Characterization of the ionization degree evolution of the PF-400J plasma sheath by means of time resolved optical spectroscopy

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Abstract. Spectral measurements in the visible range of the plasma sheath ionization degree evolution on the plasma focus device PF-400J are presented. The measurements were done with temporal and spatial resolution in a plasma focus device of low stored energy: PF-400J (176-539 J, 880 nF, 20-35 kV, quarter period $\sim$ 300ns) [1]. An ICCD was attached to a 0.5 m focal length visible spectrometer, which enabled the acquisition of time resolved spectrum with 20 ns integration time throughout the whole current pulse evolution. The spatial resolution was attained using a set of lenses which allowed the focusing of a small volume of the plasma sheath in different positions of the inter-electrode space. Discharges were carried out in mixtures of Hydrogen with gases in different proportions: 5% Neon, 5% Krypton and 2% Nitrogen. Discharges using Neon as an impurity showed no ionization of the gas, just a very low intensity emission of Ne I at times much larger than the maximum current. Nitrogen, on the other hand, showed a high ionization reaching N V (N^{4+}) at the end of the axial phase, with a distinctive evolution of the ionization degree as the plasma sheath moved towards the end of the electrodes. A mixed result was found when using Krypton, since the ionization degree only reached levels around Kr II/III, even though it has an ionization potential lower than Neon.

1. Introduction

Plasma focus devices have recently become of interest to the international plasma community for its capabilities as a self scale plasma device [2], neutron source [1; 3–7], pulsed X-ray source [8], plasma shock [9], ultrasonic plasma jets [10], filamentation[11], scaled astrophysical experiments [9; 10] and a source for material testing for future fusion reactor walls [9; 12]. The interest in improving the yield of particles and radiation has lead to some studies in the influence that gas impurities could have on that production, showing that under the right conditions, an order of magnitude increase in neutron yield can be attained [13; 14]. Although this is an important finding, the observation of the ionization degree evolution of the gas impurity during the axial phase has been ignored. Speed and thickness characterization of the plasma sheath evolution for pure gases have been developed in detail in references [15; 16]. Few studies using visible spectroscopy have shown the ionization degree at the pinch for discharges in Argon [17] and the evolution of the plasma when it interacts with a target [18]. Results on the evolution of the plasma sheath ionization degree when using Neon, Nitrogen and Krypton as impurities during the axial phase of the discharge will be shown.

2. Experimental details

The experimental observations were developed at the low energy plasma focus device PF-400J (176-539 J, 880 nF, 20-35 kV, quarter period ∼300 ns) [1]. The device was operated in three configurations: a mixture of 95% Hydrogen and 5% Neon; a mixture of 98% of Hydrogen and 2% of Nitrogen; a mixture of 95% Hydrogen and 5% Krypton. The mixture pressure was determined by maintaining the gas mass as close as possible to the equivalent mass used for pure Hydrogen shots. The device was operated at a repetitive scheme with a charging voltage of ∼ 27 kV and the spectra was acquired with a 0.5m focal length Cerny-Turner spectrometer coupled with a 576x384 pixel ICCD detector. A 300 groove/mm diffraction grating was used due to the broad spectral region available and good response to the observed region. The plasma emission from two positions at the inter-electrode region (figure 1) was focused into a 19 circular-to-linear fiber optic bundle connected to the entrance of the spectrometer (see figure 2).The ICCD-Spark gap system was synchronized externally, allowing the acquisition of time resolved measurements with integration times of 20 ns.

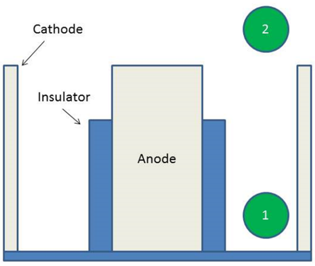

Figure 1. Plasma emission from two positions of the inter-electrode volume (green circle) was focused into the lens-to-fibre optic system.

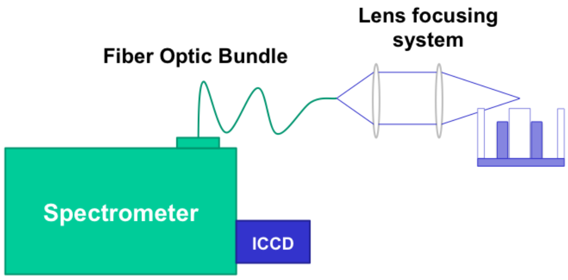

Figure 2. Scheme of the experimental setup for the spectroscopy measurements in both devices.

