

Initial stages in hundreds of Joules plasma focus operating in deuterium – argon mixtures: Preliminary results

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Abstract. In plasma focus research, the mixture of deuterium with noble gases has been one of the attempts for both improving the radiation yield and for understanding of the origin of the fusion reactions. However, differences on the neutron emission from the plasma focus operating with gas mixtures according to the device energy have been reported. In an attempt to improve the understanding of such experimental observations, experiments in a very low energy plasma focus device (400J) working with gas mixtures are presented. Different stages prior to the final compression of the plasma focus discharges were studied; such as the breakdown phase and the plasma sheath movement. The electrical signals analysis shows differences on the breakdown voltage but similar axial sheath velocities. Nonetheless, these preliminary observations must be corroborated with additional experimental data.

1. Introduction

The plasma focus (PF) [1,2] is a z-pinch type discharge, where an axial current flowing through a cylindrical plasma provides both energy input and magnetic field for its confinement. In these discharges, the plasma is generated from the ionization of the background gas using two coaxial electrodes separated by an insulator. This ionization takes place over the insulator surface and the pulsed current flows over the resulting plasma. As the current generate its own magnetic field, there is a resulting Lorentz force that produces the detachment of the plasma from the insulator, forming a dynamic plasma sheath. When this plasma sheath arrives to the top of the coaxial electrodes, the magnetic force drives a radial implosion forming z-pinch over the central electrode. This pulsed plasma device has been widely studied in basic plasma physics and applied research related to x-ray, ions and neutrons sources (the latter, from D-D fusion reactions). Most of the research in PF devices has been performed in large machines (in terms of size, weight and stored energy), but during the last years there has been an effort on the miniaturization of these devices in order to use them for field applications [3]

The neutron yield obtained from PF devices vary according to electrode geometry, deuterium filling pressure [4,5] and stored energy [6]. Variations on the discharge characteristics have been made in order to enhance the neutron yield further from the scaling laws. Some of these are the modification of the anode geometry, inclusion of deuterated targets and noble gas doping to the discharge. The latter has shown different variations on the total neutron yield according to the device energy changes.



Experiments performed in a 28kJ PF device using neon, argon and krypton as doping gas, show a decrease in the total neutron yield for in comparison to pure deuterium discharges. They also observed an increase in the neutron emission anisotropy and changes in the pinching phase according to the atomic number of the doping [7]. Other experiments in a 3.3kJ PF device evidenced variations from 0.8- to 1.8-fold the neutron yield in pure deuterium, depending of the percentage of argon doping [8]. For energies below 1kJ, the total yield is improved drastically compared to pure deuterium operation. For a 500J PF device, it was found an increase of 5-fold and 8-fold for neon and argon respectively [9] and 3.6-fold on argon and krypton doping [10]. Another experiment in a 200J PF device found an increase up to 30-fold using krypton doping [11]. These studies (below 1kJ) [9,11] also observed variations on the implosion time of the discharge. A summary of these results is shown in table 1

Table 1. Summary of previous results on deuterium + noble gas on PF devices.

Device	Device characteristics	Mixture	Total neutron yield changes
DPF – 78 [7]	28kJ T / 4 ~ 1,5 μ s	D ₂ + Ne D ₂ + Ar D ₂ + Kr	0.3x to 0.6x 0.4x to 0.8x 0.7x to 0.9x
UNU / ICTP PFF [8]	3,3 kJ T / 4 ~ 2,5 μ s	D ₂ + Ar	0.8x to 1.8x
AASC DPF [9,10]	500 J T / 4 ~ 600ns	D ₂ + He D ₂ + Ne D ₂ + Ar D ₂ + Kr	1x (No change) 1x to 5x 1x to 8x Up to 3x
FMPF-1 [11]	200 J T / 4 ~ 400ns	D ₂ + Kr	0.2x to 30x

The present work is motivated by these reported differences on neutron yield variations when noble gas doping is used. In contrast to the existing published studies, this work does not concentrate in the total neutron yield from the gas mixtures, but in the previous phases; i.e. the breakdown over the dielectric and the plasma sheath movement. It is expected that a proper understanding of these previous phases using gas mixtures will give some keys for the physical processes that produce the observed differences in the final neutron emission.

2. Experimental setup

The experiments were carried out in the very low energy plasma focus device available at our lab, named PF-400J [12]. This PF device operates at energies of 400J its capability of producing fusion neutrons have been previously demonstrated [12,13]. The ratio of the effective length of the anode to its radius is nearly the unity, which means they are classified as hybrid-type PF devices. A schematic diagram of the PF electrode configuration, together its dimensions are shown in figure 1. In order to diagnose the discharge, the voltage and current derivative were measured using resistive divider and Rogowski coil respectively.

