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Evidence of nuclear fusion neutrons in an extremely small plasma focus device operating at 0.1 Joules

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We report on D-D fusion neutron emission in a plasma device with an energy input of only 0.1 J, within a range where fusion events have been considered very improbable. The results presented here are the consequence of scaling rules we have derived, thus being the key point to assure the same energy density plasma in smaller devices than in large machines. The Nanofocus (NF)—our device—was designed and constructed at the P^4 Lab of the Chilean Nuclear Energy Commission. Two sets of independent measurements, with different instrumentation, were made at two laboratories, in Chile and Argentina. The neutron events observed are 20σ greater than the background. The NF plasma is produced from a pulsed electrical discharge using a submillimetric anode, in a deuterium atmosphere, showing empirically that it is, in fact, possible to heat and compress the plasma. The strong evidence presented here stretches the limits beyond what was expected. A thorough understanding of this could possibly tell us where the theoretical limits actually lie, beyond conjectures. Notwithstanding, a window is thus open for low cost endeavours for basic fusion research. In addition, the development of small, portable, safe nonradioactive neutron sources becomes a feasible issue. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4989845]

I. INTRODUCTION

Fusion, as a relevant area of research and development, has attracted a lot of attention. In addition to the well-established large facilities,[1–3] proposals have been made that nuclear fusion processes can be obtained in table-top devices, even operating at room temperature. Claims we remember as "cold" fusion and "bubble" fusion[4,5] have been received with a justified resounding rejection and scepticism, respectively.[6,7] However, after a few years, an interesting fusion table-top device driven by a pyroelectric crystal was reported.[8] Also, new alternatives have now been explored in small devices experiments, aiming to produce net energy.[9]

The field includes plasma focus devices (PF), a pinch discharge in which a high-pulsed voltage is applied to a low-pressure gas between coaxial cylindrical electrodes. Due to its capacity to produce hot/warm, dense plasmas, it reproduces the scenario of high energy density, intense beams of charged and neutral particles, radiation emission,[10] plasma shocks,[11] filaments,[12] and jets.[13] Thus, it has become a laboratory for fundamental and applied research on fusion, neutron production, hard X-ray, high brightness soft X-ray production, materials for fusion reactors,[14] and astrophysical phenomena.[13] Also, PFs could have applications as pulsed non-radioactive neutron sources.[15–19]

II. SMALL PLASMA DEVICES

The energy input, to drive a PF, typically ranges from kilojoules to megajoules. Most of the experimental studies have been focused on facilities that use tens to hundreds of kilojoules. By observing that some scaling laws hold for the PF plasma,[10,20] some years ago, we considered the possibility of developing lower energy input devices. The key point was to assure the same energy density for the pinch. The pinch radius and length are proportional to the anode radius a, and its volume, proportional to a^3. We observed that the ion density in the pinch n and the ratio E/a^3 (E is the stored energy in the capacitor bank) are approximately invariant for devices from 1 kJ to 1 MJ.[10,20,21] Because the pinch temperature is essentially given by the energy per ion and is therefore proportional to $E/(a^3 n)$, this invariance suggests that most nuclear and atomic reactions occurring in large plasma foci should also be expected in a miniaturized pinch, given the proper scaled design. We concluded that it was possible to scale plasma foci in a wide range of energies and sizes, and keeping the same value for ion density, magnetic field, plasma sheath velocity, Alfvén speed, and temperature. Notwithstanding, plasma stability will depend on the size and energy of the device.[20] Following the line of reasoning outlined, we were able to build fully operational PF devices with energy inputs of tens of joules. In 400 J and 50 J PF devices with deuterium, neutrons were produced and accurately measured.[15,16] By determining the neutron energy by

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[a)] Author to whom correspondence should be addressed: lsoto@cchen.cl time-of-flight techniques, thus resulting in 2.51 ± 1.0 MeV for the PF-400J and 2.71 ± 1.8 MeV for the PF-50J, we confirmed that the neutrons had a D-D fusion reaction origin. At present, other laboratories are doing research using PF devices in the range of tens to hundreds of joules.[17–19]

III. NANOFOCUS (NF) DESIGN

The Nanofocus (NF) was constructed following the scaling rules that we have explained earlier. It consists of a pair of brass electrodes of 200 mm diameter, separated by four 80-m dielectric polyvinylidenefluoride films, the whole acting as a 4.9 nF capacitor for driving the discharge (see Fig. 1). A copper cylinder of 0.42 mm diameter, covered with a quartz tube, is attached to the centre of the anode plate and passes through a small hole in the cathode centre. The anode is enclosed within a small vacuum chamber filled with gas at low pressure—deuterium for neutron emission. The overall device dimensions are ∼20 cm × 20 cm × 5 cm (Fig. 1); further details can be found in Ref. 22. The temporal derivative of the current, dI/dt, is measured using a Rogowski coil; the charging voltage $V(t)$ is controlled using a resistive divider. The discharge period in short circuit geometry is 30 ns, and the measured inductance is 4.9 nH. The driven capacitor is charged by a primary 28 nF capacitor through a pulse. Figure 1(b) shows a photograph of the NF, while Fig. 1(c) shows a time-integrated photograph of the discharge with a bright spot visible on the anode top.

