Development of Miniature Plasma Focus as Portable Neutron Source

R VERMA[1,2] P LEE[1], S V SPRINGHAM[1], T L TAN[1],
M KRISHNAN[3] and R S RAWAT[1]
[1]*NSSE, NIE, Nanyang Technological University, 1Nanyang Walk 637616, Singapore*
[2] *Pulsed Power Group, Institute for Plasma Research, Bhat, Gandhinagar 382428, India*
[3]*Alameda Applied Sciences Corporation, San Leandro, California 94577, USA*

Abstract

A fast miniature plasma focus device 'FMPF-1' has been designed and constructed to be used as a compact and portable pulsed neutron source. It has 2.4μF capacitor bank formed by 4 capacitors, operates at 14kV and delivers 80kA peak discharge current in a quarter time period of ~400ns. The system operates with deuterium gas and produces average yield in the order of 10^5 – 10^6 neutrons/pulse in 4p sr. in the filling gas pressure range of 4 to 9mbar. A distinct and sharp dip in the current derivative signal indicates strong pinching action with subsequent emission of hard x-rays (HXR) followed by a neutron pulse. The neutron flux measurement has been performed with 3He proportional counter. Plastic scintillator (NE102A) coupled with high gain photomultiplier tube has been used for obtaining time resolved information of HXR and neutron emission. The overall dimensions of the apparatus, which includes capacitor bank, spark gap switch and the focus chamber is 0.2m × 0.2m × 0.5m and the total mass of the system is ~25kg.

1. Introduction

Plasma focus is a kind of pinch discharge in which a pulsed high voltage is applied to a low pressure gas between coaxial cylindrical electrodes generating, short duration high density plasma. The miniature plasma focus device reported here utilizes Mather-type geometry [1], in which a coaxial discharge arrangement uses a fast-rising current pulse. In our application the inner electrode is the anode and the outer electrode is the cathode. The plasma discharge is initially ignited along a dielectric insulator at one end of the electrode structure, and generates $J\times B$ force that drives the plasma sheath down the electrode bore. Once the plasma sheath has traversed the length of the anode, magnetic forces rapidly accelerate the plasma radially inward across the top of the electrode. The high pressure induced by this magnetic pinch rapidly compresses and heats a small volume of gas to very high temperature [2]. The maximum pinch compression is made to coincide with the peak current in order to achieve best efficiency. The typical velocity of the current sheath is of the order of 1×10^5 ms^{-1} in the axial phase and of the order of 2.5×10^5 ms−1 in the radial compression phase. Pinch formation generates beams of ions and electrons, and ultra-short burst of x-ray pulses. In the pinch, the temperature is of the order of ~200eV to 1keV and the density is ~10^{24}–10^{26} m^{-3}. Using deuterium as fueling gas, as a consequence of D–D fusion reactions, fast neutrons of energy ~2.5MeV and energetic protons of energy ~3MeV (leaving behind 3He and 3H) are produced. The neutron burst typically lasts about tens to hundreds of nanoseconds. [3]. The major advantage of plasma focus as pulsed neutron source over passive radioactive source of fast neutrons of similar energy is that passive sources like 252Cf with similar mean energy or Am-Be with a harder spectrum, emits continuously causing inconvenience in handling and storing [4]. Where as, plasma-focus devices, though they are pulsed, do not have any activation problem for storage and handling. In the last few decades, various plasma focus devices ranging from kilojoule to Mega-joule [5] have been studied. In the medium energy range of 2kJ to 3kJ [6-8], there are various characterization results on different operating and design parameters of plasma focus, reported by the Asian-African Association for Plasma Training Network (AAAPT) using UNU/ICTP PFF facility. So far most of the experimental studies done related to plasma focus dynamics were mainly focused in medium and large facilities from tens to hundreds of kJ and not many results have been reported on plasma focus devices of sub-kilojoule range. Infact it's implausible in plasma focus community, whether efficient pinching could be achieved in sub-kilojoule range of plasma focus devices, and if so whether existing scaling laws will still be valid?. In the recent years experimental research on miniature plasma focus devices of sub-kilojoule range has now started gaining momentum [9-11] as they are much smaller in size and cost effective in comparison to medium and high energy banks and also easier to operate in a repetitive regime from few Hz to kHz range since the driving power requirement is consequently lower. In this paper, we present observation of strong pinches and neutron yield measurements from a newly designed and constructed deuterium filled Mather type 'Fast Miniature Plasma Focus device (FMPF-1)' that produces maximum yield of $1.23 \pm 0.18 \times 10^6$ neutrons/discharge at 5.5mbar deuterium filling gas pressure. It has been demonstrated as compact and portable fusion apparatus producing fast (~2.45MeV) neutrons.

