# Emulation of neutron induced signals in detectors using lasers

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# Emulation of neutron induced signals in sensors using lasers

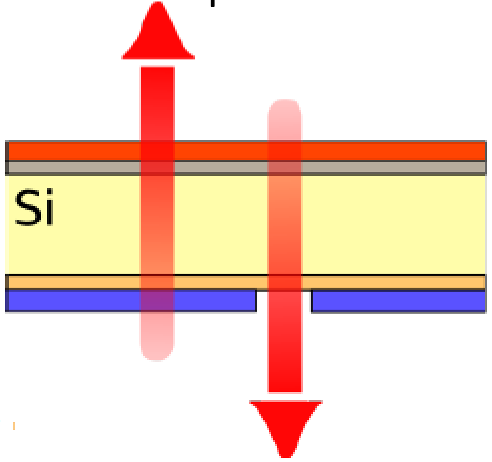
**The main idea is very simple:**

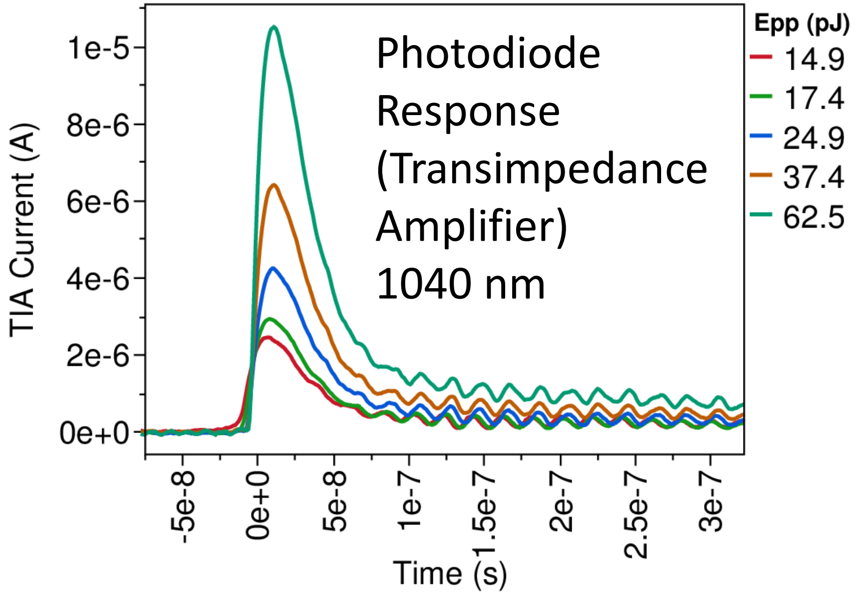
1. Neutron irradiation of semiconductors generates recoil ions ($^{28}$Si elastic scattering, $^{28}$Si(n,$\alpha$)$^{25}$Mg, $^{28}$Si(n,p)$^{27}$Al, etc) in the semiconductor bulk. Those secondary ions have a short flight range in the device, generating **internal localized ionization volumes**.
2. 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 ultrashort pulsed **lasers.** Ultrashort laser pulses (<<1 ps) mimic the secondary ion flight lapse.

We want to record a signal dataset from neutron interaction inside a photodiode. We will also generate a second signal dataset illuminating the photodiode with pulsed lasers, with a wavelength $\lambda$=1040 nm (Single Photon Absorption regime) and with a wavelength $\lambda$=1550 nm (Two Photon Absorption regime) . **The purpose is to cross calibrate neutron signals with laser signals in commercial photodiodes, easily accesible.**

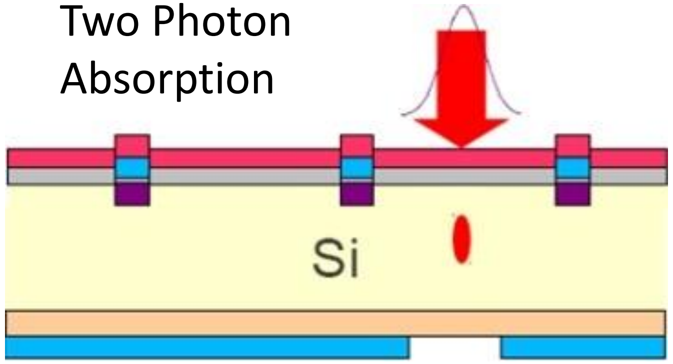
Related approaches: Y.Chiang et al.;Investigate the equivalence of neutrons and protons in single event effects testing: A Geant4 Study, Applied Science,10, 3234 (2020) , M.A.Clemens et al.: The effects of neutron energy and high-Z materials on single event upsets and multiple cell upsets, IEEE Trans.Nucl.Sci.,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

Single Photon Absorption

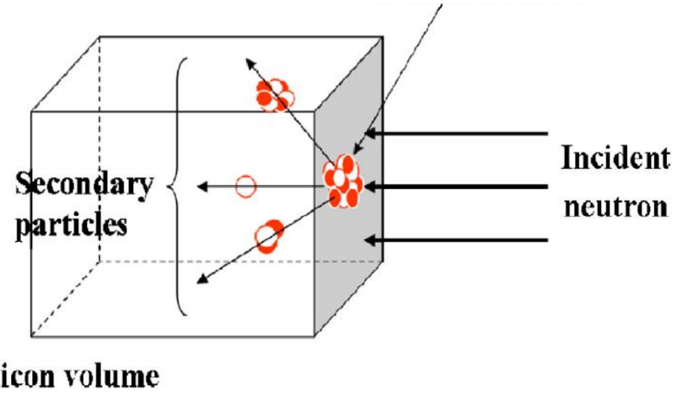




Two Photon Absorption



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)

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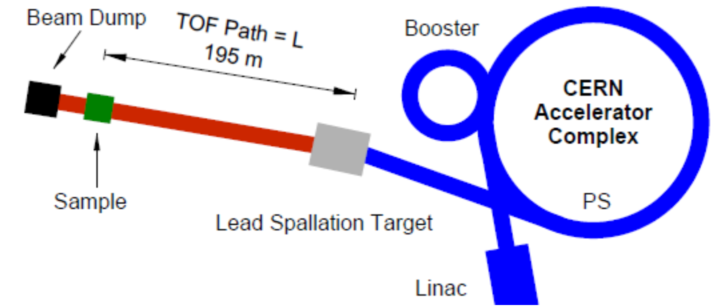
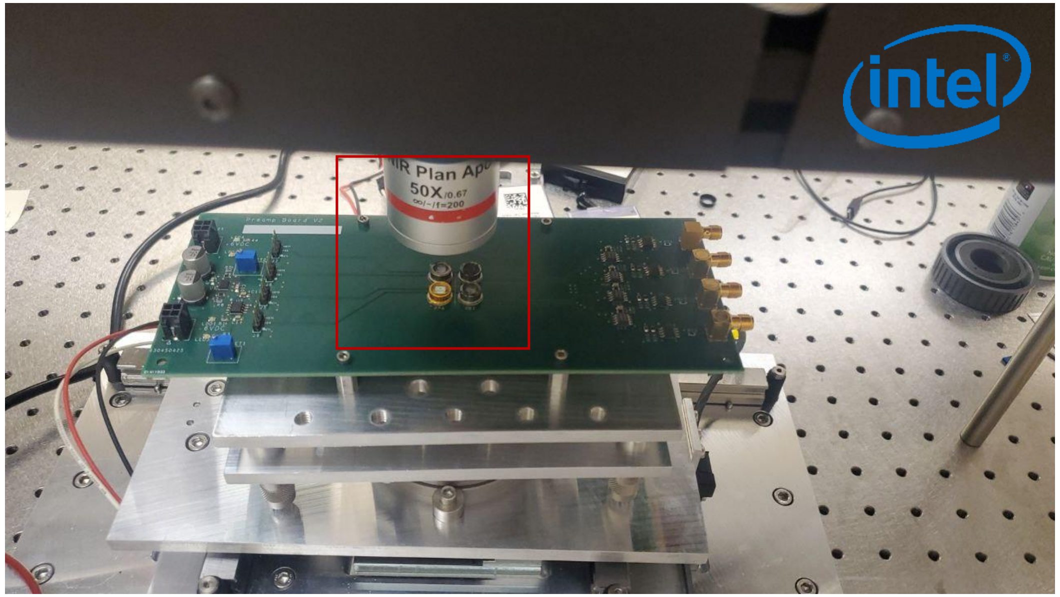
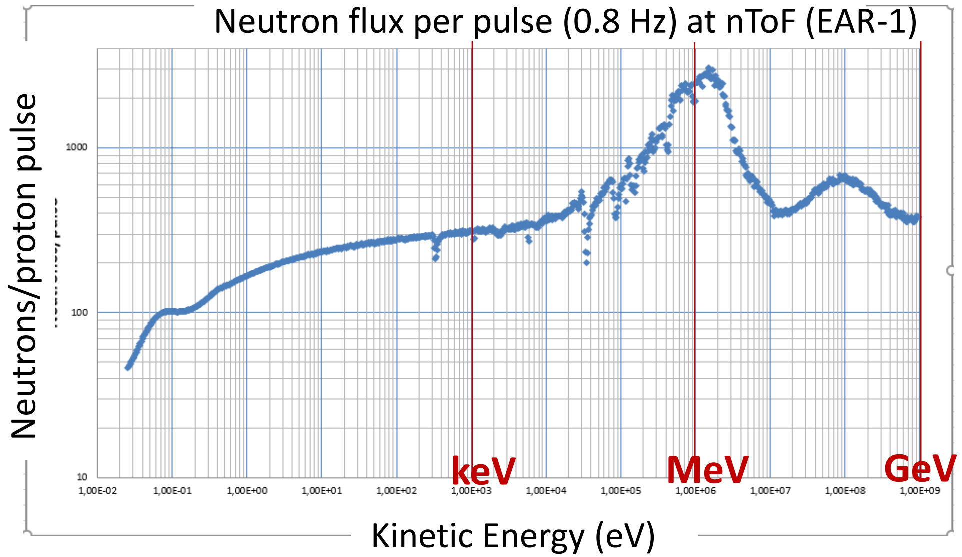
# Emulation of neutron induced signals in sensors using lasers