Plasma dynamics was previously observed by us using an intensified charge-coupled device (ICCD) camera gated at an exposure time of 4 ns, which was synchronized with the discharge to obtain images of the visible light emitted. The evolving plasma dynamics was clearly observed.[22] First, the plasma is initiated over the insulator, connecting the anode with the cathode plate at the base, the plasma covering the anode. Second, the plasma radial compression occurs at the anode. Third, the plasma separates from the anode in the axial direction. The time from stage one to three is about 50 ns. In addition, clear evidence that radial compression (the pinch) is actually occurring was indicated by the dip in the current derivative signal, concurrent with a drop in the electrical current.[22] Thus, we have enough evidence that the Nanofocus device produces and compresses the transient plasma in a way similar to Z-pinches and other plasma focus devices. Moreover, in contrast to higher energy PF devices, the NF could present enhanced stability due to resistive effects.[20] In the present article, we report evidence of neutron emission from this extremely small PF device.

The empirical scaling laws established from larger plasma focus devices[10,23] permit us to predict the neutron yield, ranging from 10^7 to 10^{12} neutrons for devices with energy ranges from kJ to MJ. By using neutron emission data from various devices in a range of energies from 1 kJ to 1 MJ, and currents from 100 kA to 1 MA, the total neutron yield Y becomes proportional to some power of the peak current I_0, i.e., $Y \propto I_0^r$, with $3.3 < r < 4.7$.[10,23] We estimated a yield of about 200 neutrons per pulse for discharges in deuterium when using a device with a current of 5 kA. This amount of neutrons is below the detectable level for usual activation-based detectors. Therefore, a special technique based on ^{3}He tubes was applied, which is appropriate for low neutron yields from D-D fusion pulses.[16,24] The detection principle is based on the ^{3}He(n, p)^{3}H nuclear reaction.[25] The ^{3}He proportional tube is embedded in a hydrogenated material to moderate (or slow down) the neutrons and exploit the increased ^{3}He reaction cross-section at lower neutron energies. In this method, the measured neutron yield becomes proportional to the charge accumulated in the detector due to