3. Experimental results

The electrical signals for a typical shot can be seen in figure 3. The timing of the images was obtained from the onset of the current derivative to the lowest point of the ICCD triggering signal labelled as (4). For the case of Hydrogen-Neon mixtures, the time was taken with respect to the moment of the maximum compression of the plasma column: a negative time indicates that the image was acquired before the pinch and a positive time, after the pinch. In order to observe the appearance of the H-alpha emission in the discharge chamber, a filtered photomultiplier tube was connected to an optical fibre pointed at the plasma volume, signal that is shown as (3) in the figure.

Figure 3 shows the evolution of the visible emission in the region around $\sim 625nm$ and $\sim 700nm$ for a mixture of Hydrogen and Neon. It can be seen that there is a broadening of the H_α transition at times close to the pinch (-16 ns), in comparison to the width at earlier times. This spectral region should show a larger emission at earlier times, since it includes the breakdown of the plasma sheath over the insulator, nevertheless this is not the case. In previous observations for a pure hydrogen discharge [19], the broadening of the H_α happened earlier in time. This might be related to the fact that for a H+Ne mixture, the plasma sheath is heavier and the breakdown conditions are modified. Also, the observation of excited Neon (Ne I) is only evident at times much larger than $1\mu s$ after the onset of the current. This might be related to either a rapid ionization of the Neon impurities, and thus the emission at different spectral regions; or the lack of any ionization due to the higher ionization potential of Neon compared

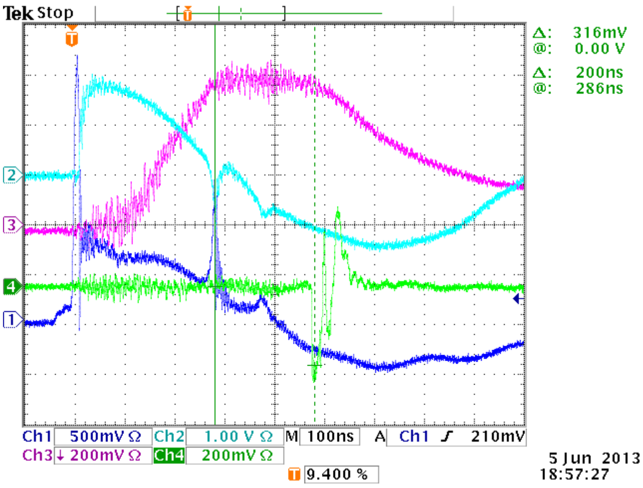

Figure 3. Electrical signals of: Voltage (1); Current Derivative, dI/dt (2); H-alpha filtered photomultiplier (3); ICCD pulser (4).

to Hydrogen. To be able to determine the emission from higher charge Neon ions, the use of a XUV spectrometer is under consideration.

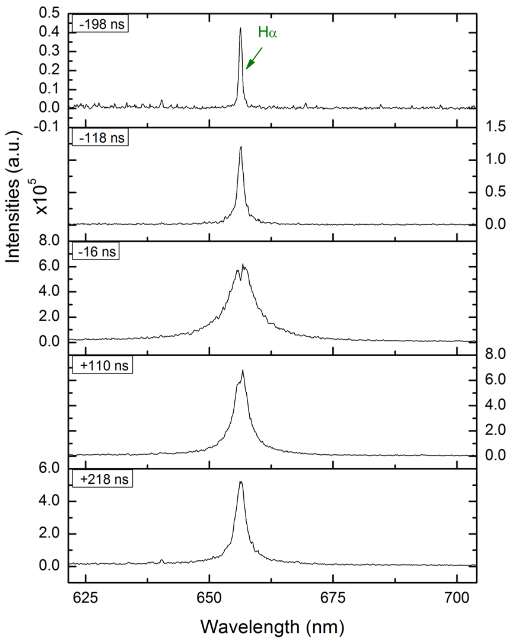

Figure 4. Evolution of the plasma sheath in time at the beginning of the axial phase. The discharge was operated at 9 mbar with a mixture of Neon (5%) and Hydrogen (95%) in the PF-400J discharge.

