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Palm top plasma focus device as a portable pulsed neutron source

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Development of a palm top plasma focus device generating $(5.2 \pm 0.8) \times 10^4$ neutrons/pulse into 4π steradians with a pulse width of 15 ± 3 ns is reported for the first time. The weight of the system is less than 1.5 kg. The system comprises a compact capacitor bank, a triggered open air spark gap switch, and a sealed type miniature plasma focus tube. The setup is around 14 cm in diameter and 12.5 cm in length. The energy driver for the unit is a capacitor bank of four cylindrical commercially available electrolytic capacitors. Each capacitor is of 2 μF capacity, 4.5 cm in diameter, and 9.8 cm in length. The cost of each capacitor is less than US$ 10. The internal diameter and the effective length of the plasma focus unit are 2.9 cm and 5 cm, respectively. A DC to DC converter power supply powered by two rechargeable batteries charges the capacitor bank to the desired voltage and also provides a trigger pulse of −15 kV to the spark gap. The maximum energy of operation of the device is 100 J (8 μF, 5 kV, 59 kA) with deuterium gas filling pressure of 3 mbar. The neutrons have also been produced at energy as low as 36 J (3 kV) of operation. The neutron diagnostics are carried out with a bank of ^{3}He detectors and with a plastic scintillator detector. The device is portable, reusable, and can be operated for multiple shots with a single gas filling.
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I. INTRODUCTION

After its invention in the early 1960s, the plasma focus (PF) device[1] has been extensively studied as pulsed sources of neutrons, X-rays, and charged particles. The plasma pinching phenomena in a PF unit is brought about by the collapse of the transient plasma due to the interaction of the current density and associated magnetic field. Bursts of neutrons lasting for a few tens of ns with energies of 2.45 MeV or 14.13 MeV are produced depending on the use of deuterium gas or mixture of deuterium gas with tritium gas. The PF devices have been developed and studied in various energy ranges, starting from a few tens of joules to mega joules of electrical energy producing pulsed D-D neutrons in the range of 10^4 neutrons/pulse[2] to 10^{12} neutrons/pulse.[3] The neutron yield in an optimized PF system appears to scale with the bank energy (current). Saturation[4,5] of the neutron yield at higher energy (current) operations has encouraged the development and study of low energy PF systems for various applications. Size of the system in addition to energy will be small, the erosion and the insulation problems will be less for the low neutron yield PF devices in comparison with the high yield systems, thereby facilitating the operation in a repetitive mode to provide more neutrons.

Several successful attempts have been made to develop miniature and portable PF devices operated with bank energy in the ranges of tens to hundreds of joules. The pinching evidence has been observed in the PF devices operated at very low bank energies of 50 J,[6] 50–70 J,[7] ≈100 J,[8] and 32–102 J,[9] leading to the generation of neutrons from such devices. A battery (12 V DC, 400 Ah) powered transportable PF device working at 125 J of bank energy has been shown[10] to produce 10^5 to 10^6 neutrons/pulse but only in 30% of the PF discharges. A sealed type PF device with battery based power supply was reported[11] to generate 10^5–10^6 neutrons/pulse at 200 J of bank energy for 150 discharges without purging the deuterium gas in between the shots. The height and the weight of these systems were 35 cm and 23 kg, respectively. A compact miniature plasma focus device has been reported[12] to generate 10^4 neutrons/shot at 200 J of bank energy. The overall dimensions of this unit were 20 cm × 20 cm × 50 cm with weight of around 25 kg. A PF device operated at 50 J (50 kA) and 67 J (60 kA) has been reported[13] to generate more than 10^4 neutrons/pulse. The size of this device was 25 cm × 25 cm × 50 cm. An 89 J (61 kA) plasma focus device has been tested[14] over experiments ranging from 7000 shots to 25 000 shots. The mean neutron yield of this unit varied from 2.6×10^5 neutrons/pulse to 4.4×10^5 neutrons/pulse with standard deviation of 50%. Specially fabricated alumina insulator was used here to enhance the lifetime of the setup. Another PF device operated at 75 J (52 kA) of bank energy with the most compact capacitor bank (CB) has been demonstrated[15] to generate neutrons and X-rays. The neutron yield of 10^4 neutrons/shot for such device was predicted. The large components used in this setup were the vacuum system and the deuterium gas container. Further improvement in the design of this system has enabled us to develop the first palm top plasma focus device capable of producing measurable neutrons with the simplest and the most compact size configuration. The detailed design and the diagnostics of this unit are reported in this paper.

