ISTITUTO
PER LA SCIENZA
E TECNOLOGIA
DEI PLASMI
Consiglio Nazionale delle Ricerche

Exploitation of a Soft X-Ray 2D triple GEM detector at the MASTU spherical tokamak

Agostino Celora
Andrea Muraro
Federico Caruggi
Gabriele Croci
ISTP team

Rory Scannel
Luca Garzotti

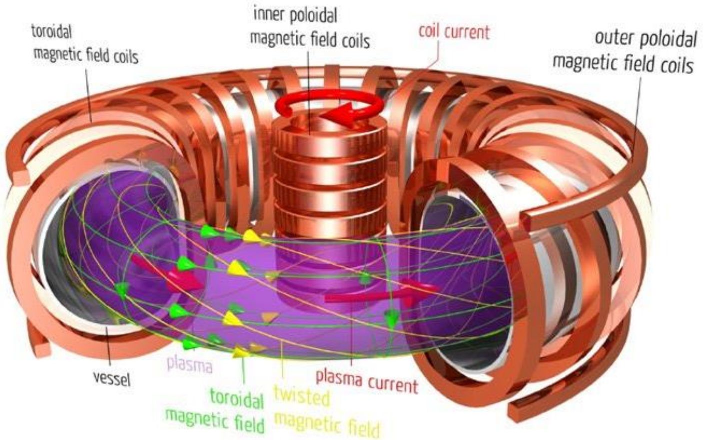
MAST-U team

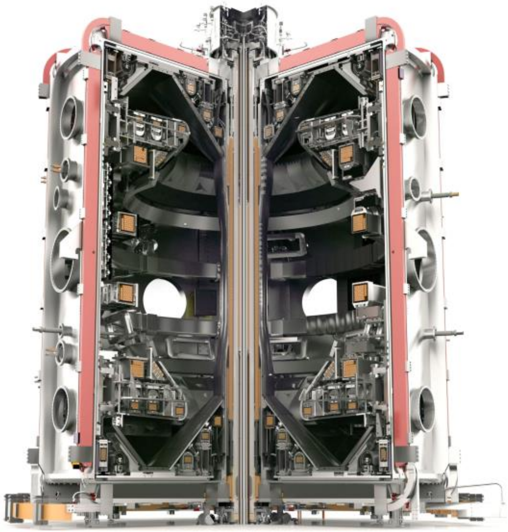
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
EUROfusion
CCFE CULHAM CENTRE FOR FUSION ENERGY
USTC HEFEI 2024

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 the vessel.





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?

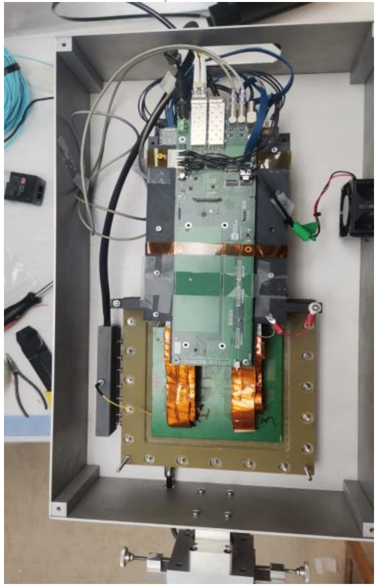
Emitted due to interactions within the plasma, mainly two types:

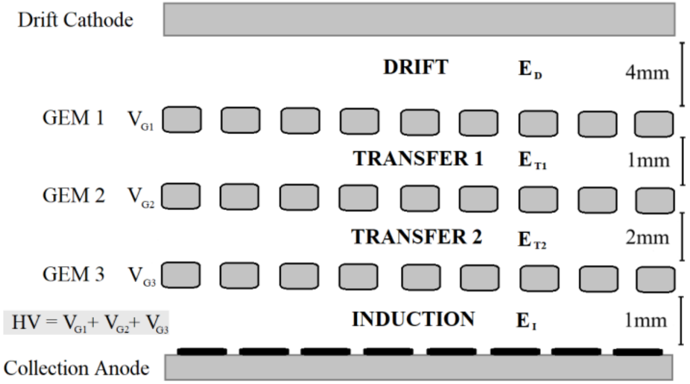
1. **Bremsstrahlung**: $\epsilon(R,\lambda) \propto \lambda^{-1} Z_{eff}(R) \cdot n_e^2(R) \cdot T_e^{-1/2} exp\left[\frac{-hc}{\lambda T_e(R)}\right]$

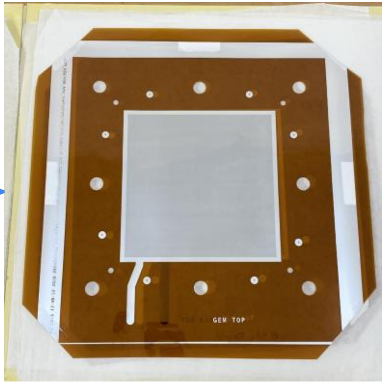
   it is one of the main energy loss channels.

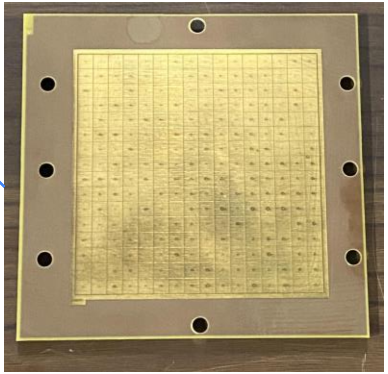
1. line transition: the radiative decay of an excited atomic state of a bound electron into a lower energy level. the contribution of line emission is given by **medium and heavy impurities**.

Gas Electron Multiplier detectors for SXR



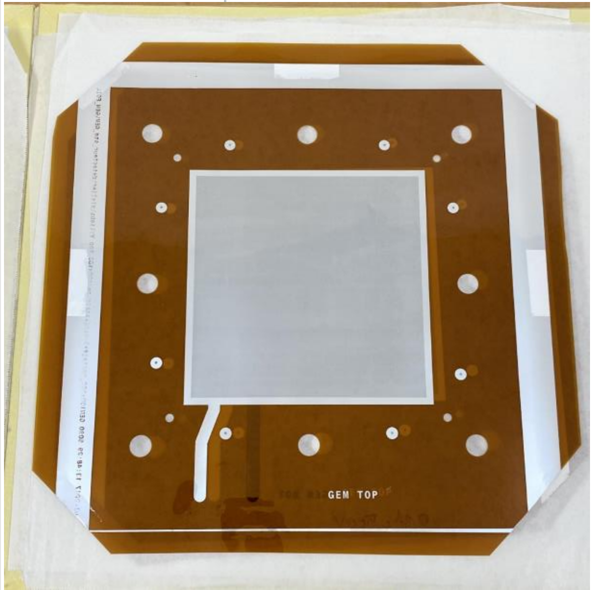


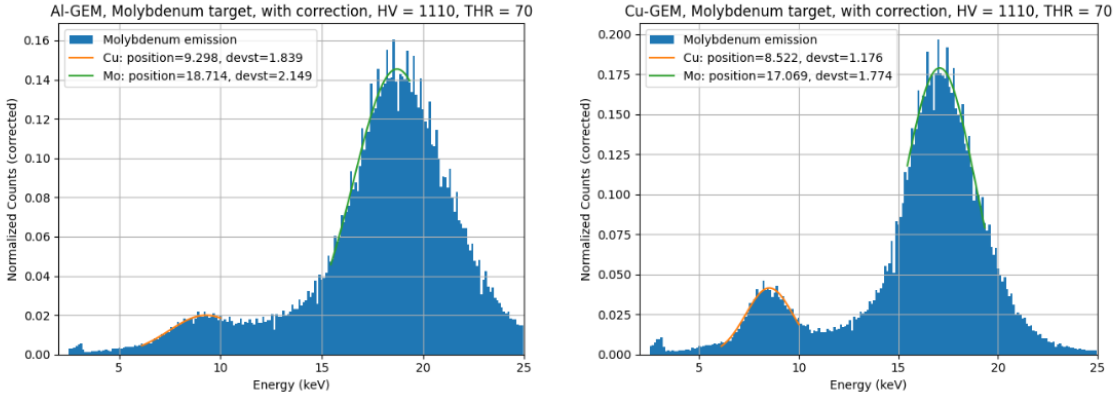




- Triple GEM configuration.
- Ar-Co2 mixture 70%-30%.
- Aluminum GEM.
- 1 MHz per pixel.
- 16 x 16 Pixel, 6mm x 6mm .

