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Demonstration of neutron production in a table-top pinch plasma focus device operating at only tens of joules

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Abstract
Neutron emission from a deuterium plasma pinch generated in a very small plasma focus (6 mm anode diameter) operating at only tens of joules is presented. A maximum current of 50 kA is achieved 140 ns after the beginning of the discharge, when the device is charged at 50 J (160 nF capacitor bank, 38 nH, 20–30 kV, 32–72 J). Although the stored energy is very low, the estimated energy density in the plasma and the energy per particle in the plasma are of the same order as in higher energy devices. The dependence of the neutron yield on the filling pressure of deuterium was obtained for discharges with 50 and 67 J stored in the capacitor bank. Neutrons were measured by means of a system based on a ^{3}He proportional counter in current mode. The average neutron yield for 50 J discharges at 6 mbar was $(1.2 \pm 0.5) \times 10^4$ neutrons per shot, and $(3.6 \pm 1.6) \times 10^4$ for 67 J discharges at 9 mbar. The maximum energy of the neutrons was (2.7 ± 1.8) MeV. Possible applications related to substance detection and others are discussed.

1. Introduction

A pinch is a transient plasma column conducting electrical current, which becomes self-confined by the associated magnetic field. Plasma pinches reproduce the scenario of high-energy density, intense beams of charged and neutral particles, with radiation emission. Thus, they become a suitable laboratory for fundamental and applied research related to fusion, neutron production, x-ray and high brightness soft x-ray production and astrophysical phenomena [1]. Generally, plasma pinches require the use of high pulsed voltages (kV–MV) to produce high currents (kA–MA) in the plasma. Several configurations for pinches have been proposed and studied for decades, namely, compressional z-pinch [2], plasma foci [3, 4], gas embedded z-pinch [5], fibre pinches [6], double column gas embedded compressional z-pinch [7], capillary discharges [8] and recently wire arrays and nested wire arrays [9–11].

Fusion D–D reactions in plasma foci, with magnetically compressed plasmas of deuterium, generate fast neutron pulses. The energy of these neutron is ~2.5 MeV and each burst of neutrons lasts from about tens to hundreds of nanoseconds, depending on the plasma duration. These devices have been constructed in a variety of sizes, in correlation with the energy stored in the pulsed electrical generator, ranging from kilojoules to megajoules. Neutron pulses are produced, about 10^7–10^{12} neutrons per shot [12, 13, 28, 29]. This neutron emission can be applied to

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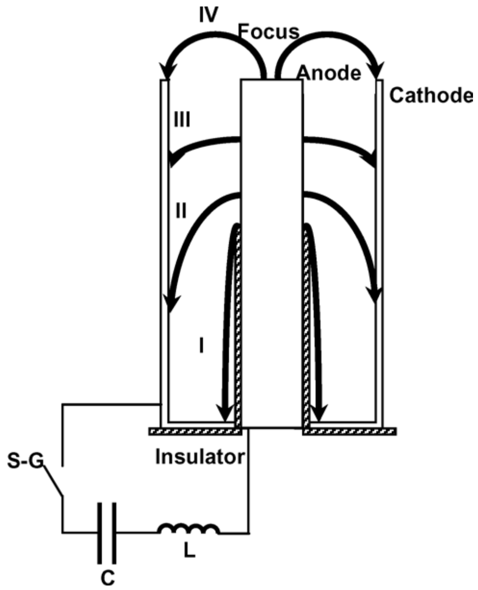

Figure 1. A scheme of the circuit and the plasma dynamics is shown. The capacitor C is discharged over the electrode through a spark gap (SG). The plasma dynamics is sketched in a side section of the electrodes, I: discharge starts over the insulator, II, III: the current sheath is accelerated along the coaxial electrodes, and IV: pinch.

perform radiography, substance analysis [34–36] and even to calibrate dark matter detectors [14]. However, large plasma foci are limited to in-lab diagnosis applications, in contrast to portable conventional radioactive sources. Hence, neutron production in a smaller plasma focus could open a window for *in situ* applications. New important applications such as explosive mine dismantling are calling for portable, safer devices.