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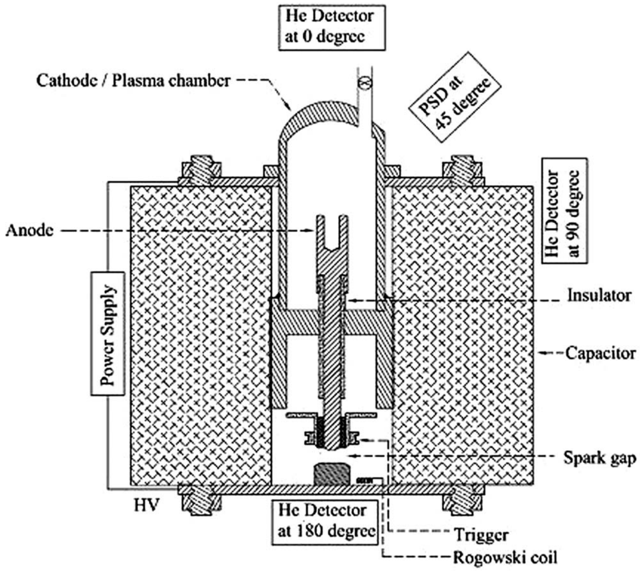

FIG. 1. Schematic of the plasma focus device.

II. EXPERIMENTAL DETAILS

The schematic of the developed system is displayed in Fig. 1. The basic components of the system are the capacitor bank, the miniature plasma focus unit, and the power supply. The diagnostics comprise a miniature Rogowsky coil for monitoring current derivative (dI/dt), a ^{3}He detector bank for neutron yield measurement, and a plastic scintillator detector (PSD) coupled to photomultiplier tube for recording time resolved neutron emissions. All the time resolved signals from the detectors are taken through the triaxial cables and are recorded in the respective digital storage oscilloscopes kept inside a shielded Faraday cage to attenuate inherent electromagnetic noise.

A. Plasma focus device

The co-axial PF device used here is of Mather type[1] configuration with stainless steel anode and cathode. It is an all metal sealed unit similar to the earlier reported[11] device. The anode is of 10 mm diameter with effective length of 20 mm. The top of the anode is tapered to a length of 15 mm with a diameter of 5 mm to provide a hollow shape structure so that electrode erosion is minimized, thereby favoring the neutron production. Unlike solid shape anode structure where the major part of the anode tip is very close to plasma pinch region, the erosion is expected to be more than the hollow shape. The erosion from the anode tip can occur due to localized heating and sputtering on ion bombardment during current reversal. The mass loss of the anode has been reported[14] to be around 6 μg/shot in a 61 kA (89 J) PF device. The eroded electrode vapour coats the insulator surface leading to improper plasma sheath formation. This reduces the neutron yield. A cylindrical cathode used here is of 29 mm internal diameter with an effective length of 50 mm. The cathode works as the plasma chamber. An insulator sleeve of polished alumina having outer diameter of 8 mm and 12 mm effective length is brazed to the anode and also to the cathode base by active silver alloy brazing. A small stainless tube of 6 mm diameter is welded to the top of the cathode and the tube is connected to a bellow sealed quarter inch valve (Swagelok make) for the evacuation and gas filling.

B. Capacitor bank

The capacitor bank consists of four cylindrical capacitors. These are very small and low cost bipolar capacitors available commercially which hardly cost US$ 10 each. Each capacitor is of 45 mm in diameter and 98 mm in length. The capacity of each capacitor is 2 μF. They are connected in parallel between two 3 mm thick aluminum plates as shown in Fig. 1 to produce a combined capacitance of 8.0 μF. The PF device is located at the centre of the CB. The top of the cathode of the PF is connected to the ground plate of the CB. An aluminum disc of 3 cm diameter (1.6 mm thick) is fixed to the high voltage plate of the CB. It acts as one side of the open air spark gap. A small copper piece of 1 cm in thickness and 1 cm in diameter is fitted to the open end of anode. This serves as the other side of the open air spark gap. A cylindrical nylon sleeve of 1.5 mm thickness is fixed to this copper piece. A copper ring is placed in a groove of the nylon sleeve. The trigger pulse to the spark gap is provided through this ring. The diameter of this PF setup with CB is close to 14 cm and the height is around 12.5 cm. The weight of this system is less than 1.5 kg.

