Dynamics and Density Measurements in a Small Plasma Focus of Tens-of-Joules-Emitting Neutrons

Ariel Tarifeño-Saldivia, Cristian Pavez, José Moreno, and Leopoldo Soto

***Abstract*—Dynamics in the radial phase and plasma conditions in the pinch phase have been studied using interferometry in a plasma focus device that operates in the range of tens of joules of stored energy in the capacitor bank and tens of kiloamperes, PF-50J. The results of these experiments using deuterium as filling gas, together with the simultaneous measurements of neutron production, are reported in this paper. The results show that the typical dynamics, pinch conditions, and electron density observed in larger machines are also present in this experiment operated at only tens of joules.**

***Index Terms*—Neutron emission, pinch plasma density, plasma focus (PF).**

I. Introduction

THE PF-50J is a small fast plasma focus (PF) device conceived to operate in the range of tens of joules and tens of kiloamperes. It has been constructed at the Chilean Nuclear Energy Commission, being an improved version of a previous design [1], [2]. The main electric characteristics of the device are as follows: 160-nF equivalent capacitance, ~40-nH total inductance in a short circuit, 150-ns first quarter of a period, 25–30-kV charge voltage, energy $E \sim$ 50–72 J, and 50–70-kA peak current in a short circuit. In a PF, after that a plasma sheet is formed over the insulator surface, the plasma sheet first moves toward the anode end (axial phase) and then implodes on the anode axis (radial phase) [3]. The last is being accompanied by the pinch evidence given by the characteristic dip and peak in the current derivative and voltage signal, respectively [4]. More recent studies have demonstrated neutron production when operating with deuterium at 50 and 67 J of stored energy in the capacitor bank. Average yields of $1.2 \pm 0.5 \times 10^4$ neutrons/shot at 6 mbar and 50 J and $3.6 \pm 1.6 \times 10^4$ neutrons/shot at 9 mbar and 67 J have been measured [5] using a detection technique based on ^{3}He-filled proportional counters specially adapted for pulsed neutron sources of low production [6]. It has been observed that the energy of the fast neutrons has a mean value of 2.7 MeV with a standard deviation of 1.8 MeV, the latter obtained using the time-of-flight technique [5].

The mechanisms of nuclear fusion and the subsequent neutron production in pinch discharges are still an open and controversial field [7]. The participation of two main processes in the total neutron yield Y produced by a pinch discharge is widely accepted: thermonuclear fusion and ion beam-target fusion. Thus, the total neutron yield is $Y = Y_{\rm th} + Y_{\rm b-t}$, where $Y_{\rm th}$ is the thermonuclear component and $Y_{\rm b-t}$ is the beam-target component. There is a wide acceptation that the $Y_{\rm b-t}$ is the most important component [7]. From theoretical assumptions, scaling laws for the neutron yield Y related to the energy stored in the capacitor bank E and to the maximum current close to the pinch time are $Y \ \alpha \ E^2$ and $Y \ \alpha \ I_p^x$, wherein the value of x depends of the fusion mechanism. Scaling laws for the neutron yield with the peak current have been proposed. Theoretically, it is possible to show the thermonuclear fusion scale with the peak current as $Y_{\rm th} \ \alpha \ I_0^4$. For the beam-target fusion, two scaling laws have been proposed. In [8], it is assumed that the ion beam current is proportional to the pinch current and the relation $Y_{\rm b-t} \ \alpha \ I_0$ is obtained while, in [9], from an inductive model for the beam acceleration, the relation $Y_{\rm b-t} \ \alpha \ I_0^{4.5}$ is obtained.

Using the results of several devices in a wide range of energies and currents (1 kJ to 1 MJ and 100 kA to 1 MA), the most accepted empirical scaling laws for the total neutron yield Y are $Y \sim 10^7 \ E^2$, with E in kilojoules, and $Y \ \alpha \ I_p^{3.3}$, with I_p in kiloamperes [10]. However, other dependence also based in experimental results in the same range of energies and currents has been proposed, for example, $Y \ \alpha \ I_0^{4.7}$ [8], [11]. In any case, it is interesting to research how to scale the neutron yield for devices operating at energies lower than 1 kJ. From results obtained in devices operating at E and I_p of 400 J and 127 kA [12], 67 J and 60 kA [5], and 50 J and 50 kA [5], respectively, the following scaling has been observed: $Y \sim 7.73 \times 10^{-5} I_p^{4.82}$ (with I_p in kiloamperes) [5], [7]. The latter observation motivates future experiments in order to determine the contribution of $Y_{\rm th}$ and $Y_{\rm b-t}$ to the total neutron yield and to corroborate this preliminary scaling law for the region of hundreds and tens of joules. In addition, despite all