- The n_TOF facility at CERN generates a neutron stream by spallation of a lead production target under bombardment of protons from the Proton Synchrotron (20 GeV/c).
- The photodiode experiment was positioned at the EAR-1 dump area, without interference with nuclear data taking at EAR-1 area.



- The $\gamma$-flash from the spallation target is used as trigger signal for neutron arrival at the dump area
- The n_TOF neutron spectrum is very wide, from 30 meV up to GeV energies.

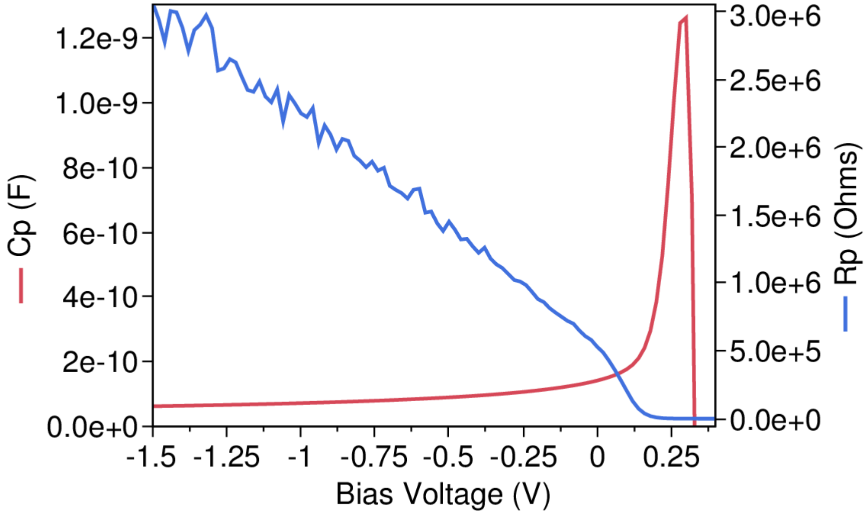




Laser injection has been demonstrated as an important tool to study the vulnerability of VLSI circuits to single event effects at a lower cost. Ultrafast laser injection has also been performed on the diodes with the same configuration as in the neutron campaign. A 1040nm laser was used to generate single photon absorption (SPA) and a 1550nm laser was used to achieve two-photon absorption (TPA) in the samples. In both cases the ultrafast pulse duration is 100fs.

# Emulation of neutron induced signals in sensors using lasers

- 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

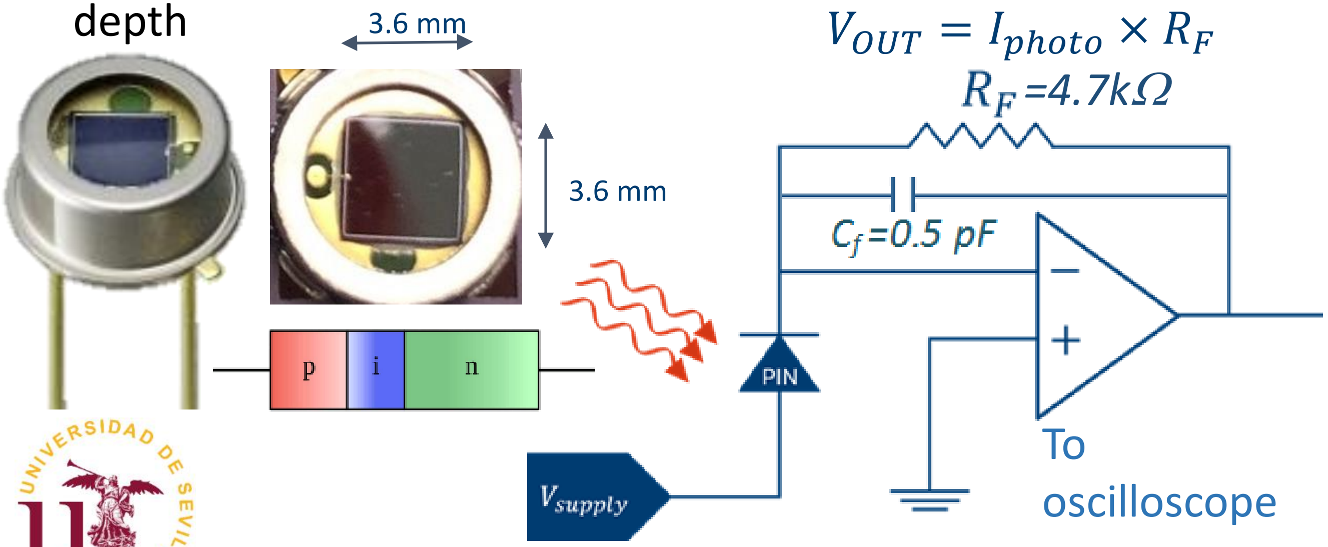


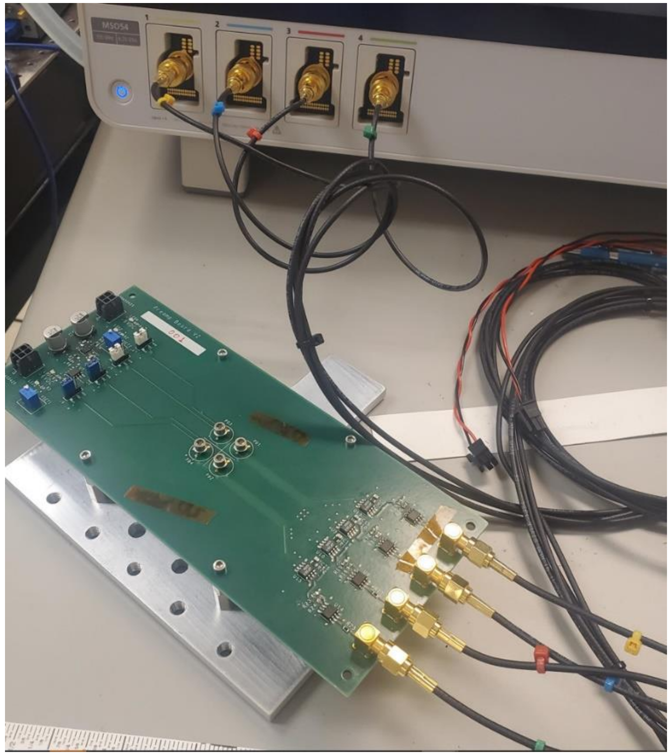
$$d = \frac{\epsilon A}{C}$$

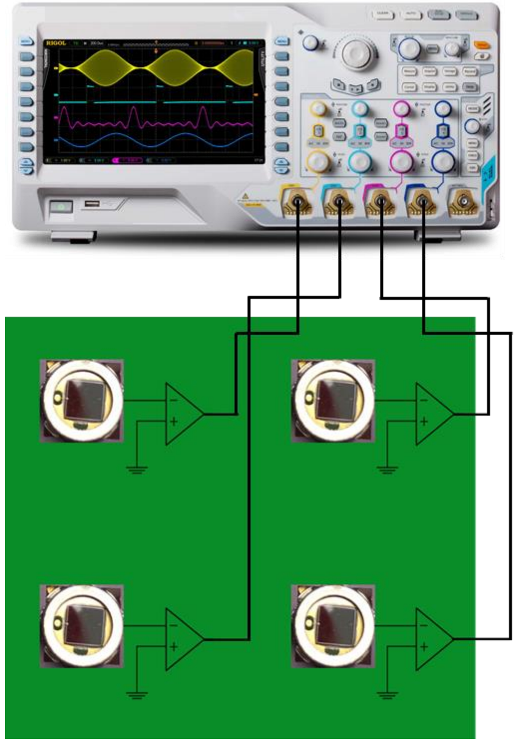
At bias=-1.5 V we calculate depletion depth from the Capacitance Formula, d=20 μm

