

Laboratory magnetoplasmas as an ideal experimental environment for nuclear astrophysics β -decay studies

Eugenia Naselli^{1,*}

¹Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN-LNS), Catania, Italy

Abstract. The PANDORA project proposes a new experimental approach aimed at using laboratory magnetoplasmas (which emulate some stellar conditions) as an environment for in-plasma β -decays investigations. In the superconducting PANDORA trap, a hot plasma containing a known concentration of β -decaying atoms can be confined and kept in dynamic equilibrium for weeks. The decay rate can be measured by detecting the γ -rays emitted by the daughter nuclei (through HPGe detector array) and correlated with the charge state distribution of radioactive ions and with the plasma thermodynamic properties using a multi-diagnostic system, whose tools and techniques are here presented.

1 Introduction

Magnetized plasmas in compact traps can become an experimental environment for studies of nuclear astrophysical interest. The PANDORA (Plasmas for Astrophysics, Nuclear Decay Observation and Radiation for Archaeometry) project [1] proposes a new experimental approach to measure in-plasma nuclear β -decays as a function of thermodynamic conditions of the environment. Theoretical models predict that the ionization state of the in-plasma isotopes can dramatically change the isotopes lifetimes [2], due to mechanism known as bound state β -decay [3], but only few experimental evidences have been collected up to now [3–5]. In the high-performance PANDORA plasma trap, a plasma is confined by multi-Tesla magnetic fields and resonantly heated by some kW of microwave power in the 18–21 GHz frequency range. The plasmas can reach $n_e \sim 10^{11} - 10^{13} \text{ cm}^{-3}$, $T_e \sim 0.1 - 100 \text{ keV}$ of electron density and temperature, respectively, and mimic some stellar-like environments, mainly in terms of the charge state distribution (CSD). Thus, radionuclides can be trapped in a dynamic equilibrium [6], maintaining an on-average locally stable density, temperature and CSD for weeks. An accuracy of about 10–15% (estimated using fast response diagnostics [7], i.e., soft-X ray spectroscopy [8]) can be achieved in terms of the maximal fluctuation of the main plasma parameters, which are deemed to be sufficient to get a good overall sensitivity in the measurement of the radioactive isotope decay. Details will be discussed in the next section. The overall structure of PANDORA setup (sketched in Fig. 1) consists of three main pillars: a) the *Magnetic Trap* [9]: a set of three superconducting coils and a hexapole for axial and radial plasma confinement; b) an *array of 14 HPGe detectors* [10] (overall photopeak efficiency 0.1–0.2%) to tag the in-plasma nuclear β -decays via the γ -rays emitted from the excited states of the daughter nuclei; c) the *plasma multi-diagnostics system* [7], consisting in a set of non-invasive diagnostic tools to locally characterize plasma thermodynamic properties.

*e-mail: eugenia.naselli@lns.infn.it

2 On-line investigation of ECR plasma thermodynamical properties

ECR plasmas are in n-LTE (non-local thermodynamic equilibrium) condition, thus the distribution function $f(\epsilon)$ is a convolution of three electron populations: the *hot* ($kT_e > 100$ keV), the *warm* (100 eV $< kT_e < 10$ keV) and the *cold* (1 eV $< kT_e < 100$ eV) one.

The experimental aim is to conceive techniques to identify the influence of extrinsic factors coming from the external plasma-environment, which influence the decay constant λ of the trapped atoms, which should be in turn a function of the plasma electron density n_e and their energy distribution $f(\epsilon)$: $\lambda \equiv \lambda(n, f(\epsilon))$. Due to the dynamical equilibrium (n_e and $f(\epsilon)$ are kept constant within 10-15% over time) the number of expected decays N scales linearly with time as: $N(t) = \lambda(n_e, f(\epsilon)) n_i V_p t$, being V_p and n_i the plasma volume and the isotope density.