Aluminum GEM





(a) Al-GEM molybdenum target, corrected

(b) Cu-GEM molybdenum target, corrected

Quantity	Al-GEM	Cu-GEM	
$K_{\alpha,\mathrm{Mo}}/K_{\alpha,\mathrm{Cu}}$	2.367 ± 0.543	2.045 ± 0.261	Expected value: 2.161
$I_{peak,\mathrm{Cu}}/I_{peak,\mathrm{Mo}}$	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

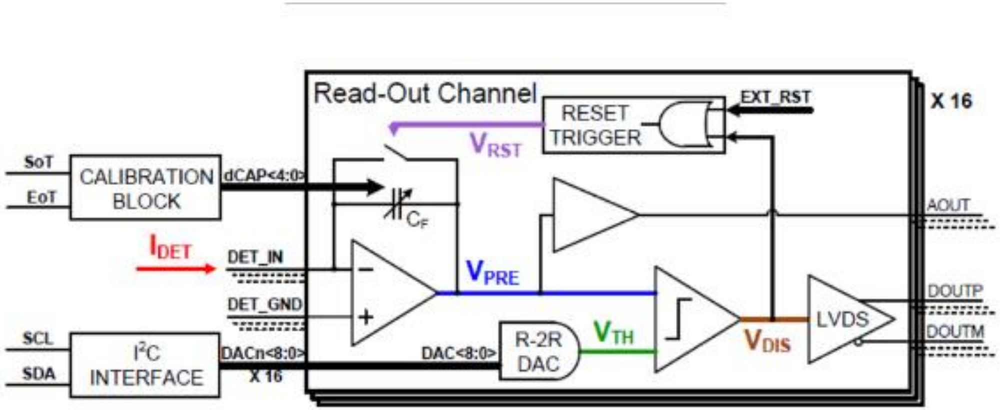
Caruggi, Federico, et al. "Performance of a triple GEM detector equipped with Al-GEM foils for X-rays detection." *Nuclear Instruments and Methods in Physics Research* 1047 (2023): 167855.

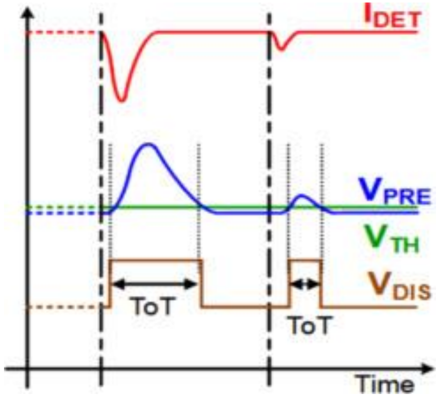
Gas Electron Multiplier detectors: Electronics

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

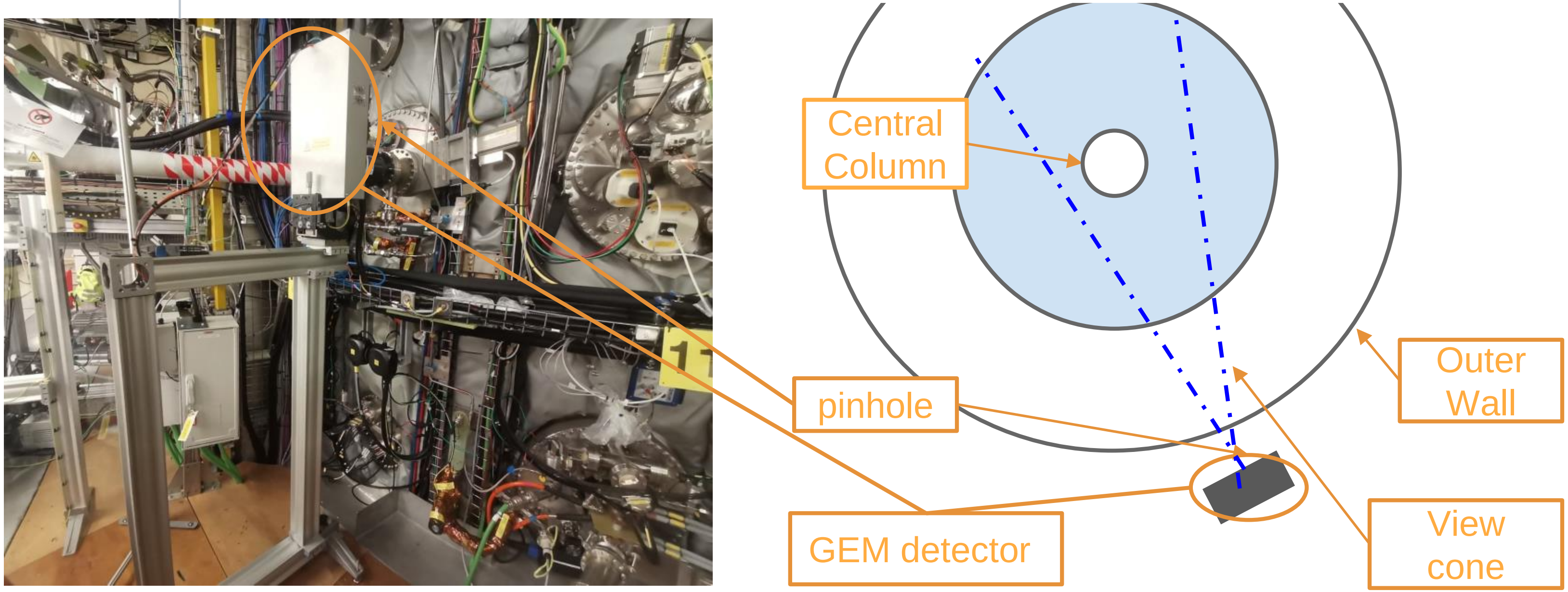
Each pixel is read by a single GEMINI channel, making the measure **asynchronous, in photon counting mode.** The energy information is retrieved by a **Time over Threshold** technique.

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



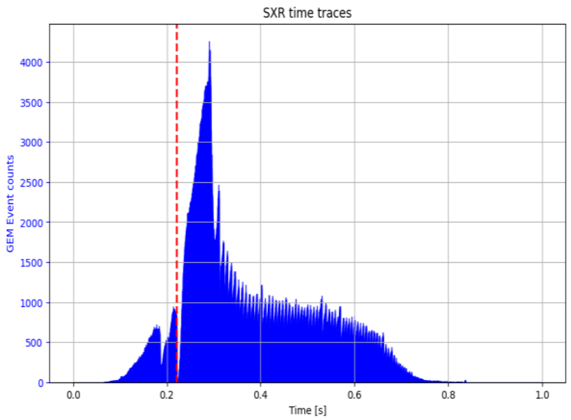


GEM diagnostic on MU03

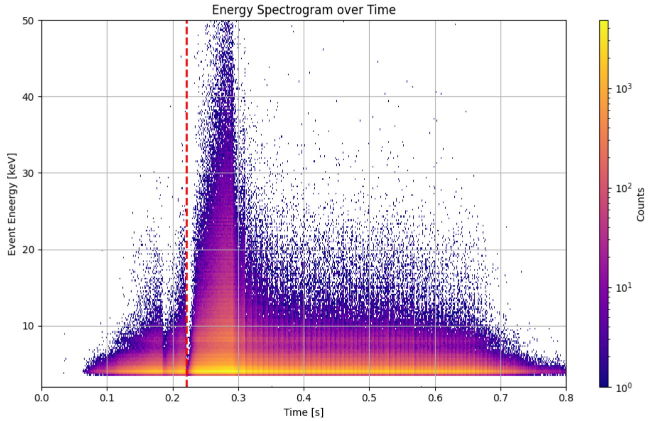


SXR timetrace and image

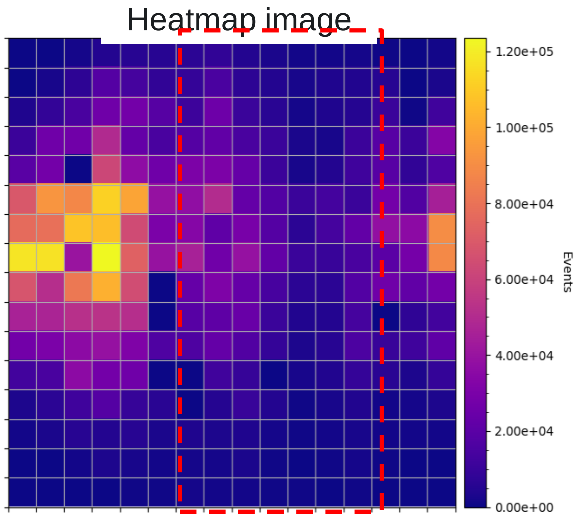
a)



c)



b)