$$V_{OUT} = I_{photo} \times R_F$$

$$R_F = 4.7k\Omega$$

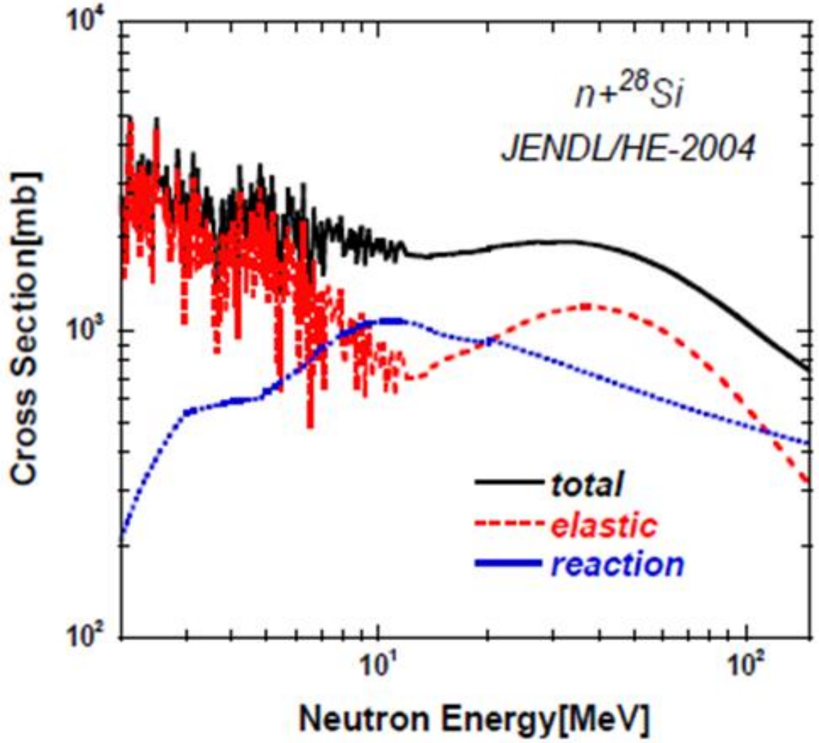




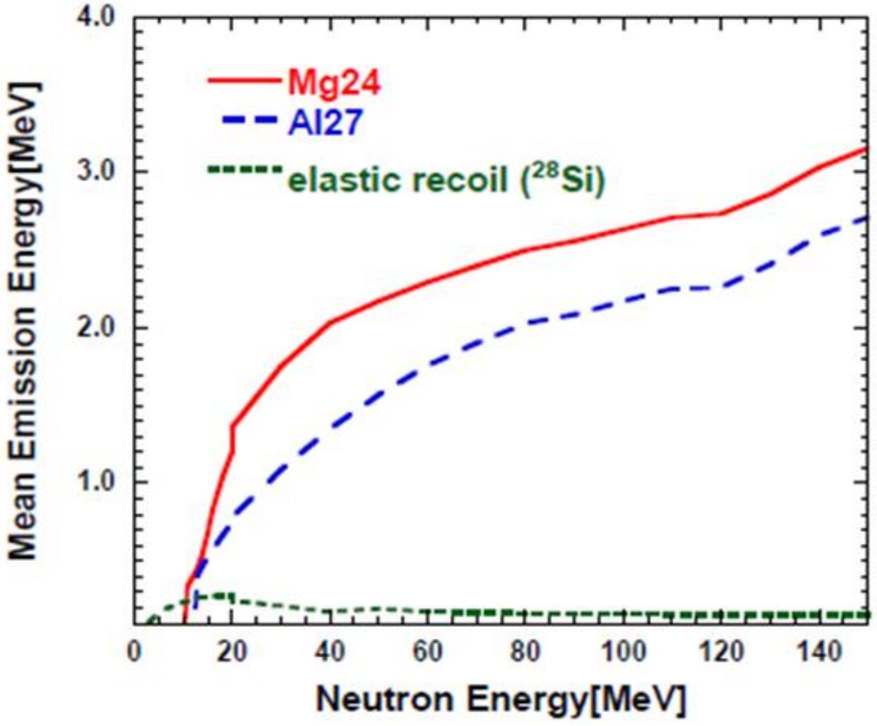


# Emulation of neutron induced signals in sensors using lasers

| 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 | 10.34 |
| $^{28}$Si(n,n,p)$^{27}$Al | 12.00 |
| $^{28}$Si(n, $^{3}$He)$^{26}$Mg | 12.58 |
| $^{28}$Si(n, 2$\alpha$)$^{21}$Ne | 12.99 |
| $^{28}$Si(n,2p)$^{27}$Mg | 13.90 |
| $^{28}$Si(n,p,$\alpha$)$^{24}$Na | 15.25 |
| $^{28}$Si(n,t)$^{26}$Al | 16.74 |
| $^{28}$Si(n,$^{15}$N)$^{14}$N | 16.97 |
| $^{28}$Si(n,n)$^{12}$C,$^{16}$O | 17.35 |
| $^{28}$Si(n,2n)$^{27}$Si | 17.80 |
| $^{28}$Si(n,p,d)$^{26}$Mg | 18.27 |
| $^{28}$Si(n, $\alpha$)$^{12}$C,$^{13}$C | 19.65 |
| $^{28}$Si(n, n,2$\alpha$)$^{20}$Ne | 20.00 |



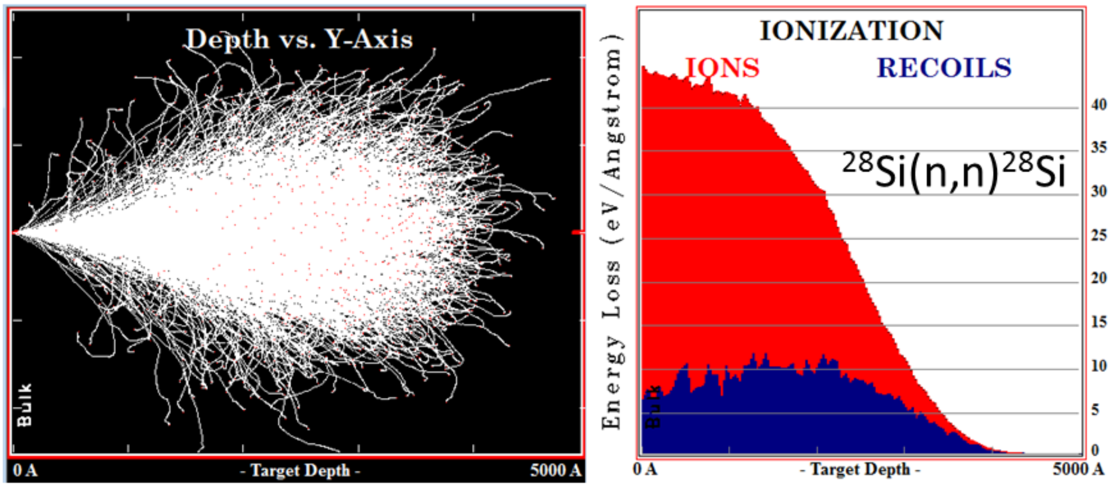
Neutron total, elastic and reaction cross-section of $^{28}$Si from JENDL/HE-2004



