Filaments in the Sheath Evolution of the Dense Plasma Focus as Applied to Intense Auroral Observations

María Magdalena Milanese, Jorge J. Niedbalski, and Roberto Luis Moroso

***Abstract*—This paper investigates the dense plasma focus (DPF) for applications in space-plasma physics. The plasma focus (a variant of Z-pinch) generates plasmas from fast high-voltage electrical discharges on coaxial electrodes suitable for very different studies: from fusion up to plasma-space modeling. In particular, the plasma sheath of the DPF is studied here and measured in some detail as a possible model for auroral observations. Deuterium gas was used in the experiments, and many helpful techniques were used, such as ultrafast photograph and neutron detection from nuclear-fusion reactions. In this paper, we show the different phases of the plasma focus correlated with discharge-current characteristics and neutron and X-ray production. Filamentary formations in the current sheath are shown, and its correlation with neutron production is done. The same number of filaments (about 60) reported in auroral observations are detected in plasma-focus discharges.**

***Index Terms*—Fast discharges, laboratory plasmas, plasma focus, space plasma.**

I. Introduction

MANY astrophysical problems must be studied on the basis of observation of the natural events and, when possible, to develop theoretical models. Others can be simulated in experiments made in the laboratory. This is the case of the plasma-focus experiment [1], which reproduces some astrophysical phenomena, for example, the volcanic phenomena in a Jovian satellite [2]; in addition, it could be applied to space problems as plasma instabilities, solar flares, and auroræ to clarify some of the still not understood processes involved in Alfvén's critical velocity [1], [3].

The plasma focus, developed from the 1960s [4], [5] as a variant of Z-pinch devices or plasma gun accelerators, generates plasmas from fast high-voltage electrical discharges on coaxial electrodes immersed in a low-pressure atmosphere [a scheme of the plasma sheath, or current sheath (CS), in different stages of the plasma focus can be observed in Fig. 1]. The sheath presents the four main stages during its brief evolution (less than 1 μs): initial breakdown, coaxial or run-down, rolloff and radial compression, and, last of all, bubble formation. At the end of the radial compression, the bulk of the plasma in our experiments is a pinch in which the Bennett equation is fulfilled on average [6]. Plasma-focus devices showed (when operated with deuterium) amazing results on nuclear-fusion energy output relative to invested energy per shot. Nevertheless, some physical processes involved in this phenomenon are not yet well understood, which is a source of exciting current investigations. Apart from nuclear-fusion studies, the plasma focus can be conceived from many other points of view: emission of hard and soft X-ray [7] and microwave brief pulses, relativistic electron and energetic ion beams [8], brief nuclear-fusion neutron pulses, plasma jets [9], etc., everyone with possible practical applications. Much of these are studied by our investigation group, for example, plasma-focus devices of very small size and energy, designed on purpose for soil-humidity determination through neutron-pulses attenuation, have been developed by us [10].

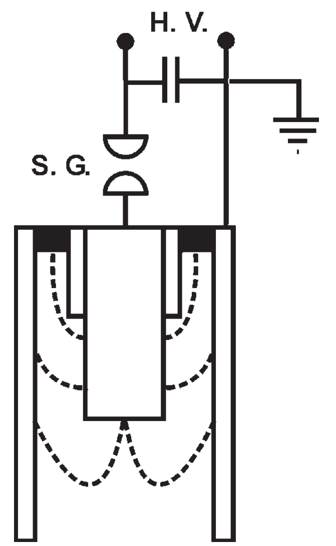

Fig. 1. Schematic of the DPF coaxial electrodes. In the dotted lines, there are indicated the positions of the plasma sheath in three typical stages: Initial breakdown on the insulator sleeve, coaxial acceleration, and radial compression.

Several phenomena registered in plasma-focus discharges seem to be a reproduction of astrophysical observations. In particular, the plasma sheath of the dense plasma focus (DPF) is studied here and measured in some detail as a possible model for auroral observations.

