A fast miniature plasma focus based compact and portable nanosecond pulsed neutron source

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A low energy fast miniature plasma focus device ‘FMPF-1’ has recently been developed to be used as compact and portable nanosecond pulsed neutron source for field applications. The system operates in deuterium producing maximum neutron yield in the order of 10^6 neutrons/ pulse in 4π sr. at ~80kA peak discharge current. In the range of 4 to 7mbar distinct and sharp dip in the current derivative signal indicates strong focusing of plasma column registering subsequent emission of hard x-rays (HXR) followed by neutron pulse. The average time duration (FWHM) of HXR and neutron pulses, obtained using NE102A scintillator photomultiplier detector is about ~15 and ~45ns respectively. The overall dimensions of the apparatus including capacitor bank, spark gap and the focus chamber is 0.2m×0.2m×0.5m and the total weight of system is ~25kg.

Keywords: miniature plasma focus, neutron source, hard x-rays, ^{3}He detector, plastic scintillator.

1. Introduction

The plasma focus was discovered independently by Mather (USA) [1] and Filippov (USSR) [2] in the early 1960’s, although the devices investigated by these two pioneers had significantly different geometries. Many plasma focus devices have since then built, but all broadly conform to one of the two original geometries, and can be classified as being either of the Mather or Filippov type, with stored bank energy typically ranging from few kilojoules to Mega-joules. In both cases when the 10-50kV capacitor bank is discharged on the coaxial electrodes through spark gap switch, breakdown occurs along the insulator and the current sheet is driven by the $\vec{J}\times\vec{B}$ force away from the insulator towards the end of the electrodes. The gas, that is swept up by the moving front is ionized by the plasma and convected towards the outer cathode, so that; there is a build-up of magnetic energy. When the current sheet turns around the edge of the anode, it is compressed to the axis with the typical velocity of 10^5 m/s to form a hot and dense plasma column that reaches densities of $\approx 10^{25}$ m^{-3} and temperatures of about ≈1keV [3]. Using deuterium as fuelling gas, owing to D – D fusion reactions, a short burst of neutrons (~2.5MeV) is produced, that lasts about few tens to hundreds of nanoseconds depending on the driver energy and device parameters.

Although in the last few decades most of the plasma focus devices were designed to operate in the typical energy range of few kilojoules but recently the studies have been expanded to energies lower than 1kJ [4-5] with the objective of fulfilling the consistently growing demand of compact and portable pulsed neutron generators that can be used for non-intrusive interrogation purposes [6]. The goal of our project is to develop a miniature PF device with energy of ~200J and investigate its viability as compact and portable pulsed neutron generator by studying the neutron emission space-time characteristics.

2. Experimental Setup

The fundamental design of the fast miniature plasma focus device ‘FMPF-1’ (2.4μF, 27nH, T/4 ~400ns, 12-15kV, 170-270J) [7] is conceived on the basis of the fact that the drive parameter/ speed factor $I_o/ap^{1/2}$ (where I_o is the peak discharge current, a is the anode radius and p is the deuterium filling gas pressure for the maximum neutron yield) [8] and the energy density parameter $E/V_p \approx 28E/a^3$ (where E is the energy stored in the capacitor bank and V_p is the plasma volume)[9] are practically constant (77±7 kAcm^{-1}mbar$^{1/2}$ and (1-10)×10^{10} Jm^{-3} respectively) in the medium [10-11], large [12-13] and mega-joule [14] energy range plasma focus devices.

In ‘FMPF-1’ the capacitor bank is made of four 0.6μF, 30kV low inductance capacitors (total weight ~ 20kg) and they all were connected in parallel in compact layout through a common transmission plate assembly (made up of SS304) of size 0.2m × 0.2m. Four layers of 125μm thick Mylar has been used as insulation in

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between the transmission plates. The connections between capacitor bank, spark gap and plasma focus has been minimized by embedding the spark gap within transmission line assembly of the capacitor bank and by directly interfacing plasma focus head to the discharge end of spark gap. The measured total system inductance (including capacitor bank inductance + transmission line inductance + spark gap inductance) is ~27nH. Snap of 'FMPF-1' device assembly is shown in Fig. 1.

