ITALIAN NATIONAL AGENCY FOR
NEW TECHNOLOGIES, ENERGY AND
SUSTAINABLE ECONOMIC DEVELOPMENT

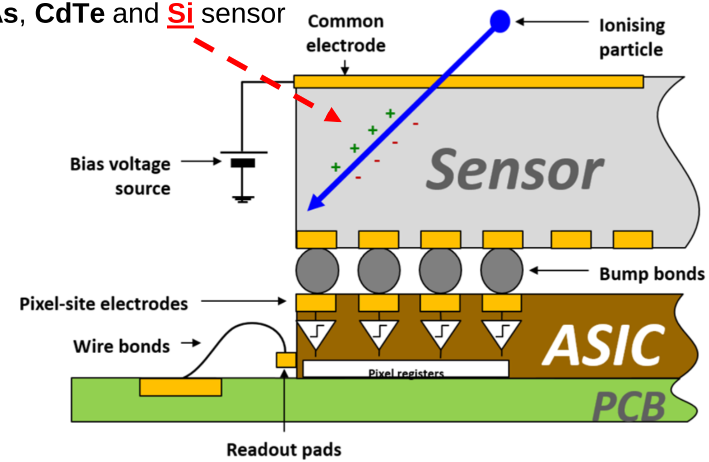
Advanced Techniques in Neutron and Tritium Detection

Centro Ricerche Enrico Fermi, 11th December 2024

Francesco Cordella/ NUC-PLAS-FIPI Lab NIXT

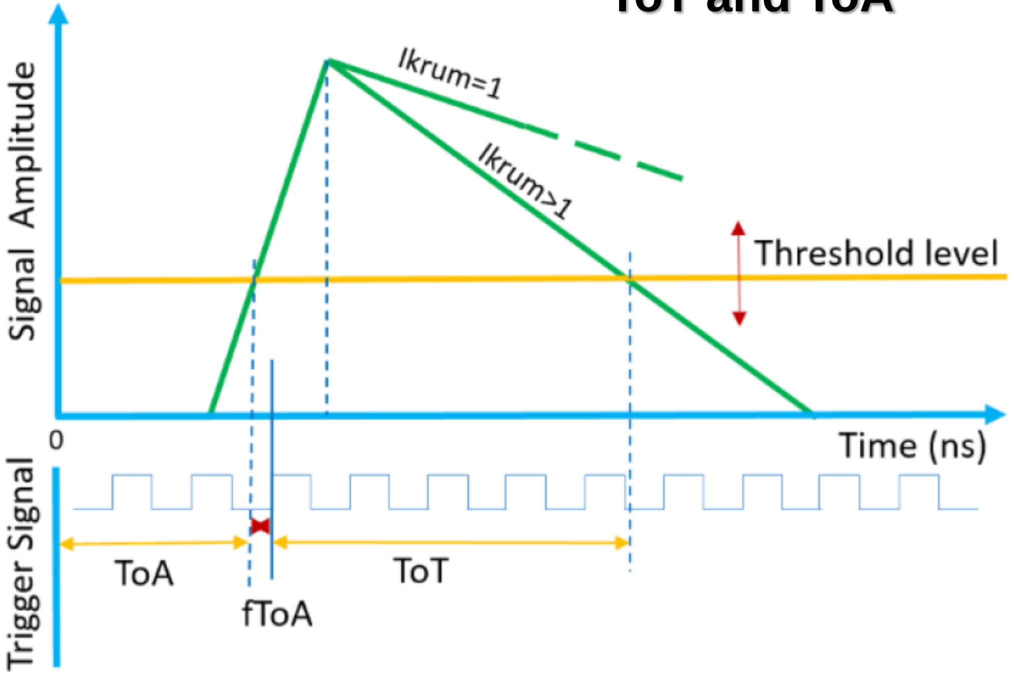
Timepix detector

Commonly used semiconductors are:
GaAs, **CdTe** and **Si** sensor



Detector efficiency	100% @10ke
Sensitive area	14 x 14 mm^2
Pixel pitch	55 µm
Energy range	1 – 35 keV
Energy resolution	2 keV (FWHM) @20 keV
Frame rate	50 readouts/s

ToT and ToA



Timepix detector family

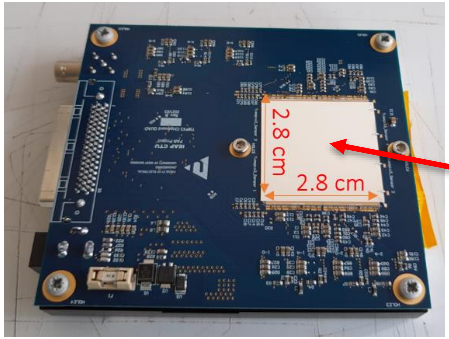
Medipix (2009-2015)
Time frame oriented
- Counting mode

Timepix (2015-2018)
Time frame oriented
- Counting mode or
- Time of arrival or
- Charge

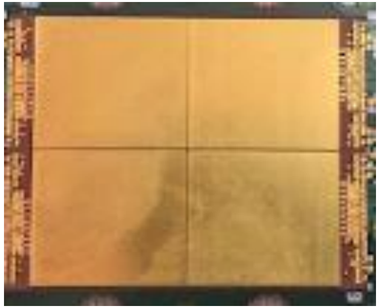
Timepix3 (2018)
Pixel oriented
- Counting mode and
- Time of arrival and
- Charge

- The Timepix ASIC consists of **256×256 hybrid CMOS pixels**, each measuring **55×55 μm^2**
- Each pixel can measure **deposited charge** and do **single particle counting**.
- The detection threshold is about **1000 electron charge**.
- There are also **Quad configurations** like 2×2 and 4×1