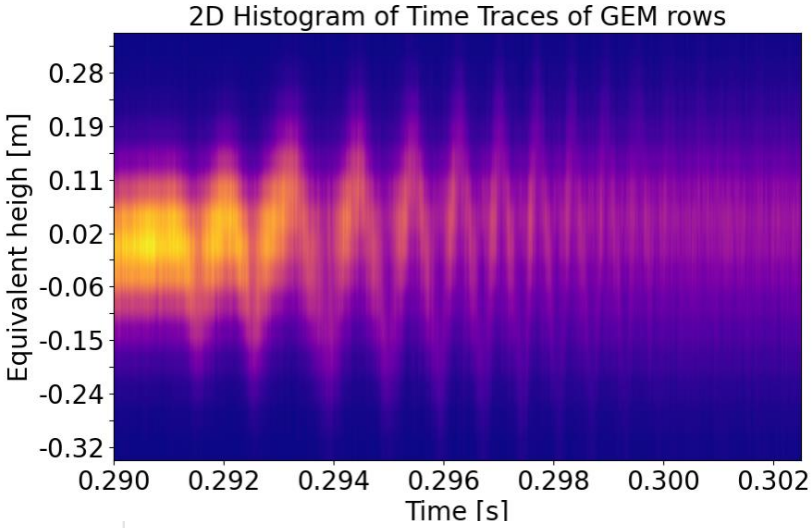


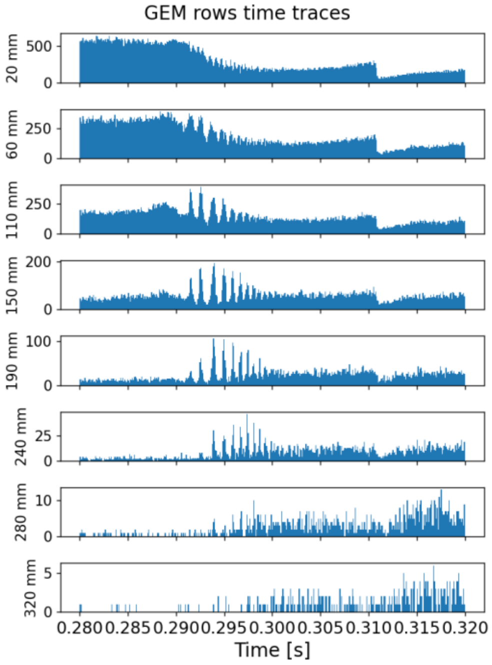
central solenoid projection

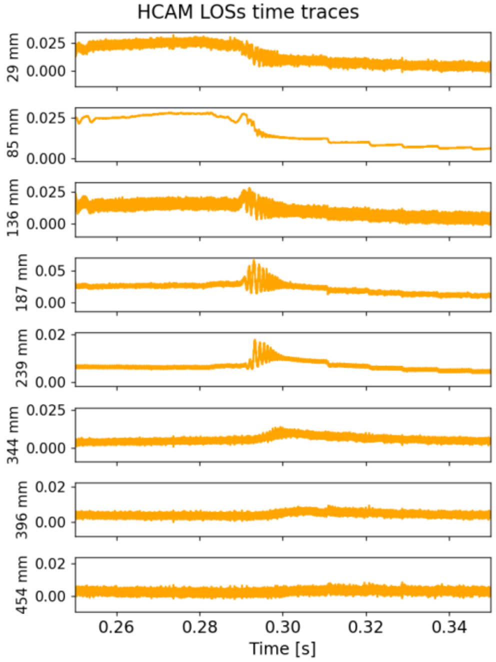
MASTU #49020:

a) SXR time trace, GEM binning at 0,1 ms.
b) GEM global heatmap.
c) Energy spectrogram, GEM binning at 0.1ms.

Localisation of a Snake Instability







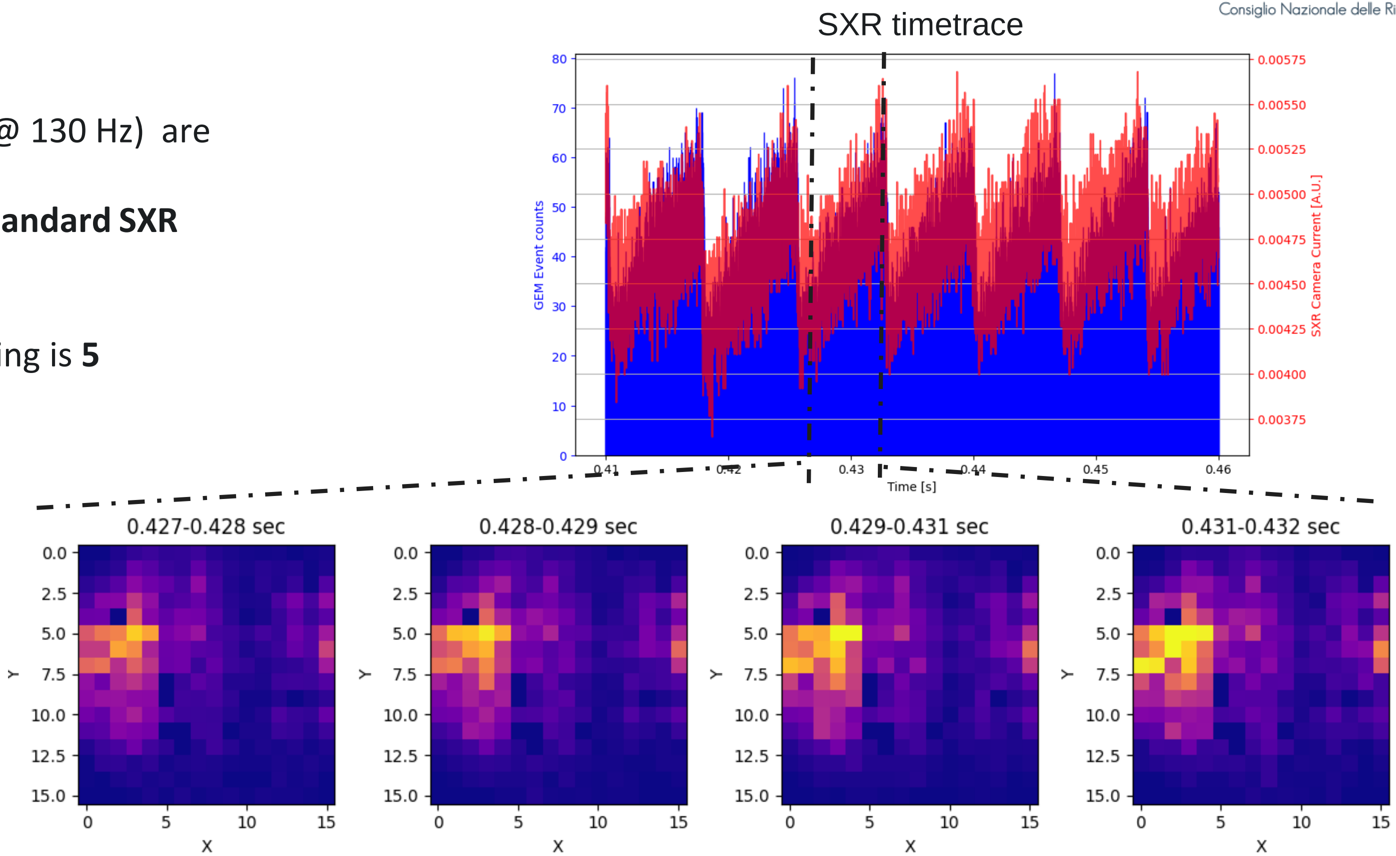
MAST-U #49020:
time binning 0.01 ms.

SAWTOOTH signal

Sawteeth crashes (@ 130 Hz) are clearly visible.
Clear **match with standard SXR diagnostic**.

The GEM time binning is **5 microSecond**.

single ramp:

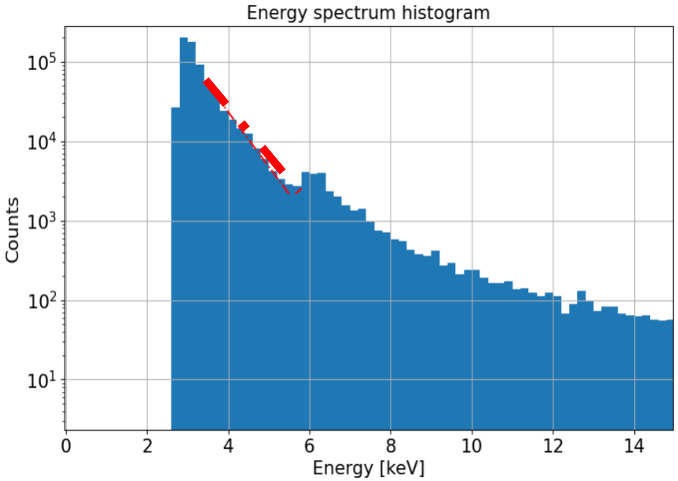


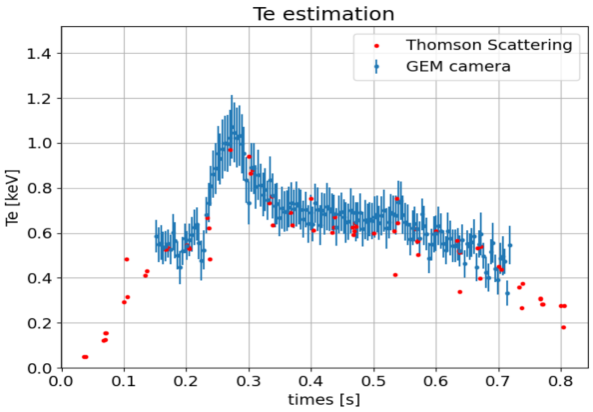
Spectroscopic capabilities: the Spectrum

Ohmic shot #49020.