C. Power supply

The CB is charged by a battery based power supply.[11] This is a DC to DC converter. This unit provides the required charging voltage to the CB and a pulsed trigger voltage to the spark gap. The input of 24 V DC (7.5 A) to the power supply is provided by two rechargeable batteries of 12 V (7.5 A, 20 h) each. The capacitor bank is charged to the set voltage (3 kV, 4 kV, or 5 kV) by the power supply through a remote hand held control box. The CB can withstand the maximum charging voltage of 5 kV. The trigger pulse is set to −15 kV for all the operations.

D. Diagnostics

The current derivative of the capacitor discharge through the PF device is monitored through a three turn miniature Rogowsky coil. For convenience, it is positioned close to the junction of the high voltage end of the spark gap and the capacitor bank. The neutron yield is measured simultaneously by three ^{3}He detectors[12,16,17] in proportional counter mode. In fact, each detector is a bank of six ^{3}He gas filled tubes. Three identical detectors are used at three angles (0°, 90°, and 180°) to the PF axis. Each detector is placed at a distance of 50 cm from the expected pinched plasma region as shown in Fig. 1. The detectors are calibrated using a silver activation neutron detector and a high yield plasma focus device before the experiment. Each peak observed in the oscilloscope through the ^{3}He detector is generated by the interaction of a single neutron in the gas filled tube. The number of peaks is counted after

20 μs of initiation of discharge to avoid spurious signal due to electronic noise. The sum of the peaks is compared with the neutron yield measured by the silver activation detector. For calibration, the silver activation detector is kept at a distance of 10 cm from the PF device. But the ^{3}He detectors are placed at three distances of 2 m, 3 m, and 4 m. The calibration factor for 50 cm is extrapolated from the data of the three distances. This is done due to the saturation effect of ^{3}He detectors for high neutron yield. The calibration factors so estimated are $(1 \pm 0.03) \times 10^3$, $(1 \pm 0.05) \times 10^3$, and $(1 \pm 0.04) \times 10^3$ neutrons/pulse for detectors placed at 0°, 90°, and 180°, respectively. One PSD[11] placed at 20 cm from the PF device is used for time resolved neutron emission measurement in the end-on direction (at 45° to PF axis) as shown in Fig. 1. The PSD is operated at a voltage of −1800 V. The PSD is put inside a cylindrical lead casing to attenuate the effect of X-rays emitted in the PF device on neutron measurements. Effective shielding for side surface of the PSD is 2 cm thick lead and 4 mm thick mild steel. But for the front surface of the PSD additional 1 cm thick lead is used.

E. Operation of the PF device

The plasma chamber was initially evacuated to a base vacuum of less than 10^{-5} millibar (mb) by a diffusion vacuum pump backed by a rotary pump for 2–3 h. Then the device was filled with deuterium gas up to 2 mb pressure. Five to six conditioning shots were taken at 4 kV charging voltage with refilling of deuterium gas for each shot. Thereafter, the device was evacuated and was refilled to the required gas pressure for subsequent operations. The reported data for only 10 shots were recorded for a single gas filling. The average value was calculated from the 6 best neutron producing shots out of these 10 shots. Normal practice was followed for the average calculation due to non-consistent neutron yield of a PF device. The average value of the neutron yield for three ^{3}He detectors or for individual ^{3}He detector was considered for each shot depending on the type of measurement.

III. RESULTS AND DISCUSSION

The necessary criterion for the successful operation of a plasma focus device is the presence of sharp singularity/dip in the current derivative (dI/dt), which is clearly seen in our experimental observations. A typical dI/dt signal during the plasma compression is shown in Fig. 2 along with the PSD signal. The signal of PSD always showed only a single pulse. It was observed[11] that this PSD with 1.5 cm lead shielding at the same operating voltage (−1800 V) attenuated X-rays emitted from a 200 J (83 kA) PF device. Thus, it was expected that the present measurement with 3 cm lead and 4 mm mild steel shielding would have stopped the X-rays emitted for the PF device operated at 100 J (59 kA) operation. Therefore, the observed single pulse can be attributed to the emitted neutrons. In most of the discharges a few weak dips were observed soon after the single strong dip. The average pulse width of neutron emission as measured with the PSD was only 15 ± 3 ns. Single neutron pulse was recorded in all the neutron yield shots though there were multiple singularities in dI/dt signal. It was evident that no measurable neutron was generated during the time of formation of weak dips. The observed weak peaks may be due to the formation of impurity assisted hot spots as reported earlier[18,19] as the generation of focus (signature of dip in dI/dt) due to propagation of subsequent sheaths is unlikely due to low energy operation.

