Instrumentation for nuclear physics experiments: the timepix chip

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on behalf of the INFN_E and n_TOF local collaborations

INFN - LNF & ENEA Frascati

Fundamental research and applications with the EuPRAXIA facility at LNF
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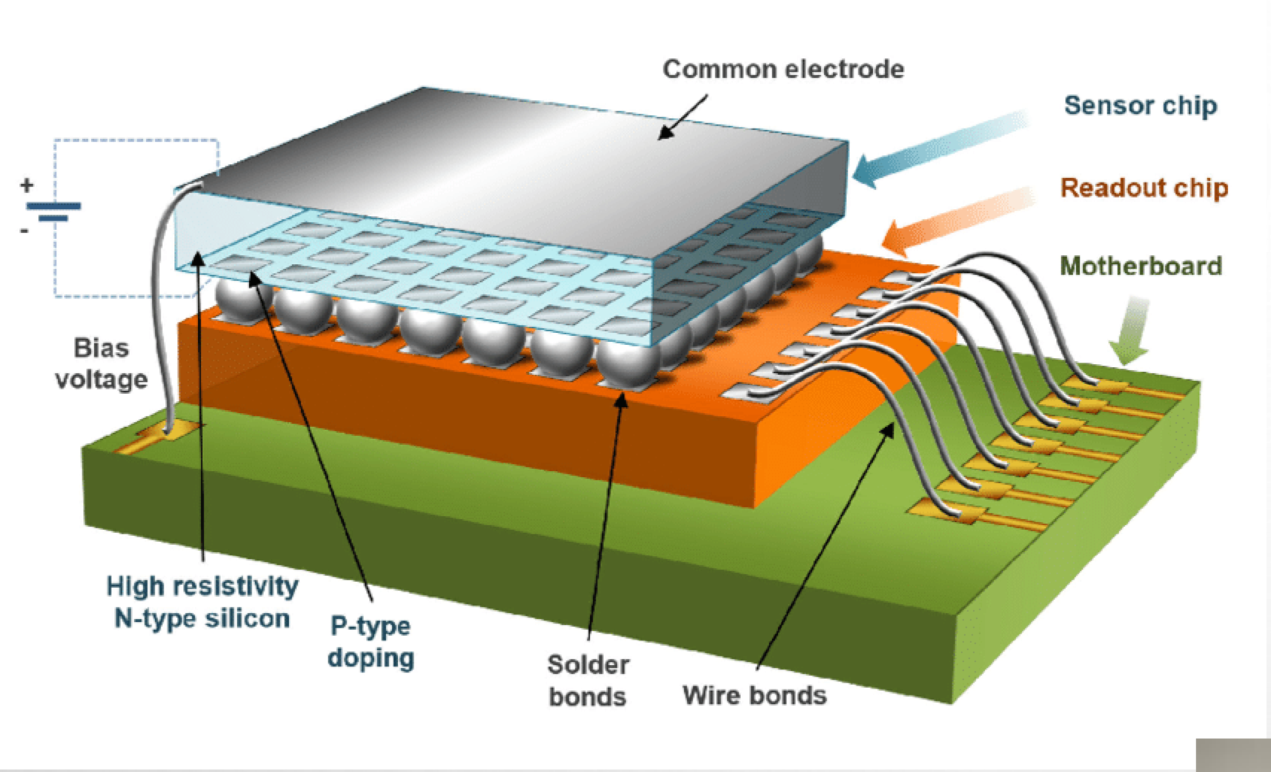
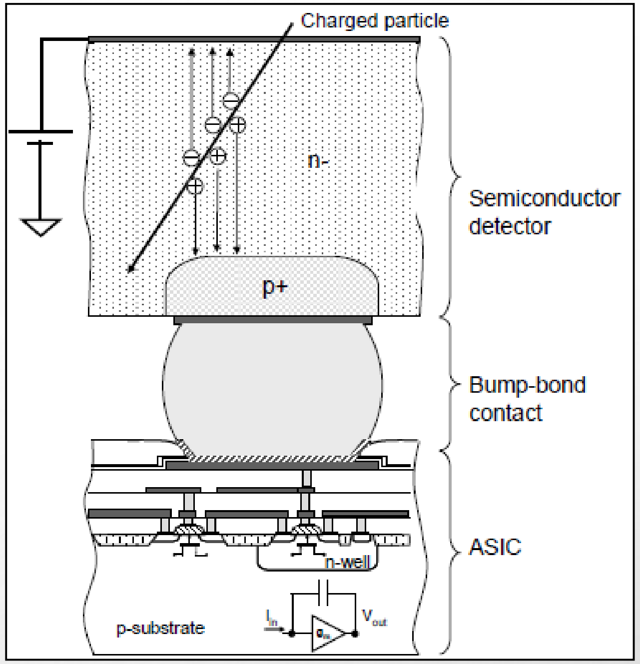
SUMMARY

1. *Timepix detectors: detector layout and basic features*
2. *Timepix3 detectors for hard-X rays, gammas and charged particles*
3. *The Diamondpix detector and diagnostic of fast neutrons from fusion reactions*
4. *The GEMpix detector and X-ray measurements in Laser Produced Plasmas*
5. *The GEMINI SIDE-ON GEM detector for X-ray measurements in Laser Produced Plasmas*
6. *The GEMpix detector for measurements of charged particles and their identification*

1. Timepix detectors: detector layout and basic features

1. The Timepix detector

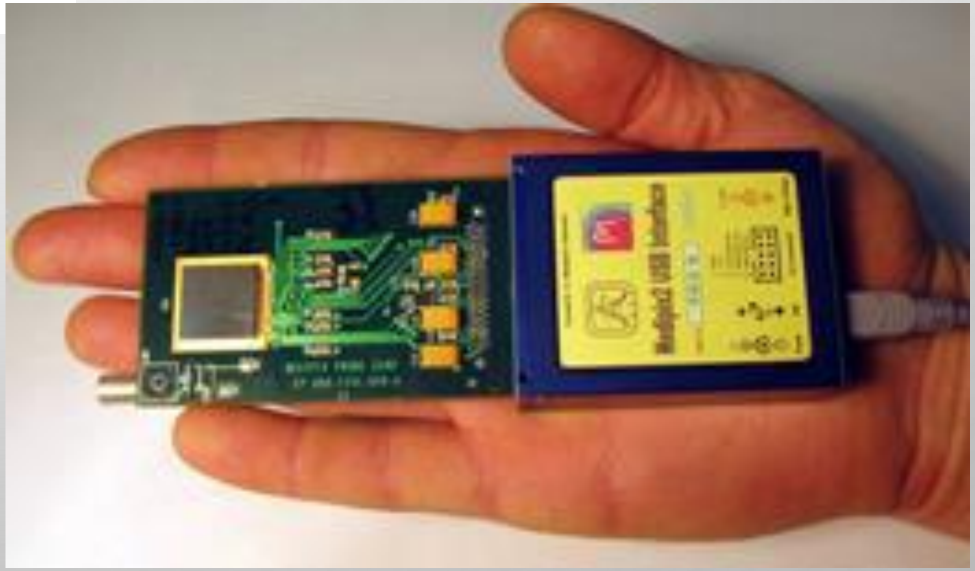




MEDIPIX SINGLE PIXEL

Some of the main characteristics of Timepix1

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



1. Timepix detectors family

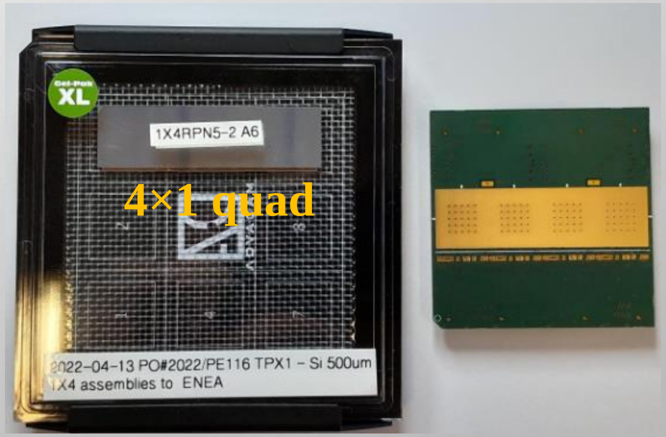
Medipix (2009-2015)	Timepix (2015-2018)	Timepix3 (2018)
Time frame oriented	Time frame oriented	Pixel oriented
• Counting mode	• Counting mode or	• Counting mode and
	• Time of arrival or	• Time of arrival and
	• Charge	• Charge

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.

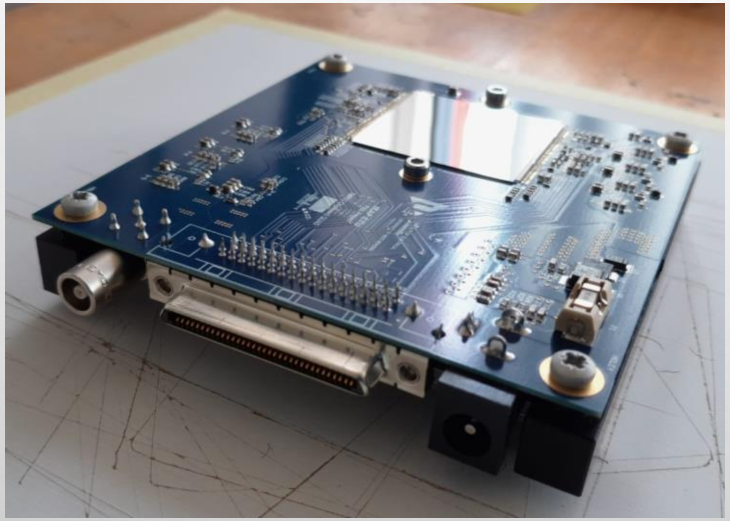
There are also quad configuration like 2×2 and 4×1

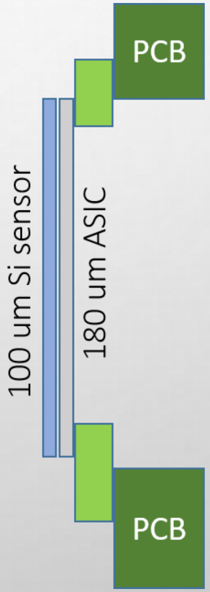


1. Timepix3 detector

Timepix3 chip covers the same area of Timepix1 (14×14 mm^2) and can be configured in quad configurations.

They can be read with different types of control modules, and we used successfully the Katherine modules that be controlled via Ethernet cables and provide also polarization bias to the semiconductor.





Recently a new Timepix3 quad has been realized. It is made with a 100 µm Silicon and has no PCB board on the back. This layout was realized to avoid the backscattering radiation that can be produced in particular experimental conditions.

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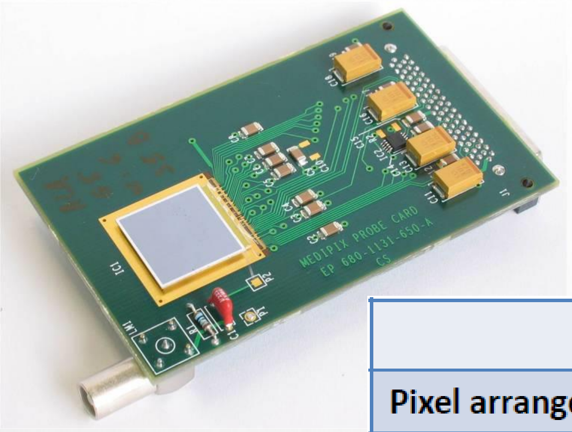
Like Timepix1, Timepix3 quad detectors are the results of the composition of 4 TPX3 and can be realize in different configurations.

1. Detector performances

Timepix1 versus Timepix3

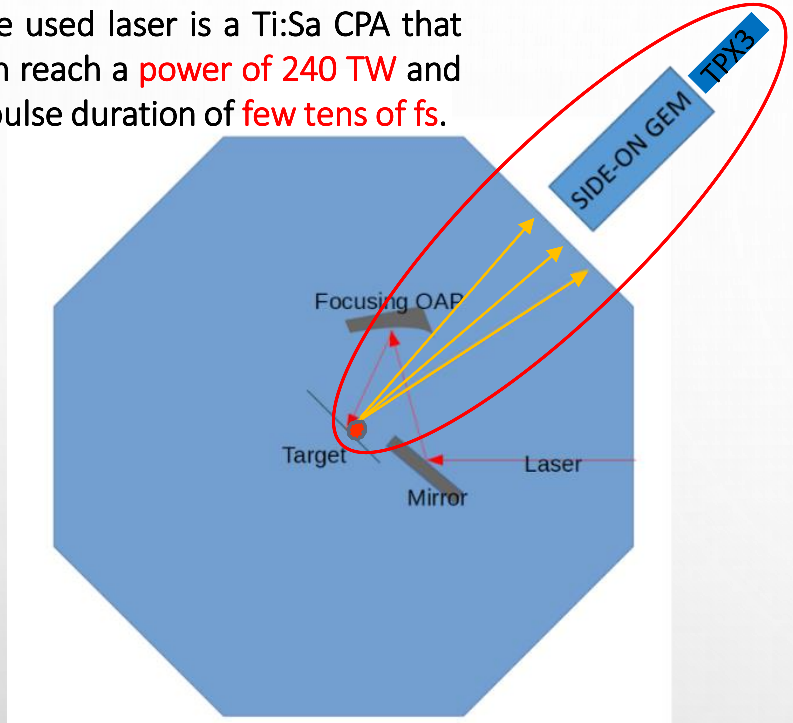


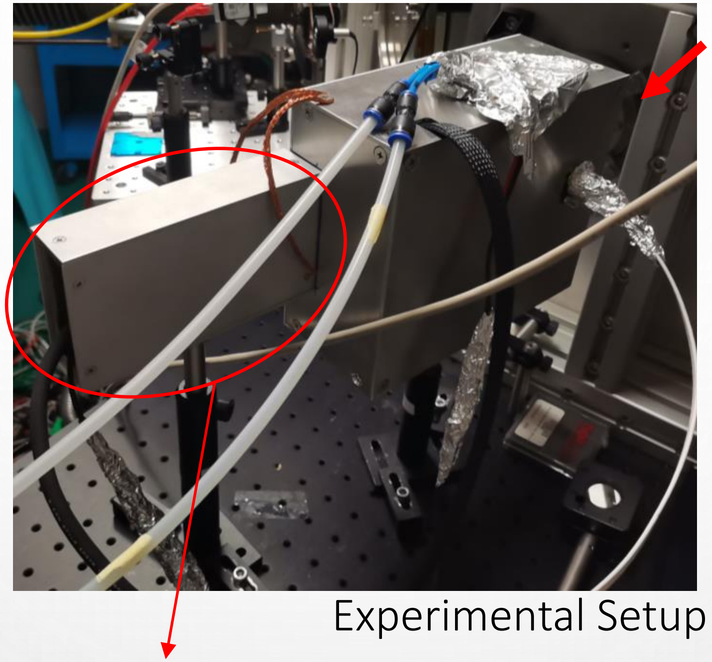
	Timepix (2006)	Timepix3 (2013)
Pixel arrangement	256 x 256	
Pixel size	55 x 55 µm²	
Technology	250nm CMOS - 6Metals	130nm CMOS - 8Metals
Acquisition modes	1) Charge (iTOT) 2) Time (TOA) 3) Event counting (PC)	1) Time (TOA) AND Charge (TOT) 2) Time (TOA) 3) Event counting (PC) AND integral charge (iTOT)
Readout Type	1) Full-Frame	1) Data driven (DD) 2) Frame (FB)
Zero suppressed readout	NO	YES
Dead time per pixel	> 300µs readout time of one frame	> 475ns ~600x Pulse measurement time + packet transfer time
Minimum timing resolution	10ns	1.562ns 6.4x
On-chip Power pulsing (PP)	NO	YES
Minimum detectable charge	~750e-	>500e- 1.5x
Output bandwidth	1 LVDS ≤200Mbps 32 CMOS ≤3.2Gbps	1 to 8 SLVS @640Mbps DDR ≤5.2Gbps 1.6x

2. Timepix3 detectors for hard-X, gammas and charged particles

2. HARD-X RAYS' MEASUREMENTS WITH TIMEPIX3 AT THE ILIL LASER PLASMA FACILITY (CNR-INO, PISA)

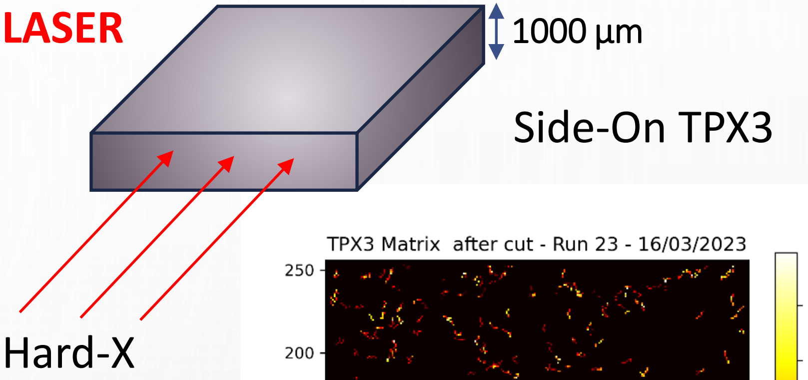
The used laser is a Ti:Sa CPA that can reach a power of 240 TW and a pulse duration of few tens of fs.

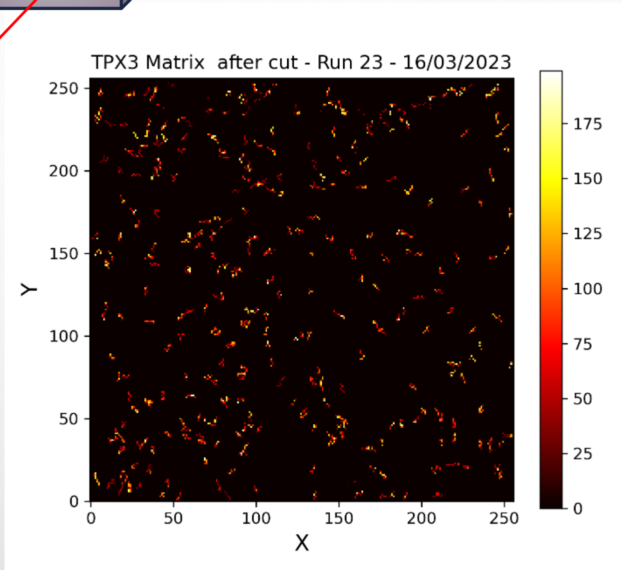


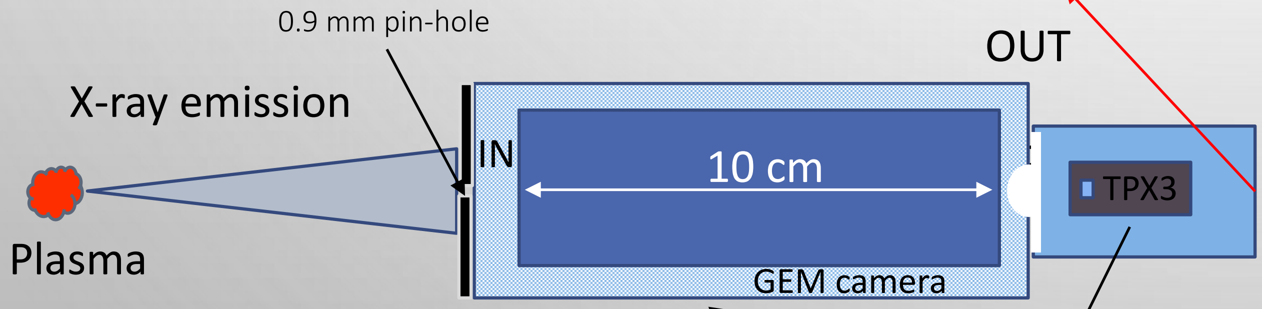


Experimental Setup

TPX3 detector inside the aluminum box with walls of 2 mm thickness







GEM detector inside the aluminum box with walls of 2 mm thickness

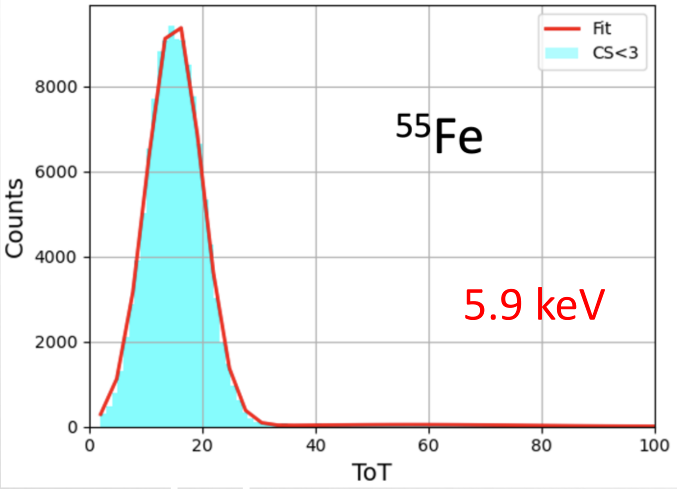
TPX3 body sensor length of 14 mm (thickness 1000 μm)

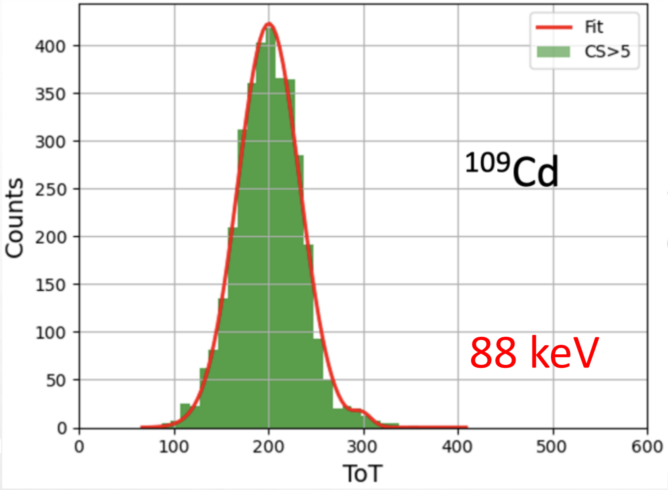
The synergistic operation of the GEM and TPX3 detectors enables spectroscopic analysis of radiation along the same line of sight, covering a wide energy range from soft X-rays to gamma rays detection (2 KeV-10 MeV)