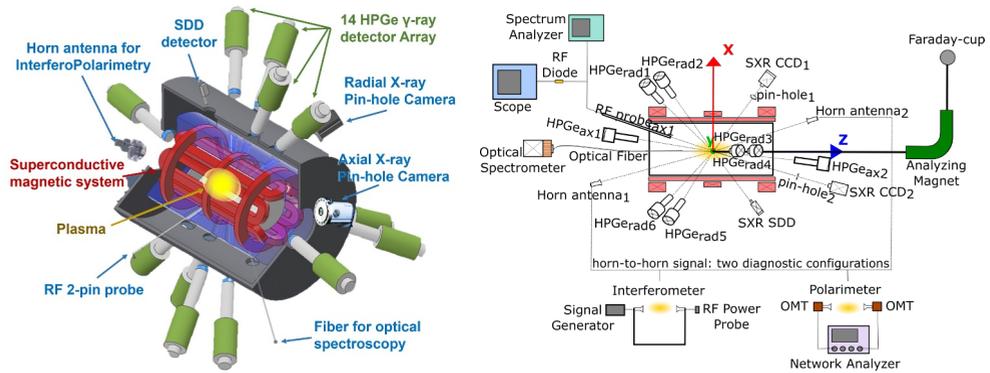


Figure 1. Rendering (left) and sketch (right) of the PANDORA setup with the systems used to measure in-plasma activity (14 HPGe detector array) and monitor plasma properties (multi-diagnostics system).

The core issue is to univocally determine n_e and $f(\epsilon)$, inherently fixing the CSD, to be correlated with the γ counting rate: this can be done identifying simultaneously plasma self emitted photons from microwaves to γ -rays. For a complete characterization of the overall $f(\epsilon)$, a multiplicity of tools and analysis methods becomes necessary [1, 7]. Due to the non homogenous nature of the plasma, this has to be done also using space and time-resolved techniques. A sketch of the multi-diagnostic system is shown in Figure 1-right and the main experimental techniques are summarized in the following. In particular, they are:

- **Volumetric X-ray Spectroscopy:** warm and hot electron populations can be studied through soft-X (Silicon Drift Detector SDD) and hard-X (HPGe detectors) volumetric spectroscopy. T_e and n_e can be estimated (with a typical relative error of around 10%-15%) by directly fitting experimental data, comparing the experimental spectrum with the theoretical one based on emissivity model [11–13]. The theoretical emissivity $J_{th}(h\nu)$ [11] is:

$$J_{th}(h\nu) = n_i n_e (Z\hbar)^2 \left(\frac{4\alpha}{\sqrt{6}m_e} \right)^3 \left(\frac{\pi}{kT_e} \right)^{\frac{1}{2}} e^{(-h\nu/kT_e)} \quad (1)$$

thus, it is possible determining n_i and n_e (from spectrum's fit intersection with the vertical axis) and T_e (inversely proportional to the slope). Fig. 2.a) shows two hard X-ray spectra in which the measured temperature is 95 keV (blue) and 35 keV (red) respectively [8].

- **Spectrally-resolved soft X-ray Imaging:** the innovative pin-hole CCD camera technique [14], operating in single-photon-counted (SPhC) mode [15], allows spectrally-resolved

imaging in the soft X-ray domain and, therefore, a deeper investigation of the parameters of the warm component. Figure 2.b) shows a SPhC soft X-ray energy-filtered image, corresponding to X-rays coming from plasma due to ionized $K\alpha$ Argon lines (red) and X-rays coming from plasma chamber wall material, due to excited Ti (green) lines. Characteristic peaks associated to the emission from each material allow to investigate the spatial structure of the plasma [16] and confinement dynamics (plasma vs. losses X-ray emission) [17]. A model to link the experimental information to local plasma parameters is under development [12]. The profile of $K\alpha$ emission intensity can be considered as: $I_{K\alpha} \propto n_{Ar}n_e < \sigma_{K\alpha} \nu >$, where $\sigma_{K\alpha}$ is the $K\alpha$ fluorescence cross section, the term $n_{Ar}n_e < \sigma_{K\alpha} \nu >$ is the total reaction rate. An estimation of $\sigma_{K\alpha}$ [12] and of the density and energy spatial distributions by simulations [13, 18] was given and the analysis for getting n_e and T_e is ongoing. In PANDORA two CCD pin-hole cameras will be used simultaneously (along the axial and radial lines) to estimate the plasma volume and thermodynamic conditions in each voxel, i.e. by a multi-pinhole tomography approach [19].

