Nuclear β-decays in plasmas: how to correlate plasma density and temperature to the activity

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Abstract. Magnetized plasmas in compact traps may become experimental environments for the investigation of nuclear beta-decays of astrophysical interest. In the framework of the project PANDORA (Plasmas for Astrophysics, Nuclear Decays Observation and Radiation for Archaeometry) the research activities are devoted to demonstrate the feasibility of an experiment aiming at measuring lifetimes of radionuclides of astrophysical interest when changing the charge state distribution of the in-plasma ions and the other plasma parameters such as density and temperature. This contribution describes the multidiagnostics setup now available at INFN-LNS, which allows unprecedented investigations of magnetoplasmas properties in terms of density, temperature and charge state distribution (CSD). The setup includes an interfero-polarimeter for total plasma density measurement, a multi-X-ray detectors system for X-ray spectroscopy (including time resolved spectroscopy), an X-ray pin-hole camera for high-resolution 2D space resolved spectroscopy, a two-pin plasma-chamber immersed antenna for the detection of plasma radio-self-emission, and different spectrometers for the plasma-emitted visible light characterization. The setup is also suitable for other studies of astrophysical interest, such as turbulent plasma regimes dominated by the so-called Cyclotron Maser Instability, which is a typical kinetic turbulence occurring in astrophysical objects like magnetized stars, brown dwarfs, etc. A description of recent results about plasma parameters characterization in quiescent and turbulent Electron Cyclotron Resonance-heated plasmas will be given.

1 Introduction

The construction phase of a new experiment finalized at measuring nuclear decays in magnetized plasmas confined in compact traps will start in 2020, supported by INFN. Since the ionization state of the in-plasma isotopes can modify, even of several orders of magnitudes, the expected isotope lifetimes [1, 2], the project, called PANDORA (Plasmas for Astrophysics, Nuclear Decays Observation and Radiation for Archaeometry) [3] aims, for the first time, to measure the influence of the plasma charge state distribution on the nuclear lifetime. An

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innovative design of a new high-performance ECR (Electron Cyclotron Resonance) plasma trap, in combination with a new multi-diagnostics setup consisting of a set of non invasive tools, has been developed and will be improved on purpose.

In the plasma trap we plan to build, the radionuclides can be trapped in a dynamic-equilibrium, in a Magneto Hydro Dynamically (MHD) plasma, living for several hours or days with on-average constant local density and temperature (the plasmas reach $n_e \sim 10^{11} \div 10^{13} cm^{-3}$, $T_e \sim 0.1 \div 100 keV$ of electron density and temperature, respectively). The CSD can be modulated according to the pumping RF power, the magnetic field and the background pressure. The decay rates can be then characterized with respect to the CSD variation, and versus the plasma density and temperature, in a stellar-like condition (as concerns, mainly, the CSD conditions).

The ECRIS plasmas displays charge distributions very closely resembling the ones of stellar environments. First calculation at ECRIS (ECR ion source) densities and temperatures confirm that even in non-LTE (non-Local Thermodynamic Equilibrium) conditions (due to the low density) the abundances of charge states are - for many of the selected physics cases of astrophysics interest - very similar to the ones occurring in astrophysical conditions, where densities are ten order of magnitude higher [4].

This makes the experiments running in an ECRIS directly scalable to astrophysical systems.

2 The PANDORA Multidiagnostic Setup

In the framework of the PANDORA project, the development of an innovative diagnostic setup and the improvement of advanced analysis methods are mandatory for two main reasons:

1) an accurate on-line monitoring of all plasma parameters aiming to characterize in detail the plasma environment; on this purpose, an innovative multi-diagnostic setup has been developed, able to investigate the plasma properties in all energetic domains, also performing high-resolution spatial and time resolved analysis. Details about characteristics of each tool and an overview of recent experimental results will be presented in the section 2.1;

2) in order to estimate the lifetime of the isotopes it is necessary to find an efficient detection method for decays tagging. Since several physics cases involve emission of γ-rays, the total amount of decays become, in these cases, detectable via γ-rays tagging by means an array of several HpGe detectors (even if also other methods will be investigated). In order to estimate the efficiency of decay-products tagging, simulations by GEANT4 have been carried out, and details will be discussed in the section 2.2.

