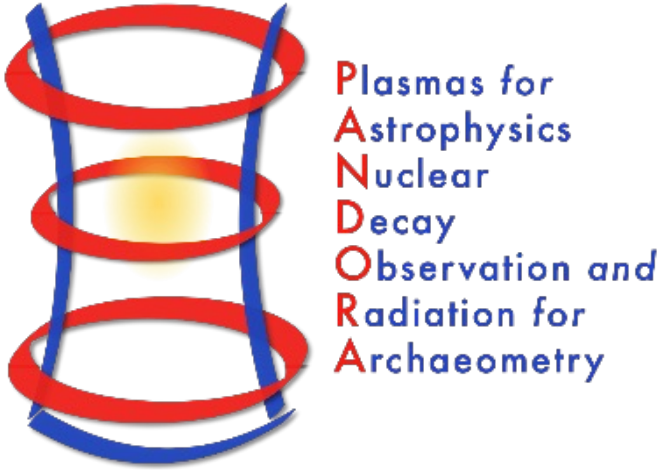
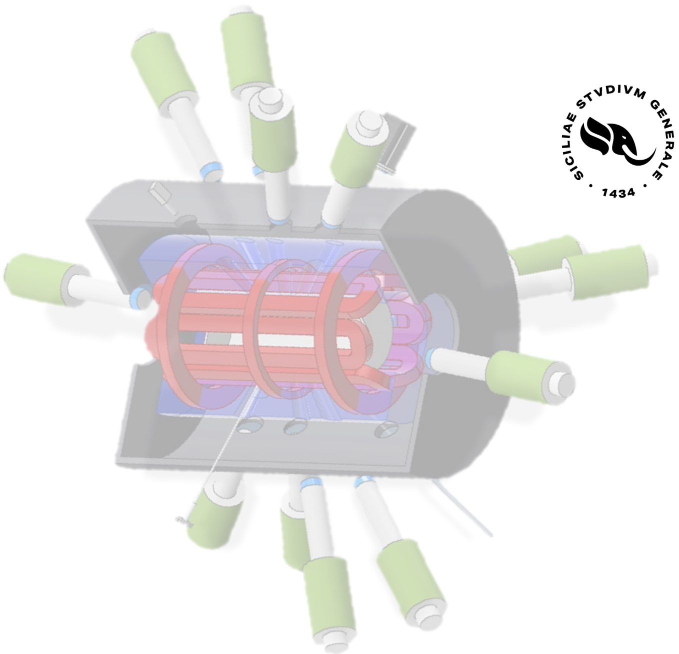
X-ray imaging diagnostics and AI analysis algorithm development – Part I

3rd PANDORA Progress Meeting





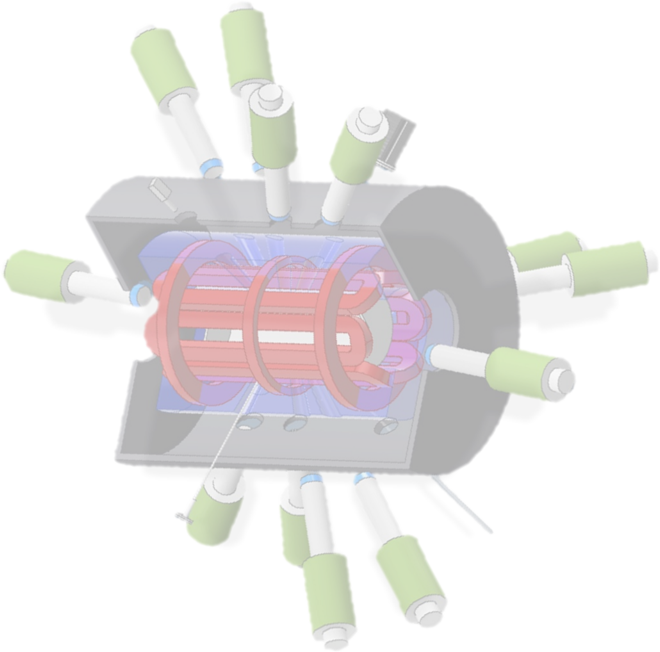
Giorgio Finocchiaro *on behalf of the PANDORA collaboration*
Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud – Catania (Italy)

Plasmas for
Astrophysics
Nuclear
Decay
Observation and
Radiation for
Archaeometry

Outline

INFN
LNS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

- Introduction: energy-resolved X-ray imaging diagnostics
- Fluorescence-filtered plasma imaging
- Local extrapolation of plasma parameters
- Acquisition system characterization
- Ongoing activities on Atomki testbench



Introduction

In perspective, for the PANDORA purpose, it will be mandatory

1. to locally characterize the **plasma parameters (n, T)**;
2. to measure the **plasma volume**;
3. to master the **plasma stability** for days, weeks or even months

- **Beta-decay investigation** → **plasma parameters monitoring**

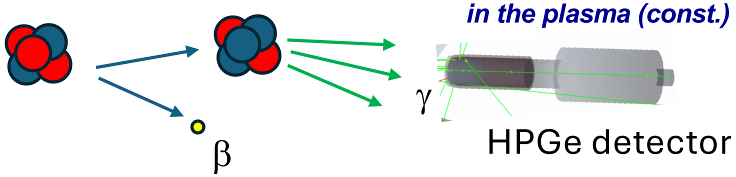
$$\frac{dN}{dt} = \lambda n_i V$$

$$N(T_{meas.}) = \lambda n_i V_{plasma} T_{meas.}$$

Isotope activity

Density of the isotope in the plasma (const.)

Plasma volume (const.)

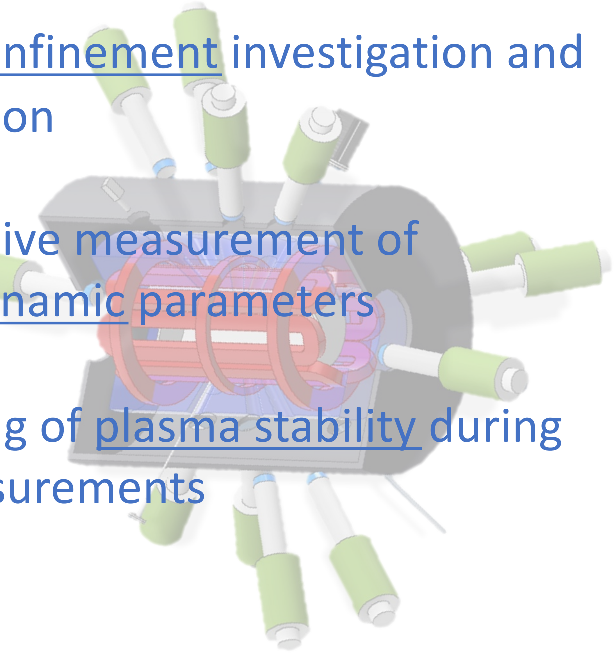


X-ray imaging goals:

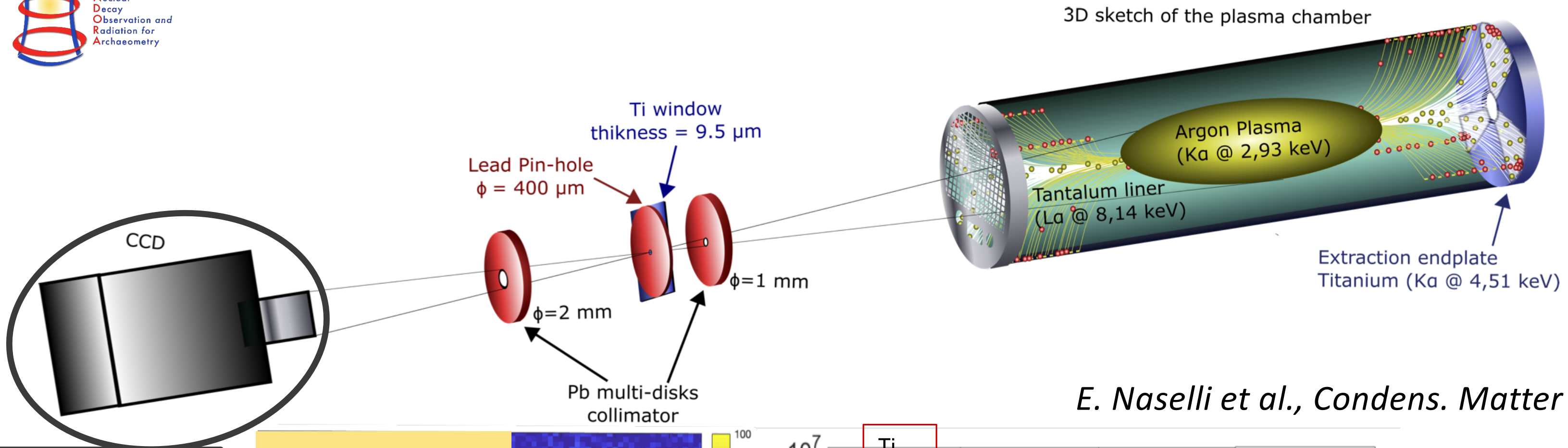
✓ Plasma confinement investigation and optimization

✓ Non-invasive measurement of thermodynamic parameters

✓ Monitoring of plasma stability during long measurements

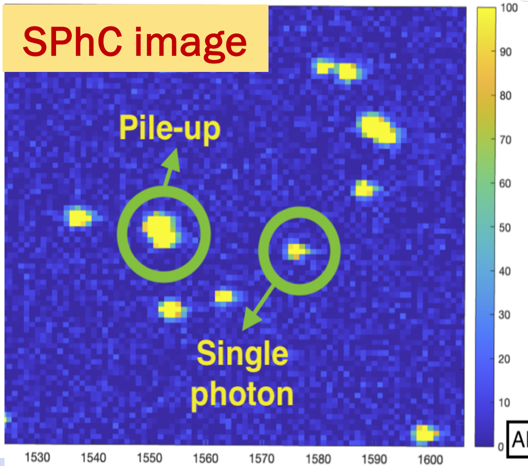


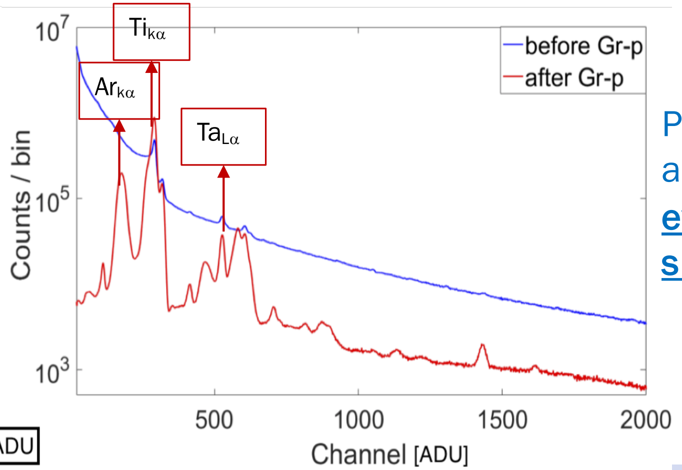
Single Photon Counting with CCD pinhole camera overview



E. Naselli et al., Condens. Matter ***1****, 0 (2021)*

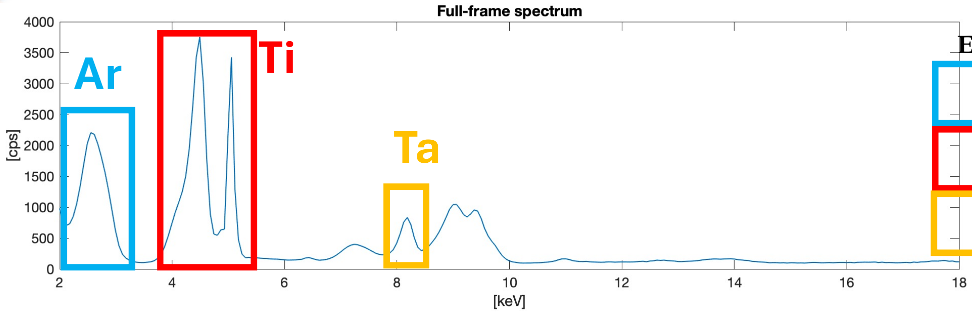
CCD camera



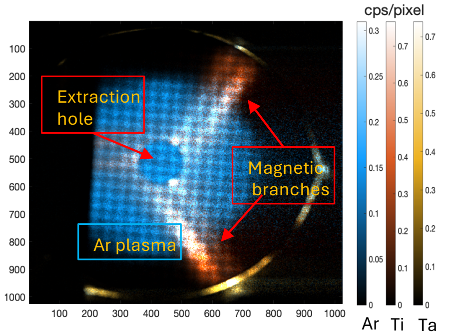


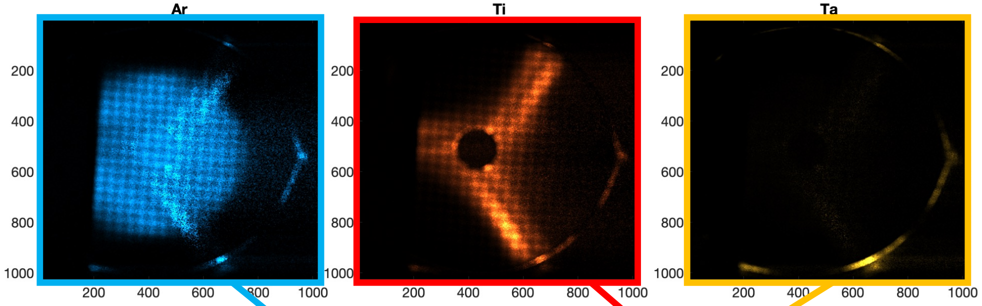
Properly developed graphic algorithm identifies **single-photon events** on CCD images to perform **space-resolved spectroscopy**