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TABLE I
SUMMARY OF OPERATIONAL CONDITIONS FOR EXPERIMENTS USING DEUTERIUM AT 6 mbar AND 67 J

D_2, 6 mbar Flow, 29kV , 67 J		
Anode	Material	Copper
	$l_{effective}$	3.5 mm
	Radius a	3 mm
	Central hollow	4.5 mm diameter, 18 mm deep
Insulator	Material	Alumina
	$l_{effective}$	23.9 mm
Cathode	8 copper rods, 5 mm diameter	
	Length	26.5 mm (6U), 24.5 mm (2U)
	Radius b	11 mm inner side, 13.5 mm from rod axes

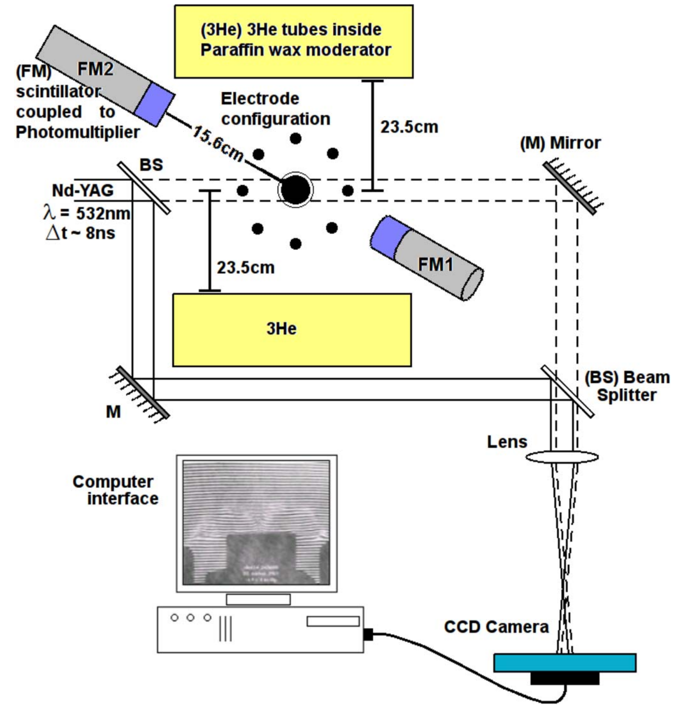

Fig. 1. Schematic diagram of the experimental setup. Electrode configuration is shown at the middle of the two ^{3}He detectors.

the accumulated evidence, there is a remaining question to be answered in order to study the scaling laws valid in the region of hundred and tens of joules. Does our experiment at tens of joules reproduce the same pinch conditions than those observed in larger machines? In particular, the value of the pinch density is one of the relevant parameters to theoretically evaluate the neutron production. To answer the last question, experiments using interferometric diagnostics have been done in order to get plasma dynamics in the radial phase and pinch density in a deuterium PF of tens-of-joules-emitting neutrons. The results of these experiments are reported in this paper.

II. Experimental Setup

A series of experiments using deuterium as filling gas was done. The experiments were conducted at 6 mbar and 67 J. With an effective anode length of 3.5 mm and anode radii of 3 mm, the characteristic dip in the current derivative signal appears close to the peak of the circuit current. A detailed summary of the experiment operational conditions is given in Table I.

A schematic diagram of the experimental setup is shown in Fig. 1. In order to measure the electron density of the plasma, a Mach–Zender interferometer was implemented. To obtain temporal resolution, an 8-ns pulsewidth Nd-YAG laser $(\lambda = 532 \text{ nm})$ was used, and the image acquisition was done by using a charge-coupled device camera. For position measurements, the error bar is assigned directly from the interferogram, while the temporal error bar is considered to be the laser pulsewidth. The experiment firing system consists of a laser control unit, which is able to produce a controlled delayed TTL or an optical pulse coupled to the trigger unit of the PF device. The image time can be controlled by adjusting the delay between the laser trigger pulse and the TTL or optical pulse in the laser control unit. Electron density profiles were obtained by Abel inversion of fringe shifts from interferograms. The electrical diagnostics used consist of a resistive divider for voltage monitoring and Rogowski coils for current derivative monitoring and image time correlation which is referred to as pinch time (lowest part of the current dip). The circuit current was obtained by numerical integration of the current derivative signal and proper probe calibration. Two assemblies of the plastic scintillator (BC408, 2-in diameter and 2 in long) plus photomultiplier tube (XP2262B) were used for verifying the neutron and X-ray production and for emission time correlation with the dip. Each scintillator assembly has a rise time of ~3 ns and a transit time in the photomultiplier tube of 31 ns. The two assemblies (namely FM1 and FM2) were placed at 15.6 cm from the top of the anode. FM1 and FM2 are arranged in angles of 45° and 0°, respectively, and referred to the horizontal plane. The neutron production was measured by using two moderated ^{3}He-filled proportional counters (^{3}He tubes) according to the technique reported by Moreno *et al.* [6]. Both detectors were arranged symmetrically side-on at a distance of 23.5 cm from the anode axis.