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.





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

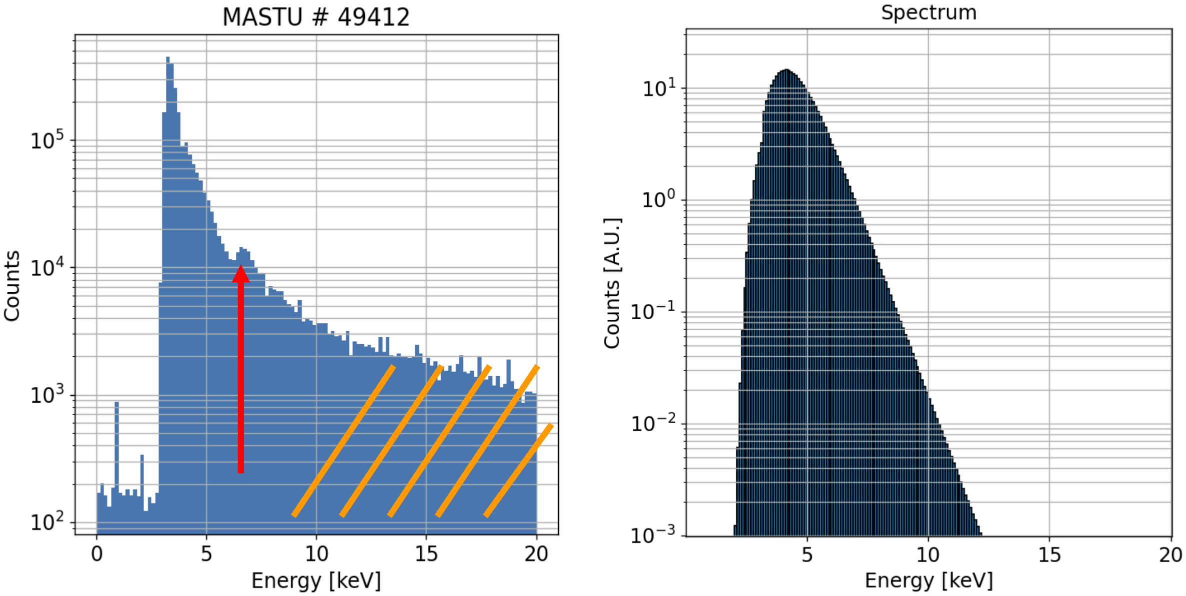
Good correspondence with standard diagnostic (Thomson Scattering) estimations.

Analysis of GEM Energy Spectrum

The acquired spectrum exhibits deviations from the simulated spectrum, revealing **non-idealities** that must be addressed to fully utilize the detected energy range. The key issues identified are:

- A secondary peak
- A high-energy tail

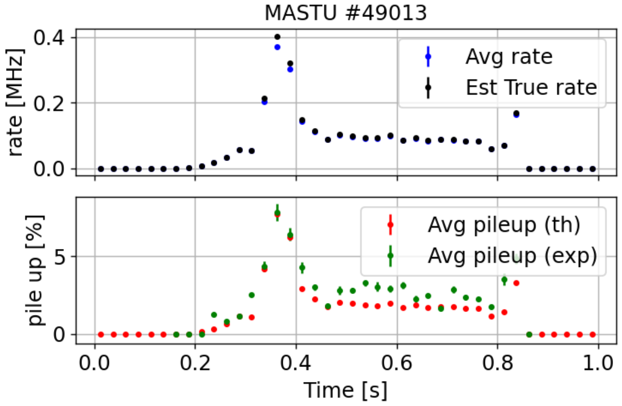
Investigating the causes and potential mitigation strategies for these discrepancies is essential.

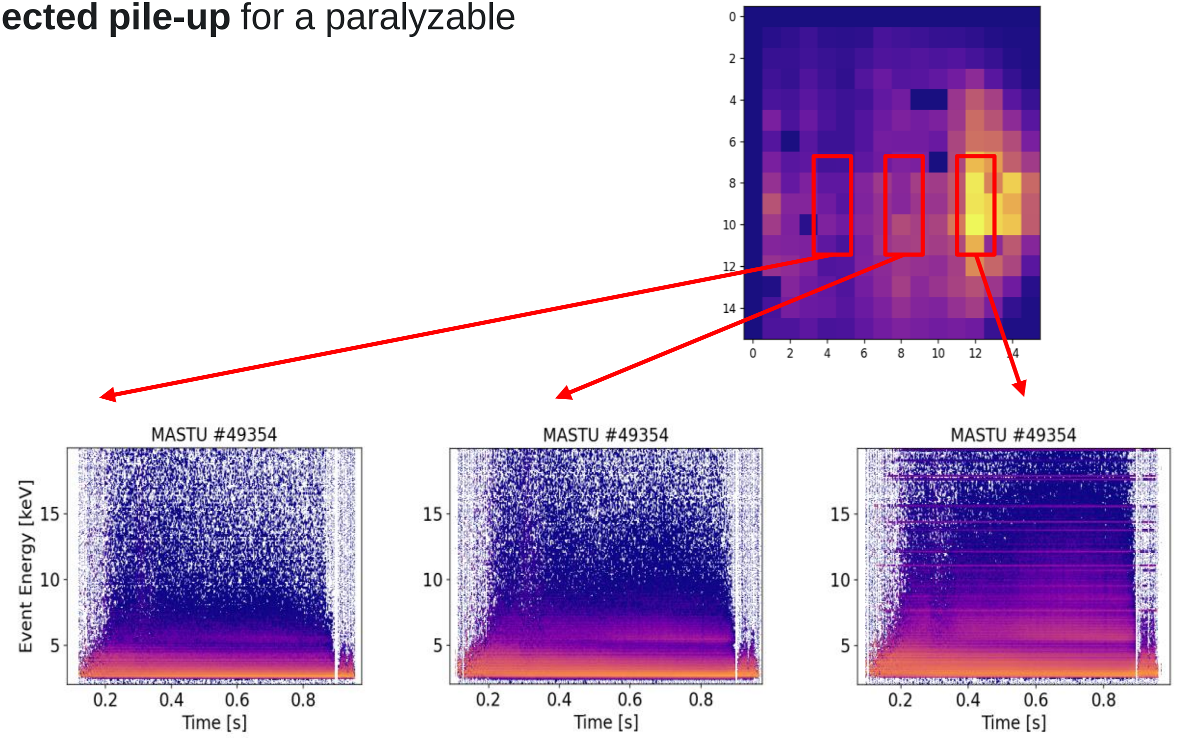


A. CELORA A. MURARO, G.CROCI et Al.

Pile-Up analysis

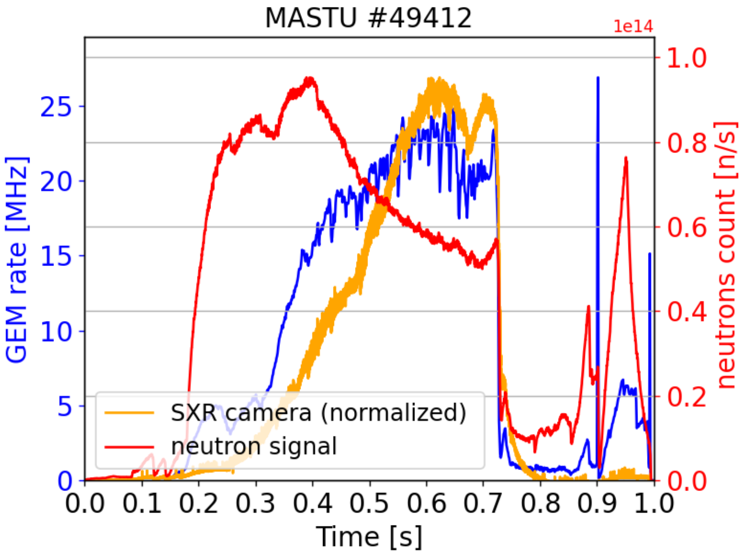
The presence of Pile-up is studied both qualitative and quantitative. with a **comparison with the expected pile-up** for a paralyzable detector with a signal of 150 ns.

