Preliminary space and time resolved characterization of X-ray emission from an ECR magneto-plasma in the PANDORA project frame

G. Finocchiaro[1,2,3], M. Bezmalinovich [4,5], S. Biri[6], G. Emma[1,3], G. S. Mauro[3], M. Mazzaglia[3], B. Mishra[1,3], E. Naselli[3], A. Pidatella[3], R. Rácz[6], D. Santonocito[3], G. Torrisi[3] and D. Mascali[3]

[1] *Università degli Studi di Catania, Italy*

[2] *CSFNSM, Catania, Italy*

[3] *INFN-LNS, Catania, Italy*

[4] *Università degli Studi di Camerino, Italy*

[5] *INFN, Perugia, Italy*

[6] *ATOMKI, Debrecen, Hungary*

Abstract: Theoretical predictions suggest that the behavior of β-decays can dramatically change in relation to the ionization state of in-plasma isotopes [1]. The PANDORA project [2] aims at measuring nuclear β-decays in stellar-like conditions in high-temperature plasmas confined in B-minimum magnetic traps. The innovative experimental method requires a continuous monitoring of plasma parameters. X-ray space-resolved emission characterization by pinhole focusing technique can provide relevant features of the magneto-plasma [3] in terms of distribution of its density and temperature. We arranged a full-field X-ray pinhole setup consisting in a 400μm hole in a lead disk embedded inside a multi disk collimation system coupled with a 4MP X-ray (0.4 – 30 keV) CCD camera. For the first time the system was coupled to a Pt-Ir shutter to suppress the readout effects, thus permitting SPhC (single photon counting) acquisitions at low exposure times, t_{exp} ~ ms. An X-Ray measurement line on the so-called Flexible Plasma Trap (used as test bench for PANDORA) was arranged. A set of measurements has been performed at different plasma conditions. First collected images will be processed by an original algorithm [4] to perform space-resolved spectroscopy and spectrally resolved imaging.

1 - Introduction

An innovative plasma diagnostic method and recent results consisting of energy-resolved X-ray imaging in Single Photon Counting (SPhC) mode, by a pinhole focusing technique on silicon CCD camera, are here presented. In collaboration with the Debrecen-Atomki research group, first energy-resolved SPhC imaging measurements were carried out in 2014, characterizing ECR plasmas at relatively low heating RF power (up to 30 W) [5]. In 2018, higher power domains (up to 200 W) were reached by the developing of a specific algorithm for data analysis [4] and improving the whole setup [6]. A further upgrade of the setup has been recently done, by installing a high-performance X-ray shutter able to suppress the readout effects and thus permitting acquisition at low exposure times as never done before. The new set of measurements, devoted to characterizing an Argon+air plasma excited by microwave at a frequency of 3.75 GHz, 300 W of power and at a pressure of 10^{-4}mbar, is described in the present work. The experimental campaign was carried out in Catania at INFN-LNS by using the Flexible Plasma Trap (FPT), an ECR plasma trap specifically designed as test bench of PANDORA.

2 - Experimental setup

ECR magnetic traps are commonly used in many research fields and applications. In these tools plasma can be excited by microwave resonance and confined by an external magnetic field. FPT consists of a stainless-steel cylindrical vacuum chamber surrounded by a system of three magnetic coils which can typically generate different magnetic field profiles. Here, a Simple Mirror profile was set (see *fig. 1, right*). The X-ray diagnostics system (see *fig. 1, left*), installed inside a dedicated in-vacuum line connected to the plasma chamber, consists of:

- Princeton X-ray CCD camera: 2048x2048 13.5μm pixels, 5 eV-30 keV of sensitivity range;
- Uniblitz XRS6 Pt-Ir shutter: X-ray blocking up to 30keV, minimum exposure time 10 ms;
- Lead pinhole collimator: 2 mm of thickness, 400 μm of hole diameter;
- Al window of 0.8 μm of thickness: in order to block visible light and X-ray up to 450

