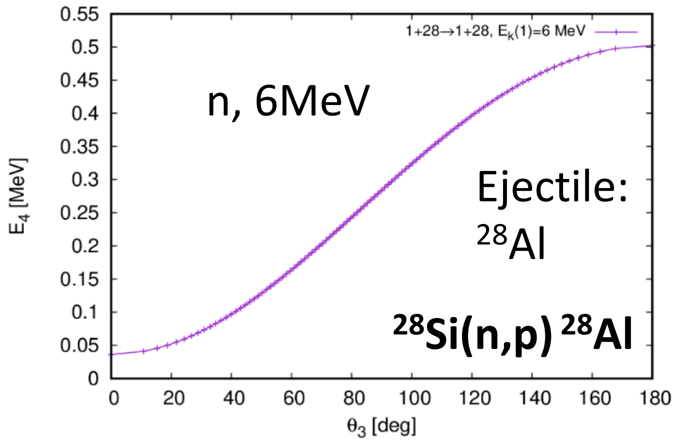
KE_4 as a function of θ_3:



Reaction summary for 1+28→1+28, $E_k(1)$=6 MeV

- The maximum 1 energy is 2.104 MeV. The minimum 1 energy is 1.638 MeV.
- The maximum 28 energy is 0.502 MeV. The minimum 28 energy is 0.036 MeV. The maximum 28 angle is 35.21 degrees.

KE_4 as a function of θ_3:



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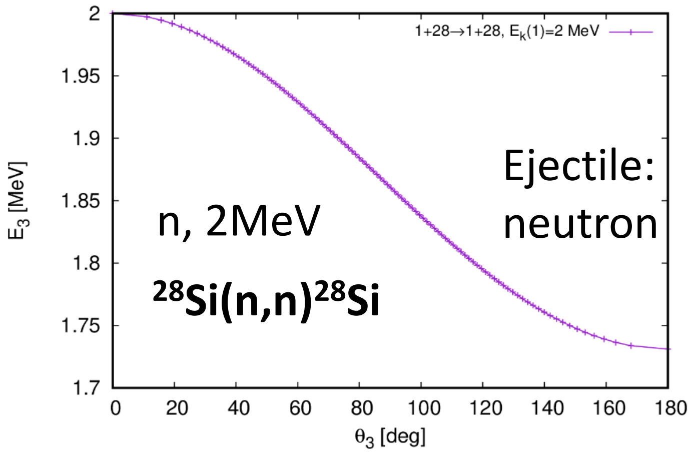
- The maximum 1 energy is 2 MeV. The minimum 1 energy is 1.731 MeV.
- The maximum 28 energy is 0.269 MeV. The minimum 28 energy is 0 MeV. The maximum 28 angle is 90 degrees.

KE_3 as a function of θ_3:



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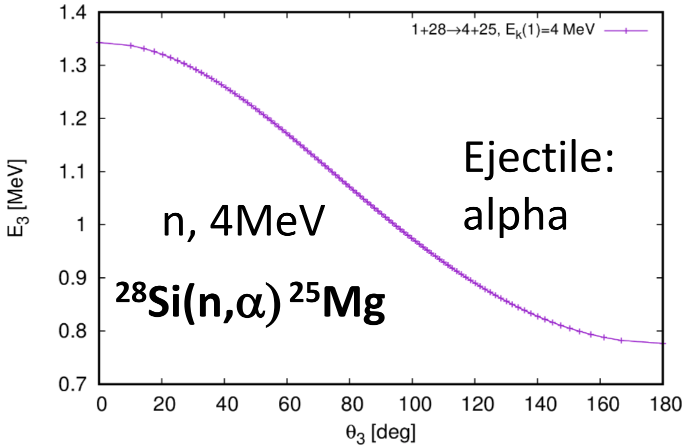
- The maximum 25 energy is 0.57 MeV. The minimum 25 energy is 0.004 MeV.

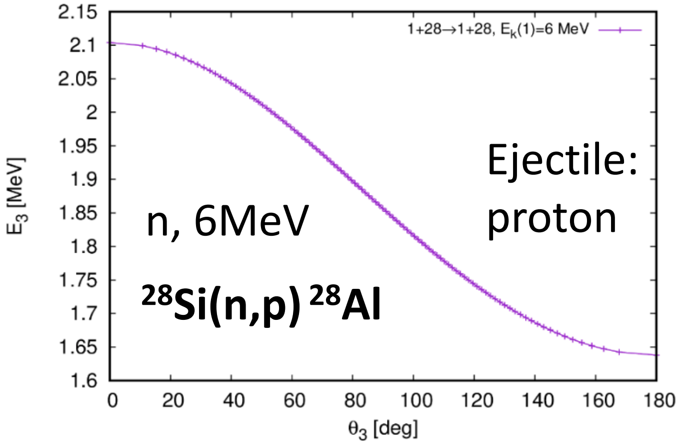
KE_3 as a function of θ_3:



Reaction summary for 1+28→1+28, $E_k(1)$=6 MeV

- The maximum 1 energy is 2.104 MeV. The minimum 1 energy is 1.638 MeV.
- The maximum 28 energy is 0.502 MeV. The minimum 28 energy is 0.036 MeV. The maximum 28 angle is 35.2

KE_3 as a function of θ_3:

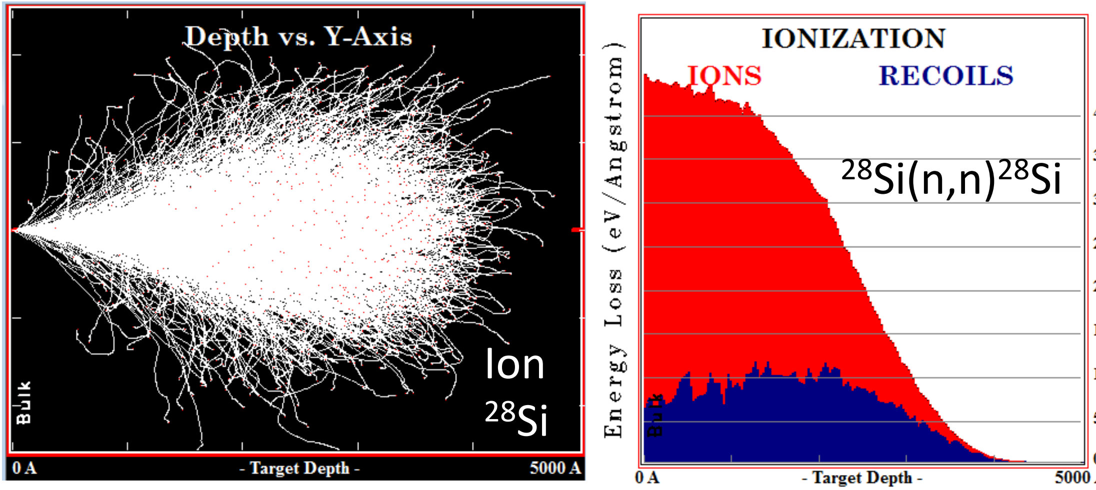


https://www.nndc.bnl.gov/qcalc/
https://skisickness.com/2010/04/relativistic-kinematics-calculator/

