Advancing Plasma Analysis: An Integrated X-ray Spectroscopy System for Comprehensive Soft and Hard X-Ray, and Gamma Radiation Detection Using GEM and Timepix3 Technologies

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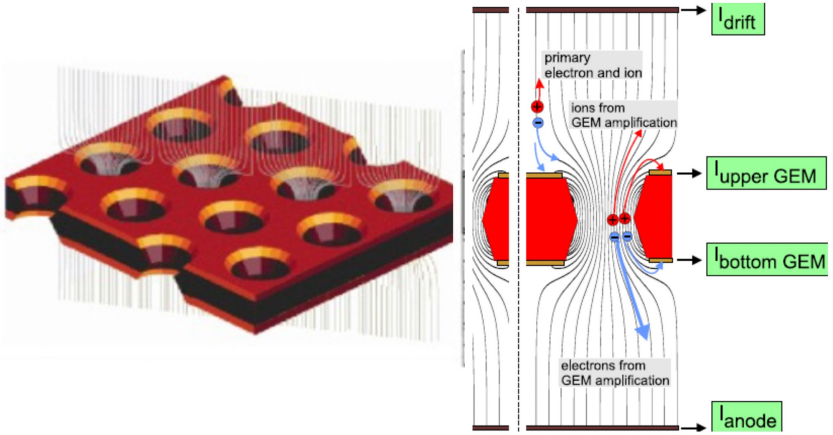
Outline

- Introduction to GEM tecnology
- Employement of the GEM camera in tokamak machines for 2D Soft X-ray diagnostics in photon counting mode
- A new paradigma of measurements has been implemented overcoming photon counting
- Use of the GEM detector in a laser plasma facility in the side-on configuration
- Description of the combined spectrocopic system GEM+Timepix3 detectors for soft-X / Hard-X and gammas with preliminary results showcasing its functionality
- Conclusions

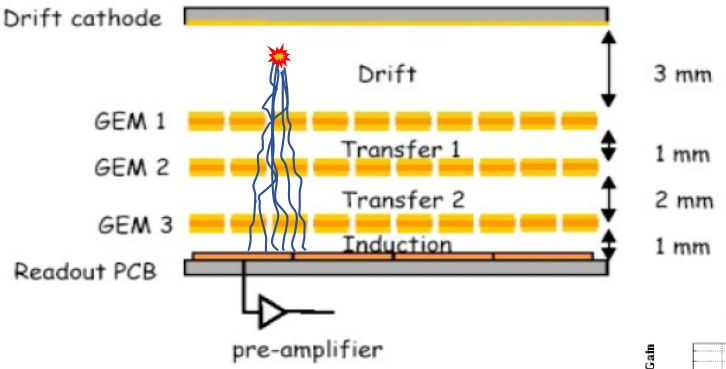
Gas Electron Multiplier (GEM) tecnology

The GEM detector is a thin polymer foil (50–100 µm), metal-clad on both sides and pierced with a high density of holes

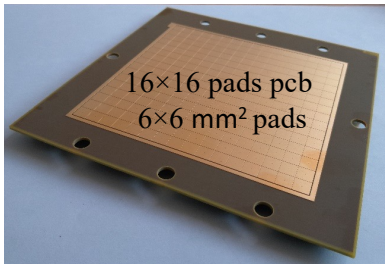


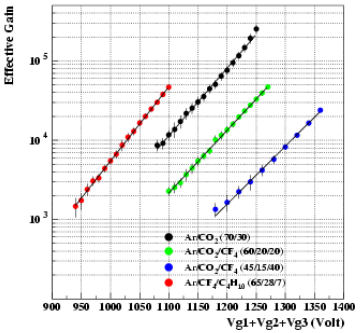
Each hole has a bi-conical structure with an external (internal) diameter of 70 µm (50 µm) and a pitch of 140 µm

The voltages applied on both sides of each foils produce high enough fields to set up an avalanche production mechanism



High dynamic range: gain from 1 to 10^5





2D Soft X-ray diagnostics in photon counting mode

(Single photon regime)

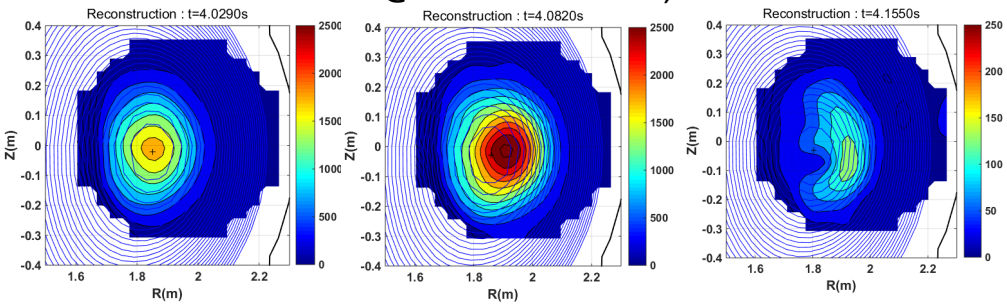
The utilization of a pinhole camera constructed with a GEM detector has proven to be a very valuable technology in the context of the plasma physics. Performing 2-D direct imaging in photon counting allows to get informations on:

- Impurity dynamics in the core
- Reconstruction of the magnetic configuration of the core
- Localized effects of heatings
- Magnetohydrodynamic (MHD) instabilities
- Energy and particle transport

Tangential X-ray pinhole camera

GEM detector 3 – 15 keV

@ KSTAR Tokamak, 2017



Accumulation of ***Tungsten impurities***

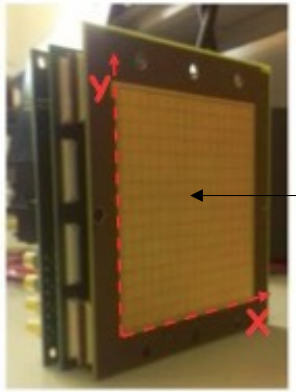
Main features of a GEM detector in photon counting mode :

- High sensitivity for soft-X detection
- Noise free
- Radiation hardness
- Intrinsic gain
- Optical flexibility
- Adjustable time resolution (from 1 ms to 10 μs)

A new paradigma for photon detection: X, Y, ToT, ToA

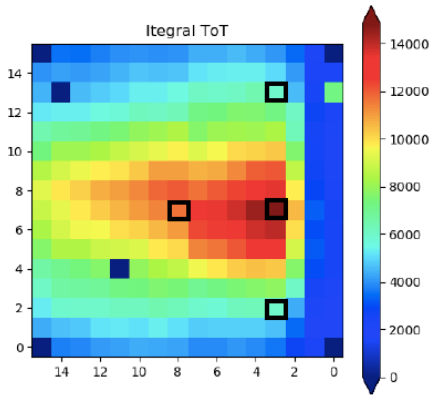
Additional features of the GEM detector working in ToT mode:

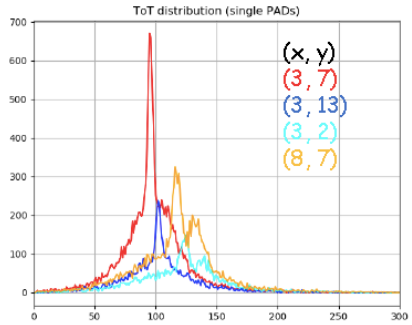
- Measurement of the position (X,Y), energy by means of the Time over Threshold variable (ToT) and the time of arrival (ToA) for each detected photon with accuracy of few ns
- Each pixel acts as a single spectrometer
- Space and time resolutions adjstable also post-process

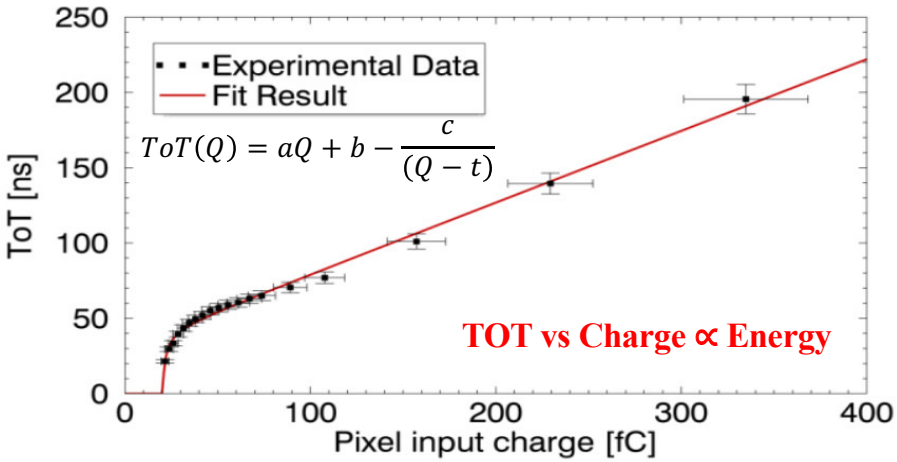


Head-on configuration

Some results from the EAST campaign







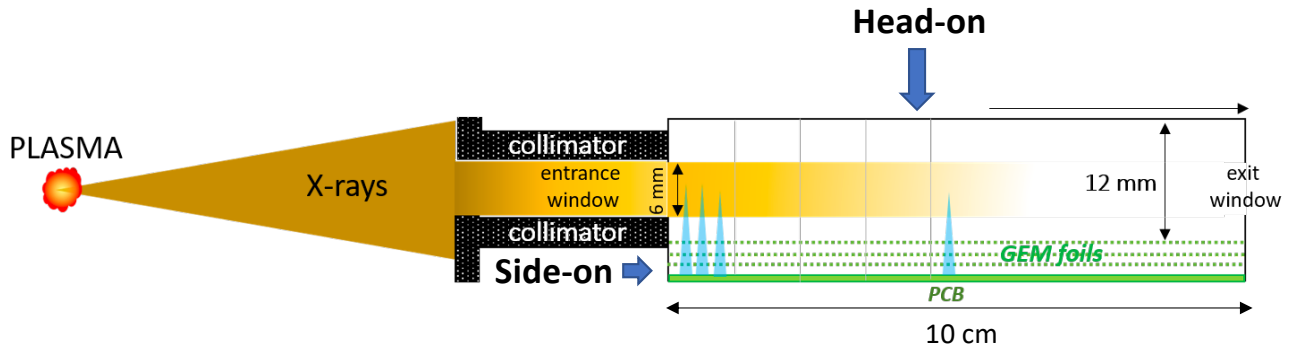
A. Muraro et al. 2019 JINST 14 C08012

Use of the GEM detector in Laser Plasma Experiment

(Multi photon regime)