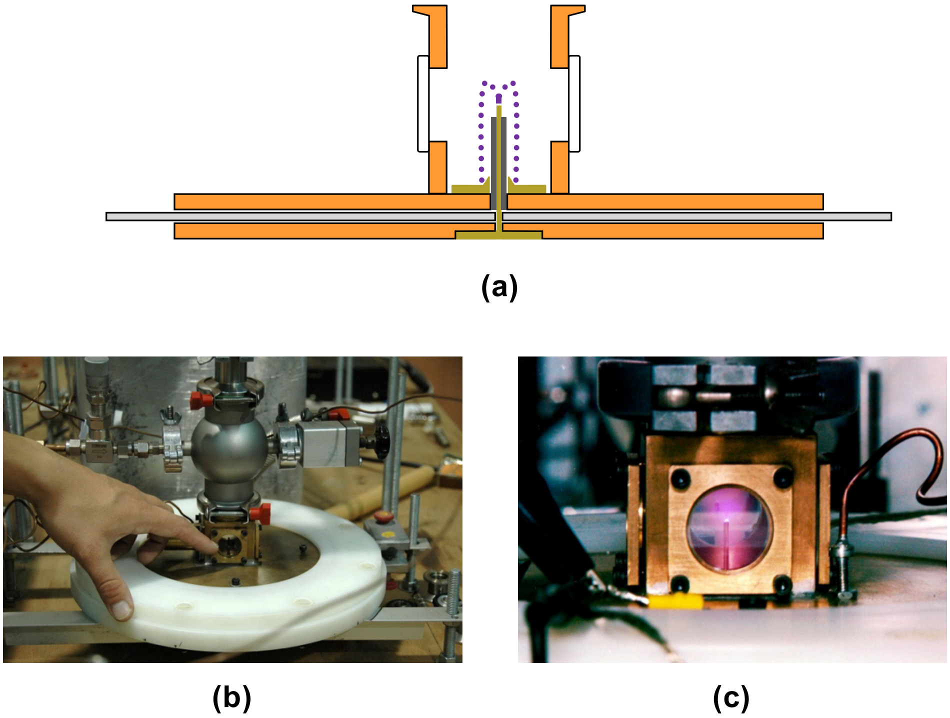

FIG. 1. (a) A sketch of the NF discharge device. The driven capacitor (5 nF) is composed of two parallel plates (lower plate: anode; upper plate: cathode). A 0.42 mm diameter copper cylinder is covered with quartz, attached to the centre of the anode plate, and passes through a small hole in the cathode centre. Plasma is formed between the top of the anode and the cathode base. (b) The NF chamber (pointed in the photograph). (c) A time-integrated photograph of the discharge. Note the bright spot on the anode top.

the interaction of several neutrons within a short time.[16,24] A reference silver activation counter was used to calibrate this neutron detection system (including the moderator). In the process, the adapted ^{3}He and the silver activation counter were placed side by side in front of a higher-energy plasma focus device [$\sim 10^2$ J PF-400J (Ref. 15)], thus producing 5×10^5 to 2×10^6 neutrons per shot, with a linearly proportional relationship. By this technique, we can detect neutron yields lower than 10^3 neutrons per shot.[24]

IV. NEUTRON EMISSION

Discharges in deuterium at pressures from less than 1 up to 20 mbar were performed. Two identical neutron detectors (I and II) with a sensitive area of 45 cm × 15 cm were located at 23.5 and 14.5 cm from the plasma pinch, respectively. Neutron signals were observed only at pressures of 15 to 16 mbar. Figure 2(a) shows the electrical signals for a 16 mbar shot in deuterium at 0.1 J of input energy, which corresponds to a charging voltage of 6.5 kV. The evidence for pinching is observed in the dip of the current derivative signals in about 20 ns (the sudden change in the dI/dt oscillation frequency). Figure 2(b) shows signals that were obtained simultaneously in detectors I and II. Based on the detected events, a total neutron yield from the shot is estimated as 100 ± 40 neutrons. As we will show below, these numbers are above the background. No signals in the neutron detectors were observed for discharges in hydrogen. The moderator provides an additional and useful characteristic insofar as neutrons that are generated in the PF pulse ($\sim$10–100 ns) are dispersed in a time window of some hundreds of μs, depending on moderator volume and geometry. Neutron signals become separated from initial electromagnetic perturbations ($\sim$1 μs) and are also leaked into the ^{3}He tubes at a reduced rate. Essentially, no neutron background is detected during this observation time window.

In addition, in discharges in air, where it is not possible to produce fusion reactions, only the initial electromagnetic perturbation ($\sim$1 μs) was observed in a time window of hundreds of μs.

NF's neutron emission was confirmed, and the background was measured in the second series of experiments at the Bariloche Atomic Centre, Argentina, with two different detector arrays. One neutron detector (A) consisted of ten