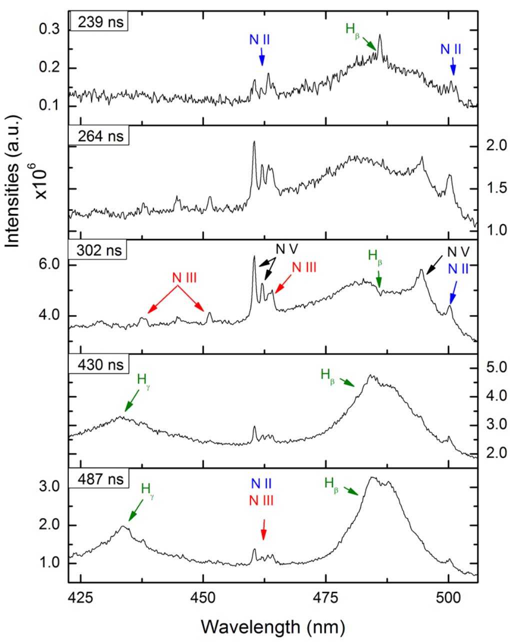

Figure 5. Temporal evolution of the visible emission of a 98% Hydrogen and 2% Nitrogen plasma, observed at the end of the axial phase in position 2 (Fig. 1).

In the case of the 98% Hydrogen and 2% Nitrogen mixtures, the acquired spectra can be seen in figure 5. The maximum current happens at $\sim 320ns$ and the pinch corresponds to $\sim 430ns$,

Journal of Physics: Conference Series **720** (2016) 012041 doi:10.1088/1742-6596/720/1/012041

times that are longer than expected compared to pure hydrogen (pinch at $\sim 280ns$). From the images it is possible to determine the evolution of the ionization degree of the Nitrogen impurity from NII(N^{1+}), $100ns$ before the pinch, to NV (N^{4+}) almost at pinch time. If the line emission intensity can be associated to the position of the plasma sheath, then the highest emission is seen at a time that should correspond to around $300ns$, which gives a difference of only $30ns$ with respect to the pinch time. This is a much shorter time than expected from observations in pure Hydrogen [15] ($\sim 85ns$), where the sheath should be lighter and faster than the one seen in a gas mixture. At this moment the authors do not have an explanation to this measurement.

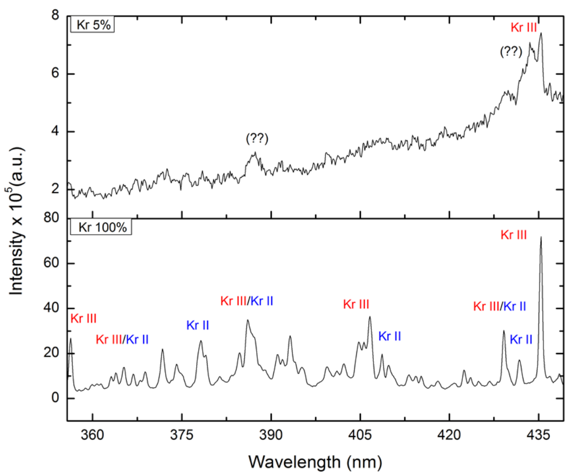

Figure 6. Spectral profiles for a 5% Krypton and a 100% Krypton discharge.

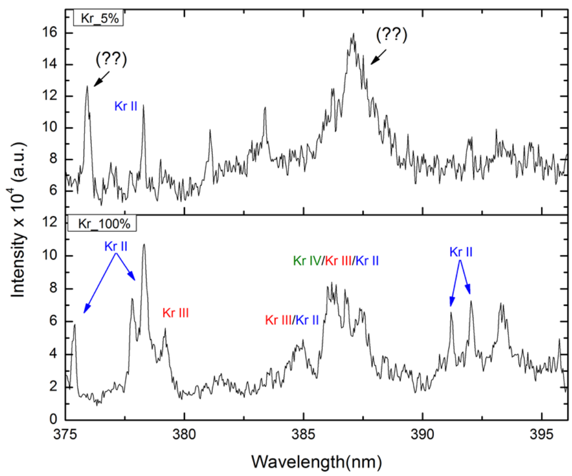

Figure 7. Detail of the spectral region of figure 6 in order to identify the broad peak at $\sim 387nm$

Several measurements were carried out using small percentages of Krypton to determine the behaviour of heavier impurities in the evolution of the plasma. Figure 6 shows two profiles, acquired at the same position as Nitrogen, where it is possible to observe that the use of a small concentration of Krypton does not allow the identification of line transitions. A 100% concentration of Krypton shows that the discharge is able to ionize the gas to low degrees of ionization (Kr II-III) but when the mixture is used, this ionization is not attained. This behaviour is not understood since the ionization potential of Krypton is even lower than the potential for Nitrogen. Further measurements using Krypton, in different spectral regions, are under development. In order to resolve the lines in the broad feature described before, spectra was acquired using the 1200 l/mm grating as seen in figure 7. From the spectra it is clear that there is no correspondence between the 5% and 100% concentration cases, an even some unresolved features can be seen.