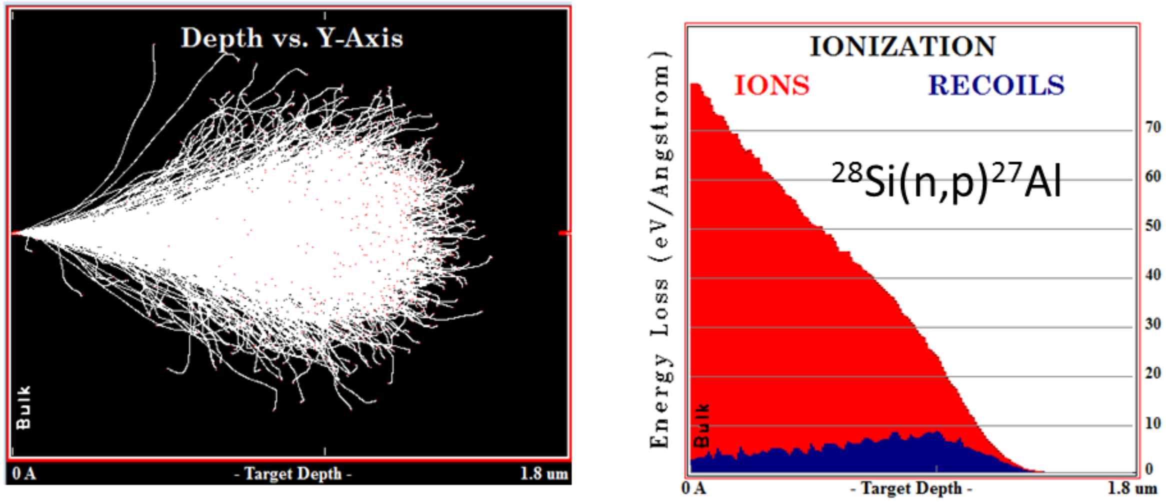
Averaged emission energy for elastic recoil $^{28}$Si(n,n)$^{28}$Si and main nuclear reactions $^{28}$Si(n,p)$^{27}$Al, $^{28}$Si(n,$\alpha$)$^{24}$Mg

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

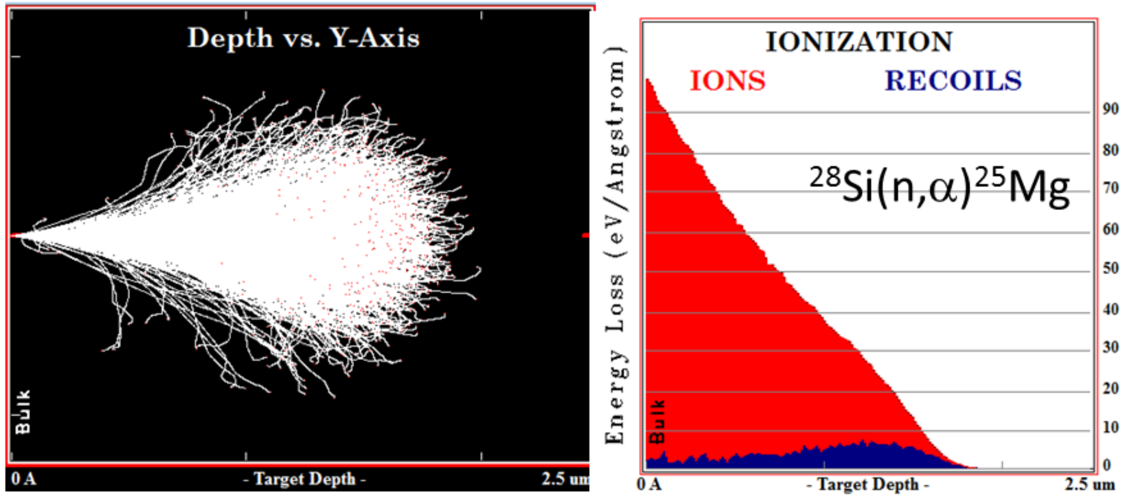
# Emulation of neutron induced signals in sensors using lasers



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 1000 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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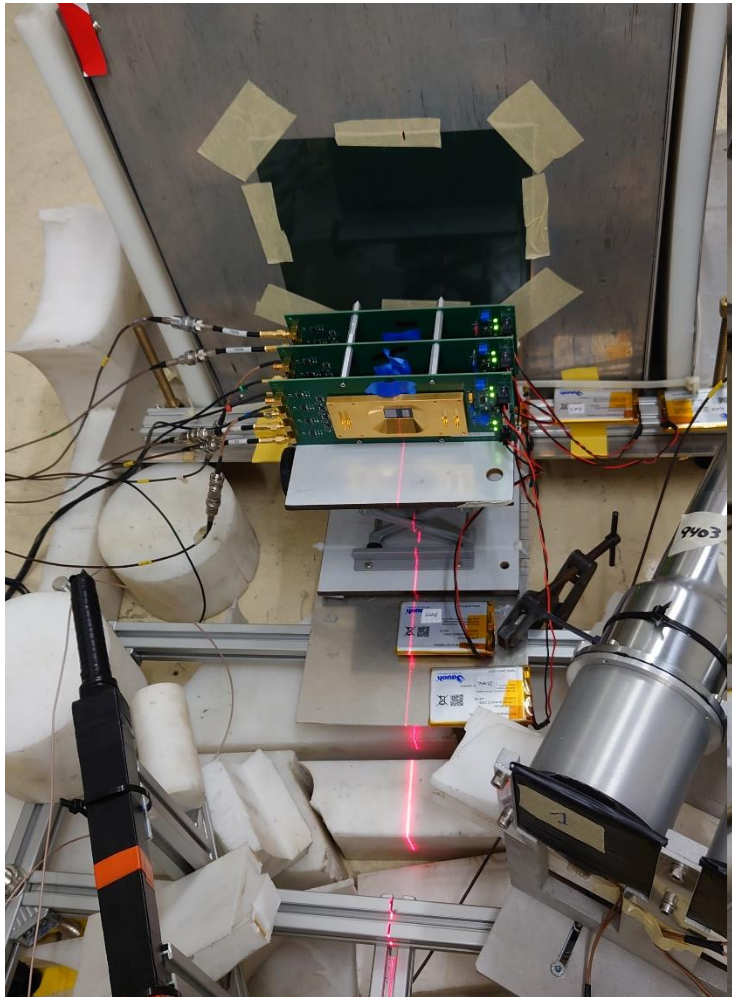
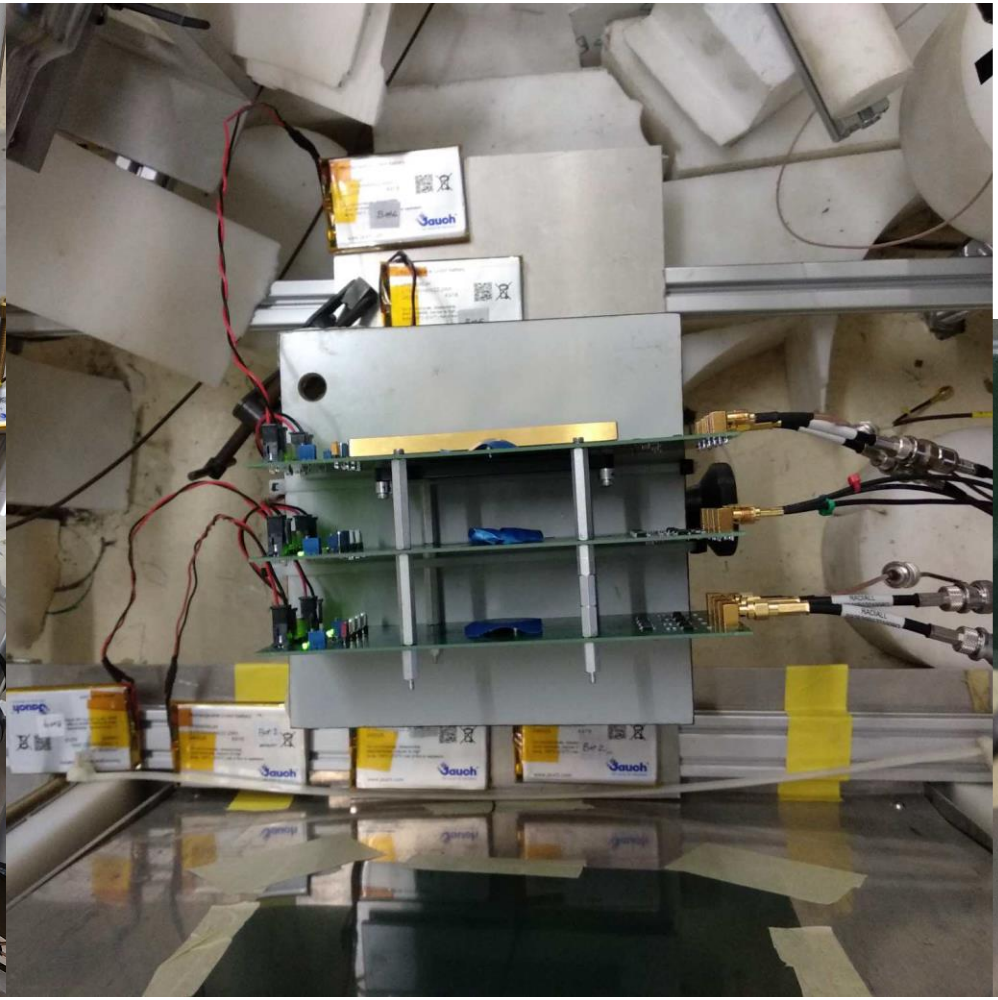
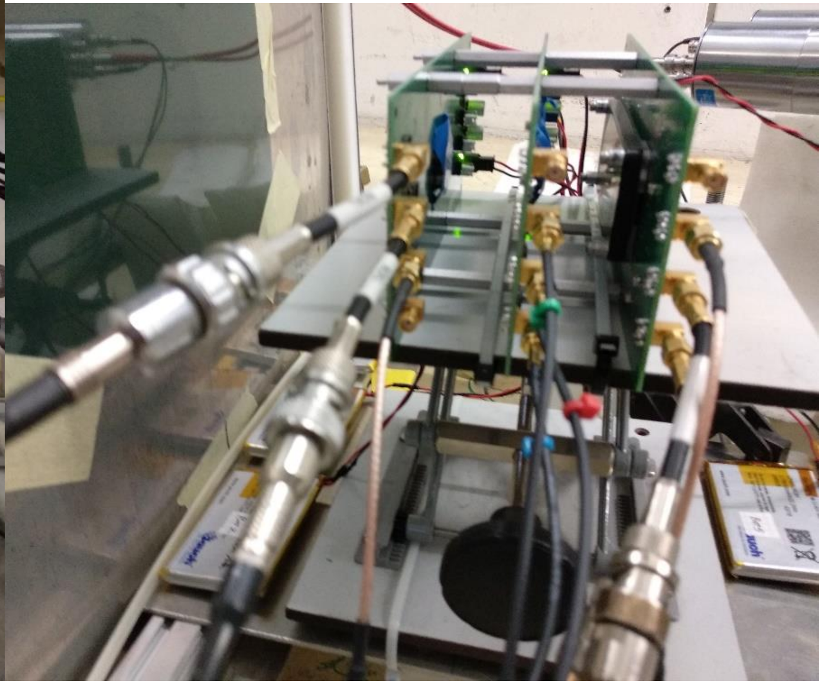
# Emulation of neutron induced signals in sensors using lasers