Let us mention another case. The range of deuterium filling pressure in plasma foci has been analyzed in previous

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works [11]. The existence of an upper pressure limit (UPL), beyond which the neutron yield (Y) drastically drops, is verified and correlated with an insufficient energy available to ionize the neutral gas. Two-dimensional MHD models have been used for calculating several parameters of the CS dynamics in each one of its stages. The energy collected by the CS per-unit mass (ε) is calculated. When ε goes down, the threshold of 1 MJ/g, just coincident with the deuterium-specific ionization energy, the high-pressure limit affects the pinch effectiveness. This fact allows the verification that is necessary to get a complete ionization of the swept gas in order to obtain an efficient pinch. When the plasma focus is working beyond the UPL, the CS becomes filamented [12]. Drastic descent of the neutron yield under the detection level is verified in every discharge beyond the UPL. One can then consider that, in the previous described situation, the energy per-unit mass ε has been not enough to ionize the neutral gas swept by the CS, then the CS presents filaments observed in all the stages of its evolution. Therefore, if at any pressure beyond which the available energy is not enough to completely ionize the CS, it would be plausible to think that the filaments could be the result of a minimal energy configuration in which the current circulates mainly into channels. In these conditions, the snow-plough magnetic-piston efficiency is low. Later, other researchers [13] experimentally verified the previous analysis using their proper facility. The Alfvén's definition of a critical velocity ν_c as a function of ε, for which there is a strong interaction between plasma and neutral gas, is well known for space plasmas [14]. The mean velocity calculated for the last stage of the plasma-focus radial compression just for the deuterium UPL has just the magnitude of deuterium in Alfvén's ν_c. This is an example in which it is possible to infer a connection between the results obtained in a laboratory experiment and the theory developed for space plasmas.

II. Experimental Systems and Methods

The experiment is based in the DPF (Mather-type) PACO [11] (Plasma Auto Confinado) operated in the Dense Plasma Laboratory [Grupo de Plasmas Densos Magnetizados (GPDM)] of the Instituto de Física Arroyo Seco, Tandil, Argentina. The experimental driver is a low-inductance (40-nH included transmission line), four elements in parallel, capacitor bank charged at 31 kV that stores 2 kJ of energy. The discharge is triggered by a single mushroom spark-gap. The anode (inner electrode) is made in oxygen-free highly conductive copper; its free length is 40 mm, and its diameter is 40 mm. The coaxial cathode is formed by 12 brass rods having 8-mm diameter each, arranged on a squirrel-cage configuration around a circle of 100-mm diameter. The insulator is a Pyrex sleeve that is 12 mm long and is located in the base of the anode. The peak current is 250 kA, and the average neutron yield is 4×10^8 per shot when pure deuterium (D_2), in the range of 1–2 mb, is used as filling gas. Deuterium gas is employed in our experiment in order to get neutron pulses. We measured them not only to investigate the plasma focus as nuclear-fusion producer but also because neutrons serve as a diagnostic technique; for example, if neutrons are produced, it can be inferred that the CS has appropriate features with respect of its ionization: the

