On Probable Fusion Mechanisms in a Mather-Type Plasma Focus

Horacio Bruzzone, Mario Oscar Barbaglia, Hugo Néstor Acuña, María Magdalena Milanese, Robert Luis Moroso, and Santiago Guichón

***Abstract*— An experimental study on plasma focus fusion mechanisms is presented in this paper. Simple diagnostic techniques such as current derivative, voltage, and time-integrated neutron detectors are used. This paper allows us to obtain information and fusion mechanisms present in a medium energy plasma focus [Auto Confined Plasma (PACO), 2 kJ, 31 kV, and $T = 2.9$ μs]. The current sheet (CS) inductance is calculated through the anode voltage and current derivative signals, for some 80 shots performed within the pressure range 0.8–2.1 mbar of deuterium. It is concluded that the CS inductance is consistent with the behavior of a unique plasma sheet moving between two coaxial electrodes. From the information collected, it is concluded that the main fusion mechanism in this device is the beam-target one.**

***Index Terms*— Beam target, Mather, plasma focus (PF), thermonuclear.**

I. Introduction

A PLASMA focus (PF) device has the capability to produce short pulses of hard X-ray and neutrons. These devices are very efficient (both energetically and cost effective) for the production of fast neutrons resulting from deuterium–deuterium nuclear fusion reactions.

The devices have been under continuous study since 50 years ago [1], [2]. The plasma inside the device reaches a maximum density of about 10^{25} m^{-3} [3] and a maximum temperature of about 5 keV [4]. However, both the ion densities and temperatures vary rapidly with time and the spatial position within the plasma column known as the pinch, so that the knowledge of maximum density and or temperature values is insufficient to discriminate between possible neutron production mechanisms.

Through measurements of the neutron emission anisotropy [5], [6] and other diagnostic methods [7], [8], it was suggested that more than one fusion mechanisms operated in the studied PF devices. One is the thermonuclear mechanism and the other is the beam-target one. The proportion of the neutron yield due to each mechanism varied from device to device. In this paper, an analysis of the data obtained in a series of some 80 shots in a medium-energy device relating the neutron yield with some experimentally determinable magnitudes, using a method previously described in [9], which can be associated with thermonuclear or beam-target mechanisms will be given.

II. Experiment Setup

This experiment was performed with the PF called Auto Confined Plasma (PACO) currently operating at the National University of the Center of the Buenos Aires Province, Argentina. This device has a 4-cm long and 4-cm in diameter oxygen-free high thermal conductivity copper anode, with a cathode consisting in 12 brass bars arranged on a 11-cm-diameter circle. The capacity of the bank is $C = 4$ μF and the parasitic inductance is $L_o = 57$ nH. The PACO device was operated at a fixed charging voltage $V_o = 31$ kV. The D_2 filling pressure, p_o, was varied between 0.8 and 2.1 mbar, which is the neutron producing range in this device. The neutron yield, Y_n, is about 3×10^8 neutrons per pulse measured with a calibrated silver activation counter. A plastic scintillator type NE102 coupled to a photomultiplier was used to measure the time history of the X-ray and neutron radiation emissions placed 2.4 m from the pinch region, and at 72° measured from the anode axis. A calibrated Rogowski coil was placed in the current return path of the current sheet (CS) to measure the current time derivative, *dI/dt*, and a calibrated fast resistive voltage divider was placed in the back of the anode for determining the anode voltage drop $V(t)$. The peak current was 240 kA, and within the experimental uncertainty (+/− 6%) was the same for all the shots.

An equivalent circuit of the device is shown in Fig. 1. L'_o is a small, fixed inductance between the voltage divider connection and the anode, L_p is the time varying CS electrodes inductance, *S–G* is the spark-gap connecting the capacitor bank, C_o, to the discharge chamber, and *S-Gp* is the closure of the circuit in the discharge chamber by the breakdown process.