Images of the full setup of photodiodes positioned in the EAR-1 dump area, aligned with the neutron beam. Data Acquisition was made with remotely controlled oscilloscopes.

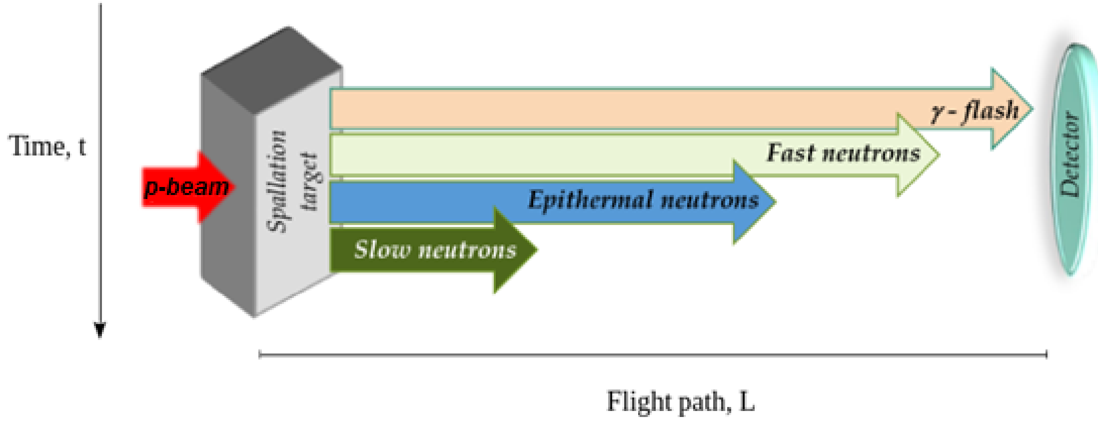


# Emulation of neutron induced signals in sensors using lasers

n_TOF uses the neutron time of flight technique so the time of arrival can be converted to the kinetic energy the arriving neutrons have. The chronometry, adjusted by relativistic kinematics calculations, with an error less than 1 µs is in the figure.

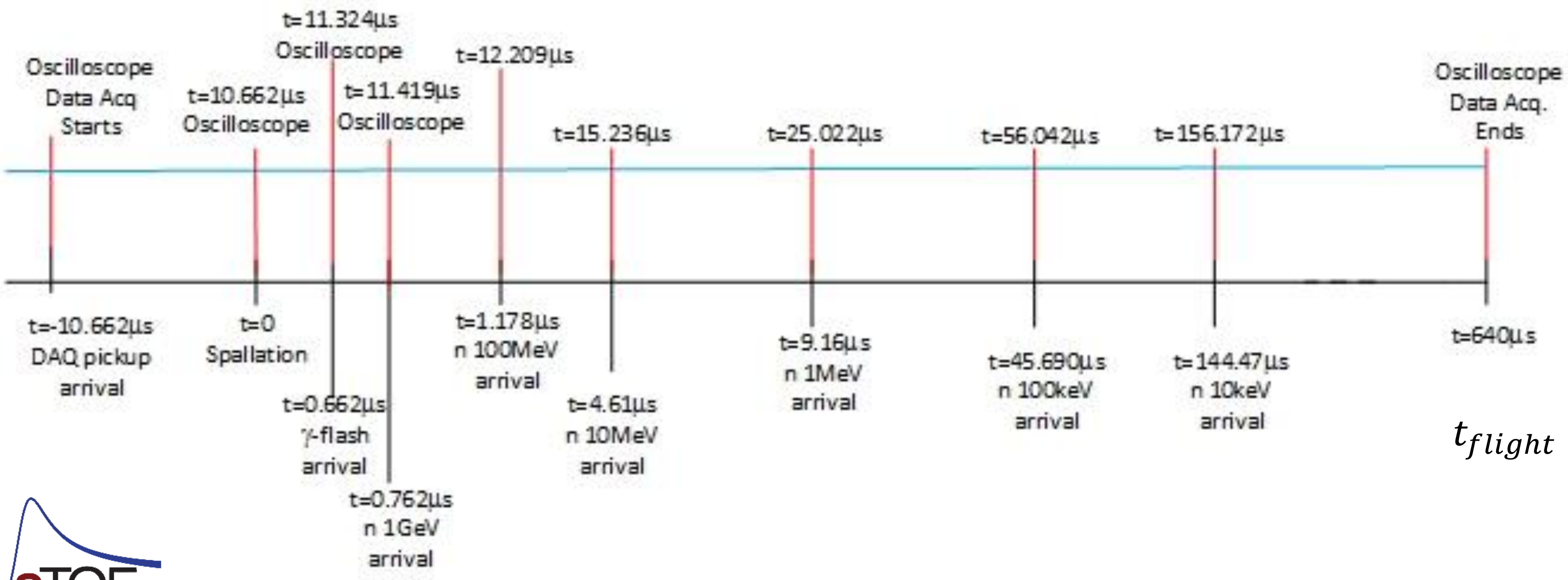
The signals generated by neutron interaction with the photodiode are recorded using oscilloscopes with an acquisition window of 640 µs maximum.

The facility provides a trigger signal (10 µs before the proton bunch arrives to the spallation target) that we use to start oscilloscopes Data Acquisition. Events produced by neutrons below 1 MeV (esentially elastic scattering) cannot be discriminated reliably by our photodiodes.



$$E_n = m_n c^2(\gamma - 1)$$

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$



$$v = c\sqrt{1-\left(\frac{1}{1+\frac{E_n}{m_n c^2}}\right)^2}$$

$$t_{flight} = \frac{d}{v} = \frac{d}{c\sqrt{1-\left(\frac{1}{1+\frac{E_n}{m_n c^2}}\right)^2}}$$

# Emulation of neutron induced signals in sensors using lasers

Typical signals captured in the oscilloscopes from interaction of photodiodes with incoming neutrons and gamma-flash (γ-flash).

The γ-flash comes from the intranuclear cascade* when a neutron impacts with a nucleus (lead) in the spallation target. Neutrons comes later on from the intranuclear cascade and from evaporation and other slower nuclear reactions.

