Ionization Quenching Factor of low-energy ions in a MICROMEGAS detector at low gas pressure

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-
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Energetic Neutral Atom (ENA)

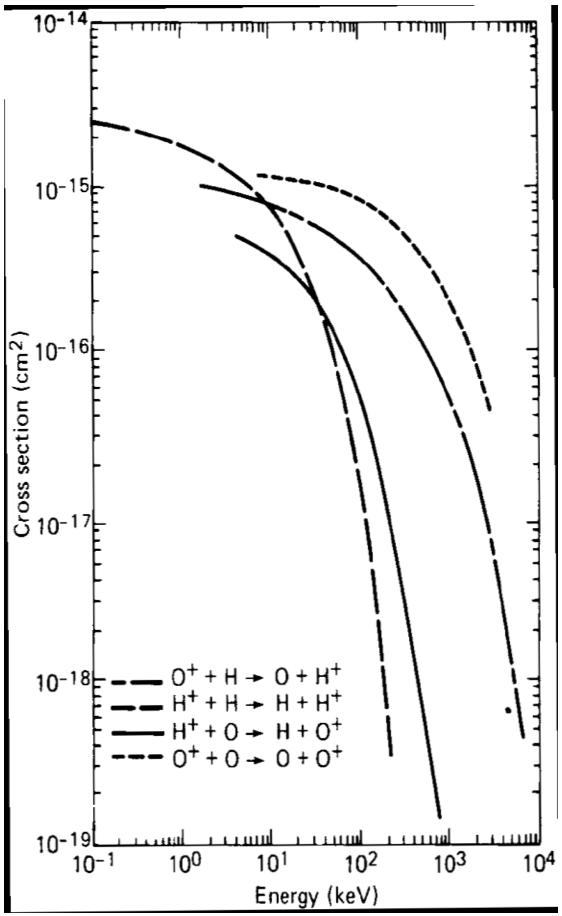
- ENA detection in space is powerful technique for Space Weather research

- ENA can be created by charge exchange processes between ions of the solar wind and atoms of the magnetosphere

- The cross section of this creation process defines the ENA energy range [1-100] keV

- The **SWEATERS Project** goal is to develop a detector that provides precise energy measurement and direction reconstruction of the incoming ENA

$$I_1 + A_2 \rightarrow A_1 + I_2$$



Doi: 265:251–288, 2000.

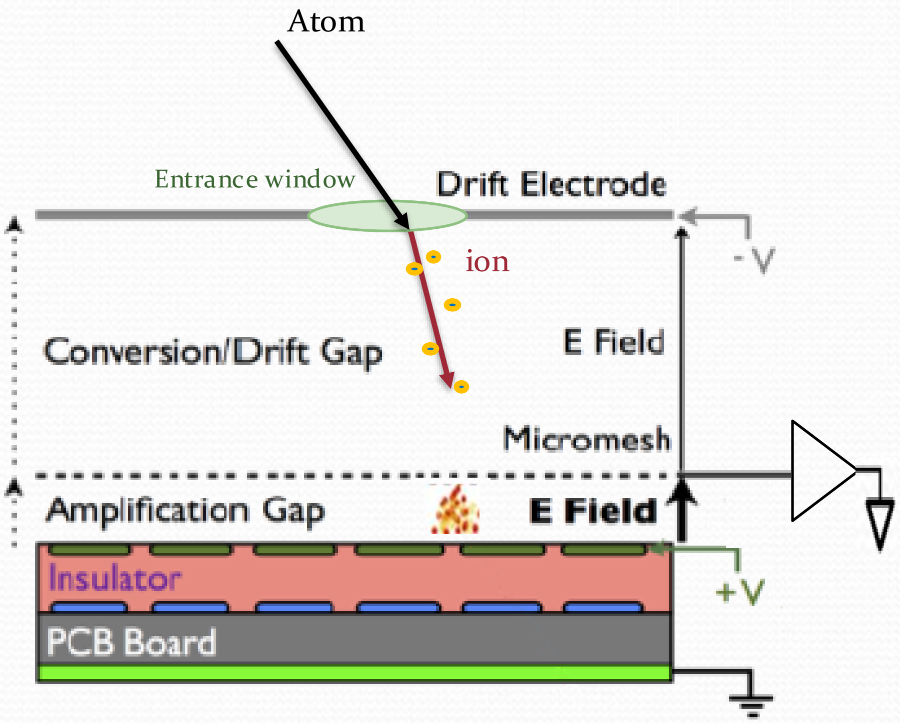
A MICROMEGAS (MM) for atoms detection in space

- A MM detector kept at low pressure can meet the requirements

- Ultrathin (2D) materials (thickness of o(nm)) can be used as gas-tight entrance window and to induce ENAs ionization as they enter the detector

- An ion of few keV of energy releases all its energy into the sensitive medium

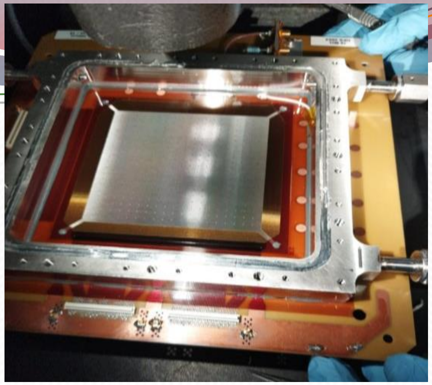
- A proper read-out chain connected to the mesh electrode is used to measure the energy