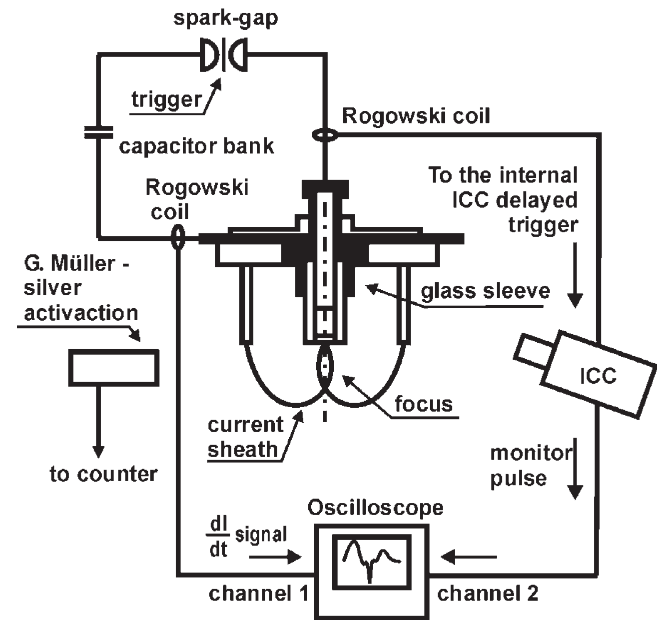
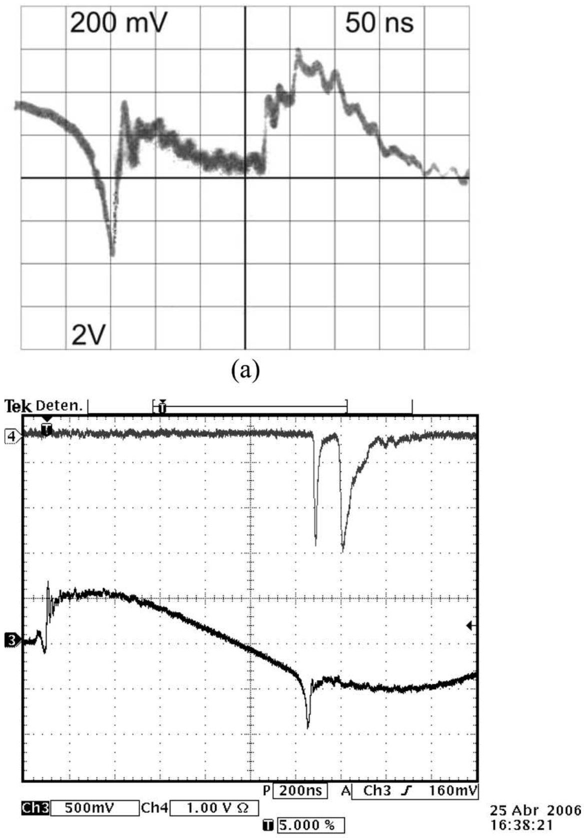


Fig. 2. Schematic of the experimental setup.

conditions of design and operation set the experiment below the UPL.

The time-evolution of the current derivative (dI/dt) is monitored by a Rogowski coil for measuring the current derivative. It is a sinusoidal signal that, under certain discharge conditions, presents a dip near the first-quarter period. The evolution of the CS from the initial breakdown to the final pinch breaking up lasts up to the first-quarter period of the current (about 1 μs in this case). The dip, and also the neutron emission, lasts 100 ns. When deuterium is used as filling gas and the mentioned dip is big enough, hard X-ray and fusion neutron bursts can be observed with a scintillator-photomultiplier (S-PMT) system [see Fig. 3(b)]. The silver-activation counter (SAC), which is located at 90° from the symmetric axis, gives the time-integrated neutron yield in each pulse. An S-PMT system, which is located 2.5 m away from the focus, registers time-resolved hard X-ray and nuclear-fusion neutron pulses. As can be easily calculated, the time between the first pulse (hard X-rays) and the second one corresponds to the 2.45-MeV neutron time-of-flight. The working principle of an S-PMT is the following: Hard X-ray (several hundred kiloelectronvolts) photons strike the plastic scintillator ionizing or exciting the molecules, which, in its de-excitation, emit visible radiation. This light falls on the photocathode of the attached photomultiplier; photoelectrons are generated and multiplied giving, finally, a current pulse recorded in a fast oscilloscope. On the other hand, 2.45-MeV neutrons emitted by the DPF strikes the plastic scintillator, transferring energy to recoil protons, which, through coulombian interactions with the molecules, produce molecular excitations. The following processes are those related before. The total resolution time of this device is less than 10 ns. We would like to emphasize that the neutron yield is checked for every shot by means of the SAC and that, in the present investigation, the second pulse in the S-PMT signal always corresponds to proportional counts in the SAC. Image converter camera (ICC), an optoelectronic device that permits aperture time as short as