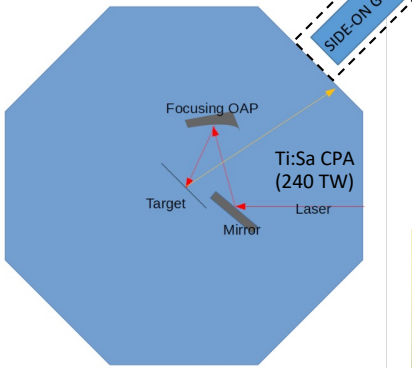
- The motivation to utilize the GEM detector in a side-on configuration originated from the requirement to monitoring the X-rays emitted from a plasma produced by a laser-target interaction

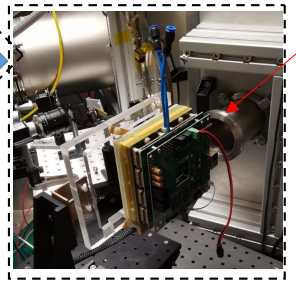
- The challenge arises from the fact that X-ray emissions tend to occur in concentrated bursts, spanning from tens of picoseconds to a few nanoseconds, which is dependent on the power and pulse duration of the laser.

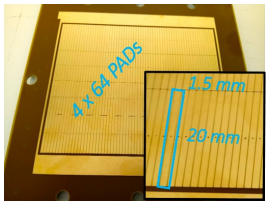


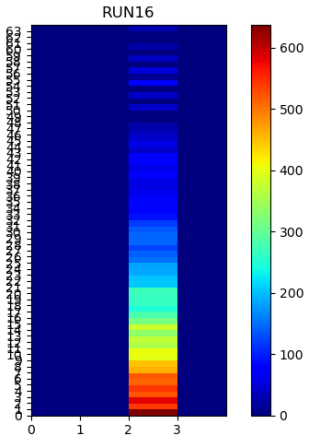
With the introduction of advanced electronics capable of conducting charge measurements, the detector in this configuration is able to estimate the X-ray spectrum from charge measurements. Additionally, the advantage of utilizing the entire gas depth of 10 cm allows for an extended energy detection range of up to 50 keV.

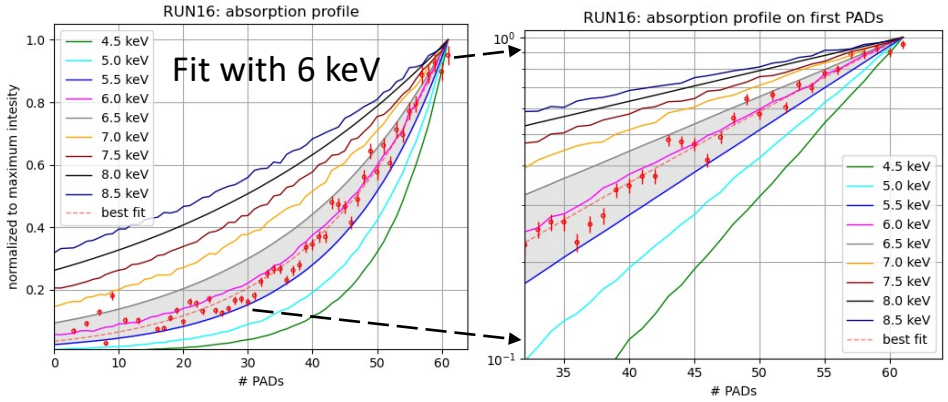
SIDE-ON GEM on Laser Produced Plasmas @ CNR-INO of Pisa

