ISTITUTO PER LA SCIENZA E TECNOLOGIA DEI PLASMI

Consiglio Nazionale delle Ricerche

Assessment of a space and energy resolved diagnostic based on GEM technology on MAST-U tokamak.

Agostino Celora
Andrea Muraro
Federico Caruggi
Gabriele Croci
ISTP team

Rory Scannel
Luca Garzotti

MAST-U team

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

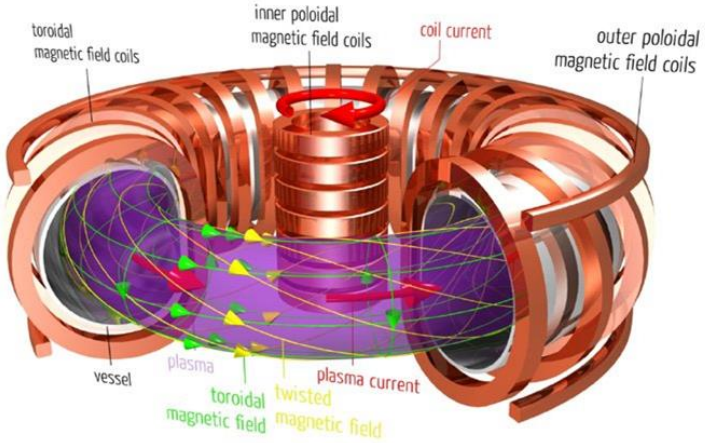
EUROfusion

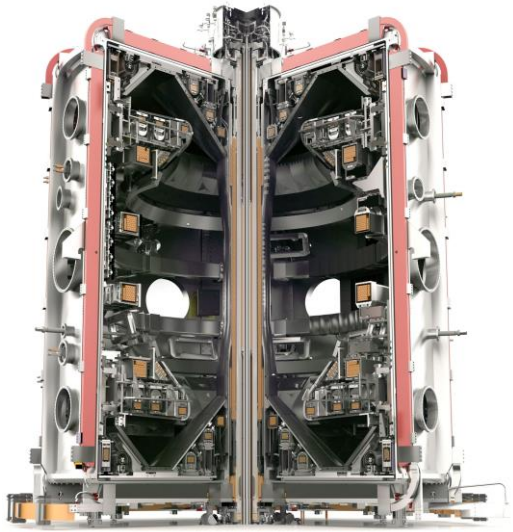
CCFE CULHAM CENTRE FOR FUSION ENERGY

Thermonuclear fusion through magnetic confinement: The Tokamak

A tokamak is a device used for achieving controlled thermonuclear fusion by **confining plasma** in a toroidal (doughnut-shaped) chamber using powerful **magnetic fields**.

- Goal: To replicate the processes occurring in the sun, providing a nearly limitless source of energy.
- Fusion Reaction: Combines deuterium and tritium nuclei to form helium and release energy.
- Magnetic Confinement: Uses magnetic fields to keep the hot plasma away from the walls of





Major and minor radii	0.7/0.5 m
Plasma current	1 MA
Plasma heating	4.5 MW (Ohmic + NBI)
Pulse duration	1-2 sec
Electron Temperature	2.5 KeV

Soft X-Ray radiation from Tokamak

Soft X-Ray emission is a crucial diagnostic tool in tokamaks, providing insights into plasma behavior and characteristics. It is essential for optimizing plasma confinement and stability.

Why?

Emitted due to interactions within the plasma, of three types:

1. Bremsstrahlung:

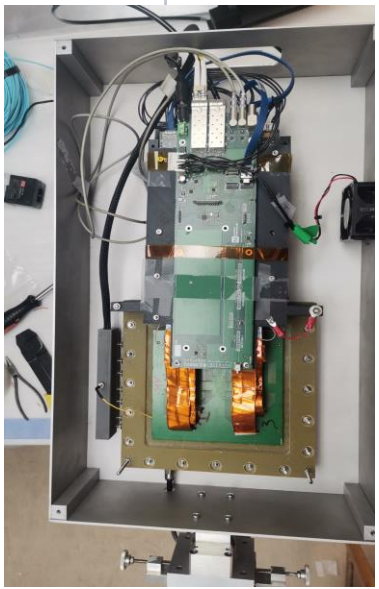
$$\epsilon(R,\lambda) \propto \lambda^{-1} Z_{eff}(R) \cdot n_e^2(R) \cdot T_e^{-1/2} exp\left[\frac{-hc}{\lambda T_e(R)}\right]$$

