High-resolution Optical Emission Spectroscopy characterization of hydrogen and argon laboratory magneto-plasmas of astrophysical interest

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Abstract

Mergers of compact binary objects, such as binary neutron stars or neutron star-black, are among the most favorable astrophysical site to produce heavy elements in Universe via r-process nucleosynthesis [1]. In this context, it is relevant the study of kilonovae (KNe). They are electromagnetic transients powered by freshly synthesized elements that can be used as spectral signatures of nucleosynthetic yields inside the expanding post-merging plasma ejecta [2]. To this aim, in the framework of the **PANDORA** (**P**lasmas for **A**strophysics, **N**uclear **D**ecays **O**bservation and **R**adiation for **A**rchaeometry) project [3] we are developing a new plasma trap where it will be attempted the emulation of KN ejecta properties at a specific stage of their evolution. This setup will allow measurements of plasma opacity for a better interpretation of the KN light-curve, and thus a sounder constraint on the nucleosynthesis yields [4]. To verify the feasibility of this kind of measurements in terms of required temperature and density (order of eV and 10^{12} cm^{-3}, respectively), we are using the flexible plasma trap (FPT), operative at INFN-LNS, as testbench for PANDORA, characterizing gaseous plasma (H_2, Ar) parameters by Optical Emission Spectroscopy. In this work, we will present the experimental results, concerning estimates of plasma density and temperature, deduced by means of the line-ratio method [5], from the analysis of the spectra detected in the visible range under different plasma trap configurations.

Theoretical background. Beyond the iron-peak, the production of the heaviest nuclei in the Universe requires neutron capture reactions, namely the slow (s-) process and the rapid (r-) process [1]. Timescales for neutron captures in case of s-process are slow (from hundreds to thousands of years) with respect to the β-decay timescales, whereas the r-process timescales are faster (0.01-10s), thus it may proceed far from the stability valley and near to neutron drip line in the chart of nuclides. In the last decades, several studies focused the attention on identifying favorable astrophysical loci for heavy elements nucleosynthesis via r-process. It was soon clear that neutron-rich environments are required, like the merging of compact objects (binary neutron stars or neutron star-black hole mergers) as suggested from the recent multi-messenger observations of gravitational waves and their electromagnetic counterparts, namely kilonovae (KNe), which are detected after the merger's event. KNe are isotropic thermal transient which play an important role because they can provide precious information on the nucleosynthetic yields inside the expanding post-merging plasma [7]. To gain a deeper knowledge on KN ejecta properties at a specific stage of their evolution, a new plasma trap called PANDORA is under construction at INFN-LNS [3]. It will allow interdisciplinary research to measure for the first time in-plasma β-decay of the radioactive isotopes involved in nuclear astrophysics processes and it will provide measurements of plasma properties in conditions suitable for the astrophysical environments of KNe.

Experimental setup. In view of the near-future experiments to be performed in PANDORA, the first experimental attempt of reproducing plasma ejecta conditions was carried out on the **Flexible Plasma Trap** (FPT), currently operative at INFN-LNS, to characterize hydrogen and argon plasma in terms of electron density and temperature via non-invasive Optical Emission Spectroscopy (OES). The FPT consists of a cylindrical plasma chamber which can host different types of diagnostics for a complete plasma characterization in all the energy regimes. For the OES setup, which allows to investigate the thermodynamical properties of cold electron component, a spectrometer coupled to a CCD detector and an optical fiber are employed (see figure 1). During the experimental session, a hydrogen plasma or a mixture of hydrogen and argon plasma were generated by electron cyclotron resonance (ECR) and characterized by OES. In the last case, a mass spectrometer, coupled to FPT and called Residual Gas Analyzer (RGA), was used to evaluate the balance of gas to inject in the plasma trap (hydrogen at 99% and argon used as contaminant at 1%).

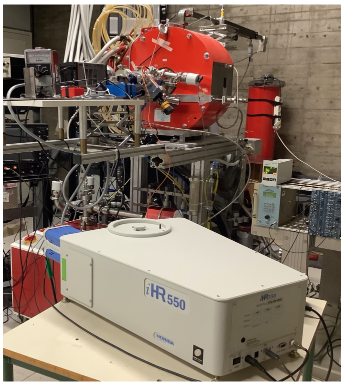

Figure 1. Experimental setup

Method of analysis. Seven experimental configurations have been explored and several spectra have been acquired for each configuration (in order to increase the statistics) under different values of microwave pumping power (P_{RF}), heating frequency (f_{RF}), gas neutral pressure (p_0) and magnetic field profile. The configurations are reported in table 1.

CONF.	P_{RF}	f_{RF} [GHz]	p_0 [mbar]	B [A]
#1. H_2	100 ÷ 250	3.76	10^{-4}	[240, 0, 180]
#2. H_2	100 ÷ 400	3.76	10^{-2}	[240, 0, 180]
#3. $H_2^{99\%}$+$Ar^{1\%}$	100 ÷ 350	3.76	10^{-2}	[240, 0, 180]
#4. H_2	40 ÷ 120	6.774	10^{-3}	[448, 45, 350]
#5. H_2	40 ÷ 100	6.786	10^{-3}	[410, -80, 345]
#6. H_2	40 ÷ 140	6.786	10^{-2}	[410, -80, 345]
#7. $H_2^{99\%}$+$Ar^{1\%}$	40 ÷ 140	6.786	10^{-2}	[410, -80, 345]

Table 1. Configurations are labelled by (#), and the gas/gas mixing type, the values of microwave power, frequency, pressure, and magnetic field are reported.