In a nutshell, the PANDORA full-scale includes the construction of an innovative superconducting magnetic trap, with advanced multi-diagnostics system, and a large array of HpGe detectors for the tagging of the decay products.

2.1 Plasma environment characterization

Since ECRIS plasmas are in non-LTE condition, the typical Electron Energy Distribution Function (EEDF) is deemed to consist of three different electron populations: the *hot* population (typical temperatures around 100 keV or more), the *warm* population (temperatures in the range 100 eV ÷ up to tens of keV) and the *cold* population (temperatures in the range of 1 eV ÷ 100 eV). For a complete characterization of ECR plasmas it is useful measuring the plasma parameters in all three different energy regimes. In table 1, all diagnostic tools developed in the last years, with their most relevant characteristics are listed (see [5, 6] for more details). Each tool is able to perform a characterization in a typical electron energy

domain: the simultaneous use of all setups plays a crucial role for the detailed and complete characterization. The setup has been already used for plasma characterization in two different *down-sized* (compared to the full-scale PANDORA trap) magnetic plasma traps: in the compact, simple-mirror plasma trap installed at INFN-LNS, called Flexible Plasma Trap (FPT); and in the ECR ion source at the ECR Laboratory of Atomki, in Debrecen, based on a B-minimum magnetic configuration.

Table 1. Lists of the non invasive tools, with their most relevant characteristics, being part of the multi-diagnostic setup.

Diagnostic Tool	Sensitive Range	Measurement	Resolution & Meas. Error
SDD	$1.0 \div 30$ keV	Soft X-ray Spectroscopy: warm T_e and n_e	Res. ~ 120 eV $\epsilon_{n_e} \sim 7\%$, $\epsilon_{T_e} \sim 5\%$
HpGe	$30 \div 400$ keV	Hard X-ray Spectroscopy: hot T_e and n_e	Res. ~ 200 eV $\epsilon_{n_e} \sim 7\%$, $\epsilon_{T_e} \sim 5\%$
Visible Light Camera	$1.0 \div 12$ eV	Optical Emission Spectr.: cold T_e and n_e	$\Delta\lambda = 0.04$nm R=12500
Microwave Interferometer	K-band $18 \div 26.5$ GHz	Interferometric Meas.: line integrated total density	$\epsilon_{n_e} \sim 50\%$
Microwave Polarimeter	K-band $18 \div 26.5$ GHz	Faraday-rotation Meas.: line integrated total density	$\epsilon_{n_e} \sim 25\%$
X-ray pin-hole Camera	$2 \div 15$ keV	2D Space-resolved soft X-ray Spectroscopy	Energy Res.$\sim$0.32 keV Spatial Res.$\sim$0.56 mm
RF probe + SA	$10 \div 26.5$ GHz *(probe)*	Frequency-resolved Spectroscopy	Resolution bandwidth: RBW = 3 MHz
RF probe + Scope + HpGe	$10 \div 26.5$ GHz *(probe)*	Time-resolved X-ray Spectroscopy	80 Gs/s *(scope)* time scales $\sim$ ns

The same multi-diagnostic setup is also suitable for other studies of astrophysical interest, such as turbulent plasma regimes dominated by the so-called Cyclotron Maser Instability, which is a typical kinetic turbulence occurring in astrophysical objects like magnetized stars or brown dwarfs. In the follow, a summary of a characterization performed in a recent experiment is reported:

- Since the RF plasma self-emission can represent signatures of plasma kinetic instabilities (characterized by fast RF and X-ray bursts), by means the use of the *two-pins probe [7]* connected to the *Spectrum Analyzer (SA)* it has been possible to detect and characterize turbulent plasma regimes, detecting the plasma self-emission; moreover it has been possible, for the first time, to give a quantitative estimation of the strength of the instabilities introducing a quantitative parameter and, consequently, to correlate the instability strength of a given configuration with other operative parameters [8].