In this set of experiments, the final working pressure of the gas mixture was achieved by partially filling the vacuum chamber with each gas at the desired concentration on each case. The main gas on these discharges is deuterium and the argon concentration was varied from 0%Ar (i.e. pure deuterium) to 10%Ar. In order to avoid contaminations on the gas mixture from the material erosion, both gases were continuously renewed using a stationary gas flux, being frequently monitored using a capacitive vacuum gauge.

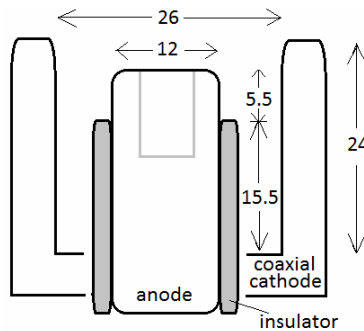


Figure 1: Schematic diagram of electrode configuration. Dimensions are in mm.

3. Results

Even if the breakdown voltage in a pulsed device depends on the voltage rise, triggering system and other generator characteristics, the trends and differences among different pressure or gases should still be observed. For studying the breakdown in our discharge, the filling pressure of the chamber was varied from 5mbar to 16mbar with different mixture percentages. In order to ensure the breakdown over the dielectric surface, the electrode configuration (particularly, the cathode) was slightly modified. The cathode can be separated in two parts, the ‘floor’ of the PF discharge and the outer coaxial electrode which consist on eight uniformly spaced copper rods. For this part of the experiment, the cathode rods were removed. Therefore, the breakdown can only occur to the remaining cathode (discharge ‘floor’) having no other path to it than the dielectric surface. Although the plasma sheath evolution will be different in this modified electrode configuration, the breakdown phase will be the same than usual PF configuration.

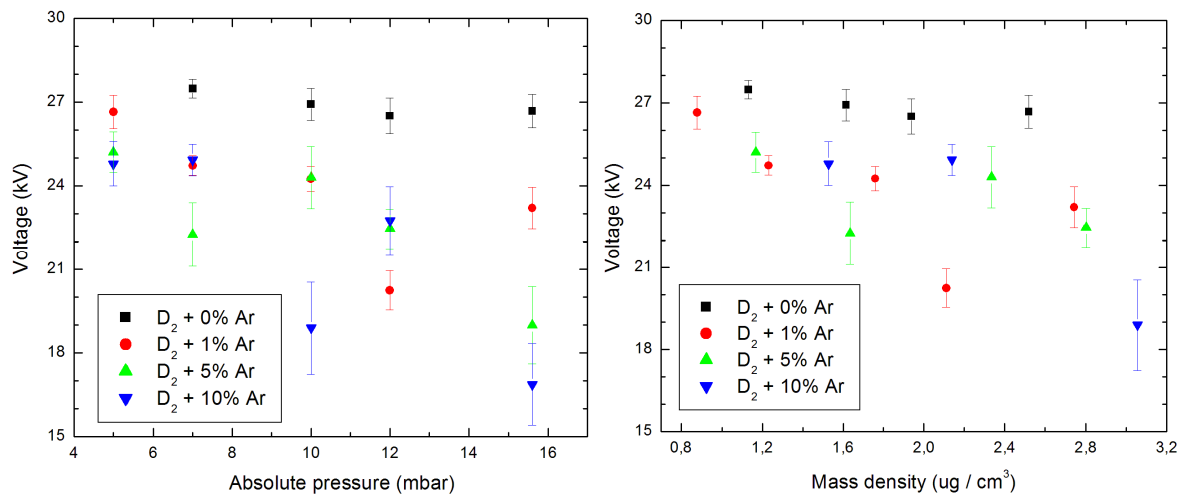


Figure 2: Measured breakdown voltages for different deuterium-argon mixtures

Figure 2a shows the measured breakdown voltages as a function of the absolute total pressure. The vertical error bars are given from shot to shot variation. From this figure, it can be seen that the breakdown voltages for pure deuterium discharges are always higher than any percentage of argon doping. This behavior can be explained from the Paschen's curve for breakdown in gases. For these pressure values, the argon Paschen curve has lower breakdown voltages than hydrogen [14]. Even when the Paschen breakdown has been defined for static voltages, the differences among gases should be maintained for pulsed voltages. On the other hand, previous studies on PF gas mixtures claimed that one of the parameters than should be kept constant for optimizing performance is the mass density

of the background gas (in comparison to pure gas discharges) [7,15]. Figure 2b shows the breakdown voltage as function of mass density of the background gas for different argon percentages. It can be seen that regardless of the argon concentration in the gas mixture, the breakdown voltage for pure deuterium is always higher. This observation is valid for every mass density studied here.