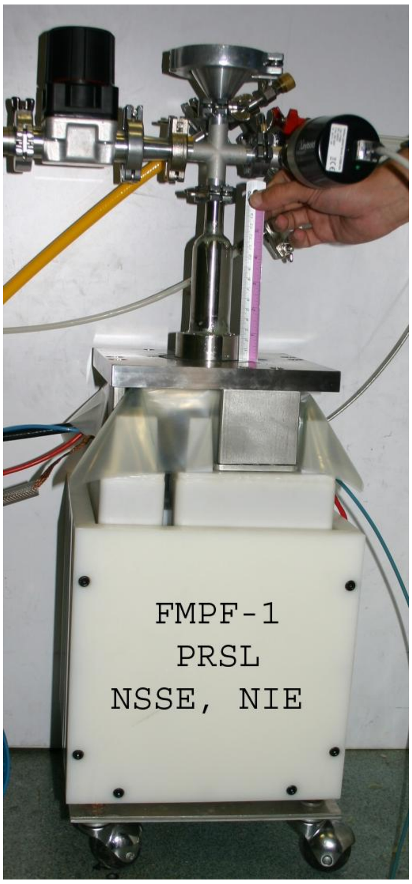

Fig.1 The 'FMPF-1' Miniature PF Device.

Optimized coaxial electrode assembly of plasma focus head consists of a 15mm long composite anode of stainless steel (SS) having tapered length of 5mm from top with initial diameter of 12mm, tapering to 7mm at the tip and a squirrel cage cathode, consisting of six numbers of 6mm diameter SS rods uniformly spaced on a pitch circle diameter of 30mm, concentric with anode axis. An insulator sleeve of Pyrex glass with a breakdown length of 5mm is placed between the anode and cathode.

3. Diagnostics Arrangement

It is well known that the current derivative signal of peak discharge current through the electrodes is key parameter that provides relevant information regarding the plasma dynamics of two important phases *i.e.* axial and radial. In the present setup, an indigenously designed and made, high bandwidth rogowski coil of 350MHz (having response time of <3ns) has been used as electrical diagnostic tool. The successful pinch compression was verified by the fast dip in the current derivative signal due to fast change in plasma tube impedance [9].

For acquiring time resolved registration of neutrons and hard X-rays with quantum energies of tens to hundreds of electron volts, two identical, 14-stage high gain photo-multiplier tubes (EMI 9813BK designated as PMT1 and PMT2 in our experiment) coupled with NE-102A plastic scintillator (of thickness-40mm and diameter-50mm) having decay time constant of 2.4ns have been used. For the unambiguous identification of the neutron pulse, PMT1 was screened with 9mm thick lead sheet whereas PMT2 was left unscreened. A model PM28B high voltage power supply from Thorn EMI electron tubes has been used for providing –1800V bias to the photo-multiplier tube. The scintillator photomultiplier tube assembly is jacketed inside 400mm long aluminum casing of 10mm wall thickness to effectively shield it from electromagnetic noise and visible light as well. The schematic of diagnostics setup is shown in Fig. 2.