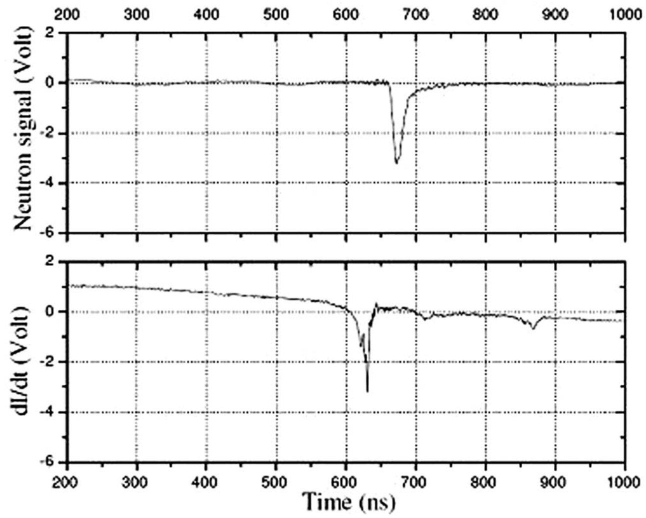

FIG. 2. Typical dI/dt during plasma pinching (bottom) and corresponding neutron signal through PSD (top).

The time integrated neutron yield was measured through the bank of ^{3}He detectors. The neutron signals recorded through three such banks placed in the direction of 0°, 90°, and 180° to the PF axis are shown in the Fig. 3. The yield at 5 kV operation (3 mb D_2 pressure) averaged over all the detectors was $(5.2 \pm 0.8) \times 10^4$ neutrons/shot into 4π steradians. The time period of the CB discharge with the PF device was 3.8 μs (no focus case). It was expected that at 5 kV (100 J, 59 kA, 80% voltage reversal) of charging voltage the neutron yield should have been 1.2×10^5 neutrons/shot as per the reported empirical scaling laws.[20] As per these laws the neutron yield, Y_n, is given by $Y_n = 10 \times E^2$ and $Y_n = 1.7 \times 10^{-10}$ $I^{3.3}$ (where E is the stored energy in J and I is the bank current in A). The average neutron yield of $(5.2 \pm 0.8) \times 10^4$ neutrons/shot is thus around 50% less than the expected value. The neutron yields averaged over all the three detectors at 3 kV (2 mb D_2 pressure), 4 kV (2.5 mb D_2 pressure), and 5 kV (3 mb of D_2 pressure) operating voltages are plotted in Fig. 4. The operating pressure was the optimized pressure for that voltage (energy) of operation. The peak current of the CB corresponding to these three voltages is also displayed in this figure. The neutron scaling parameters for this low energy PF device appeared to be very low. For peak current of the bank, the range was from 0.7 (for 36 J) to 0.9 (for 100 J), normally it should have been 3.3. Similarly for bank energy it was 1.5 (for 36 J) to 1.9 (for 100 J) compared to 2.0 for the normal case. The neutron production has been observed even at 3 kV (36 J) of charging voltage. In this case, the yield was around $(2.0 \pm 1.0) \times 10^3$ neutrons/shot into 4π steradians. The lowest voltage of operation of a PF device for neutron production has been shown[15] earlier to be 4.2 kV.