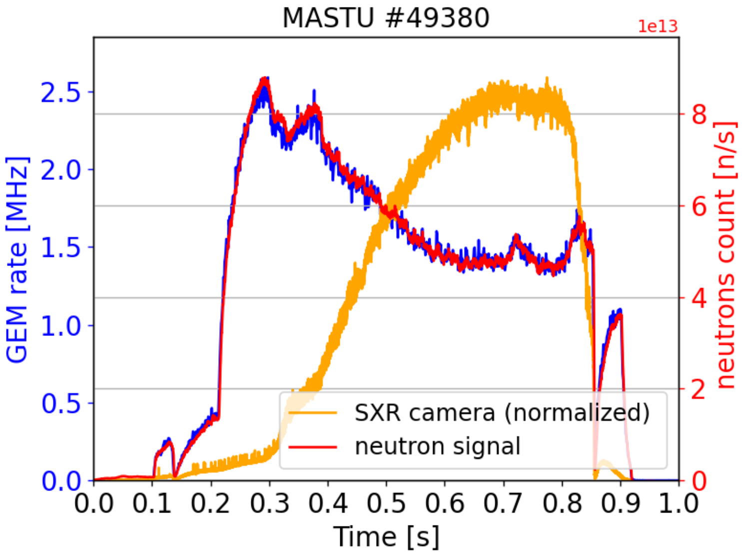




Neutron background

1. gate open = direct neutrons + gammas + SXR.
2. gate closed = direct neutrons + gammas.



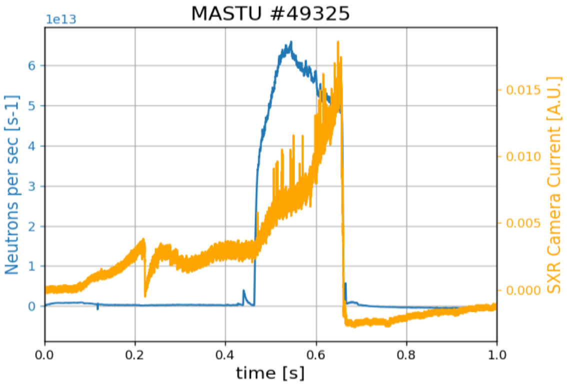


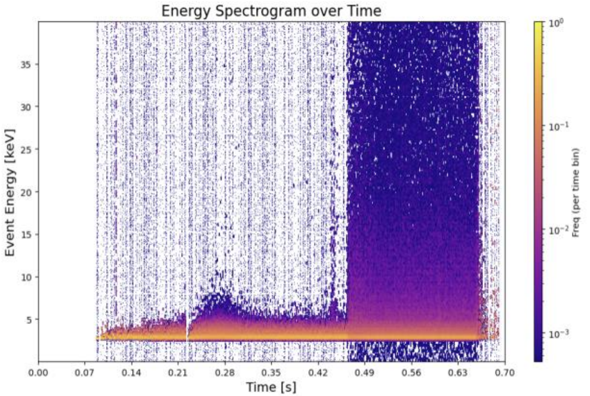
Neutron Background: differences between Ohmic & NBI shots

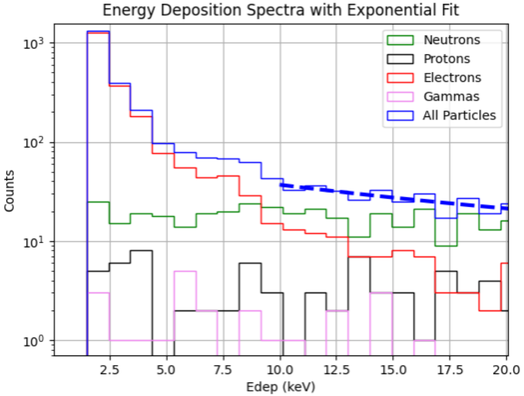
The shot #49325 shows an **transition** at 0.46s **to high performance plasma state** (LH transition).

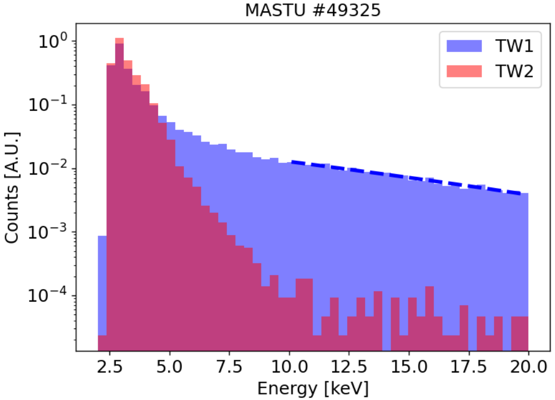
It implies a s**udden rise in the neutron flux**.

It is possible to observe clearly the influence of neutrons on the GEM signal.









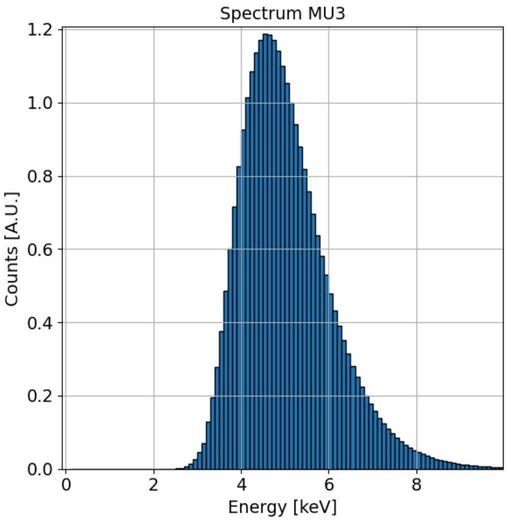
Neutron background mitigation

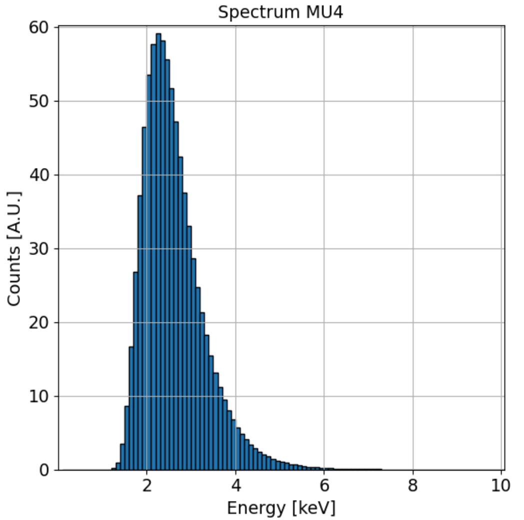
Design Upgrades are planned to optimize the set-up:

1. **Detector gas** mix from ArCO2 to **NeCO2**.
2. Apply an **Helium buffer** in front of the GEM.
3. Utilize **smaller pads**.
4. Utilize a **smaller aperture** in front of the pinhole.
5. Switch to a tangential point of View.

Expected results:

1. **Higher SNR ratio**: *up to 2 order of magnitude*.
2. **Reduction of pileup**.
3. Signal starting from <2 keV.
4. Study Argon impurities in the tokamak.