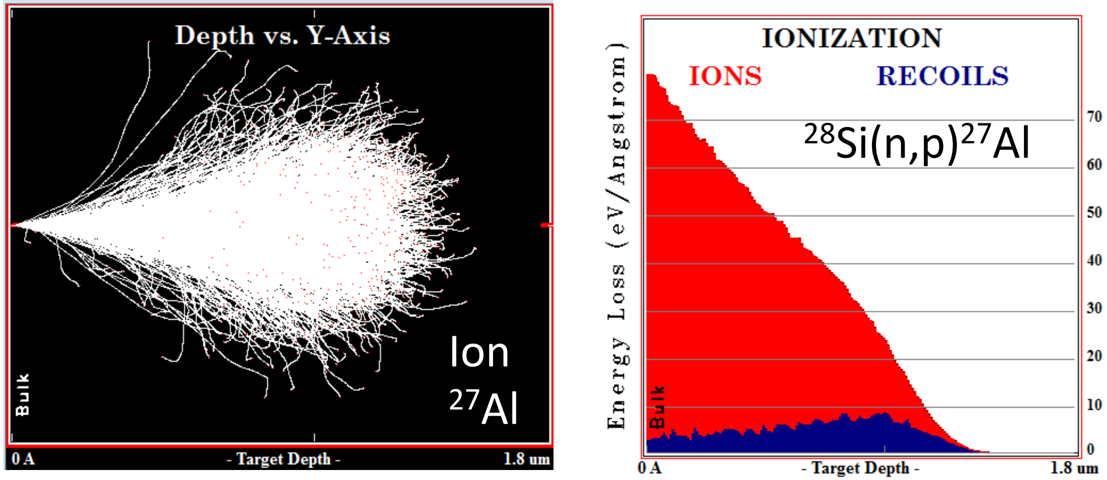
Detection of neutron induced reactions in silicon photodiodes at the HISPANoS facility

Expected Nuclear reactions in silicon

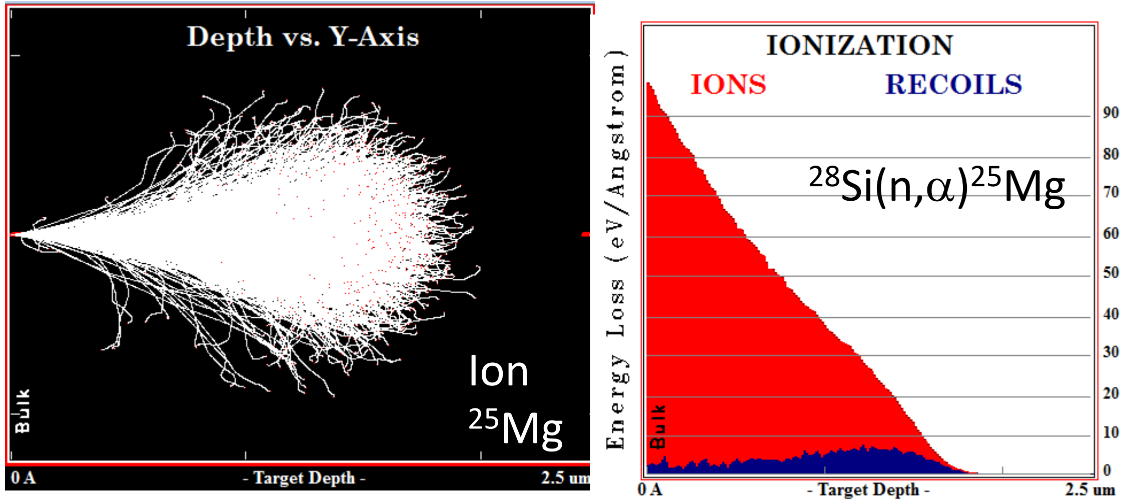
SRIM simulations for α, Si, Mg and Al ions at different possible kinetic energies from a nuclear reaction gives a hint about LET (minimum) and range in the Silicon Detector Bulk: the ions give all their energy to the bulk and get trapped.



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



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



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

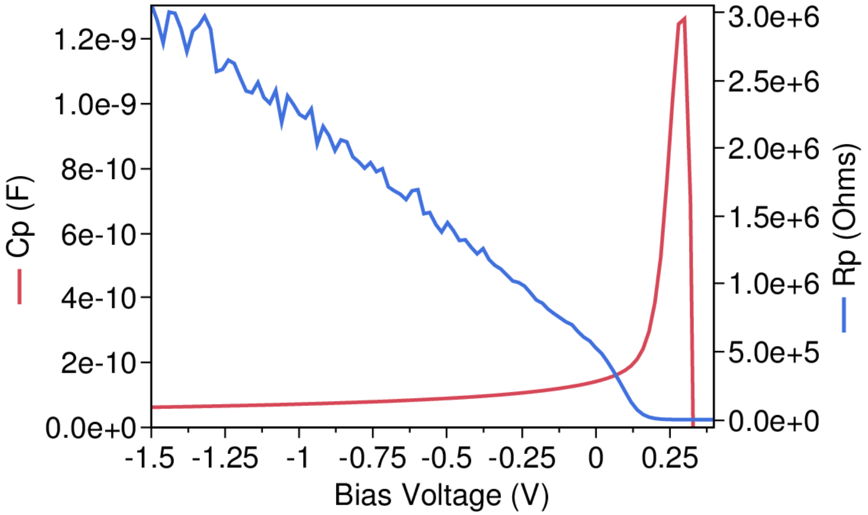
Ion	IEL (eV/Å)	LET (MeV/cm^2-mg)	Mean Range Long./Lateral (µm)
^{28}Si (elastic recoil)	~20	~0.8	~0.27/0.06
^{25}Mg (from $^{28}Si(n,\alpha)^{25}Mg$)	~50	~2.1	~1.4/0.3
^{27}Al (from $^{28}Si(n,p)^{27}Al$)	~40	~1.7	~1.1/0.2
α (from $^{28}Si(n,\alpha)^{25}Mg$)	~30	~1.3	~3,5/0.2

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

Detection of neutron induced reactions in silicon photodiodes at the HISPANoS facility