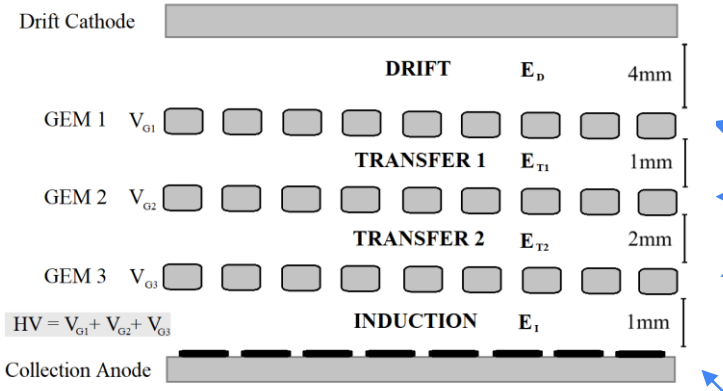
it is one of the main energy loss channels.

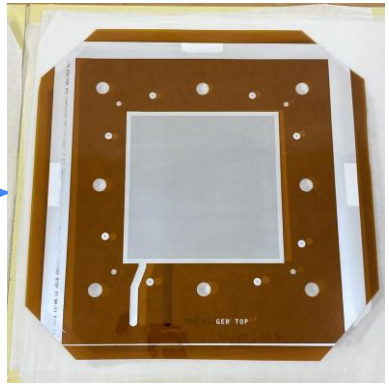
1. line transition: the radiative decay of an excited atomic state of a bound electron into a lower energy level in the same ionization stage. the contribution of line emission is given by **medium and heavy impurities**.

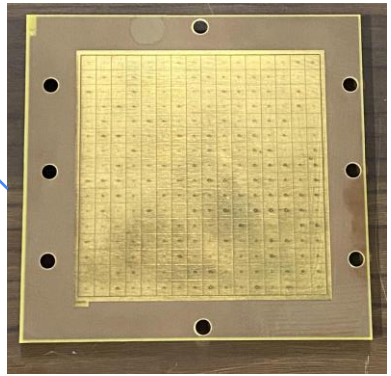
1. radiative recombination*: free electrons of the plasma are captured by the ions, it is a secondary contribution in thermonuclear plasmas.

Gas Electron Multiplier detectors for SXR



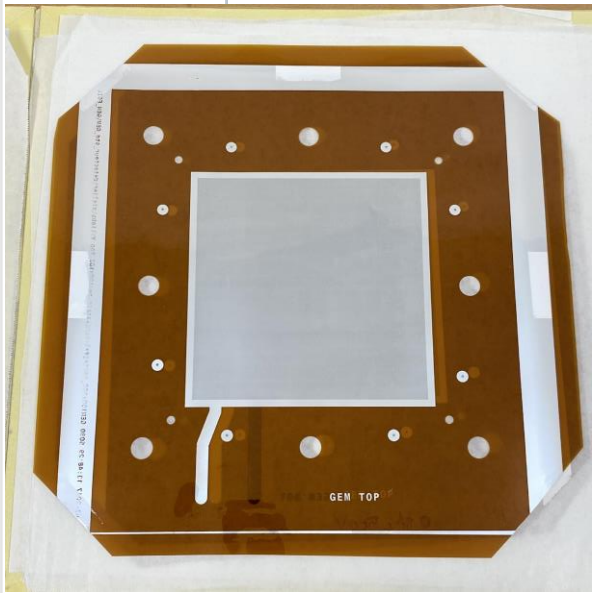


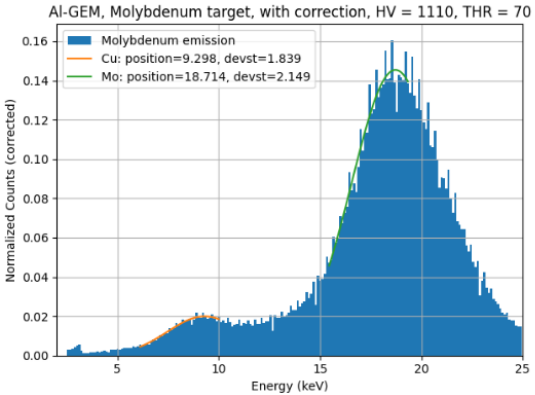




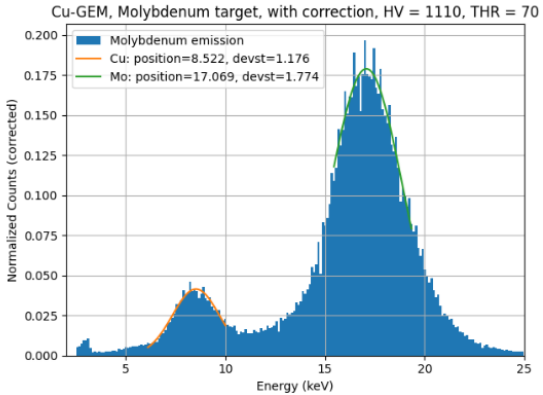
- Ar-Co2 mixture 70%-30%.
- Aluminum GEM.
- 1 MHz per pixel.
- 16 x 16 Pixel, 6mm x 6mm .