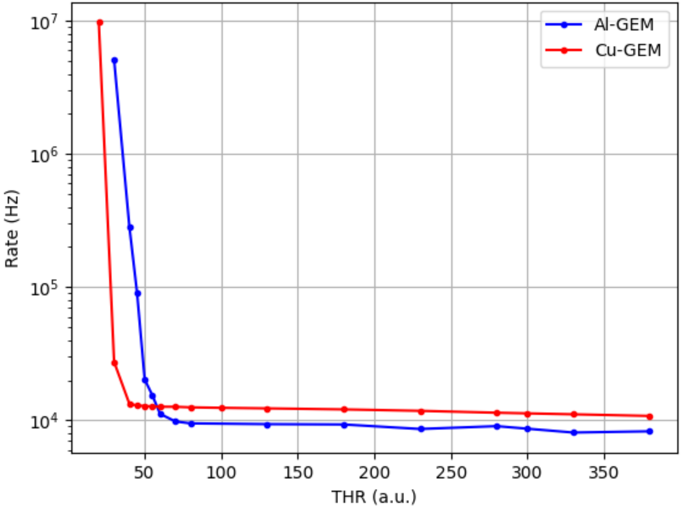




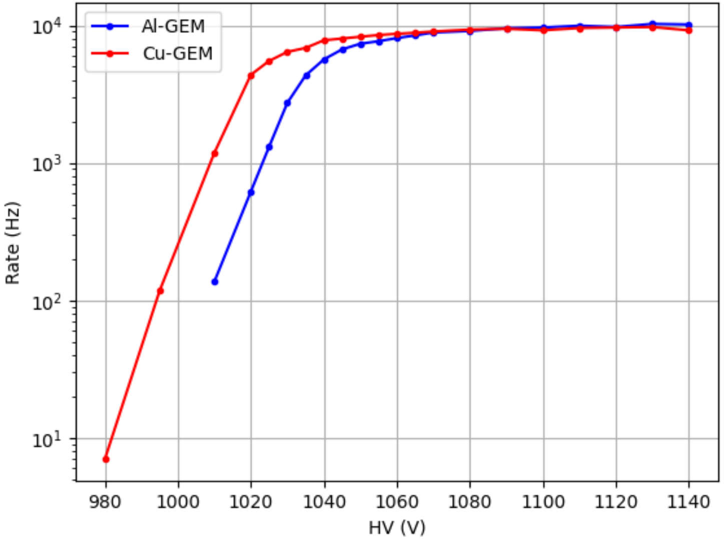
Thank you

Al GEM working point: Threshold and Voltage scan

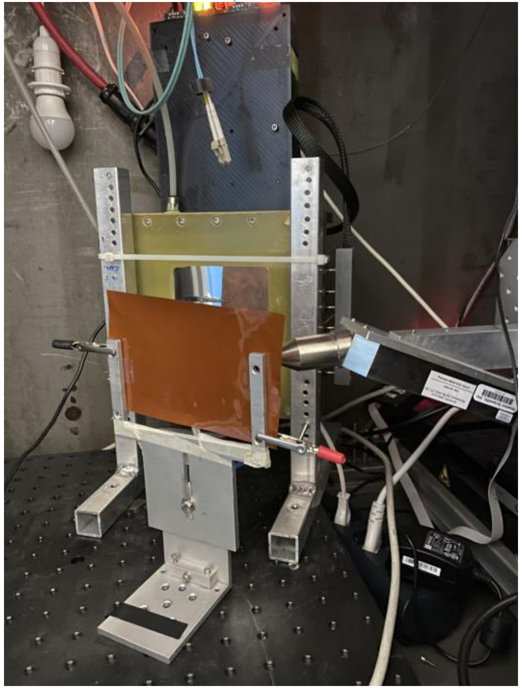
Threshold scan



Voltage scan



Energy Calibration

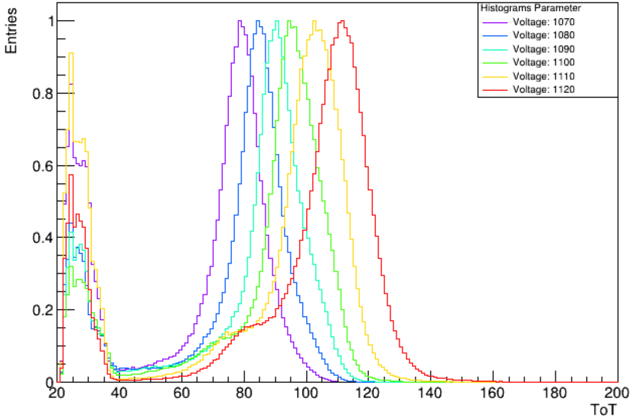


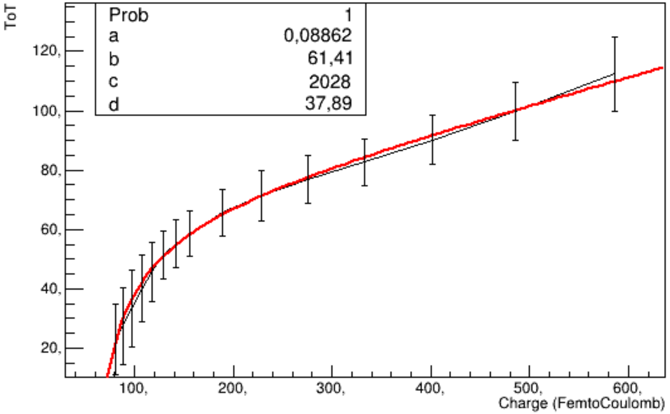
x data:

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

y data:

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



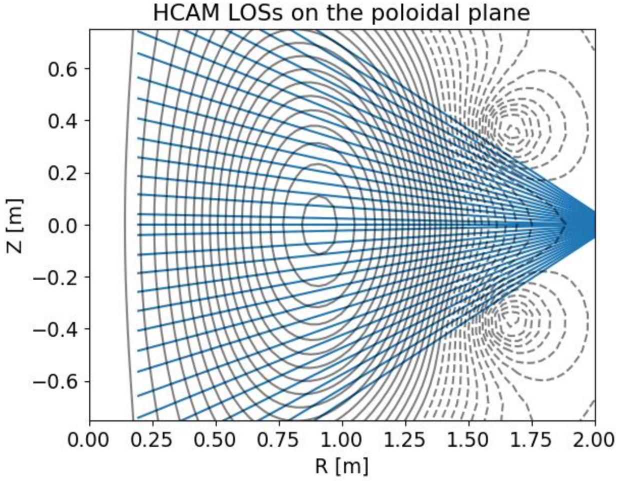


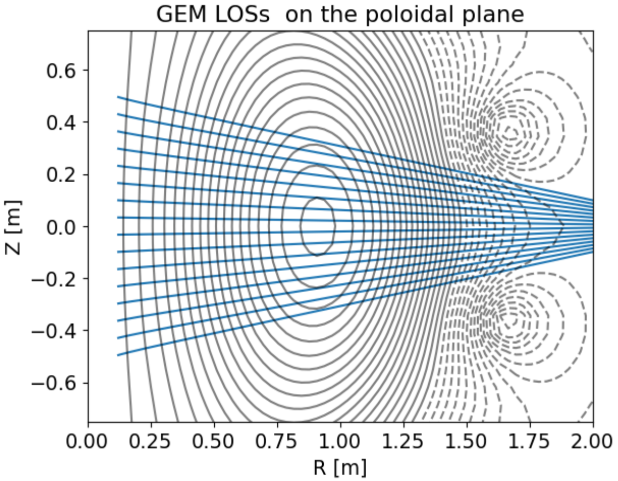
Comparison with MAST-U Horizontal Camera

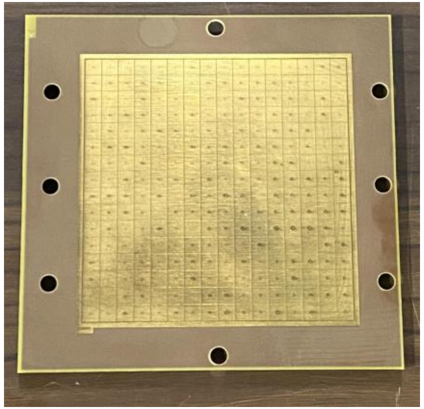
The differences:

- GEM camera has a smaller number of LOSs and plasma coverage compared to the horizontal camera.
- The horizontal camera signal is a current signal over time, the GEM camera allows photon counting.
- The horizontal camera's Beryllium foil is 12.5μm thick, resulting in an energy cut-off at 1keV. The GEM camera's Beryllium foil is 25μm t