In order to study the evolution of the discharge, the time varying inductance has been obtained. This information can be extracted using circuit analysis, where both generator and plasma are included. To compute the time varying inductance, the following equation is used [16]

$$L_p(t) = \frac{\int_{t_0}^t V(t)dt + (L'_0 + L_p(t_0))I(t_0)}{I(t)} - L'_0 \quad (1)$$

where $V(t)$ and $I(t)$ are the measured voltage and current, respectively; t_0 is the first peak on the dI/dt signal and corresponds to the time when the initial gas breakdown is complete and equation (1) can be applied. L'_0 is the inductance from the plasma to the voltage probe connection. In order to get the inductance information, details on the processing method of the electrical signals can be found elsewhere [16,17]. Even though the inductance calculations do not consider any specific load geometry, the temporal trends can be associated to the different phases of the plasma evolution; i.e., the axial and the radial phase. The axial phase has a relatively constant slope, which lasts up to a sudden increase in the inductance value. This sudden increase is associated to the radial phase. After some few nanoseconds the inductance slope diminishes, which is associated to the later expansion of the plasma after focusing. Calculated inductances for single shots of different gas mixtures can be seen on Figure 3. For these shots, the mass density was kept constant on $1.4\mu\text{g}/\text{cm}^3$, which is the equivalent mass density of the optimal deuterium pressure for neutron emission on this device (9 mbar)

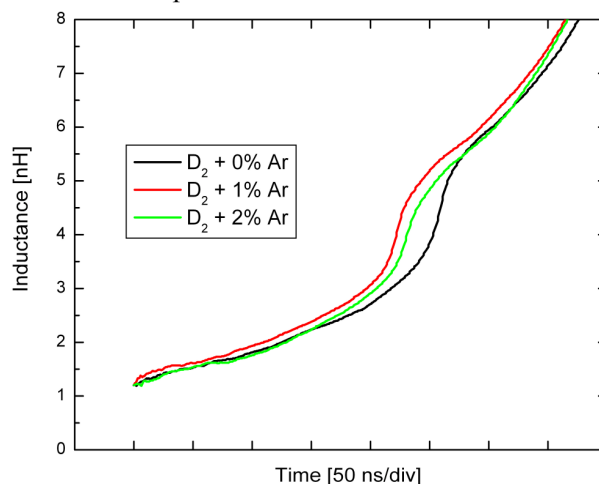


Figure 3: Calculated time varying inductance

Since the geometrical calculation of the inductance in a coaxial geometry has a linear dependence with the electrodes height; it is possible to relate the slope of the inductance on the axial phase with the average axial speed of the plasma sheath. The slopes of the axial phases of the inductance traces in Figure 3 do not show significant variation according to the argon doping on the discharge. From this observation, it is possible to state that the average axial speeds are nearly the same for the pure and doped deuterium discharges, i.e., the global dynamics of the plasma sheath do not change as far as the mass density remains constant. Even though this observation can be rather obvious given that the Lorentz force does not depend on the working gas, it states that plasma components have larger kinetic

energy (due to the argon ion mass), which can be later transfer to the pinched plasma in the radial phase. On the other hand, the inductance values are also nearly equal for the studied gas mixtures. Since the inductance is a geometrical measurement of the plasma sheath, it is possible to observe that the shape and curvature for the plasma sheath have not significant variation for these argon doping levels. However, additional data are needed in order to either corroborate or discard such observations.

4. Conclusions

Preliminary results on very low energy plasma focus using deuterium-argon mixtures were presented. Using a 400 joules plasma focus, it was found that the argon doping on deuterium discharges reduces the breakdown voltage required to produce the initial plasma sheath over the insulator surface. This observation is independent on the mixed gas pressure and the load mass density. On the other hand, the time varying inductance calculations shown that the average axial speeds of the plasma sheath and its geometrical shape and curvature remain nearly constants. These observations indicate that the global dynamics of the discharge remains unchanged with the argon doping; but the energy of the plasma components differ. This difference can be possibly related to the differences on the final neutron emission of such configurations. Nonetheless, further experimental data which includes neutron yield measurements are required in order to obtain a deeper understanding of the phenomena.

The authors would like to acknowledge financial support from the programs PBCT-ACT26 and PSD-01, Center for Research and Applications in Plasma Physics and Pulsed Power – P⁴ Chile

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