Aluminum GEM





(a) Al-GEM molybdenum target, corrected



(b) Cu-GEM molybdenum target, corrected

Quantity	Al-GEM	Cu-GEM	
$K_{\alpha,Mo}/K_{\alpha,Cu}$	2.367 ± 0.543	2.045 ± 0.261	Expected value: 2.161
$I_{peak,Cu}/I_{peak,Mo}$	1.176 ± 0.246	1.560 ± 0.304	ratio: 0.754
(with energy correction)	0.125 ± 0.027	0.201 ± 0.041	ratio: 0.622

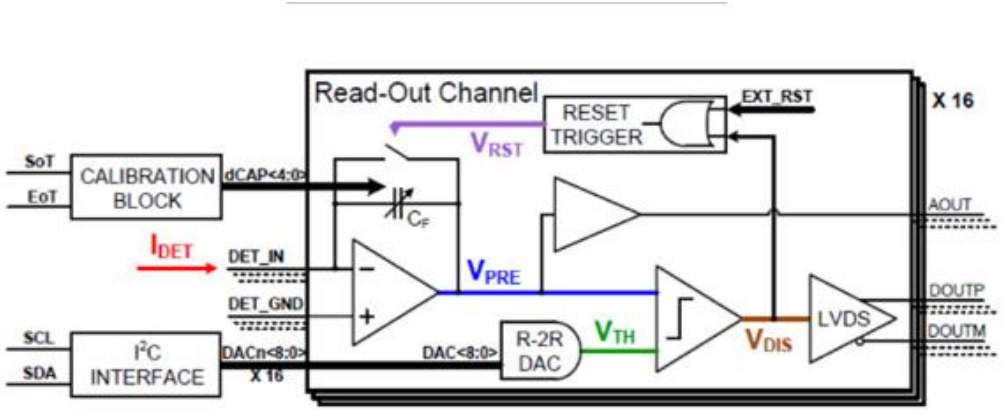
Caruggi, Federico, et al. "Performance of a triple GEM detector equipped with Al-GEM foils for X-rays detection." *Nuclear Instruments and Methods in Physics Research* 1047 (2023): 167855.

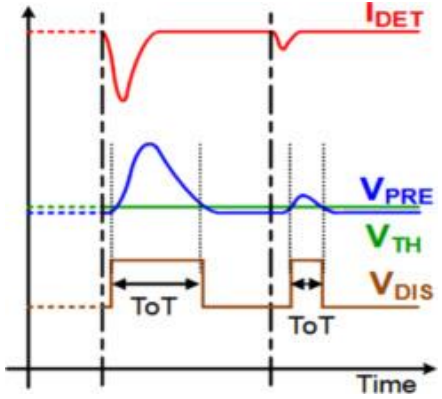
Gas Electron Multiplier detectors: Electronics

A compact Readout electronics composed by an Application Specific Integrated Circuit (ASIC) called GEMINI and a custom made FPGA.

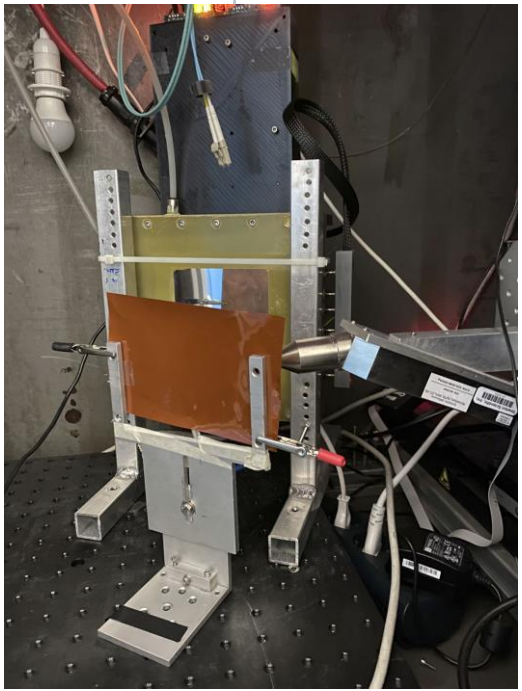
Each pixel is read by a single GEMINI channel, making the measure **asynchronous, in photon counting mode.** The energy information is retrieved by a **Time over Threshold** technique.