- Using the *two-pins probe connected to the scope* and the *HpGe detector* we studied also the time evolution of Radio and X-ray spectra: a) radio-signals detected along and across the magnetic axis have been measured in a timescale <100 nsec; b) fast HpGe detectors provide the evolution of the X-rays emitted axially and radially, allowing time-resolved spectroscopy; Both RF and X-ray signals can be ranked on a temporal sequence which provides the whole characterization of the instability.

- We simultaneously used the *pin-hole camera* as very powerful method to study the plasma structure and to investigate the intensity of the electron losses from the magnetic trap, al-

lowing, in particular, to study the confinement dynamics (plasma vs losses X-ray emission) discriminating the radial losses from the axial ones.

- When using the volumetric spectroscopies (both *HpGe and SDD*) we also measured the hard and soft X-ray rates - which provide information on the hot and warm electron components of the plasma, respectively - in different regimes (turbulent plasmas present an high X-ray rate and temperature compared to the stable configurations) [9]. Whilst, a *Visible Camera (VC)*) has been used for the plasma-emitted visible light characterization for characterizing the cold electron components of the plasma.

- Finally, the CSD of the extracted beam has been measured by means of a *mass spectrometer*.

The table shows that now the plasma temperature and density can be measured - eventually in space and resolved way - with an uncertainty that is less than 7% for the temperature, and around 25% for the total density. Partial densities of warm and hot electrons are measured via X-ray spectroscopy with less than 10% uncertainty, while use of Optical Emission Spectroscopy (OES) in the next future will allow to reduce density measurements uncertainties of at least a factor 2.

## 2.2 Isotopes decay tagging

In PANDORA, plasma parameters have to be correlated to the number of decays per second, namely the activity, of the in-plasma trapped radioisotopes, also including the plasma strong X-ray self-emitted background. In order to estimate the efficiency of decay-products tagging, by detecting characteristic γ-rays, a Monte Carlo simulation by GEANT4 toolkit has been carried out [10]. In summary, the geometrical design (a simplified sketch is shown in fig.1) consists of: 1) a stainless steel chamber (radius 175 mm, length 800 mm and thickness 10 mm) drilled with 12 holes of diameter 25mm, in order to connect long collimators for γ-rays detection; b) the overall magnetic system consisting in three NbTi superconducting coils (coloured in yellow) and the Cu hexapole (coloured in green); c) six iron bars places in the hexapole interspaces drilled in order to use them as collimators and suppress as much as possible photon flux coming from the walls and not directly from the plasma core, improving the signal to noise ratio; d) an array of 14 cylindrical γ-detectors (length ∼ 8 cm, radius ∼ 3 cm), 2 placed in the axial line (coloured in red) and 12 in the radial one (coulored in blue), placed collinearly at each collimator.
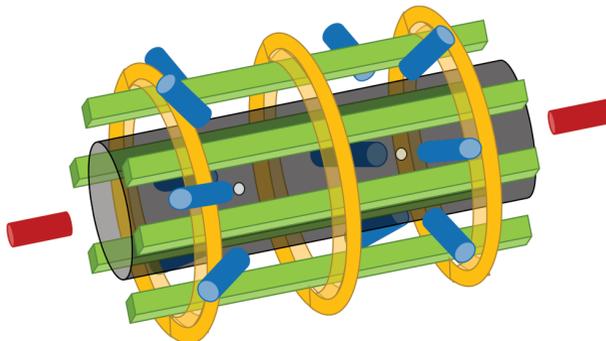
Figure 1. Sketch of the PANDORA's trap with the magnetic system (coils in yellow, hexapole in green), and the array of 14 cylindrical γ-detectors, 2 placed in the axial line (red) and 12 in the radial one (blue).

The aim of the simulations has been to estimate the total detection efficiency in order to evaluate the feasibility of the detection by means of γ-rays spectroscopy, and also to choose the best type of detector in terms of efficiency and resolution. We performed the simulation implementing and comparing two different types of detectors: HpGe detectors and Lanthanum bromide scintillation detectors ($LaBr_3$). We performed the simulation considering the emission by an isotropic source placed in the center of the plasma chamber, changing the energy of the source in the range from 100 keV to 2 MeV (typical energies of the decay-products of the radionuclides in the PANDORA physical cases). By simulations we obtained the total detection efficiency. The noise (consisting, especially, in the plasma self-emission) can affect the detection of the signal; we report in fig.2-left a typical noise spectrum, due to plasma self-emission (at $n=10^{13}cm^{-3}$, volume of 1000 cm^3 and already corrected for the evaluated efficiency).