The construction of smaller plasma focus devices has not been considered for decades, since lower energies were presumed insufficient to generate strong plasma discharges or even to produce a detectable number of neutrons. Here, we present the evidence of neutron emission from a table-top plasma focus operating at tens of joules. The measured neutron production is of the order of 10^4–10^5 neutrons per shot. This result opens a new experimental region to check present theoretical models for dense plasmas. A quite relevant point is that it is not only possible to get a dense plasma, but also the plasma energy density is of the same order as for higher energy devices. This implies that most of the processes occurring in larger machines are also present here.

A plasma focus in a low pressure gas environment produces a hot (∼0.3–1 keV) and dense (∼10^{25} m^{-3}) transient plasma for some nanoseconds [29, 30], induced by a high pulsed voltage between a pair of coaxial cylindrical electrodes. The hot plasma is the result of the time evolution of the electrical discharge which travels along the coaxial electrodes. In a few microseconds, or less, a current sheath is magnetically driven and compressed to form a plasma pinch. Figure 1 shows a scheme of the circuit and the plasma dynamics. The electrodes are vertical and coaxially disposed; the anode in the centre is partially covered by a coaxial insulator from its base to a certain height. The discharge starts over the insulator surface, and then the plasma sheath comes off axially accelerated by the magnetic field generated by the current itself. After the current sheath runs over the upper end of the central electrode, the plasma becomes rapidly compressed to a small region resulting in very hot and dense plasma (the focus or pinch).

Feasibility objections have been made to devices with charging energies lower than 1 kJ for not having enough energy and time to generate, move and compress the plasma. Another objection is related to the capability to measure the emitted radiation in PF devices below 1 kJ. However, in recent years plasma foci operating at hundreds of joules have been reported, contradicting the above-mentioned preconceptions [16, 17, 25]. Hence, the testing of the capabilities of devices operating at still lower energies is a reasonable and valuable experimental goal. In this paper, we report a study conducted in a small plasma focus device (PF-50J) operating at tens of joules.

2. The device and diagnostics

PF-50J is a plasma focus device designed and constructed at the Chilean Nuclear Energy Commission (CCHEN), being an improved version of a previously published design [18–21]. It achieves 50 kA in 140 ns when it is charged at 50 J (160 nF capacitor bank, 38 nH, 20–30 kV, 32–72 J). The electrodes consist of a copper tube central anode, of 6 mm diameter and 28.8 mm length, and an outer cathode formed by eight copper rods, 5 mm diameter, 29 mm long, uniformly spaced on a coaxial circumference of 27 mm diameter. The anode and the cathode are separated by an insulator alumina tube of 24 mm length, which covers the anode (figure 1). A shorter effective anode (4.8 mm long) is adequate for the short time of the discharge current, due to the small bank capacity. The size of this table-top device is 25 cm × 25 cm × 50 cm.

Diagnostics include electrical signals, fast photography from visible plasma light and neutron detection (total yield and time resolution).

Electrical signals. Voltage, total current and current derivative are measured with the usual monitors, a fast resistive divider and a Rogowskii coil. The voltage monitor was located close to the plasma load. The Rogowskii coil monitored the current-derivative signal in the capacitor bank.

Images from the visible plasma light. An intensified CCD (ICCD) camera gated at 5 ns exposure time, and synchronized with the discharge, has been used in order to obtain side view images of the visible light emitted from the plasma [20]. For imaging the plasma over the microchannel plate in the ICCD camera, a regular bi-convex lens, of 12.5 cm focal length and 5 cm diameter, was used. In order to increase the field depth a mask with an open circle of 1 cm diameter was attached to the lens, leading to an optical number $F = 1/12.5$. A magnification $m = 0.2$ was used. The resolution of the camera for magnification $m = 1$ is 23 μm, thus for $m = 0.2$ a resolution of 95 μm (∼0.1 mm) is achieved.

