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Neutron emission from a fast plasma focus of 400 Joules

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The neutron emission from a small and fast plasma focus operating in deuterium is presented. The system operates at low energy in the hundred of joules range (880 nF capacitor bank, 38 nH, 20–35 kV, 176–539 J, ~300 ns current rise time). The neutrons were measured by means of a silver activation counter, and the total neutron yield versus deuterium gas filling pressure was obtained. For discharges operating at 30 kV charging voltage, the maximum neutron yield was $(1.06 \pm 0.13) \times 10^6$ neutrons per shot at 9 mbar.
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In dynamic pinches, short-duration high-temperature and high-density plasmas are produced, which can emit x rays and intense neutron pulses (when deuterium is used in the discharge). A plasma focus (PF) is a particular pinch discharge in which a high pulsed voltage is applied to a low pressure gas between coaxial cylindrical electrodes. The central electrode is the anode partially covered with a coaxial insulator. The discharge starts over the insulator surface, and afterwards the current sheath is magnetically accelerated along the coaxial electrodes. After the current sheath runs over the ends of the electrodes the plasma is compressed in a small cylindrical column (focus). In most of the devices these three stages last a few microseconds. The pinch compression should be coincident with peak current (really with the magnetic flow) in order to achieve the best efficiency. The pinch generates beams of ions and electrons, and ultrashort x-ray pulses. Using deuterium gas, plasma focus devices produce fusion D–D reactions, generating fast-neutrons pulses (~2.5 MeV) and protons (leaving behind ^{3}He and ^{3}H). The neutrons burst usually lasts about tens to hundreds of nanoseconds. The emitted neutrons can be applied to perform radiographs and substance analysis, taking advantage of the penetration and activation properties of this neutral radiation. The plasma focus is a pulsed neutron source especially suited for applications because it reduces the danger of contamination of conventional isotopic radioactive sources. A passive radioactive source of fast neutrons with similar energy (for instance ^{252}Cf with similar mean energy or Am/Be with a harder spectrum) emits continuously, causing inconveniences in handling and storing. In turn, plasma-focus generators do not have activation problems for storage and handling.

During the last 30 years, substantial effort and resources have been invested in plasma focus devices.[1–5] The studies range from small devices of around hundreds of joules, to large facilities of about 1 MJ. Specifically in the 3 kJ range[4,5] there are numerous results obtained by the Asian-African Association for Plasma Training Network. Repetitive plasma-focus devices for x-ray emission have been reported by Lebert *et al.*[6] and Prasad *et al.*,[7] both with 2–5 kJ of electrical energy stored in the capacitor bank and a repetition rate of the order of 2 Hz; and Lee *et al.*[8] with 3 and 1.9 kJ, 3 and 16 Hz of repetition rate, respectively. In relation to neutron emitting plasma focus emissions have been found ranging from 10^7 neutrons with 1 kJ driver up to 10^{12} neutrons with 1000 kJ. If small portable PF devices were available, the value of the emissions would be substantially increased, for a number of nuclear techniques could be produced in wider domains of applications. There are few published works about devices designed to operate at hundred joules[9,10] and they operate with slow drivers (~10 μF capacitor bank, ~100–70 nH, ~7 kV, ~250 J, ~1.3 μs current rise time). In this letter we present observations of the neutron emission from a very small and fast plasma focus operating at 400 J (880 nF capacitor bank, 38 nH, 20–35 kV, 176–539 J, ~300 ns current rise time) in deuterium.

In spite of all the accumulated research, there are several questions still waiting for answers, particularly those concerning the sheath formation, insulator conditioning and influence of gas impurities. An area of research that is not well explored is that of the very-small low-energy plasma foci. Most of the experimental studies were focused in medium and large facilities from tens to hundreds of kilojoules, or small devices about some kilojoules. In fact, we can question if good focussing can be achieved below 1 kJ, and if so which are the appropriate design criteria in this energy region.

Experimental research with a plasma focus driven by a capacitor bank of tens to hundred of joules would allow to extend the theoretical models to the region of low energy.[11–14] Moreover, a capacitor bank under the kilojoule has a small size in comparison with banks in the kilojoules range, thus it would be easier to operate in a repetitive regime from hertz to kilohertz, since the power requirements and the spark-gap erosion are consequently lower.

