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AI Tools for Plasma Diagnostics by X-ray Imaging and Spectroscopy in ECR plasmas

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Magnetized ECR plasmas in compact traps are used in ion-source technology, accelerator physics, materials science, and beyond. At INFN-LNS the novel PANDORA facility is also thought as a powerful plasma-based infrastructure dedicated to fundamental research on nuclear decays in plasmas and for various applications. In this frame, an advanced diagnostic system has been developed, enabling non-invasive measurements of plasma properties. Indeed, plasma parameters critically influence the extracted beam's current, charge state, emittance, and stability, therefore their careful investigation is needed to address future development of ECRIS.

We have developed an innovative algorithm for soft X-ray imaging in Single-Photon Counting (SPhC) mode, enabling space-resolved soft-X-ray spectroscopy and magneto-plasma diagnostics (local thermodynamics, confinement dynamics, structure) via an X-ray pinhole CCD camera. This work presents its further development and optimization through an AI-based machine-learning model implemented in MATLAB.

Using datasets acquired under varied plasma conditions in two magnetic traps—the B-minimum ECR ion source at ATOMKI (Debrecen) and the simple-mirror Flexible Plasma Trap (FPT) at INFN-LNS—each photon event on the CCD was characterized by geometric and intensity-related features. A K-means clustering–based AI tool characterized similar events, revealing parameters that discriminate real from spurious signals. From these clusters, we built a labelled dataset in order to train a neural network that minimizes spurious pile-up events. This approach aims to accelerates plasma emission-spectrum retrieval with improved energy and spatial resolution, maximizes signal-to-noise ratio, and delivers significant speed and accuracy in characterizing soft-X-ray fluorescence and bremsstrahlung emissions from such plasmas.

Primary author: PERI, Bianca (Istituto Nazionale di Fisica Nucleare)

Co-authors: Dr PIDATELLA, Angelo (Istituto Nazionale di Fisica Nucleare); Dr MISHRA, Bharat (Istituto Nazionale di Fisica Nucleare); Prof. MASCALI, David (Istituto Nazionale di Fisica Nucleare); Dr SANTONOCITO, Domenico (Istituto Nazionale di Fisica Nucleare); Dr NASELLI, Eugenia (Istituto Nazionale di Fisica Nucleare); Mr FINOCCHIARO, Giorgio (Istituto Nazionale di Fisica Nucleare)

Presenter: Dr NASELLI, Eugenia (Istituto Nazionale di Fisica Nucleare)

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