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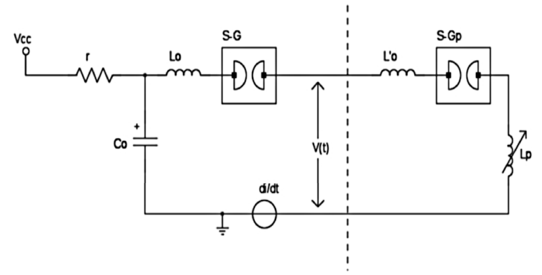

Fig. 1. PF equivalent circuit. Dashed line: the vacuum chamber.

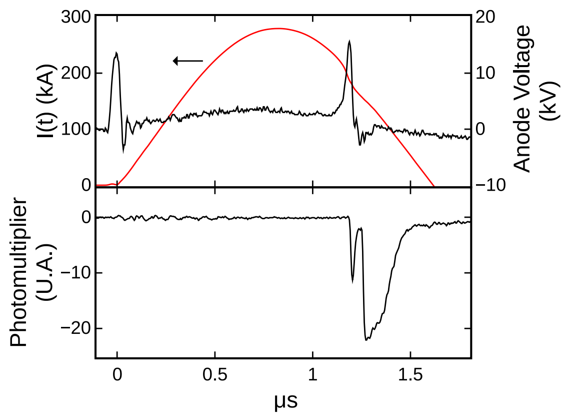

Fig. 2. Current, $I(t)$, at the top, anode voltage, $V(t)$, in the middle, and at the bottom, the signal from the scintillator-photomultiplier device.

Typical signals of $I(t)$, $V(t)$, and the photomultiplier pulse are given in Fig. 2, as an example for a shot performed at 1-mbar filling pressure.

III. Analysis of the Measurements and Data Elaboration

The events start with the closure of *S–G*, which produces the initial rise in $V(t)$ until a breakdown is achieved within the electrodes, that is, closing *S-Gp*. Once *S-Gp* is closed (that is, its resistive impedance drops sufficiently below that in the rest of the circuit, which corresponds roughly to the time t_o of the first smooth maximum of *dI/dt*), one can write

$$V(t) = \frac{d}{dt}\left[(L_0' + L_p(t))I(t)\right]$$

and hence

$$L_p(t) + L_0' = \frac{\int_{t_0}^{t} V(t)\,dt + (L_0' + L_p(t_0))I(t_0)}{I(t)}.$$

The evaluation of the time-varying inductance of the device following this procedure was originally done in [10] at Los Alamos, and later on, in [11]–[13]. In this case, the inductance was evaluated for the full set of signals and an example is shown in Fig. 3 together with $I(t)$ for the same shot at 1 mbar shown in Fig. 2. $L_p(t) + L_0'$ is plotted because L_0' (∼1–2 nH) is too small to be separately determined with sufficient accuracy. The inductance sum starts from an approximately constant value (∼4 nH) before gently increasing, which corresponds to the liftoff stage from the insulator. Later

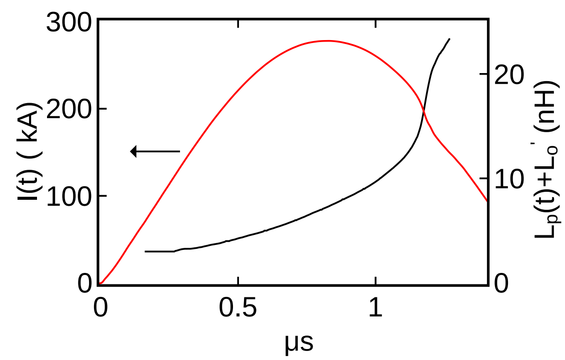

Fig. 3. Typical current and CS inductance history for a shot at 31-kV and 1-mbar D_2.

