Time resolved visible spectroscopy studies of the plasma sheath evolution in a low energy plasma focus device

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Abstract. We present the study of the evolution of the ionization degree of the plasma sheath in a low energy plasma focus device with time and spatial resolution, by means of visible spectroscopy. The measurements were developed in the low energy plasma focus device PF-400J (176-539 J, 880 nF, 20-35 kV, quarter period \(\approx\)300 ns) \cite{1}, using an ANDOR Shamrock 500i visible spectrometer with an ICCD that enabled the acquisition of spectra with time resolution in the order of tens of nanosecond. The use of a lens system improved spatial resolution, allowing the study of the plasma sheath in different stages of the discharge dynamic. In this work we present results from the pinch volume to study the evolution of the ionization degree of the plasma. The results include discharges in pure Hydrogen and a mixture of noble gases and Hydrogen, such as Neon and Helium, which were introduced in the discharge by small percentages ranging from 2 to 5%.

1. Introduction
New interest on small plasma focus devices has been developing over the years for its capacity as a pulsed neutron source \cite{2–4} and a pulsed X-ray source \cite{5}. Several reports indicate an increase in the neutron emission depending on the gas impurity used, yield that can improve in an order of magnitude \cite{6; 7}. Although this is an important finding, studies about the ionization degree evolution for those impurities in the plasma sheath are none existent. Plasma sheath kinematics on a low energy plasma focus device have been studied in detail by Veloso et al.\cite{8; 9}. Few studies using visible spectroscopy have shown the ionization degree at the pinch for discharges in Argon \cite{10} and the evolution of the plasma when it interacts with a target \cite{11}. The following report shows preliminary results for the measurements of the ionization degree of impurities at the pinch volume of low energy plasma focus devices.

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 \(\sim\)300 ns) \cite{1} and at the plasma focus device PF-2kJ “Peputnik” (1.6-3.6 kJ, 8000nF, 20-30 kV, \(\sim\) 960 ns time to peak current, dI/dt \(\sim\) 2.7 \(\times\)10\textsuperscript{11}A/s). For the observations presented here, the PF-400J device was operated with Hydrogen at 9 mbar or with a mixture of Neon (2\% - 5\%) and Hydrogen (98 \% - 95\%) at...
an equivalent pressure of 9 mbar in Hydrogen. The device was operated at a repetitive scheme with a charging voltage of 27 kV. The spectra was acquired by means of a ANDOR Shamrock 500i spectrometer which had a Princeton Instruments ICCD-576/EMG camera attached to the exit port. A 300 groove/mm diffraction grating was used due to the broad spectral region available and good response to the observed region, which in this report spans from $\sim 620 \text{ nm}$ to $\sim 705 \text{ nm}$. The plasma emission from the pinch volume 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. The measurements taken at the PF-2kJ device were done with a mixture of Neon (2%) and Hydrogen (98%) with the same optical setup as the one used with the PF-400J.

![Figure 1. Scheme of the experimental setup for the spectroscopy measurements in both devices.](image1)

![Figure 2. Plasma emission from the pinch volume (green circle) was focused into the lens-to-fiber optic system.](image2)

3. Experimental results

Figure 3 shows the evolution of the plasma emission for the PF-400J discharge at 9 mbar of Hydrogen. Times are taken with respect to the pinch moment: a negative time corresponds to a spectra taken before the pinch and a positive time corresponds to a spectra acquired after the pinch. In the sequence it is possible to observe the appearance of a very broad $H_\alpha$ line with a self-absorption dip. The broadest profile is observed at the pinch time which is related to a high density plasma\cite{12}. For later times the line becomes narrower and the self absorption dip disappears. The wings and central dip observed in the Balmer-$\alpha$ line have been reported before \cite{13}: the wings are related with high velocities of the excited hydrogen emitters and electric fields of the discharge \cite{14} and the dip is associated with ion dynamic effects \cite{15}. A more detailed study of this phenomena is going to be treated in a future report.