The time binning can be adapted to different event rates, the maximum event rate is **1 MHz per channel.**





Energy Calibration

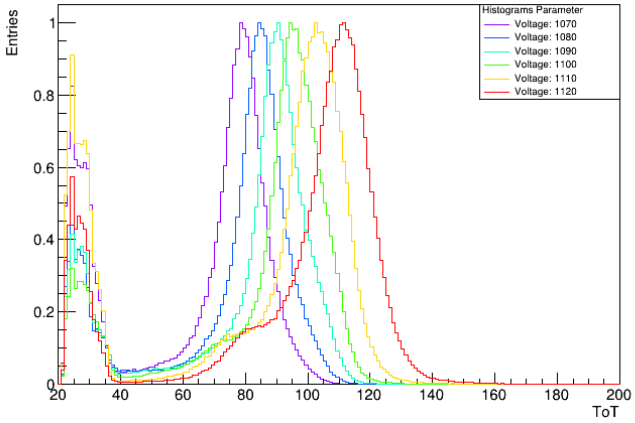


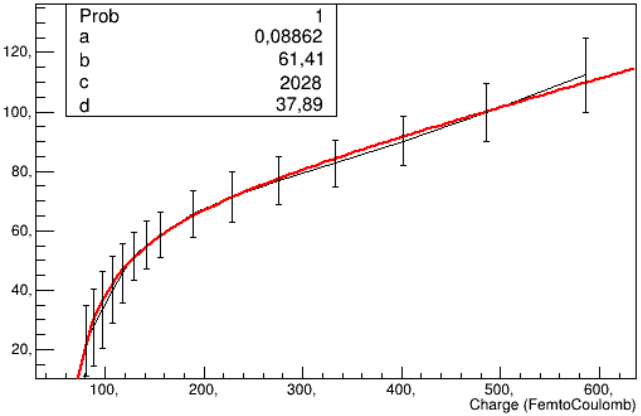
x data:

$$q(E) = Gain \cdot \frac{E}{W_i} \cdot 1.6 \cdot 10^{-19} C$$

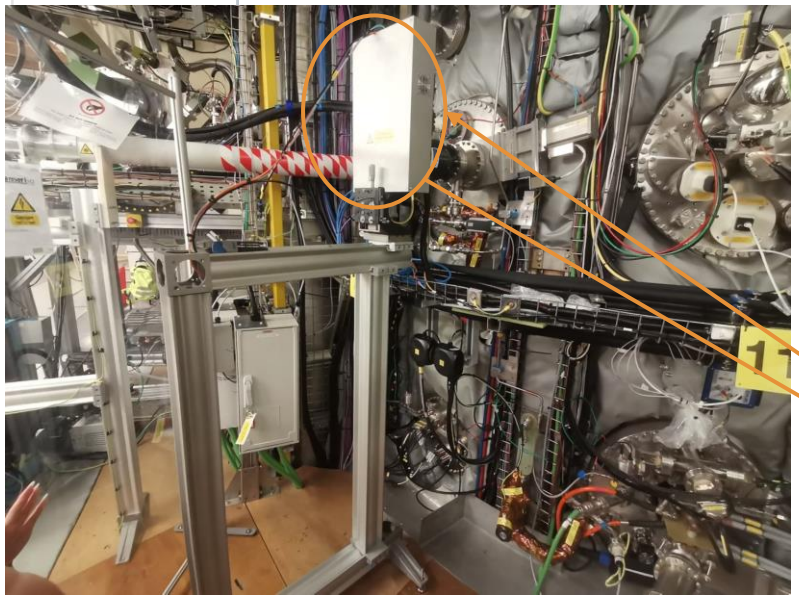
y data:

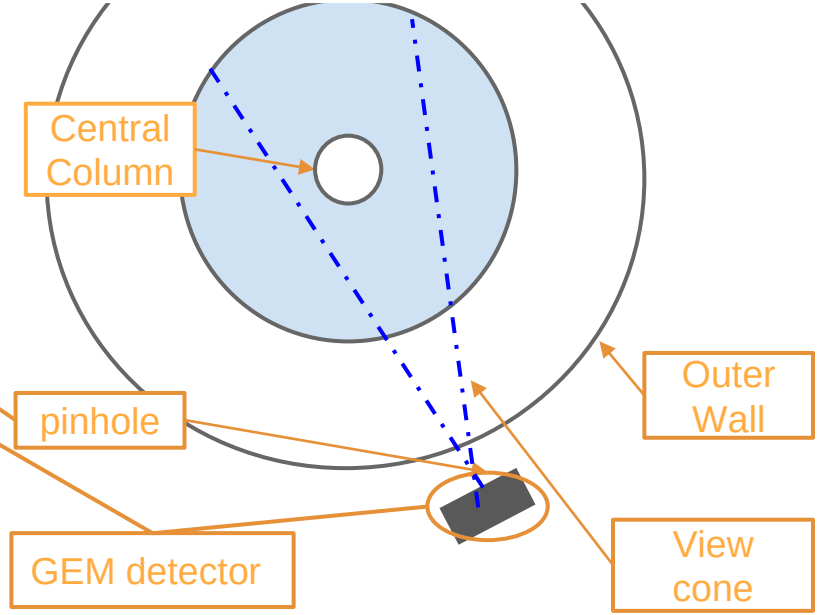
$$ToT\ (q) = a + b \cdot q - \frac{c}{q - d}$$