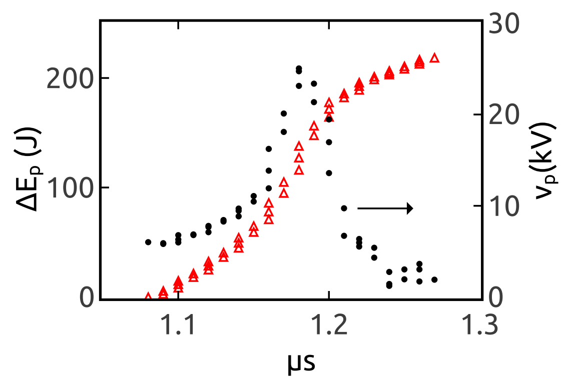

Fig. 4. $V_p(t)$ and $\Delta E_p(t)$ as functions of time.

on, the smooth growth associated with the axial traveling stage ends in a faster inductance rise stage—pinch stage—lasting some 100 ns, which correlates with the voltage peak and the *dI/dt* dip. The value of the $L_p(t)$ at the beginning of the pinch stage (L_{coax}) is substantially constant in all the shots and is in reasonable agreement with what should be expected from a single CS collapsing on axis at the end of the electrode system. This fact was also found in [2], [10], and [11].

The evaluation of $L_p(t)$ makes it possible to calculate two important magnitudes of these devices. The first one is the voltage drop in the pinch $V_p(t)$ as

$$V_p(t) = V(t) - \left[L_p(t) + L_o'\right]\frac{dI}{dt}.$$

The second one is $\Delta Ep(t)$, this paper done on the collapsing plasma during the formation of the pinch [12]. $\Delta Ep(t)$ is defined as

$$\Delta E_p(t) = \frac{1}{2}\int_{t_c}^{t} I^2 dL_p'.$$

Here, t_c is the instant of time at which the *dI/dt* dip starts, and dL'_p is the differential increase in $L'p$ (which can be calculated from the experimental data) during the pinch stage. In Fig. 4, we show an example of both V_p and ΔE_p as functions of time during the pinch stage, for the same shot as before. It can be seen that ΔE_p is a continuously rising function up to a value $\Delta E_p^{\max}$ while V_p passes by a maximum $V_p^{\max}$ roughly in the middle of the pinch stage. It should be noted, by the way, that $V_p^{\max}$ is always larger than

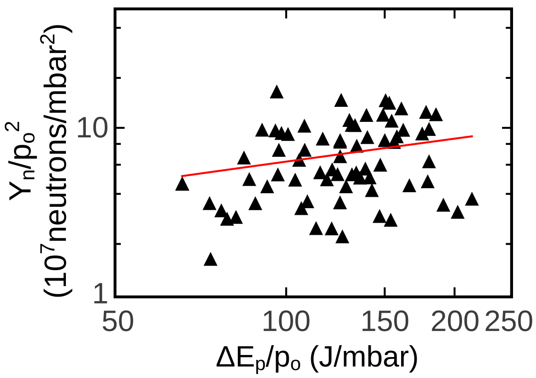

Fig. 5. Correlation between the neutron production Y_n by each particle and the particle energy delivered to the pinch. Continuous line: the best fit to the thermonuclear mechanism.

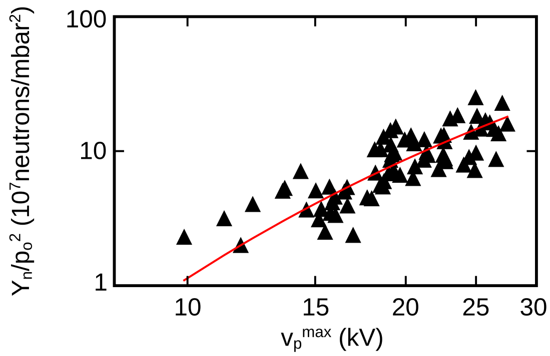

Fig. 6. Correlation between the neutron production Y_n by each particle and the maximum pinch voltage $V_p^{\max}$. Continuous line: the best fit to the beam-target mechanism.

the maximum in $V(t)$. The increment is not large in our case, but it could be quite significant in other devices (particularly in the large ones) because of larger *dI/dt* values and also larger $L_p(t) + L_0'$ values.

A. Correlations With the Emission of Neutrons and X-Rays

As discussed in [12], the neutron yield per particle pair, Y_n/p_0^2 should be expected to be a function of $\Delta E_p^{\max}/p_0$ in thermonuclear production, while Y_n/p_0 should correlate with $V_p^{\max}$ if a beam-target mechanism is the relevant one producing the fusion reactions. In the quoted work, the authors have shown that for the Buenos Aires GN1 PF device, the results of 60 shots performed between 1- and 6-mbar D_2 yielded a better correlation for the thermonuclear mechanism (0.75) than for the beam-target one (0.30).