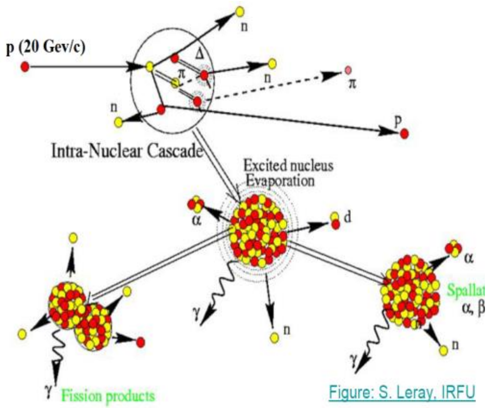
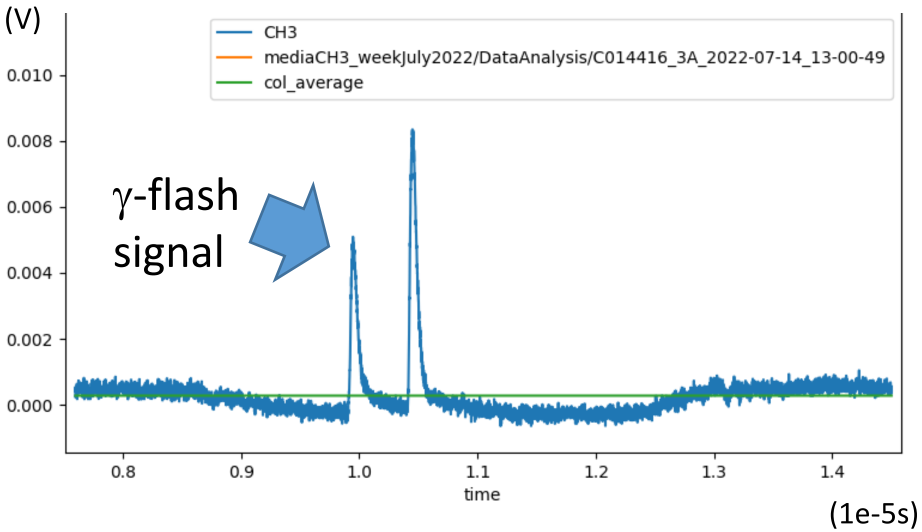
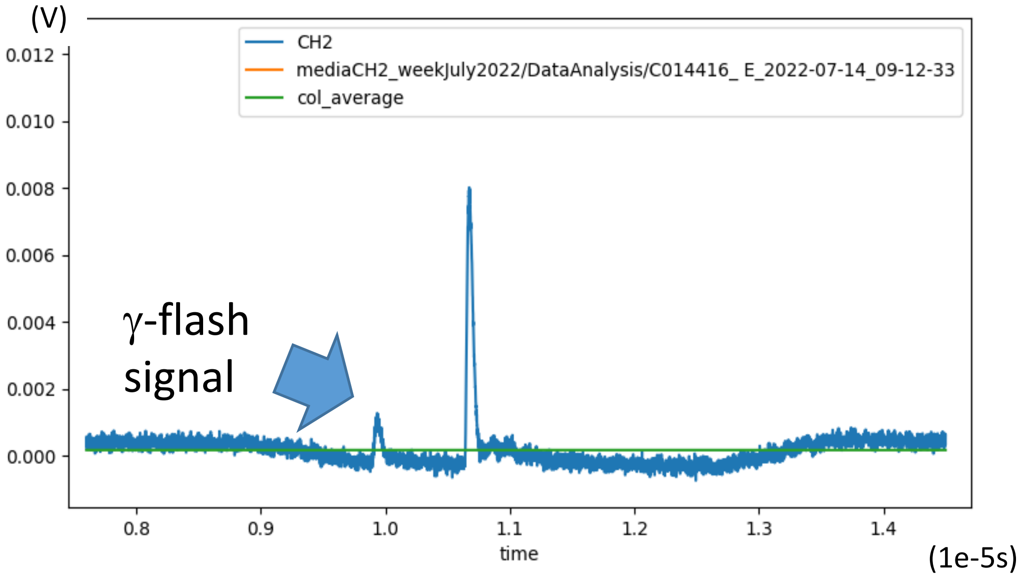