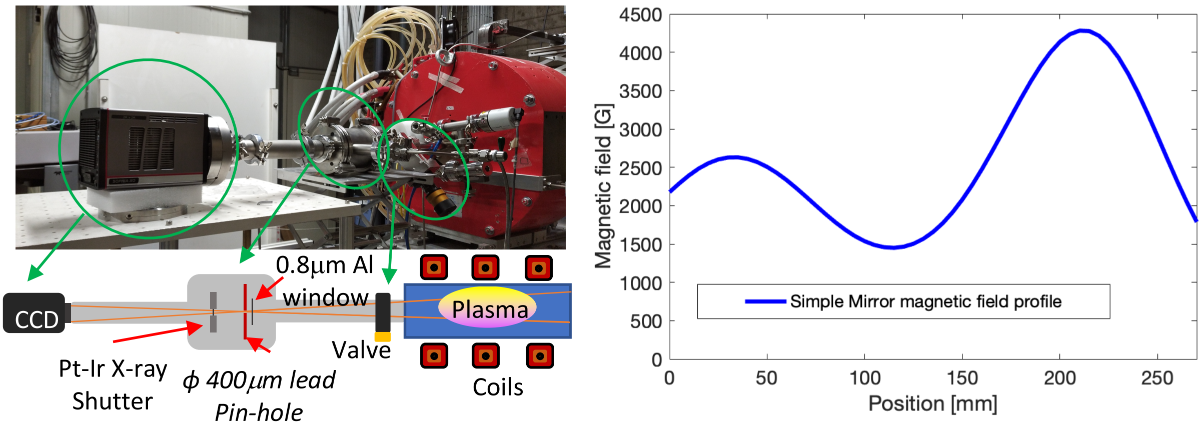
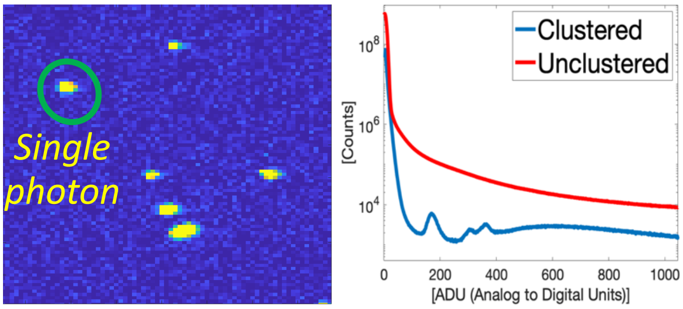


Figure 1 – Picture and sketch of the experimental setup (left) and typical magnetic field configuration (right).

All these components are aligned in a ϕ=40mm vacuum pipe to focalize X-ray on the CCD with a magnification of 0.72 at the middle of the plasma chamber. The shutter is triggered by the camera acquisition to avoid the exposure during the readout time, allowing to acquire very readout-clean pictures. This is very important particularly considering the high reading time (~2s) compared to the typical exposure time (t_{exp}~ms). In order to perform SPhC analysis and obtain spectrally-resolved imaging, it is in fact necessary to minimize signal pile-up and, so the t_{exp} must be drastically reduced at the minimum (10 ms). To collect enough photon counts, 2000 frames have been acquired for a total t_{exp} of 20s performed in 2 hours of continuous acquisition.

3 - Photon counting data analysis and preliminary experimental results

The main feature of this method is the SPhC imaging. To perform this, a specific algorithm was properly developed [4] to recognize each single photon event and the respective overflowed cluster of pixels, as shown in *fig. 2a*. Every count on energy spectra is obtained by the sum of all the charge on the cluster of each single photon event (blue spectrum in *fig. 2b*), once the spurious events due to multi-photons are recognized and filtered out.



(a) *(b)*

Figure 2 – (a) Zoomed-in frame showing clusters of pixels of single photon events. (b) Energy spectrum of single pixel raw data (red line) compared to the one obtained by cluster-postprocessed analysis (blue line)

As shown in *fig. 2b*, energy spectra representing pixel per pixel information of the raw data without applying the clustering process (shown in red), completely loses all the photons energy information. A typical spectrum obtained by post-processed analysis is shown in *fig. 3* (on the top-right).