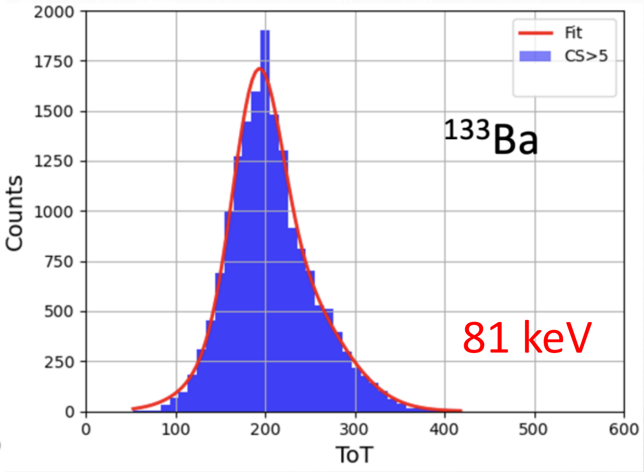
The first week was dedicated to the measurements of the X-rays spectra coming from different types of targets: **Titanium**, **Aluminum**, **Copper** and **Mylar**

2. Hard-X rays' measurements with a 1 mm thick Timepix3 detector on the ILIL laser plasma facility (CNR-INO, Pisa): gamma energy calibration with laboratory sources

The response of the detector was assessed by employing well-known emission gamma sources:

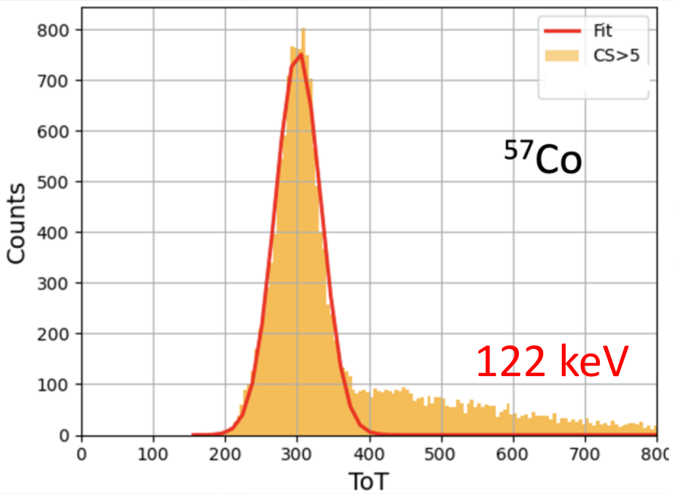


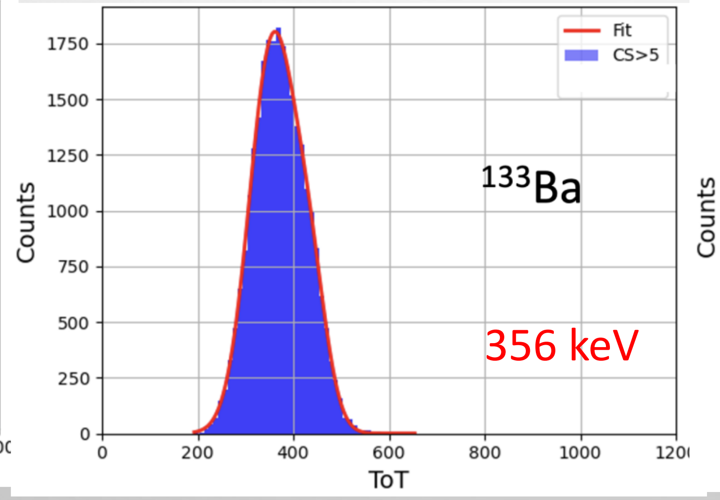


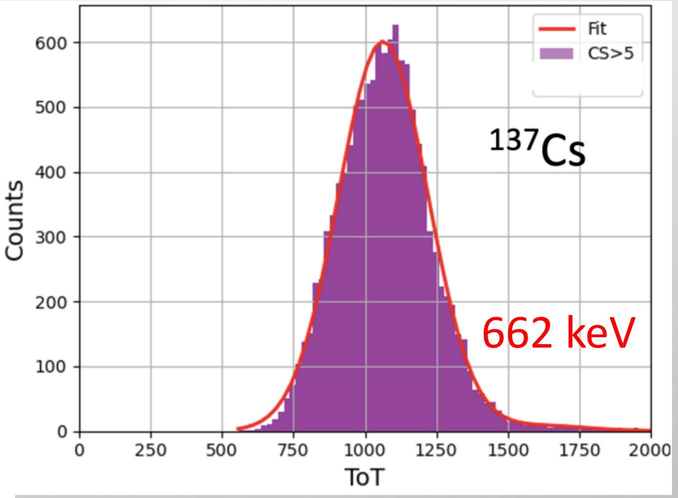


The ToT charge distributions have been obtained by applying appropriate cuts on cluster parameters:

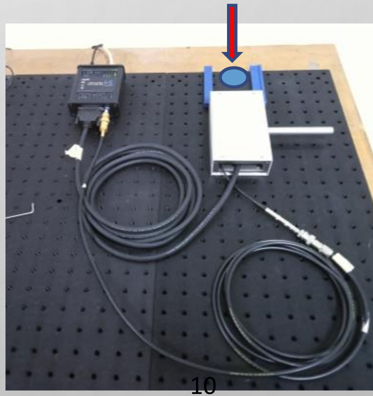
- Cluster size (CS)
- Roundness (Rnd)
- Linearity (Lin)





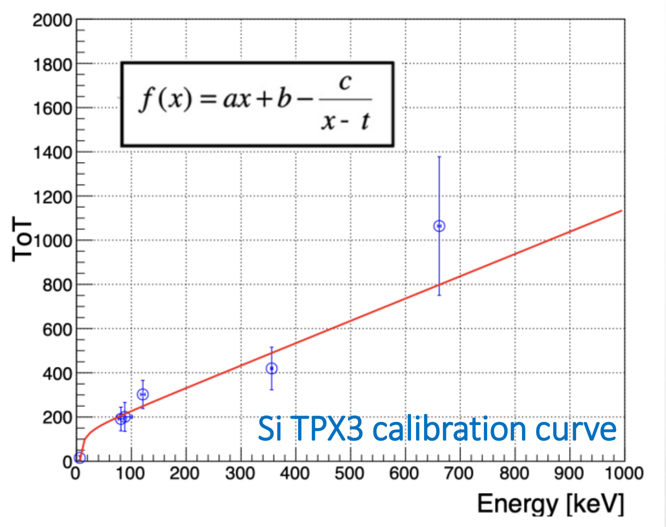


Gamma Source

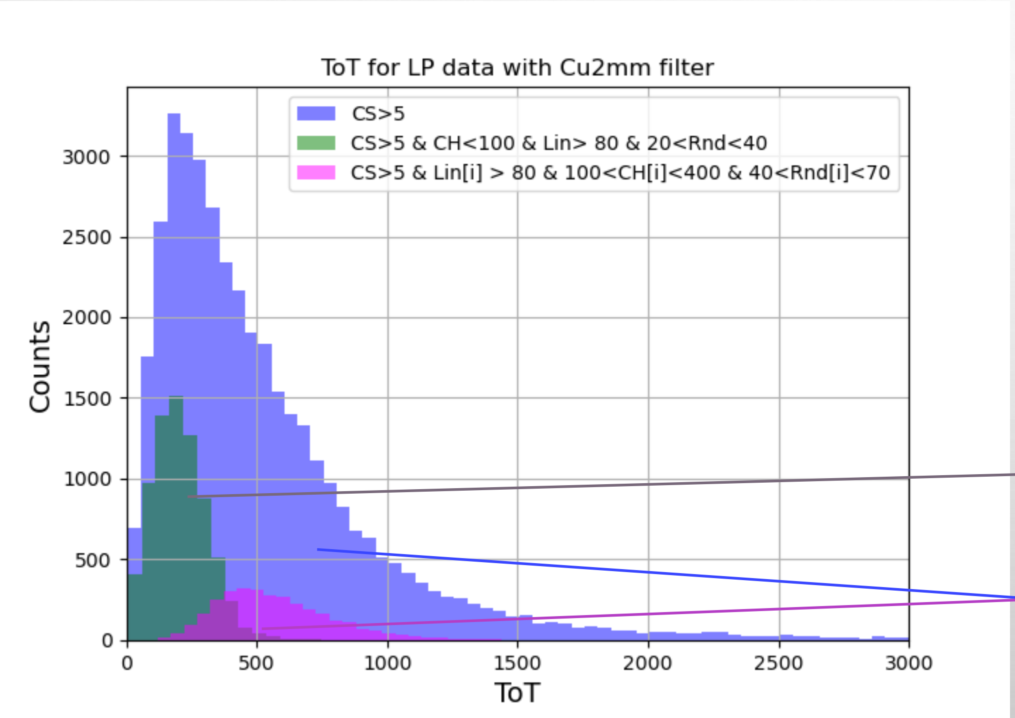


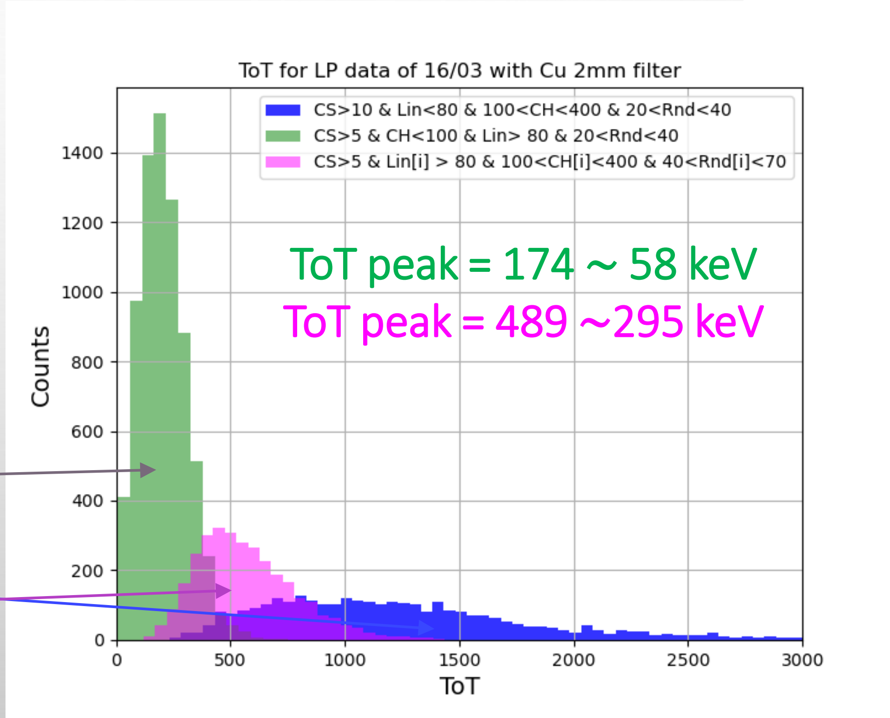
2. Hard-X rays' measurements with a 1 mm thick Timepix3 detector on the ILIL laser plasma facility (CNR-INO, Pisa)

Energy (keV)	ToT (μ)	Error (σ)
5.90 (^{55}Fe)	15.05	4.91
81.00 (^{133}Ba)	191.14	26.75
88.04 (^{109}Cd)	200.74	32.69
122.06 (^{57}Co)	301.72	31.83
356.02 (^{133}Ba)	356.72	48.13
661.66 (^{137}Cs)	1064.11	156.79



Hard-X rays' detection with side-on Si TPX3





By applying specific cuts on Cluster Size, Linearity, Cluster Height (CH) and Roundness, it was possible to highlight two main populations with the respective central energies.

De Leo, V.; Claps, G.; Cordella, F.; Cristoforetti, G.; Gizzi, L.A.; Koester, P.; Pacella, D.; Tamburrino, A., Combined Spectroscopy System Utilizing Gas Electron Multiplier and Timepix3 Technology for Laser Plasma Experiments, Condens. Matter 2023, 8, 98. https://doi.org/10.3390/ condmat8040098

2. Gamma energy estimation in LPPs with a Timepix3 silicon detector (2018)

VEGA laser facility:

laser wavelength: ***800 nm***

laser Energy: ***4.5 J***

pulse width: ***35 fs***

laser Power:

130 TW on target

beam diameter: ***~ 10 µm***

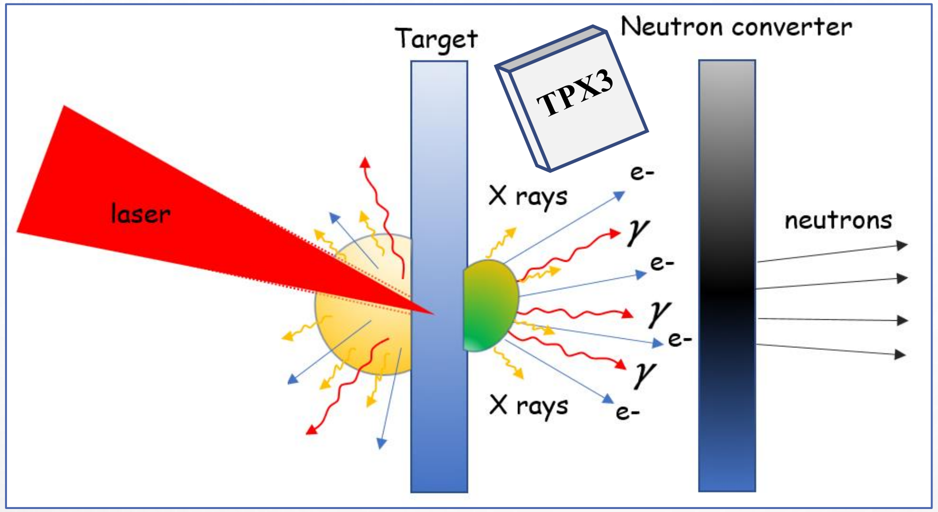
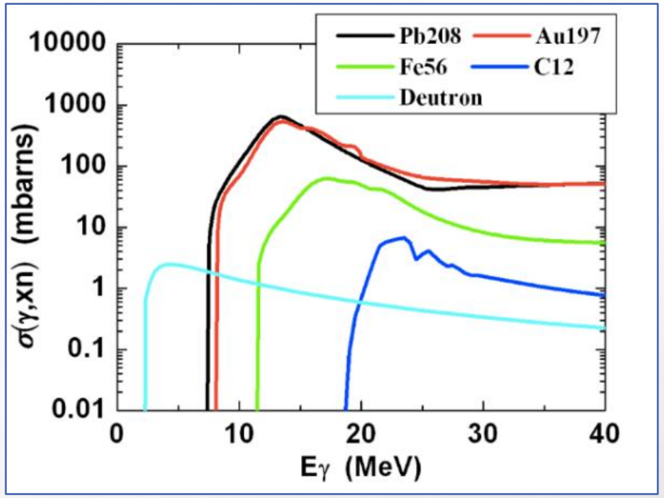
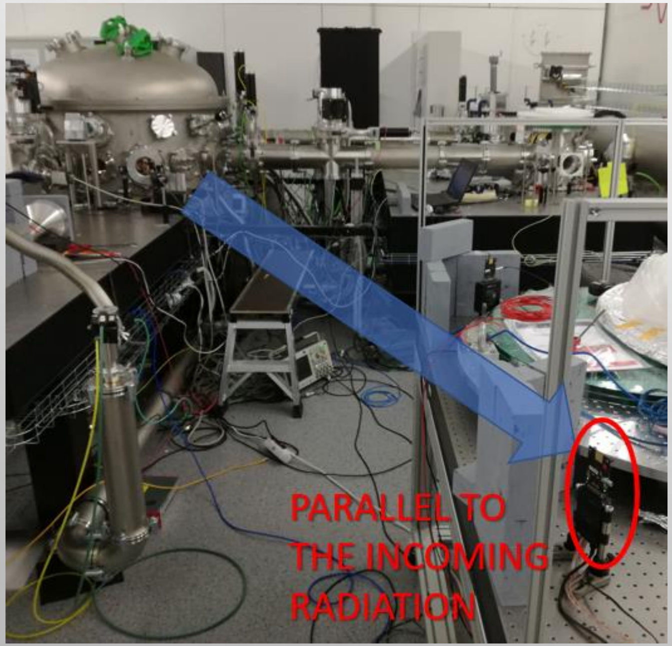


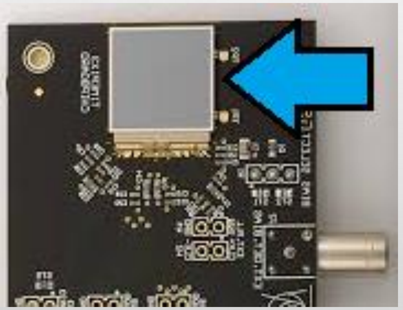
photo nuclear reaction cross sections

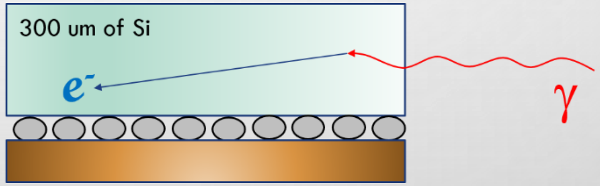


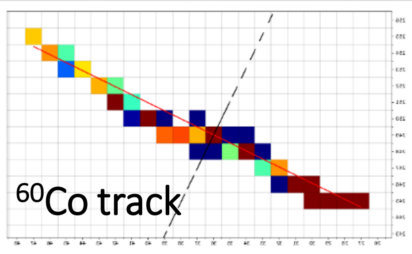


Timepix3 has been placed at 390 cm from the target

Timepix3 has been mounted on an experiment aimed to produce neutrons through **GAMMA PHOTO PRODUCTION** on different solid targets.







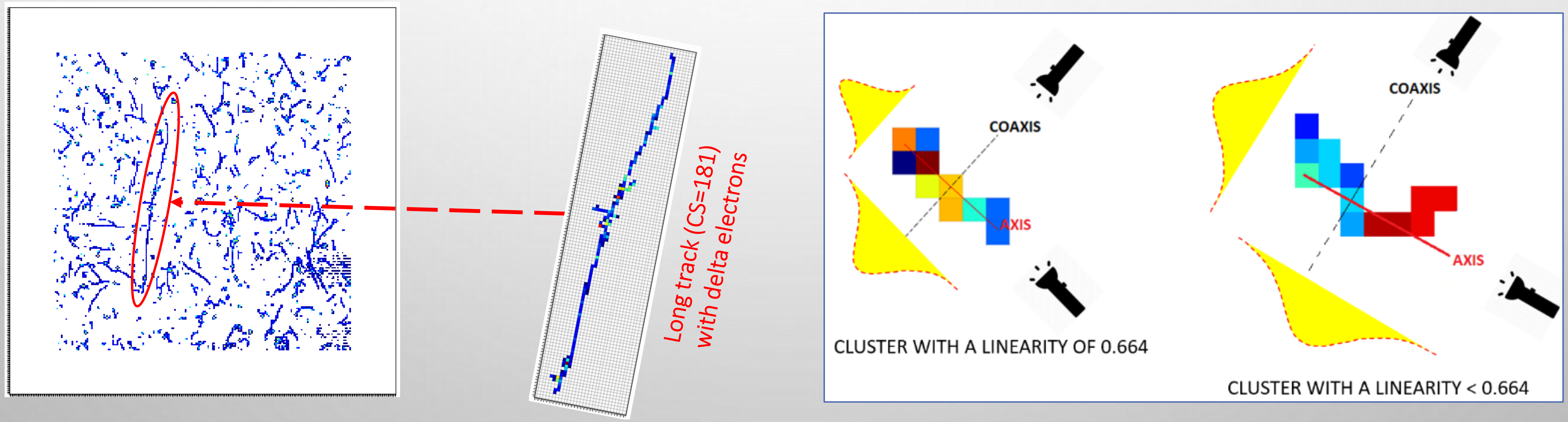
Detector was used in side-on configuration for two reasons:

- reduce the gamma flux reaching the detector
- observe a fraction of electron tracks released by Compton interaction.

2. Gamma energy estimation in LPPs with a Timepix3 silicon detector

A cluster analysis algorithm developed at ENEA Frascati, has been applied to analyze the tracks and make an estimation of the energy of the primary gamma photon. Ii is based on the definition of three characteristic track parameters:

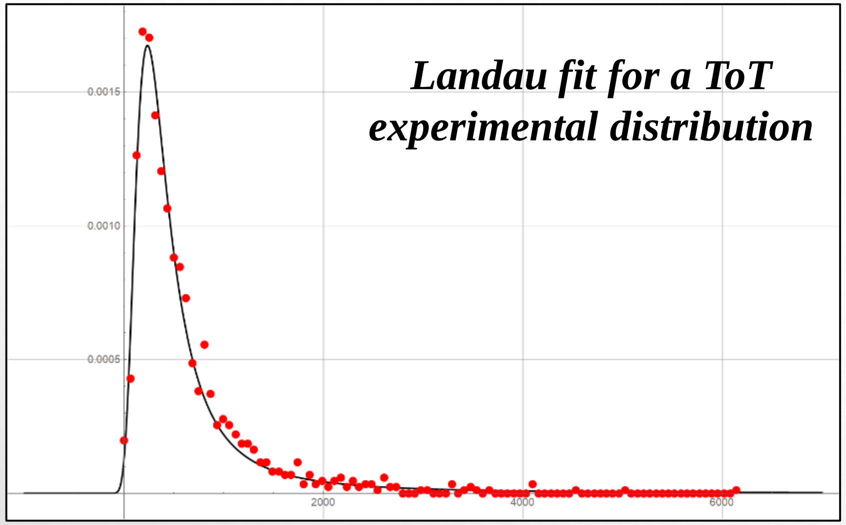
- **Cluster size**: the number of adjacent pixels in a single cluster
- **Total charge**: the sum of all ToT counts in a single cluster
- **Linearity**: it is defined as one minus the ratio between the sum of the weighted squared distances of all pixels from the best fit axis and the same weighted sum computed for the line perpendicular to this axis crossing it in the center of gravity, the co-axis.