Neutron detection. Using empirical scale laws, for a device of tens of joules a neutron yield of about 10^4–10^5 neutrons per pulse is expected, which is below the detectable level

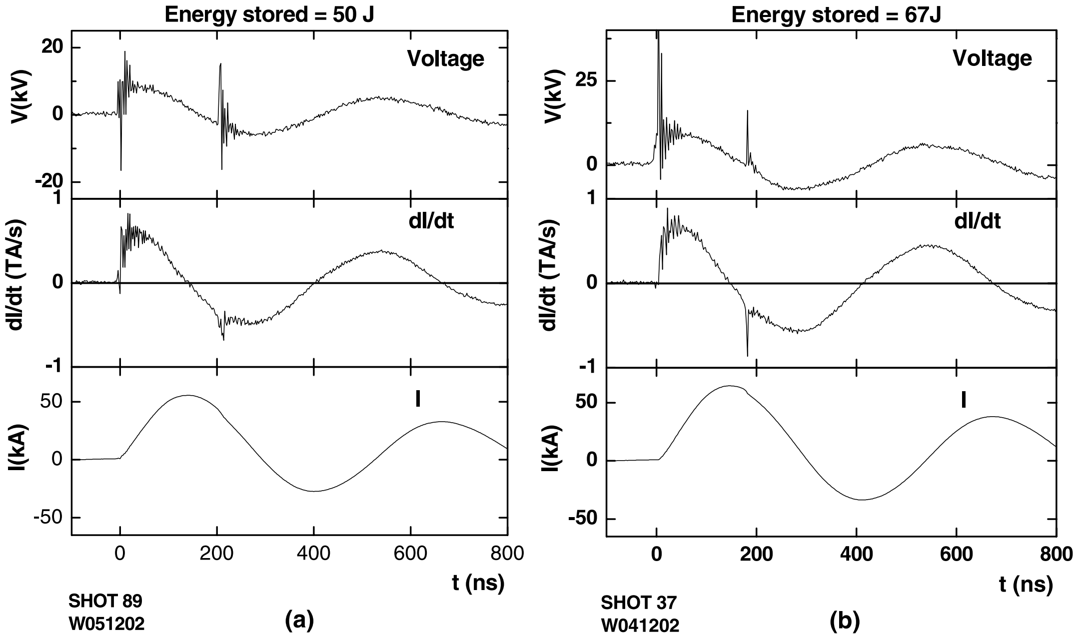

Figure 2. Voltage between electrodes, current derivative and current intensity, for discharges of 50 J (*a*) and 67 J (*b*) in deuterium at 9 mbar. The corresponding peak currents are 50 ± 3 kA and 60 ± 3 kA, respectively. The dip in the signal of the current derivative when the voltage increases is the indication of the plasma pinch (focus). The pinch formation induces a sudden variation of the total inductance of the circuit, which in turn produces the current dip and the sudden voltage peak.

of detectors based on activation. Therefore, to be able to detect neutron yields lower than 5×10^5 neutrons per shot a system based upon ^{3}He proportional counter was developed [22]. A conventional neutron detection technique was adapted to measure low neutron yields from D–D fusion pulses. ^{3}He proportional counters are well-known neutron detectors whose detection principle is based on the nuclear reaction, n(He^3, H^3)p [23]. An analogue signal corresponding to the current generated in the ^{3}He tube is processed through a preamplifier whose output is directly connected to a digital oscilloscope. Note that the ^{3}He proportional counter is used in 'current mode', meaning that the time-integrated signal is the charge generated in the ^{3}He tube and it is proportional to the neutron yield. The integration time is determined by the characteristics of the preamplifier and is about some hundred microseconds. No neutron background is detected during this temporal window. To calibrate the neutron detection system (with moderator included) a calibrated silver activation counter was used as reference. During the calibration, the adapted ^{3}He and the silver activation counter were placed simultaneously in front of a higher energy plasma focus device, PF-400J [16], operating at hundreds of joules, detecting neutron yields from 5×10^5 to 2×10^6 neutrons per shot. A linear proportional relation was obtained between the ^{3}He time-integrated signal and the neutron yield measured by the silver activation counter. Neutron yields lower than 10^3 neutrons per pulse are detectable with this technique [22].