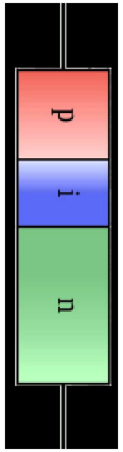
Photodiode Experiment

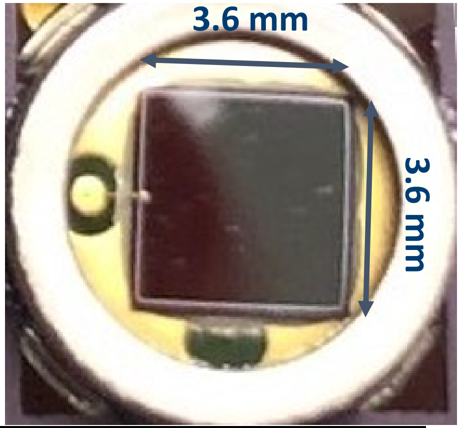
- **Direct Measurement with Trans Impedance Amplifiers to get raw signals.**
- Key to successful result is to achieve a very low noise, high speed pre-amplifier. Battery-powered pre-amp board (remove AC noise).
  - Single trans-impedance amplifier, 500MHz BW, femtoA input bias, femtoF input cap (from 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 to mimic Single Event Effect (SEE) experiments**

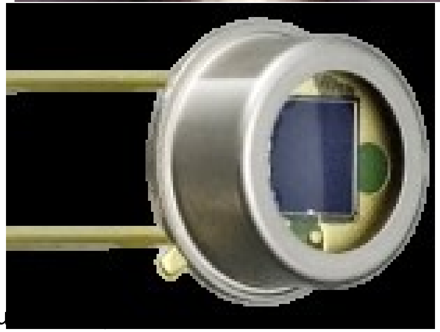


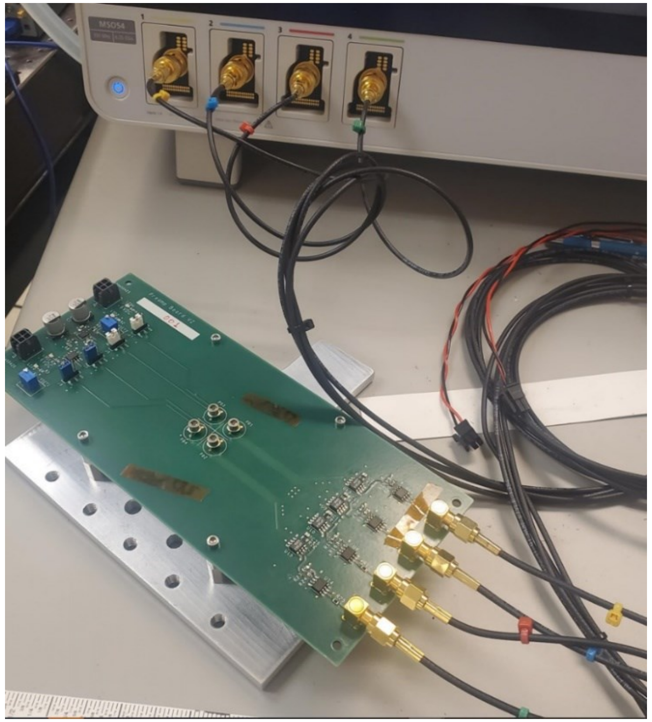
$$d = \frac{\epsilon A}{C}$$

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









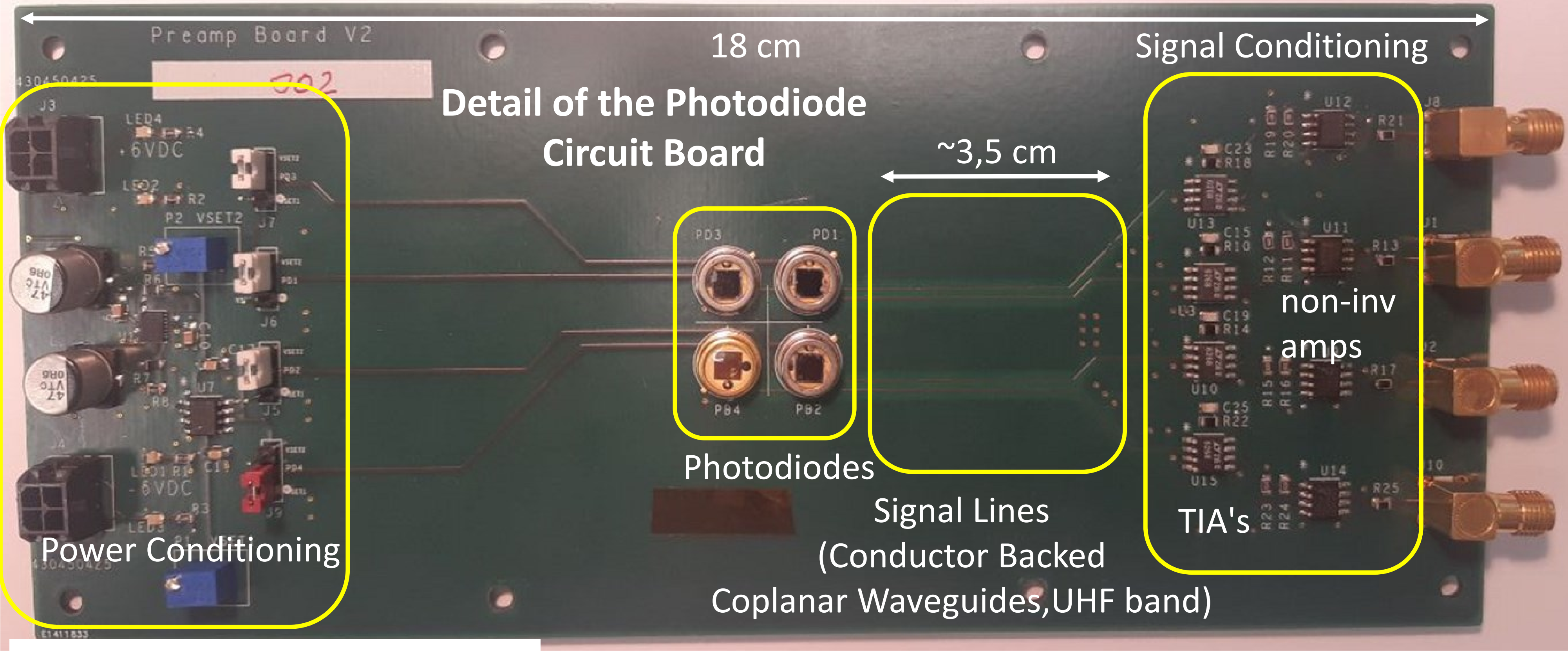
Detection of neutron induced reactions in silicon photodiodes at the HISPANoS facility

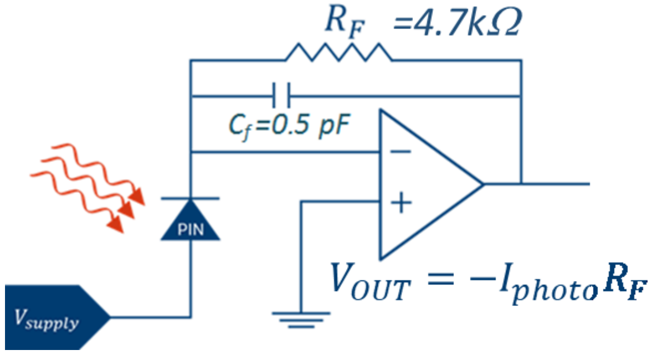
https://indico.ijclab.in2p3.fr/event/9751/ ARIEL H2020 Final Workshop, 17-19 Janvier 2024, Lab Joliot-Curie, Orsay

The Photodiode Set is separated enough from the Power and Signal Conditioning Electronics to avoid unnecesary neutron exposure of electronics.