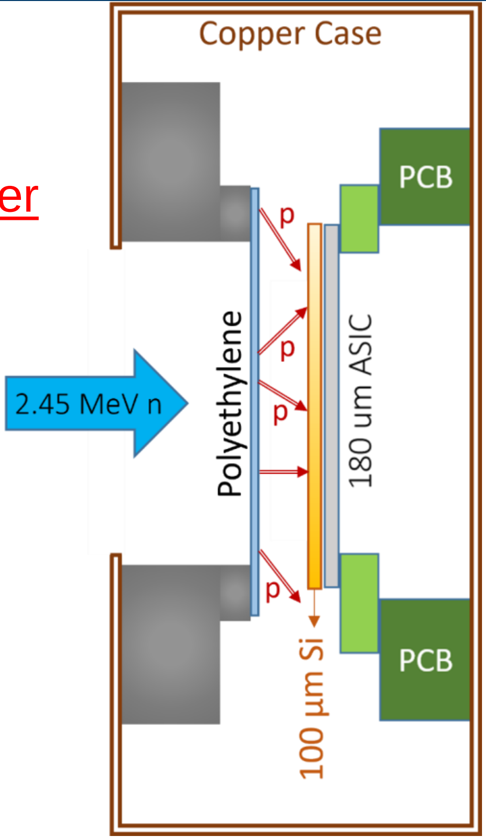
Timepix3 new «Quad» detector with PE converter



2×2
TPX3

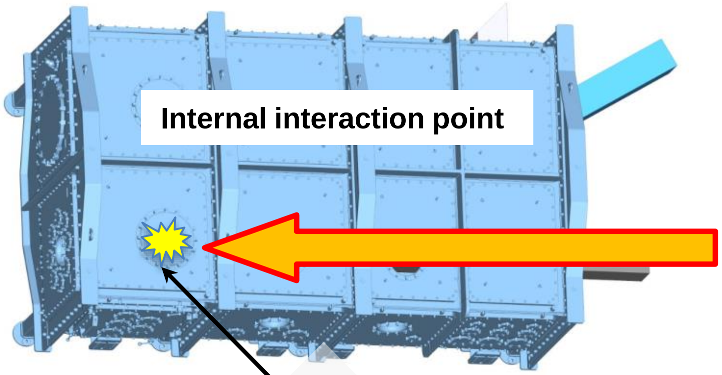


+ PE converter

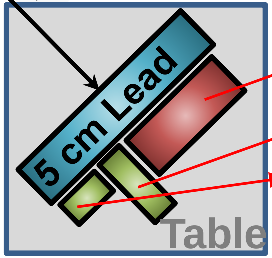


A new Timepix3 **quad** has recently been developed. It features a **100 µm silicon sensor** and does **not have a PCB board on the back**. This design was implemented to minimize backscattering radiation under certain experimental conditions. The detector is equipped with a **polyethylene converter** approximately 1 mm from its surface, allowing it to detect neutron interactions effectively.

Fast neutron detection at the ELI Beamlines facility (Prague)



LASER
- ~10 J
- ~ 30 fs
- ~ 0.5 PW



~ **3.18** n/shot/cm^2 @ 100 cm

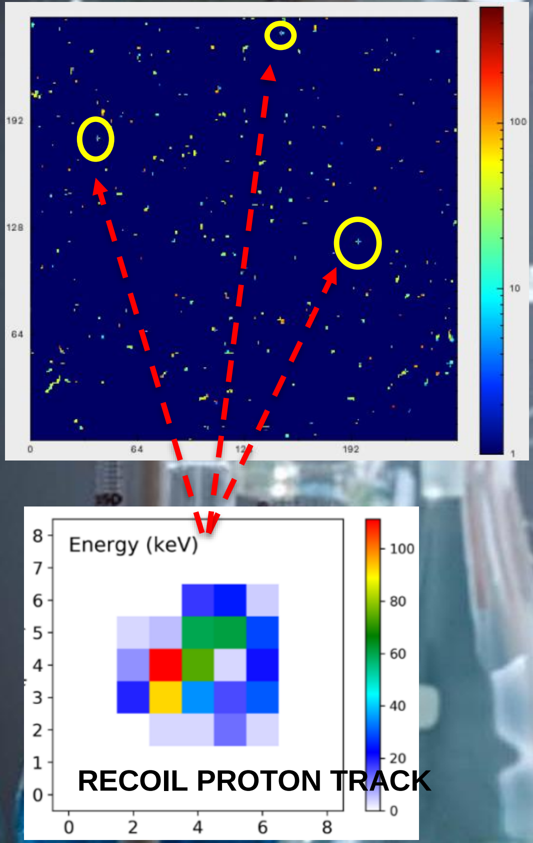
$$t_{100cm} = \frac{L}{v_n} = \frac{1.35\ \mathrm{m}}{17.6\times10^{6}\ \frac{\mathrm{m}}{\mathrm{s}}} \approx \mathbf{77\ ns}$$