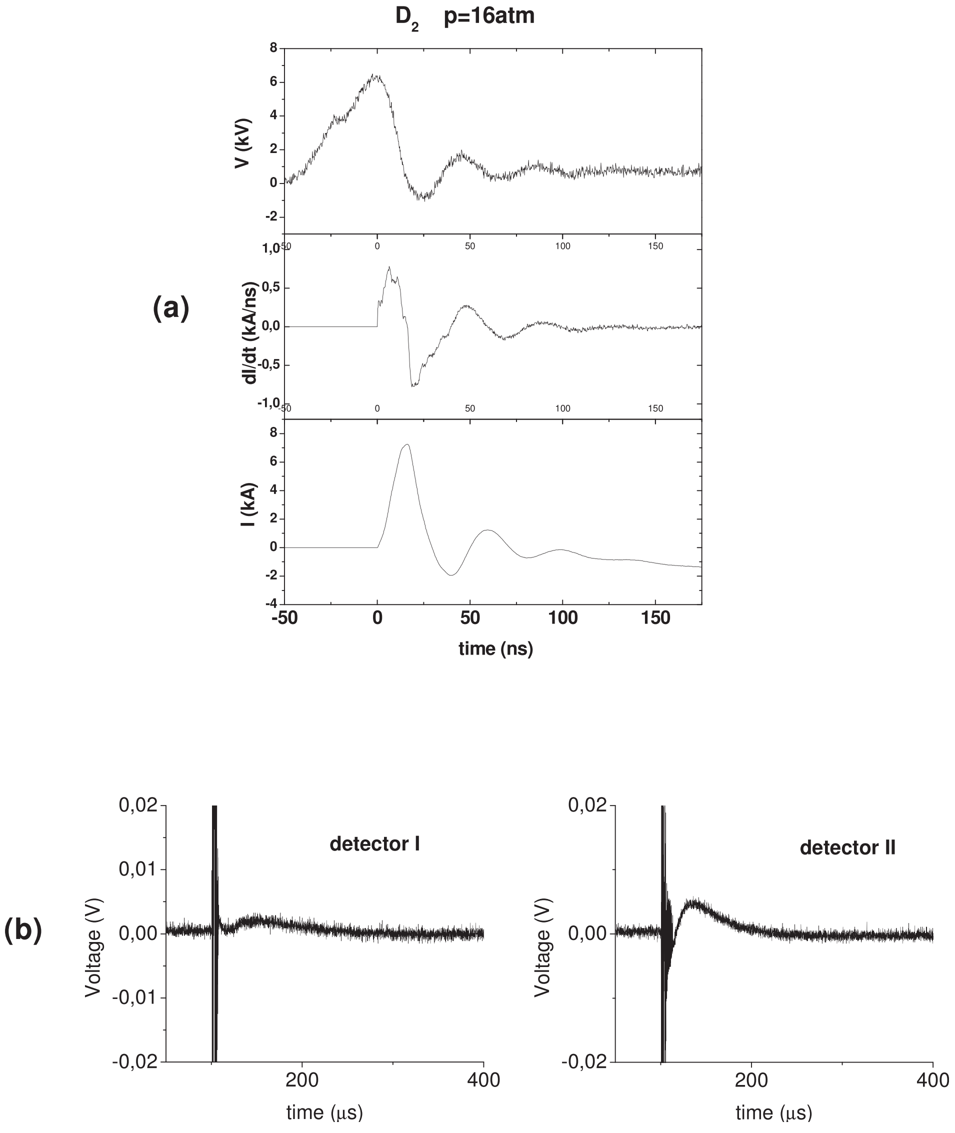

FIG. 2. (a) Electrical signals during a discharge in deuterium at 16 mbar, with an initial charge of 6.5 kV (i.e., 0.1 J) and also a 0.21 mm anode radius. A peak current of 6 kA was obtained. (b) Simultaneous signals were obtained in the two neutron detectors based on ^{3}He proportional counters in charge-integrated mode.[24] The neutron yield is proportional to the charge accumulated in the detector, i.e., the number of neutrons is proportional to the area under the curve of the signal. Detectors I and II are located at 23.5 cm and 14.5 cm, respectively, from the plasma pinch. The electromagnetic pulse from the plasma discharge triggers the oscilloscope, and the neutron detection coincides with the plasma discharge. According to the detectors calibration, the total neutron yield is estimated to be 100 ± 40 neutrons.

^{3}He tubes connected in parallel with 4 atm filling gas pressure and embedded in a polythene moderator. The detector provided a 110 cm × 130 cm of sensitive area to neutrons. The second moderated detector (B) was composed of six ^{3}He tubes with 10 atm filling gas pressure and a 25 cm × 40 cm detection area. Wrapping both systems in cadmium provided a shield for slow ambient neutrons.

For determining the influence of the discharge on the detectors, 3000 discharges were performed using an electrode configuration in a gas that was not able to produce fusion reactions. The oscilloscope was triggered by the electromagnetic pulse of the discharges, with no signals related to neutron counts. This permits us to conclude that both A and B ^{3}He detector arrays are adequately shielded, and they are insensitive to spurious counts due to the influence of NF operation. Thus, it was possible to measure the background using different methods over more extended periods in order to gather a useful amount of counts that lend themselves to numerical evaluation. The corresponding Poisson uncertainty is the square root of those counts.

The NF was operated at a rate of 20 shots per minute during 20-min runs and discharging in deuterium with pressures of less than 1 mbar to 20 mbar. The total duty time was 6 h and 15 min corresponding to 7500 shots and rendering a total effective observation time of 2.7 s. Digital oscilloscopes registered the signals from the events with the correct pulse shape. The ^{3}He tubes were polarized in the proportional regime and employed in the "counter" operation mode. A and B detectors were located at 22 cm and 16 cm, respectively, from the plasma pinch. The oscilloscope, triggered by the electromagnetic pulse discharged by the plasma, registered data during 360 μs after the trigger, which was considered an appropriate time window for the moderator. The moderator die-away time was 180 μs.