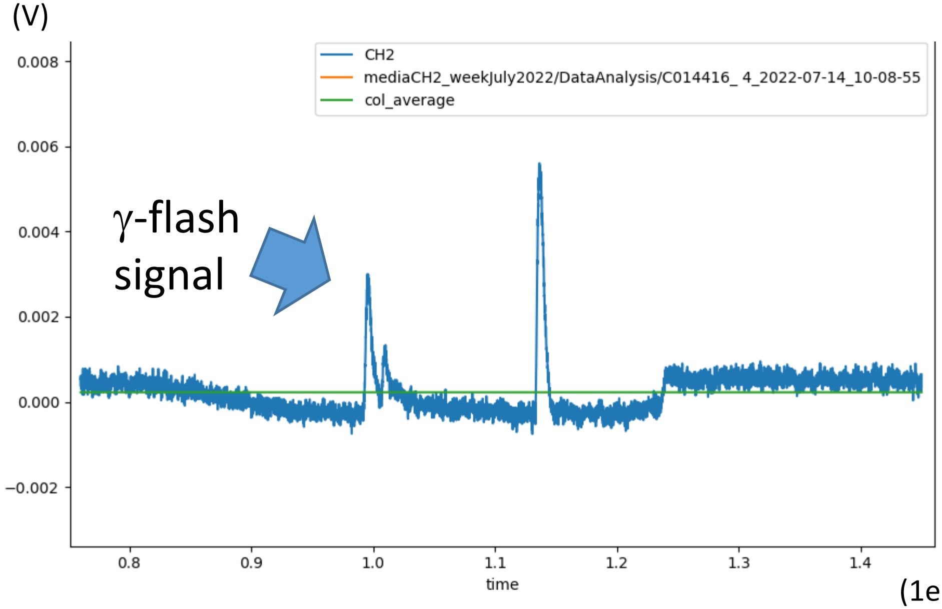
Figure: S. Leray, IRFU



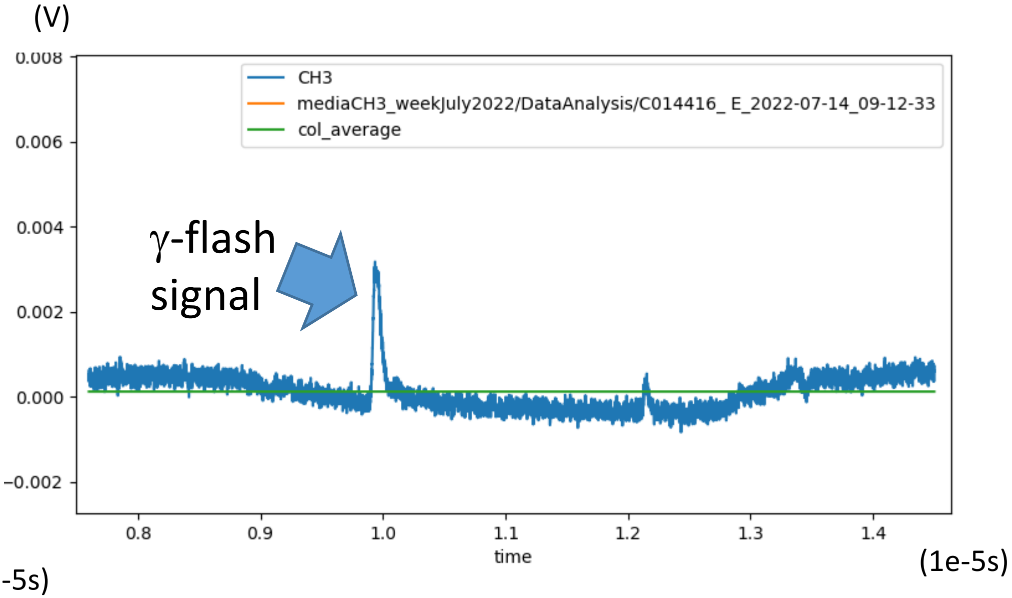
γ-flash signal



γ-flash signal



γ-flash signal



γ-flash signal

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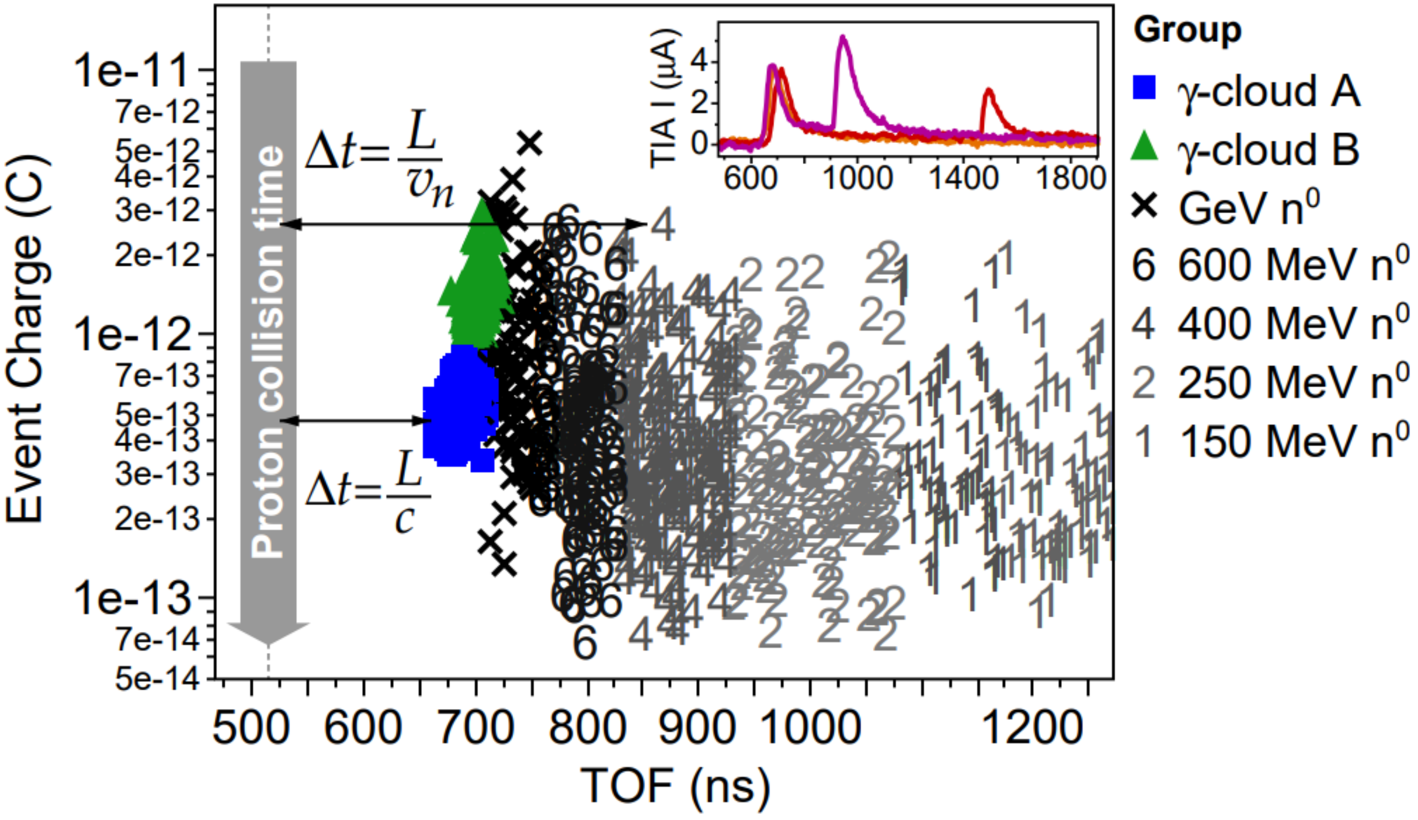
*A.Boudard et al. Liege Intranuclear cascade model INCL Phys. Rev. C87, 014606

# Emulation of neutron induced signals in sensors using lasers

The signal dataset (oscilloscopes captures) was statistically analyzed using the JMP software package.
The event sequence of analized traces shows:

| Event | Population |
|---|---|
| Gamma - neutron | 63% |
| Gamma only | 36% |
| Neutron only | 1% |

From the signal statistical analysis we get a plot of estimated event charge vs. event onset time. The two initial clouds are interpreted as the detection of the gamma flash arriving first from the spallation target. Later events are classified as neutron events. Neutrons are grouped by energy and noted in gray numbers.In the inset is shown an example of current traces showing the gamma peaks in all cases and neutron signals at later times.



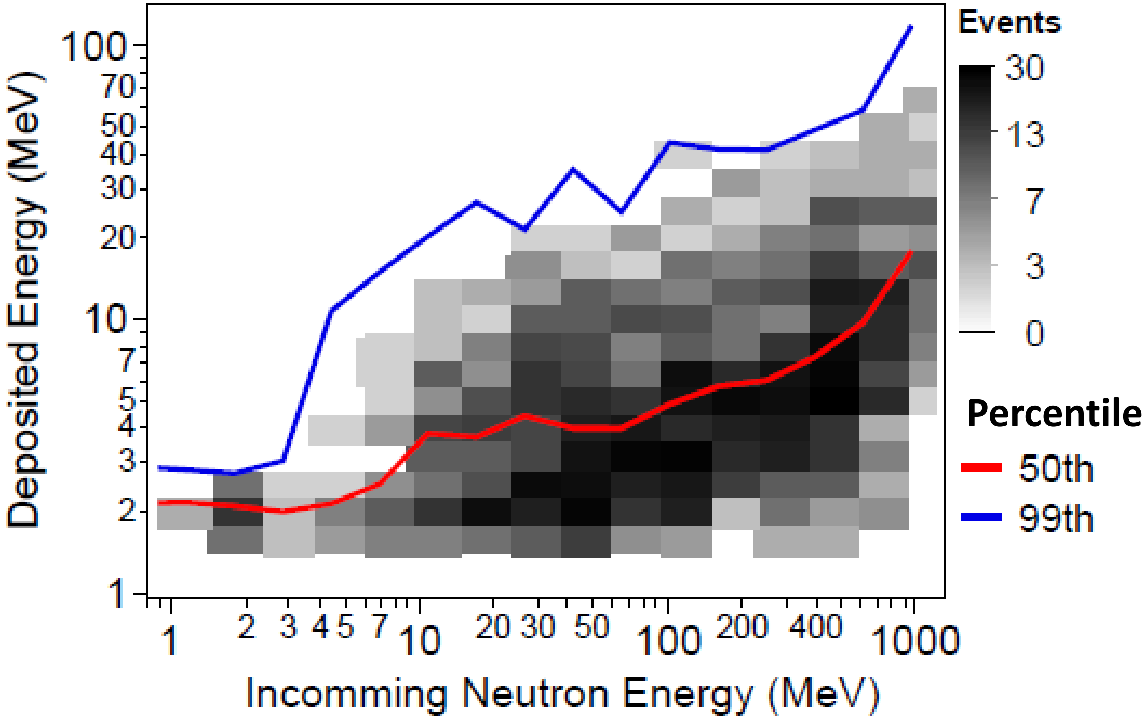
# Emulation of neutron induced signals in sensors using lasers

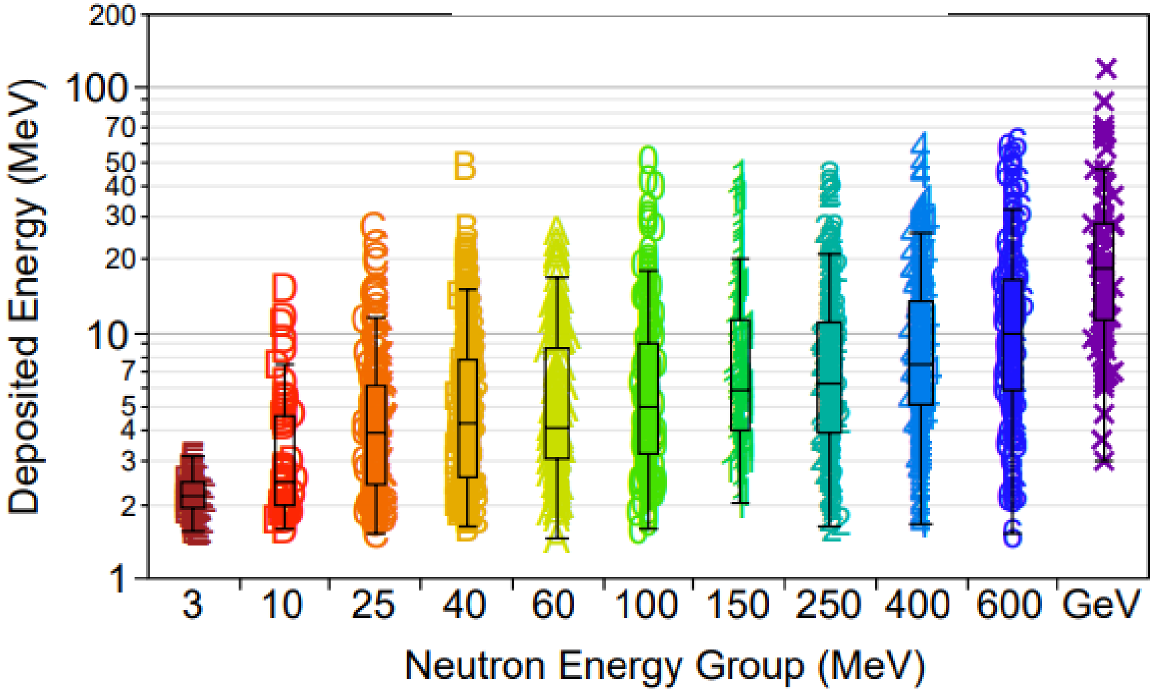
The estimation of the maximum deposited energy (i.e. charge) at a certain incoming neutron energy is important to enable a calibrated prediction of the SEE susceptibility and further enables the experimental use of laser for reliability assessments.
Gamma events are captured with high levels of precision. A the total number of events have been 1120. The final performance of the detector is shown in the right plot.