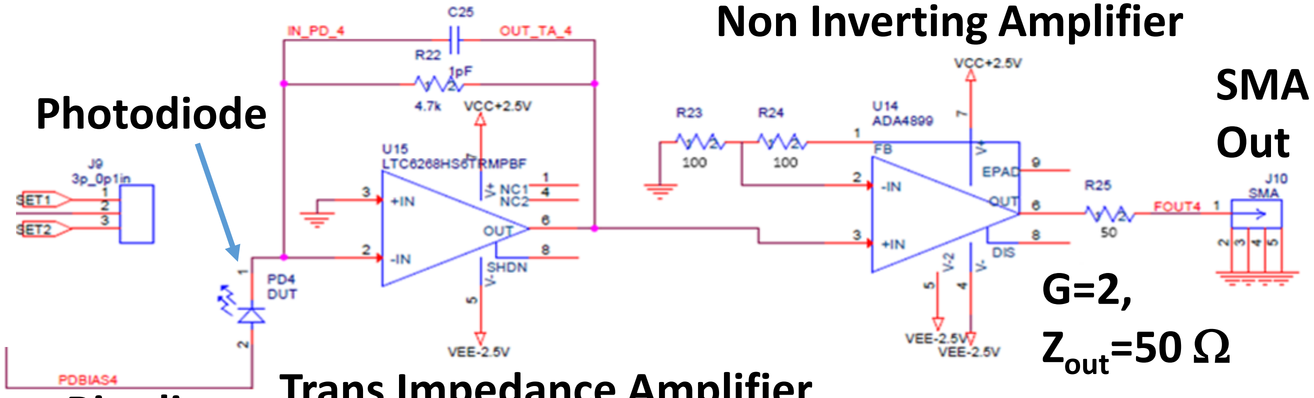
The design was optimized and tested in a previous experiment* at n_TOF (CERN) with a very good behaviour at the n_TOF EAR1 dump area radio frecuency interference (EMI) environment

A small photodiode active region (20 µm) is the best to mimics active regions in electronics for Single Event Effects





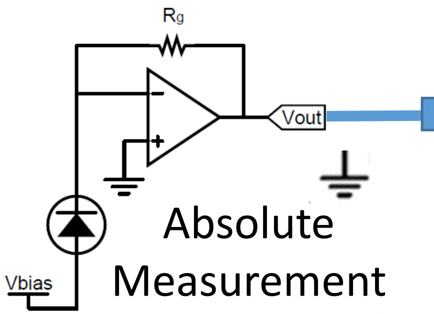
Trans Impedance Amplifier

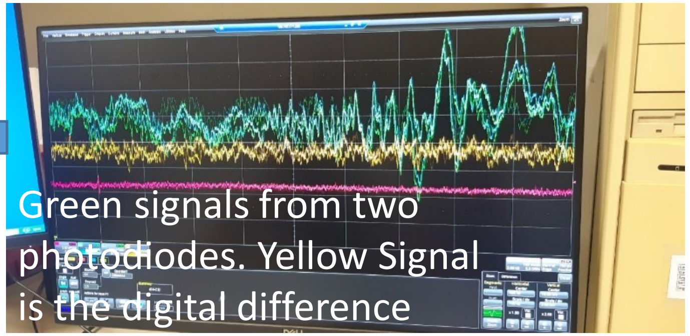


* https://indico.cern.ch/event/1132520/contributions/5140044/

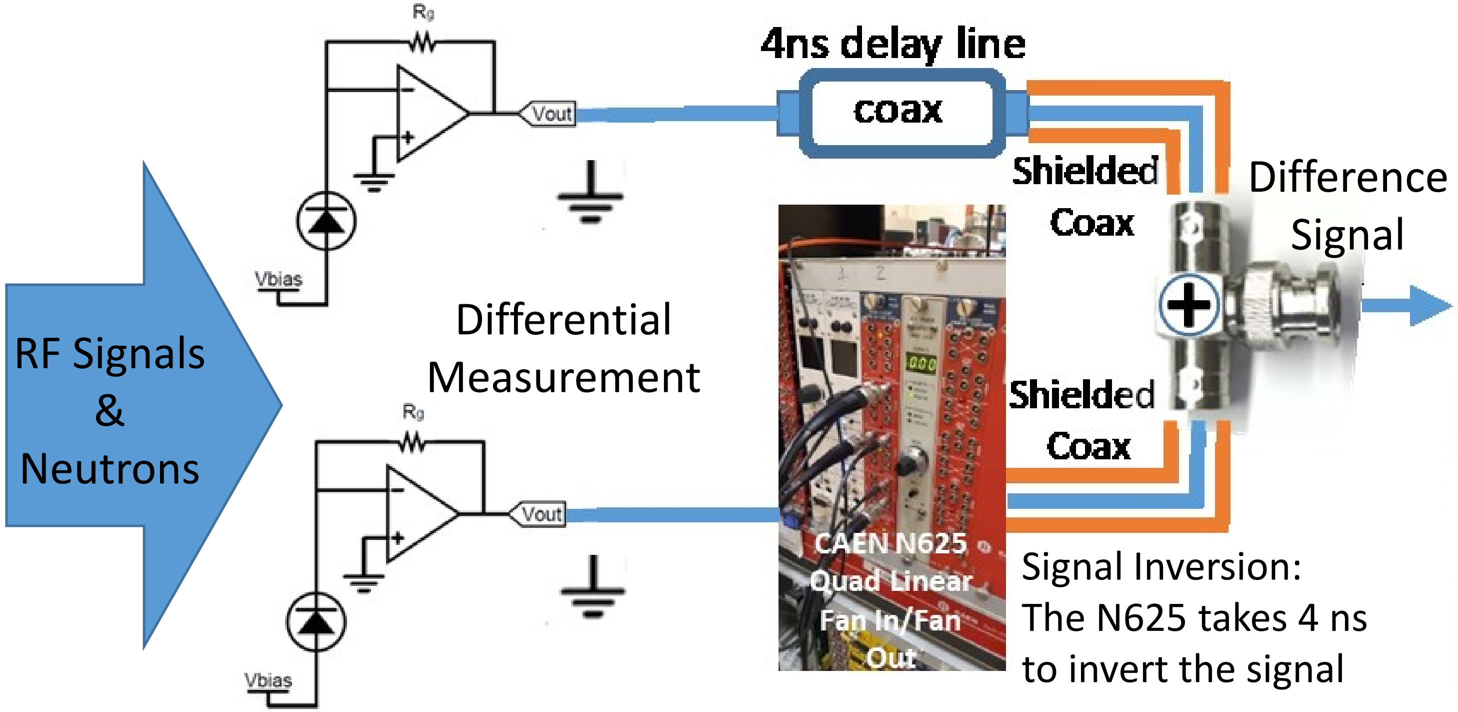
Detection of neutron induced reactions in silicon photodiodes at the HISPANoS facility