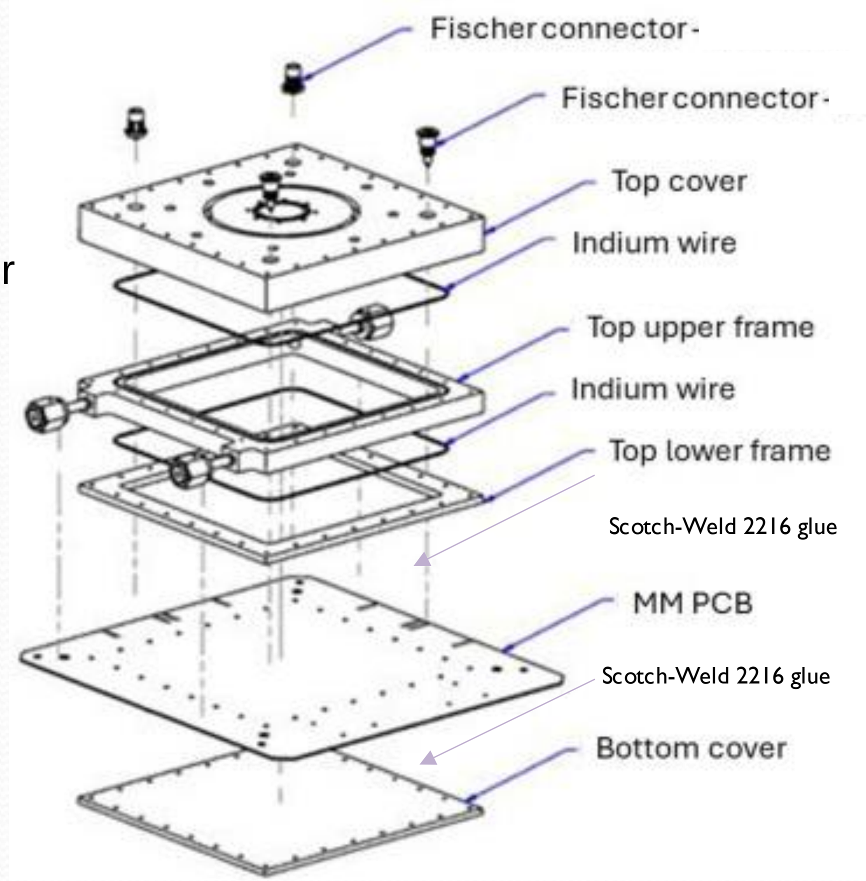
To guarantee the integrity of the entrance window and to increase the atom track:

gas pressure must be lower than 100mbar

SWEATERS detector

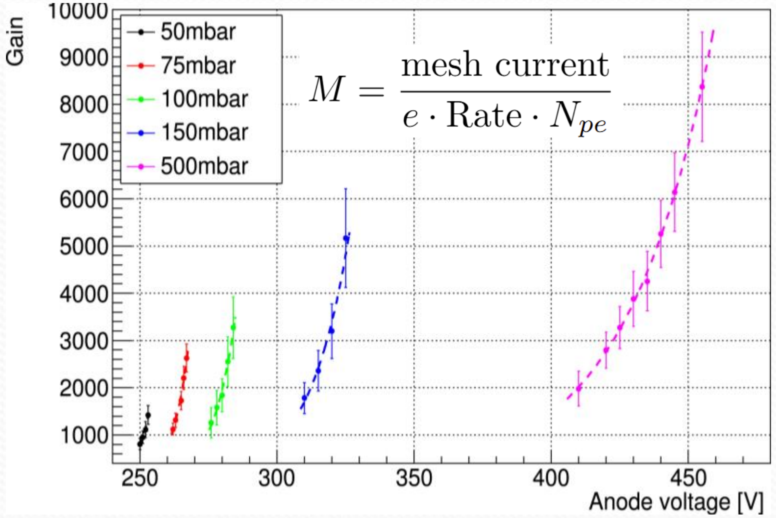


- Our MM was produced by CERN EP-DT Micro Pattern Technology (MPT) Workshop:
  - single DLC resistive layer (50MΩ/sq)
  - 102.4x102.4 mm^2 of active area
  - 2 orthogonal layers of 256 strips (400 um pitch)
  - **Nominal avalanche gap of 192um**
- Custom mechanical frame to improve the detector resistance to the pressure differential and to set the drift gap to 20mm.
- Sealing with indium wire and Scotch-Weld 2216 glue
- Gas distribution system:
  - mass flow controller for gas mixing (**Ar/CO_2 93/7**)
  - fine regulation of the flux (40 cc/min) for the continuous renewal of the sensitive gas

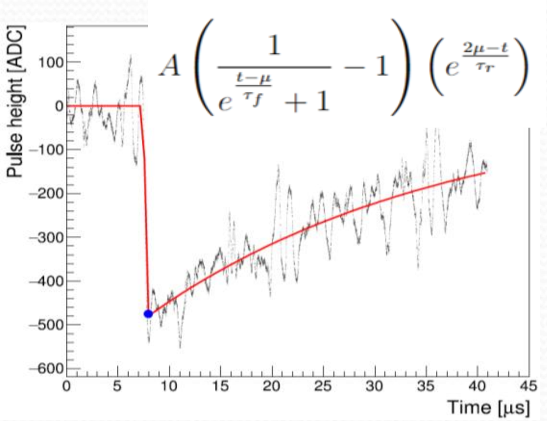


^{55}Fe X-ray characterization

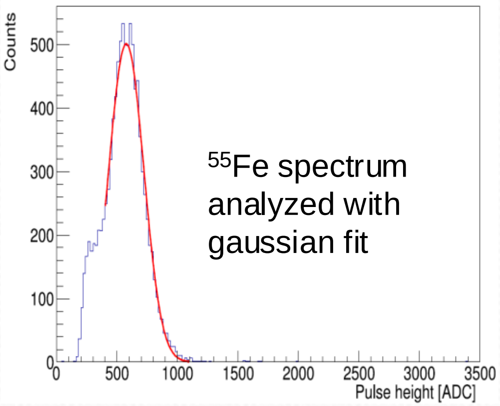
- **GAIN (*M*)** measurament: picoammeter + ratemeter connected to the MM mesh
- **ENERGY RESOLUTION**: mesh signal readout by a custom Charge Sensitive Preamplifier (CSP) + CAEN digitizer an ADC https://doi.org/10.1016/j.nima.2022.167915