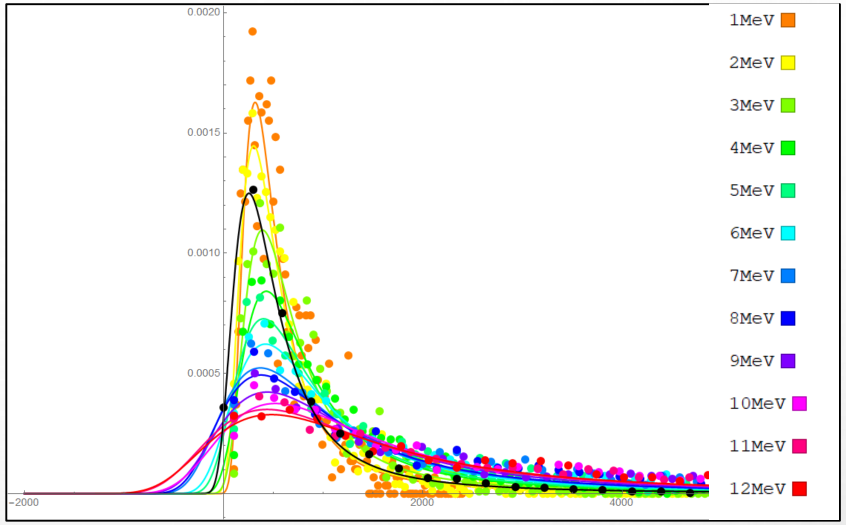


The flux reaching the detector must be low enough in order to distinguish the tracks.

2. Gamma energy estimation in LPPs with a Timepix3 silicon detector

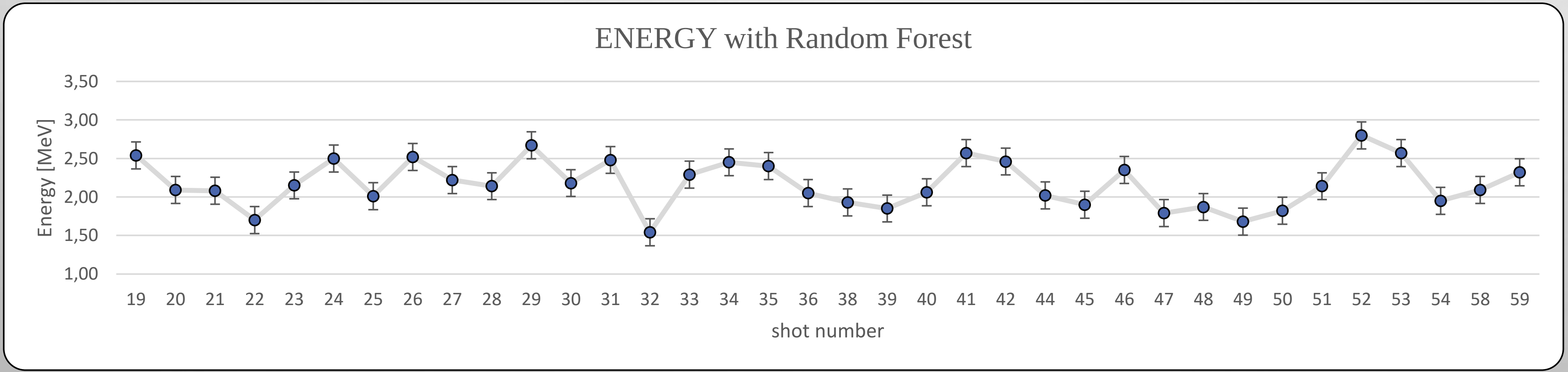
ToT charge distributions are obtained setting a LOWER LINEARITY LIMIT OF 0.8 AND A MINIMUM CLUSTER SIZE OF 6 PIXELS.





Comparison between an experimetal ToT distribution (BLACK, 1.95 MeV) and simutated distributions (COLORED) from 1 to 12 MeV

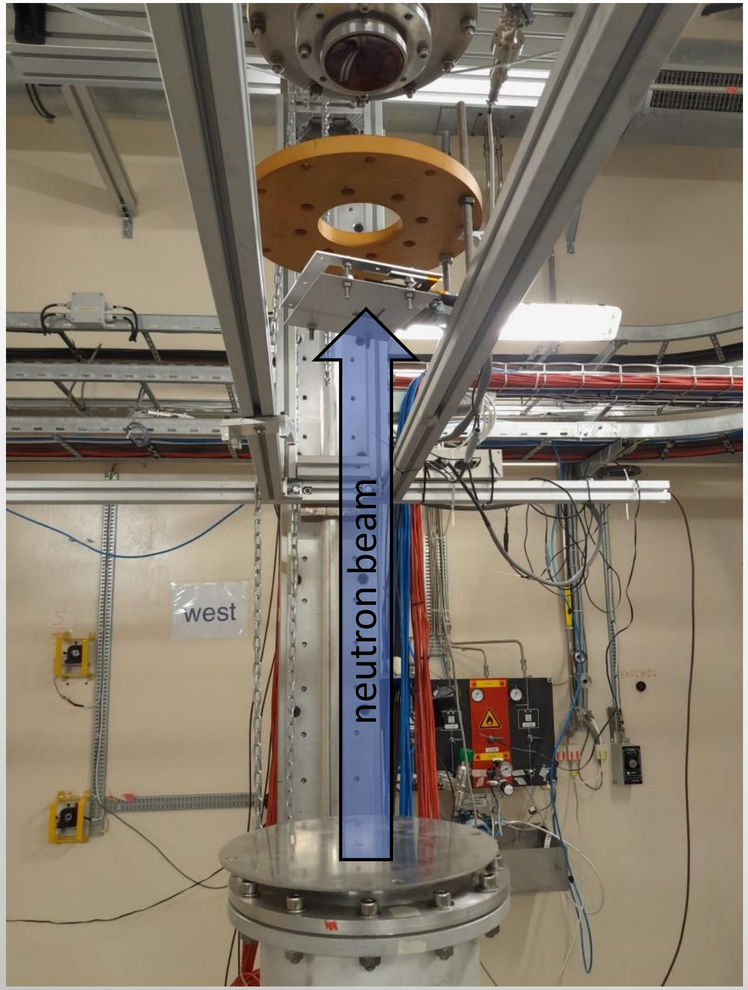
We produce a Landau fit of the experimental data (μ*, σ*) and compare them to the μ, σ of the Landau fits to the simulated distributions obtained with GEANT4 or with standard sources (few values).

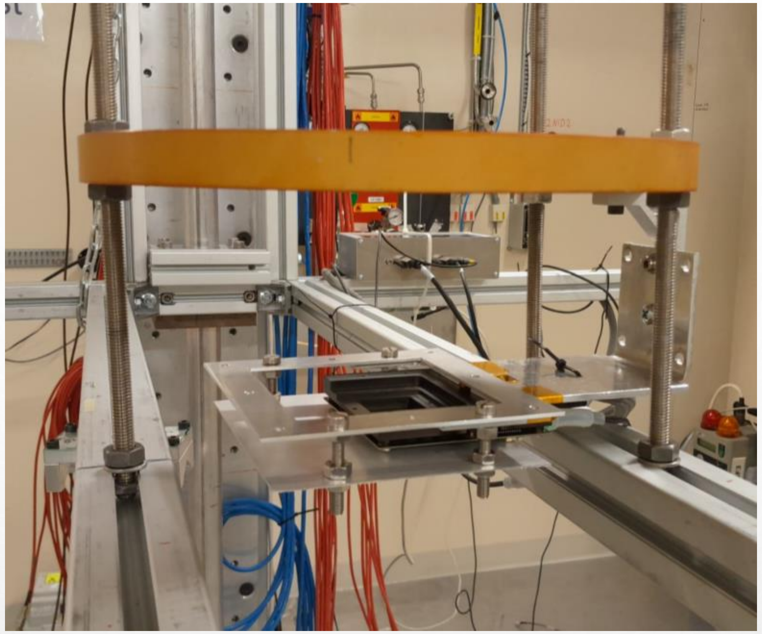


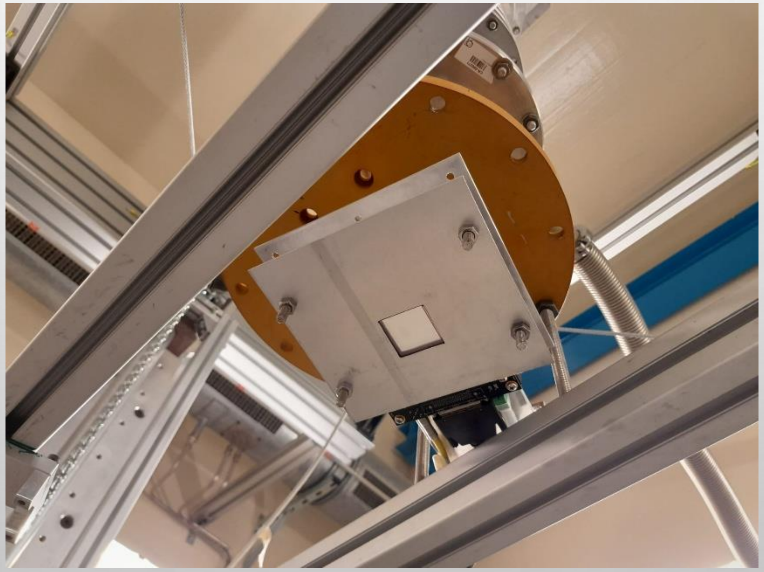
This allowed an estimation of the gamma energies shot by shot. We used a Machine Learning technique, in particular the Random Forest method which provides us the best results.

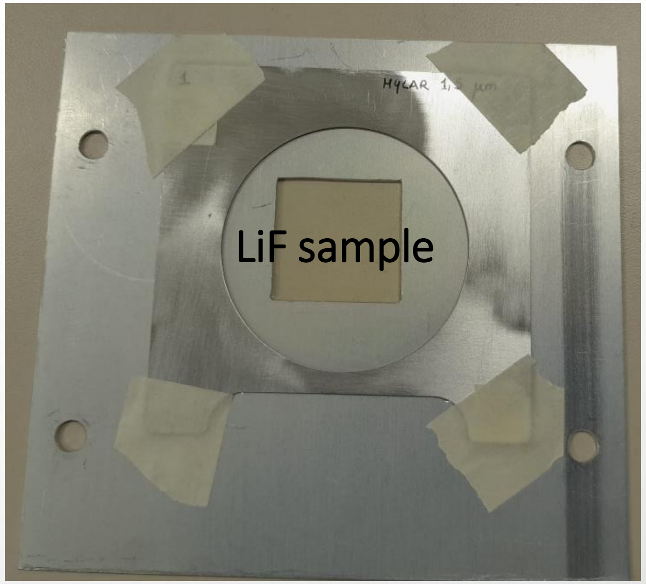
F. Cordella et al., Timepix3 detector and Geant4-based simulations for gamma energy detection in Laser Produced Plasmas, 2019 *JINST* **14** P09005 (2019)

2. Charged particles measurements: first results withTPX3 QUAD in EAR2 (n_TOF)









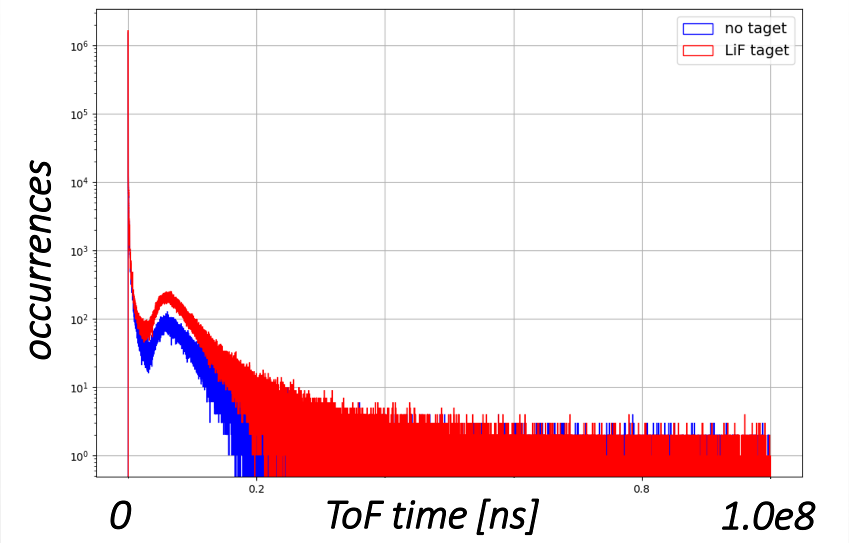
The QUAD was placed at about 3 m from the floor after the annular detector.

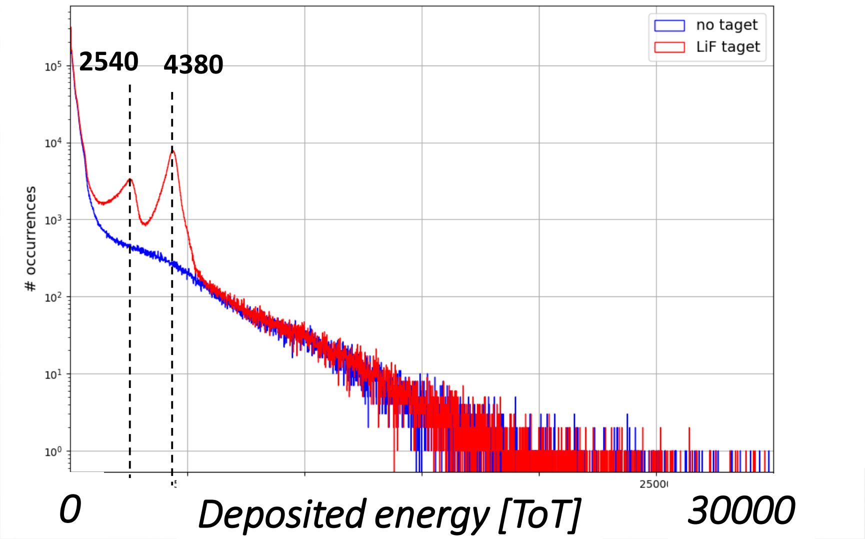
The test was performed using the 400 nm thick **LiF sample enriched at 95% with** ^6Li $(100\,\mu g/cm^2)$ deposited on a 1.6 μm mylar foil.

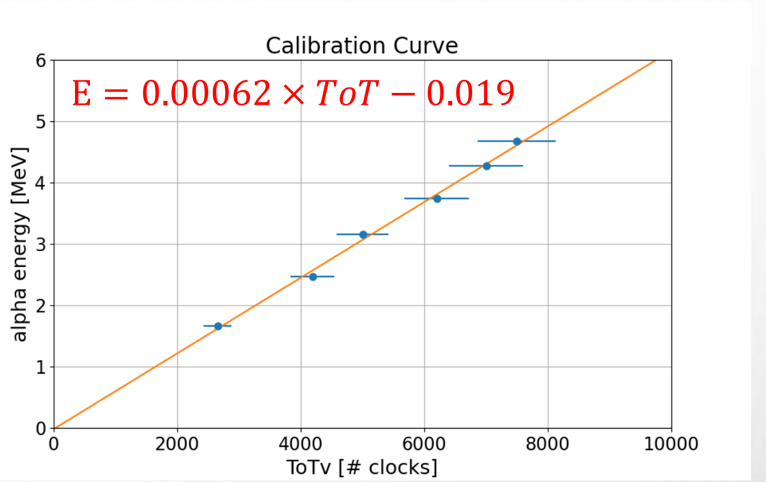
The correct operation of the QUAD was achieved by applying a hardware delay of 2.5 μs with respect to the gamma flash and shifting the detector with respect to the beam.

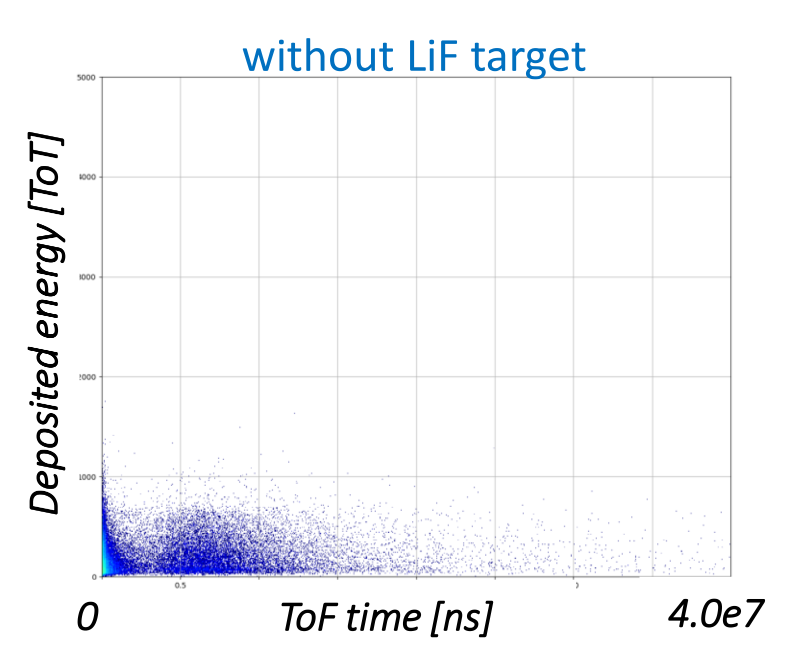
2. Charged particle measurements: first results with TPX3 QUAD in EAR2 (n_TOF)

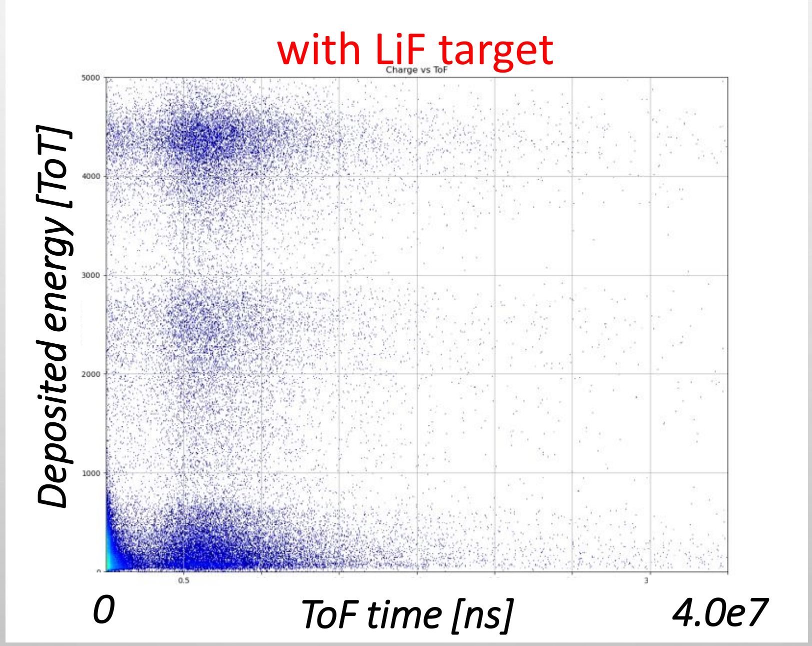
4000 Triggers, LiF target covering all the detector surface











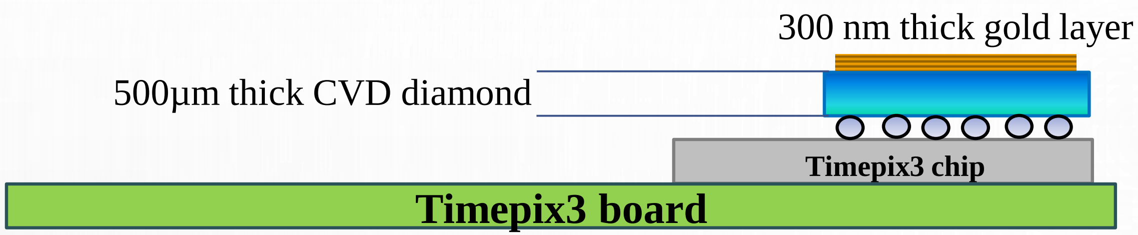
It is clear the presence of alphas and tritons due to LiF.

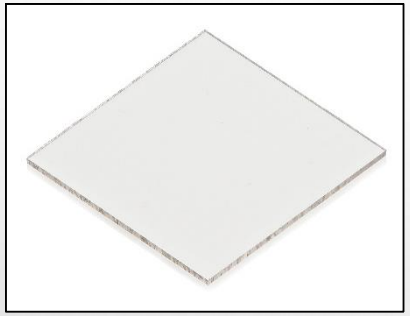
In addition, by applying the calibration curve, the estimated energies on the two peaks are about 1.5 and 2.7 MeV, in accordance with the energies of ^{6}Li reaction products.