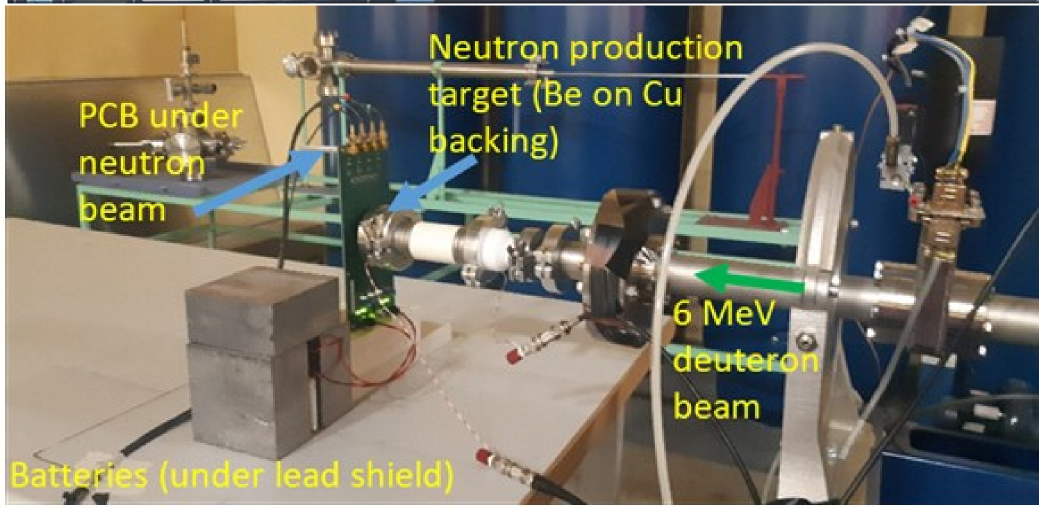
Photodiode Experiment





Direct measurement (Trans Impedance Amplifiers) is useful to get signals directly but it is very sensitive to Electro Magnetic Interference. There is plenty of EMI when Hispanos is on (observed in the UHF band) , with no less than 30 mV amplitude. The EMI signal is the same in both detectors but the ionization signal, at an instant, happens in only one.





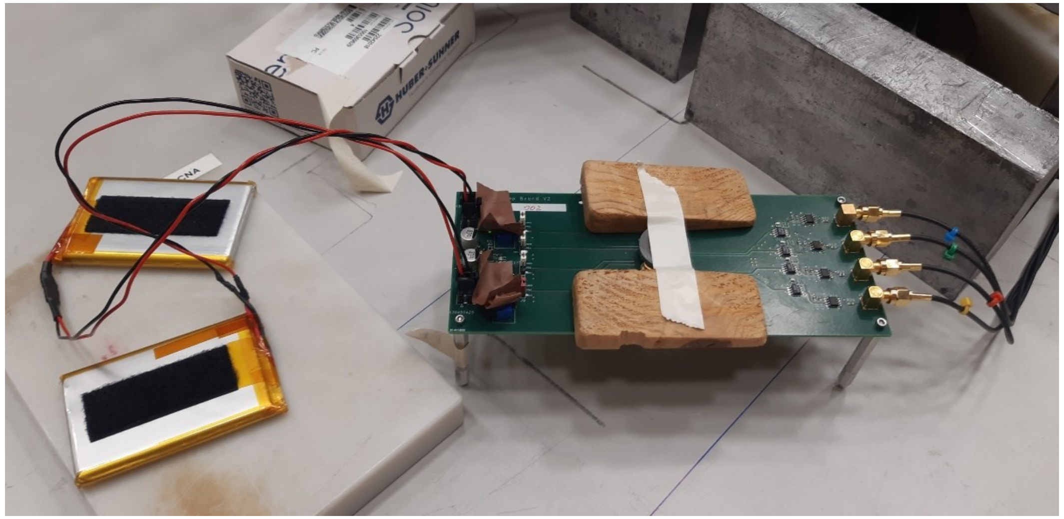
The synchronous difference signal shows only the ionization pulse when a neutron arrives at one detector. Changing Level Trigger Sign selects pulses from one or the other detector. The difference signal in the analog domain enables the use of a trigger.

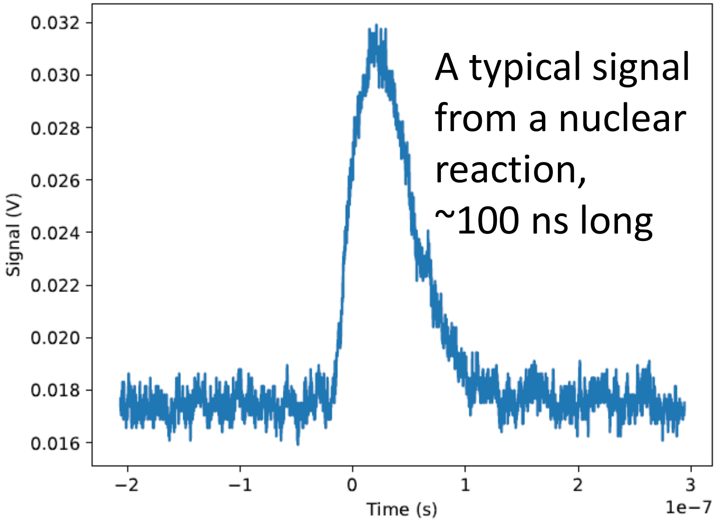
Detection of neutron induced reactions in silicon photodiodes at the HISPANoS facility

Photodiode Experiment

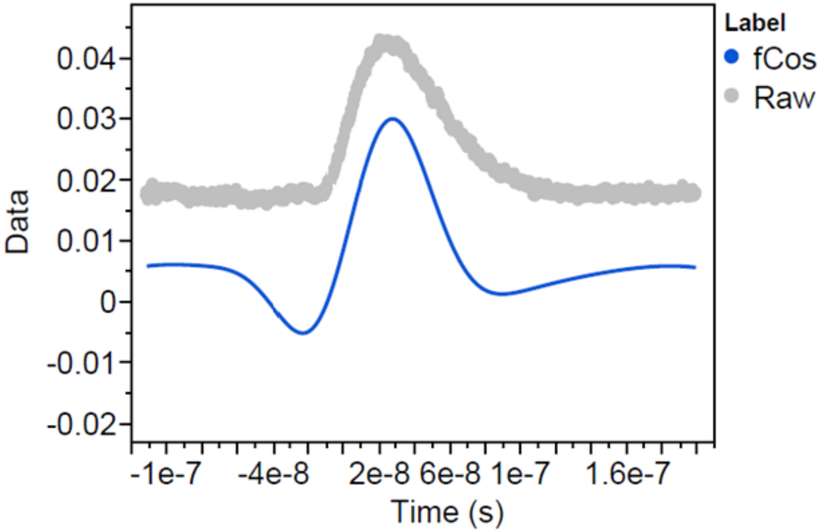
Just for calibration we put the same setup under gamma radiation from a Co60 source (accelerator shut off). We detect no spike from gamma photons so we concluded the dataset from the experiment with the accelerator on was due to neutron induced nuclear reactions in the photodetectors silicon bulk.