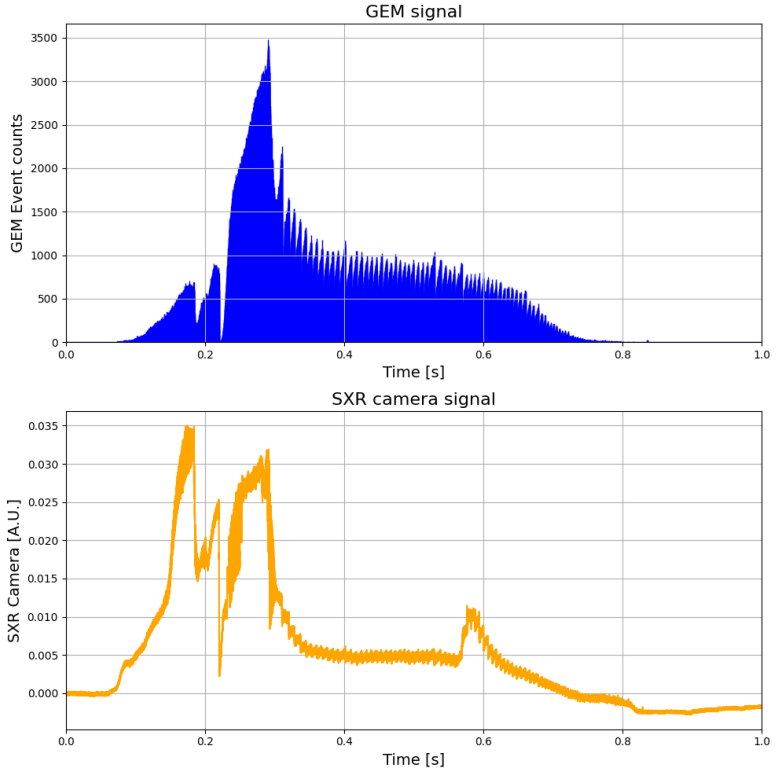
GEM diagnostic on MU03



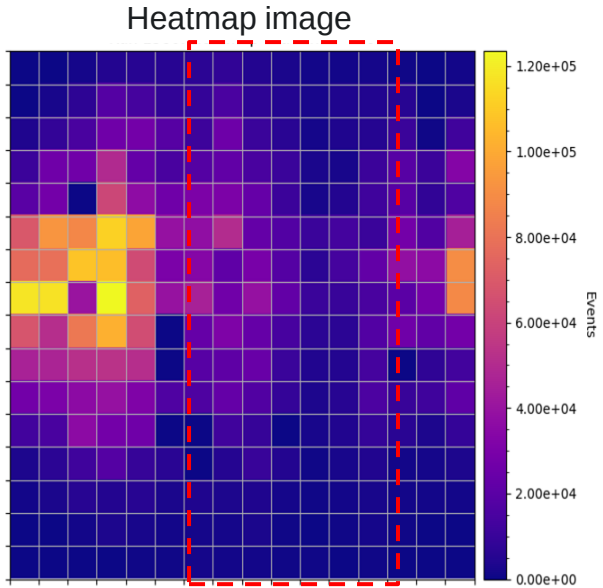


SXR timetrace and image

a)



b)



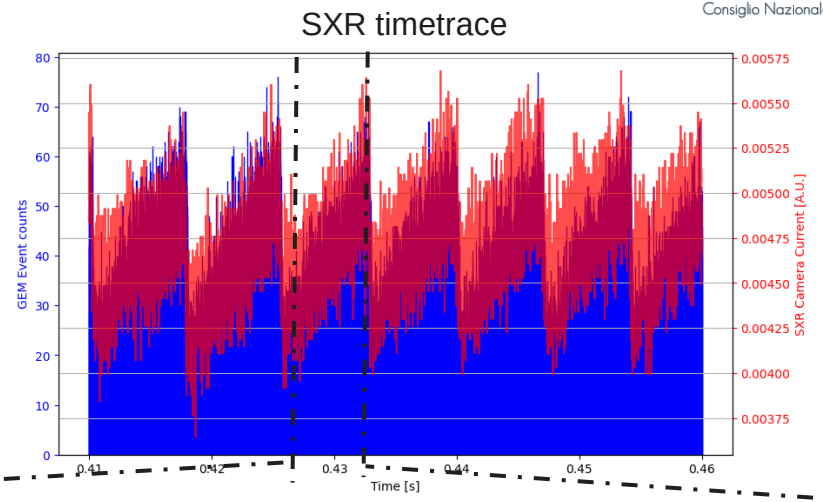
MASTU #49020:

a) SXR time trace comparison, GEM binning at 0,1 ms.
b) GEM global heatmap

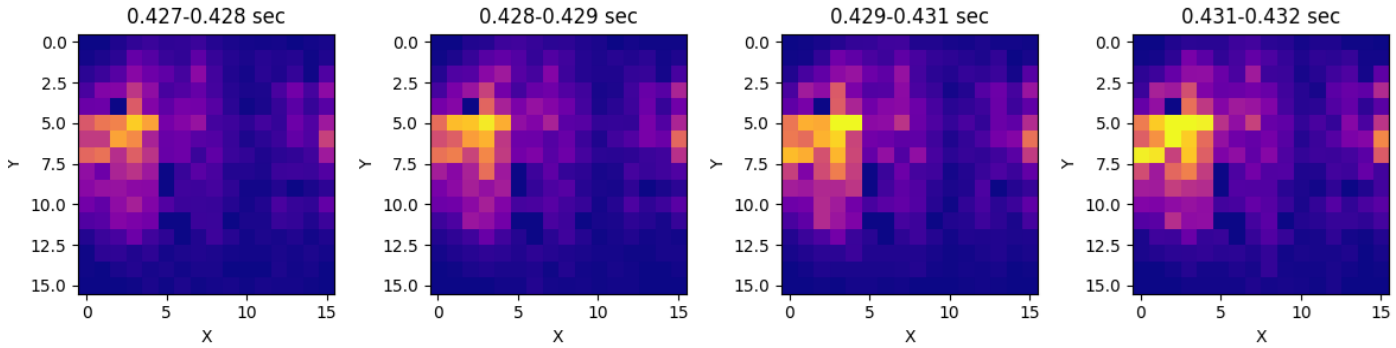
SAWTOOTH signal

Sawteeth crashes (@ 130 Hz) are clearly visible.

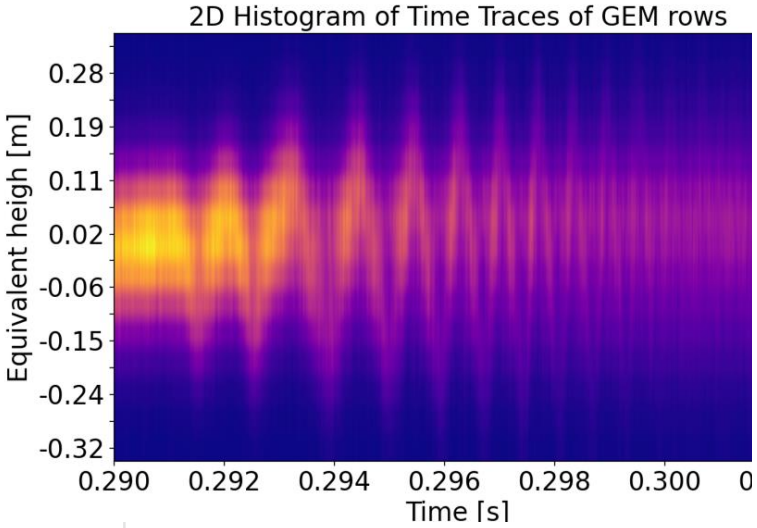
The GEM time binning is 5 microSecond.