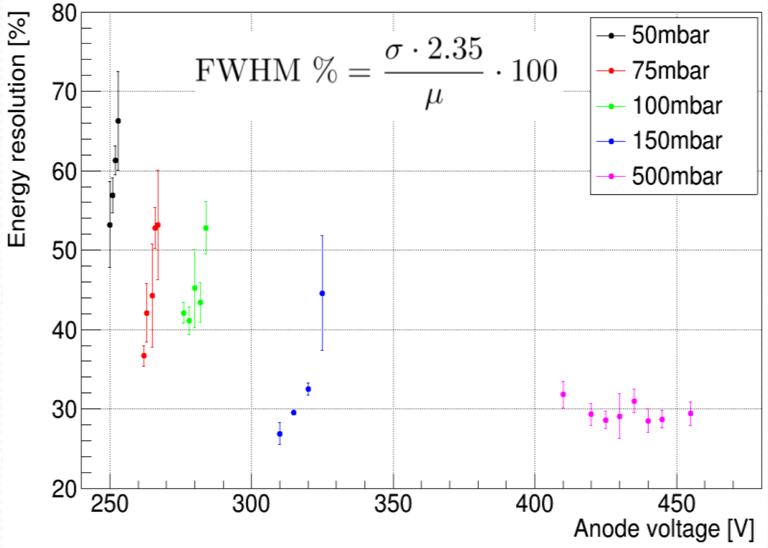
$$M = \frac{\text{mesh current}}{e \cdot \text{Rate} \cdot N_{pe}}$$



$$A\left(\frac{1}{e^{\frac{t-\mu}{\tau_f}}+1}-1\right)\left(e^{\frac{2\mu-t}{\tau_r}}\right)$$



^{55}Fe spectrum analyzed with gaussian fit



$$\text{FWHM}\ \% = \frac{\sigma \cdot 2.35}{\mu} \cdot 100$$

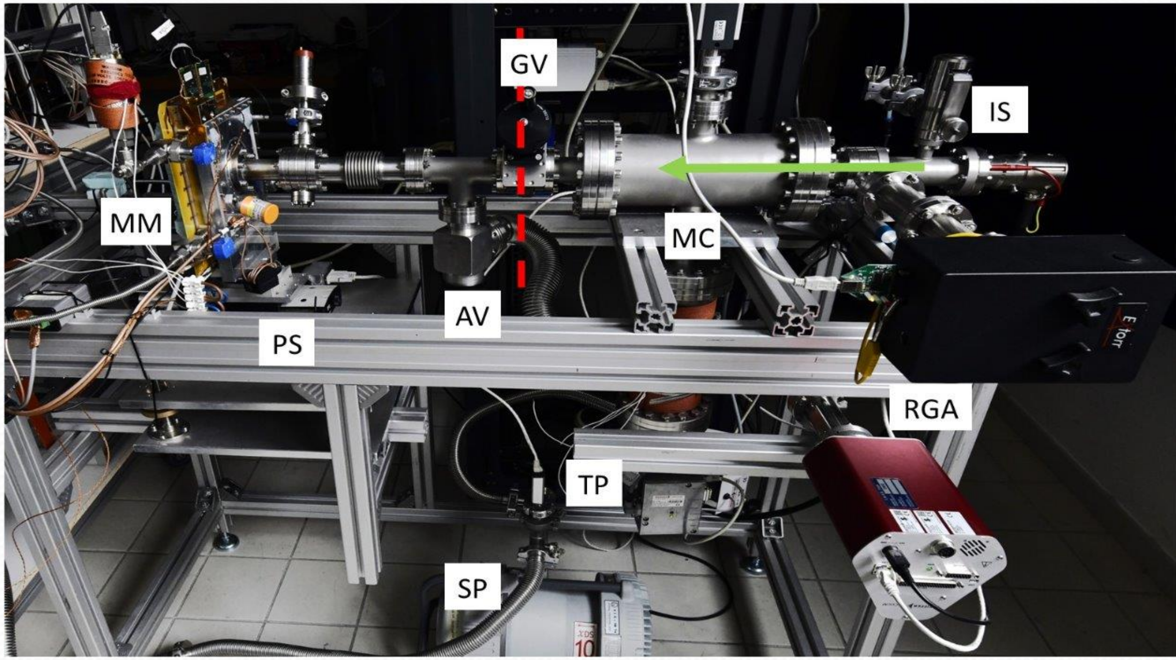
- The detector gain and the FWHM energy resolution were studied as a function of the gas pressure and the anodic voltage. https://doi.org/10.1016/j.nima.2024.169494

Our MM detector has demonstrated its ability to work at pressures down to 50mbar

Ion Beam Facility (IBF)

https://doi.org/10.1016/j.nima.2024.169918

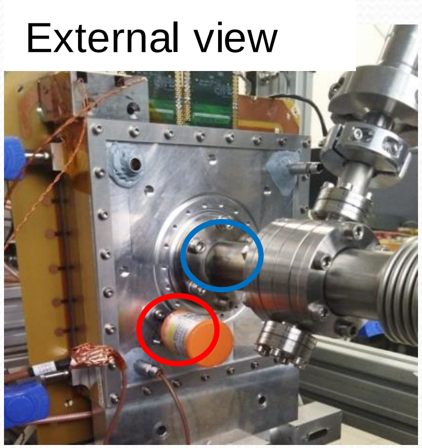
- The IBF consists of:
  - main chamber (MC)
  - commercial ion source (IS), energy range 0.2-5 keV
  - residual gas analyzer (RGA)
  - scroll pump (SP) and turbo pump (TP)
  - positioning system (PS)
  - valves to separate the IBF sections (AV, GV)