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





Digital Data Processing (low pass convolution filter)



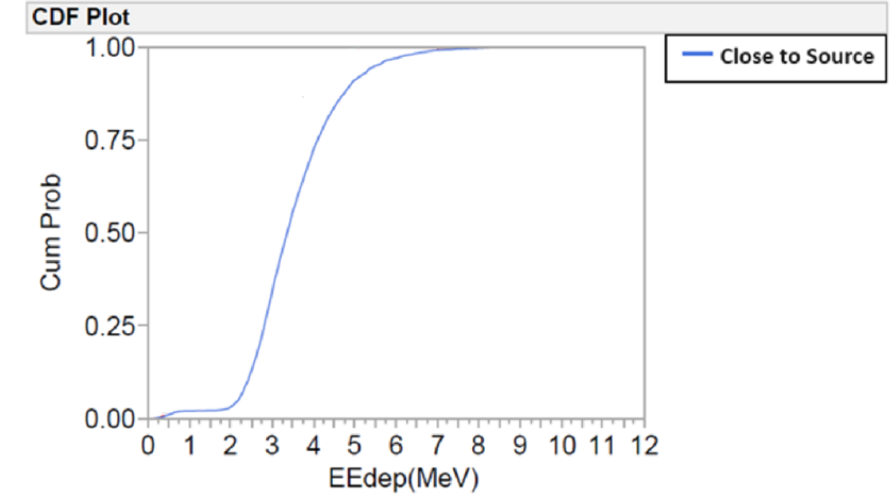
$$s(t) * k(t) = \int s(\tau)k(t-\tau)d\tau$$

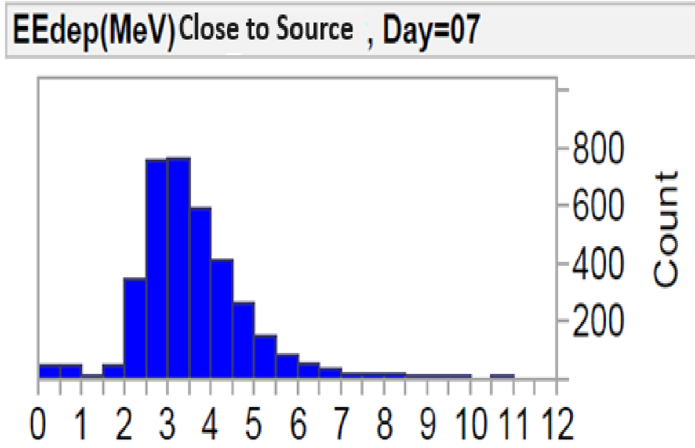
$$k(t) = \frac{2}{w\sqrt{\pi}} e^{-2\left(\frac{t-w}{w}\right)^2} \cos\frac{2\pi t}{w}$$

low pass filter kernel

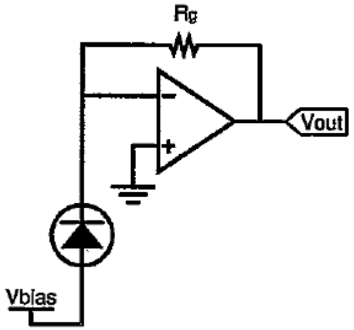
Detection of neutron induced reactions in silicon photodiodes at the HISPANoS facility

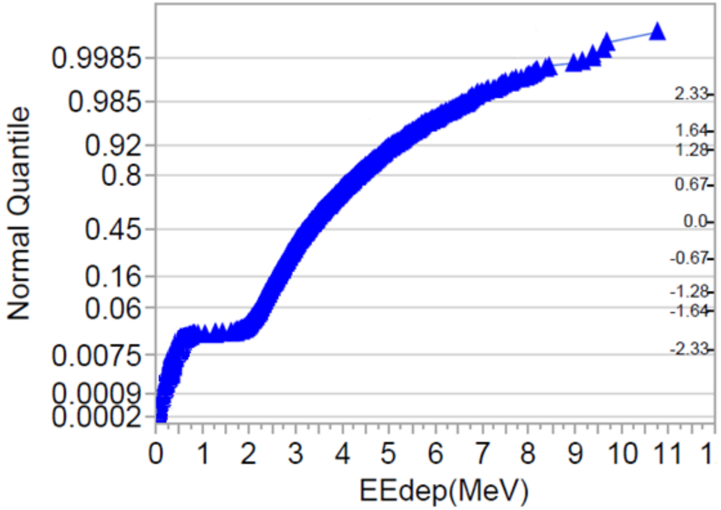
Photodiode Experiment



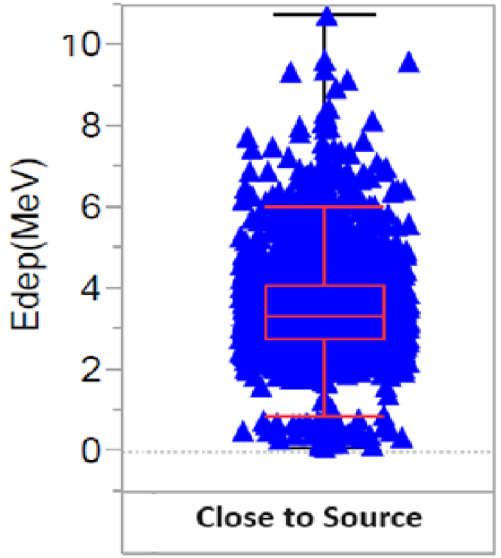


Summary Statistics	
Mean	3.5234581
Std Dev	1.1329032
N	3499
Minimum	0.0875928
Maximum	10.764085