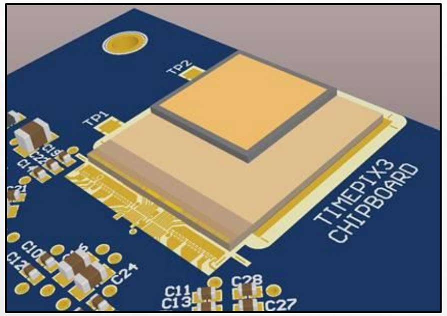
$^6L(n, \alpha)^3H$	α (2.05 MeV) ^3H (2.73 MeV)

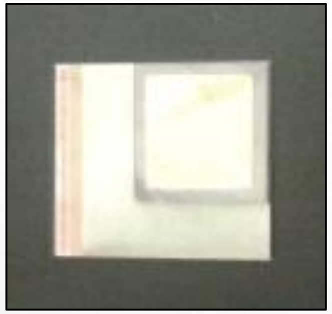
3. The Diamondpix detector and diagnostic of fast neutrons from fusion reactions

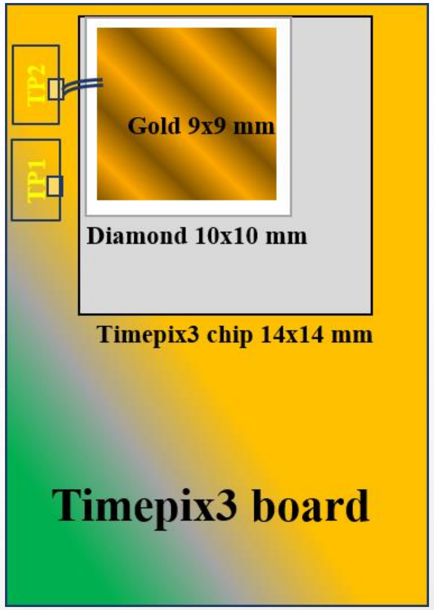
3. Diamondpix detector for fast neutron detection in nuclear fusion

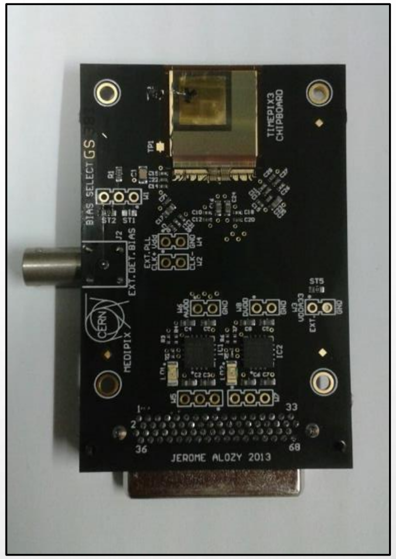






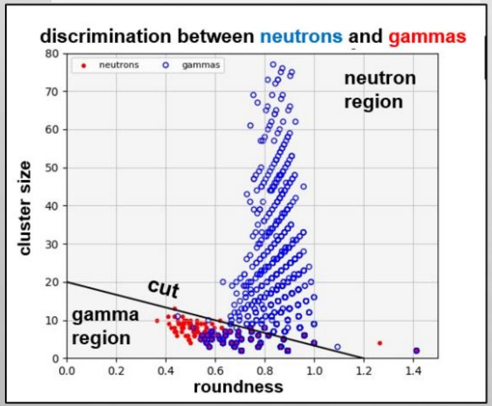






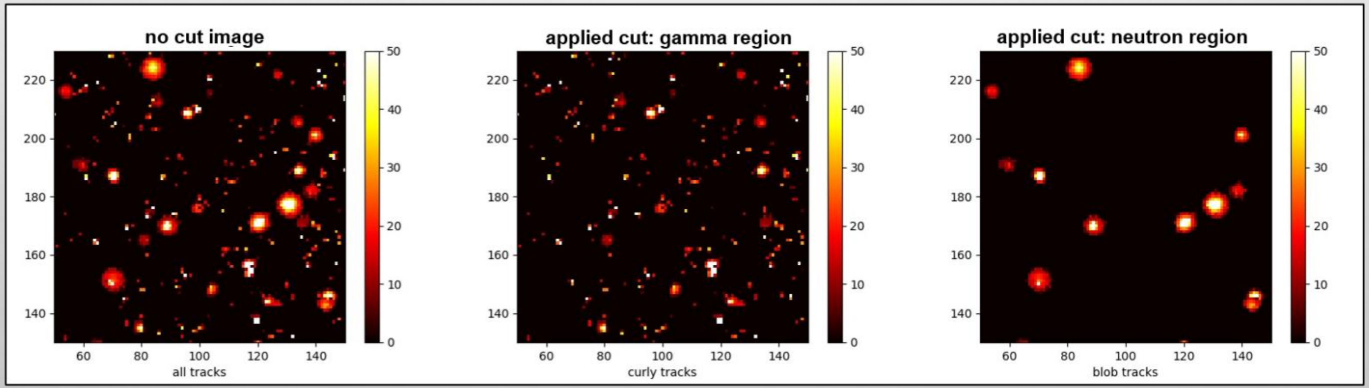
A CVD polycrystalline diamond has been coupled to a Timepix3ASIC through the bump-bonding technique.

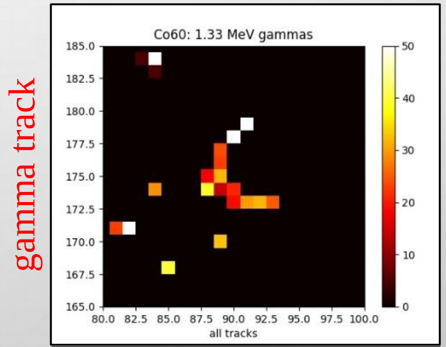
FNG facility, ENEA Frascati

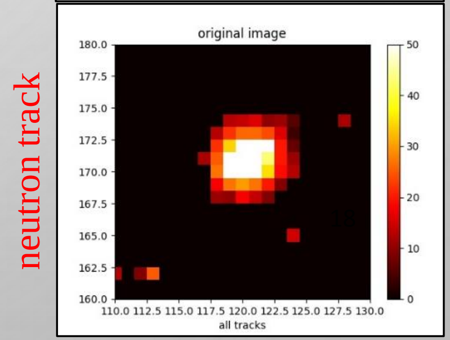


Neutrons discrimination against gammas

14 MeV neutrons



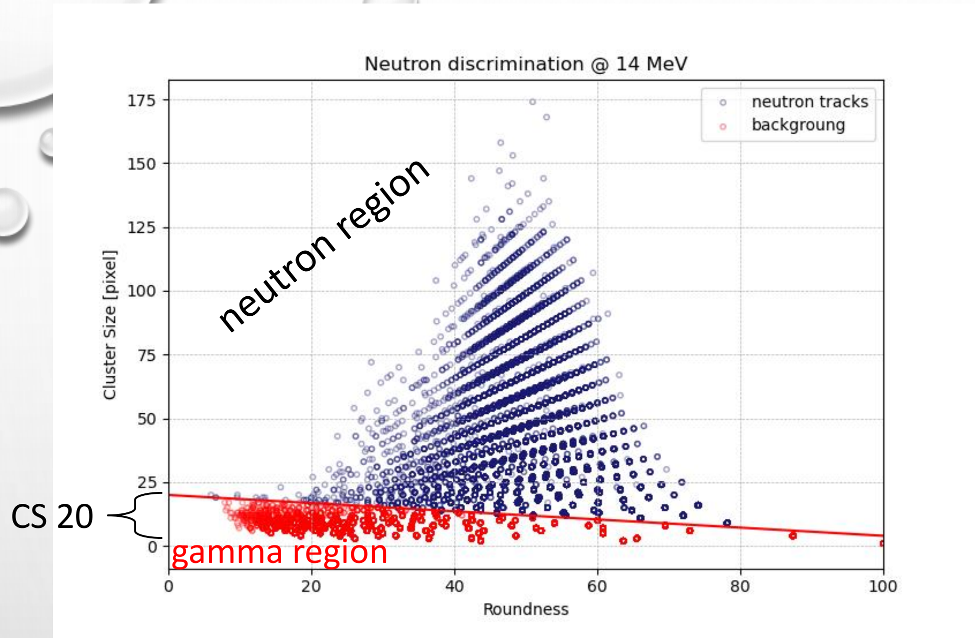


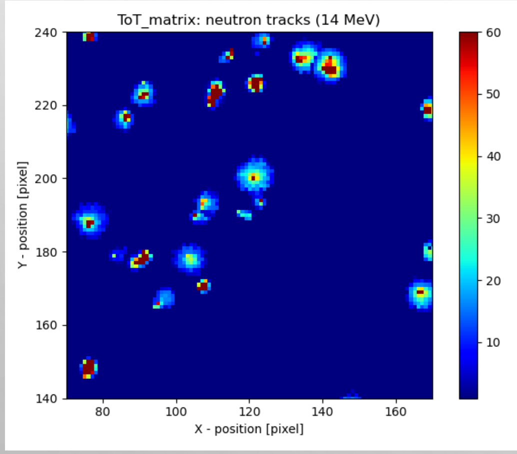


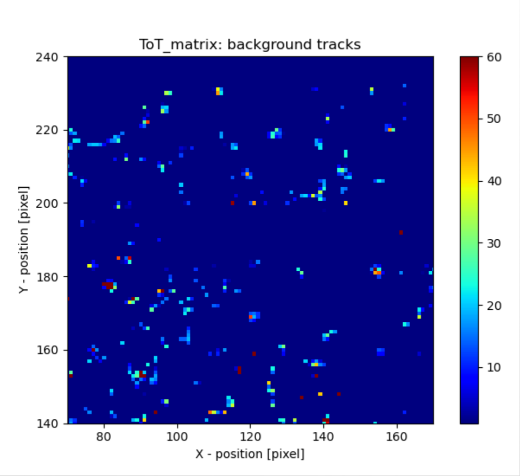
In order to selects tracks according to their morphological parameters and their deposited energy a dedicated algorithm was realized and applied to experimental data.

G. Claps et al., *Diamondpix: A CVD diamond detector with timepix3 chip interface, IEEE Trans. Nucl. Sci.* **65** (2018) 2743

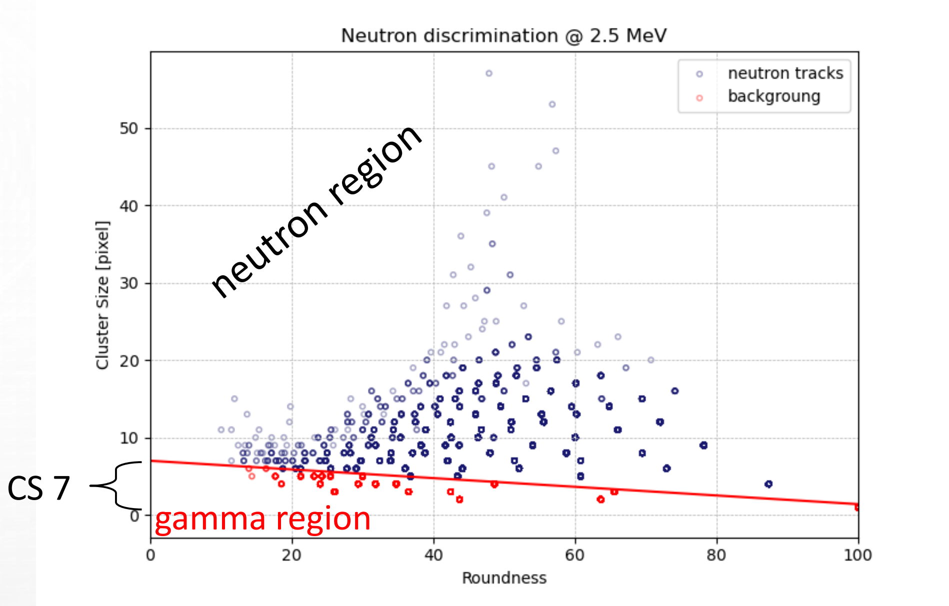
3. Estimation of efficiency for 14 and 2.5 MeV (FNG facility)

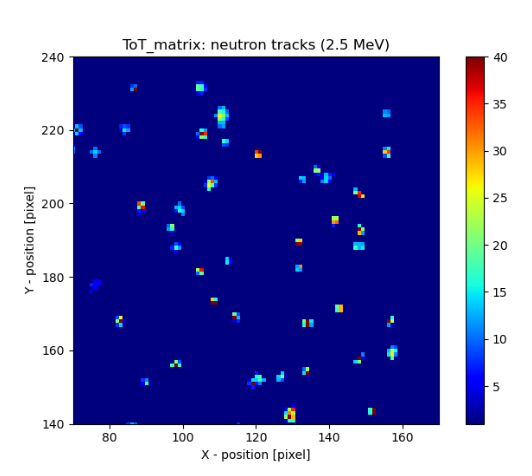


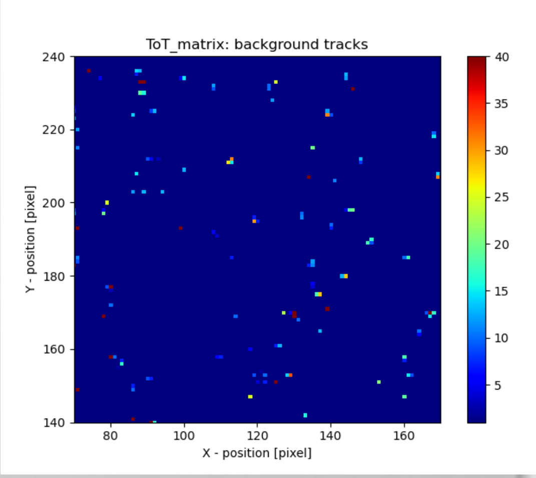




A neutron flux scan (from 6.0×10^8 to 1.6×10^{10} n/s) on FNG allowed an efficiency estimation obtaining a value of *2.5 ± 0.1 ‰*



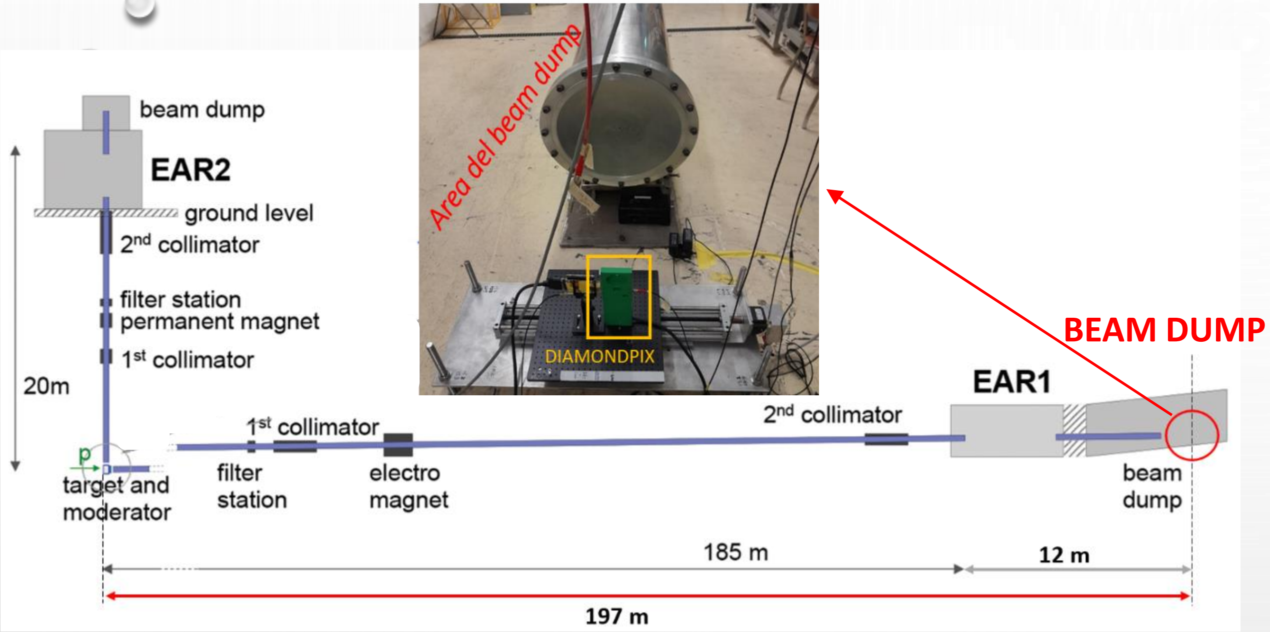




A neutron flux scan (from 2.1×10^8 to 2.5×10^8 n/s) on FNG allowed an efficiency estimation obtaining a value of *6.8 ± 0.5 ‰*

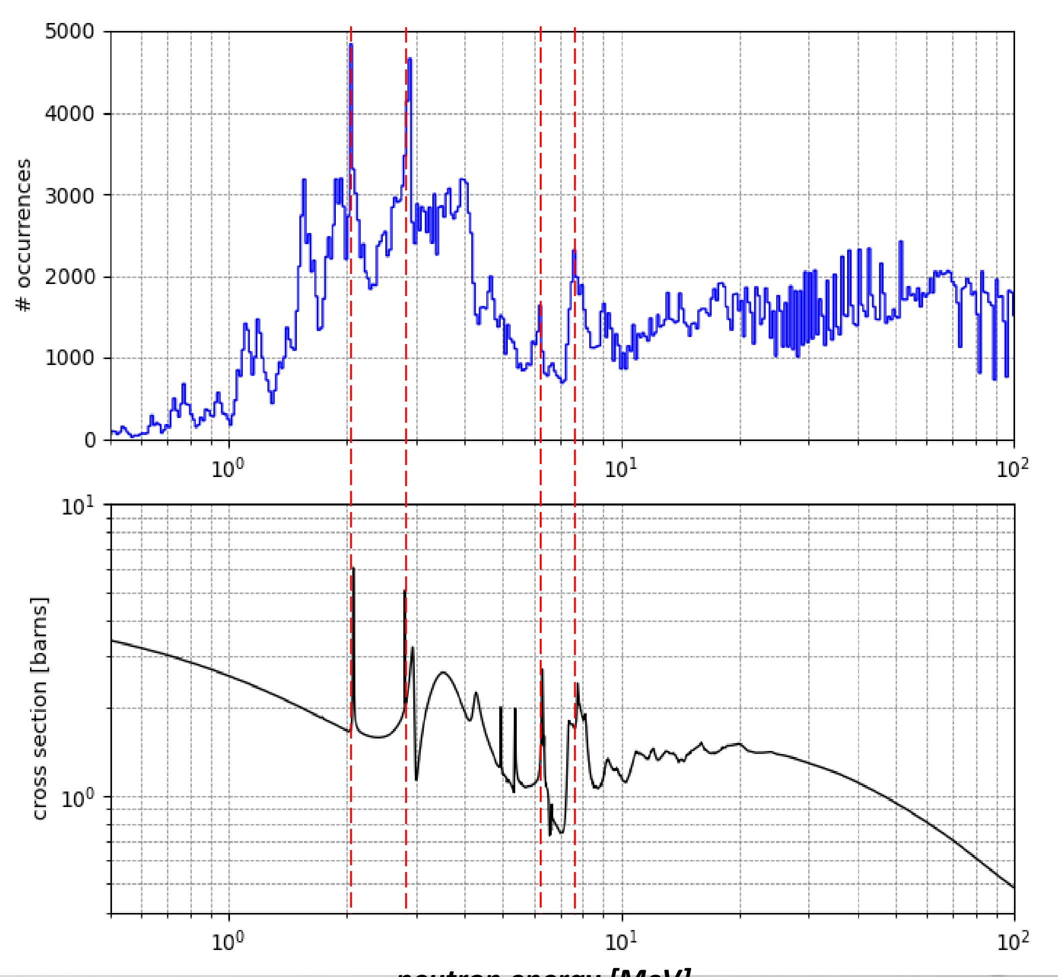
3. Time of flight measurements in the DUMP AREA of the n_TOF facility

Experimental set-up on the n_TOF facility



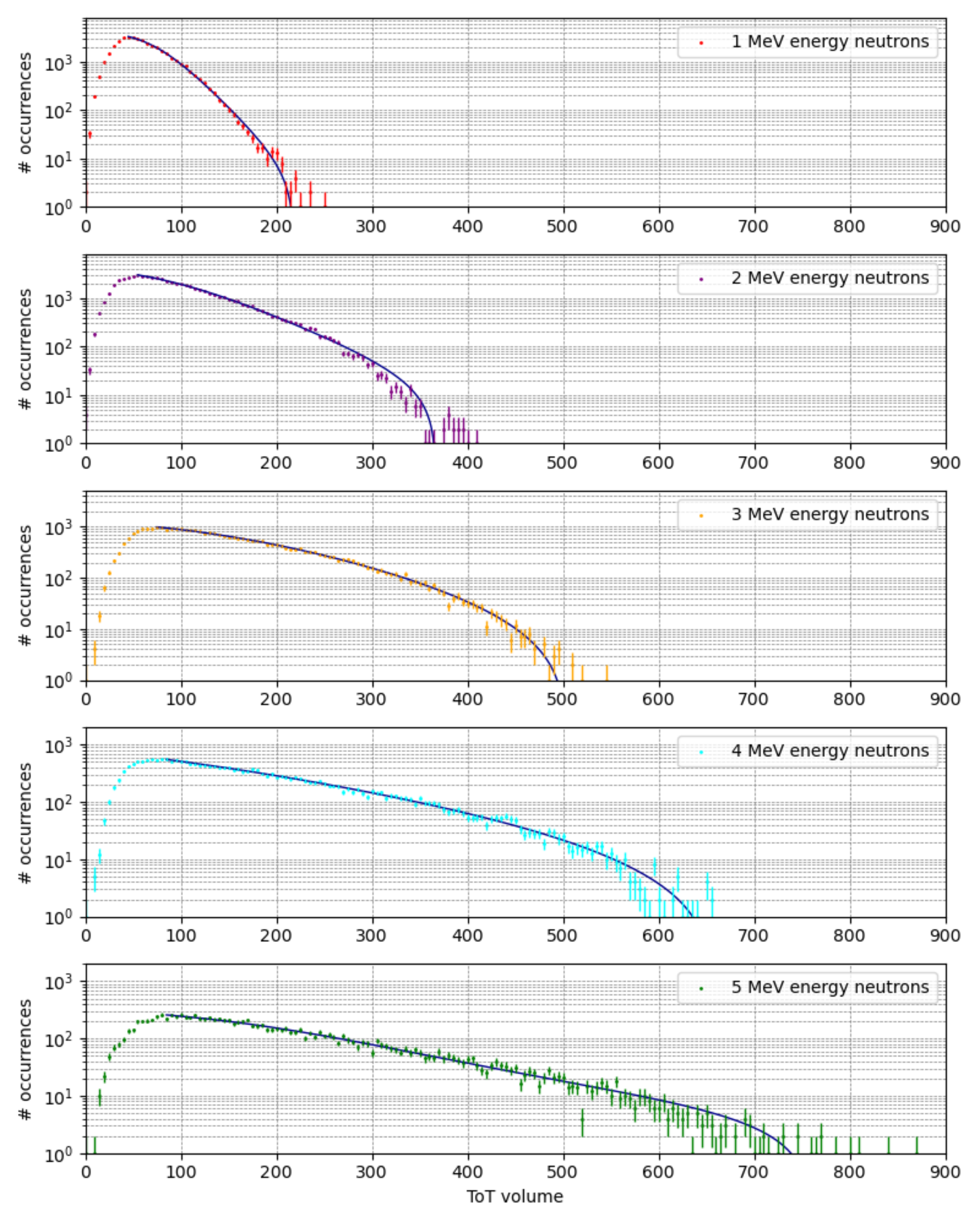
ACQUISITION PARAMETERS

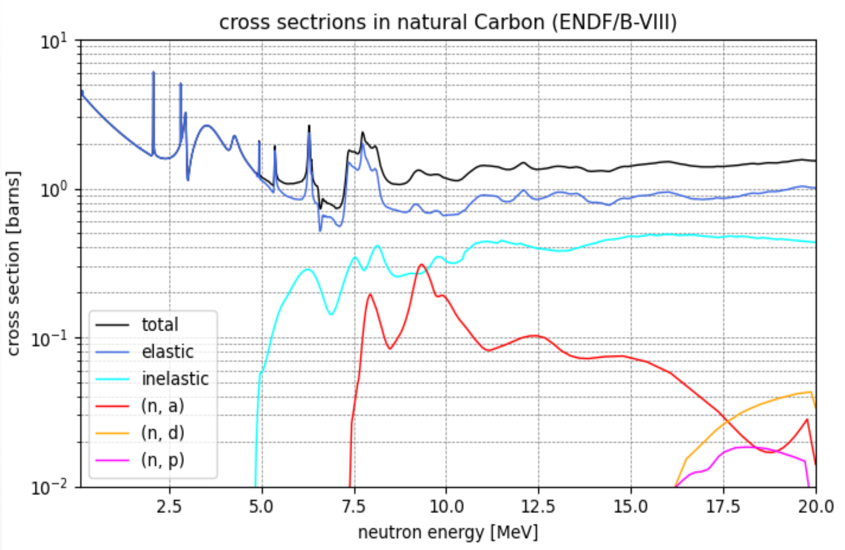
- TPX3 was controlled by the katherine module
- DATA-DRIVEN MODE
- ACQUISITION MODE: ToT & ToA (charge and time)
- Acquisition time window: 150 ms (1 GeV – 10 meV)



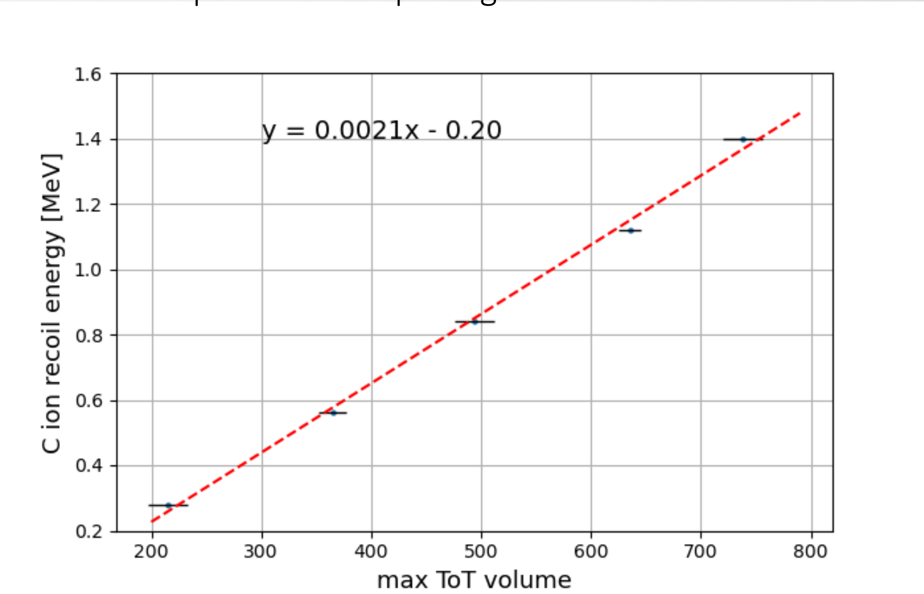
Some tof peaks are observed in correspondence of the characteristic cross-section resonances of Carbon. This result validates the spectrum reconstruction and allows the correct selection of the exanimated energies.