We use the term *Deposited Energy* ($E_{dep}$)
to describe the charge collected by the Si photodio
$Q_{coll}$, assuming a Si electron-hole ionization energy E
of 3.62eV.

$$Q_{coll} = \int I_{PD}(t)dt$$

$$E_{dep} = \frac{Q_{coll}}{e} E_i$$





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# Emulation of neutron induced signals in sensors using lasers

The current transients generated by the lasers (modes SPA and TPA) are very similar to those induced by neutrons hits (ionization by nuclear reactions in Si). As the photodiode S1336 depletion depth is reduced, just 20 µm, the differences between SPA and TPA responses are small but the energy pulses are different. Anyway, for other applications as emulation of neutron induced Single Event Effects in microelectronics the TPA mode will have advantages due to the Silicon transparency to laser light with wavelength bigger than 1100 nm (dye backside access).

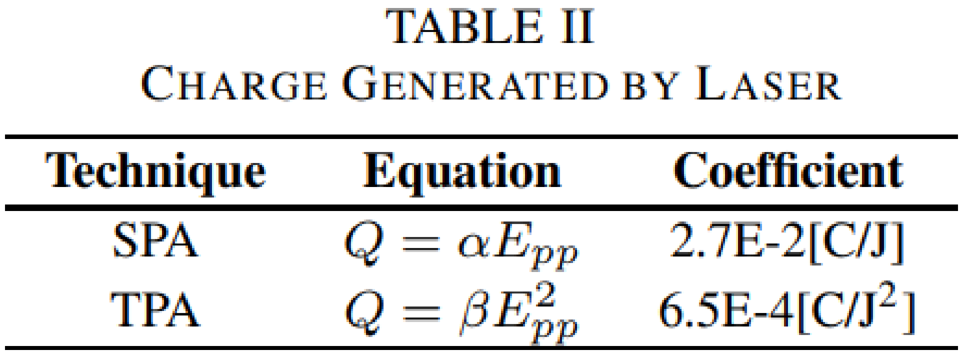


TABLE II
CHARGE GENERATED BY LASER

| Technique | Equation | Coefficient |
|---|---|---|
| SPA | $Q = \alpha E_{pp}$ | 2.7E-2[C/J] |
| TPA | $Q = \beta E_{pp}^2$ | 6.5E-4[C/J$^2$] |

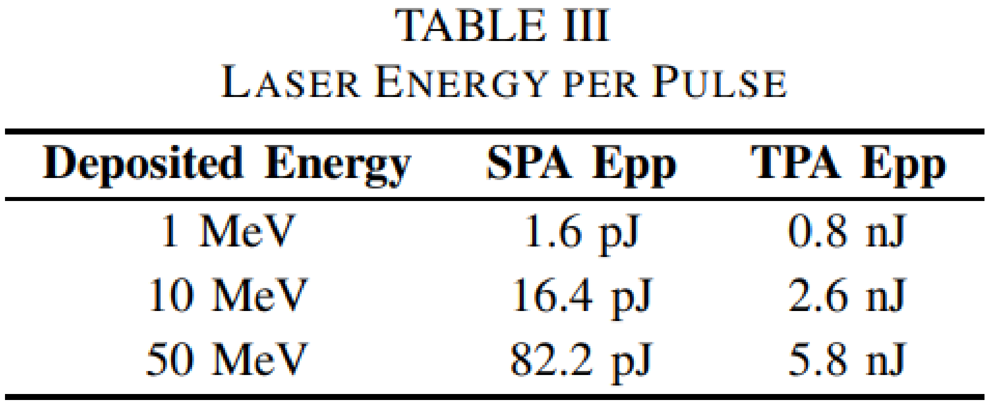
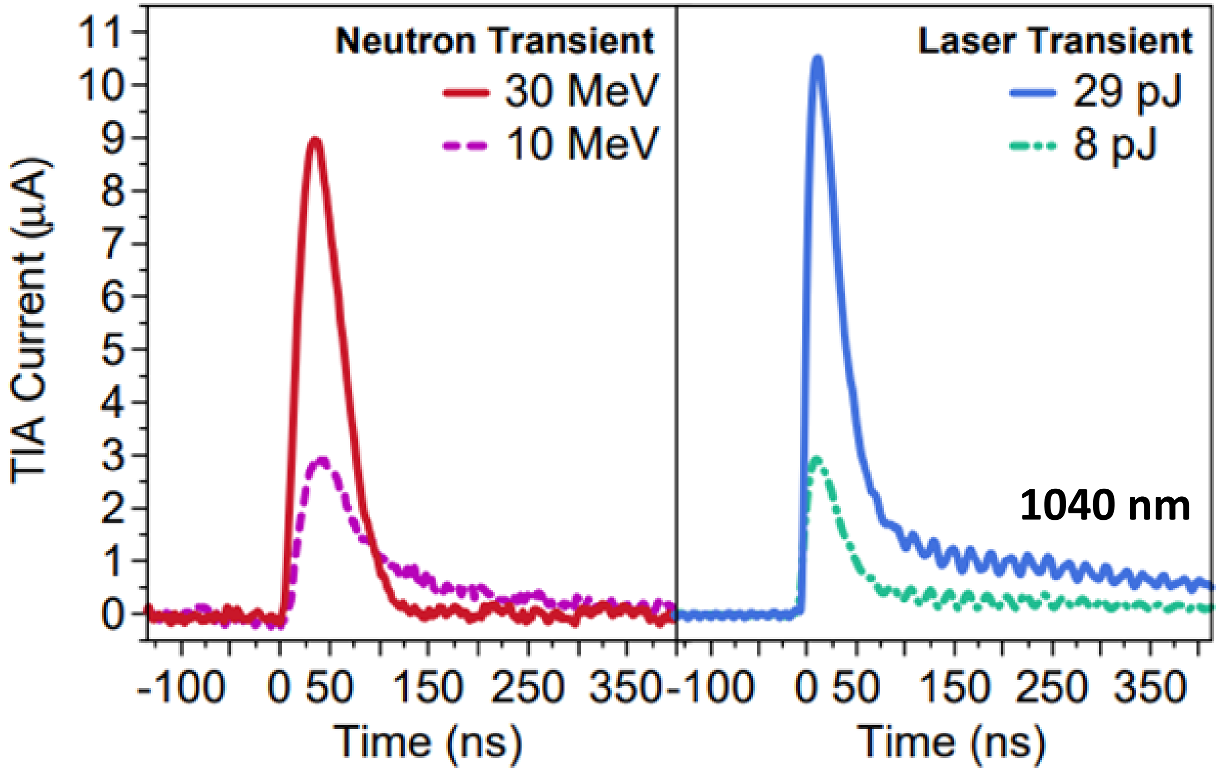


TABLE III
LASER ENERGY PER PULSE

| Deposited Energy | SPA Epp | TPA Epp |
|---|---|---|
| 1 MeV | 1.6 pJ | 0.8 nJ |
| 10 MeV | 16.4 pJ | 2.6 nJ |
| 50 MeV | 82.2 pJ | 5.8 nJ |



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# Conclusions

- Laser emulation of neutron induced responses in silicon is possible
- We need to improve the calibration for neutron low energy reactions ($^{25}$MeV, $^{28}$Al) using monoenergetic neutron beams for a precise signal classification.
- Next step: repeat the calibration for microelectronic structures to reproduce neutron induced SEE’s with ultrashort pulsed lasers.

# Thanks for your attention!

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