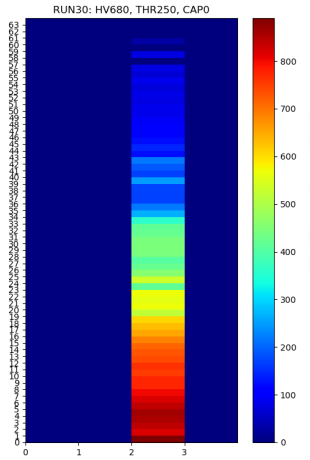


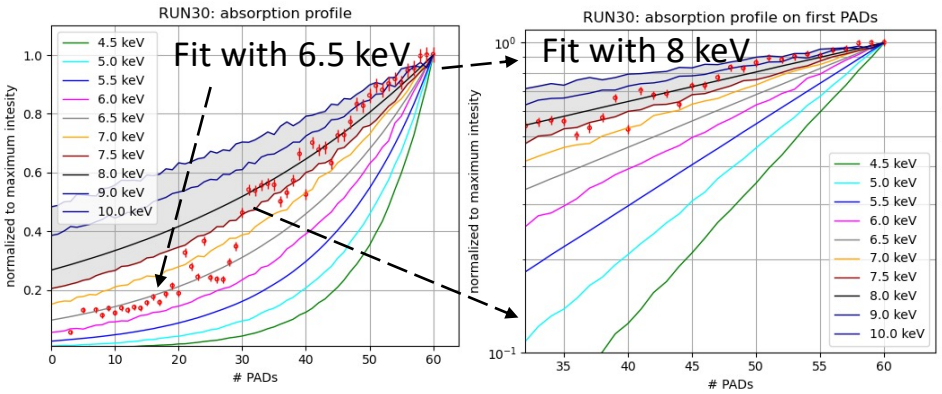








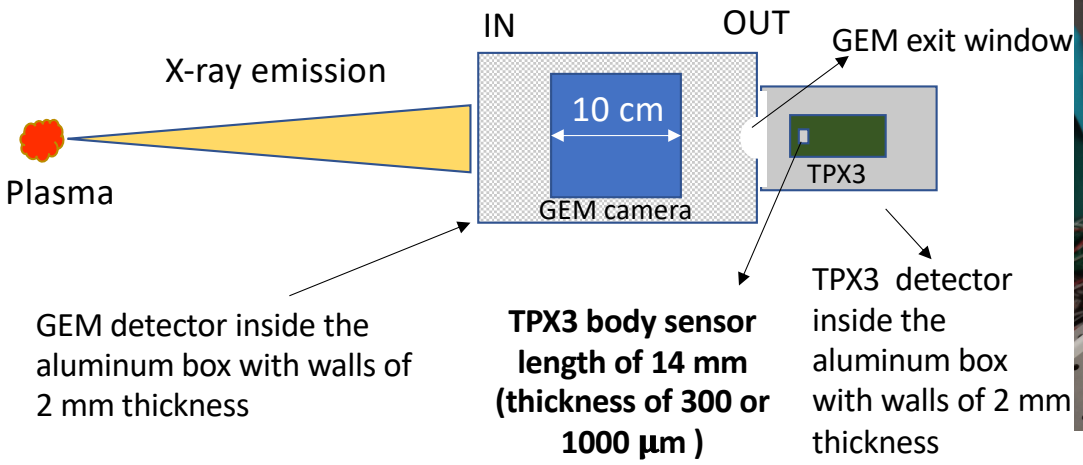


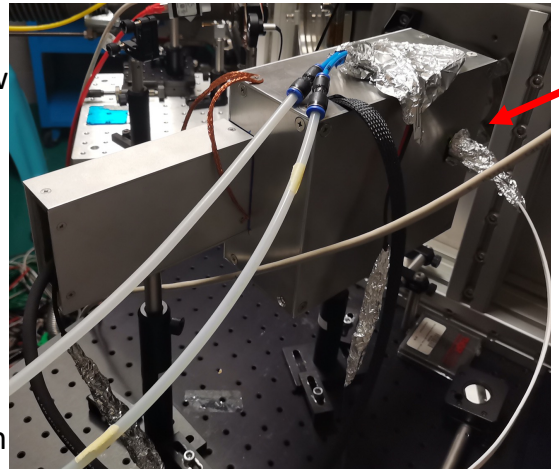


Absorption profiles measured with the side-on GEM detector for a single laser shot on a Ti target of 5 µm compared with simulated monoenergetic emission profiles

Measurement focused on only one pad row

Combined spectroscopy system utilizing GEM and TPX3 tecnology for laser plasma

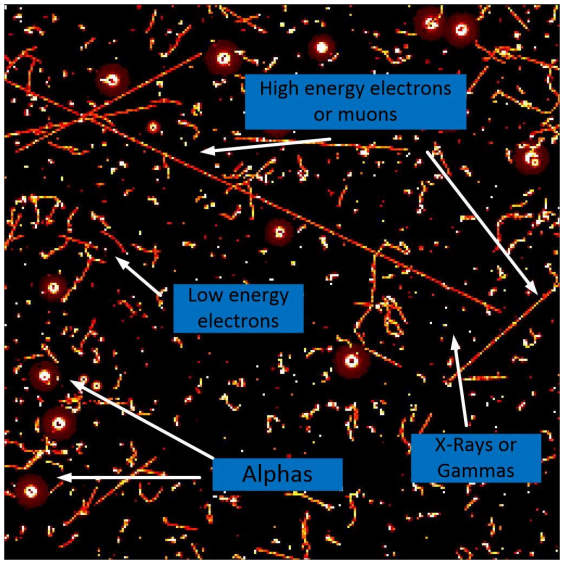




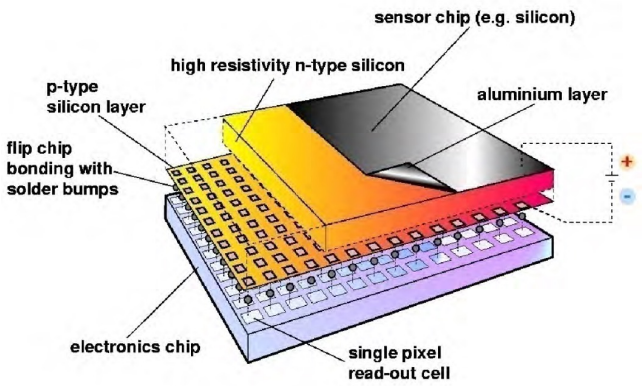
Experimental Setup @ the Laser Plasma facility of CNR-INO of Pisa