3. Diamondpix energy calibration at the n_TOF facility



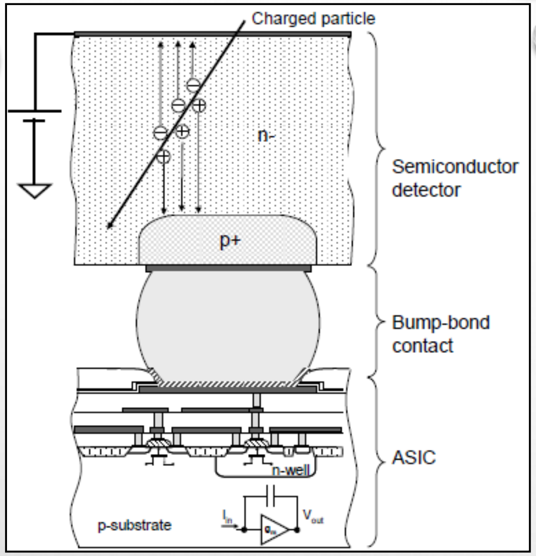


The calibration curve has been obtained considering the maximum recoil energy of Carbon ions obtained with neutron energies less than 5 MeV in order to prevent the opening of other reaction channels.

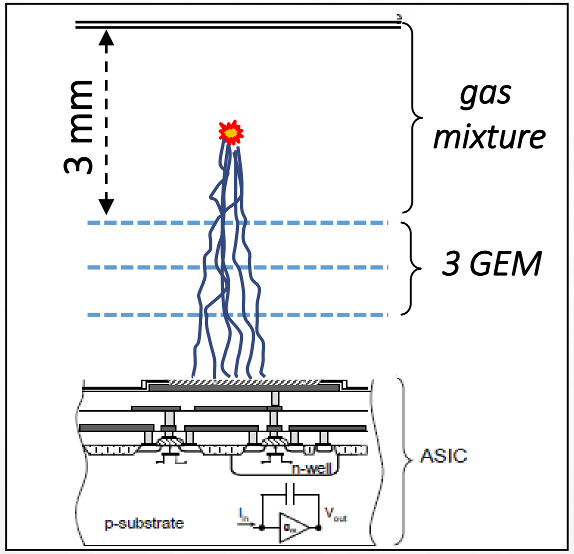


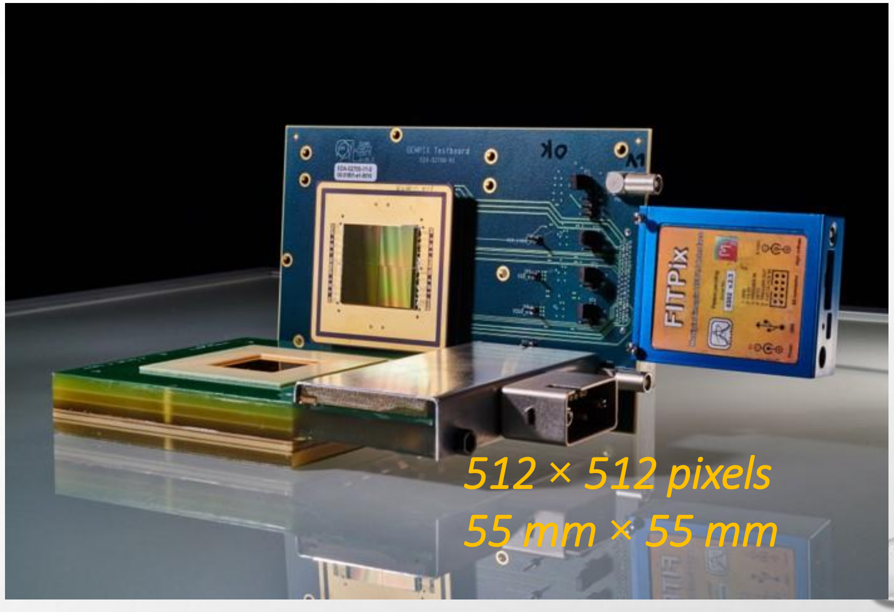
4. The GEMpix detector and X-ray measurements in Laser Produced Plasmas

4. GEMpix: a GEM detector with Front-End-Electronics based on Timepix chip

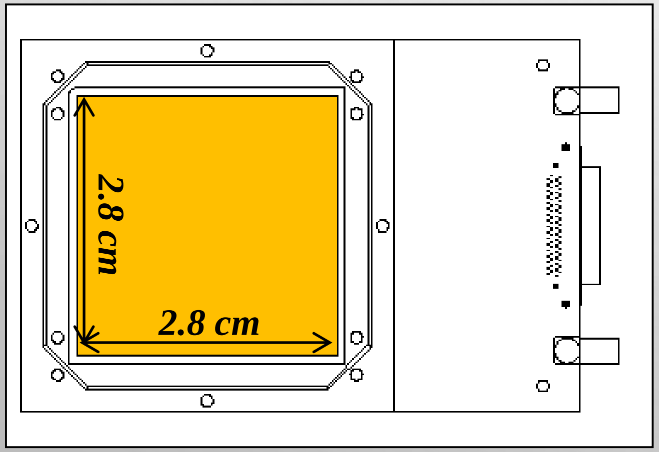


from Silicon to Triple-GEM





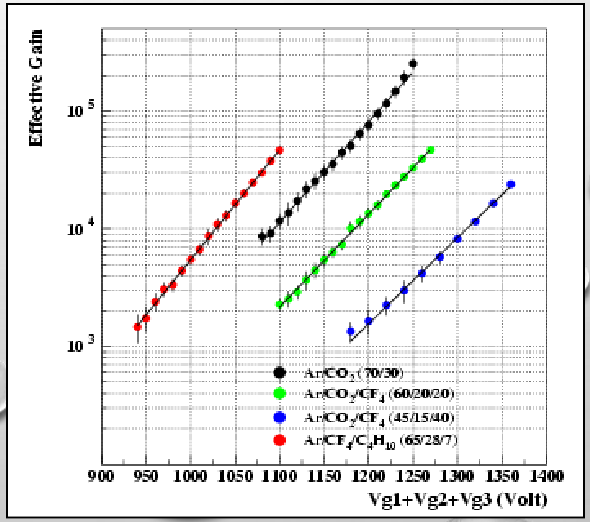
High spatial resolution (55 x 55 µm² pixels)



Timepix1 Quad without Silicon (512 x 512 pixels).

The triple-GEM gain can range on at least 4 order of magnitude, then this detector can work with a high dynamic range.

By exploiting this peculiar characteristic, it has been used successfully for X-ray measurements in LPPs.

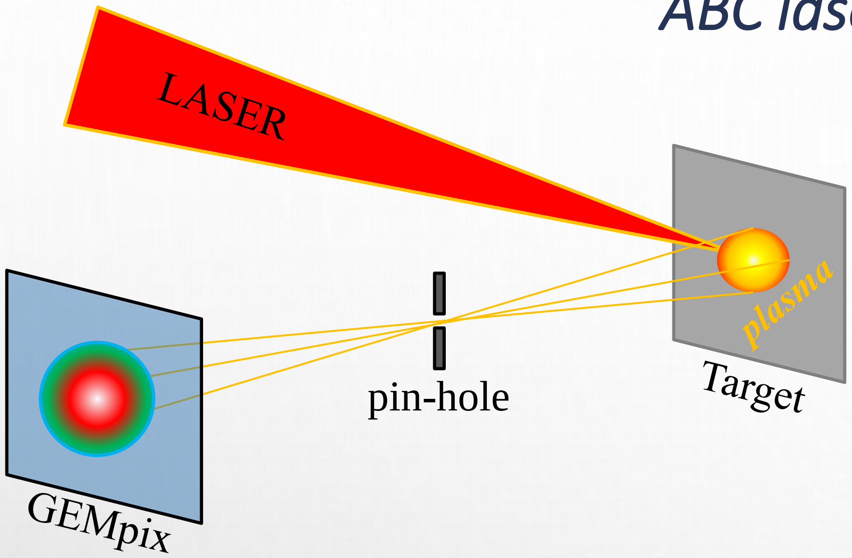


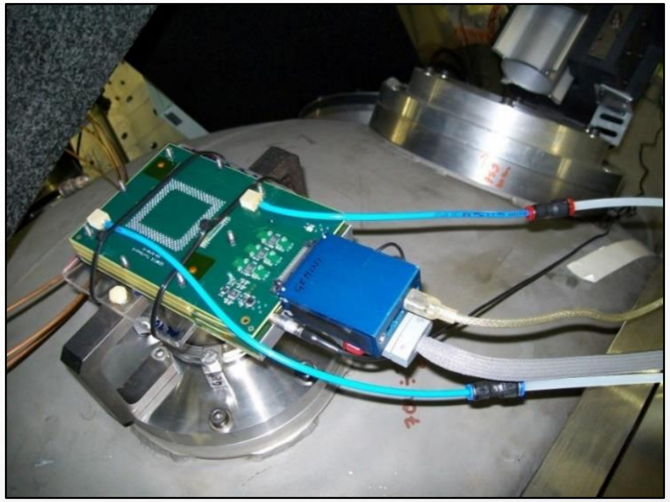
GEMpix detectors are highly versatile and have been realized in different configurations.

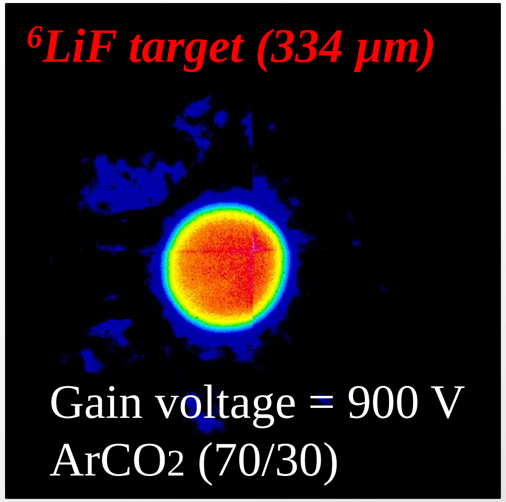
In particular, in a side-on configuration with a drift of 1/2 cm with lateral windows.

F. Murtas, *3rd International Conference on Micro-Pattern Gaseous Detectors*, Zaragoza, Spain, 1–6 JULY, 2013

4. GEMpix detector for X-ray imaging on Laser Produced Plasmas: ABC laser facility (ENEA, Frascati 2015)

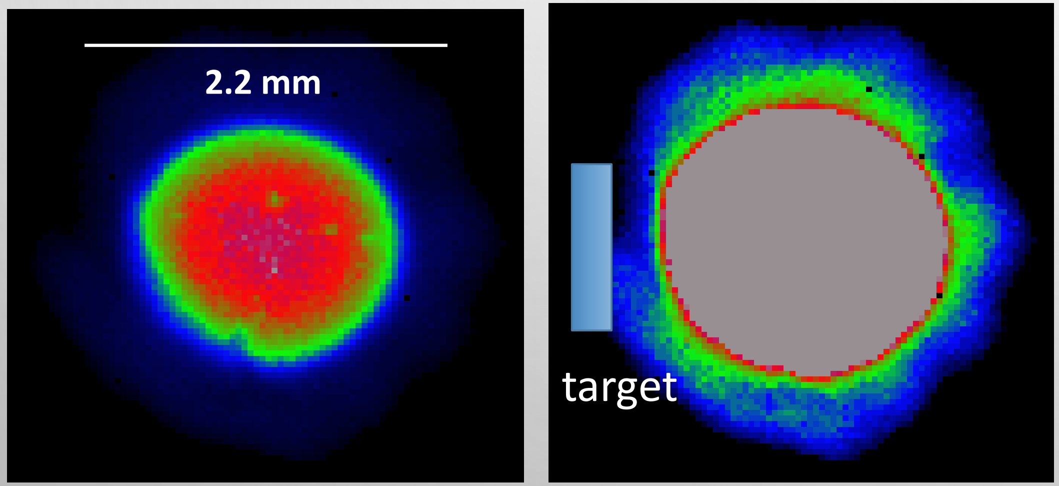






ABC LASER: Nd: glass (***1.054 μm***) which can deliver up to ***100 J*** in pulses few nanoseconds long (2-5 ns).

GEMpix was mounted on a port with a pin-hole of 200 um with a ***magnification of 1.5***. The target was an aluminum foil 7 μm thick.



GEMpix was mounted on a port with a beryllium window 5 mm in diameter and 50 μm thick (no imaging)

The presence of a corona around the plasma core becomes visible. This corona exhibits clearly ***poloidal modulations***, imaged with a spatial resolution of about 50 mm. On one side it is possible to observe a cut which identifies the ***target***, from which the plasma plume comes out.

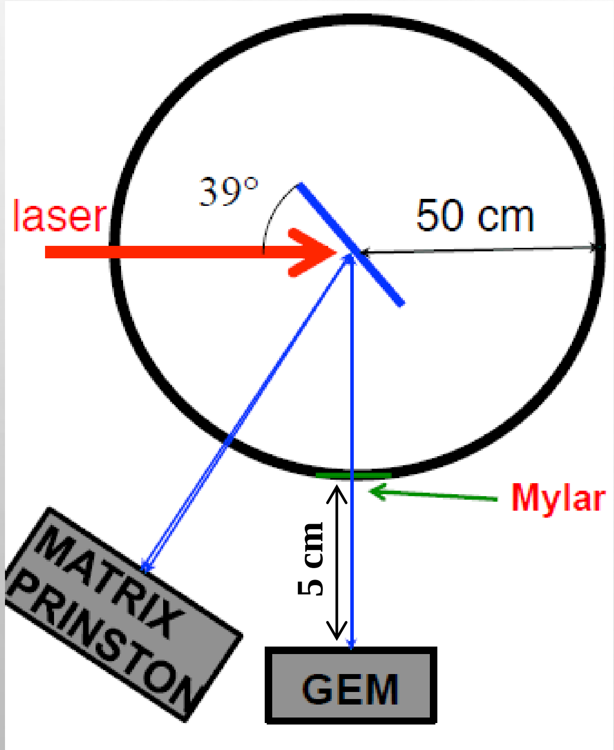
D. Pacella et al., An hybrid detector GEM-ASIC for 2-D soft X-ray imaging for laser produced plasma and pulsed sources, Journal of Instrumentation, 11 (3), art. no. C03022 (2016)

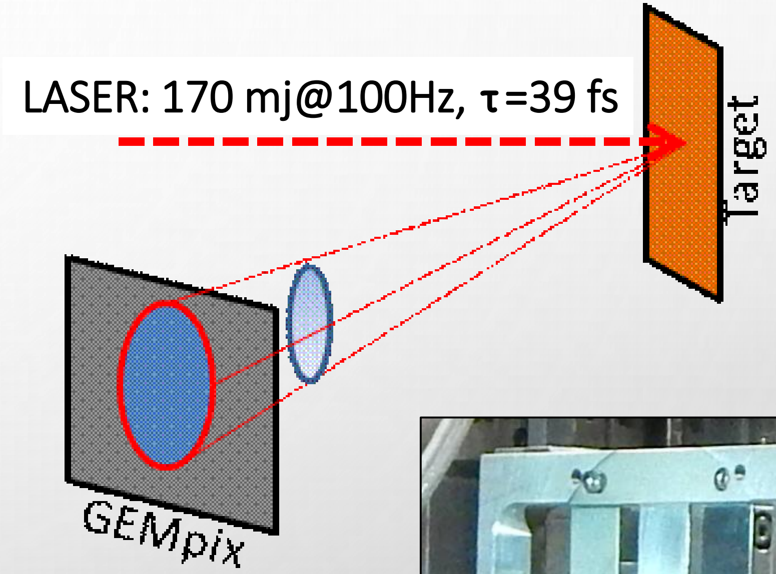
4. GEMpix detector energy response studies on the ECLIPSE laser facility (Bordeaux, France) (2015-2017)

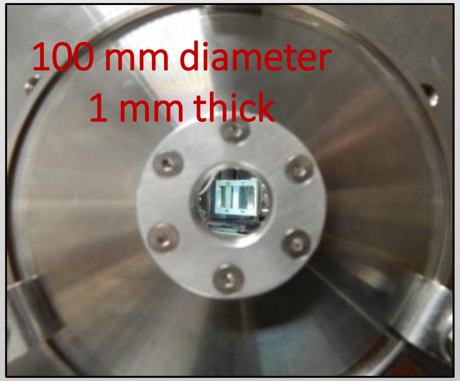
laser pulses:

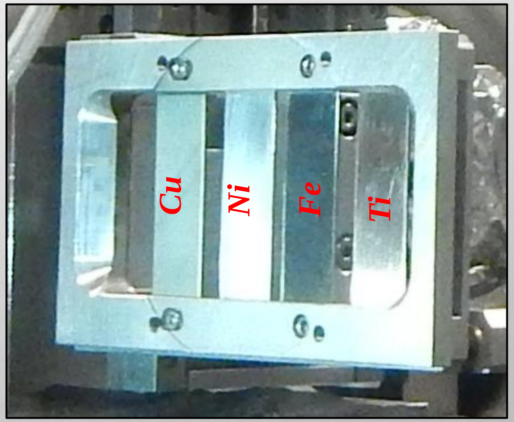
- laser wavelength = 800 nm
- Cu - 170mJ at 100 kHz, τ = 39 fs
- Ni, Fe, 175 mJ @ 100 kHz, τ = 39 fs
- Focal spot 10 um (at target)

For this type of experiment, we have exploited the ***k-α emission***: in the laser-target interaction, there is an over-thermal population of electrons which ionize the atoms interacting with the k-shell electrons. The ***characteristic k-α monoenergetic transitions*** are produced due to the outer electrons transition to the k-shell.