Fluorescence-filtered imaging results



Element	X-ray line	Energy (keV)
18 Ar	$K\alpha_{1,2}$	2.96
18 Ar	$K\beta_1$	3.19
22 Ti	$K\alpha_{1,2}$	4.51
22 Ti	$K\beta_1$	4.93
73 Ta	$L\alpha_1$	8.15
73 Ta	$L\alpha_2$	8.09

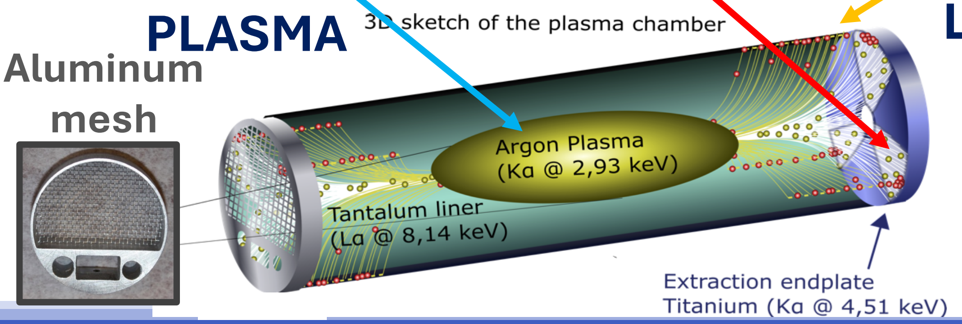




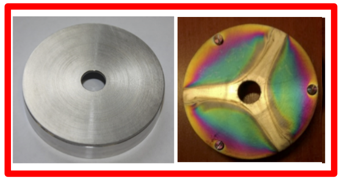
Structural analysis (fluorescence imaging)

- **ECR surface analysis**
- **Deconfinement phenomena**

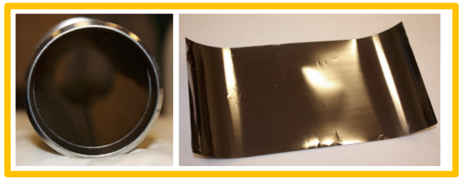
G. Finocchiaro et al., Phys. Plasmas 31, 062506 (2024)



LOSSES

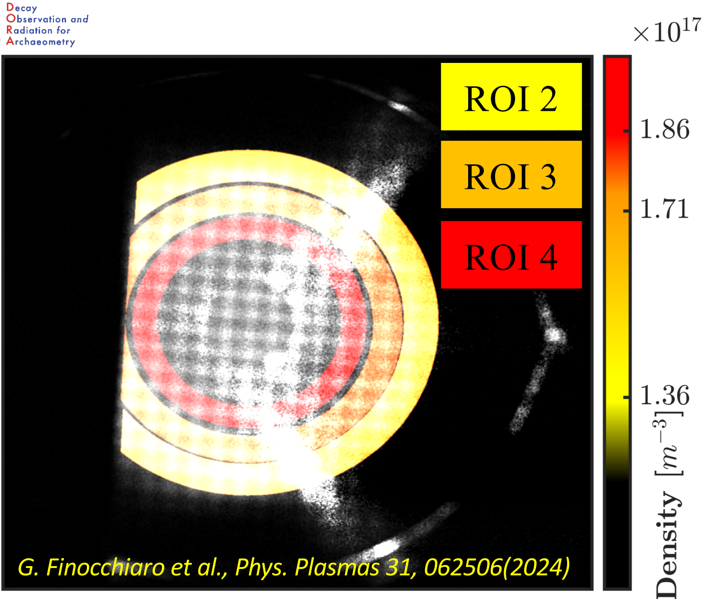


Titanium

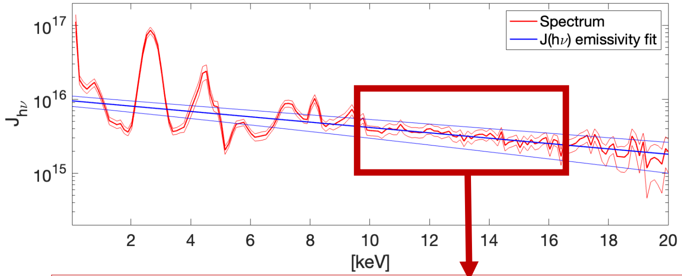


Tantalum

Local extrapolation of plasma parameters



G. Finocchiaro et al., Phys. Plasmas 31, 062506(2024)



Temperature and **density** values extracted in different image regions

Experimental emissivity density (red line)

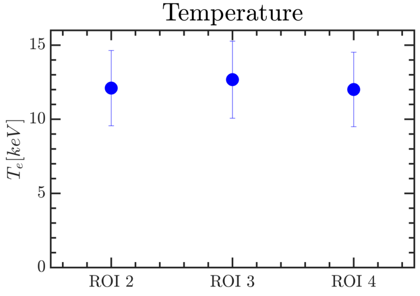
$$\boxed{J_{exp}(h\nu) = h\nu \frac{N^p(h\nu)}{t} \frac{4\pi}{\Delta E V_P \Omega_g}}$$

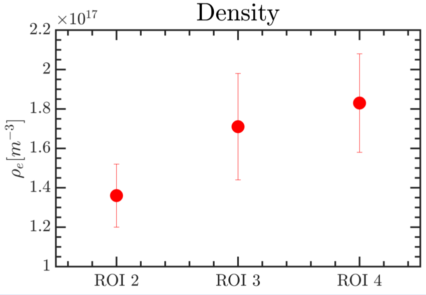
Geometrical model

- Maxwell-Boltzmann emissivity model fit (blue line)

$$J^{M-B}_{bremss}(h\nu) = \underset{\text{Density}}{\boxed{\rho_e \rho_i}} (Z\hbar)^2 \left(\frac{4\alpha}{\sqrt{6m_e}}\right)^3 \sqrt{\frac{\pi}{k_B T_e}}\, e^{-\frac{h\nu}{k_B \boxed{T_e}}} \ \text{Temperature}$$