blue: close to neutron source



Event distribution of captured events

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

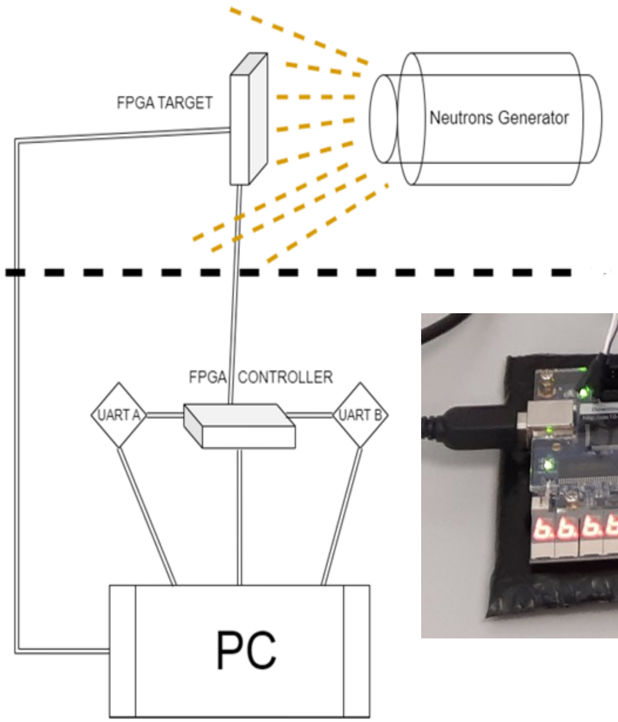
$$E_{dep} = \frac{Q}{e}(3.6\ eV)$$

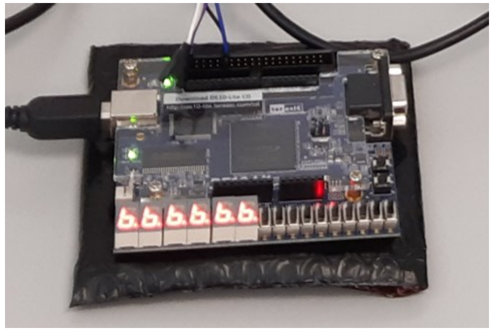
The analyzed data is consistent with the hypothesis that signals come from ions generated by neutron induced nuclear reactions in Silicon, as expected.

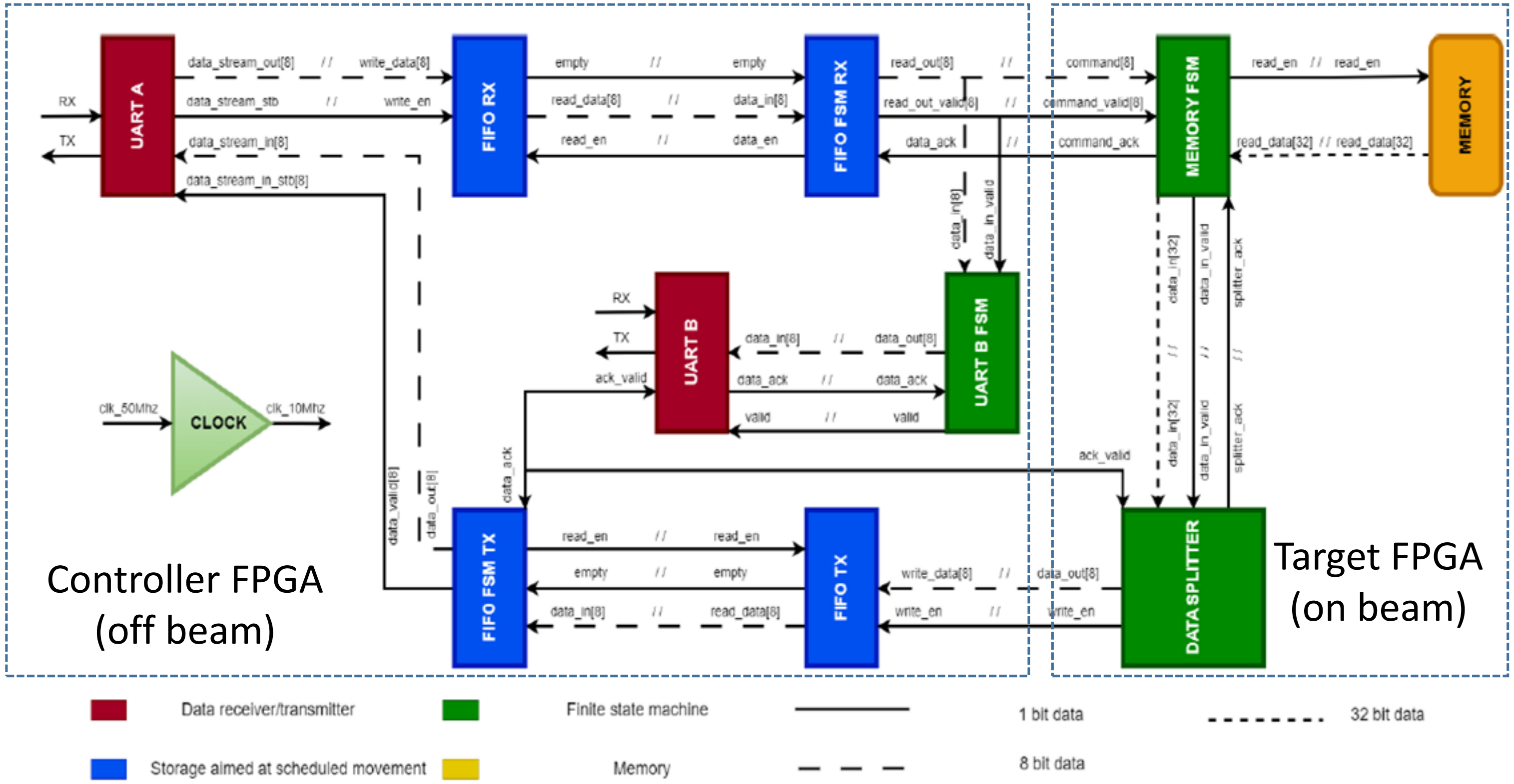
Detection of neutron induced reactions in silicon photodiodes at the HISPANoS facility

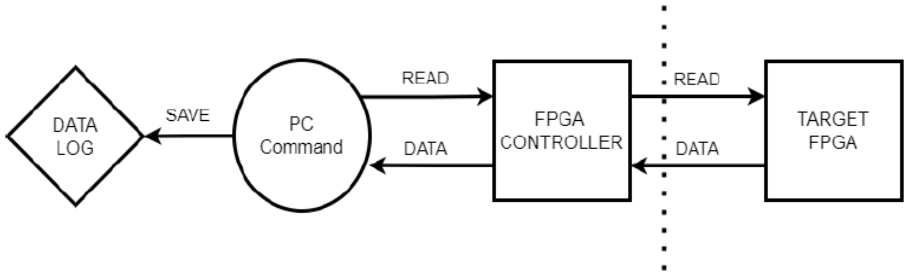
FPGA Experiment

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.