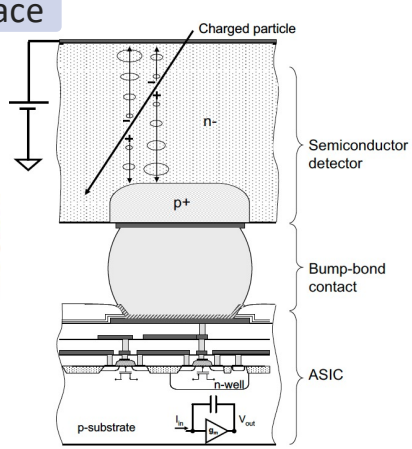
The synergistic operation of the GEM and TPX3 detectors enables spectroscopic analysis of radiation along the same line of sight, covering a wide energy range from soft X-rays to gamma rays detection (2 KeV-10 MeV)

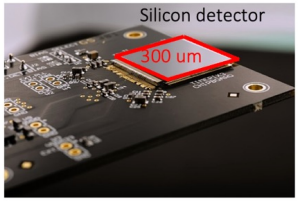
Timepix3 (TPX3) Solid-state detector

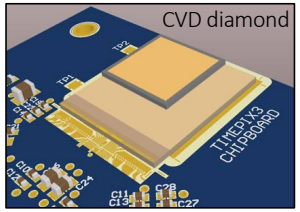


Semiconductor diode with a pixelated surface









The detector enables the identification of the interacting particle type by performing a morphological analysis of the track produced by the detected particle

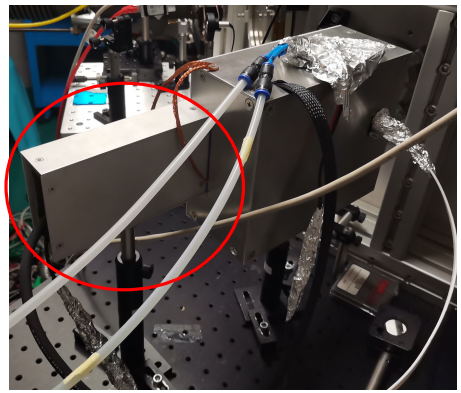
Simultaneous measurement of the energy (ToT) and time of arrival (ToA) of each particle

Compact detector

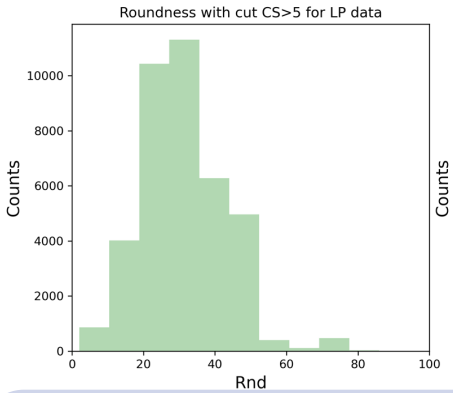
Characteristics	
Pixel Arrangement	256 X 256
Pixel Size	55µm X 55µm
Technology	130nm CMOS – 8 metalization layers
Acquisition Modes	Time of Arrival (ToA) Time over Threshold (ToT) Energy Event counting Integral ToT
Readout Modes	Data Driven (zero suppressed) Frame based (zero suppressed)
Dead time per pixel	475 ns (pulse measurement and packet transfer time)
Minimum Timing resolution	1.56 ns
Minimum detectable charge	500e-
Output bandwidth	1 to 8 SLVDS lines @ 640Mbps (DDR)

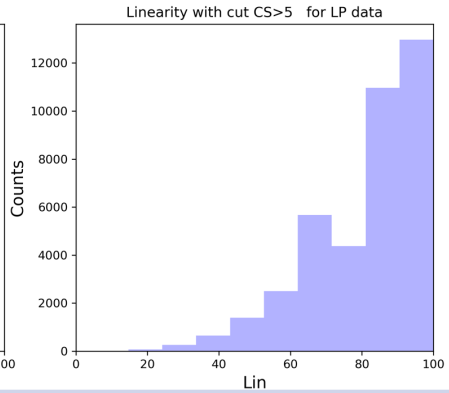
Combined spectroscopy system utilizing GEM and TPX3 tecnology @ CNR-INO of Pisa

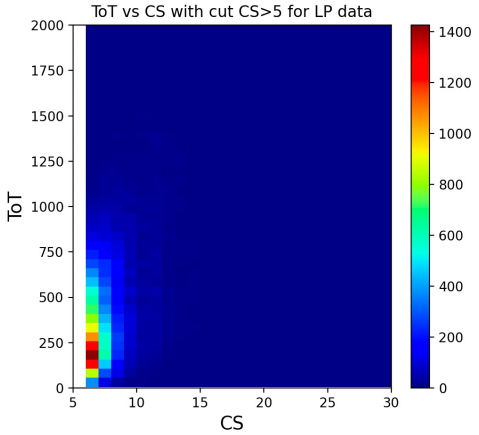
Ti:Sa CPA (Chirped Pulse Amplification) of 240 TW