III. Experimental Observations

A sequence of the radial phase dynamics is shown in Fig. 2; for the sequence, time is measured with respect to the dip. From the results, the radial phase lasts around 50 ns. The end of the radial phase is given by the stagnation of the plasma sheet to form a dense column which is appreciable in Fig. 2(e) (shot14_24Jul08). The time evolution of the radial piston is followed for each interferogram at the position $z = 0.5$ mm with respect to the top of the anode. The radial piston dynamics is shown in Fig. 3. From these data, the maximum piston velocity is estimated to be around 10 cm/μs at the end of the radial phase. The column length (z_p) and radii (r_p) are

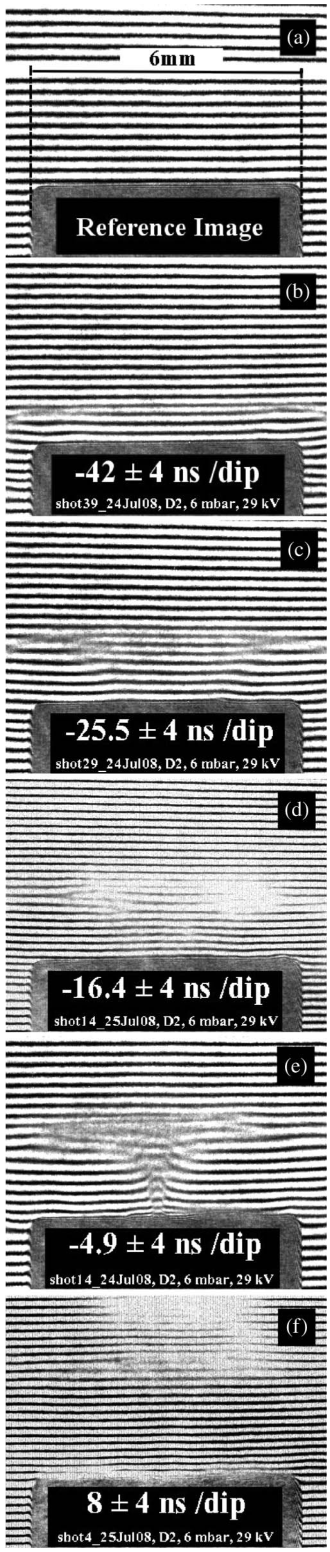

Fig. 2. Interferometric sequence for the radial and pinch phases. (a) Spatial reference image. (b) Early radial phase. (c) and (d) Radial phases close to time of maximal radial piston velocity, around 10 cm/μs. (e) Pinch phase (note the formation of a high-density column). (f) Time after column disruption (note remaining material over the place of previous column formation).

close to the expected values scaling with a, i.e., of $z_p \sim a$ and $r_p \sim 0.1a - 0.2a$ (where a is the anode radius).

For shot14_24Jul08 [see Fig. 2(e)], around the moment of the pinch formation, measurements of the neutron yield and electrical signal are shown in Figs. 4 and 5, respectively. The neutron yield measured with the ^{3}He-filled proportional counter (see Fig. 4), for this shot, gives evidence of a neutron yield of 1.6×10^4 neutrons/shot, which is in agreement with measurements in a similar electrode configuration reported in [5] and [6]. From the electrical diagnostics with time resolution (see Fig. 5), it is possible to clearly observe a dip formation in the current derivative signal, as well as an induced voltage, associated to the fast compression and pinch formation. The time differences between the pinch time and FM's start of signal are 31.3 ns for FM1 and 37.8 ns for FM2 (see Fig. 5); subtraction of the transit time in the photomultiplier tube (31 ns) allows concluding from the time of flight that the first slope in the FM1 signal is due to X-ray detection, whereas the slope in the FM2 signal is due to neutron detection. Consecutive slopes and peaks in both signals correspond to pulses generated by detected neutrons in the scintillators. The signal shape and maximal neutron energy $(E_{\max})$ from the time of flight are in agreement with those reported in a previous and more detailed study, where $E_{\max}$ was found to be $E_{\max} = 2.7 \pm 1.8$ MeV [5]. It should be noted that the difference observed at the beginning of each signal in the photomultiplier tubes, despite both detectors being equidistant from the plasma, would be associated to the anisotropy in the hard X-ray and neutron angular distributions as well as to the low yield that small devices present, as have been observed in other PF devices [13]. From electrical signals, the peak voltage at the pinch time is 11 kV, the peak current is 50 kA, and the circuit current at the moment of the pinch is estimated to be 47 kA. After some nanoseconds (6–10 ns), the column is disrupted as it could be seen from Fig. 2(f).