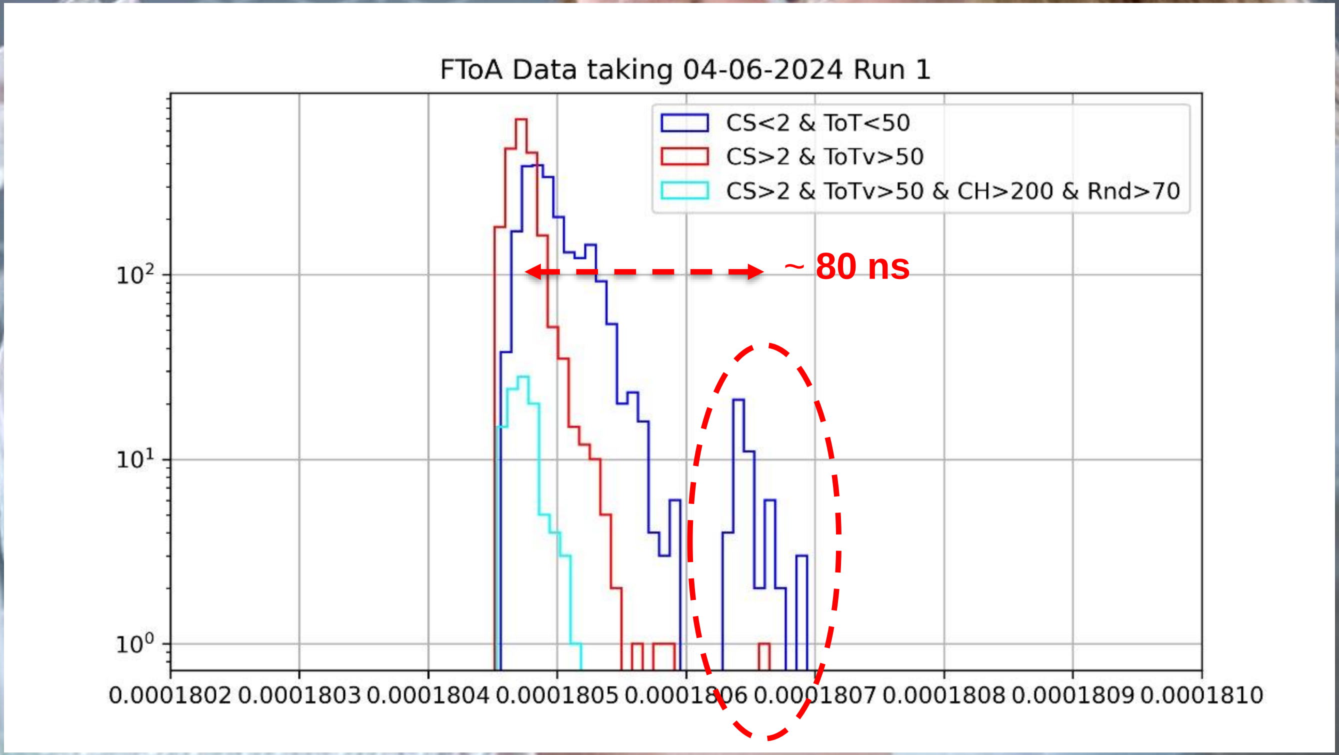
…since TPX3 has a time resolution of 1.56 ns, that means **~50 clocks units**

$${}_{1}^{2}\mathrm{D} + {}_{1}^{2}\mathrm{D} \rightarrow {}_{2}^{3}\mathrm{He}(0.82\ \mathrm{MeV}) + \mathrm{n}(2.45\ \mathrm{MeV}) \quad 50\% \quad \text{n-branch}$$

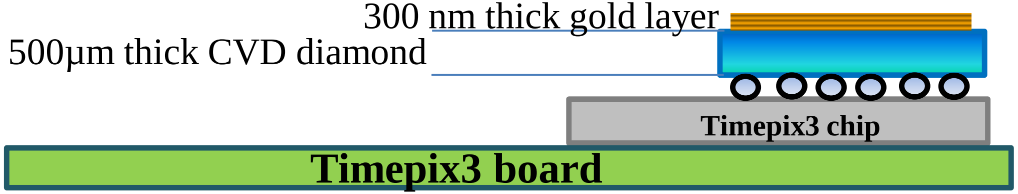
$${}_{1}^{2}D + {}_{1}^{2}D \rightarrow {}_{1}^{3}T(1.01\ MeV) + p(3.02\ MeV) \quad 50\% \quad \text{p-branch}$$

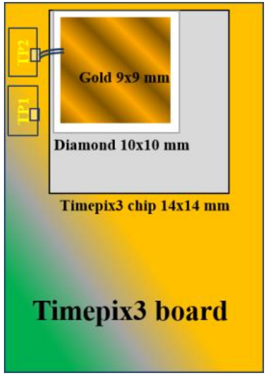
ELI data 04/06 Run 1 – deuterated target

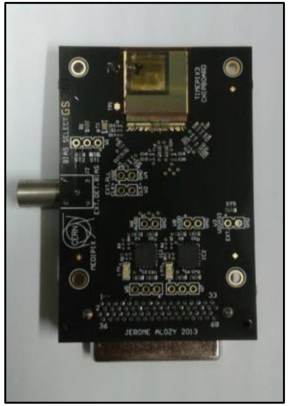




Diamondpix for fast neutron detection in nuclear fusion





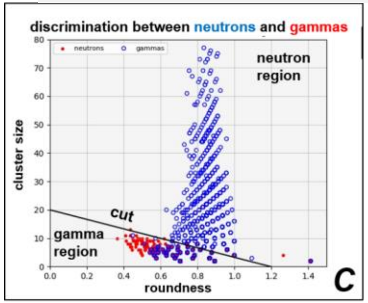


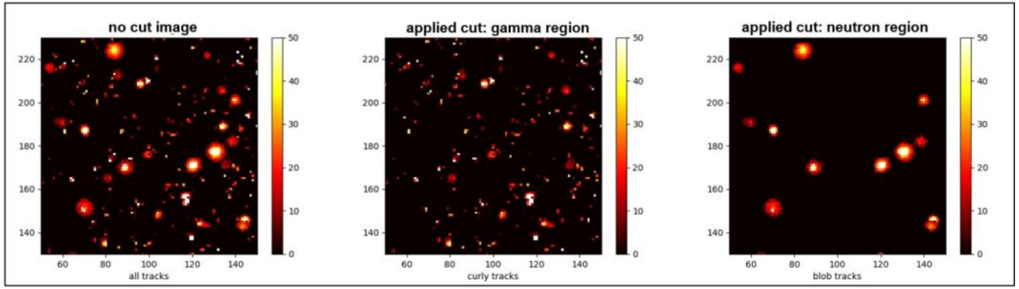
A CVD **polycrystalline** diamond has been coupled to a Timepix3ASIC through the bump-bonding technique.