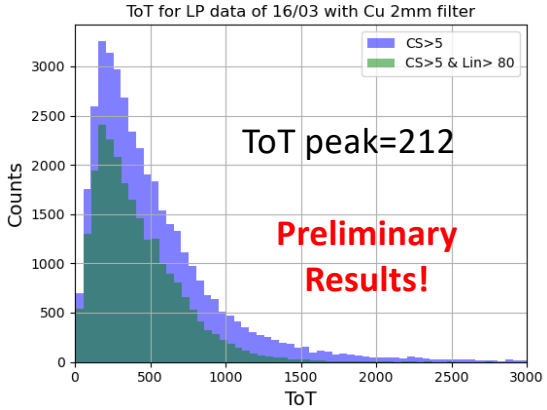


Hard-X rays detection with Si TPX3



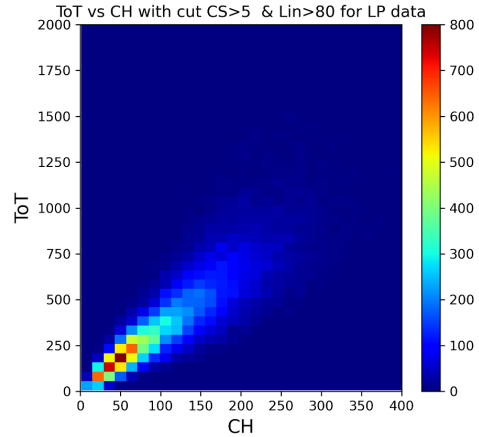






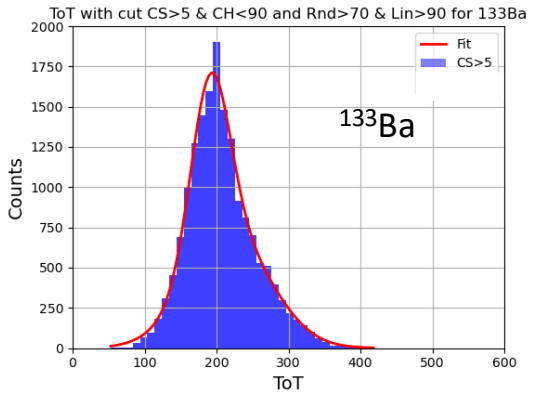
<u>Particle discrimination performed using</u>:

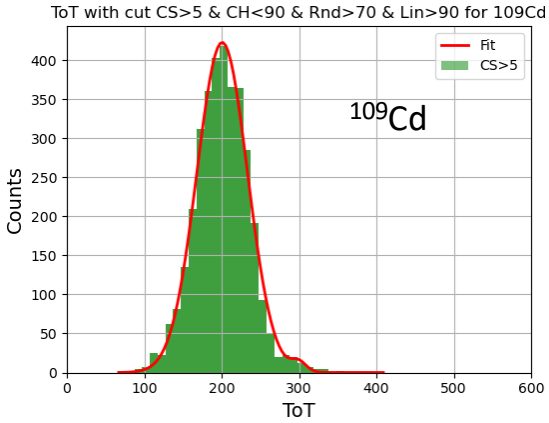
- ***ToT value*** (sum of all pixels ToT),
- ***Cluster Height*** (Maximum ToT pixel value in a cluster)
- ***Linearity*** *(line_pixels /number_of_pixels_in_cluster) where line_pixels* sum how many of pixels have distance to the *Line* (passing through the most distant pixels) less or equal to 1.0
- ***Roundness*** (Rnd = CS/[(D/2)^2*π], with D given by the most distant pixels in a cluster)
- ***Cluster Size*** (CS)

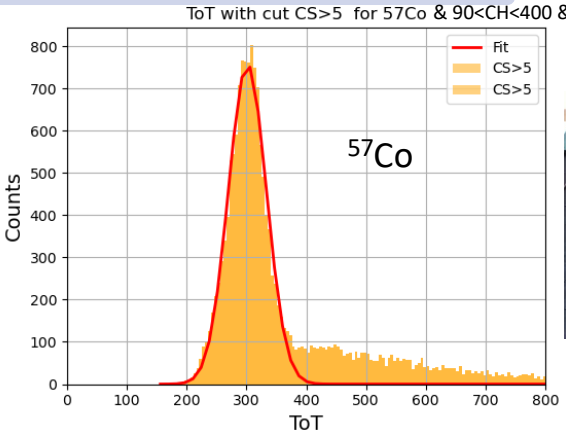


Si TPX3 calibration for Hard X (50 – 1000 keV)

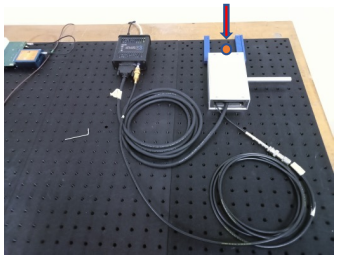
The response of the detector was assessed by employing well-known emission gamma sources:

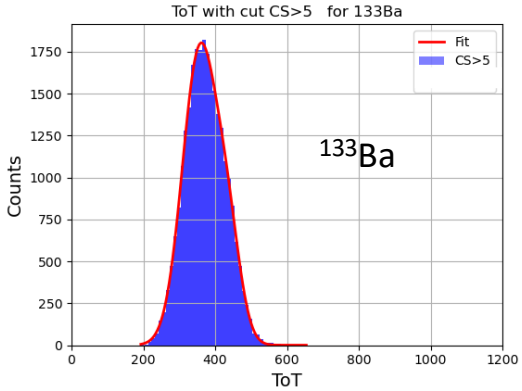




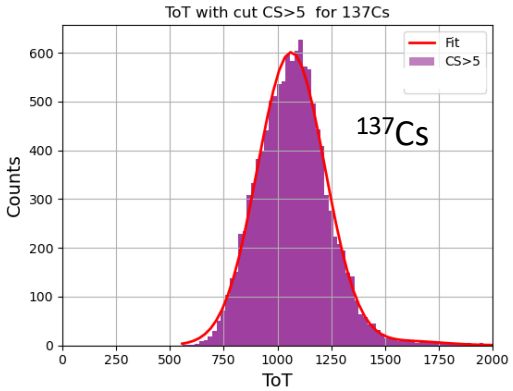


Gamma Source





5<CS<10 & 100<CH<170 & 60<Rnd<70 & Lin > 80



CS>17 & 100<CH<400 & 20<Rnd<40 & Lin < 80

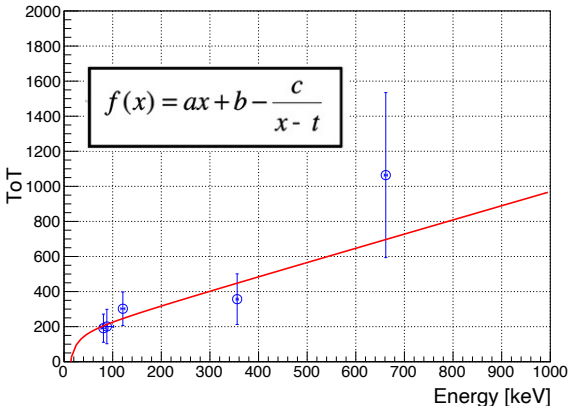
Preliminary

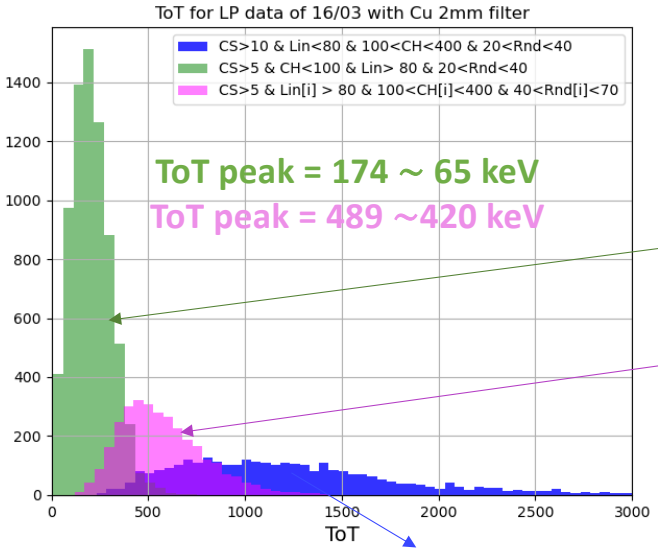
Energy [keV]	*ToT*	*Error*
80.00 (^{133}Ba)	191.14	80.26
88.04 (^{109}Cd)	200.74	98.06
122.06 (^{57}Co)	301.72	95.48
356.02 (^{133}Ba)	356.72	144.38
661.66 (^{137}Cs)	1.064.114	470.36

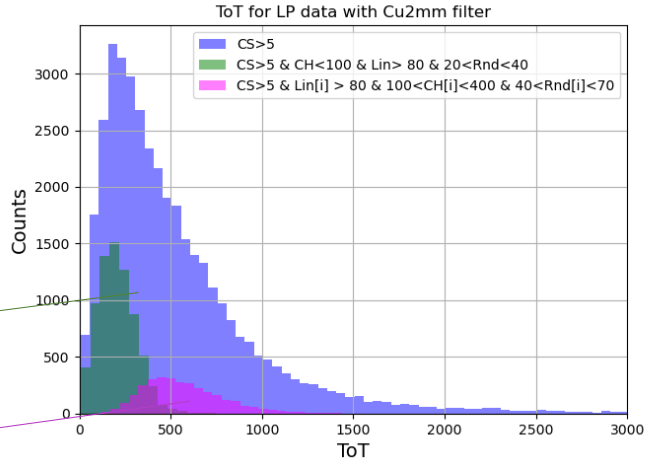
Combined spectroscopy system utilizing GEM and TPX3 tecnology @ CNR-INO of Pisa

Hard-X rays detection with side-on Si TPX3

Si TPX3 calibration curve







Low statistics for higher energy radiation (> 1MeV)

Preliminary results! Analysis in progress

Conclusions

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- The utilization of GEM cameras in tokamak machines (NSTX, FTU, EAST, KSTAR) for 2D plasma soft X-ray imaging or tomography in the head-on configuration, in the range 2-20 keV, has emerged as unique and valuable technology in the field of plasma physics

- In the context of laser plasma facilities (VEGA-2, GeKKo XII, ILIL CNR-INO etc.), GEM detectors have been employed in a side-on configuration. This configuration enables charge measurements of X-ray emissions from laser plasma and allows working in the range 2 -50 KeV

- A combined spectroscopy system that incorporates GEM and Timepix3 detectors has been developed. This system aims to achieve enhanced spectroscopic capability in regime of multi photon (laser plasmas) in the range 2-50 keV. A timepix3 detector coupled on the exit of GEM allows assessment of Hard-X radiation (50 - 1000 keV) or gammas (1-12 MeV), encompassing both soft, hard X-rays and gamma rays along the same line of sight.
- Moreover, both devices are able to operate even in the presence of high background radiation (at least up neutron flux of the order of 10^7 n/s·cm^2) which can be also monitored using a CVD diamond TPX3.