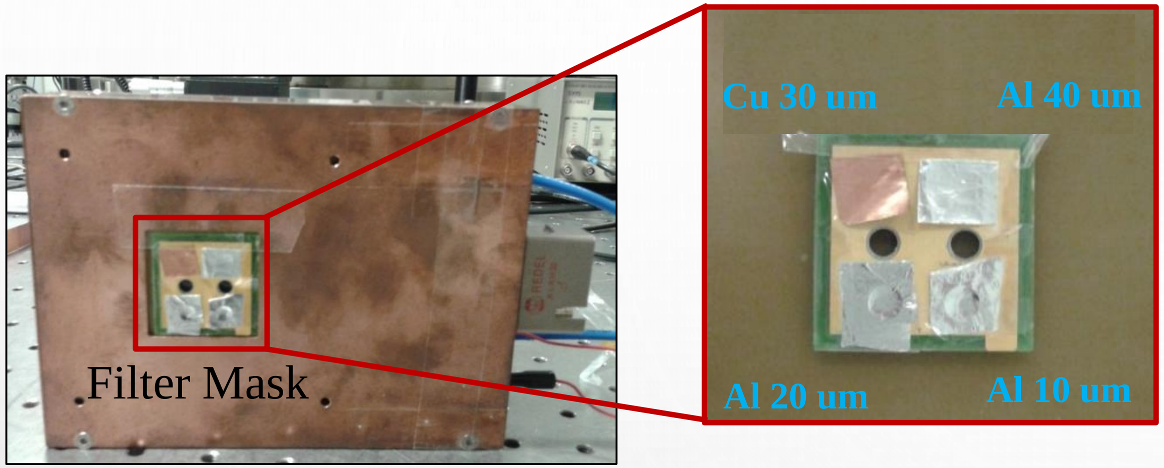




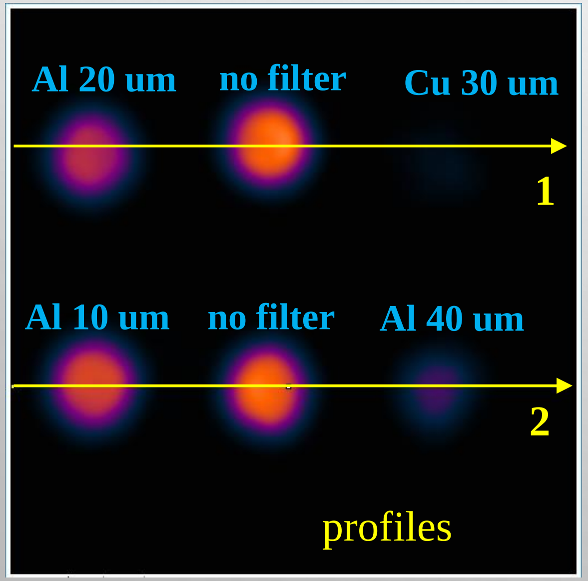
Targets for the laser

G. Claps et al., **The GEMpix detector as new soft X-rays diagnostic tool for laser produced plasmas,** Review of Scientific Instruments 87, 103505 (2016)

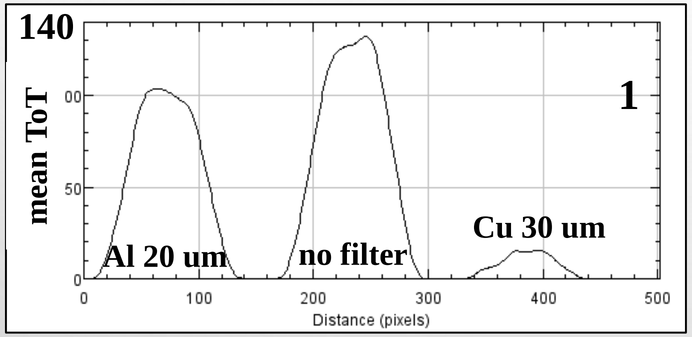
4. GEMpix detector energy response studies on the ECLIPSE laser facility (Bordeaux, France)

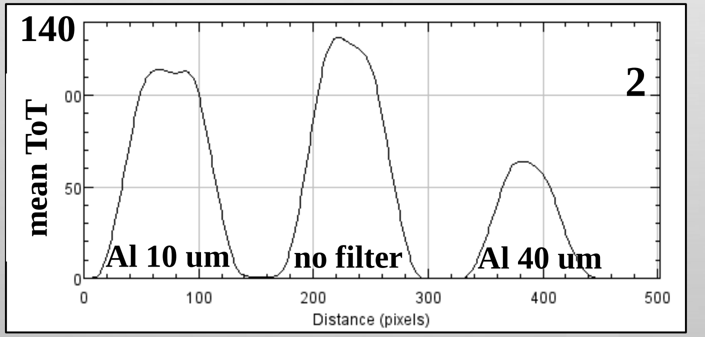


signal for Cu target

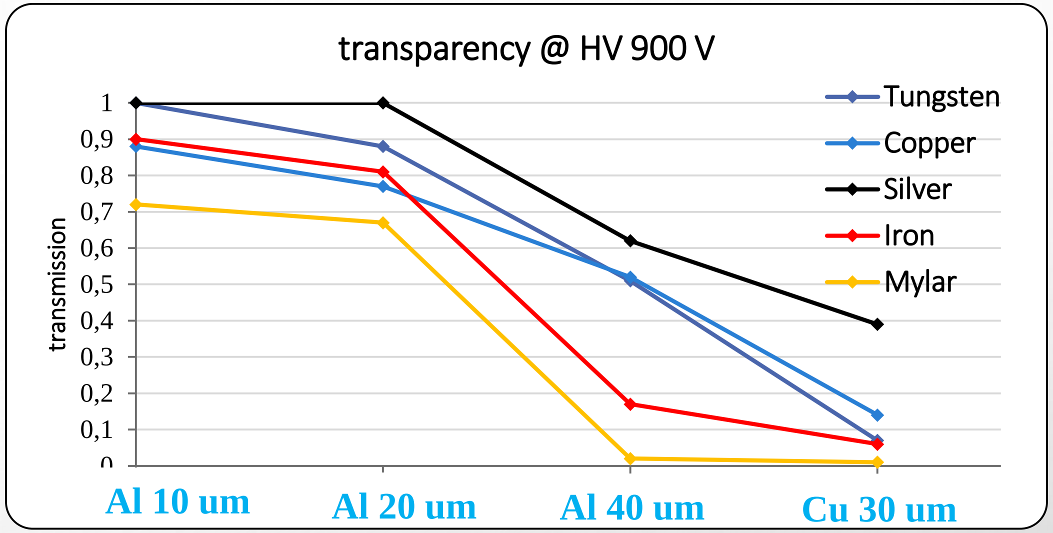


filter profiles for Cu target

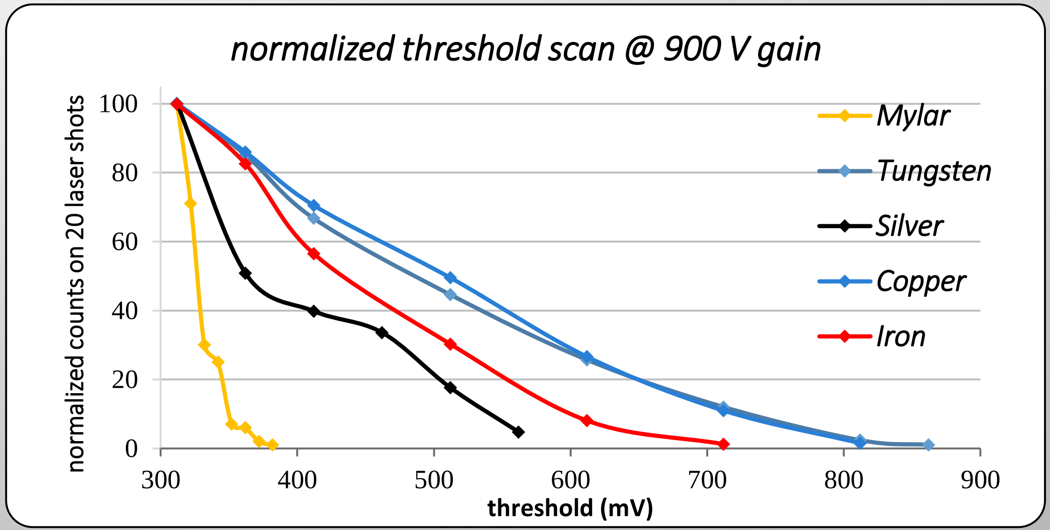




GEMpix shows a good response to mono-energetic lines produced by the different target materials.

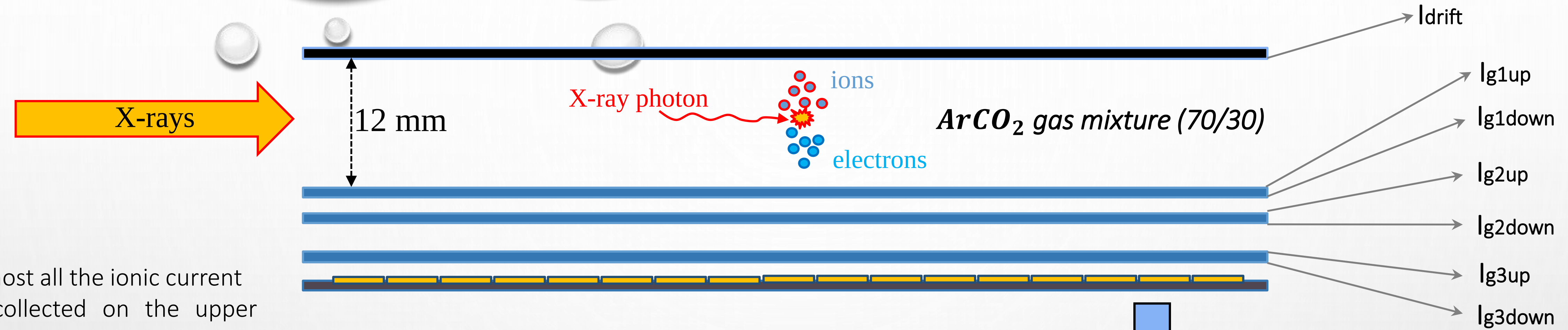


Response to the different energy has also been pointed out through a threshold scan.

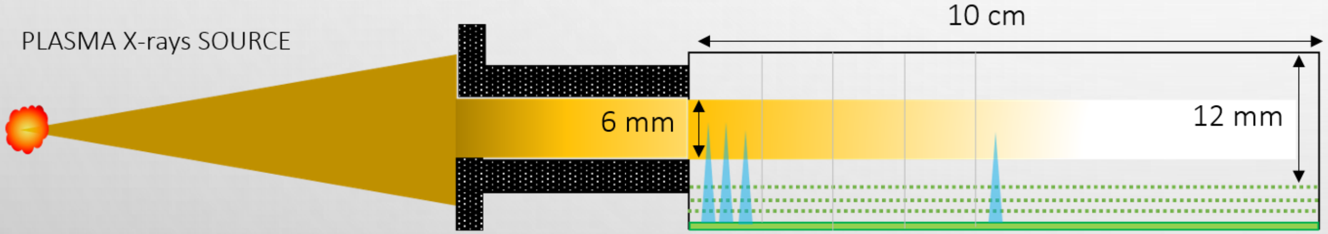


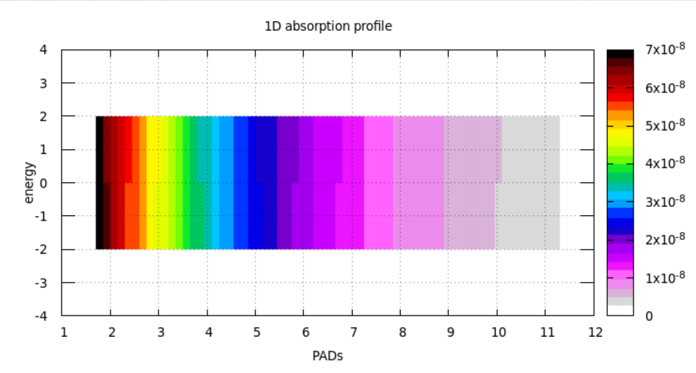
5. The GEMINI SIDE-ON GEM detector for X-ray measurements in Laser Produced Plasmas

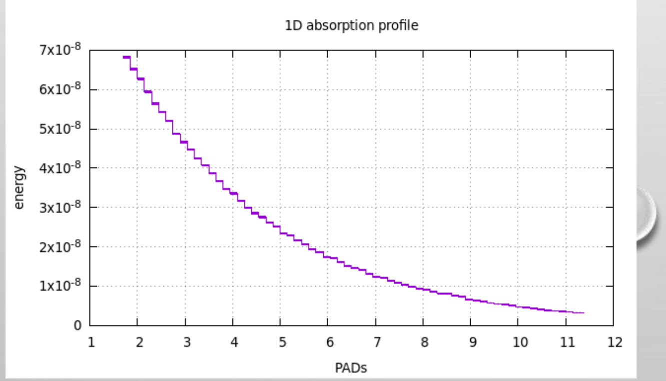
5. SIDE-ON GEM detector layout: measurements in counting and charge

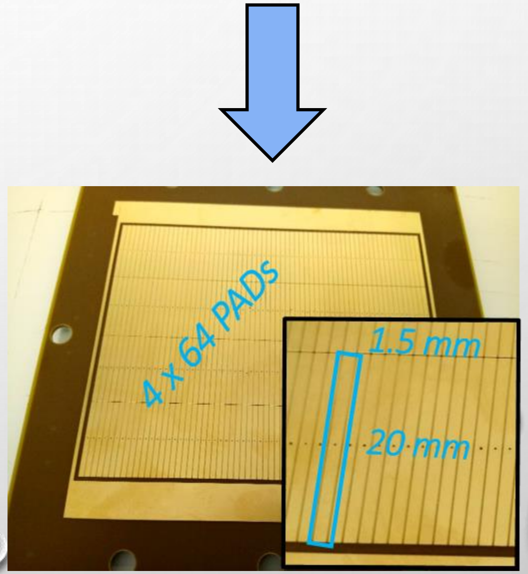


Almost all the ionic current is collected on the upper electrode of the GEM.

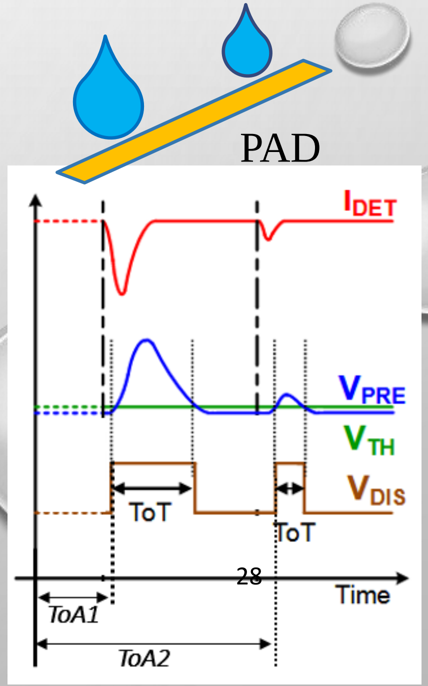




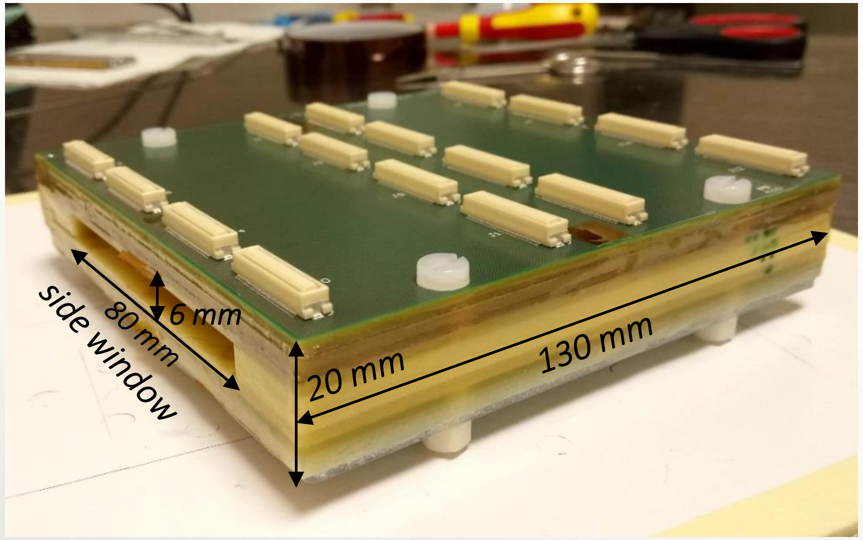


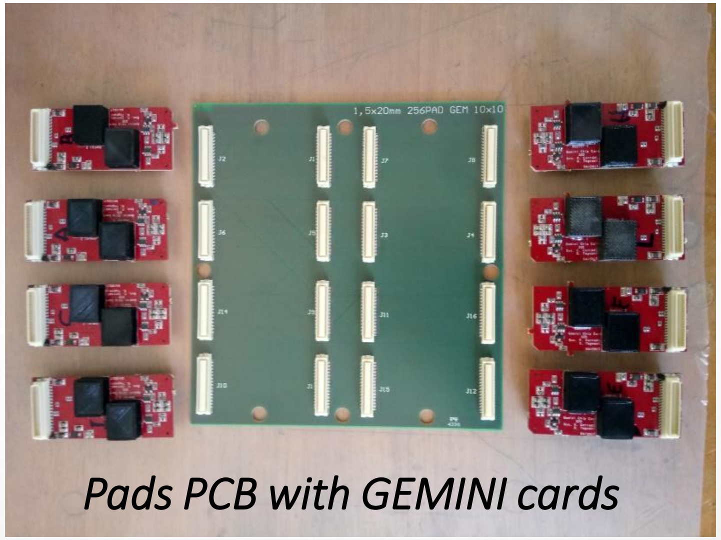


For each pad, it is possible to count the signals over threshold and measure their current and time

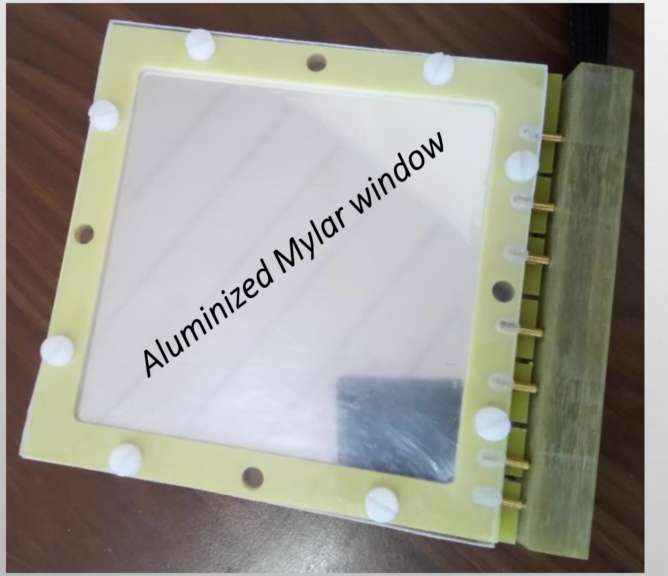


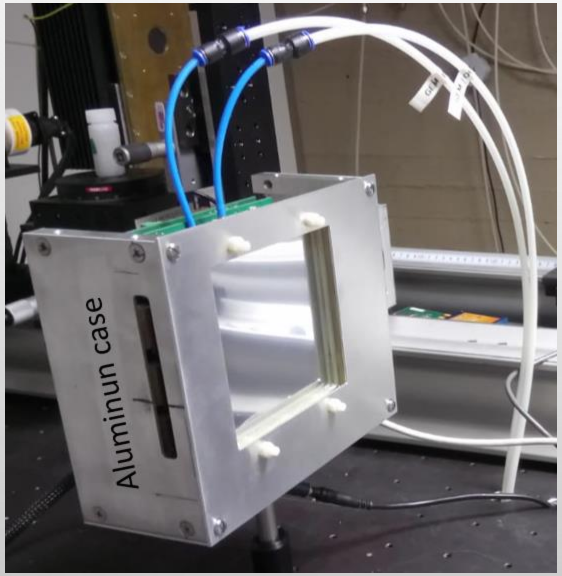
5. The SIDE-ON GEM detector and the 32D GEMINI read-out electronics





MULTI-FPGA READ OUT BOARD



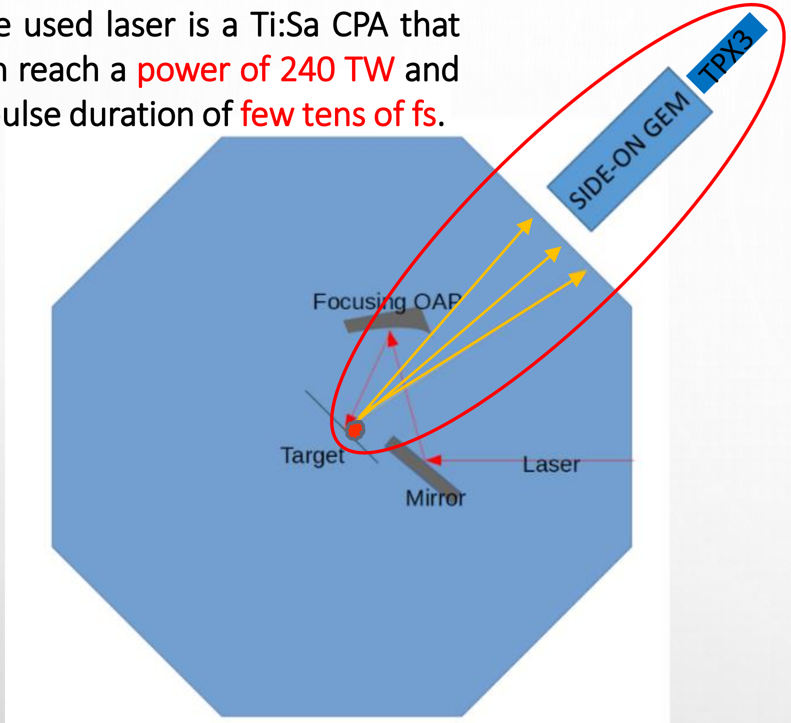


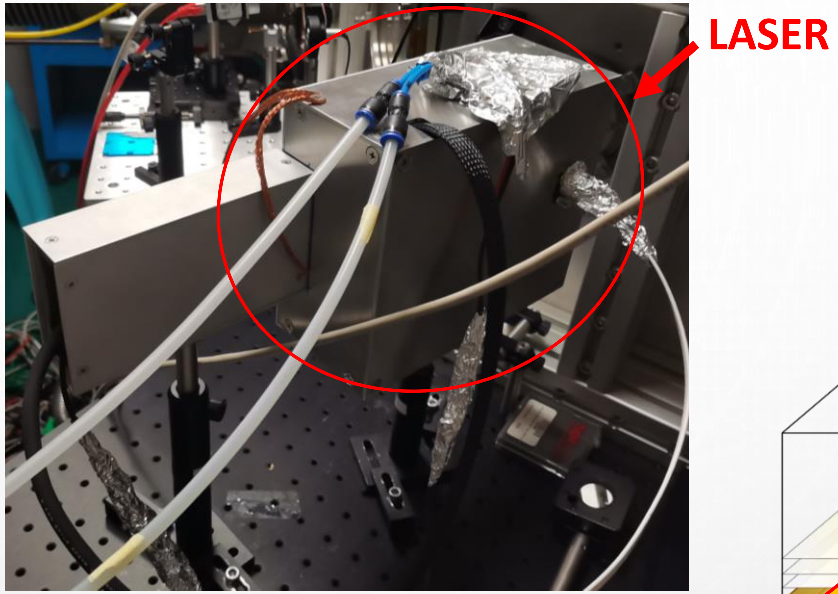
Read-out Board:

- Stand-alone unit
- Easy to interface to any PC/LAPTOP
- Single Ethernet cable
- Possibility to sync with external T0
- *Up to 8 Mcps on full detector*
- Tested at 400 Mevents/s per board with the optical link
- Low-cost system (just the board)
- List Readout mode

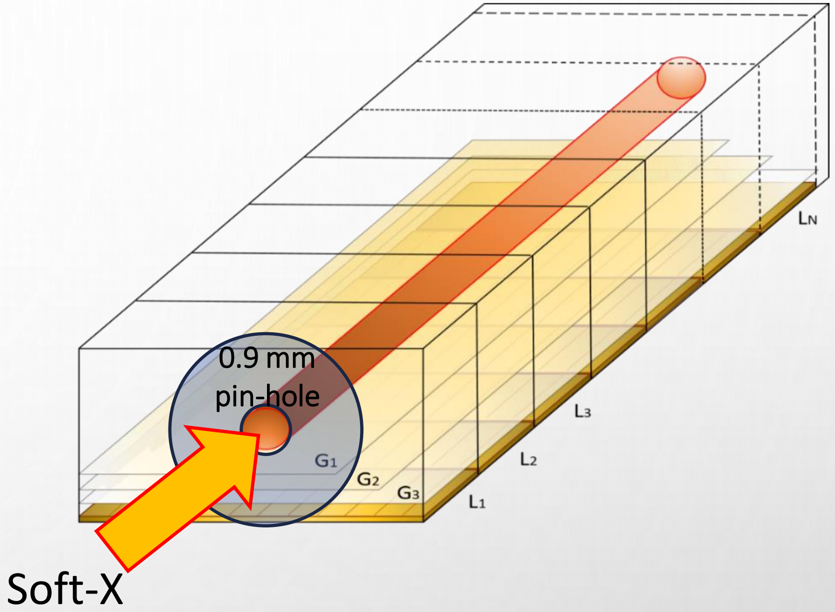
5. X RAYS' MEASUREMENTS AT THE ILIL LASER PLASMA FACILITY (CNR-INO, PISA)

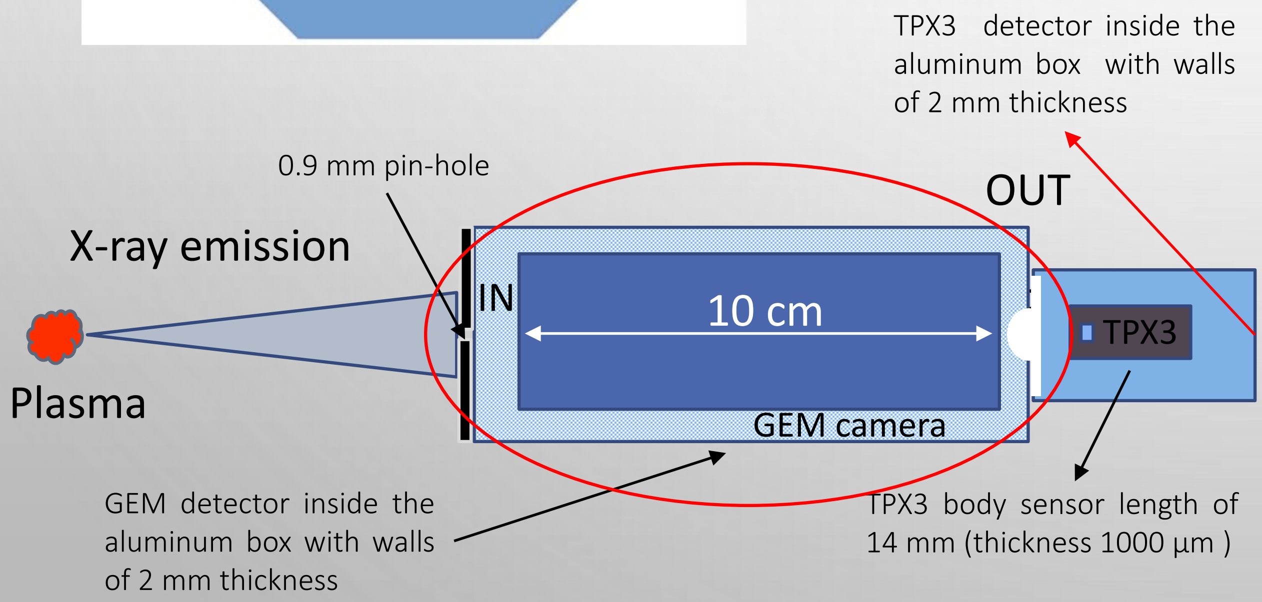
The used laser is a Ti:Sa CPA that can reach a power of 240 TW and a pulse duration of few tens of fs.