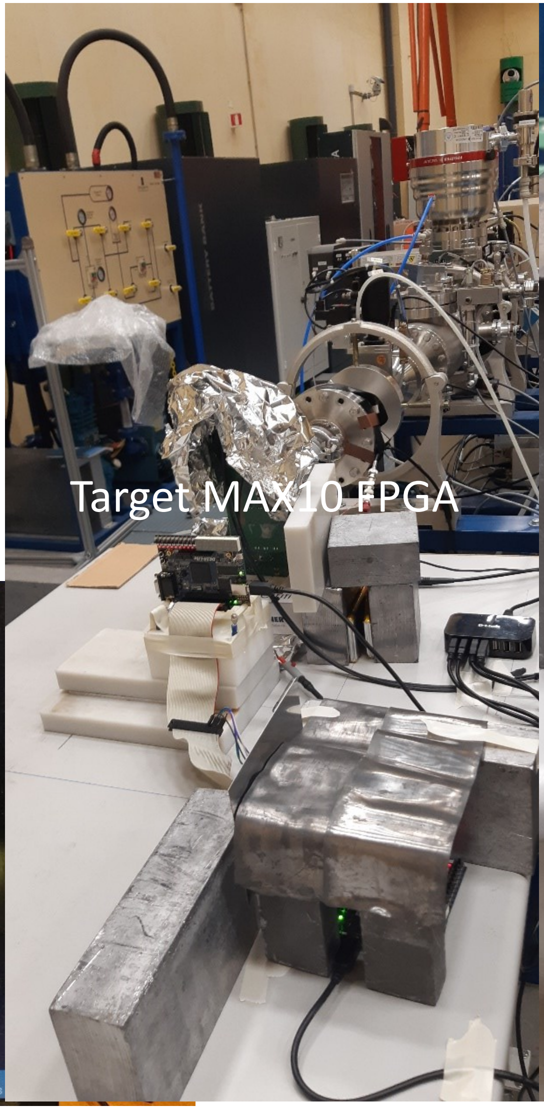


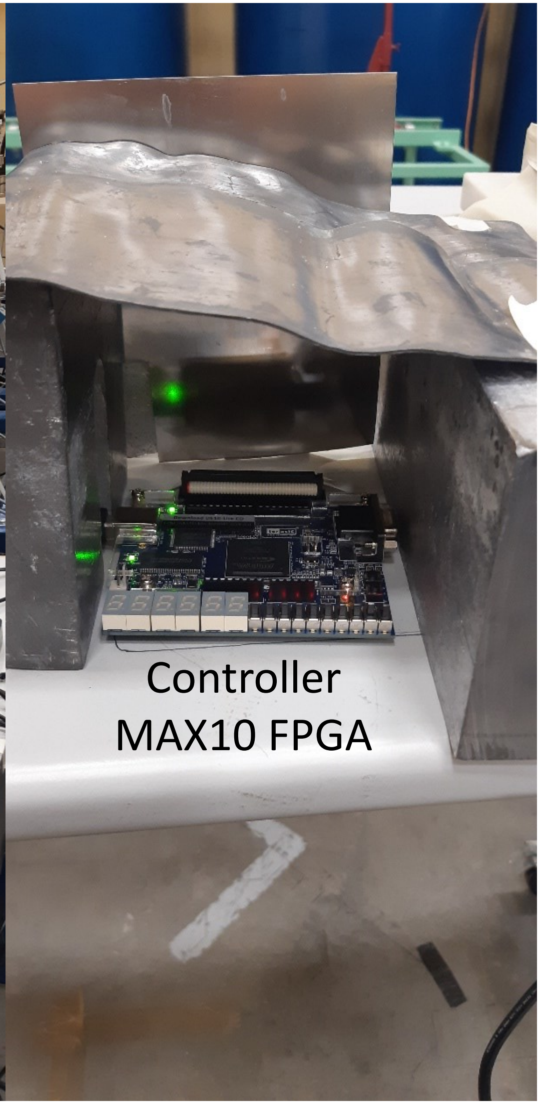
In this experiment the difficult part is at the digital design. Irradiation data analysis is very easy (just a disagreement in the fff... word received).

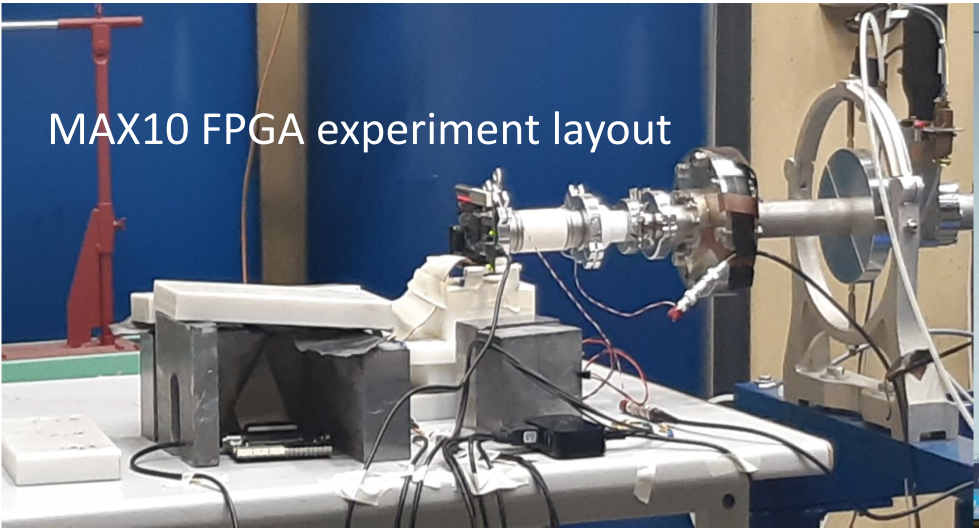
Detection of neutron induced reactions in silicon photodiodes at the HISPANoS facility

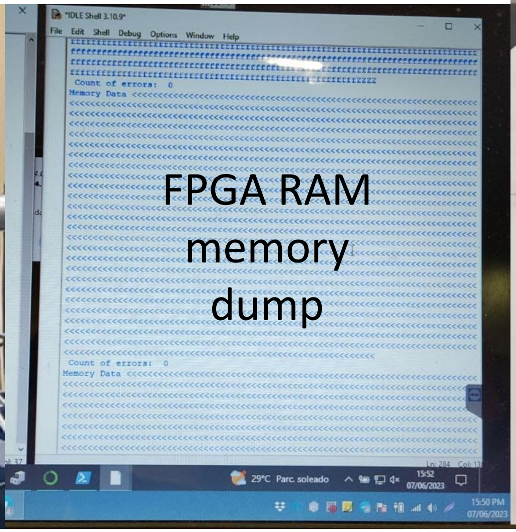
FPGA Experiment

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

- The photodiode experiment opens the way to more sophisticated detector experiments in the facility. The differential measurement scheme is resistant to the ElectroMagnetic Interference from the facility (observed in the UHF band, ¿secondary electron bremsstrahlung from the backing, SNICS II ^{2}H source?). 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 for your attention!

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