B. Mishra et al. Physics of Plasmas 28, 102509 (2021)





	e- temperature [keV]	e- density [m^{-3}]
ROI 2	12.10 ± 2.54	(1.36 ± 0.16) $\cdot 10^{17}$
ROI 3	12.67 ± 2.60	(1.71 ± 0.27) $\cdot 10^{17}$
ROI 4	12.01 ± 2.51	(1.83 ± 0.25)$\cdot 10^{17}$

Power of this method:

- **Not invasive**
- **Space-resolved**

Local extrapolation of plasma parameters

Geometrical model

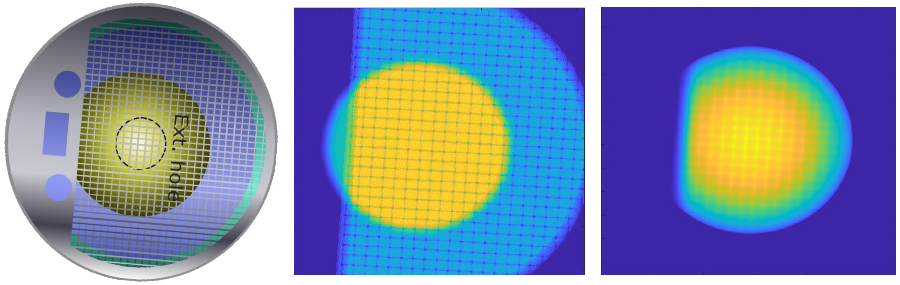
$$J_{exp}(h\nu) = h\nu \frac{N^p(h\nu)}{t} \frac{4\pi}{\Delta E V_P \Omega_g}$$

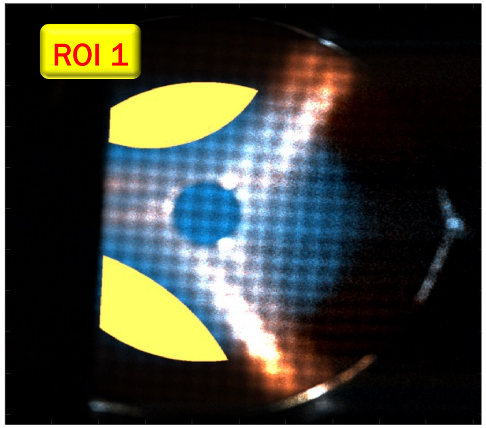
Emitting plasma volume

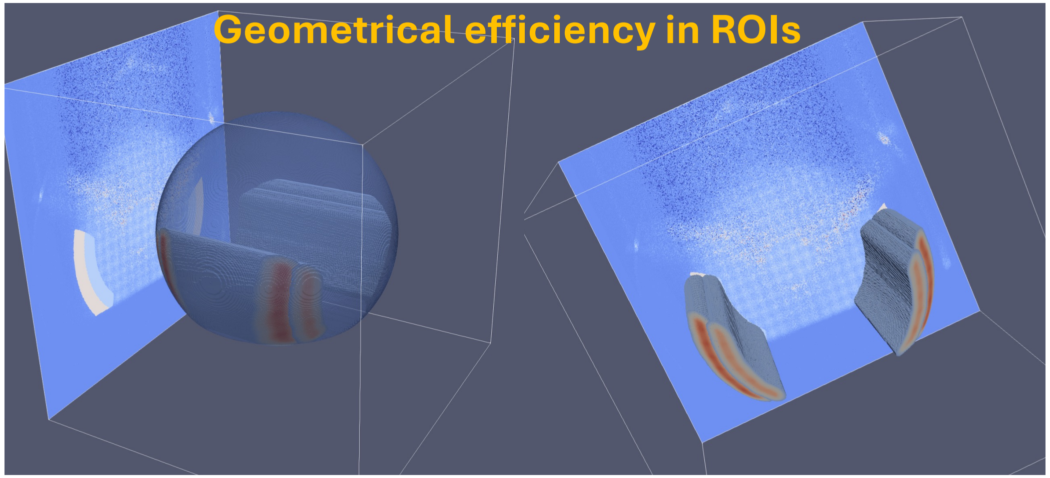
Geometrical efficiency

2D ROI projection on 3D **plasma model** to define the observed plasma **volume** and the respective geometrical X-ray **detection efficiency**

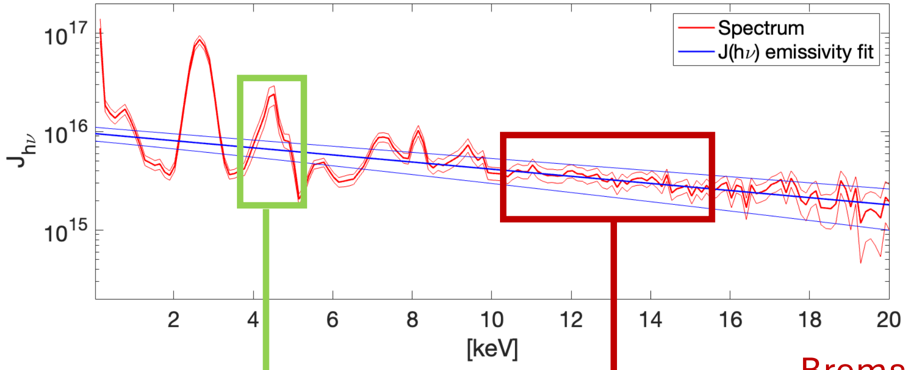
Aluminum mesh and plasma simulation







Emissivity model improvement



Fluorescence emission included in the model

- **Robust fit constraints**
- **Short measure time**
- **Deconfinement thermodynamics study**

Bremsstrahlung emissivity

$$J_{theo,brem}(h\nu) = \rho_e\rho_i(Z\hbar)^2\left(\frac{4\alpha}{\sqrt{6m_e}}\right)^3\left(\frac{\pi}{k_BT_e}\right)^{1/2} \mathrm{e}^{(-h\nu/k_BT_e)}$$

$$J_{nl\to nl'} = \frac{h\nu_{nl\to nl'}}{\Delta E}\rho_e\rho_i\omega_{nl\to nl'}\int_I^\infty \sigma_{nl,ion}(E)v_e(E)f(E)\mathrm{d}E$$

Fluorescence emissivity (confined plasma)

$$J_{nl\to nl'} = \frac{h\nu_{nl\to nl'}}{\Delta E V_P}\rho_{e,loss}N_i\omega_{nl\to nl'}\int_I^\infty \sigma_{nl,ion}(E)v_e(E)f(E)\mathrm{d}E$$