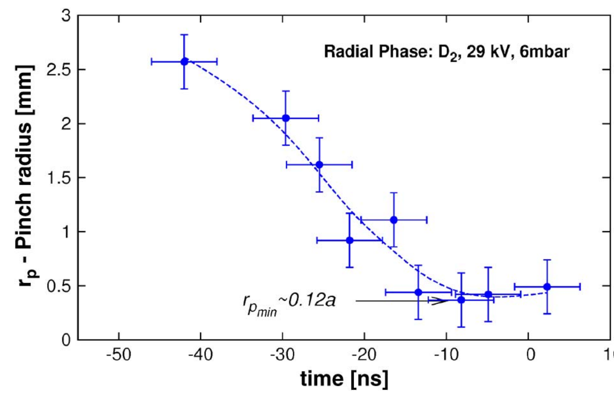

Fig. 3. Radial phase dynamics from interferometric measurements. Zero time referred to time of dip occurrence in dI/dt signal. Pinch formation close to zero time.

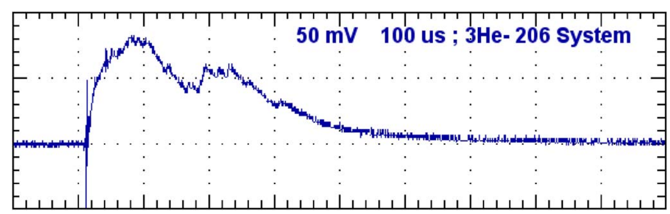

Fig. 4. Electrical signal delivered by one of the ^{3}He-filled proportional counters. The spread in the timescale and the piled-up electrical signals of the neutrons are determined by the moderator effect as it is explained in [6].

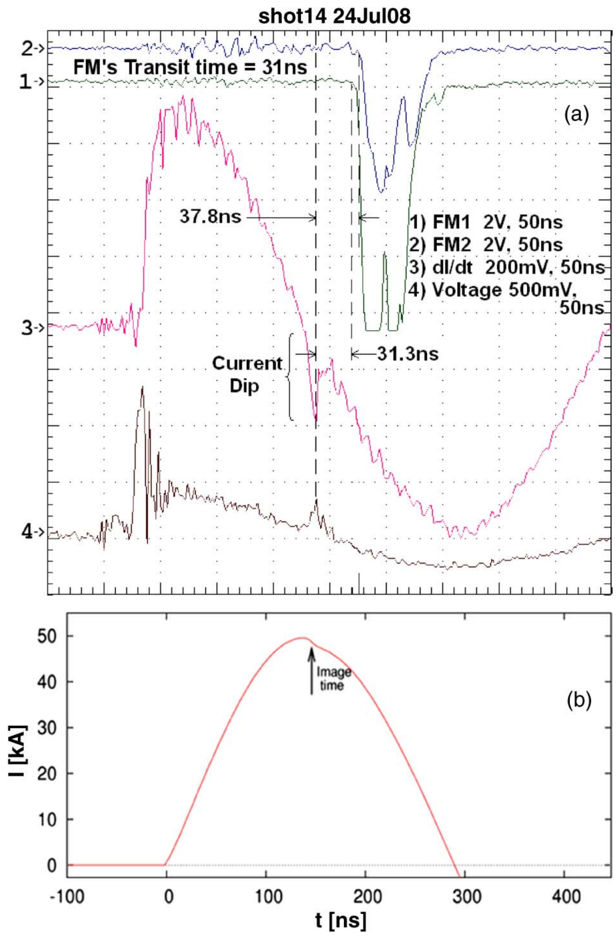

Fig. 5. (a) Electrical and scintillator assembly signal. Assemblies FM1 and FM2 were placed at 15.6 cm from anode axis. The transit time of 31 ns in the photomultiplier tubes must be considered. (b) Current signal from numerical integrated dI/dt signal. Time referred to start of dI/dt signal.