(a)

(b)

Fig. 3. (a) Oscillogram corresponds to dI/dt with (negative) focus "dip" followed by (positive) ICC monitor pulse. The scale of the abscissa axis (time) is 50 ns per division. In the ordinates are two oscilloscope channels added: the dI/dt (Rogowski coil signal previously attenuated by a factor 100) in an oscilloscope scale of 200 mV/div and monitor pulse in a scale of 2 V/div. (b) Oscillograms corresponds to the upper trace S-PMT system with an X-ray pulse followed by a neutron one (scale: 1 V/div) and the lower trace corresponds to dI/dt (scale: 50 V/div).

5 ns and intensifies the images, records the plasma images in different stages. In this paper, it was placed in different angles in order to take front, oblique, and side-on photographs of the plasma sheath. Fig. 2 shows a scheme of the experimental setup. The timing of the different time-resolved diagnostic has been carefully made. The ICC is shot with the beginning of the Rogowski coil output, so as the oscilloscope, where dI/dt and ICC monitor signals are registered. ICC monitor signal is a voltage pulse that the device sends just in the instant in which the picture is taken. Then, from measurements on the oscilloscope signals, it is possible to temporally correlate (with a resolution on the order of 10 ns) the current derivative, hard X-ray, and neutron pulses and image of the plasma. In our experiment, both ICC monitor and dI/dt signals have been taken on the same oscilloscope signal. The monitor pulse has a fixed delay in order to resolve it from the dI/dt. S-PMT and dI/dt signals can be seen in other oscilloscope screen, which is triggered with the Rogowski coil start. An example of the mentioned oscilloscope screens can be seen in Fig. 3(a) and (b).

Because the image acquisition system (ICC) is able to take only one image per shot, a laborious statistic work is required (about 15 shots were made for each condition).

III. Experimental Results

Along several hundred discharges did in the DPF PACO in deuterium with different initial conditions, ICC pictures 5-ns exposure time, have been taken and correlated with dI/dt respective oscillogram and nuclear-fusion production. When the conditions are good for neutron production, with the pressure below the UPL, the CS images show a uniform light density. In Fig. 4, several stages of a discharge in the mentioned conditions can be observed. The images have been taken with the ICC in side-on position.

On the other hand, when the discharge is affected by the UPL (pressure higher than 2 mb for the PACO device), structures of filaments are observed. Fig. 5(a) to (e) shows several stages of the plasma-sheath evolution, taken in oblique-on position: formation on the insulator, coaxial trajectory or run-down, and rolloff and radial compression up to the final pinch. Two zones can be distinguished in each image of this figure [particularly Fig. 5(a) to (c)]: the frontal region in which the CS must to charge at the neutral gas and ionize it; the other zone is a cylindrical-shaped like a "tail," in which part of the electrical-charged particles comes from the front and are accelerated by the electric field, then the current must practically only be maintained. The first zone is filamented while the other one looks uniform. In Fig. 5(d) and (e), several azimuthal filaments can be also observed, forming together with the radial ones some kind of "honeycomb" structure. Our intention is to study the described behavior in more detail in future works. In Fig. 6(a) and (b), two images of the CS in different stages of its evolution are shown. Filaments are not observed here, contrarily to Fig. 5. The conditions for discharges, like Fig. 6, set the system below the UPL. In Fig. 7(a) to (d), frontal views of the CS in different stages of its evolution can be seen (discharges affected by the UPL). In these frontal views, it can be observed that, in the coaxial stages, the central "hole" (moving border of CS) has the dimension of the anode, while in the last two photos, the central circle is smaller, indicating the convergence of the plasma sheath. Twelve symmetric shadows that seem to correspond to the cathode bars alternated with brighter sectors can be mainly seen in Fig. 7(c) and (d). In this case, it must be taken into account that the filamented part forms the pinching column; the part shown in these photos is the uniform tail that, in this very advanced stage, has already encountered the metallic bars that probably cool the plasma.