In order to evaluate the measurement time needed to have a significative 3σ level signal, we considered, for sake of example, a signal of 0.25 cps (counts per second) in the multi detector array at a given fixed energy and we integrated the noise – estimated by the spectrum in fig.2-left) - in the resolution window of each type of detector.
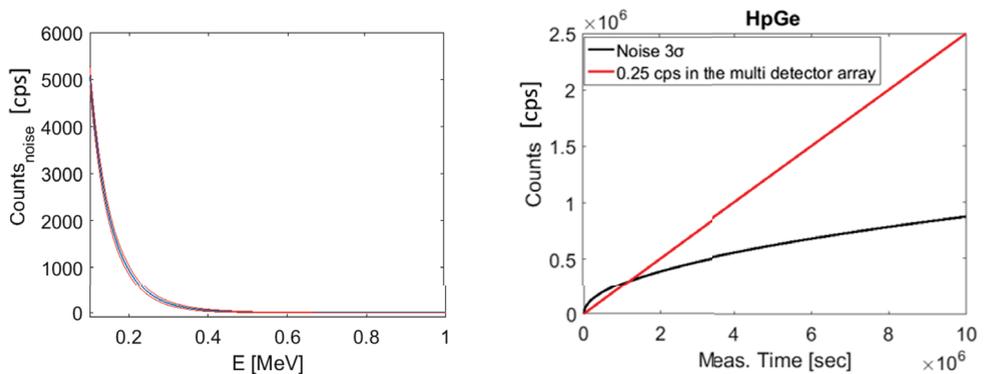
Figure 2. Left - typical noise spectrum, due to plasma self-emission. Right - trend of the *real* signal counts (in red), considering a rate of 0.25 cps (counts per second) in the multi HpGe detector array, and of the 3σ the noise level (in black).

In fig.2-right, the trend of the signal counts estimated by theory (in red) compared to the 3σ (in black) are shown, in order to see where and when the crossover point between the two curves occurs. The intersection from the two lines shows the point where the signal overcomes the 3σ noise level, and the correspondent abscissa is the measurement time needed to have a 3σ level of confidence. The results highlighted that after about several days it is possible to obtain a 3σ level using the array of HpGe detectors, whilst in the case of the array of $LaBr_3$ a much longer time is needed, the measurement resulting very challenging or, eventually, not-feasible. In this way we estimated the measurability of several physic cases, such as the Lutetium ^{176}Lu, where a γ at 306.78 keV is emitted, and the simulation results show that for the variations of the lifetime expected from the theory in our laboratory plasmas, we expect that a measure lasting from tens of days to a couple of months is needed in order to obtain a 3σ level of confidence. Similar considerations and plots have been performed also for the other physics cases of interest for PANDORA (see also [11] for other details).

3 Conclusion

In the paper, diagnostic tools that have been designed and developed to simultaneously probe an ECR plasma produced in compact magnetic traps have been presented. Other than providing valuable information for correlating nuclear decays to plasma properties, these tools are useful also for monitoring the plasma self-emitted background of X-rays, since the high energy tail can in principle affect the reliability of the detection of characteristics γ rays coming from the decay-products. GEANT4 simulations have been used to estimate and then compare the total efficiency of a 14 HpGe vs. 14 LaBr detectors arrays. The efficiency has been then used to estimate - once given a certain γ emission rate - the integral time needed to achieve statistically consistent measurements, at 3-σ level of confidence. Simulation results indicate that the experiment is feasible under a complete monitoring of plasma parameters, X-ray background and for γ ray emission rates in plasma, into the overall solid angle, of the order of 20 to 80 cps at least (which correspond, when considering the total efficiency, to the above mentioned 0.25 cps in the multi-array detector).

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