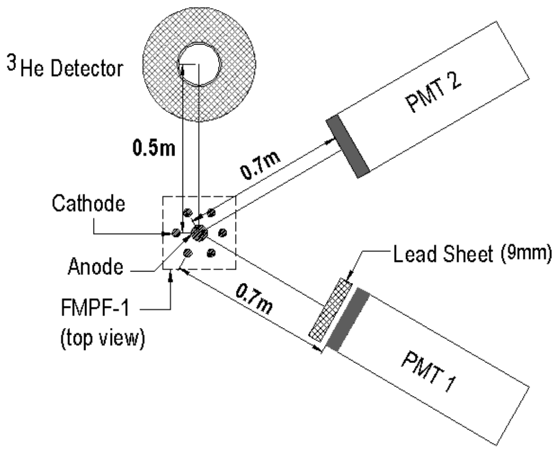

Fig. 2 Implemented diagnostics setup

Since typical neutron yield in miniature plasma focus device, as per existing scaling laws was expected in the range of ~10^3-10^6 neutrons/shot under optimized conditions; this requirement compelled us to tailor high sensitivity, Gas filled thermal neutron detector *i.e.* ^{3}He Proportional Counter setup, details of this customized setup is provided in reference [7]. A high sensitivity ^{3}He neutron detector tube – RP-P4-1636-203 from GE Reuter-Stokes (having nominal sensitivity length of 36" with 2" diameter) has been used in the proportional counter mode along with Amplifier-ORTEC 485 and low noise fast rise time charge sensitive Preamplifier – CAEN A424A. Because of strong energy dependence, ^{3}He gas filled neutron detector tube was surrounded by paraffin wax wall of thickness ~10cm, to thermailze neutrons and maximize the counting efficiency.

4. Results and Discussion

The results shown and discussed in the following section are the average of 20 shots for every set of gas pressure and the gas is refreshed after every five shots. Nominal pressure rise of 0.05mbar is observed after each shot. For the absolute measurement of pressure, barocel capacitance manometer (model 600) from BOC Edwards has been used. It has accuracy of 0.15% in the range of 0 to 10mbar. The charging voltage was kept fixed at 13.8kV through out the investigation.

Time resolved measurements of neutrons were performed using scintillator photomultiplier detectors (PMT1 and PMT2) located in side-on position, 0.7m away from the focus in order to distinguish the hard x-ray pulse from neutron pulse. Figure 3 shows the current derivative signal along with neutron time of flight (TOF) oscilloscope traces (from PMT1 and PMT2) for a shot at 5mbar deuterium gas pressure. The negative peak of the current derivative signal obtained from the rogowski coil is taken as the time fiducial reference for all time resolved measurements. The time resolved signals: current derivative (Ch1) and scintillator-photomultiplier signals (Ch2 and Ch3) are registered simultaneously in fast digital oscilloscope DL9140; and similar lengths of cables have been used for signal transport. It is important to note here that the appearance of HXR peak (in Ch3 trace) after the peak of the current derivative signal (Ch1 trace) is because of the inherent latency (~30ns) in PMT.

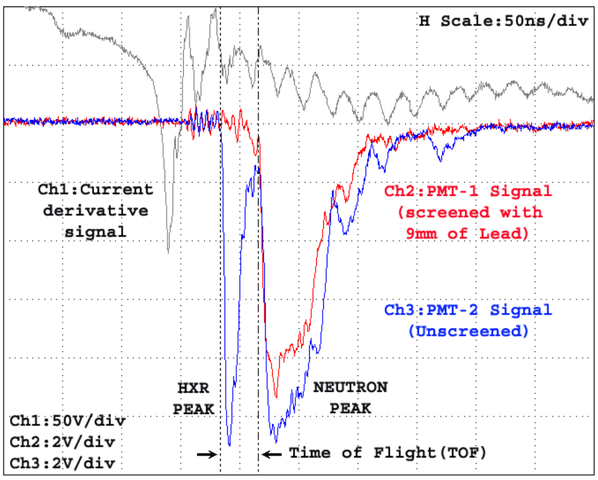

Fig. 3 Current derivative signal trace with HXR/neutron signals at 5mbar operating gas pressure.

The first peak of scintillator photomultiplier signal (Ch3, PMT2) is due to non-thermal hard x-rays produced by the interaction of energetic electrons with the anode. The second peak is confirmed to be the neutron peak by estimating the energy of the neutrons from the time-of-flight difference between the x-ray peak and the neutron peak. Also, signal obtained with lead screened scintillator photomultiplier (Ch2, PMT1) re-confirmed the production of neutron pulse. Since x-rays travel with velocity of light *i.e.* 3×10^{10}cm/s, and neutrons of energy 2.45MeV with velocity of 1.96×10^{9}cm/sec therefore arrival of neutron pulse on PMT is expected ~32ns after the arrival of HXR pulse. The estimated energy agrees with the neutron energy of ~2.45MeV produced by D–D fusion reaction and confirms the time of flight measurement. The average duration of HXR and neutron irradiation is obtained about ~15ns and ~45ns respectively in the optimum pressure range.