FNG facility, ENEA Frascati

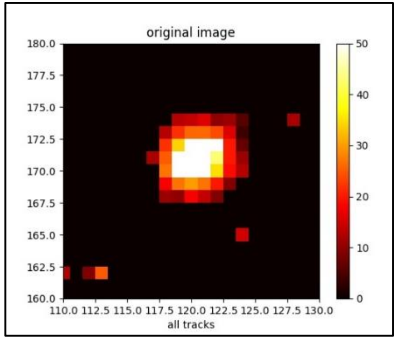
14 MeV neutrons

Neutrons discrimination against gammas





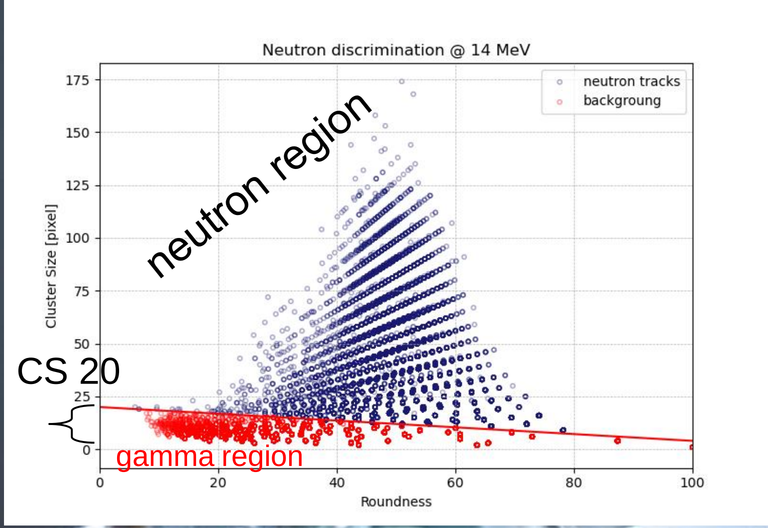
neutron track

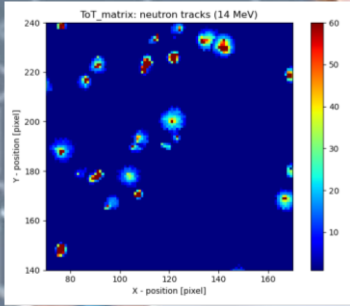


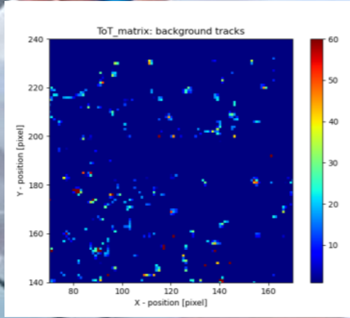
A dedicated algorithm was realized and applied to experimental data to select tracks according to their morphological parameters and their deposited energy.

Estimation of efficiency for 14 and 2.5 MeV (FNG facility)

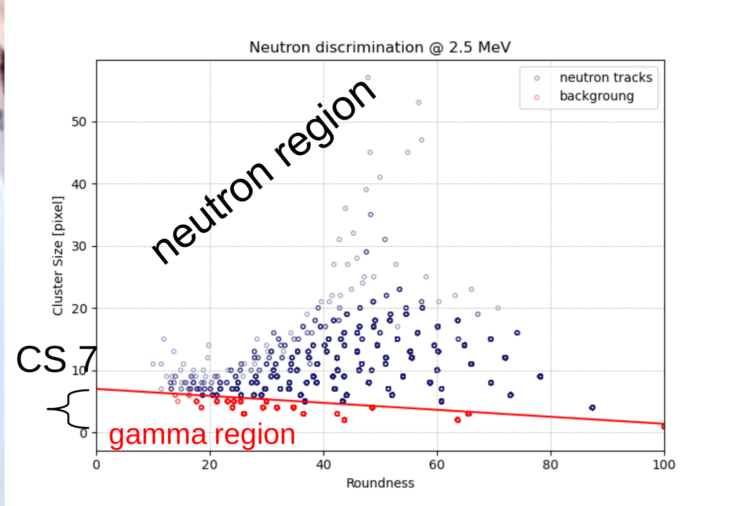
14 MeV







2.5 MeV

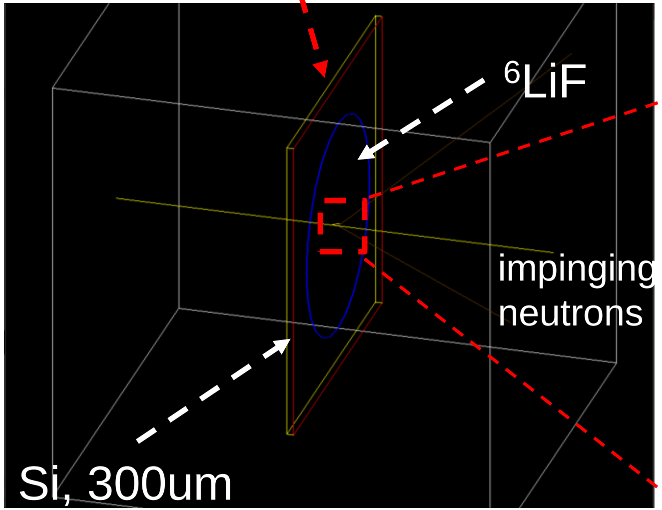


A neutron flux scan (from 6.0 × 10^8 to 1.6 × 10^{10} n/s) on FNG allowed an efficiency of *2.5 ± 0.1 ‰*

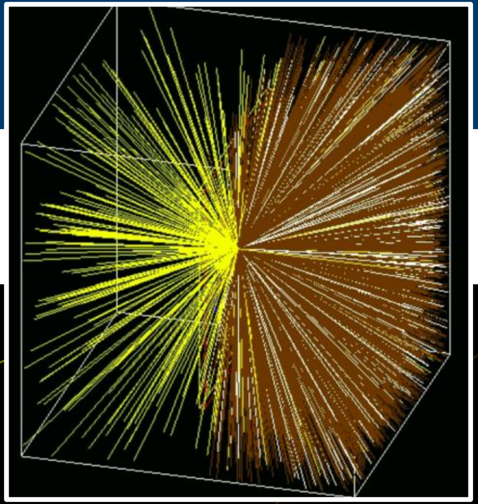
A neutron flux scan (from 2.1 × 10^8 to 2.5 × 10^{10} n/s) on FNG allowed an efficiency of 6.8 ± 0.5 ‰