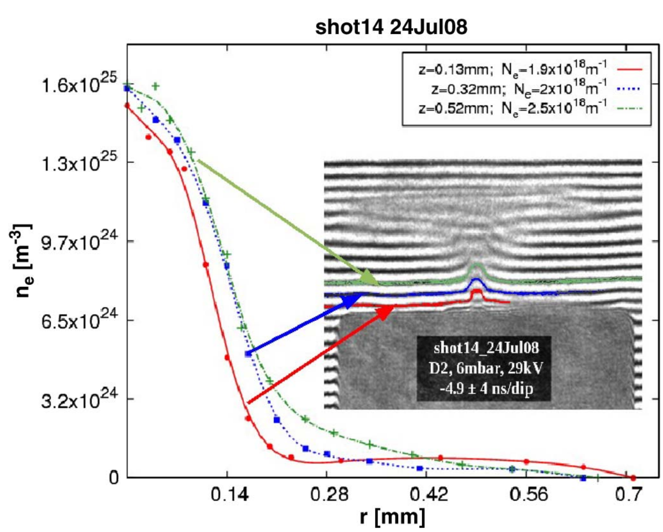

Fig. 6. Electron density profiles obtained by Abel inversion of fringe shifts from interferograms for shot14_24Jul08.

The electron density profile measurements for shot14_24Jul08 [see Fig. 2(e)] are shown in Fig. 6. We used single fringes in the analysis, assuming axial symmetry and independence of z in the region analyzed (0.1 mm $< z < 0.6$ mm, with z measured from the bottom to the top). Thus, a numerical Abel inversion was applied. The fringe deviation was measured with an accuracy of 1/20 of the fringe. For this shot, three different fringes were considered. From the bottom to the top, the fringes are placed at $z_1 = 0.13$ mm, $z_2 = 0.32$ mm, and $z_3 = 0.52$ mm from the anode top edge. From the shift fringe, average densities of 3×10^{24} m^{-3} at z_1, 3.8×10^{24} m^{-3} at z_2, and 4.25×10^{24} m^{-3} at z_3 are found. The peak density for each profile is always reached on the axis and has values of 1.53×10^{25} m^{-3} at z_1, 1.6×10^{25} m^{-3} at z_2, and 1.62×10^{25} m^{-3} at z_3, and an error was estimated to be 30%. The number of electrons per unit length, line density N_e, is given as 1.9×10^{18} m^{-1} at z_1, 1.96×10^{18} m^{-1} at z_2, and 2.52×10^{18} m^{-1} at z_3. By using the measured values of the electronic density, it is possible to estimate the ratio f_m of ionized particles to neutral gas. This calculation is made with the assumption that the column of gas over the anode is the volume to be compressed during the radial phase so that $f_m = N_e/N_0$ (N_0 being the line density of neutral gas in a column of a radius). This parameter can be understood as the piston efficiency, and it could be used to compare the simulation results from 0-D codes, such as the Lee model code [14]. In the case of shot14_24Jul08, the f_m factor is estimated to be 0.23 at z_1, 0.23 at z_2, and 0.30 at z_3. Averaging over the three profiles obtained a mean of $\langle f_m \rangle = 0.253$. Hence, the magnetic piston has an average efficiency of 25%.

IV. Summary

By means of interferometric diagnostics, dynamics and density measurements have been done for the radial phase and pinch phase in a small PF, namely the PF-50J device, operating with deuterium in the range of tens of joules and tens of kiloamperes. As result, a maximal piston velocity in the radial phase of around 10 cm/μs is estimated at the end of the radial phase, and average densities of around 3.5×10^{24} m^{-3}, peak densities of around 1.6×10^{25} m^{-3}, and line densities of around 2×10^{18} m^{-1} in the pinch phase have been observed. Estimations of the ionization proportion of particles in the radial phase from neutral gas showed an efficiency of around 25% in our experiments.

The pinch geometry and lifetime are also in agreement with the expected values from scaling rules [7], [15]. The ion density is of the same order as kilojoule to megajoule PF devices [16]–[20]. From the aforementioned results, it is clear that the dynamics and pinch density observed in larger machines are also present in PF devices operating at only tens of joules.

For future work on this device, it is intended to get optimized conditions for neutron production and to study the validity of the scaling laws in the range of subkilojoule stored energy in the capacitor bank.

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