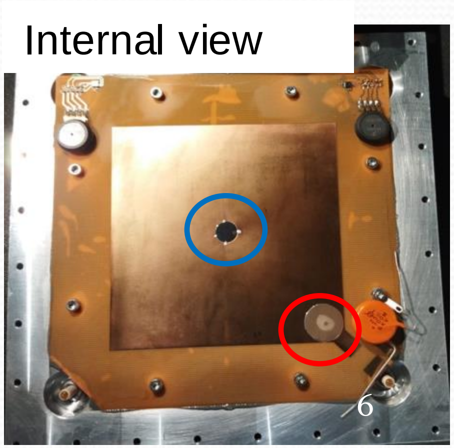


- For online detector calibration, the MM top cover is equipped with two entrance windows:
  - 5um diameter pin-hole (CW)
  - 2x50um thickness PEEK layer (LW)

CW

LW


External view


Internal view

Ion-gas interaction

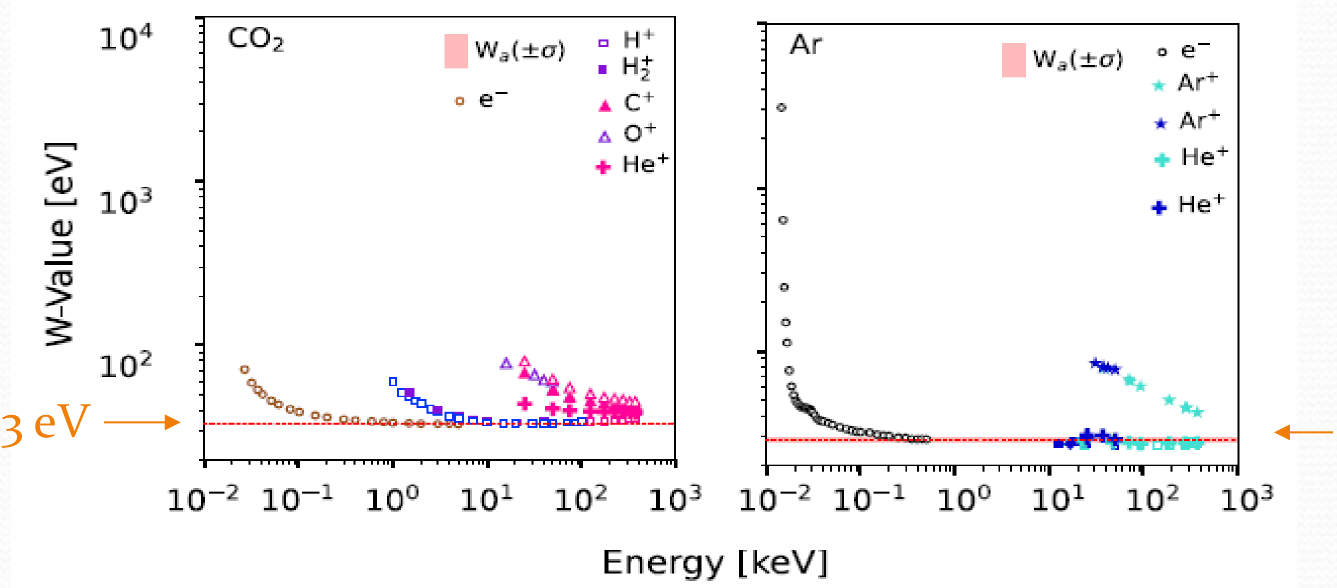
I. Katsioulas, doi: https://doi.org/10.1016/j.astropartphys.2022.102707

- The interaction of ionizing radiation with kinetic energy *T* of few keV with a gaseous medium depends on the projectile type and its kinetic energy

- The **Ionization Quenching factor (IQF)** is defined as the ratio between the kinetic energy of an electron and that of an ion, resulting in the same “visible” energy in the ionisation detector

$$\mathrm{IQF} = \frac{T_e}{T_i} = \frac{N_f \cdot W_e(T)}{N_f \cdot W_i(T)} = \frac{W_e(T)}{W_i(T)}$$

where N_f is the number of primary electrons



33 eV →

← 26.4 eV

Detector calibration procedure

- At the Ion Beam Facility (IBF) in our laboratory, the MM was irradiated with He and H_2 ion beams accelerated at energies between 2.5 and 5 keV, which pass through the central window on the top cover of the MM

- An X-ray ^{55}Fe source was placed in the MM lateral window for online calibration

- The collected data were analyzed to study the dependence of IQF on the gas pressure (75 mbar, 100 mbar and 150 mbar) and the anodic voltage

- The experimental results were compared with the IQF estimated by the SRIM simulation software.