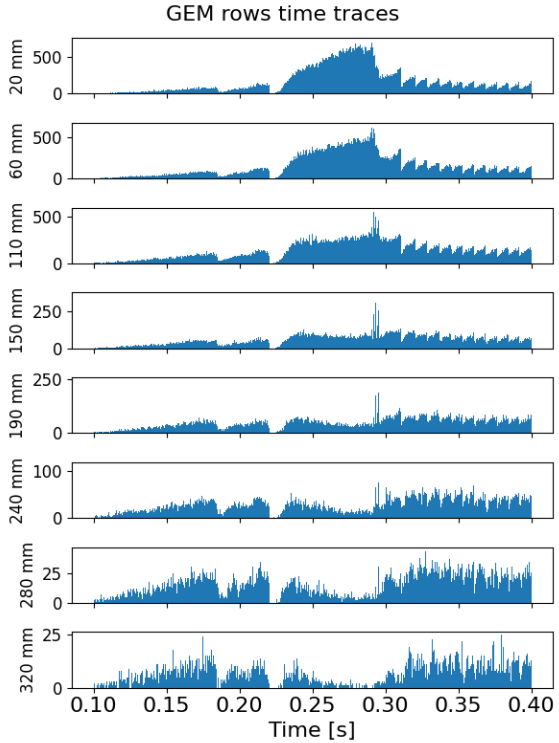


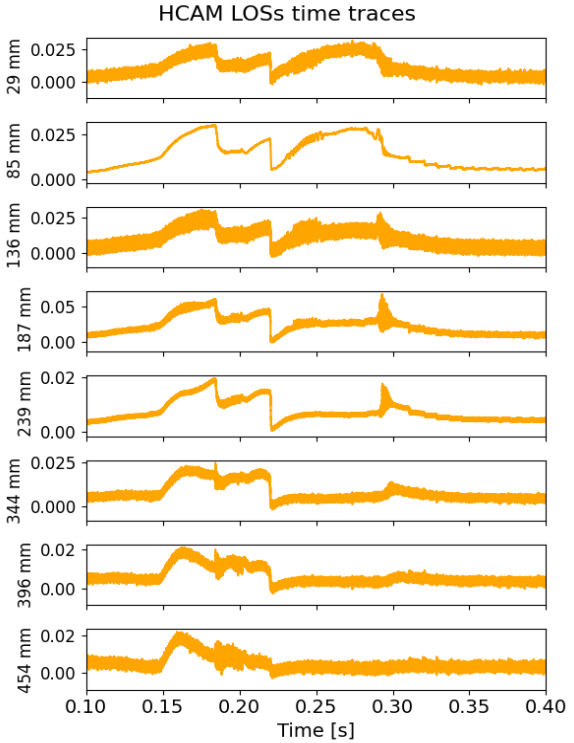
single ramp:



Localisation of a Snake Instability







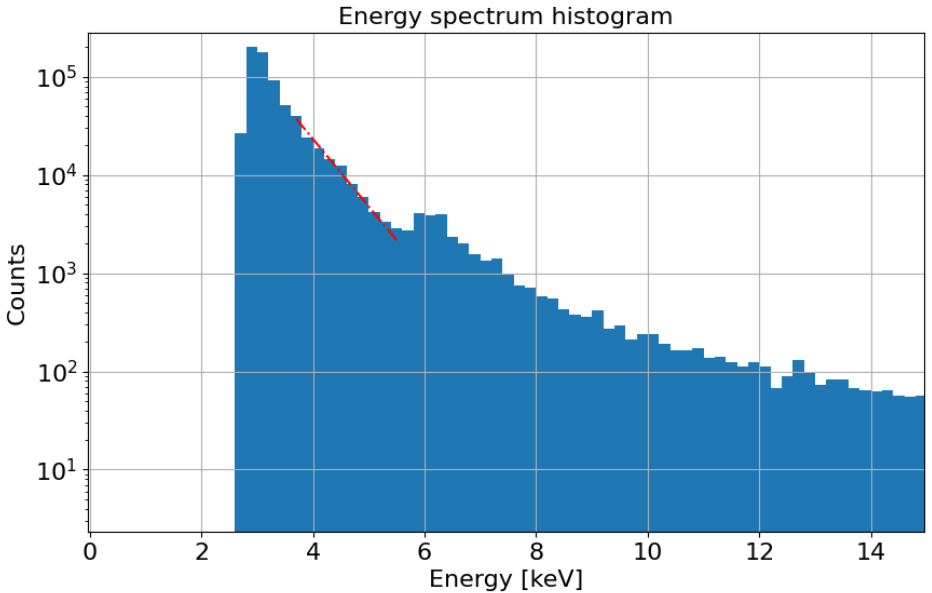
MAST-U #49020:
time binning 0.01 ms.

Spectroscopic capabilities: the Spectrum

Ohmic shot #49020.

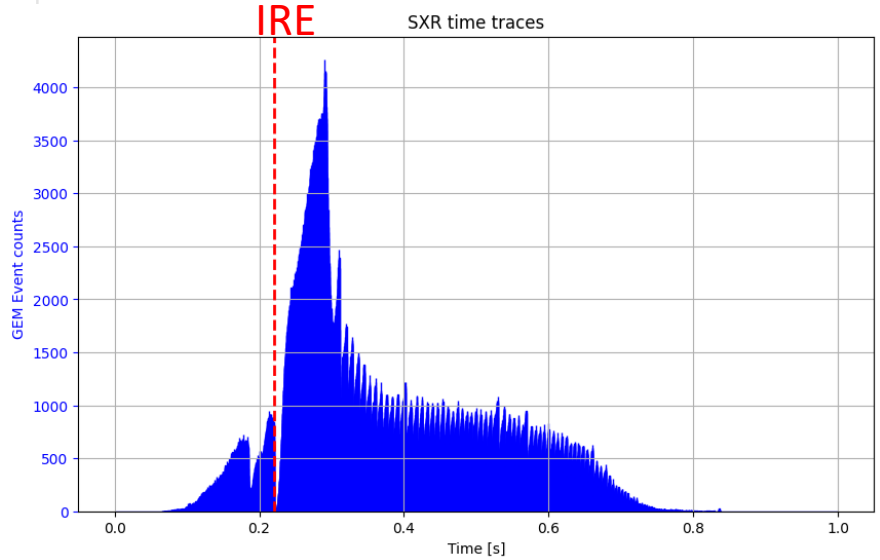
Example of a GEM Energy spectrum integrate over the
full pulse and over the entire camera.