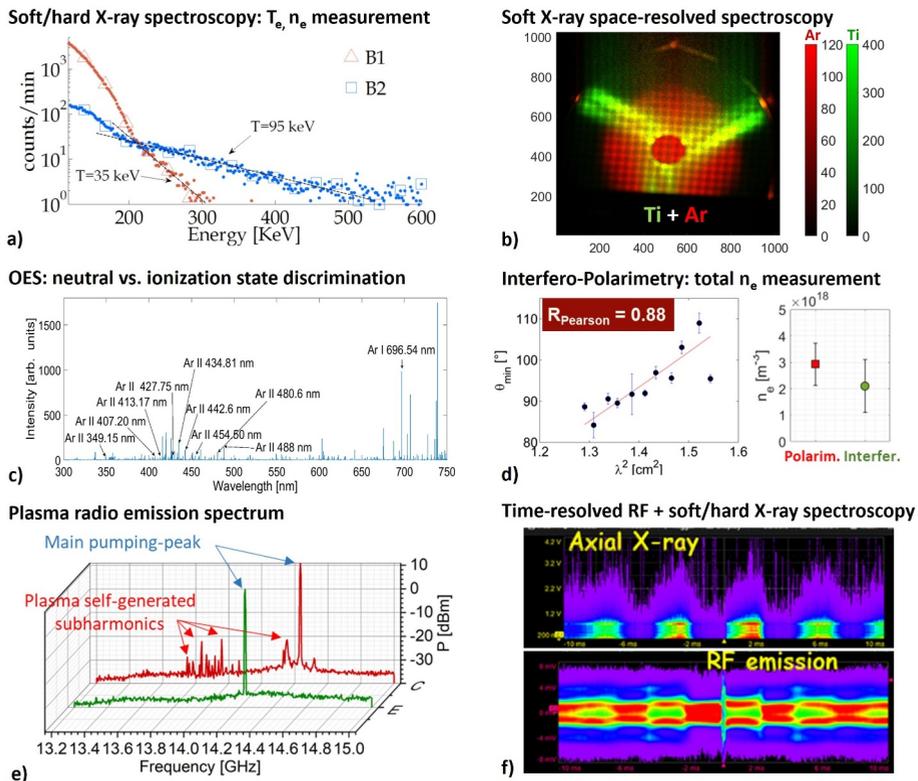


Figure 2. Overview of the main experimental results obtained through the multi-diagnostic system. a) Volumetric hard X-ray spectrum for two magnetic field profiles; b) Energy-filtered SPhC image of fluorescence X-rays coming from plasma (Ar) and from chamber walls materials (Ti); c) Optical emission spectrum of an Ar plasma; d) Faraday angle vs. probing wavelength in a polarimetric measurement (left) and total n_e measure by microwave interferometer and polarimeter (right); e) Plasma radio emission spectrum in a stable (green) and turbulent regime (red); f) time-resolved RF and hard X-ray spectra.

- **Optical Emission Spectroscopy (OES):** the cold population can be characterized by OES measurements, comparing the experimental measured line ratio with the theoretical one

estimated by means of a Collisional Radiative model [20–22], measuring the cold n_e and T_e with uncertainties that are less than 15% and 30%, respectively. Figure 2.c) shows a typical optical spectrum where it is possible to discriminate the neutral vs. the ionization state of an Ar plasma. For hydrogen plasma is possible to distinguish the molecular vs. atomic state and the lines of interest are the Balmer series (H_β/H_γ and H_α/H_β ratios). In perspective, the powerful spectrograph SARG (Spetrografo Alta Risoluzione Galileo), installed at LNS and reaching $R=160.000$ of resolution, will allow in-plasma on-line CSD measurement.