In addition, plastic scintillators connected to a photomultiplier were used for neutron detection with temporal resolution. In order to measure the energy of the emitted neutrons, by means of the time of flight technique, two plastic scintillators BC408 coupled to photomultipliers were placed at distances of 30.5 and 78.5 cm from the axis. The scintillators have a diameter of 5 cm and a thickness of 5 cm.

3. Results and discussion

Discharges were performed in deuterium at low pressure, from 2 to 12 mbar, with two different charging voltages, namely, 25 ± 2 and 29 ± 2 kV (approximately 50 and 67 J stored in the capacitor bank). The corresponding electrical signals (voltage between the electrodes, current derivative and current intensity) for 9 mbar are shown in figure 2. Peak currents of 50 ± 3 and 60 ± 3 kA are obtained. The formation of a pinched plasma column (the focus) is indicated by the dip in the signal of the current derivative at the moment that the voltage increases. The pinch formation induces a large sudden increase in the total inductance of the circuit. This change is responsible for the observed dip in the current and the sudden increment in the voltage. The highest efficiency condition is achieved when the pinch compression is nearly coincident with the peak current, but slightly after that peak.

Figure 3 shows a fast photograph of the plasma obtained with 5 ns exposure time, using an ICCD camera, at 196 ns from the beginning of the discharge and close to the moment of maximum compression. From the photograph it is possible to estimate the size of the plasma column, with an approximate radius of 0.3 mm and a height of 3.0 mm. Therefore, the pinch volume is $V_p \sim 8.5 \times 10^{-10}$ m^3.

It is customary to use the parameter E/V_p (E being the initial energy stored in the capacitor bank) to compare the plasma energy density between devices. Of course, this number should only be used for comparison, since only a fraction of the initial energy is transferred to the plasma. For the PF-50J operated at 50 and 67 J, E/V_p is about 6 to

8×10^{10} J m^{-3}, which is comparable to the ratio occurring in higher energy devices (kJ–MJ) [21, 27].

From the photograph shown in figure 3 it is also possible to estimate the ion density in the plasma pinch. The pinch ion density can be roughly estimated from the filling density compressed to the final pinch plasma column by the fraction of ionized gas. In a plasma focus in which the radial phase dominates over the sheath formation stage and over the axial run-down (as it does in the PF-50J), the plasma mass per unit length in the pinch roughly equals the mass per unit length of the gas initially contained over the inner electrode (i.e. the mass in a cylinder above the anode, with an initial radius coincident with the anode radius [20]). Thus, the number of ions per unit length of the plasma pinch (N, line density) can be estimated as the filling density multiplied by the cross section of the anode, and multiplied by the number of atoms of each molecule (2 in D_2) and by the fraction of ionized gas. From calculations based on a widely used model developed by Lee [12], a fraction of ionization, f_r, in the radial phase with a value of $f_r \sim 30\%$ fits with experimental results of several devices of different energies.

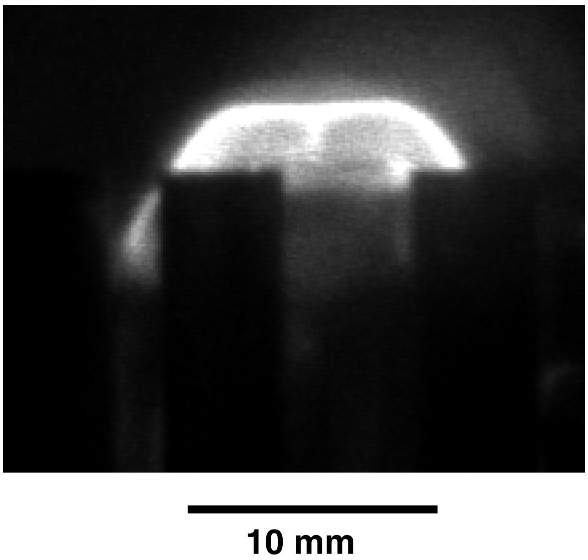

Figure 3. Side-on photograph of the plasma obtained with 5 ns exposure time at 196 ns, close to the moment of maximum compression.