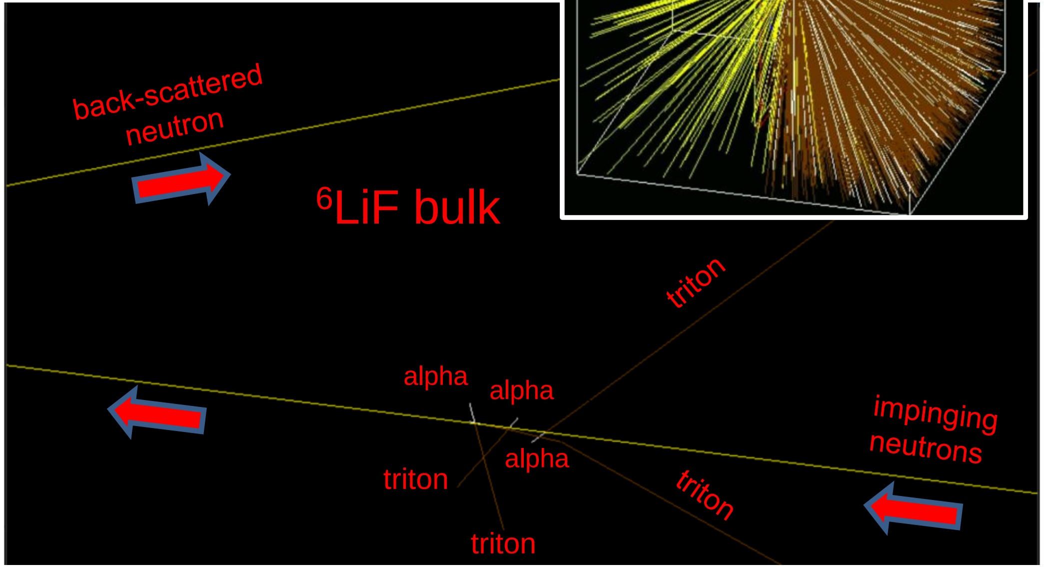
Example of Geant4 (G4) simulation

TPX + material deposition stacked layers



Zoom

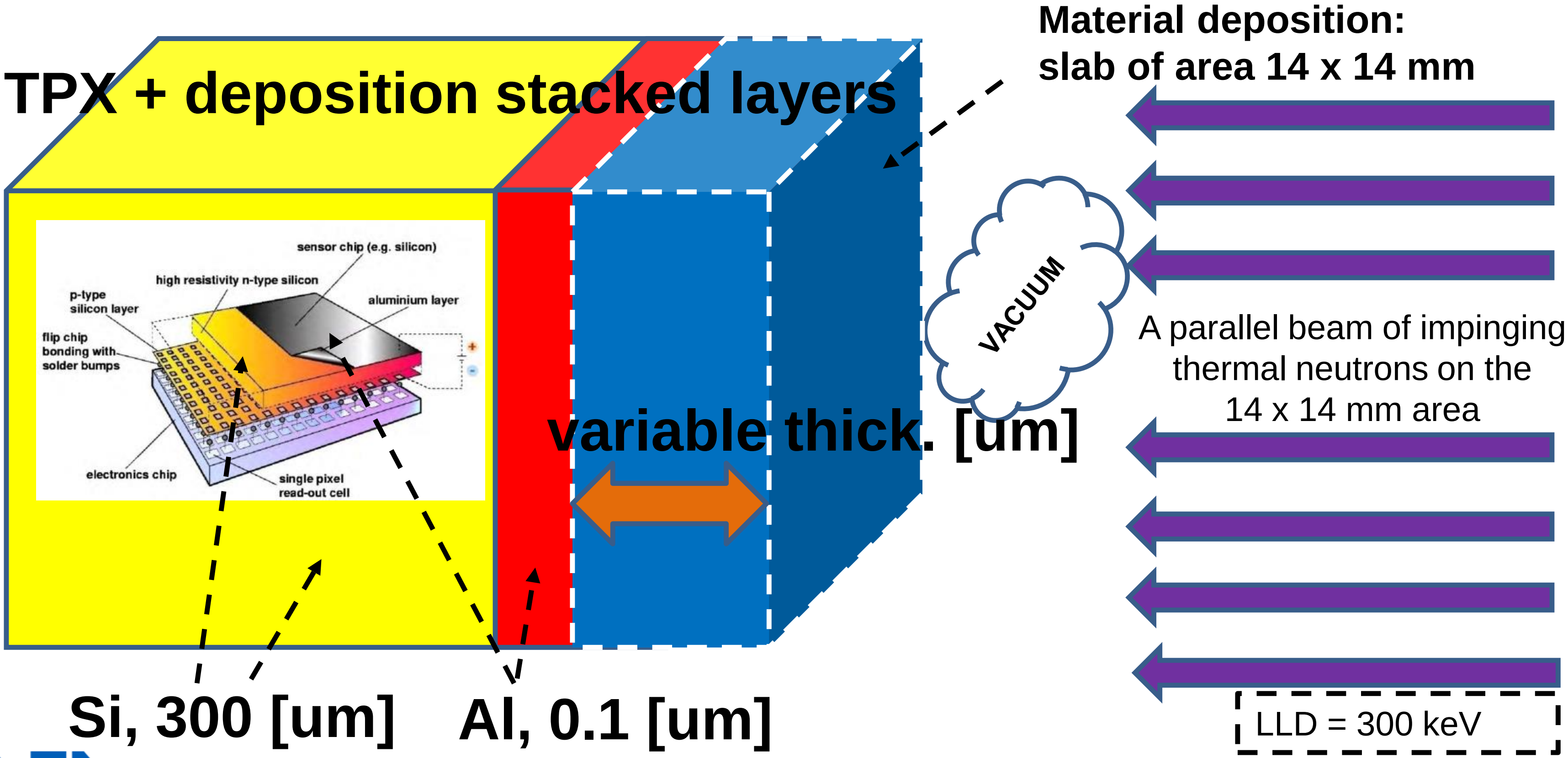




<u>**Example of a G4 simulation results**</u>:
A linear beam of 10 impinging **thermal neutrons** on a ^{6}**LiF** cylindrical layer (30 um thickness) deposited on the Al layer of a TPX