We can recognize about 60 radial current filaments in the sheath, from run-down to radial compression stages in oblique-on [as in Fig. 5(c)] and end-on [as in Fig. 7(b)] views, time-referred to the total current derivative in a pattern similar to the one shown in [15]. Even if the number of cathode bars did not change (up to date), the amount of filaments seems to be independent of it.

IV. Final Remarks

The experimental results obtained in this paper from the DPF PACO show that, under discharge conditions beyond the UPL, the plasma sheath presents always, in every stage of its evolution, filamentary structure. Plasmas that present filaments are observed in many astrophysical phenomena (by example,

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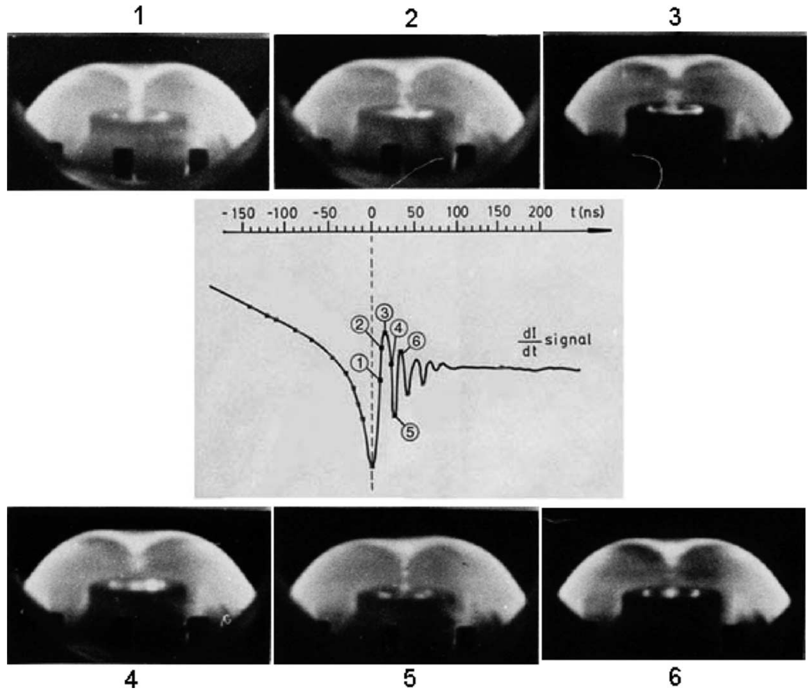

Fig. 4. Images sequence of CS, for maximum neutron yield condition, taken with ICC from side-on angle. They are correlated with successive instants of the Rogowski oscillogram.