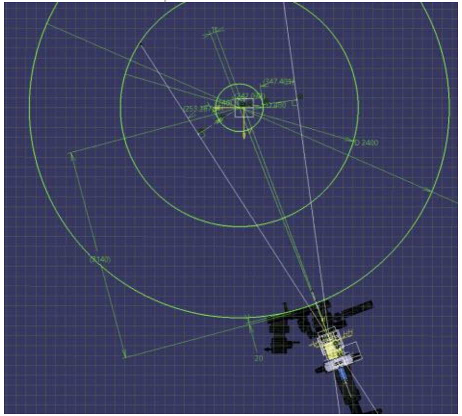
nse,

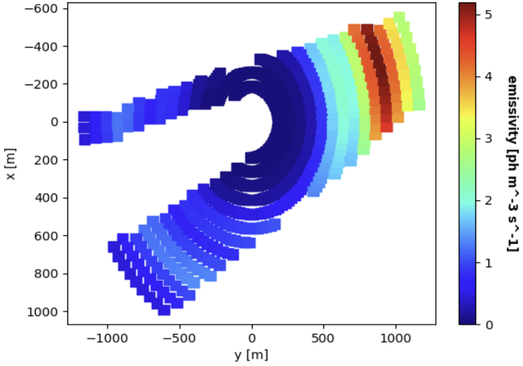




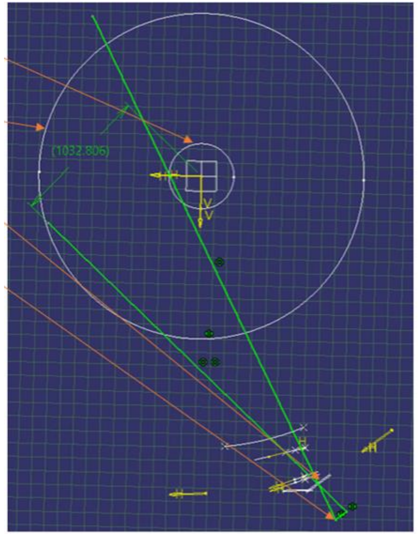


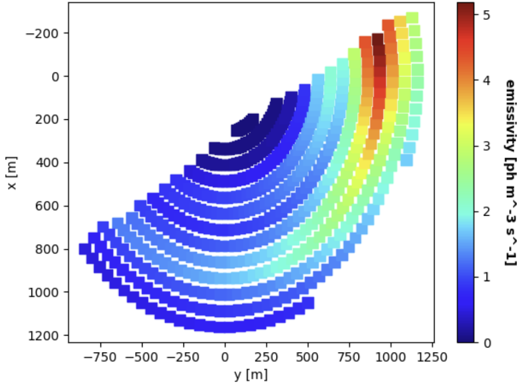
LoS Optimization: The view cone





Emissivity in the x-y plane at fixed Z = -37.5

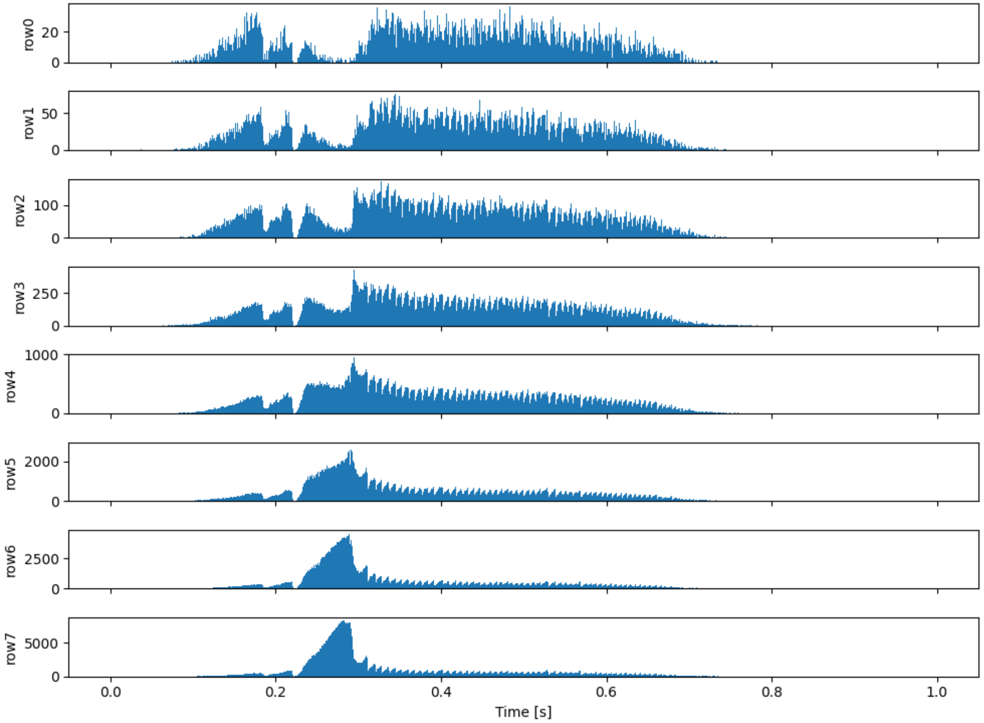




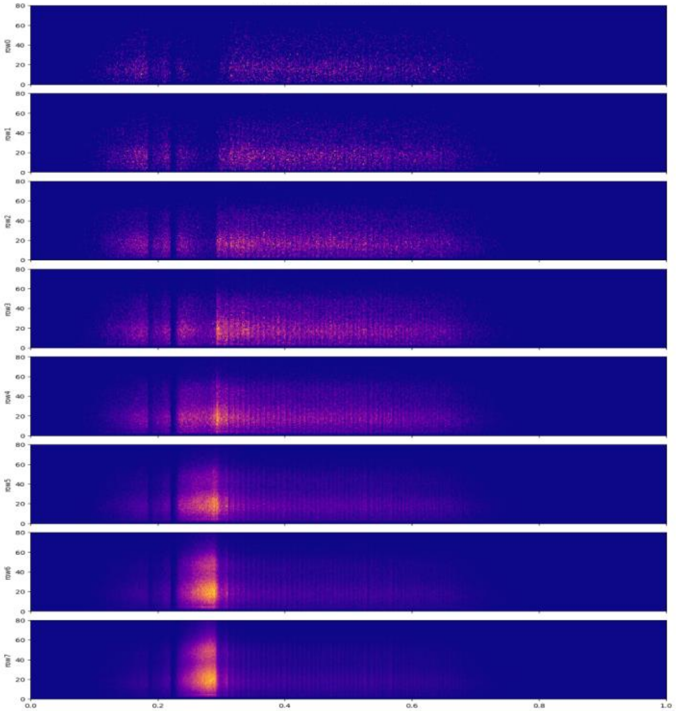
Emissivity in the x-y plane at fixed Z = -37.5

IRE Localization: the Energy spectrogram

timetrace for different LoS



Energy spectrogram for different LoS



shot #49020:

Neutron background

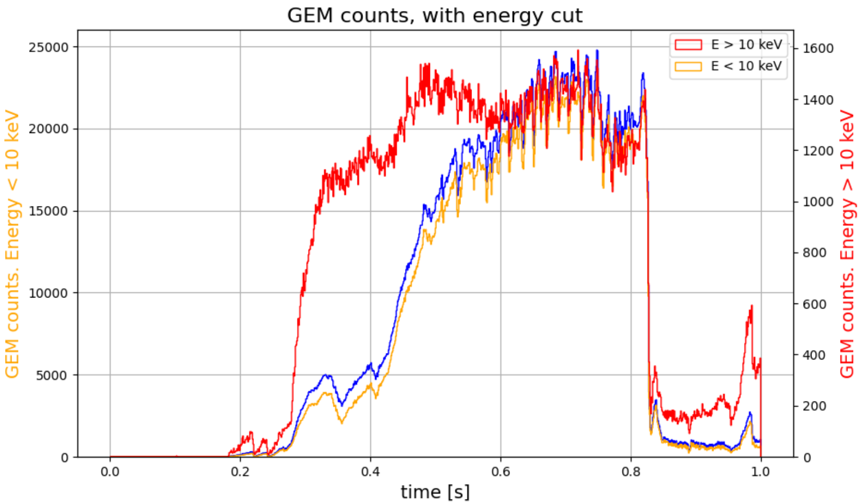
Performing an energy cut on the GEM signal, for a double beam shot, the signal trend, in orange, can follow either:

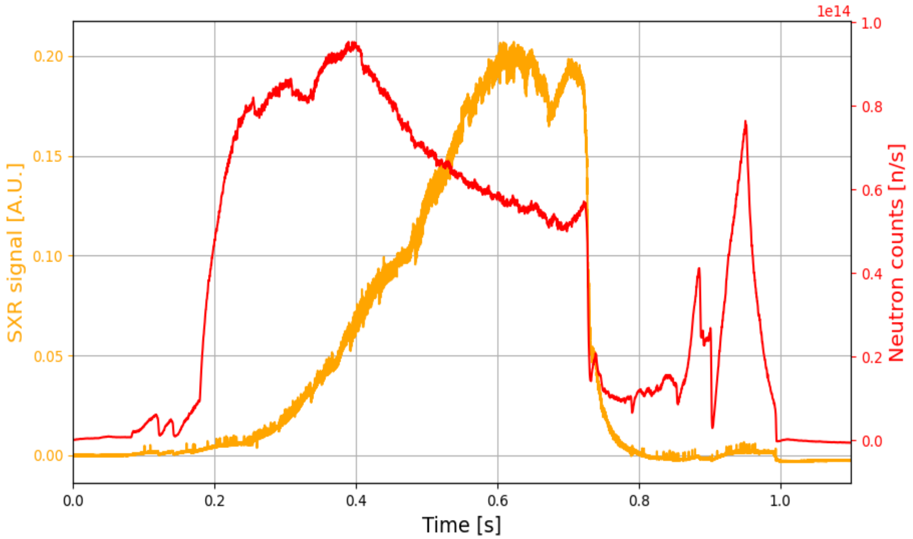
the SXR core signal from the MAST-U camera for Energies < 10 keV,

or

the neutron counting camera, in red, for Energies > 10 keV.