- The reaction products are released in **opposite directions** when thermal neutrons are absorbed by the material
- Penetration depths of **alpha** and **tritons** in 6LiF are very different

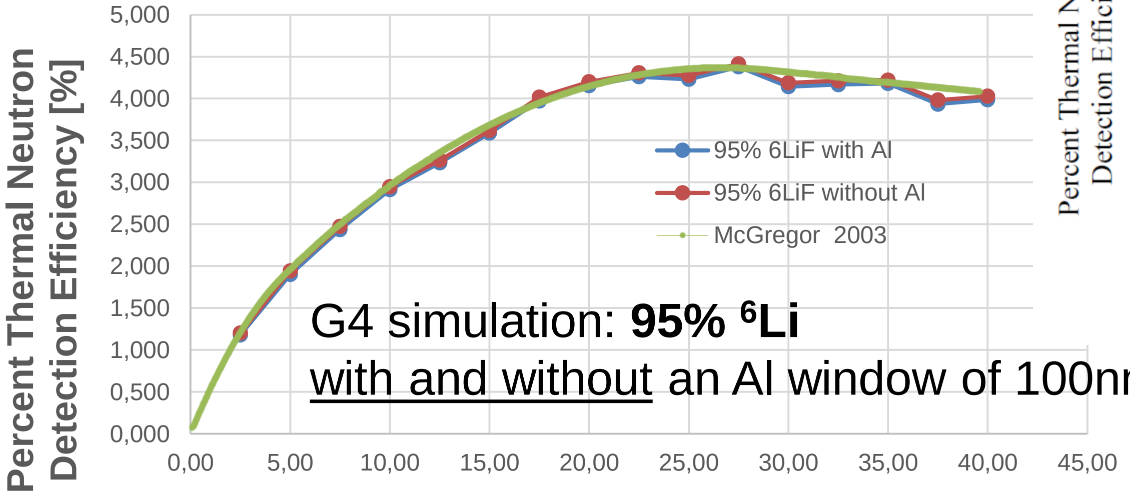
Example of Geant4 (G4) simulation



G4 vs. McGregor 2003 article results (Fig. 16, 6LiF Orthogonal Front Irradiation)

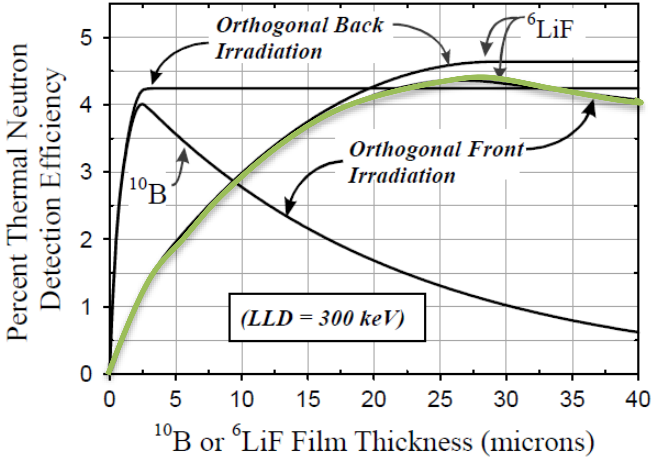
Parallel beam of **10^5 neutrons**, **25 meV** incident on the front face of the detector

TPX + ^{6}LiF deposition



^{6}LiF (95% enriched) Film Thickness (microns)