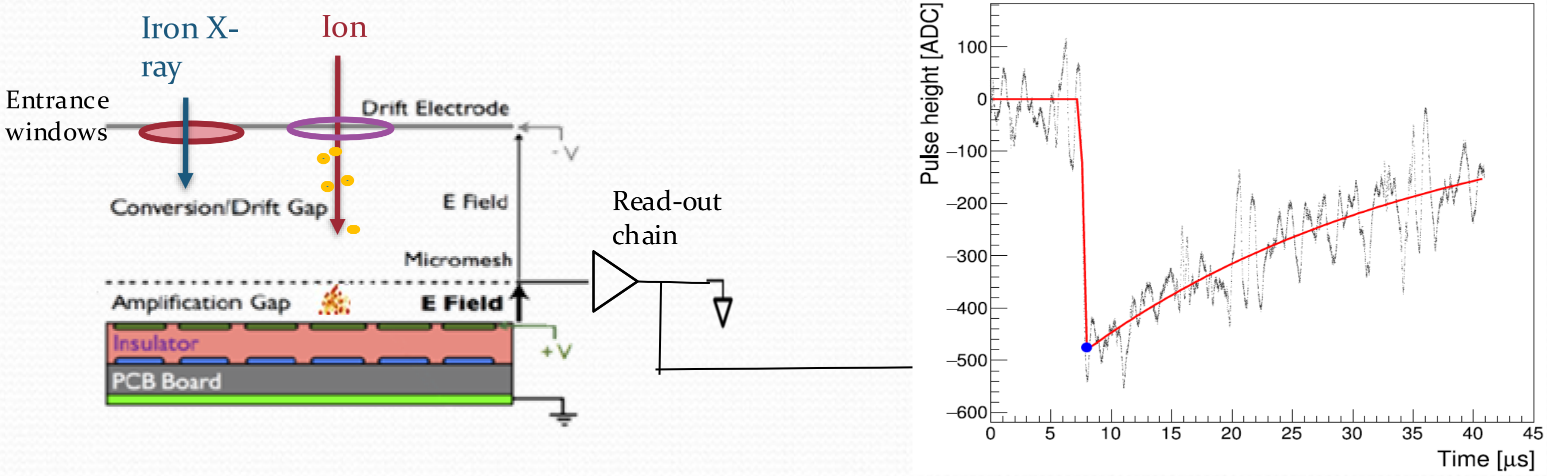
IQF measurement method

- The IQF formula has to be rewritten to depend only on quantities that can be measured with our detector
- In the MM detector, the primary electrons N_{pe} *produced in the drift region by an ionizing particle of kinetic energy T,* generate avalanches in the gap region inducing a charge $Q(T)$ by a gain M on the mesh electrode

$$Q(T) = N_{pe} \cdot M = \frac{T}{W} \cdot M$$

- The read-out chain of the mesh electrode produces a digitized waveform of the signal induced by the charge (Q), the amplitude of which is linearly dependent on Q.

$$H(Q) = a + b \cdot Q$$



IQF formula

- Using the relation between *W*, N_{pe} and *Q*(*T*) the IQF formula becomes:

$$\mathrm{IQF} = \frac{W_e(T)}{W_i(T)} = \frac{N_i(T)}{\cancel{T}}\frac{\cancel{T}}{N_e(T)} = \frac{Q_i(T)}{\cancel{M}}\frac{\cancel{M}}{Q_e(T)}$$

- The *H*(*Q*) parameters *a b* can be computed by calibrating the detector with two radiation sources (marked 1 and 2 in the formulae)

$$\begin{cases} \frac{H(Q)-H_1}{H_2-H_1} = \frac{Q-Q_1}{Q_2-Q_1} \\ b = \frac{H_2-H_1}{Q_2-Q_1} = \frac{H_2-H_1}{T_2-T_1}\cdot\frac{W_e}{M} \\ a = -Q_1\cdot b + H_1 = -T_1\frac{W_e}{\cancel{M}}\frac{H_2-H_1}{(T_2-T_1)\frac{W_e}{\cancel{M}}} + H_1 \\ Q = \frac{H-a}{b} \end{cases}$$

- The *W* value for electrons does not depend on T in the keV energy region, then Q_e(T) in the IQF formula can be calculated from the charge measured irradiating the MM with X-rays (5.96 keV) from a ^{55}Fe source

$$\mathrm{IQF} = \frac{Q_i(T)}{Q_e(5.96)}\frac{5.96}{T} = \frac{H_i(T)-a}{\cancel{b}}\frac{\cancel{b}}{H_e(5.96)-a}\frac{5.96}{T} = \frac{H_i(T)-a}{H_e(5.96)-a}\frac{5.96}{T}$$

The IQF does not depend on the detector working point!!!

Calculation of the parameter *a*

- The parameter *a* can be calculated as

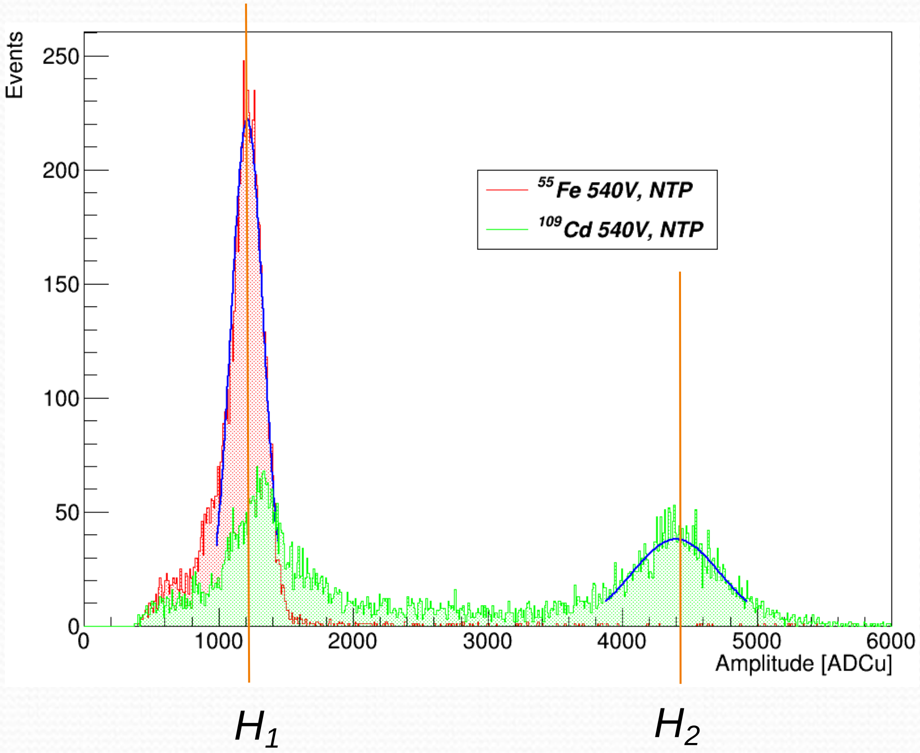
$$a = -T_1 \frac{W_e}{\cancel{M}} \frac{H_2 - H_1}{(T_2 - T_1)\frac{W_e}{\cancel{M}}} + H_1$$