4. Conclusion

The results presented above show the behaviour of the spectroscopic emission from the plasma sheath for different conditions of gas impurity in different positions of the plasma focus discharge. The addition of small concentrations of different gases directly impact the dynamics of the plasma sheath: It becomes slower, even when the mass is kept constant; and the ionization of the impurities is not related to the ionization potential (Nitrogen vs Krypton). The difference seen between the evolution of Nitrogen and Krypton impurities needs further studies, searching for higher ionization degrees in different spectral regions (UV-Visible/XUV).

Acknowledgments
The authors would like to acknowledge the financial support from CONICYT-PAI Inserción 791100020, FONDECYT Iniciación 11121587, CONICYT-PIA Anillo ACT1115, Bilateral Project Chile-Argentina: CONICYT ACE-01 / ANPCyT-PICT-2697 and FONDECYT Regular 1120801

References
[1] Silva P, Moreno J, Soto L, Birstein L, Mayer R E and Kies W 2003 *Applied Physics Letters* **83** 3269–3271
[2] Soto L, Pavez C, Tarifeno A, Moreno J and Veloso F 2010 *Plasma Sources Science and Technology* **19** 055017
[3] Soto L, Silva P, Moreno J, Zambra M, Kies W, Mayer R E, Clausse A, Altamirano L, Pavez C and Huerta L 2008 *Journal of Physics D: Applied Physics* **41** 205215
[4] Soto L, Pavez C, Moreno J, Barbaglia M and Clausse A 2009 *Plasma Sources Science and Technology* **18** 015007
[5] Soto L 2005 *Plasma Physics and Controlled Fusion* **47** A361
[6] Klir D and Soto L 2012 *Plasma Science, IEEE Transactions on* **40** 3273–3279
[7] Veloso F, Pavez C, Moreno J, Galaz V, Zambra M and Soto L 2012 *Journal of Fusion Energy* **31** 30–37
[8] Pavez C, Pedreros J, Zambra M, Veloso F, Moreno J, Ariel T S and Soto L 2012 *Plasma Physics and Controlled Fusion* **54** 105018
[9] Soto L, Pavez C, Moreno J, Inestrosa-Izurieta M J, Veloso F, Gutiérrez G, Vergara J, Clausse A, Bruzzone H, Castillo F and Delgado-Aparicio L F 2014 *Physics of Plasmas* **21** 122703
[10] Pavez C, Pedreros J, Tarifeño-Saldivia A and Soto L 2015 *Physics of Plasmas* **22** 040705
[11] Soto L, Pavez C, Castillo F, Veloso F, Moreno J and Auluck S K H 2014 *Physics of Plasmas* **21** 072702
[12] Inestrosa-Izurieta M, Ramos-Moore E and Soto L 2015 *Nuclear Fusion* **55** 093011
[13] Verma R, Lee P, Lee S, Springham S, Tan T, Rawat R and Krishnan M 2008 *Applied Physics Letters* **93** 101501–101501
[14] Bures B L, Krishnan M, Madden R E and Blobner F 2010 *Plasma Science, IEEE Transactions on* **38** 667–671
[15] Veloso F, Tarifeño-Saldivia A, Pavez C, Moreno J, Zambra M and Soto L 2012 *Plasma Physics and Controlled Fusion* **54** 095007
[16] Veloso F, Moreno J, Tarifeño-Saldivia A, Pavez C, Zambra M and Soto L 2012 *Measurement Science and Technology* **23** 087002
[17] Feugeas J and Grigioni G 1997 *Journal of Physics D: Applied Physics* **30** 2026
[18] Skladnik-Sadowska E, Malinowski K, Sadowski M, Kubkowska M, Jakubowska K, Paduch M, Scholz M, Garkusha I, Ladygina M and Tereshin V 2011 *Contributions to Plasma Physics* **51** 288–292
[19] Avaria G, Cuadrado O, Moreno J and Soto L 2015 *Journal of Physics: Conference Series* **591** 012024