Thus, for 6–9 mbar in diatomic D_2, the filling pressure range implies an initial atom density from 3.24×10^{23} to 4.86×10^{23} particles m^{-3}. Hence, the maximum line density N could be between $((3.24–4.86)\times 10^{23}\ \mathrm{m}^{-3})(\pi)(3 \times 10^{-3}\ \mathrm{m}^2)$, i.e. $(9–14)\times 10^{18}$ particles m^{-1}. After the plasma is compressed to a cylindrical column of radius $r_{\mathrm{pinch}} \sim 0.3$ mm, with a fraction of ionization of $f_r \sim 0.3$, an ion density, $n = f_r N/\pi r_{\mathrm{pinch}}^2$, of about 0.9 to 1.5×10^{25} particles m^{-3} is expected in the pinch. Interestingly, this level of ion density is comparable to those reachable in high-energy plasma focus devices [29].

The total neutron yield was measured using the detection system based upon the ^{3}He proportional counter in 'current mode' described briefly above and in detail in [22]. Figure 4 shows the dependence of the neutron emissions of PF-50J on the gas filling pressure. Each point represents the average of ten shots and the bars represent the standard deviations. There is a detectable neutron yield, whose average was measured as $(1.2 \pm 0.5) \times 10^4$ neutrons per shot at 6 mbar for discharges operated with 50 J in the capacitor bank. For discharges operated at 67 J the average neutron yield was $(3.6 \pm 1.6) \times 10^4$ neutrons per shot, at 9 mbar. The maximum neutron yield raised in a shot at 50 J was 3×10^4 and 7×10^4 in a shot at 67 J.

In order to measure the energy of the emitted neutrons, two plastic scintillators BC408 coupled to photomultipliers (5 cm of diameter) were placed at distances of 30.5 cm (FM1) and 78.5 cm (FM2) from the axis. Figure 5 shows a signal from these scintillators. Unfortunately, it was not possible to correlate the signals peak to peak. The reasons for this are the very low count number of neutrons (i.e. considering a shot emission of 10^4 neutrons in a 4π solid angle, on average about 17 neutrons arrive at FM1 and only 2 or 3 at FM2), and the random and complex mechanism of neutron emission in the plasma, including anisotropy. Nevertheless, using 20 shots it was possible to determine the starting time of the neutron signal in both detectors (shown with arrows in the figure), thus obtaining the time of flight of the particles, which can be used to estimate an upper bound of the neutron energy. A mean value of 2.7 MeV with a standard deviation of 1.8 MeV was calculated. In addition, the time lag between the signal indication of the pinch (i.e. the current-derivative dip coincident with the voltage peak) and the neutrons arrival

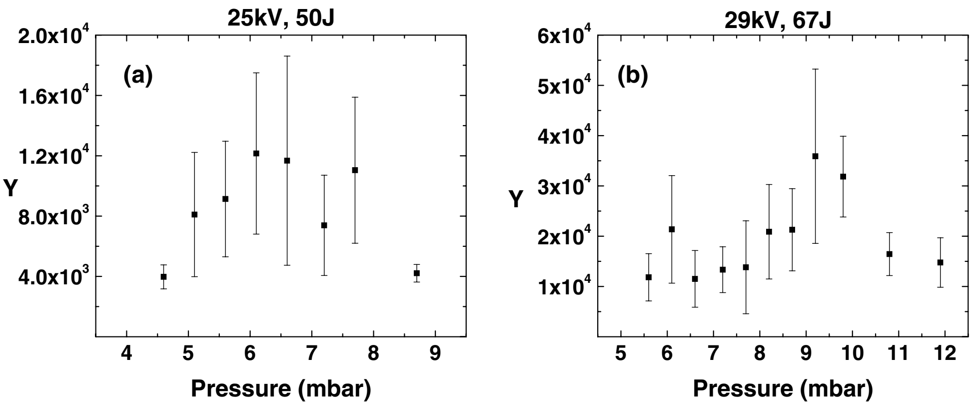

Figure 4. Dependence of the neutron yield of the PF-50J on the gas filling pressure, operating at 50 J (*a*) and 67 J (*b*).