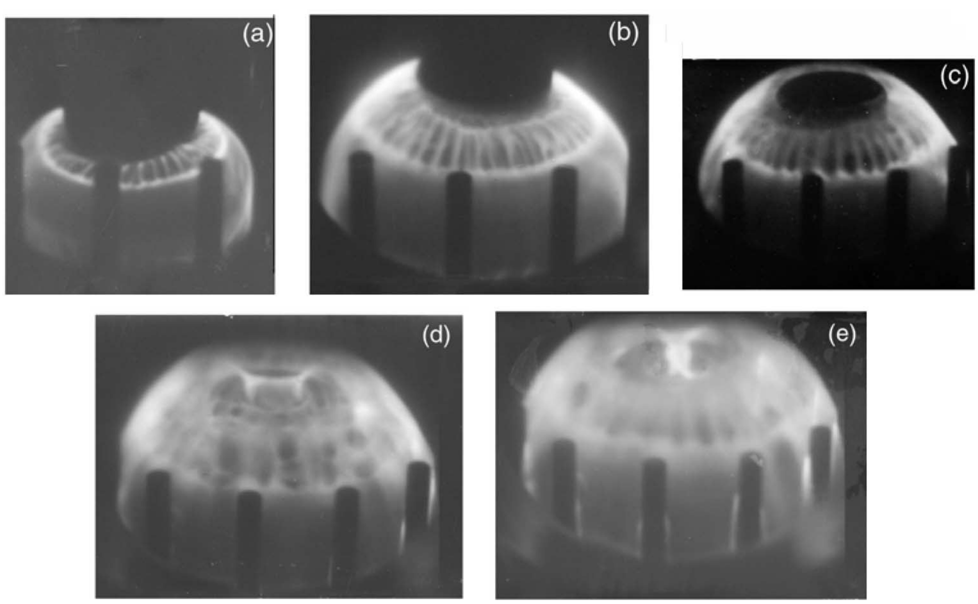

Fig. 5. ICC oblique-on views of filamentary CS. (a) Initial breakdown. (b) Coaxial stage. (c) Rolloff: Transition from coaxial to radial stages. (d) Radial compression. (e) Final constriction or "focus." The images in this figure were taken in a pressure condition above the UPL.

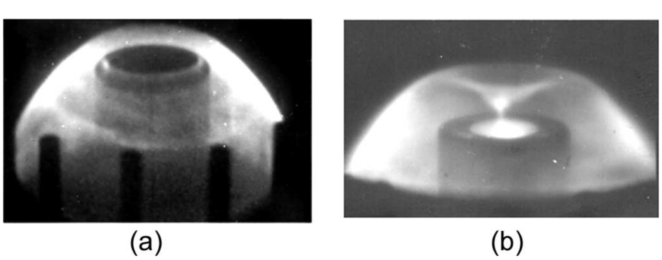

Fig. 6. ICC oblique-on views of uniform CS. (a) Rolloff stage. (b) "Focus" stage. The images in this figure were taken in a pressure condition below the UPL.

the filamentation of the solar corona [16], [17] or that of the Cat Eye nebula, studied by H. Alfvén). The phenomenon of auroræ presents similitude with Z-pinch and plasma-focus discharges. In fact, several phenomena related with auroral observations described by Peratt in [16], seems to be reproduced, in small scale, by plasma-focus discharges. Such is the case of the observation of filaments in auroræ, which is very similar to those in the plasma-focus CS and also in equal number.

Then, it could be possible to conceive plasma-focus experiments to reproduce in laboratory and, then, to better understand many astrophysical problems; in particular, auroræ [15].

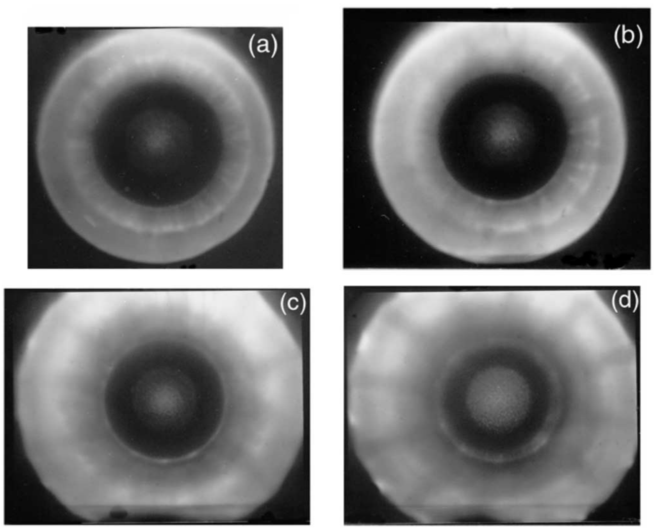

Fig. 7. ICC end-on views of filamentary CS. (a) Initial breakdown. (b) Coaxial stage. (c) Radial compression. (d) "Focus." The images in this figure were taken in a pressure condition above the UPL.

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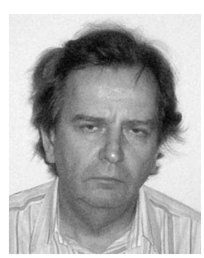

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