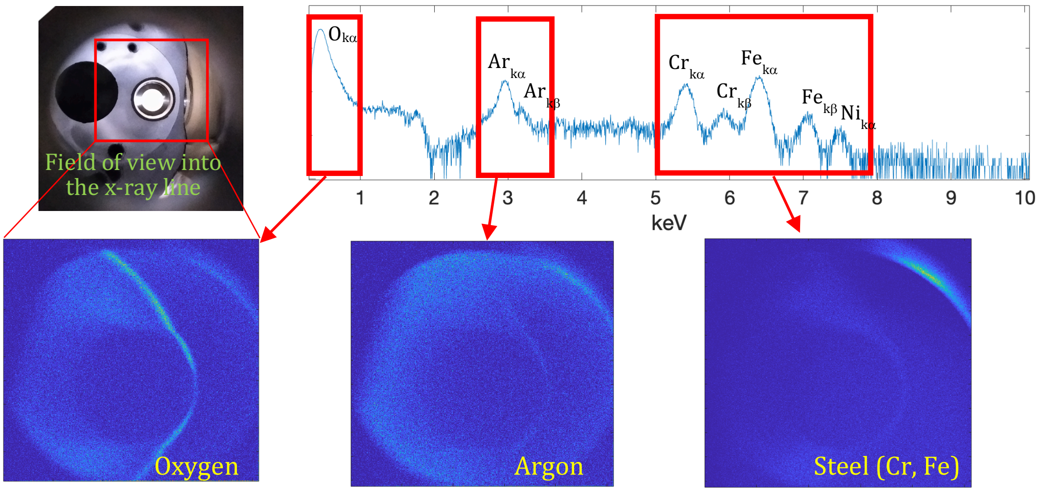


Figure 3 – Top-left: field of view into the X-ray line; top-right: measured X-ray spectrum with highlighted main fluorescence peaks. Bottom: energy-filtered imaging in the respective energy ranges of O, Ar, Cr, Fe

The energy resolution is 230 eV (measured at 3 keV), with a respective calculated space resolution of 700 µm. It is possible to well distinghuish the characteristic fluorescence peaks of the atomic species into the field of view, coming from both the plasma and the chamber's walls emission. The identification of the fluorescence peaks in the spectrum allows to investigate the elemental spatial-distribution and produce the corresponding energy-filtered images. *Fig. 3* (bottom) shows the energy-filtered images obtained by selecting the fluorescence emission coming from oxygen (Kα @ 525 eV), argon (Kα @ 2.96 keV) and the main components of steel (Cr, Fe: respectively, @ 5.41 keV and 6.40 keV). The gas mixing operations highlight the different displacement of atomic species into the plasma. By analyzing these images and comparing the emission coming from different ROI (Regions of Interest), it is possible to study in details plasma structure and confinement dynamics. Moreover, also dynamics of losses investigation can be carried out: the emission from steel elements shown in *fig. 3* (bottom) evidences a flux of deconfined electrons impinging on the plasma chamber walls. This approach allows powerful invesigations compared to the previous studies on losses dynamics [7], which were performed operating only in long exposure time mode, losing the energy information of photons.

Conclusions and perspectives: Experimental results confirm that the described imaging method is a valid and powerful plasma diagnostic tool. Energy-resolved imaging make possible the study of elemental space distribution, giving information about plasma structure and confinement dynamics, with outstanding spatial resolution. The improvement of the setup allowed to acquire SPhC images of a plasma heated at high power domain, setting very low t_{exp}, suppressing almost totally the huge readout effect. The next step will be a characterization of different plasma configurations, (i.e., pressure, gas mixing, frequency, power, magnetic field). In addition, the use of the shutter will allow space- and time-resolved acquisitions, i.e., during plasma discharge or transient of plasma between stable and turbulence regimes. Ongoing analysis is being developed to extrapolate local thermodynamic plasma parameters from the continuum shape of energy spectra. According to the emissivity models [8], it is possible to fit the experimental emissivity with a Maxwell-Boltzmann distribution, which provides plasma temperature and density. Moreover, a new model to directly link the experimental local information to local plasma parameters is under development [9]. The analysis for plasma density and temperatures is ongoing and will be the subject of the paper soon.

References

[1] Takahashi, K.; Yokoi, At. Data Nucl. Data Tables 1983, 36, 375

[2] D. Mascali et al. Universe 2022, **8(**2), 80

[3] E. Naselli et al. J. Instrum. 2022, 17, C01009

[4] E. Naselli et al. Condens. Matter 2022, 7, 5

[5] R. Rácz et al., Plasma Sources Sci. Technol. 26 (2017) 075011.

[6] S. Biri et al., J. Instrum. 2021, 16 P03003.

[7] D. Mascali et al., Plasma Phys. Control. Fusion, 2022, 64 035020.

[8] A. Gumberidze et al., Rev. Sci. Instrum. 81 (2010) 033303.

[9] B. Mishra et al., Phys. Plasmas. 28 (2021) 102509.