The plasma focus device used in the experiments reported here, PF-400J, consists of a capacitor bank that is discharged over the coaxial electrode through a spark gap.

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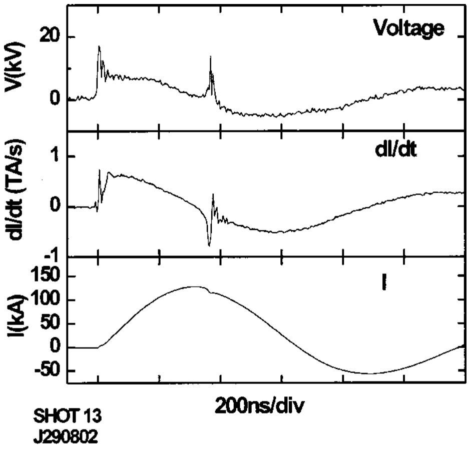

FIG. 1. Electrical signals for a shot in deuterium. Pressure = 8.7 mbar, charging voltage = 28 kV (345 J energy storage in the capacitor bank) in this shot. The typical dip in the signal of the current derivative associated with the formation of a pinched plasma column on the axis was observed. The voltage and current were measured with a 5% of accuracy.

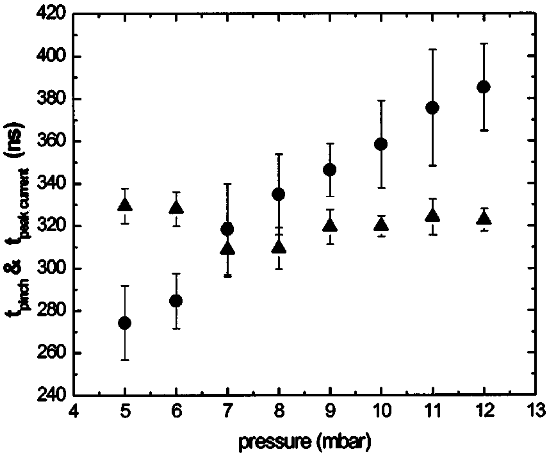

FIG. 2. Pinch time vs filling pressure for deuterium (●). The time to peak current vs filling pressure is also shown (▲). Device operating at 30 ± 2 kV charging voltage. Discharges taking place in deuterium close to 7 mbar produce compression close to the peak current in the device studied here.

The capacitor bank consists of four capacitors (220 nF, 20 nH) connected in parallel (880 nF, 5 nH). The device operates with charging voltages of 20–35 kV. In order to obtain low inductance the capacitors were connected in a compact layout. Thus, a short and coaxial spark gap was designed for the same purpose. The length of the connections between capacitor bank, spark gap, and electrodes was minimized directly connecting the capacitor bank to the spark gap and the electrodes. The measured total external inductance is 38 nH. The total impedance of the generator is of the order of 0.2 Ω. To determine the size of the electrodes the design relations suggested by Lee[4] and a theoretical model of plasma focus for neutron production[15] were considered. It is known that the pinch phase in a plasma focus is highly dependent of the current sheath formation over the insulator. Unfortunately, there are still not validated theoretical models to determine the dimensions of the insulator. Therefore, several tests with different insulator length and diameter, scanning pressure range from 1 to 12 mbar, were necessary to determine the size of the insulator in order to obtain a homogeneous initial sheath. The current sheath was studied with an image converter camera with 5 ns exposure time. Finally, structure of electrodes consists of a 28 mm long, 12 mm diameter cooper tube anode, and an outer cathode of eight 5 mm diameter cooper rods uniformly spaced on a 31 mm diameter. Anode and cathode were separated by an alumina tube of 21 mm length. Such configuration resulted from the short first quarter period of the discharge current (some 300 ns, due to the small bank capacity), which require a short effective anode (7 mm). The size of the device is of the order of 25 cm × 25 cm × 50 cm.

Voltage, total current, and current derivative are measured with 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 of the capacitor bank. A silver activation counter, previously calibrated with an Am–Be source, placed at 30 cm in the side-on direction was used to record the integrated neutron signal.