G4 simulation: **95% ^{6}Li**
with and without an Al window of 100nm



LLD = 300 keV

P. T. Matthews, Introduction to Quantum Mechanics, 1968:

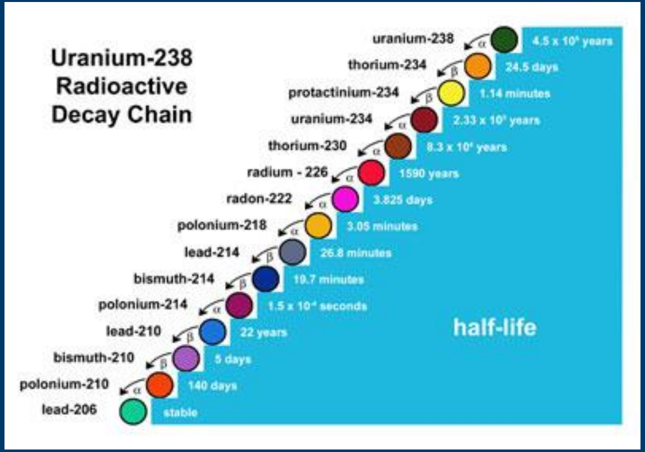
CHAPTER 10

SCATTERING THEORY

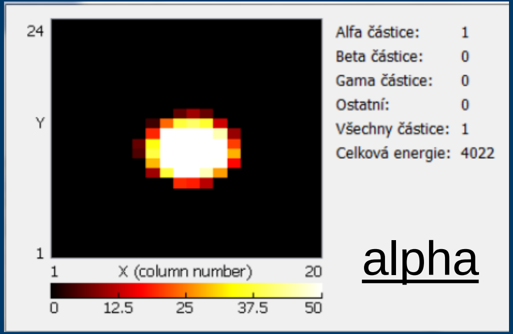
§ 10.1 Introduction

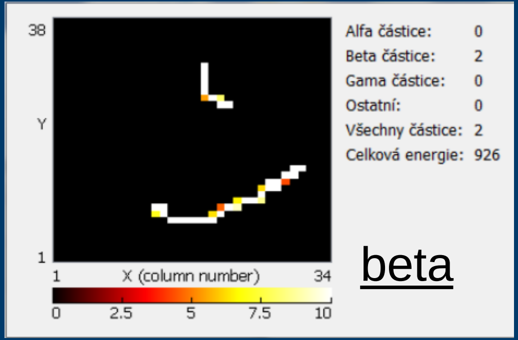
The only way to investigate the nuclear potential is to bring the nucleons together and study their mutual interactions, much as one studies magnetic forces by bringing two magnets together to find how they react on each other. To do this systematically one needs a beam of nuclear particles; a target of nuclei (or nucleons); and some detection device to see how the beam is deflected—or scattered—by the nuclear interactions between the particles in the beam and those in the target. The typical nuclear experiment is thus like playing a hose on some object, and trying to deduce the shape of the object—analogue of the shape of the interaction potential—from a detailed study of the angular distribution and intensity of the splash. Since the beam is scattered by the target, these are known as scattering experiments, and they are analysed by scattering theory. We are dealing with quantum systems so this has to be a quantum scattering theory, but to clear one's ideas it is very useful to see first how such experiments go under purely classical conditions.

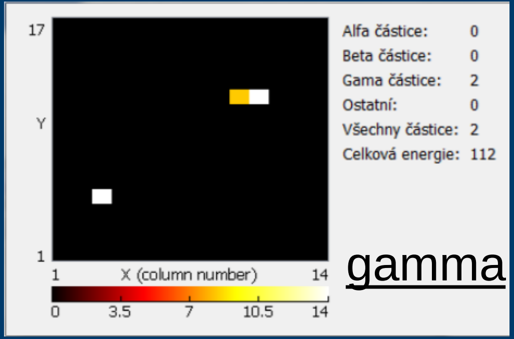
URANIUM GLASSES EXPERIMENT



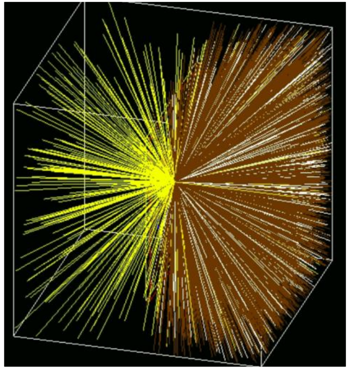
Weak source of ionizing radiation:



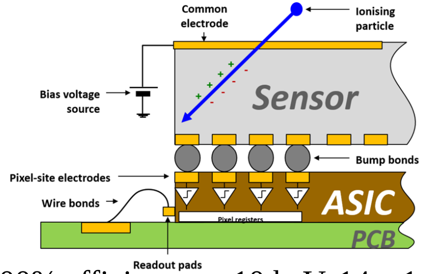




Summary Slide



Advanced Techniques in Neutron and Tritium Detection



Presenter: Francesco Cordella

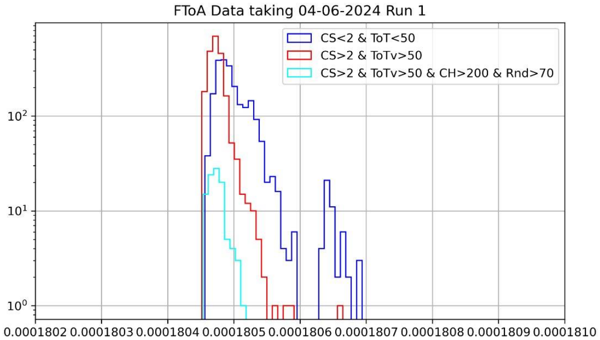
Date: 11th December 2024

Venue: Centro Ricerche Enrico Fermi

Key Topics:

- **Timepix Detector**: Uses GaAs, CdTe, Si; 100% efficiency at 10 keV, 14 x 14 mm² area, 55 µm pixel pitch, ToT and ToA.
- **Timepix3 Quad Detector**: 100 µm silicon sensor, minimizes backscattering, polyethylene converter for neutron detection.
- **Applications**: Ionizing radiation, fast/thermal neutron detection, Diamondpix for nuclear fusion, Monte Carlo simulations.
- **Future**: Timepix4 improves hit rate, energy resolution, and time measurements.

Contact: francesco.cordella@enea.it



BACKUP SLIDES

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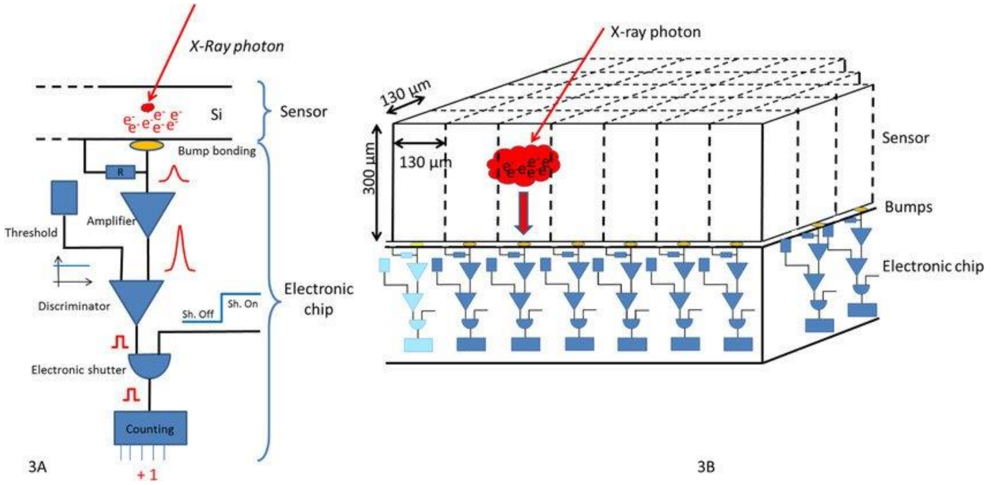
Timepix4: comparison with Timepix3

- A 300 μm thick p+ in n detector and mounted on the Nikhef chip carrier board.
- The ASIC is composed of 448 × 512 pixels. It is designed to be connected to a sensor which is composed of 448 × 512 square pixels at a pitch of 55 μm.
- Timepix4 cover an area of 28.2×24.6 mm^2 and has several improvements respect to Timepix3, in particular hits rate, energy resolution and time mesurements.