Experimental Setup



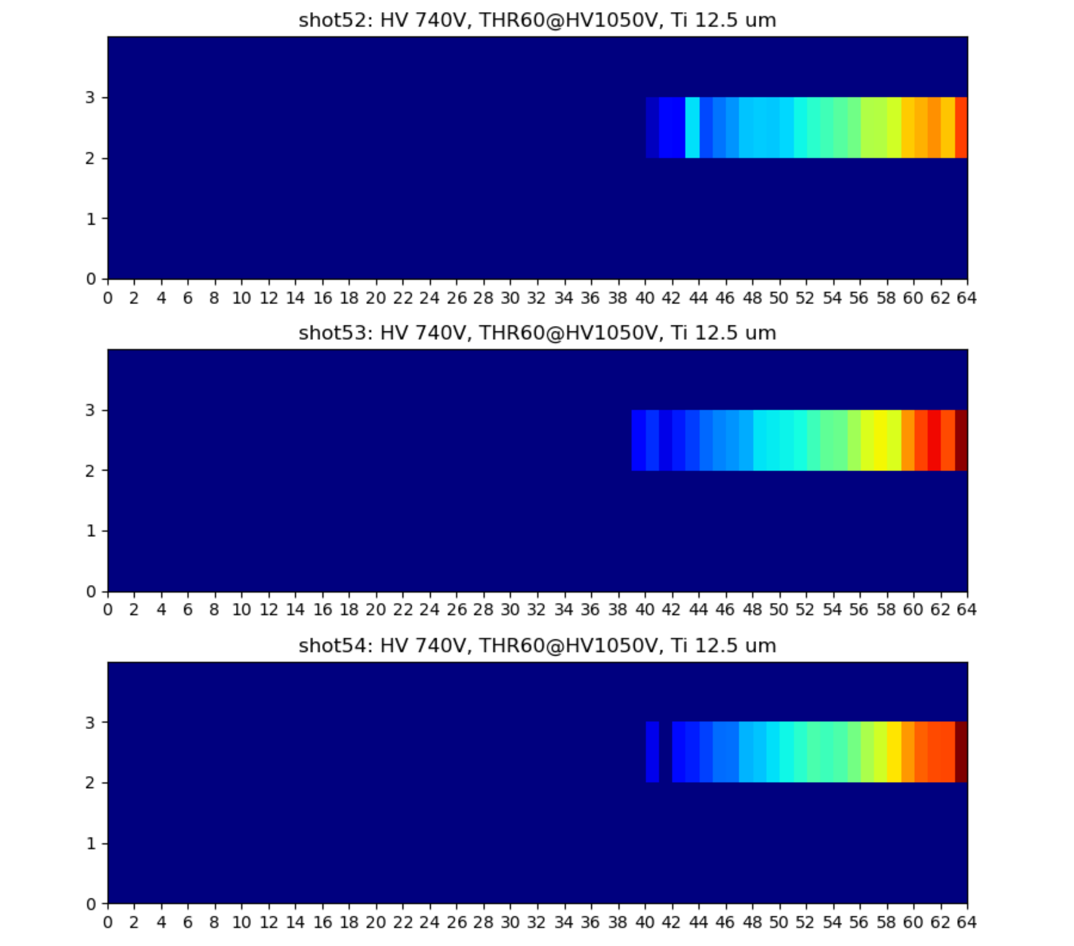


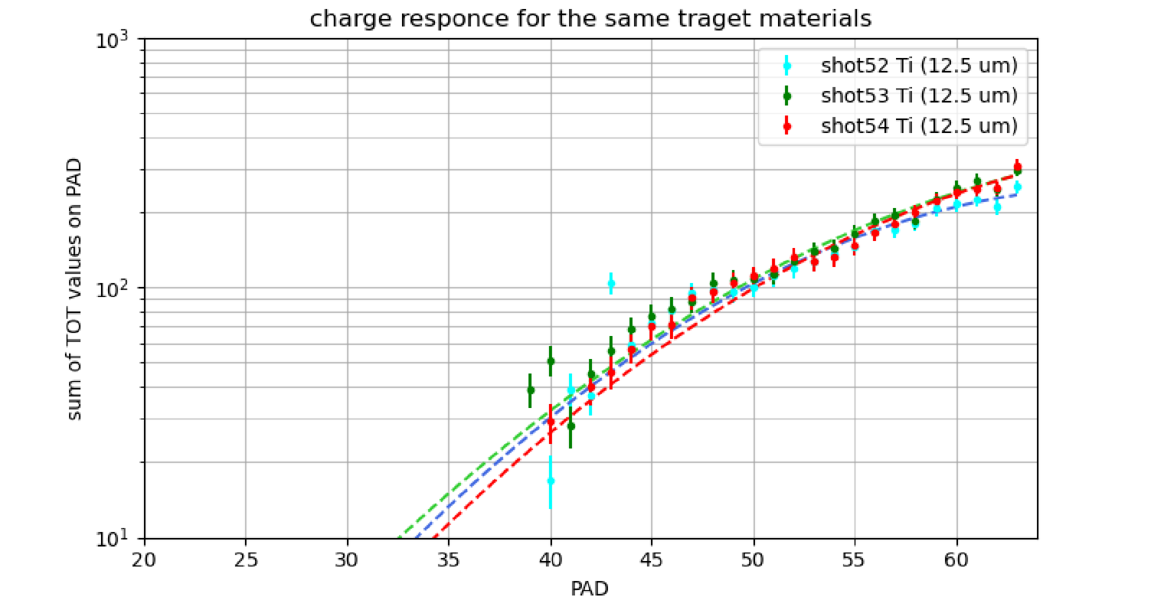
The synergistic operation of the GEM and TPX3 detectors enables spectroscopic analysis of radiation along the same line of sight, covering a wide energy range from soft X-rays to gamma rays detection (2 KeV-10 MeV)

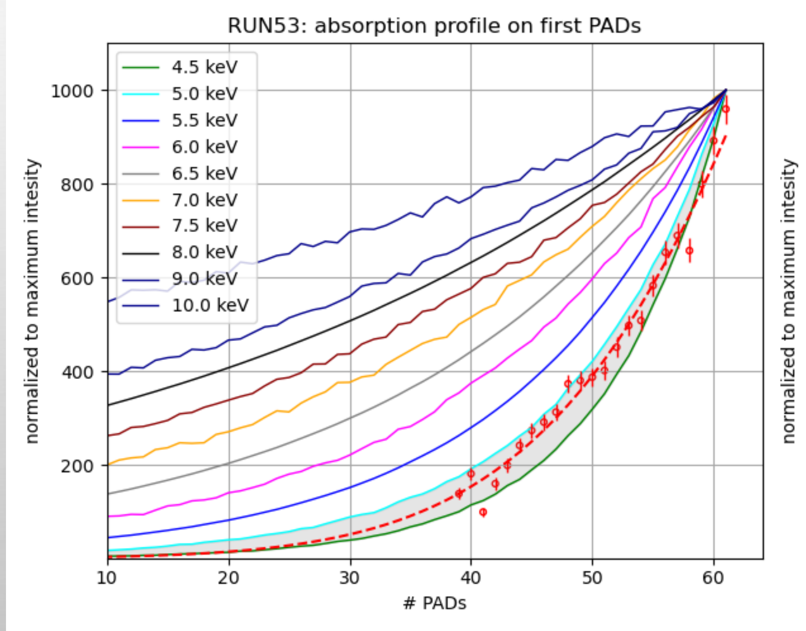
The first week was dedicated to the measurements of the X-rays spectra coming from different types of targets: **Titanium**, **Aluminum**, **Copper** and **Mylar**

5. Absorption profiles with the same targets and GEM acquisition parameters Ti (12.5 um)

GEM gain ≈ 12 , THR60@ HV1050V



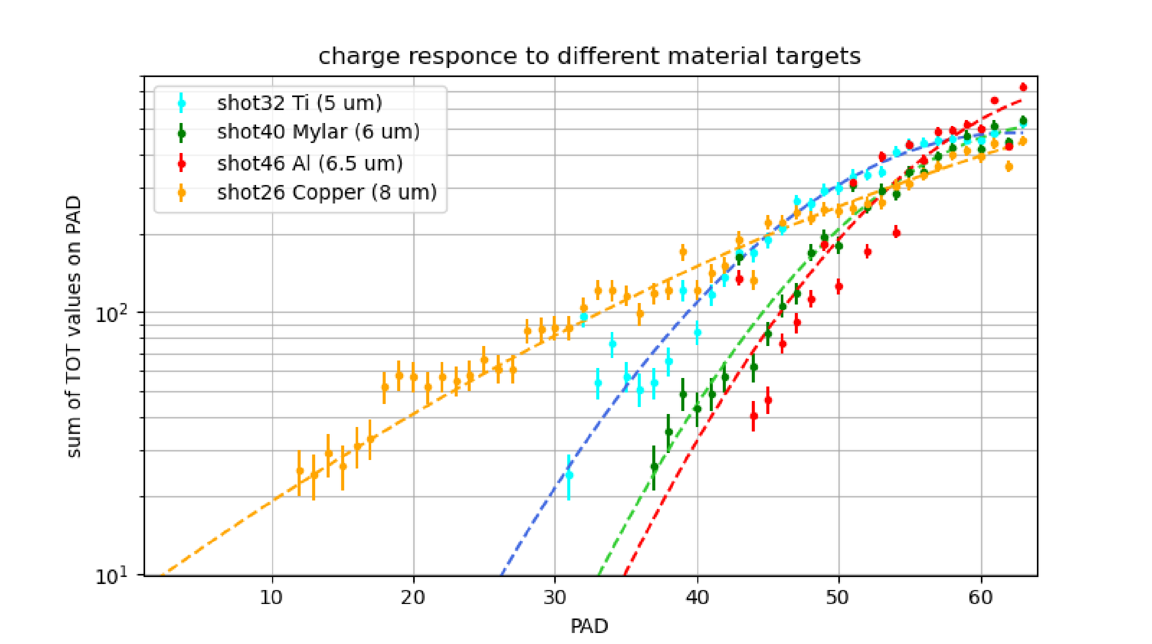


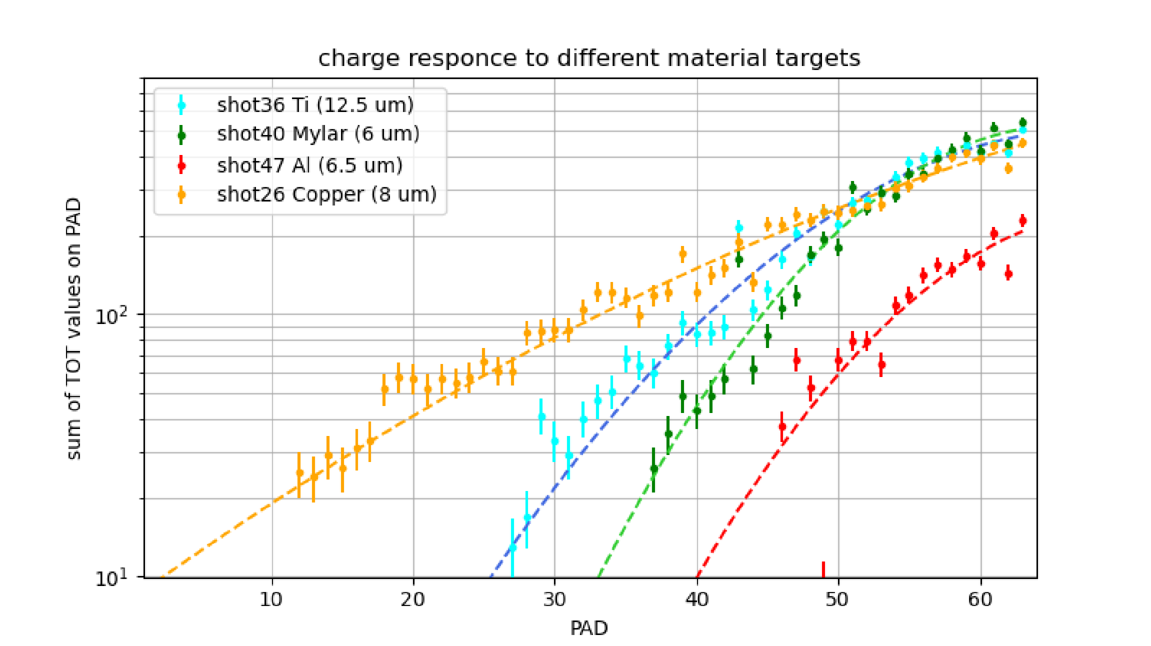


Shot	Fuoco	Target	Spectrometer Voltage = 3kV/3,2kV/0,8kV
52	13,842	Ti 5 um	3,6 MeV
53	13,842	Ti 5 um	4,2 MeV
54	13,842	Ti 5 um	3,2 MeV

5. Comparison between absorption profiles from different target materials (March 2023)

Shot number	GEM HV (gain)	GEM THR	Target	Thickness [um]
22	740	250	Cu	8
26	*740*	*300*	*Cu*	*8*
27	740	250	Cu	8
32	*740*	*300*	*Ti*	*5*
36	*740*	*300*	*Ti*	*12.5*
37	740	300	Ti	12.5
38	740	300	Ti	12.5
40	*740*	*300*	*Mylar*	*6*
43	740	300	Mylar	6
46	*720*	*300*	*Al*	*6.5*
47	*720*	*300*	*Al*	*6.5*





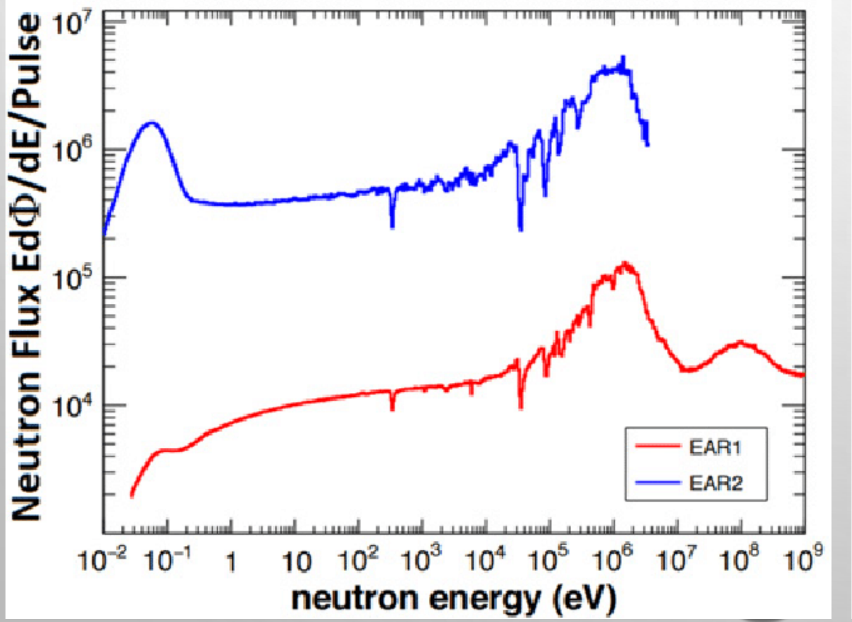
6. The GEMpix detector for measurements of charged particles and their identification

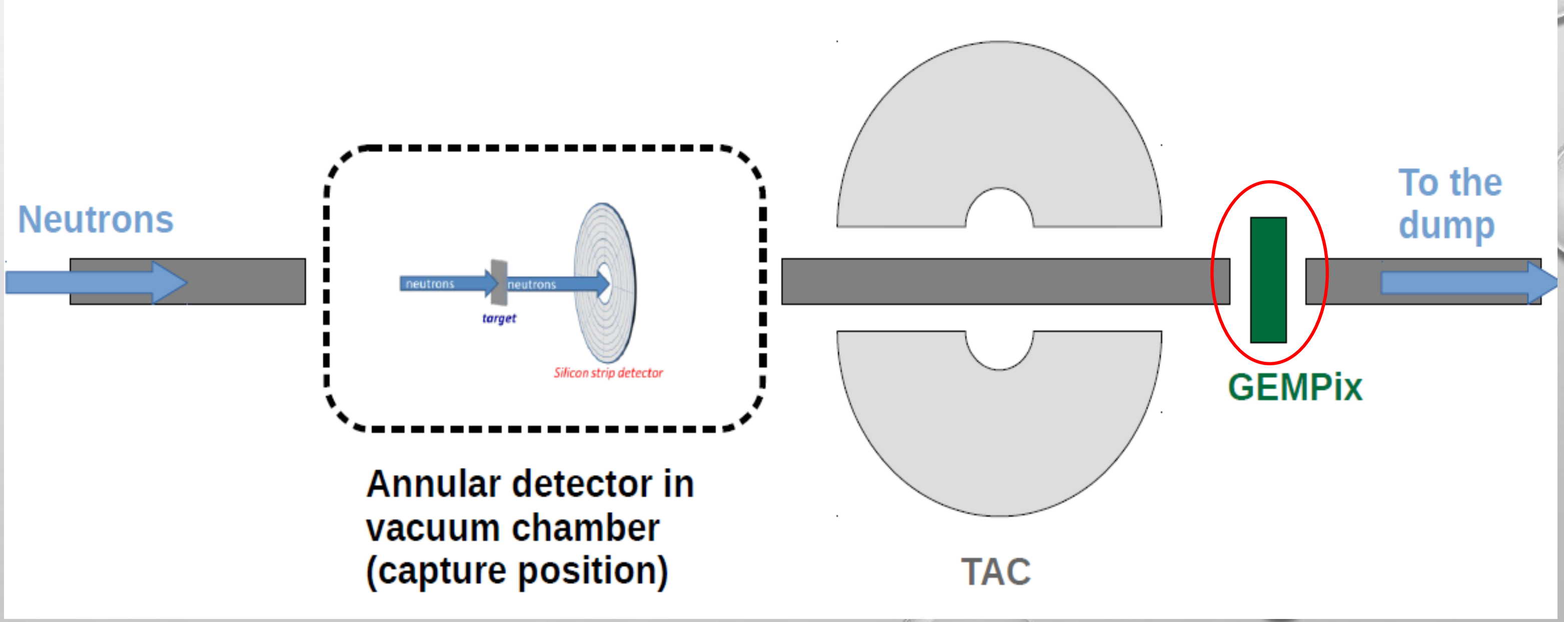
6. GEMpix detector for low energy charged particles from (n, cp) reactions (n_TOF proposal)

GEMpix has been proposed as a new detection system for the measurement of charged particles coming from neutron-induced reactions, especially those of interest for modeling the structural materials in fusion reactors

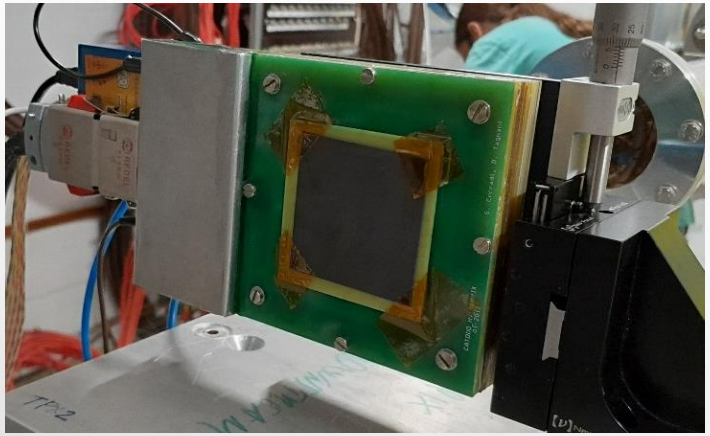
- ✓ It is a gas detector with a small active volume and offers the possibility to measure low energy charged particles, in particular from 0.5 to 2 MeV, a range difficult to explore from the other diagnostic systems.