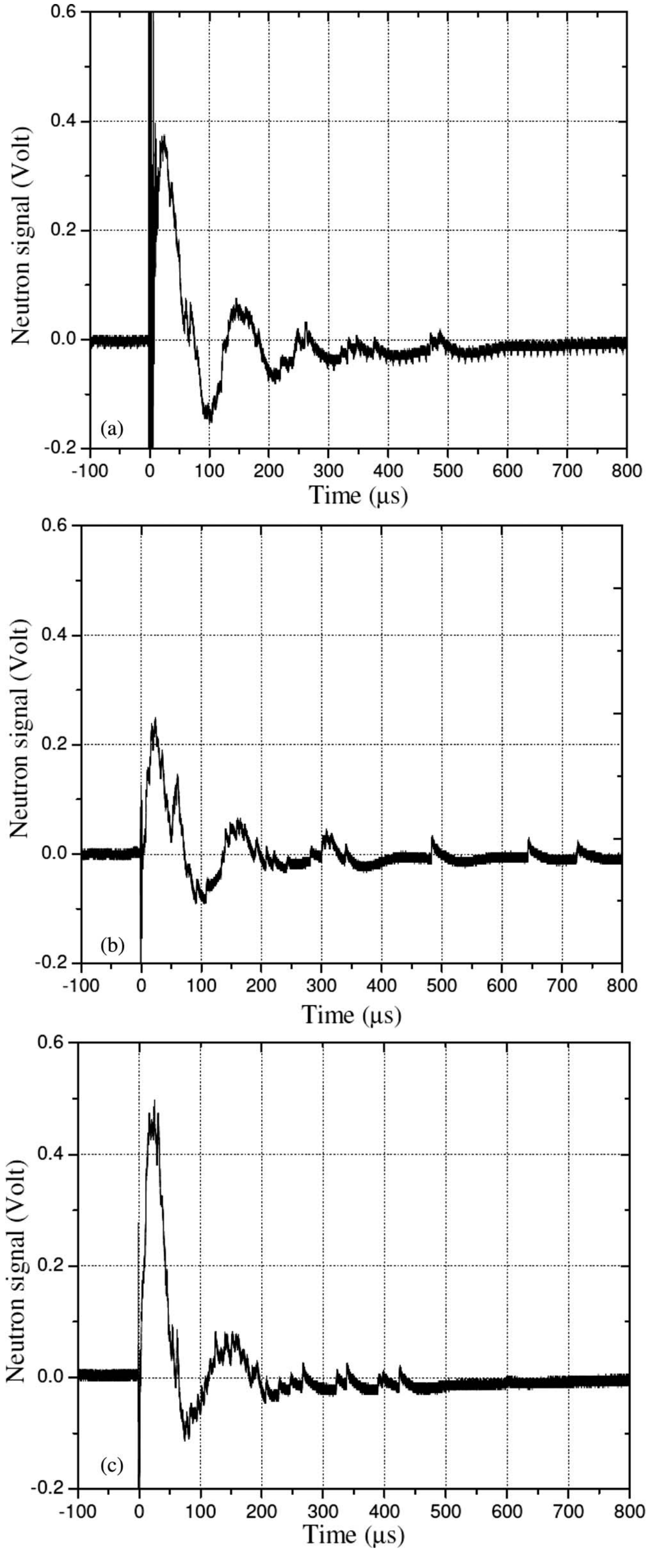

FIG. 3. Typical simultaneously observed neutron signals through ^{3}He detectors placed (a) at 0°, (b) at 90°, and (c) at 180° for a shot with a yield of ≈5 × 10^4 neutrons.

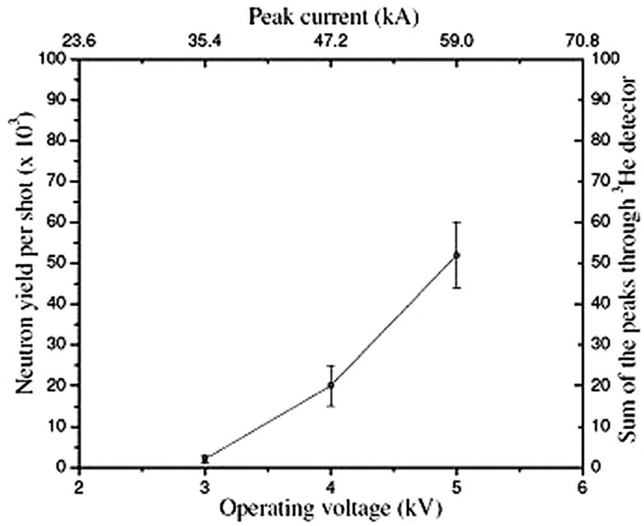

FIG. 4. Neutron yield per shot at different charging voltages and peak currents.