- **Microwave Interferometry and Polarimetry:** an interfero-polarimeter system, based on two high directive horn-antennas [23], allows to measure the total line-integrated density n_e . The polarimetric measurement is based on the evaluation of the Faraday rotation angle θ_{Far} of the polarization plane of a probing wave crossing the plasma, which is proportional to the square of the wavelength λ , to n_e (measured by fitting) and to magnetic field B (known), see fig. 2.d)-left. The equation is shown in the follow, where e , m , c , L are the charge and mass of electron, the speed of light and the plasma chamber length, respectively:

$$\theta_{Far} \propto \left(\frac{e^3}{2\pi m^2 c^4} \int_0^L n_e B dz \right) \lambda^2 \quad (2)$$

The interferometric n_e measurement is based on the phase-shift induced by the plasma refractive index. Results obtained by interferometry and polarimetry are in good agreement [24] (fig. 2.d-right), with errors respectively of 50% and 27%. Further improvements are expected by a new approach under development, based on a superheterodyne scheme to detect the Lissajous figure of the probing RF signals crossing the plasma [23], and in perspective by means of the microwave imaging profilometry to also measure the n_e profile.

- **RF diagnostics - plasma RF emission:** plasmas have to be maintained stable for weeks, avoiding onset of kinetic turbulences. Plasma stability can be monitored by means of a multi-pins RF probe connected to a Spectrum Analyzer, able to perform spectral analysis in the frequency domain [24]. Since plasma kinetic instabilities are characterized by RF and X-ray bursts (respectively with timescales of ns and ms), plasma radio-emission can be used as signature of turbulences. Two typical plasma radio emission spectra, respectively for a stable (green) and turbulent (red) regime, are shown in Fig. 2.e). In the latter case, the sub-harmonics are well visible and allow to quantitatively measure turbulences. For this purpose, a new parameter I_S was semi-empirically defined as follow [25]:

$$I_S = \left(\int_{13GHz}^{15GHz} \frac{dP(f)}{df} df - P_{mp} \right) (1 + w(N_{sub} - 1)) \quad (3)$$

where P_{mp} is the integral of the power of the main peak of pumping frequency, N_{sub} the number of sub-harmonics and w a weight factor. Since the instability strength is related both to the amplitude of the sub-harmonics and to their frequency spread, I_S was defined accordingly. It was calculated considering the amplitude (integral of the power) of RF plasma-self emitted signal, once subtracted the main pumping wave contribution, and then multiplied by a factor which considers the number of sub-harmonics N_{sub} with a proper weight factor w , which was optimized and set at 0.1. Experimental evidences demonstrated that I_S follows in a reasonable way what happens in the plasma in unstable conditions.

- **Time-resolved RF + soft/hard X-ray spectroscopy:** by connecting the RF probe with a diode and a scope it is possible to obtain high-resolution time-resolved (but totally integrated) power emitted from the plasma, using this value as trigger signal for X-ray detectors in order to perform volumetric X-ray spectroscopy [24]. Fig. 2.f) shows a comparison between the time-resolved RF spectra (bottom) vs. X-ray flux acquired by HPGe detector

(top, reporting X-ray bursts in a turbulent regime of the plasma). This tool allows spectrally and timely characterization of turbulent plasma regimes, with a twice relevant outcome: i) a new "knob" for mastering plasma instabilities and maintain the plasma stable for weeks; ii) reproduce and study phenomena of astrophysics interest (kinetic turbulence occurring in astrophysical objects, i.e. Cyclotron Maser Instability [26]) in laboratory plasmas, measuring several properties even in the transient regimes. In perspectives, simultaneously space- and time-resolved spectroscopy will be performed by triggering the pin-hole system at the onset of plasma turbulences: this will allow to reach unprecedented capability of analysis of plasma dynamics, studying how the plasma shape and morphologies change during the time in a turbulence regime, also locally determining plasma parameters.

All diagnostics tools will operate simultaneously with a Faraday cup to measure the CSD.

3 Conclusion

PANDORA represents a promising experimental setup to verify, for the first time, the theoretical predictions on the dependence of lifetime on ion CSD. When the PANDORA setup will be ready (expected by 2024) the system will allow the simultaneous characterization of plasma properties, by a multidagnostic system whose tools and techniques were described in this paper, and β -decay rates, also monitoring plasma stability and mitigating turbulences.

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