Discharges were performed in deuterium at different pressures, 5–12 mbar, with a charging voltage of 30 ± 2 kV, i.e., ~400 J stored in the capacitor bank. Electrical traces for a shot in deuterium at 9 mbar pressure is shown in Fig. 1 where 127 ± 6 kA peak current is obtained at those conditions. The typical dip in the signal of the current derivative associated with the formation of a pinched plasma column on the axis was observed. From the current derivative signals the implosion time (pinch time, measured at the moment for the minimum in dI/dt) versus filling pressure was obtained and it is shown in Fig. 2. The maximum compression of the plasma occurs close to the peak current for a pressure close to 7 mbar.

The neutron yield measured by the activation counter is shown as a function of the filling gas pressure in Fig. 3. Each point is the average of ten shots and the error bars are the standard deviations. The maximum measured neutron yield was $(1.06 \pm 0.13) \times 10^6$ neutrons per shot at 9 mbar. This maximum occurs for discharges with pinch close but after the current peak. The maximum observed yield agrees roughly with the empirical scaling laws available in the literature for drivers with energy in the range 1–100 kJ,[16] $Y = 10^7\ E^2$ and $Y = I^{3.3}$ (the storage energy in the driver E in kilojoules and the current pinch I in kiloamperes). It is probably that the electrodes and insulators size could be opti-

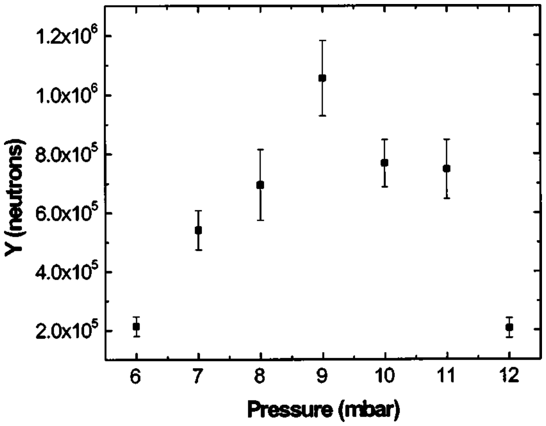

FIG. 3. Total neutron yield, Y, vs deuterium filling pressure.

mized in order to increase the neutron emission.

Most of the plasma-focus devices operate with capacitor banks that produce electrical discharges with a quarter of period, $T/4$, in the range of 1.5–4 μs. It should be stressed then that PF-400 is much faster in comparison with conventional devices. Thus, the differences of the plasma-focus device presented here are the energy stored in the capacitor bank (hundreds of joules) and the duration of the discharge (current rise time, $T/4 \sim 300$ ns). Under these conditions we are reporting neutron yields up to $(1.06 \pm 0.13) \times 10^6$ neutrons per shot.

The device studied here is useful both for basic research and applications. Experimental research with this device would allow the extension of the existing theoretical models to the low energy region. This type of fast electric discharge instruments could provide microinstabilities and turbulent plasmas, capable of producing energetic electron and ion beams, x-ray emission, neutrons, and protons (using deuterium). Although the measured neutron yield is low in comparison with devices that operate at some kilojoules, this kind of very small device could be operated easily in a repetitive regime from hertz to kilohertz, increasing the radiation fluence, offering space for useful applications. Potential applications of small and repetitive plasma-focus devices are substance detection by transient activation analysis, x-ray imaging, and neutrography. In accordance with commercial information readily available on fast neutron radiography using a charge coupled device coupled to a Gd converter, it may be concluded that the proposed 10^6 neutron per shot source, placing the sample 5 cm from the source, a 5 cm^2 analysis area may be recorded with 10^3–10^4 shots, depending on sample nature and shape. With a 10 Hz repetition rate this fluences will attained after 100–1000 s. The device presented here conceived for laboratory purposes, is a single shot machine which can be operated only at 0.5 Hz. According to the same commercial information, sources based on generators with an accelerating tube filling with deuterium providing 10^6–10^8 neutrons/s at 10 kHz repetition rate are useful for prompt gamma neutron analysis. This translates into a 10^2–10^4 neutrons/shot. A plasma focus device in the tens of joules range and $\sim 10^4$ neutrons/shot is currently being tested.

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