		Timepix3	**Timepix4**
Technology		IBM 130nm	TSMC 65nm
Pixel Size		55 x 55 μm	≤ 55 x 55 μm
Pixel arrangement		3-side buttable 256 x 256	4-side buttable 256 x 256 or bigger
Operating Modes	Data driven	PC (10-bit) and TOT (14-bit)	CRW: PC and iTOT (12...16-bit)
	Frame based	TOT and TOA	
Zero-Suppressed Readout	Data driven	< 80 MHits/s	< 500 MHits/s
	Frame based	YES	YES
TOT energy resolution		< 2KeV	**< 1Kev**
Time resolution		1.56ns	**~200ps**
Readout bandwidth		5.12Gb (8x SLVS@640 Gbps)	20.48 Gbps (4x 5.12 Gbps)
Front-end		"with" Volcano	No volcano → Dynamic gain But supply only 1.2V

Hybrid pixel detector



These detectors are based on the direct detection and individual counting of x-ray photons. This sensor layer is micro-soldered with a step-size of 1 pixel to an electronic chip by the bump-bonding technique, an operation called ***hybridization***.

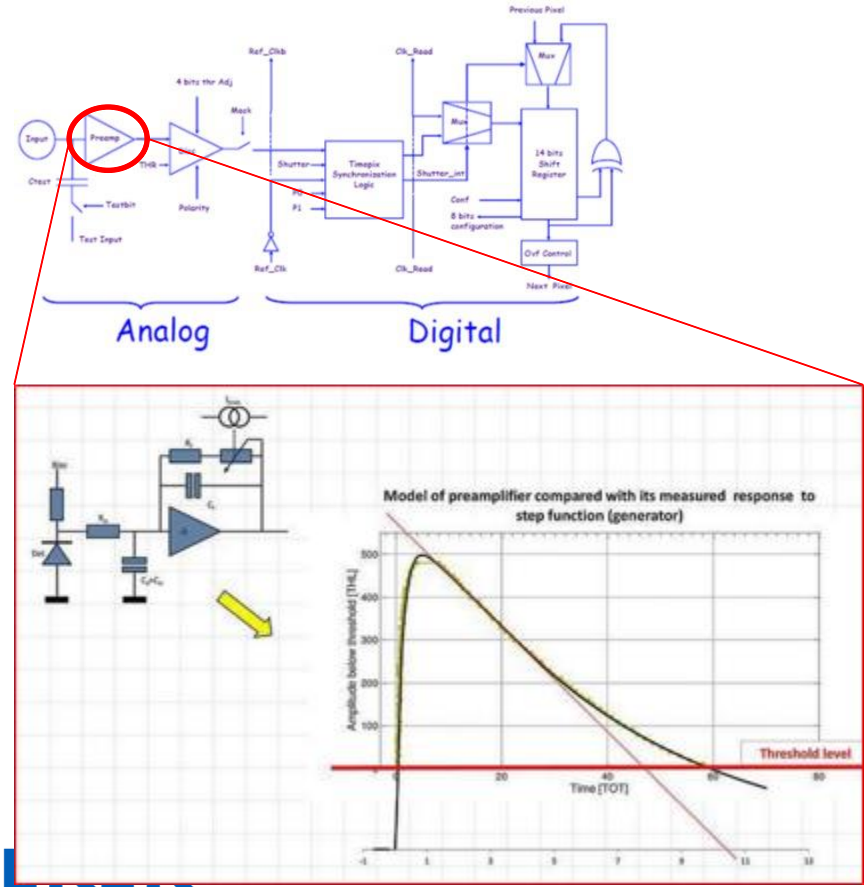
Hybrid pixel detectors consist in a sensor layer (Si, CdTe, GaAs) where the x-ray photon is directly converted into a current.

The sensor layer can pixelized with a size of 172 × 172 µm^2 (PILATUS), 130 × 130 µm^2 (XPAD), 75 × 75 µm^2 (EIGER), 55 × 55 µm^2 (MEDIPIX).

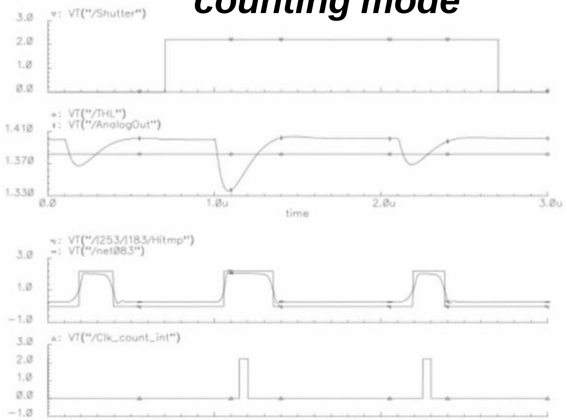
Each pixel works like a point detector. The electronics in the pixel performs the following operations:

- Conversion of the collected electrons into an electrical impulse, amplification and formatting of the impulse.
- Comparison of the impulse to a reference threshold (defined for each pixel) and validation (or not) of the counting event (discrimination).
- The discriminated impulse passes through a logic gate which is open/closed by an externally controllable electrical signal. This allows the implementation of a fast electronic shutter.
- The discriminated impulse is 'authorized' to pass the electronic shutter, is counted and stored in the counter.

Timepix detector: acquisition modes



counting mode



Time over Threshold mode