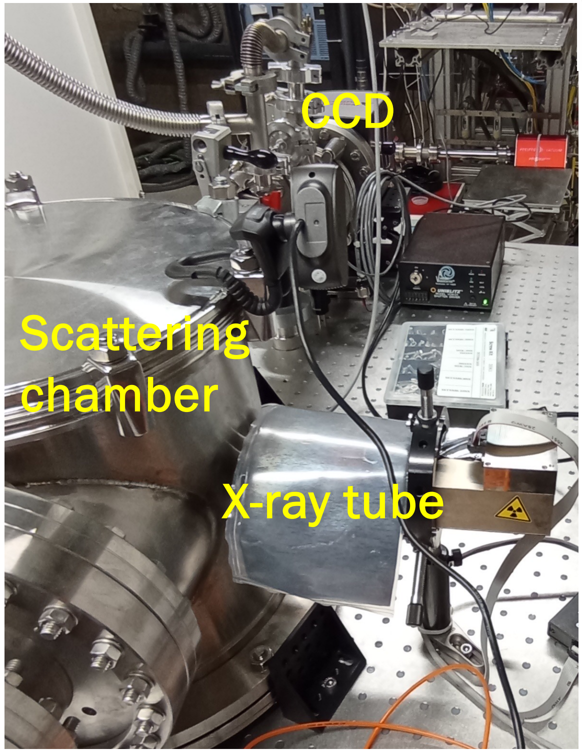
Fluorescence emissivity (deconfined plasma)

B. Mishra et al. Physics of Plasmas 28, 102509 (2021)

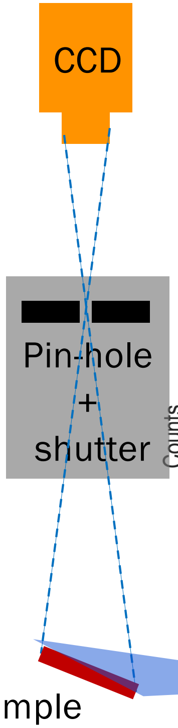
Plasmas for Astrophysics Nuclear Decay Observation and Radiation for Archaeometry

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

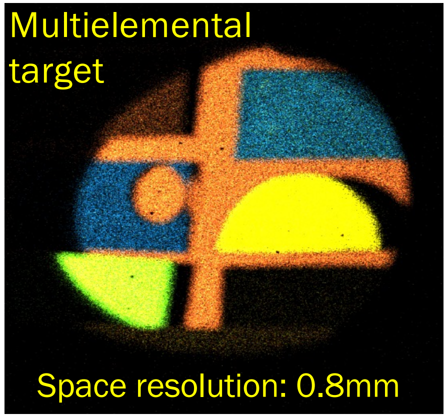
CCD characterization by X-ray tube

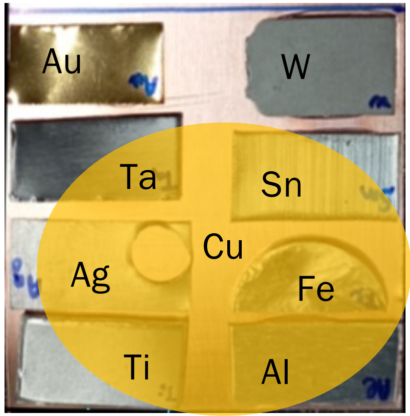


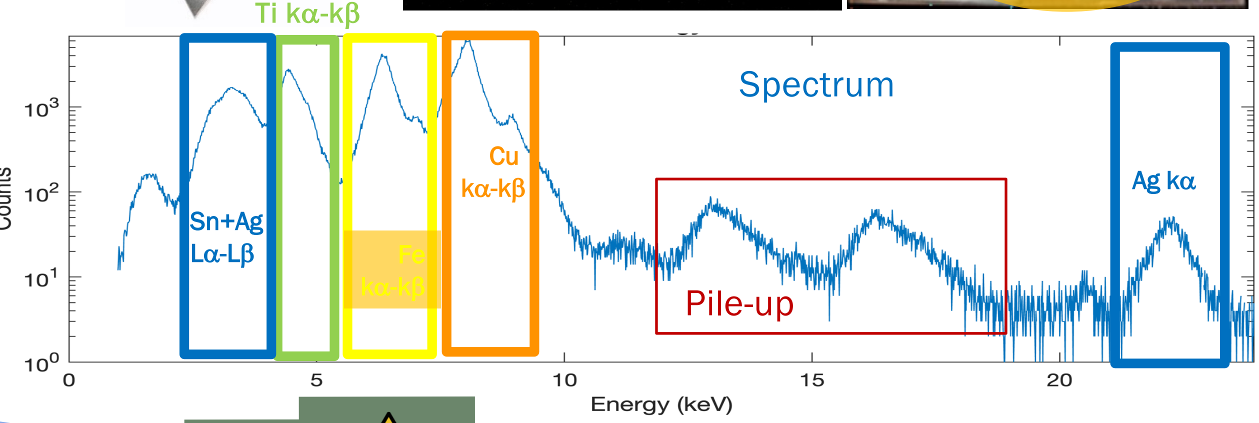
CCD
TELEDYNE PRINCETON INSTRUMENTS
Everywhereyoulook