A typical hydrogen spectrum is shown in figure 2 where Balmer emission lines, H_α, H_β , H_γ, at λ=656.28, λ=486.13 and λ=434.05 nm respectively, are indicated.

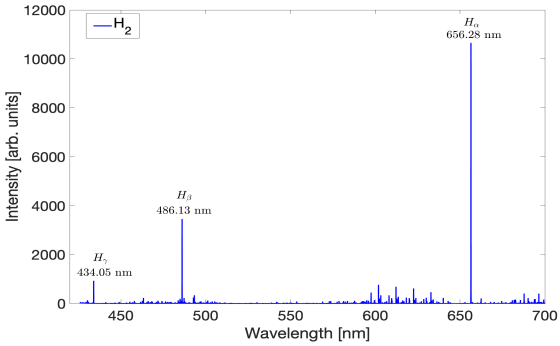

Figure 2. Hydrogen spectrum.

To determine plasma parameters, namely electron density and temperature, we applied the line-ratio method [5] to the Balmer lines by calculating the ratios $H_{\alpha\beta}$ =H_α /H_β and $H_{\beta\gamma}$=H_β/H_γ. A spectral analysis was performed on each spectrum, and it included the following steps: calculation of the ratios, $H_{\alpha\beta}$ and $H_{\beta\gamma}$, considering the area under the peaks of interest; error propagation procedure to evaluate uncertainties on the ratios; evaluation of the mean ratios and errors over all the spectra of every single configuration. Once obtained the mean ratios and the associated uncertainties, we calculated the values of density and temperature. In figure 3, the experimental $H_{\alpha\beta}$ and $H_{\beta\gamma}$ ratios are shown as solid lines in the (n_e,T_e) plane as resulting from the comparison with the expected theoretical ratios from the collisional-radiative model YACORA [8], as a function of density and temperature. The intersection is representative of a possible estimate of the average electron density and temperature. Figure 3 also shows upper and lower intersections which correspond to the maximum and minimum limits of n_e and T_e. Finally, in figure 4 values of electron density and temperature are reported together with the error bars for all the seven configurations as function of RF power.

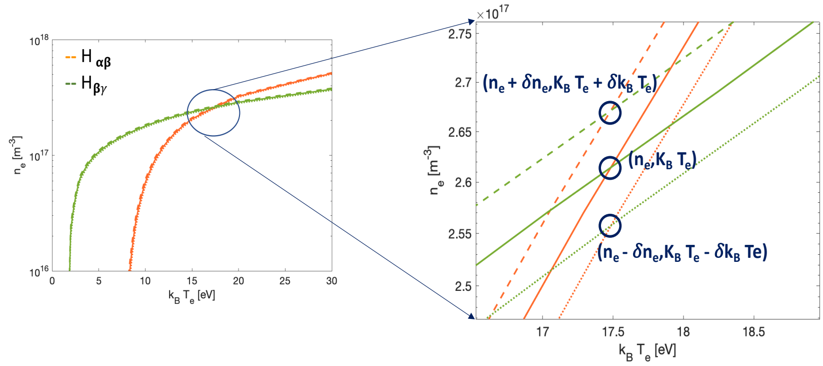

Figure 3. Example of cross between H-Balmer line ratios.

The resulting densities are of the order of 10^{17} m^{-3}, while temperatures range from few eV to 30 eV. The behavior as function of RF power is coherent with what we expect: there is an enhancement of T_e as the power increases. To resemble the astrophysical environments, the required temperature must be of few eV. Thus, from figure 4, suitable configurations are the ones explored in high-pressure and high-frequency conditions (#6 and #7 as reported in Table 1). A decreasing in temperatures is also observed in configurations where argon was present as a contaminant. Such a result requires further investigation to be fully understood. Further experimental measurements are planned to investigate other possible favorable configurations.

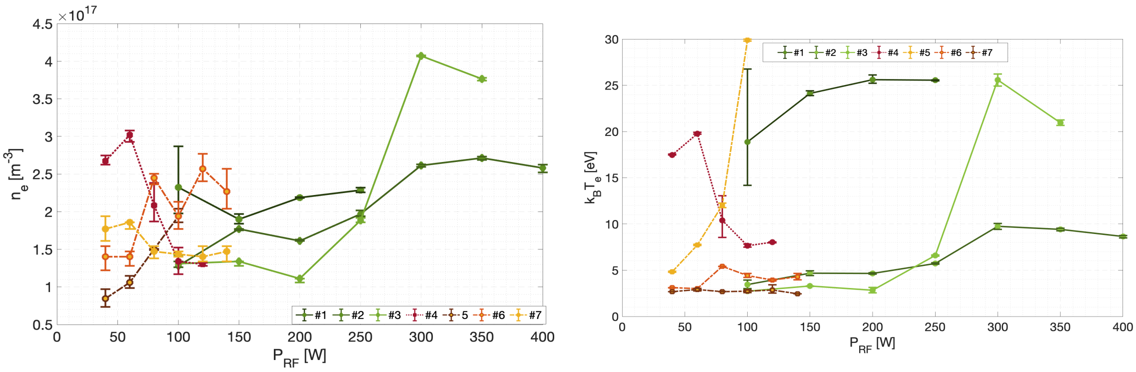

Figure 4. Values of electron density and temperature with their uncertainties.

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