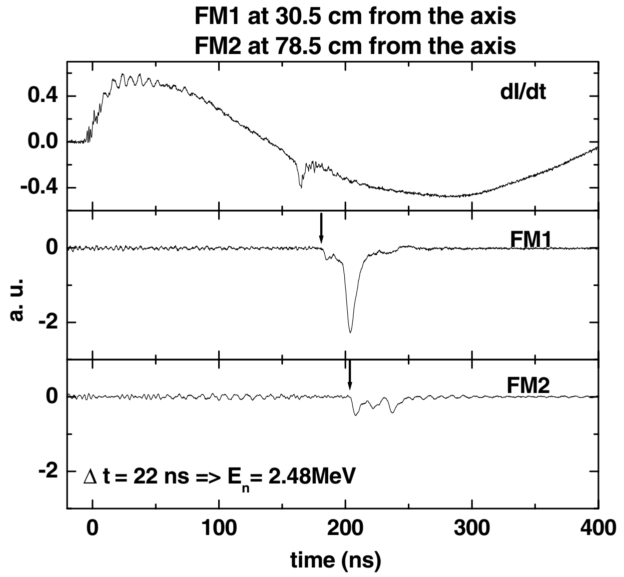

Figure 5. Two BC408 plastic scintillators with coupled photomultipliers were placed at 30.5 and 78.5 cm from the discharge axis in order to obtain the time of flight of the neutrons emitted. The time in which the neutron signal starts (arrows) was measured in both detectors, thus obtaining the time of flight of the particles. In the figure, a time of flight of 22 ns was measured for a distance of 48 cm, corresponding to an energy of 2.48 MeV for the neutrons. A mean value of 2.7 MeV with a dispersion of 1.8 MeV was obtained over 20 shots. Therefore, it is possible to conclude that the particles seen are neutrons from fusion D–D reactions.

at the plastic scintillators is consistent with the time of flight of 2.7 MeV neutrons. This evidence strongly supports the conclusion that the pinch is the source of the neutron pulse.

Several physical magnitudes are practically invariant in plasma focus devices operating with energies from 1 kJ to 1 MJ. Actually, several of these magnitudes are kept in the PF-50J near values found for larger plasma foci. One of them is the ion density (of the order of 10^{25} m^{-3} for devices from 1 MJ to 1 kJ), which in the present device of tens of joules was estimated at about $\sim 1 \times 10^{25}$ particles m^{-3}. Likely, plasma compression occurs at an average radial velocity of about 10^5 m s^{-1} (near the axis was measured $\sim 2 \times 10^5$ m s^{-1}) [20]. This value is similar to the compression velocity in higher energy devices.

Another relevant invariant parameter in plasma foci, related to neutron production, is the so-called drive parameter ($I_0/ap^{1/2}$) [24, 26], where I_0 is the peak current, a is the anode radius and p is the gas filling pressure for the maximum neutron yield. It is remarkable that, for neutron-producing devices in the range 3 kJ–1 MJ, the drive parameter is practically the same, $I_0/ap^{1/2} = 77 \pm 7$ kA cm^{-1} mbar$^{-1/2}$ [13, 24]. The drive parameter for the PF-50J is calculated as 50 kA/(0.3 cm $\times$ $6^{1/2}$ mbar$^{1/2}$) = 68 kA cm^{-1} mbar$^{-1/2}$ (for 50 J), and 60 kA/(0.3 cm $\times$ $9^{1/2}$ mbar$^{1/2}$) = 66.7 kA cm^{-1} mbar$^{-1/2}$ (for 67 J). Furthermore, it is worth noting that the energy density parameter E/V_p, the ion density n, and consequently the energy per ion, proportional to $E/(V_p n)$, in the PF-50J, are similar to the corresponding numbers in devices operating between kJ and MJ.

Summing up, it is possible to conclude that plasma pinches produced with plasma focus discharges of only tens of joules have the same ion and energy densities, the same energy per particle, and drive parameter, as higher energy devices which operate in the range of kJ–MJ. The PF-50J thus becomes a small-scale laboratory for studying hot, dense plasmas.