The evolution of the plasma emission for the PF-400J with a mixture of Neon (2%) and Hydrogen (98\%) is shown in figure 4. The image shows the spectra emitted from the pinch volume at different times during the evolution of the discharge where a similar behavior as figure 3 is seen in the sequence. Notice that at a time close to the pinch, the intensity and width of the $H_\alpha$ line does not resemble the same characteristics seen in the pure hydrogen discharge. In this case, it looks like the plasma is taking longer to reach the anode center which could be related with the mass on the sheath. Even though the gas mixture is set up to achieve an equivalent mass, it appears from the experimental observations that the plasma sheath could be heavier than calculated. Future measurements will include a different calculation of the gas proportion which takes into account sheath velocity parameters \cite{16}. At a time around +50 ns, the line profile is similar to the one seen in pure hydrogen, nevertheless, the evolution of the line at times larger than +100 ns is different from the pure hydrogen case. It can be seen that for
times larger than +100 ns, the balmer-α line stays broader and it starts to become narrower at times over 400 ns after the pinch. The spectra taken at +112 ns shows the very dim appearance of the Ne I emission in the region of 630-645 nm, emission that is evident at later times.

In figure 5 a detailed spectra sequence for times larger than +100 ns can be seen. From the image it is clear that a very small emission from Ne I is present and its intensity grows from the background level at times larger than 200 ns after the pinch. Spectral regions where emission of Ne II-IV ions is expected were probed, but no line emission was detected.

In order to check if the stored energy of the discharge is the reason for the results obtained, the optical setup was moved to the PF-2kJ discharge. The gas mixture was kept on the same proportion, but the equivalent pressure was increased to 12 mbar in order to follow the scaling rules determined by L. Soto et al [17] for devices with this stored energy. Time evolution of the spectra showed identical results as the ones seen in the PF-400J: only excited Neon and no ionization of the impurity. To observe if the emission was appearing at a different time during the discharge evolution, time integrated shots were acquired. Figure 6 shows a spectra integrated during the whole current pulse at the pinch volume (figure 2). As seen from the image, only excited Neon is detected and some ions of Aluminium appear in the profile. The latter emission comes from the Alumina (Al₂O₃) insulator used to cover the anode of the discharge. Nevertheless no emission from the electrode material was detected, these results are in agreement to the ones presented by Skladnik-Sadowska in PF-1000 [11]. Similar observations have been made by Feugeas [10] were emission from the insulator material was measured. The reason for the observed behavior in both devices (PF-400J and PF-2kJ) is not understood and further research is needed to fully comprehend these results.

Figure 3. Evolution of the spectra taken at the pinch volume for a discharge in pure Hydrogen on the PF-400J device.
Figure 4. Evolution of the plasma sheath in time at the pinch volume. The discharge was operated at 9 mbar with a mixture of Neon (2%) and Hydrogen (98%) in the PF-400J discharge.

Figure 5. Detail of the appearance of Ne I line emission for the PF-400J discharge. Notice that the line emission appears at times that are hundreds of nanoseconds after the pinch.

Figure 6. Time integrated spectra from the PF-2kJ discharge. From the image is evident that only excited Neon (Ne I) is detected, as well as some aluminium that comes from the insulating sleeve.

4. Conclusion
The results presented above show the behaviour of the plasma sheath for different conditions on different plasma devices. From the measurements done in pure Hydrogen it is possible to observe the presence of a dense plasma at the time of the pinch, which relaxes in times in the order of hundreds of nanoseconds. When the discharge is done in a mixture of Neon and Hydrogen, a
change on the evolution of the sheath is evident: the broadening of the $H_a$ line occurs later than the pinch time and this broadening continues until times larger than the ones observed in pure Hydrogen. The appearance of excited Neon at later times than the pinch is still under study and not understood at this time.

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