Shutter
Uniblitz® XRS6



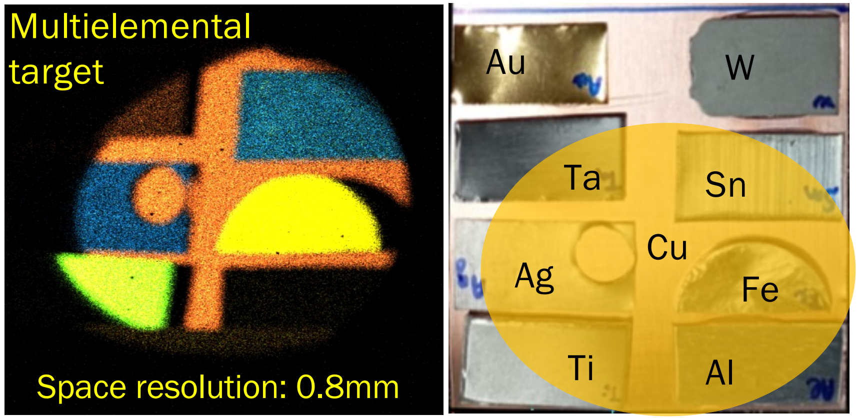


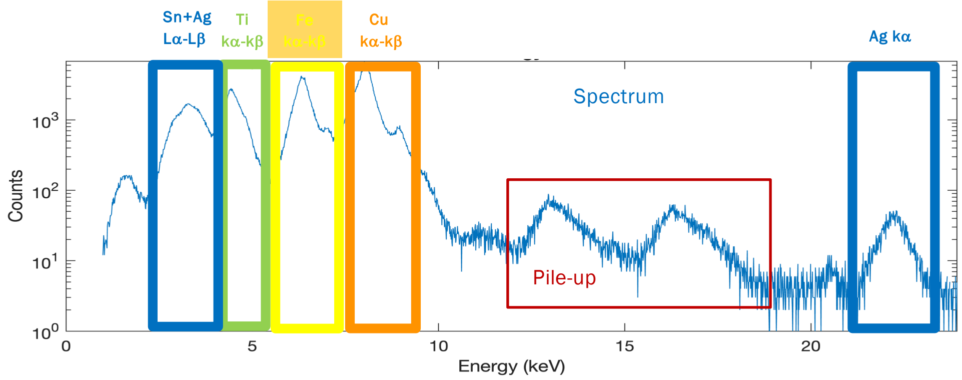


Multiparametric energy calibration

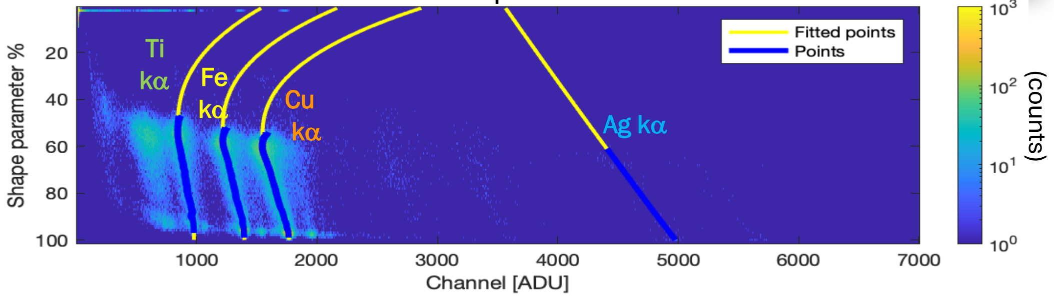
- **Parameter-dependent energy resolution: FWHM vs statistics trade-off**
- **Parametric energy calibration**

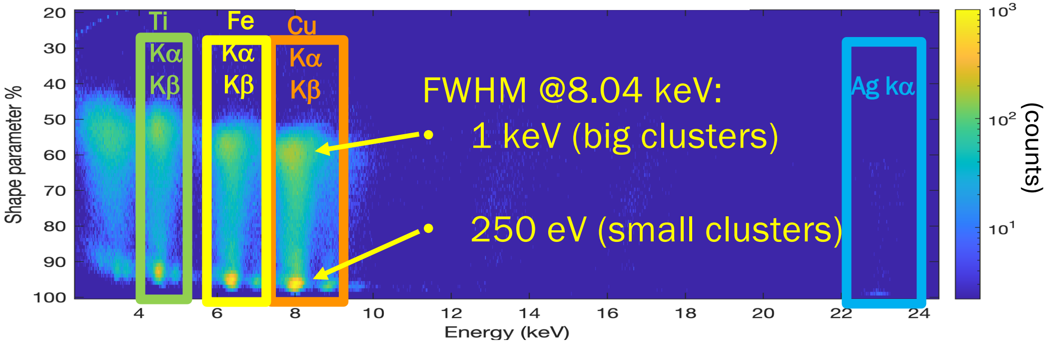
Stay tuned for Part II: B. Peri – AI Analysis Algorithm Development





SPhC spectra

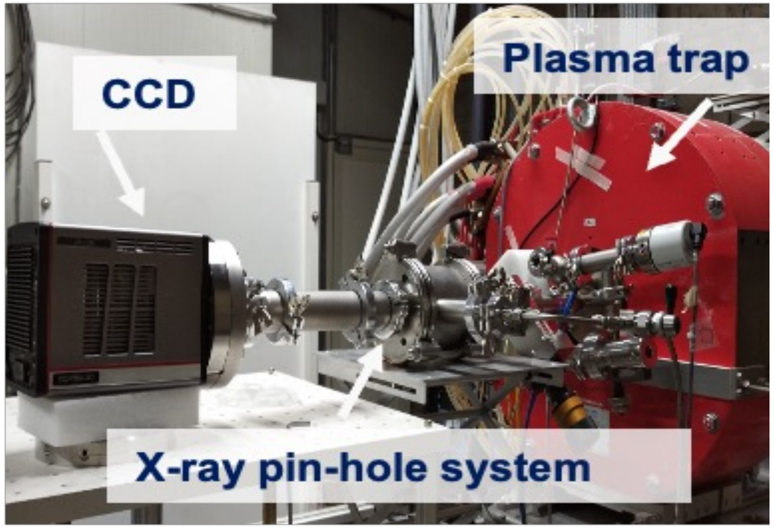




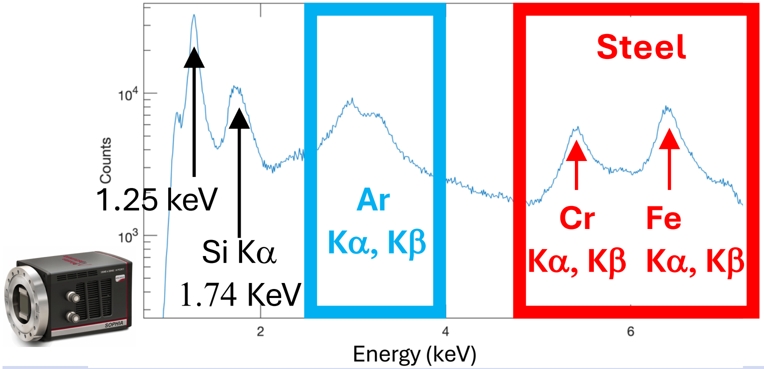
FWHM @8.04 keV:

- 1 keV (big clusters)
- 250 eV (small clusters)

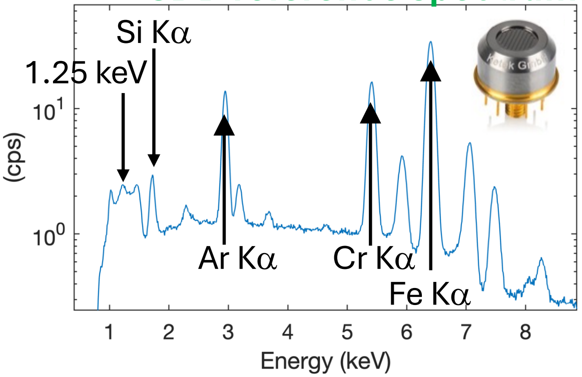
Plasma imaging on FPT (LNS)