- The MM was kept at ambient pressure and X-ray sources of ^{55}Fe (H_1) and ^{109}Cd(H_2) were used

- A Gaussian was fitted to the main peak of each spectrum

- The main peak value is taken from the NIST tables: 5.96 keV for ^{55}Fe (T_1) and 23.1 keV for ^{109}Cd (T_2).

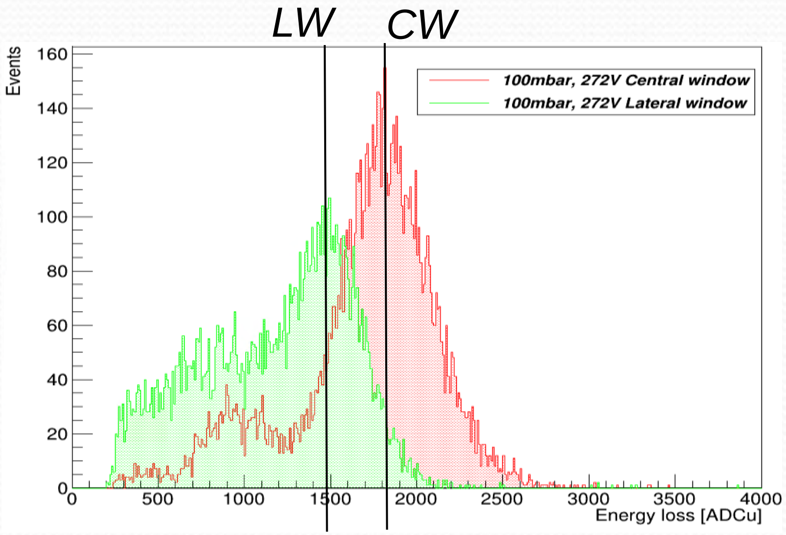
- By averaging several measurements, the resulting value of *a* is (35 ± 25) ADC