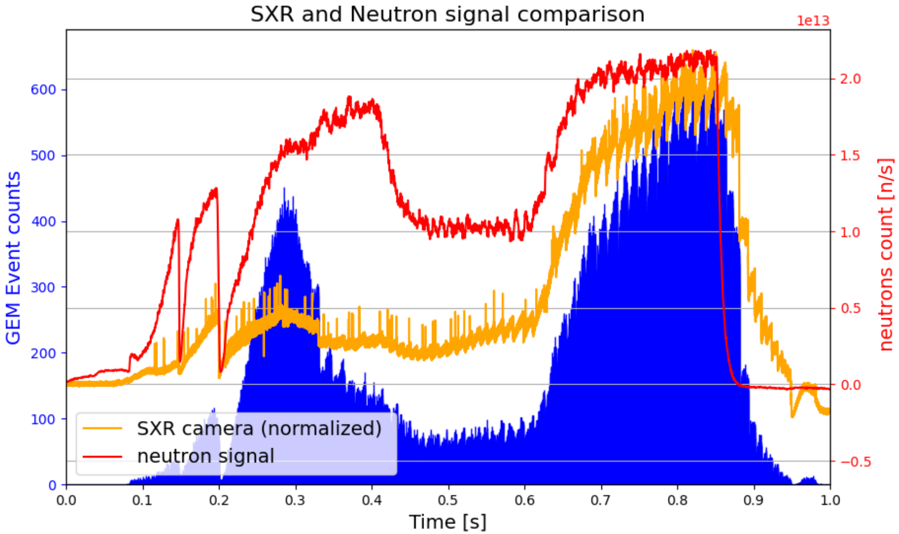
Neutron background estimated between 1-10%

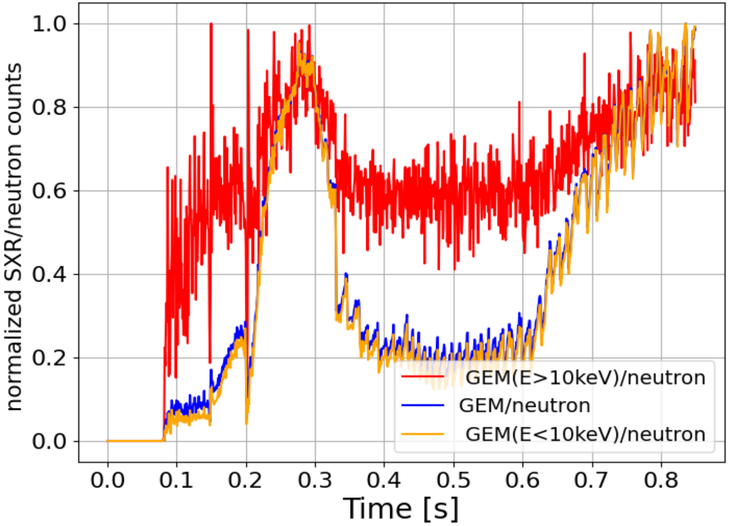




MASTU #49412

SXR vx NEUTRON: post IRE peak





The peak in the GEM SXR signal is given by an effective peak of the SXR signal:

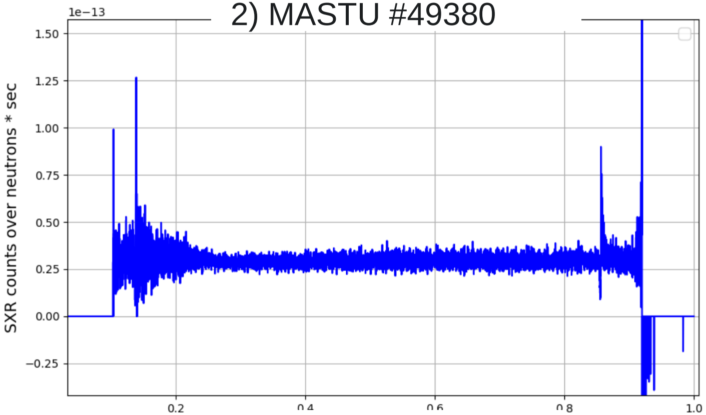
- the SXR/Neutron timetrace shows a peak post IRE
- the low energy side of the signal shows a peak, but the high energy signal peak is one third .

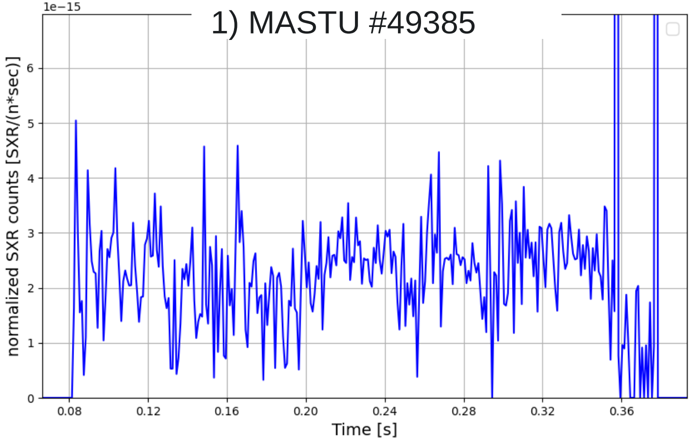
MASTU #49452

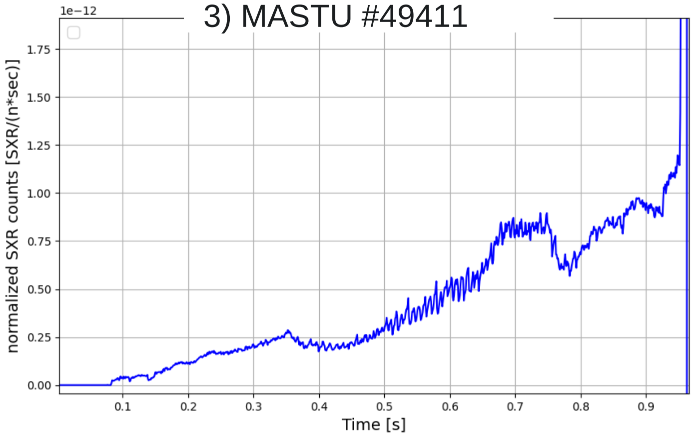
Neutron background: signal over neutron counts

With the gate closed the SXR/neutron trace is flat. The shot with the open valve return an estimation of the neutron background, valued between 1% and 10 %

1. Low gain & gate closed = direct neutron
2. High gain & gate closed = direct neutrons + gammas
3. High gain & gate open = direct neutrons + gammas + SXR


2) MASTU #49380

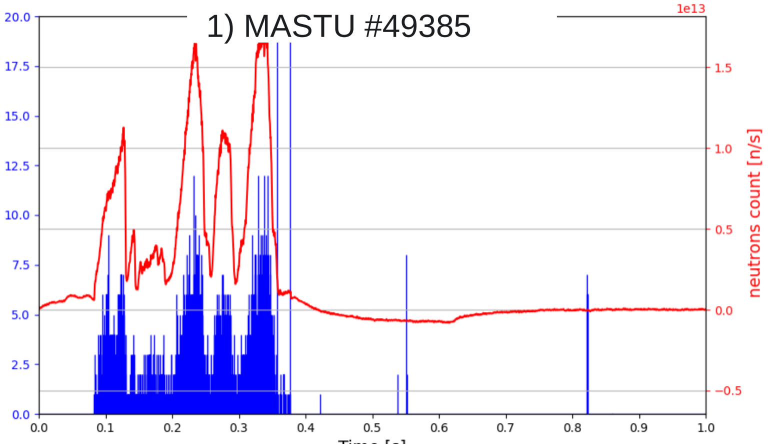

1) MASTU #49385

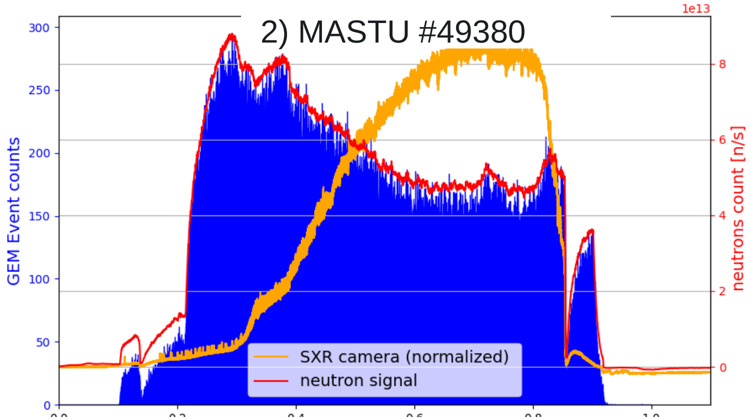

3) MASTU #49411

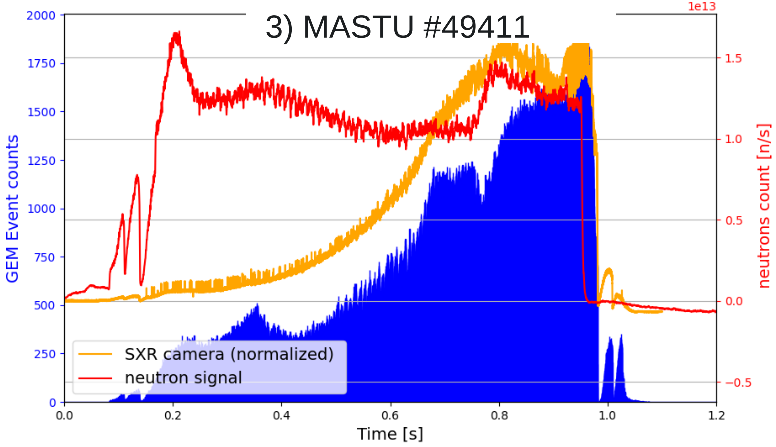
Neutron background

- For some shots the gate in front of the Be windows is kept shut, to study the neutron contribution on the GEM signal.

1. Low gain & gate closed = direct neutron
2. High gain & gate closed = direct neutrons + gammas
3. High gain & gate open = direct neutrons + gammas + SXR


1) MASTU #49385


2) MASTU #49380


3) MASTU #49411

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. 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.