CCD spectrum

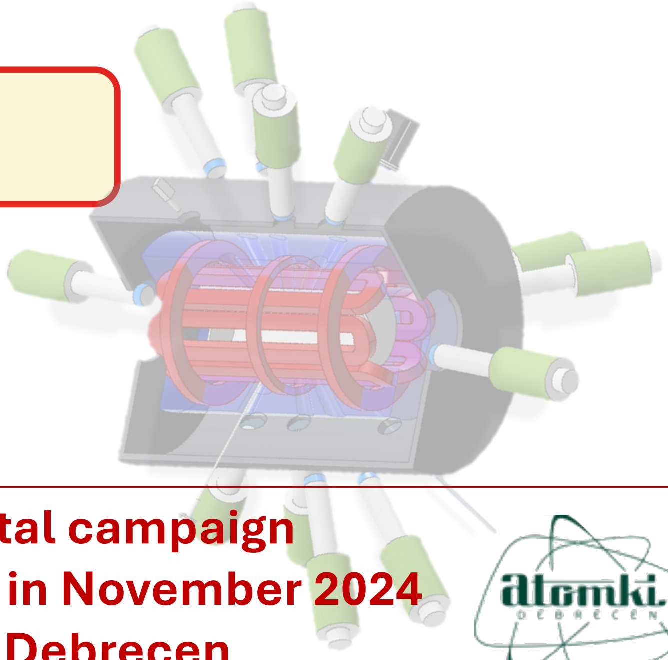


SDD reference spectrum



- X-ray CCD + shutter tested on plasma imaging
- Validation of calibration algorithm at the lowest energy

What's next?



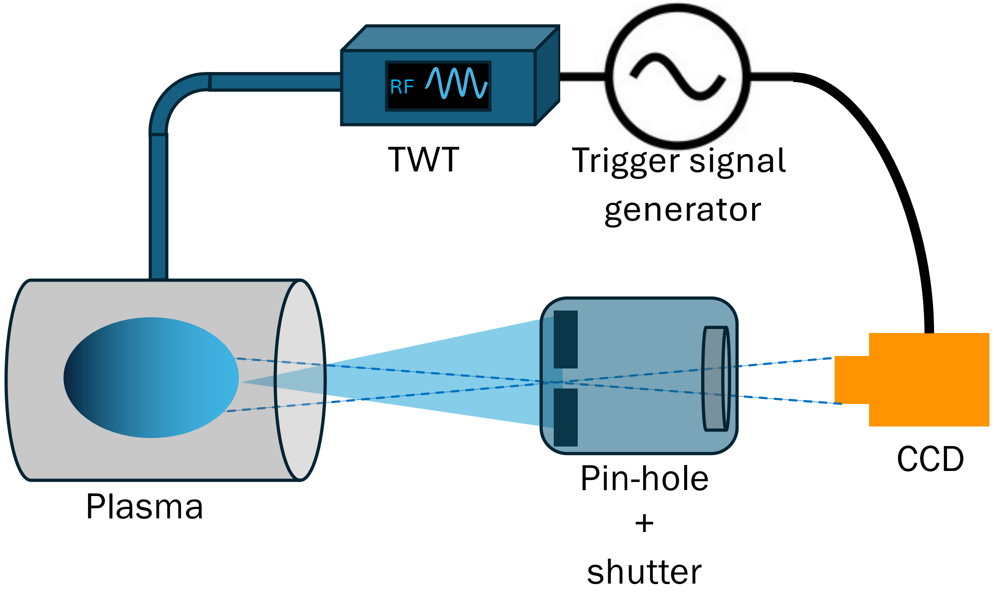
Experimental campaign
Scheduled in November 2024
at Atomki, Debrecen

atomki DEBRECEN

Time-resolved study of plasma transient

Plasma ignition transient investigation

- External trigger on both plasma ignition and CCD shutter



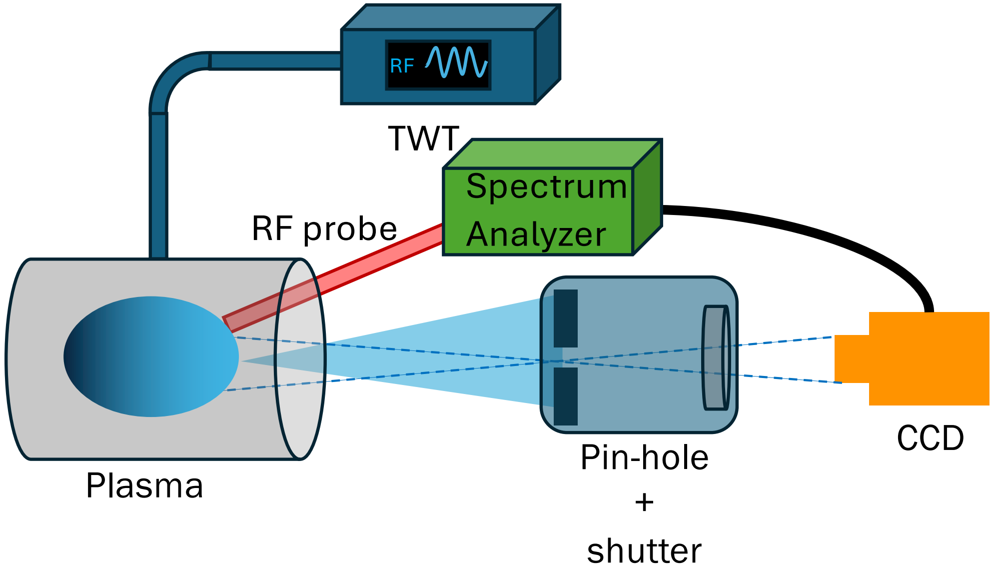
Feasibility study to evaluate the potential of the technique for plasma monitoring

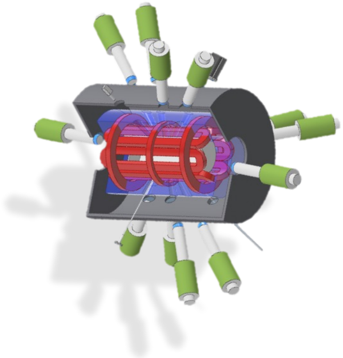
Experimental campaign Scheduled in November 2024 at Atomki, Debrecen

Time-resolved study of plasma instability

Plasma instability investigation

- Acquisition triggered by plasma instability RF emission
- X-ray burst analysis



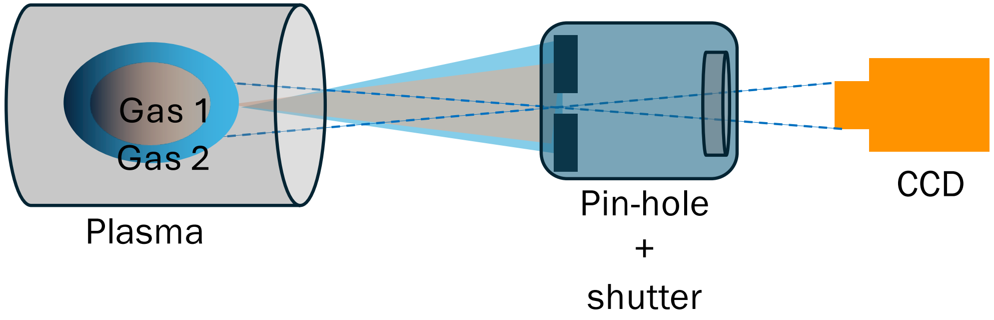


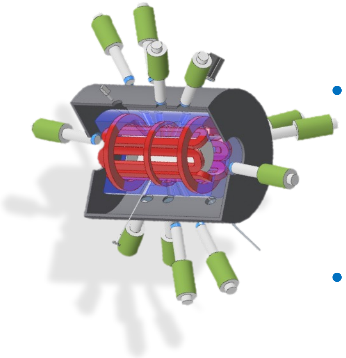
PANDORA β-decay measurements will require the continuous monitoring of **plasma stability**