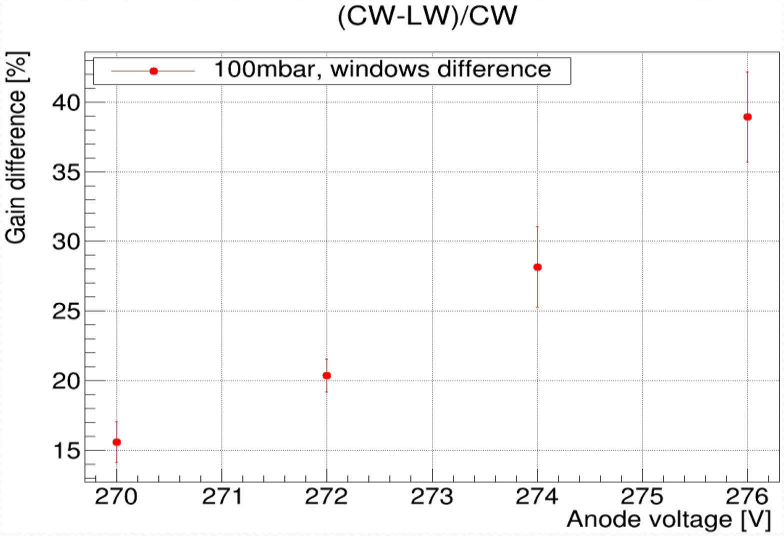


^{55}Fe signals: from the lateral to the central window

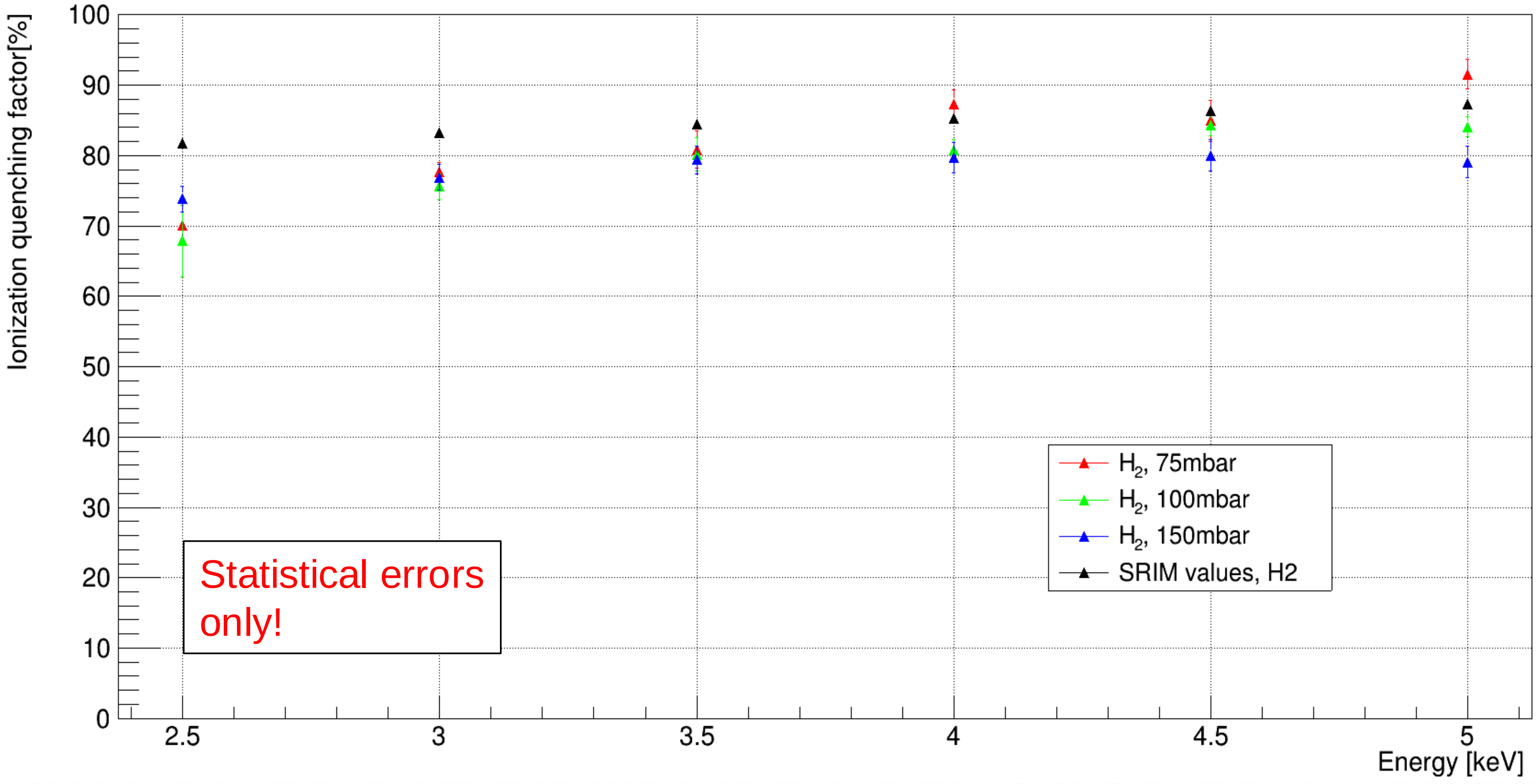
- The uniformity of the detector response was tested placing the ^{55}Fe source in the central (CW) and in the lateral window (LW)
- The ratio of the main peak positions in the two configurations (*CW/LW*) is used as correction factor
- *CW/LW* is not equal to one and constant varying the avalanche voltage. This effect is still unknown; simulations and studies are ongoing
- *CW/LW* is used to correct the pulse height of the electrons (H_e) in the IQF formula