Because of the low fluence, the time of flight distance was kept short (i.e. 0.7m), that may limit the accuracy of energy measurement. However, 0.7m of separation has been experimentally found enough to temporally resolve the 2.45MeV neutron pulse from hard x-ray pulse. In some of the traces the second peak was found to be partially merged with hard x-ray pulse indicating the presence of energetic (>2.45MeV) neutrons. Stainless steel vacuum chamber having wall thickness of 5mm filters out hard x-rays produced with energy above 50keV. Hence, 50keV can be taken as lower energy threshold in our hard x-ray measurements.

As aforementioned, the neutron yield measurements were performed using ^{3}He detector in proportional counter mode at fixed bias setting of +650V. An analog signal corresponding to the current generated in the ^{3}He detector tube is registered through a preamplifier (CAEN A424A) whose output is directly connected to a digital oscilloscope.

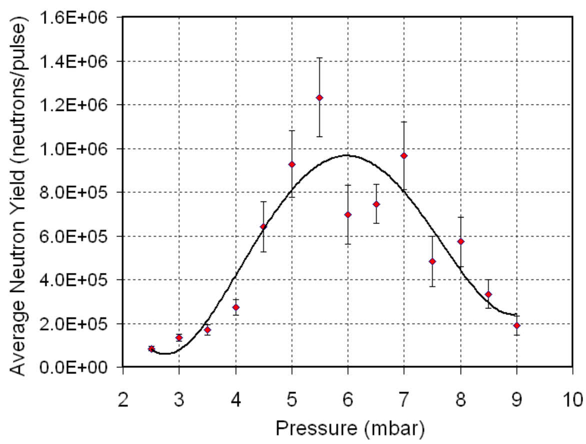

Fig. 4 Experimentally measured values of neutron yield as a function of D_2 filling gas pressure

The pressure dependence of the neutron yield per pulse for pure deuterium discharges on 'FMPF-1' is shown in Fig. 4. As shown in graph maximum neutron yield of $1.23\pm0.18\times10^6$ neutrons/pulse was achieved at 5.5mbar (each point shown in the graph is the average of twenty shots at corresponding pressure). There is an optimum pressure which produces a maximum neutron yield. This can be explained using the effect of ambient gas pressure on thermonuclear and beam target mechanisms. From a thermonuclear point of view [16], the optimum neutron yield can be achieved provided the peak current occurs simultaneously with pinch (with the neutron yield proportional to I^4). This condition was shown to have the interdependence among anode length, charging voltage and filling gas pressure. If two of the parameters are kept fixed, then the third can be fine tuned to satisfy the condition for obtaining the optimum yield. Moreover, logically, the initial increase in filling gas pressure increases the plasma density in the pinch, increasing thereby the reaction rate probability and the neutron yield. But beyond a critical pressure, which depends on the other operating parameters of the focus machine, increasing the pressure does not increase the neutron yield as the time to pinch increases further and the pinch does not occur simultaneously with peak current resulting in lower heating of the pinch plasma and thus lowering of neutron yield. At lower pressures, the growth rate of RT instabilities will be too high (because of higher acceleration of the current sheath) to allow the formation of well defined pinch plasma column resulting in poor neutron yield. Near the optimum operating pressure, the current sheath acceleration is adequate for efficient instability formation. This results in strong instability generated deuteron beam resulting in higher neutron yield by efficient beam-target mechanism [7]. It may however be noted that since the neutron anisotropy measurements have not been done by us so far and hence it is not appropriate for us to comment that which one is more dominant mechanism of neutron production in our miniature plasma focus device.

5. Conclusion

In the context of developing a compact, miniature PF based pulsed neutron source, the preliminary results of newly developed device 'FMPF-1' have been reported. It produced maximum neutron yield of the order of 10^6 neutrons/shot with pulse duration of ~45ns. The precisely engineered device construction and judiciously chosen electrode parameters (with the help of Lee Code [15] formulations) made realization of this high performance device possible. To make this device further useful for 'transient activation analysis' applications, efforts are underway to increase the time averaged fluence of neutron yield, by running in repetition mode at similar energy level.

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