Experimental campaign
Scheduled in November 2024
at Atomki, Debrecen

Gas-mixing confinement investigation

Fluorescence analysis to map the magnetic confinement of mixed gas configurations



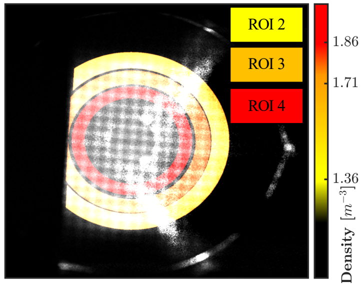


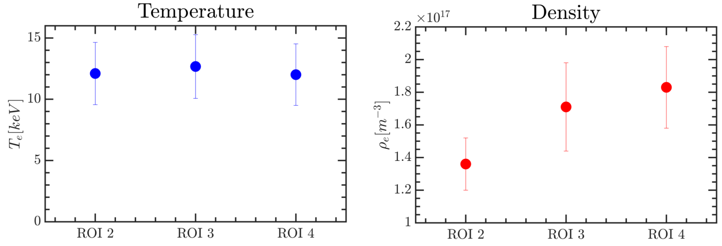
- Relevance in PANDORA measurement (effects of gas-mixing on plasma stability and confinement dynamics)
- Interest in ECRIS research

Experimental campaign
Scheduled in November 2024
at Atomki, Debrecen

Conclusions

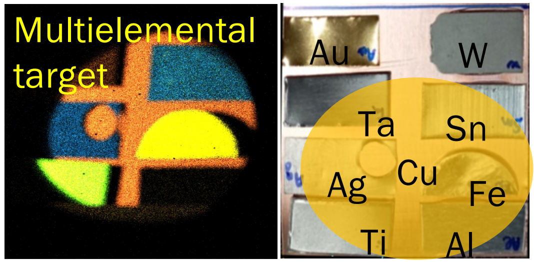
- **Space-resolved extrapolation of plasma parameters**

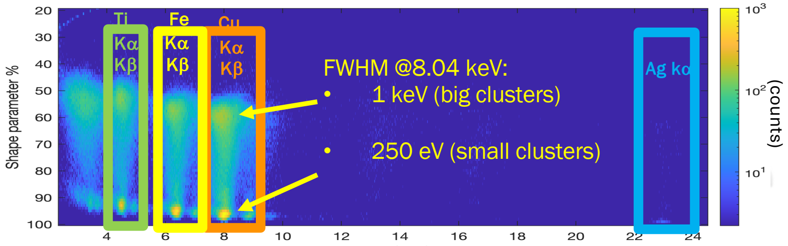




G. Finocchiaro et al., Phys. Plasmas 31, 062506(2024)

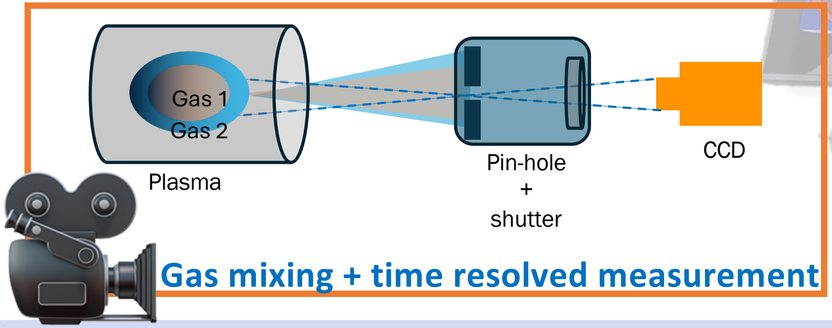
- **Acquisition system characterization**



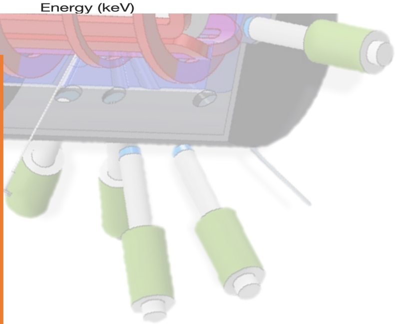


FWHM @8.04 keV:
- 1 keV (big clusters)
- 250 eV (small clusters)

- **Experimental campaign at Atomki**



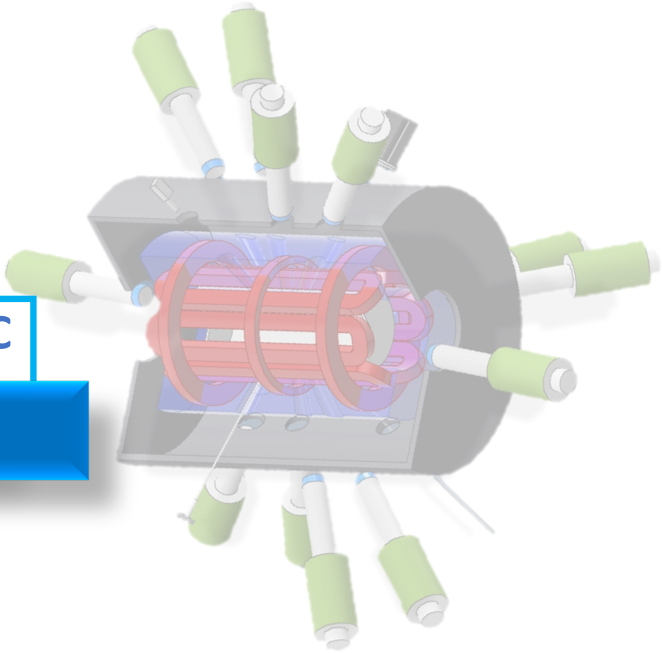
Gas mixing + time resolved measurement



Ongoing and perspectives

- 3D plasma tomography technique development
- On-line plasma thermodynamics monitoring during PANDORA β-decay measurements
- AI-based algorithm development to enhance the SPhC imaging analysis

Part II:
Bianca Peri



Thanks for your attention