$$IQF = \frac{H_i(T) - a}{H_e(5.96) \cdot \frac{CW}{LW} - a} \frac{5.96}{T}$$

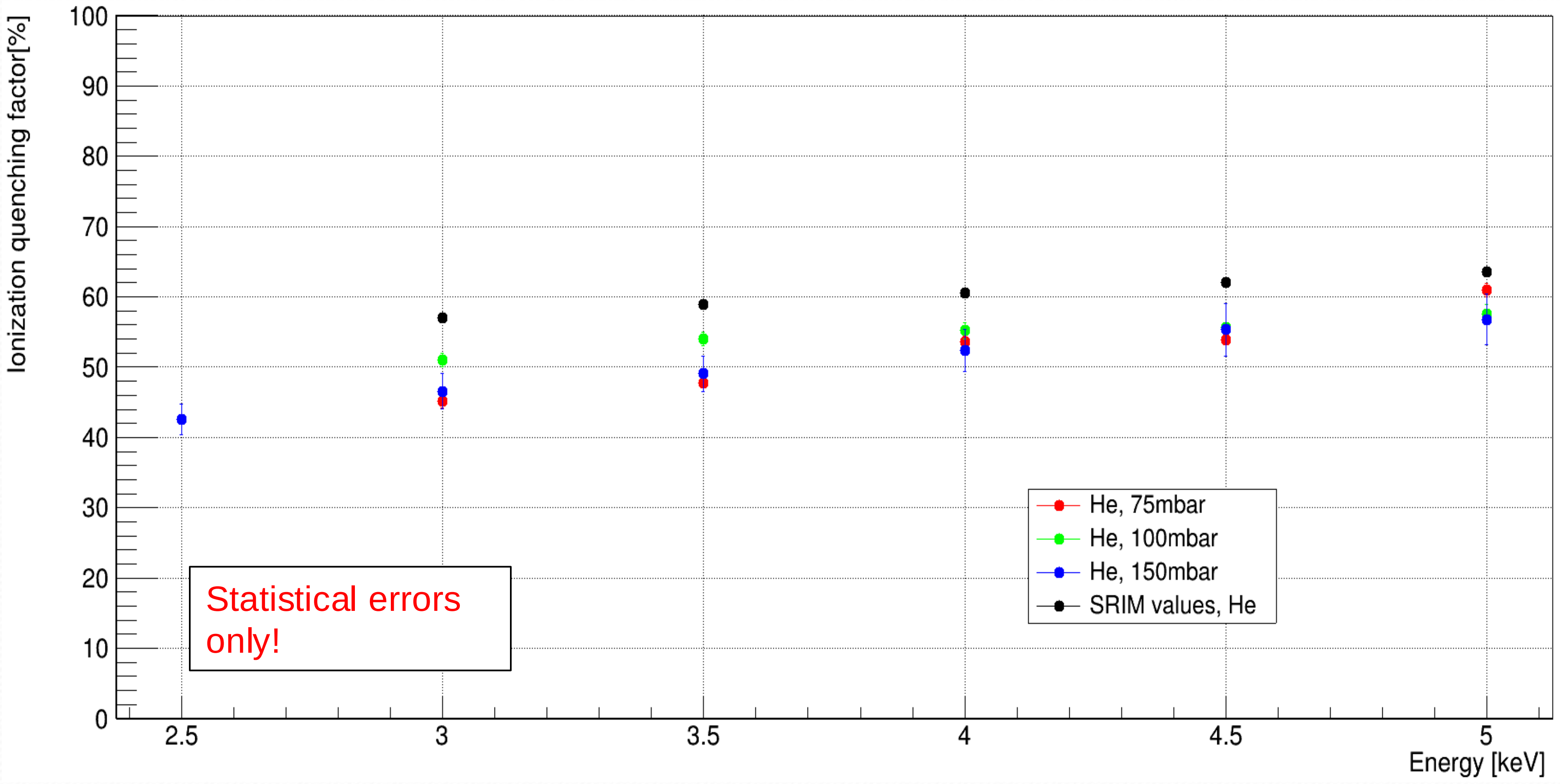




Gas pressure dependence of IQF for H_2 ions

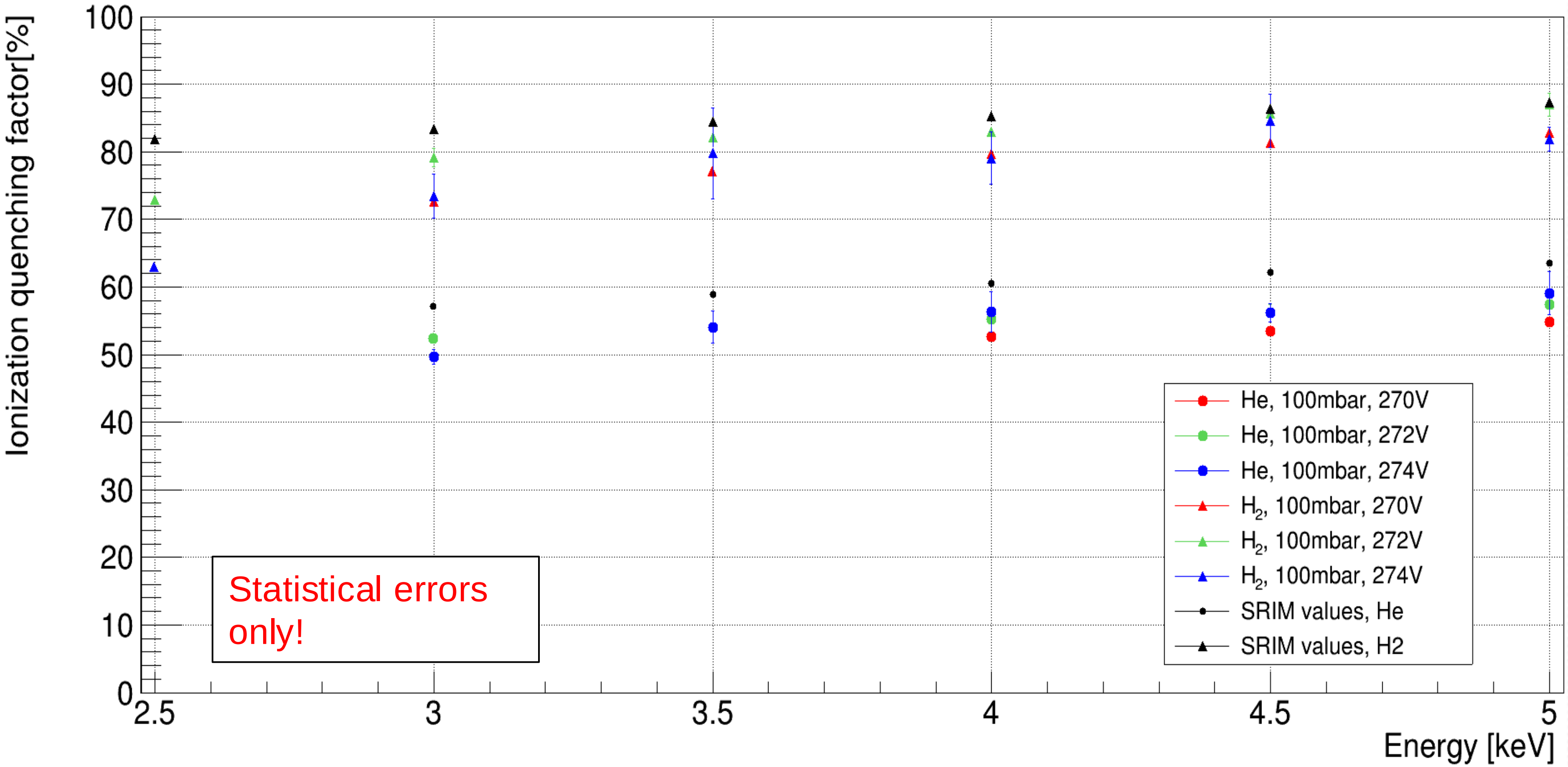


Gas pressure dependence of IQF for He ions



Statistical errors only!

Anodic voltage dependence of the IQF



Statistical errors only!

Conclusions

- With the ion beam facility set up in our laboratory, we were able to make very precise measurements with low energy beams of light ions
- Our MM detector working at low pressure demonstrated its ability to detect H_2 and He ions at energies between 2.5 and 5 keV
- A method of calculating the IQF that is not affected by the uncertainties of the detector gain estimate has been developed, giving more accurate and consistent results
- We have confirmed that the IQF is independent of the detector gain, as verified by varying the gas pressure and anodic voltage
- The SRIM simulation results are in fairly good agreement with our data, showing less than 5% overestimation of the IQF
- Evaluation of systematic uncertainties is ongoing