A similar correlation was done with the results obtained in this paper, and in Fig. 5, Y_n/p_0^2 versus $\Delta E_p^{\max}/p_0$ is shows, whereas Y_n/p_0 versus $V_p^{\max}$ is plotted in Fig. 6. It can be seen by simple inspection that, the results of our measurements have an opposite fitting tendency, the beam target yielding a better fit than the thermonuclear one. The least square fit yields a correlation factor of 0.6 for the beam-target function, while for the thermonuclear case, the correlation factor was 0.03.

The amount of X-ray production in any shot can be reasonably evaluated by the amplitude of the X-ray voltage peak (Y_x) of that shot. A plot of Y_x versus $V_p^{\max}$ is shown in Fig. 7.

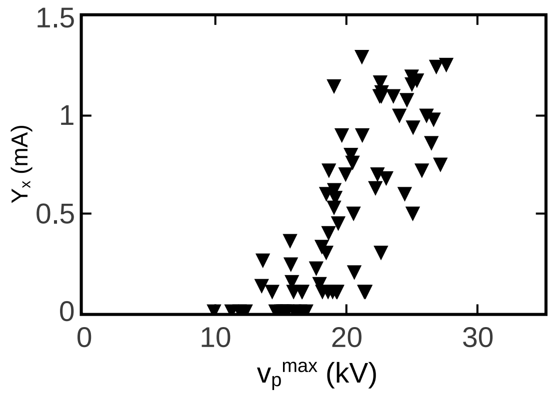

Fig. 7. X-ray peak maximum amplitude Y_x versus $V_p^{\max}$.

It can be seen that for $V_p^{\max}$ values lower than a certain one (approximately 12 kV in this case), no X-rays are emitted. This fact has been previously shown in a smaller PF device [14] and, as discussed in the previous work, can be understood in terms of the Dreicer condition for charged particles runaway [15], [16], a necessary condition for particle acceleration in a plasma.

IV. Conclusion

The evaluation of a time-varying CS inductance using electrical measurements in the PACO device yields results, which are in reasonable agreement with what should be expected if the discharge development proceeds with a single CS bridging the coaxial electrodes. In this sense, our results coincide with those found in the GN1 device [10], [16] and also with that of the 400 J PF device at Chilean Nuclear Energy Commission [11]. These results are not compatible with the notion of alternative CSs existing within the electrodes during the rundown and pinch stage, and neither to the presence of anomalous resistances in the plasma. Such phenomena have been suggested in other devices and while we have no ground to challenge these interpretations of the plasma behavior, we are confident in that such is not the case in the devices quoted in this paper.

The measurements show a dependence of the X-ray fluence with the pinch voltage. This agrees with the model proposed by Dreicer electron runaway regime noted before and agrees with the regimen found in other plasma-focus devices.

The better correlation of the neutron production with a beam-target scenario respect to a thermonuclear one, just the opposite of what was found in the GN1 device suggests that both mechanisms contribute to the fusion reactions. The presence of both mechanisms in the nuclear fusion production was also reported long time before in [7] and [8]. Further research is needed for establishing which are the operating conditions—filling pressure, geometry, and so on—favoring one or the other mechanism.

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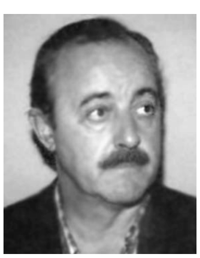

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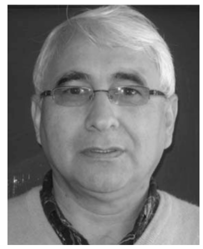

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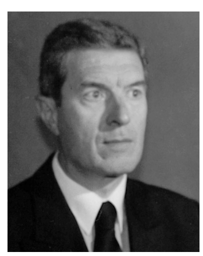

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