These findings highlight the potential of this hybrid system for enhancing plasma analysis and enabling comprehensive radiation characterization in demanding experimental environments.

A rightful and grateful tribute to ***Fabrizio Murtas***
(1962 – 2022)

You have made those who have had the privilege of having you as a friend and colleague fortunate and honored

Your memory and teachings will accompany us forever. THANK YOU FABRIZIO!!!

Much of what has been presented here is thanks to you!

Working area @ INFN-LNF

Fabrizio's laboratory is still alive….

Laboratory recently equipped with:

- work bench
- NIM modules
- gas lines
- equipment for clean room work
- hood for clean room work

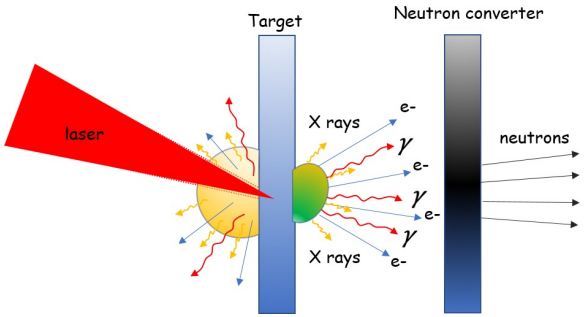
ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

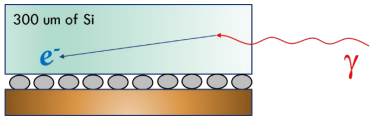
Thank you for attention!

Spare

Side-on TPX3 for gamma detection (1-12 MeV) in laser plasmas

The TimePix3 detector has been successfully utilized in the side-on configuration at the VEGA-2 laser facility (CLPU, Salamanca, Spain) with the objective of generating neutrons through photonuclear reactions on various types of solid targets





VEGA laser facility:

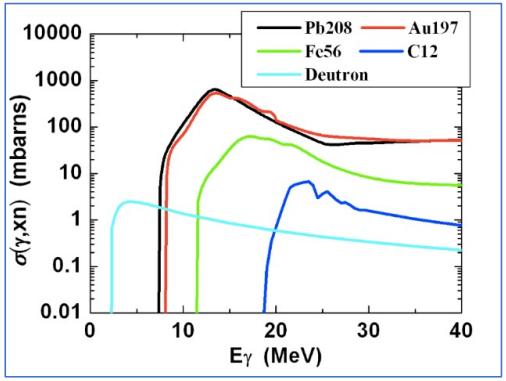
laser wavelength: **800 nm**

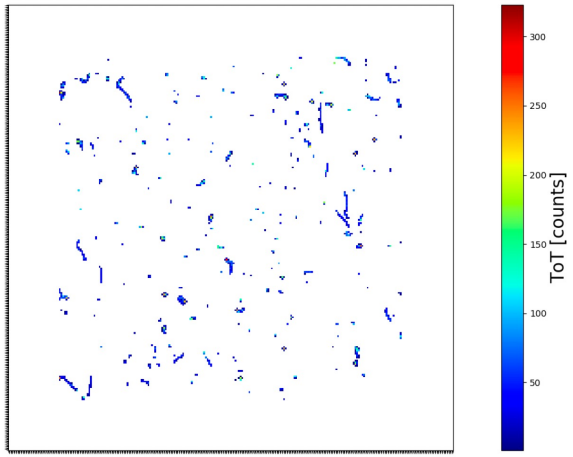
laser Energy: **4.5 J**

pulse width: **35 fs**

laser Power:
130 TW on target

beam diameter: **~ 10 µm**

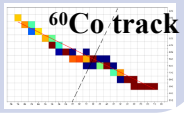


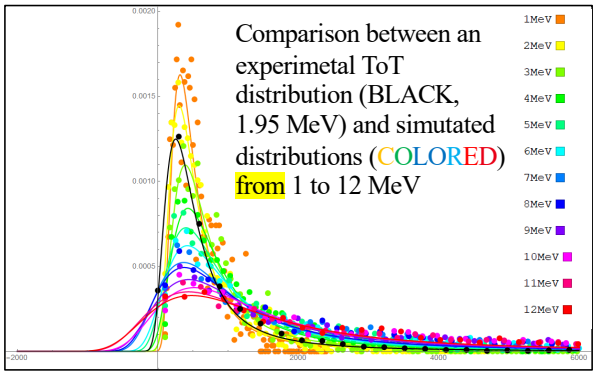


Experimental run from VEGA-2 campaign

Detector response characterized using some known laboratory gamma sources and the related Geant4 simulations.

Morphological features of the clusters used to select the events of interest based on the cluster size (CS > 5), *Time over Threshold* (TOT) counts and Linearity (> 80%).





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