The observed maximum neutron production roughly agrees with the empirical scaling laws available in the literature. The most accepted criterion outlined for drivers with an energy from 1 to 100 kJ [12] establishes that the neutron yield, Y, satisfies $Y = 10^7 E^2$ and $Y = I^{3.3}$ (with E, the storage energy in the driver, in kJ, and I, the current at the pinch moment, in kA). On the other hand, using the results from our experiments in plasma foci with hundreds of joules PF-400J (produces 1.2×10^6 neutrons at 127 kA) [16] and the results for the PF-50J, it is observed that the total neutron yield scaling is $Y \sim 7.73 \times 10^{-5} I_0^{4.82}$ (with I_0 in kA). More experiments are required to corroborate this preliminary scaling law for the region of hundreds and tens of joules.

4. Conclusions

A plasma focus of only tens of joules (PF-50J) has been designed and constructed. Neutrons were measured by means of a system based upon a ^{3}He proportional detector operating in current mode. This is the first device operating at tens of joules where neutron emission is reported. It is possible to conclude that plasma pinches produced in plasma focus discharges of tens of joules have similar energy density, ion density, energy per particle and drive parameter as higher energy devices operating between kJ and MJ. The PF-50J thus becomes a small-scale laboratory for studying hot dense plasmas. Moreover, the present design can probably be improved in order to increase the neutron production, particularly optimizing the anode length in order to produce pinches closer to the peak current.

This small nuclear-fusion machine constitutes a significant tool for research, being applicable to a wide technological domain in related sciences, industry, medicine, mining, agriculture, civil safety, etc. In fact, the pinch plasma reported here is a size-friendly pulsed neutron source especially suited for applications with a significant reduction of contamination problems. In effect, passive radioactive neutron sources with similar energy (e.g. $\sim$2.5 MeV ^{252}Cf or Am/Be) emit continuously, carrying inconveniences in handling and storing. In turn, plasma focus generators are safer since they do not have such activation problems. Other non-radioactive sources of neutrons are based on continuous beam accelerators on deuterated targets; this kind of device works with voltage supplies of $\sim$100 kV. The advantage of portable devices based on plasma focus technology is that power supplies of only tens of kilovolts or less are required.

A repetitive neutron pulsed generator (Hz–kHz) based on a very low energy plasma focus such as the PF-50J reported here could lead to a breakthrough in engineering applications such as soil humidity measurements, medical neutron therapies, substance detection (explosives, drugs, minerals, etc) and others. This feature is greatly facilitated by the lower energy required to produce neutrons. In fact, according to the available commercial information, fluxes of 10^6–10^8 neutrons s^{-1} are adequate for prompt gamma neutron analysis [32] and for detection of substances by means of neutron back scattering 10^4–10^5 neutrons s^{-1} are required [31]. A PF-50J operating at 1 kHz and 1 Hz, respectively, could be adapted for that kind of application. We expect that the results reported here will be useful as a technological basis for engineering small portable repetitive plasma foci, as an on–off source of radiation 'nanoflashes'. Recently, several proposals for applications related to substance detection have been presented [12, 34–36].

Furthermore, the scientific questions that the results presented here give rise to are even more interesting. The neutron angular distribution [15] and the mechanism of neutron emission (thermonuclear fusion versus beam target fusion) are open controversial areas, which has not been studied in devices operating at energies lower than 1 kJ. How low can we go in loading energy and still obtain the hot dense plasma and neutron emission? When do the surface effects start to be relevant? Could the latter be favourable in order to increase the plasma energy density for much smaller devices, thus improving fusion reactions and radiation generation? Following this line, an ultraminiature pinch focus device of less than 1 J operating at hundreds of hertz is currently being developed and engineered at the Chilean Nuclear Energy Commission [27, 33]. The authors hope that the present results will encourage other researchers to further study these and other interesting issues, taking advantage of the enormous capabilities of small plasma focus devices.

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Author contributions

L Soto, conceptual and practical design, experiments and analysis. P Silva, practical design and experiments. J Moreno, experiments and neutron detection. W Kies, improvements to the original design. R E Mayer, neutron detection techniques. A Clausse, L Huerta, M Zambra, L Altamirano and C Pavez collaborators.

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