The effect of the cathode structure of a miniature plasma focus device on the neutron yield has already been reported.[21] The neutron yield has been shown there to reduce drastically from $(1.15 \pm 0.2) \times 10^6$ to $(1.82 \pm 0.52) \times 10^5$ neutrons/shot by changing cathode structure from squirrel cage to cylindrical geometry at a fixed operating energy of 230 J. Due to the cylindrical structure of cathode the radial outflow of the plasma is blocked and it leads to plasma stagnation on the inner cathode surface. This increases the density near the inner surface of the cathode. As the magnetic field is the same for the close cathode and the open (squirrel cage or with holes) cathode structures, the plasma sheath moves with less axial velocity due to increase in density. The plasma front becomes stiff compared to umbrella shape front for an open cathode case. Convenient unfolding of the umbrella shaped plasma during the collapse phase enhances neutron yield. This is lacking in a cylindrical cathode case. Moreover, the inter-electrode gap gets constricted due to plasma buildup and the impurity from the cathode surface also enters the plasma. The presence of impurity is evidenced from the multiple weak spikes in observed dI/dt signal here. Observation of multiple weak peaks in dI/dt signal suggests the formation of hot spots[18,19] due to the presence of impurity. The impurity enhances the thermal bremsstrauhlung radiation loss, thereby diminishing neutron yield. The neutron production in this device appears to be isotropic. The yield of individual detector is plotted in Figure 5. The average yield of individual detector is taken into account here at maximum operating voltage of 5 kV (3 mb). The result is inconsistent with others[21] that at low neutron yields the anisotropy factor approaches one. The neutron emission in case of 5 kV (100 J) operation was observed here in more than 95% of the shots but for 4 kV (64 J) operation it was 50%. It was very less (20%) with 3 kV (36 J) operation. Such inconsistent neutron production in a low energy plasma focus device has been observed,[10] where a 125 J of PF device generates 10^5–10^6 neutrons per pulse only in 30% of the discharges. Neither strong focus formation (dip in dI/dt) nor neutron emission was found below 3 kV of operation (even at less than 1 mb of D_2 pressure).

The neutron yield and the life of the setup are sacrificed to have a compact PF structure with CB of low cost bipolar capacitors. The sealed tube PF device is observed to work for 500 shots at 5 kV (100 J) operation and stops working after that due to breakage of the sealing/insulator. But the life of

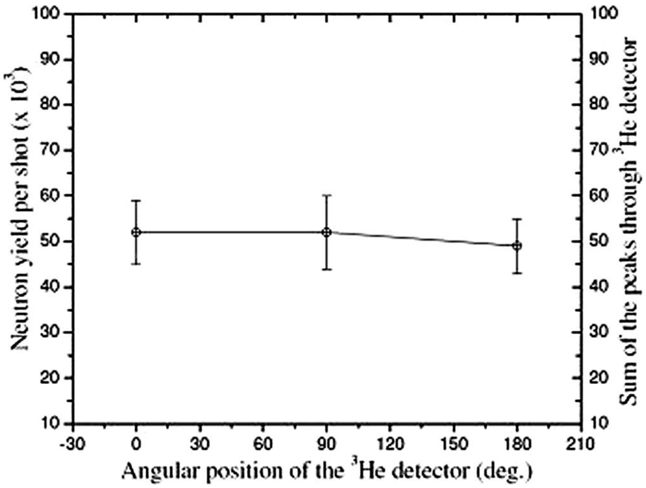

FIG. 5. Neutron yield for different angular positions at 5 kV operation.

the setup is limited by the capacitors. The capacitor becomes non-functioning after 50 shots of operation at 5 kV (100 J) due to rupturing in the used dielectric material.

IV. CONCLUSIONS

Development and operation of a palm top plasma focus device of weight less than 1.5 kg have been successfully demonstrated. It is a battery based sealed type and portable device. The neutron yield of this device is also characterized. The device generates $(5.2 \pm 0.8) \times 10^4$ neutrons/shot isotropically with a pulse width of 15 ± 3 ns at 100 J of bank energy. The yield is less than that expected based on yield scaling laws. The cylindrical cathode geometry and insertion of impurity are suggested to be the cause of yield deterioration. It is a low cost device and can be used for academic interest. It has application in testing and in calibration of low threshold neutron detectors. It also can be used in place of isotopic neutron sources wherever necessary. Because of limited life of the setup due to the low cost bipolar capacitors, it can be used as a disposable pulsed neutron source.

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