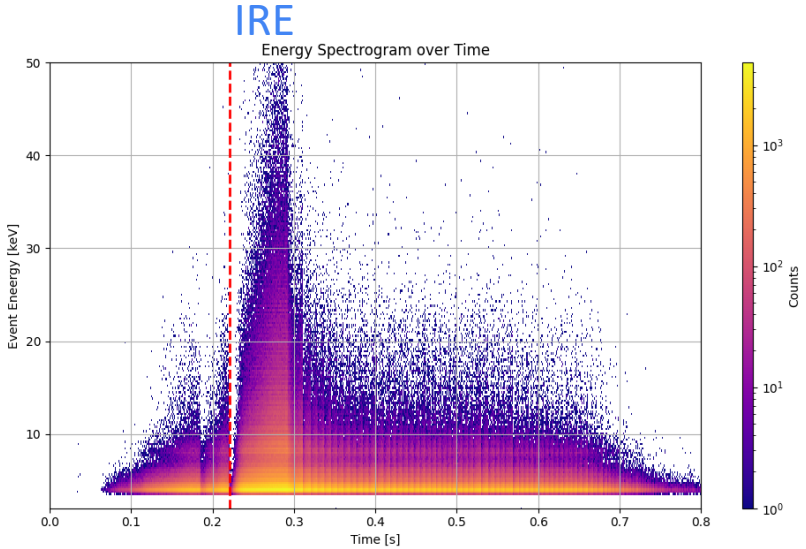
Example of exponential fit in the region 3.2 - 5.5 keV.



IRE and electron acceleration

The IRE is characterized by a collapse in the SXR signal, followed by a temporary Electric Field that accelerate the electrons, clearly visible in both the GEM timetrace and Energy spectrogram.





MAST-U #49020:
time binning 1ms.

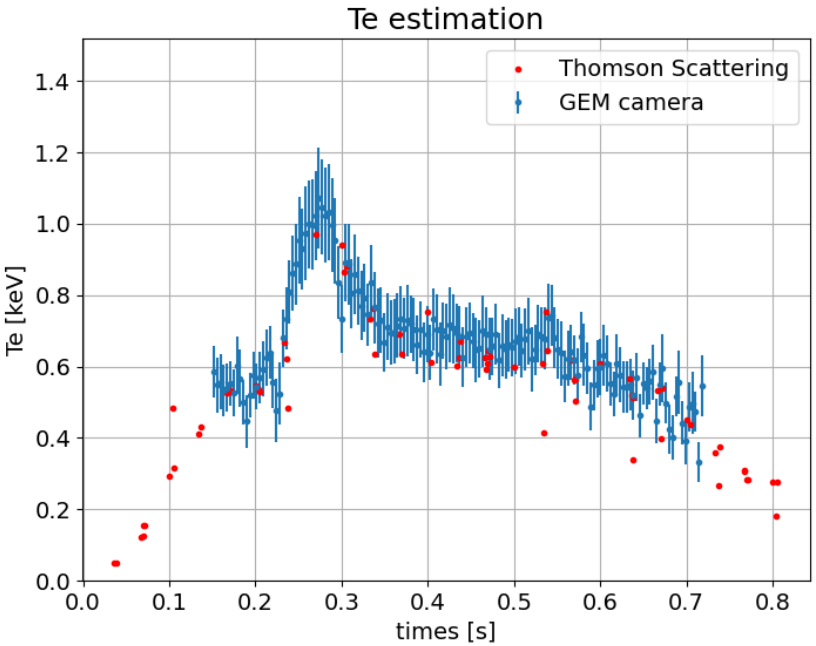
A. CELORA A. MURARO, G.CROCI et Al.

Spectroscopic capabilities: Te estimation

Assumption:

- Maxwellian plasma.
- No additional feature in the fitting range.

$$f(E) = \frac{1}{\sqrt{\pi(kT)^3}} \cdot \sqrt{\frac{E}{m}} \cdot e^{-\frac{E}{kT}}$$



MAST-U #49020:
time binning 1ms.

Thank you