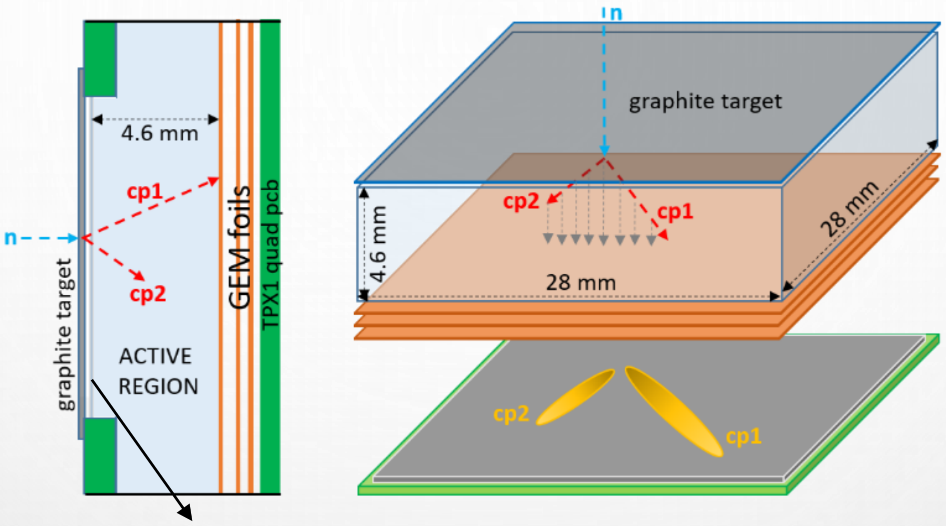
- ✓ Measurements focalized on the on the study of charged particles from a Carbon target and aims to validate the technique that exploit track analysis to discriminate the produced particles.



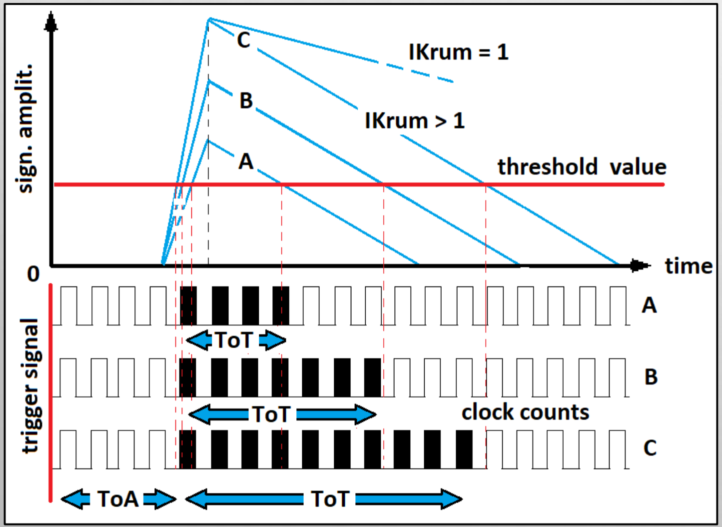


6. GEMpix detector for low energy charged particles from (n, cp) reactions: detector layout and charged particles acquisition





aluminized mylar window (15 µm)



It is based on a Timepix1 quad that can acquire in counting, charge (ToT) and time (ToA), separately.

Acquisition is frame-based: counting, ToT and ToA are acquired in a set time window

The neutron energy range can be observed by setting an appropriate software delays.

In this case, the minimum energy was about 10 keV and the maximum was set from 0.5 until to 20 MeV.

Particles are identified by measuring the deposited energy and exploiting their morphology (cluster analysis).

Main track parameters:

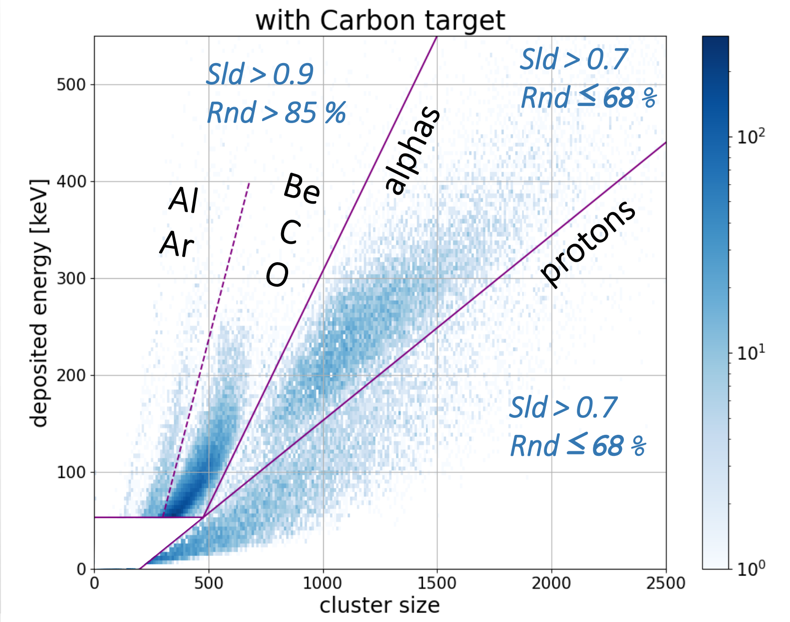
Cluster Size (CS): sum of all the pixels of the track as observed on the quad (i.e. cluster).

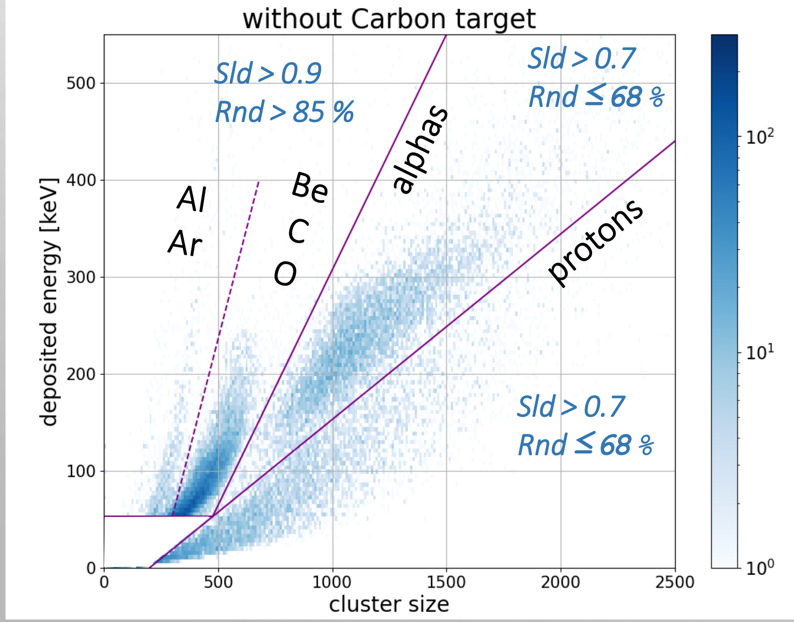
ToT volume (ToTv): sum of all the ToT pixel values of the cluster.

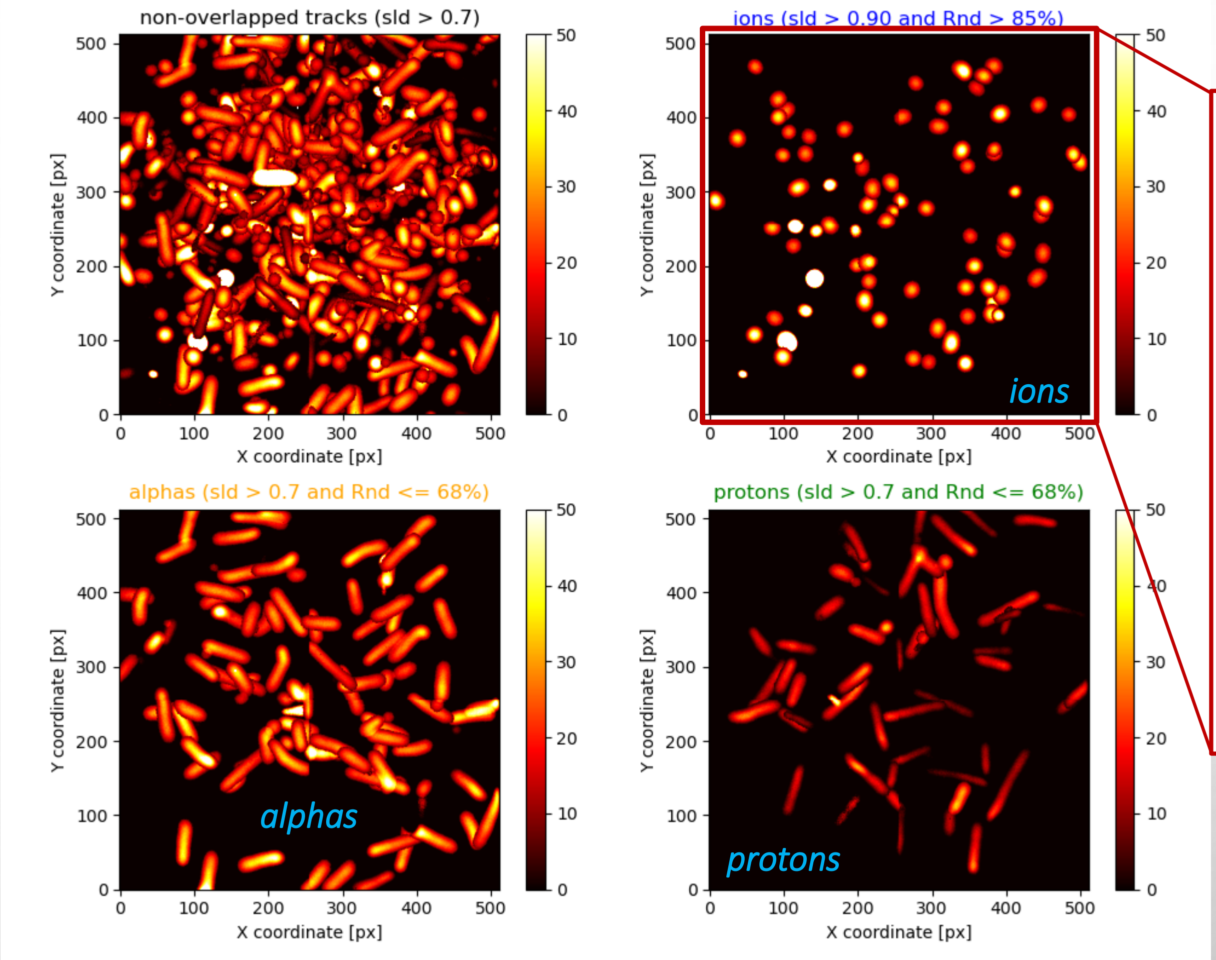
Solidity (Sdl): ratio between CS and convex hull (the smallest convex set of pixels that contains it)

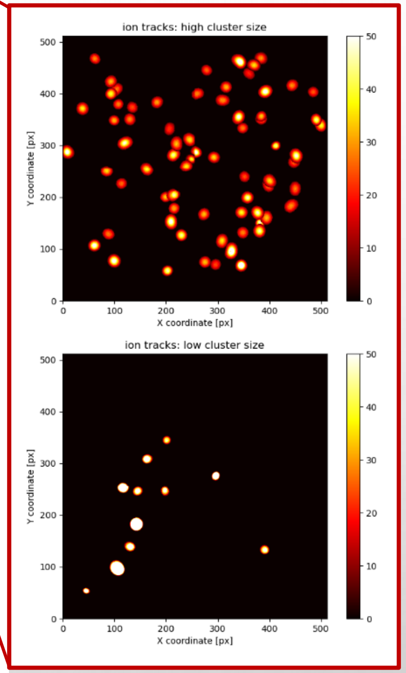
Roundness (Rnd): ratio between CS and the circumference area of diameter equal to most distant pixels in the cluster.

6. GEMpix detector for low energy charged particles from (n, cp) reactions: particles discrimination for neutron energies lower than 10 MeV







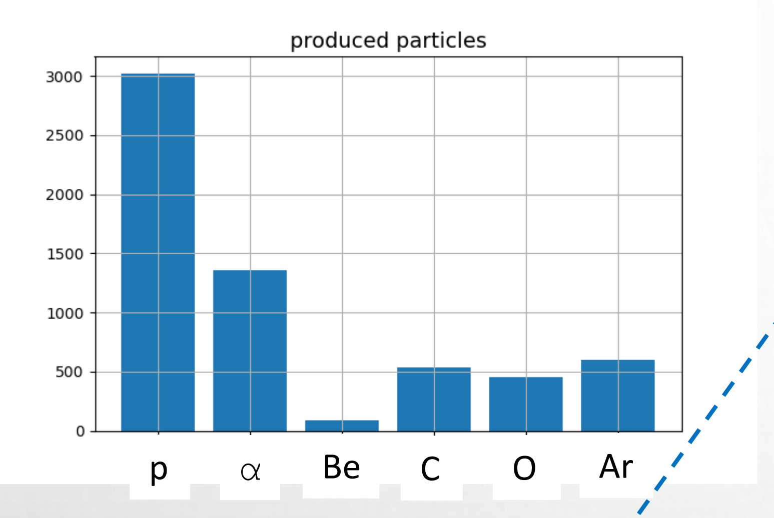


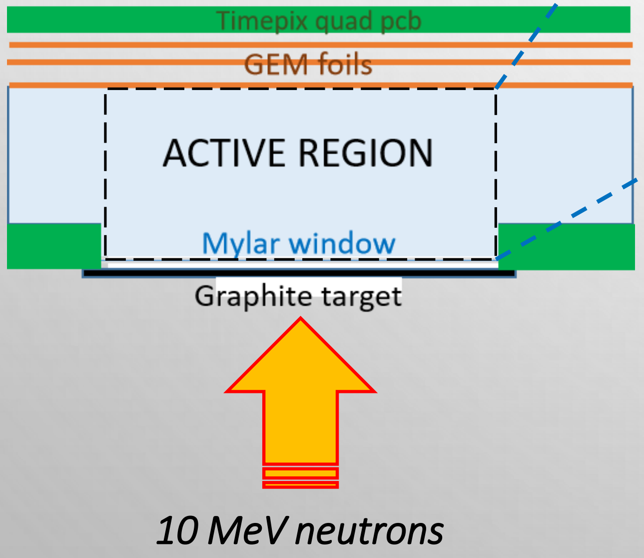
More than one ion population can be distinguished.

graphite	protons [×10³]	alphas [×10³]	heavy ions [×10³]	Total [×10³]
with target	8.98 ± 0.09	12.2 ± 0.1	14.4 ± 0.1	35.6 ± 0.2
without target	8.52 ± 0.09	11.2 ± 0.1	13.3 ± 0.1	33.0 ± 0.2

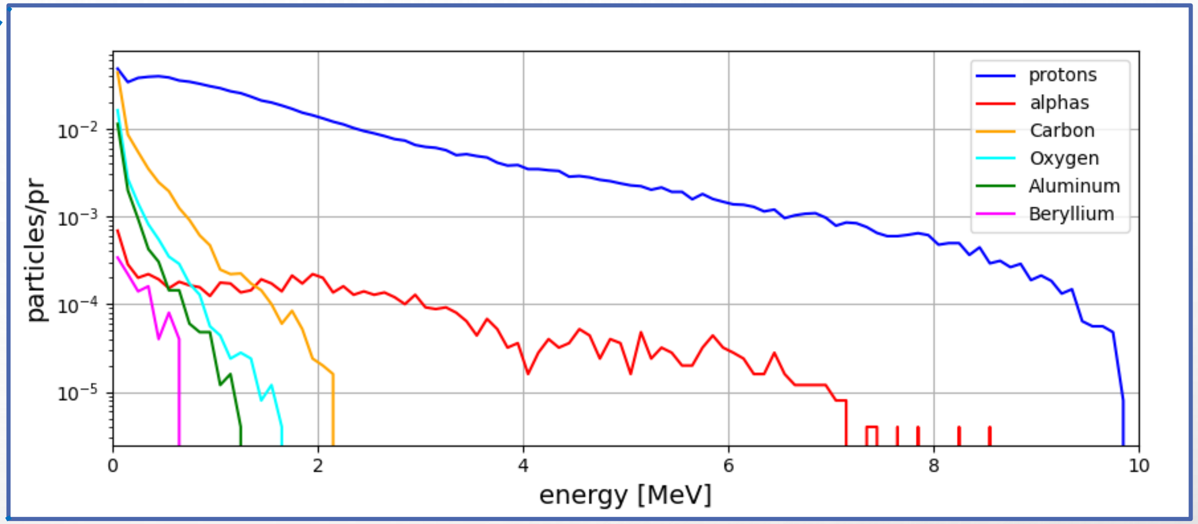
With Carbon target, the estimated number of particles increases of about 8 % and the minimum energy of the discriminated particles reaches a value of 0.1 MeV.

6. GEMpix detector for low energy charged particles from (n, cp) reactions: fluka MC simulation and evaluation of the main particle contributions

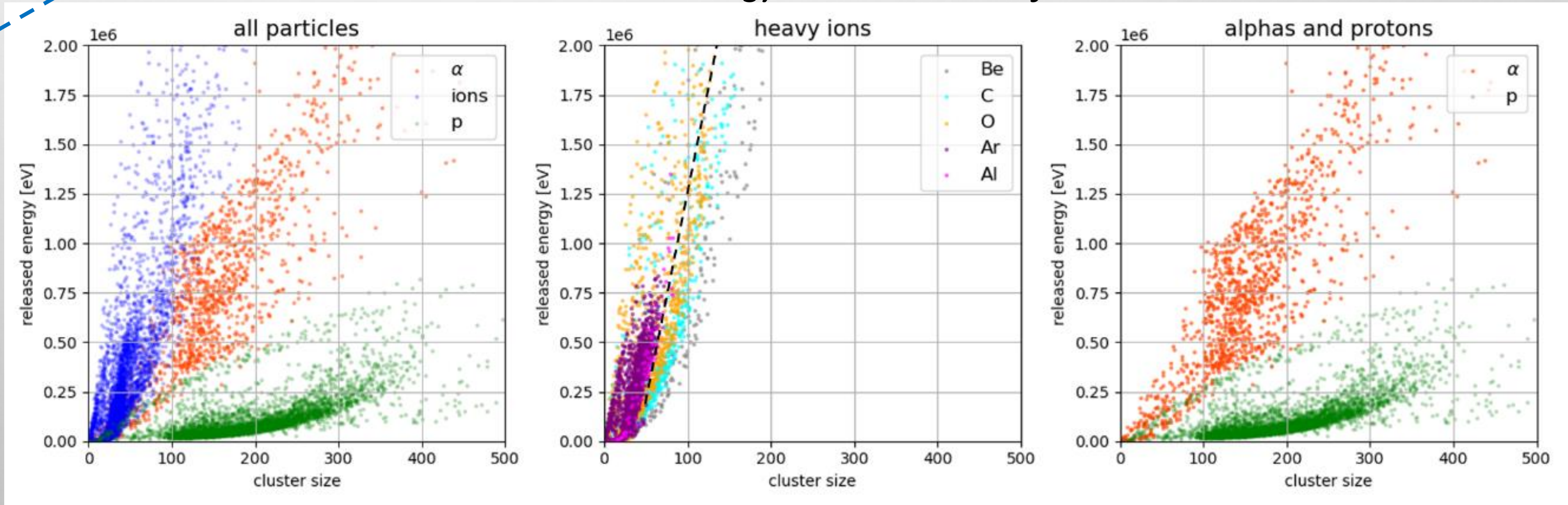




Spectra of charged particle entering in the active volume



Correlation between released energy and cluster size for simulated tracks



primaries 5×10^7

Conclusions

- For almost 10 years, our work with Timepix focalized for some specific applications in the field of Laser Produced Plasmas. In particular a side-on Timepix can realize an estimate of the hard-X and gamma emission with energies from few tens of keV until to about 10 MeV.

- Based on this technology, we developed new detectors for specific applications: diamondpix and GEMpix.

- The diamondpix was characterized and demonstrated as a good alternative to the detection of fast neutrons with respect to the classical diamond detectors in terms of particles discrimination.

- The GEMpix, the coupling of a GEM chamber with a timepix quad readout, shows a very good potentiality in the measurements of soft-X rays on Laser Plasma thanks to its large dynamic range.

- The GEMpix proved to be also particularly efficient in the detection and discrimination of low energy charged particles. This covers an energy range (0.1 – 2 MeV) over which conventional solid-state detectors are limited.

- For the detection of soft-X rays from laser plasma, we realized also a new GEM camera in side-on configuration that shows a good sensitivity to different target materials with an energy resolution of about 0.5 keV.

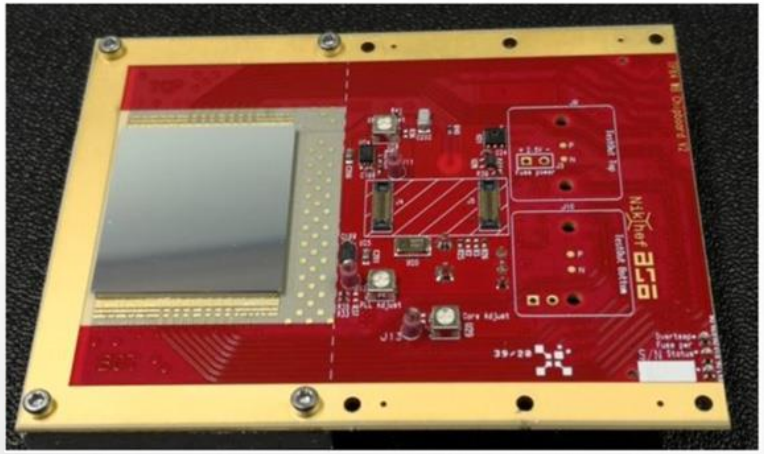
- We are constantly improving our detection systems especially for laser plasma diagnostic and could be useful for us to have the opportunity to participate to new experiments in this field.

Thanks for your attention!!!

Fundamental research and applications with the EuPRAXIA facility at LNF
4-6 December 2024

BACKUP SLIDES

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 covers an area of 28.2×24.6 mm^2 and has several improvements with 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