For the background, it was considered the sum of the counts from both detectors systems in order to have a meaningful statistics. The total background was determined by continuous recording, with the plasma device off and 3000 pinchless discharges, thus obtaining 1.96 ± 0.14 neutron events per second (the corresponding uncertainty is the standard deviation of the Poisson distribution). The Poisson distribution of counts permits us to extrapolate these measurements to the effective observation time for 7500 shots, thus obtaining 5.29 ± 0.38, 5.62 ± 0.39, and 5.48 ± 0.12 background events for three different determinations.

The detectors only gave off neutron signals in deuterium discharges under pressures from 1 to 4 mbar and from 14.5 to 17.5 mbar. Measurements from both detectors were above their respective backgrounds. Figure 3 summarizes the results in neutron emission. The number of recorded neutron events was 18 ± 4.2, which is more than three times the background, with no overlap in σ. The interval between the minimum statistical value for neutron events (i.e., $18–4.2 = 13.8$) and the maximum statistical value for the background (i.e., $5.62 + 0.39 = 6.01$) is about 20 times the background. In fact, the neutron events occur at more than three times the background level.

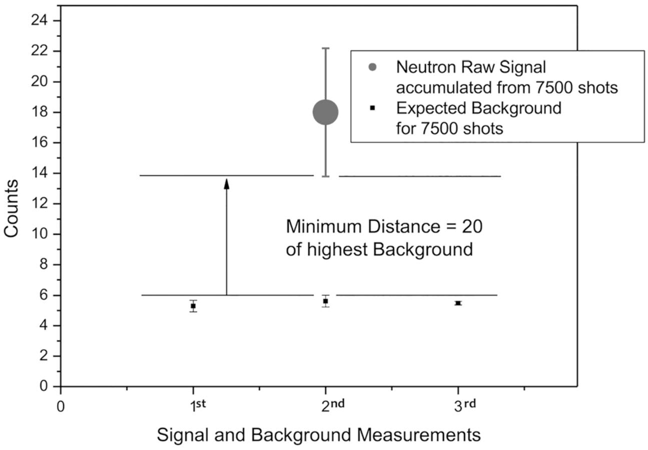

FIG. 3. Neutron events (i.e., along the ordinate axis) arising from 7500 shots and several background determinations (1st, 2nd, 3rd) extrapolated to statistically expected values for an equal number of shots. The minimum between those measurements is indicated in the plot, 20σ above the highest background value.

V. DISCUSSION AND CONCLUSIONS

The mechanisms of nuclear fusion and the subsequent neutron production in pinch discharges are still an open field. The participation of two main processes in the total neutron yield Y, by a pinch discharge is widely accepted, namely, thermonuclear fusion and ion beam–target fusion. This total neutron yield becomes $Y = Y_{th} + Y_{b\text{–}t}$, where Y_{th} is the thermonuclear component, and $Y_{b\text{–}t}$ is the beam–target part. For a thermonuclear mechanism, an isotropic emission is expected. However, in larger and medium PF devices, it has been observed that most of the emission is in the axial direction than in the radial direction.[10] Further experiments to measure anisotropy in the NF's neutron emission could provide evidence for answering the question about the mechanism that allows nuclear fusion as the devices are scaled down.

We conclude that there is enough scientific evidence that the NF, an extremely small plasma device operating at only 0.1–0.2 J, can produce D-D fusion reactions. Two independent sets of measurements in different laboratories (at our P^4-Lab, CCHEN, in Chile, and at CAB, in Argentina) have confirmed the NF's neutron emission as a solid conclusion, with a close correlation between neutron detection and shots, excluding the existence of spurious signals on ^{3}He systems. These results, and those obtained for a 50 J PF, permit us to anticipate that a device working at a few joules, with 10^3 to 10^4 shots at a frequency of 10 to 100 Hz, will produce a neutron yield of 10^4 to 10^6 events per second, although a more accurate determination of the absolute neutron yield could be desirable for this extrapolation. A deuterium-tritium mixture would boost this by up to 100 times. For applications, some technological issues remain to be tackled, particularly to improve reproducibility of neutron emission for periods longer than minutes when the NF operates at hundreds of Hz. Scientific questions raised by the results presented here are pertinent. The scale rules we applied here have proven to be a powerful tool for expanding the boundaries beyond what was expected. But, is there a lower bound on the size of a PF to generate the conditions for nuclear fusion? In much smaller devices, the surface/volume ratio seems to be more favorable for plasma heating and compression. Could this actually increase plasma energy density and improve the output in fusion reactions and radiation? How stable will the plasma be? These are some of the questions that will guide the future work in this line of research.

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