2. Experimental Apparatus

The FMPF-1 device is of Mather type configuration with two cylindrical coaxial electrodes of stainless steel (SS 304). In order to make the system efficient, significant efforts have been made, specially to reduce the driver inductance. The capacitor bank is made of four 0.6μF, 30kV low inductance capacitors (total weight ~ 20kg) and they were all connected in parallel in compact layout of size 0.2m × 0.2m. Four layers of 125μm thick Mylar has been used as insulation in 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 27±2nH. A snap of the 'fast miniature plasma focus' device assembly is shown in Fig 1.

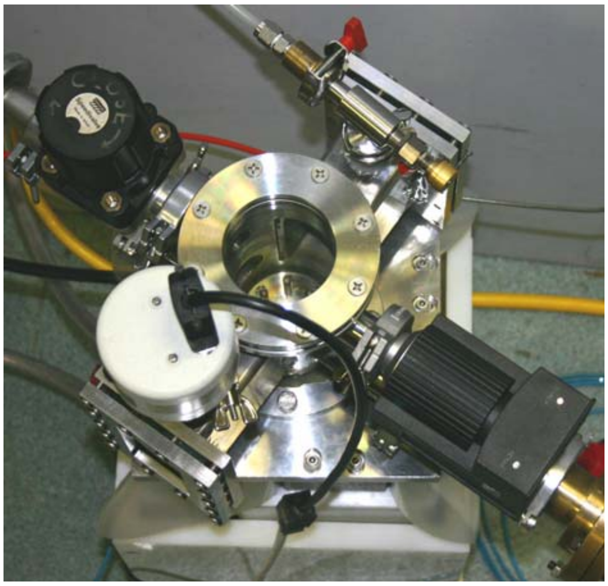

Figure 1. Photograph of 'FMPF-1' Miniature Plasma Focus Device

It can be seen in the photograph the three major parts of the plasma focus i.e. the electrode system, the spark gap and the feeding transmission lines; all have been closely integrated for eliminating the use of cables and thus reducing down the inductances of the system. The control system of the plasma focus was shielded and contained in a Faraday cage due to the associated intense electromagnetic noise.

A computational code developed by S Lee [12] has been used to optimize the FMPF-1's parameters to maximize neutron yield. Coaxial electrode assembly of plasma focus head consists of a 17mm long anode of stainless steel having tapered length of 7mm from top with initial diameter of 12mm, tapering to 6mm at the tip and an outer cathode of six, 6mm diameter SS rods, uniformly placed on diameter of 30mm. An insulator sleeve of Pyrex glass with a breakdown length of 5mm is placed between the anode and cathode.

3. Diagnostics Setup

The successful pinch compression is verified by the fast dip in the current derivative signal due to fast change in plasma impedance [3]. Hence for measuring current derivative of the discharge circuit a high bandwidth rogowski coil having response time <3ns has been indigenously designed and made using strip winding technique [13].

For acquiring time resolved registration of neutrons and hard X-rays with quantum energies of tens to hundreds of electron volts a 14-stage high gain photo-multiplier tube (EMI 9813BK) coupled with NE-102A plastic scintillator (of thickness-40mm and diameter-50mm) having decay time constant of 2.4ns has been used. 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 aluminium casing of 10mm wall thickness to effectively shield it from electromagnetic noise. It must be noted that PMT 9813BK has latency of ~50ns.

Since typical neutron yield expected in sub-kilojoule range miniature plasma focus device may vary in the range of $\sim 10^3$ to 10^6 neutrons/pulse; this requirement compelled us to tailor high sensitivity, gas filled thermal neutron detector *i.e.* 3He Proportional Counter setup for measuring yields. The detection principle is based on the nuclear reaction: *3He + n → 3H + 1H* + 765 keV. The neutron causes the break-up of the nucleus into tritium nucleus, *3H* and a proton, *1H*. The triton and proton share the 765 keV reaction energy. Thus, the amount of energy deposited by this nuclear reaction leads to release of energetic charged particles into the gas. When operated in proportional mode, ionization produced by these particles initiates the multiplication process that leads to neutron detection. The cross section for the *3He* reaction is 5330b for thermal neutrons. It is important to note that cross section has strong influence on the incident neutron energy *E* and has roughly 1 *E* dependence [14]. Because of this strong energy dependence *3He* gas filled neutron detector tubes are customary surrounded by a local moderating medium like paraffin wax with thickness of ~10cm to maximize the counting efficiency. In our setup, high sensitivity *3He* 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.

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 negative peak of the current derivative signal obtained from rogowski coil is taken as reference for all time resolved measurements though it corresponds to minimum pinch diameter (*i.e.* end of pinch phase) [15-16].

The distinct and sharp dip (as shown in oscillogram, Fig. 2) of the current derivative signal (*di/dt*) of plasma focus discharge indicates the formation of focusing action of the plasma column and subsequent emission of x-rays and fast neutrons. The dip of the negative spike in the current derivative signal is considered as a measure of strong focusing. Higher focusing peak amplitude infers strong focusing and energetic radiation.

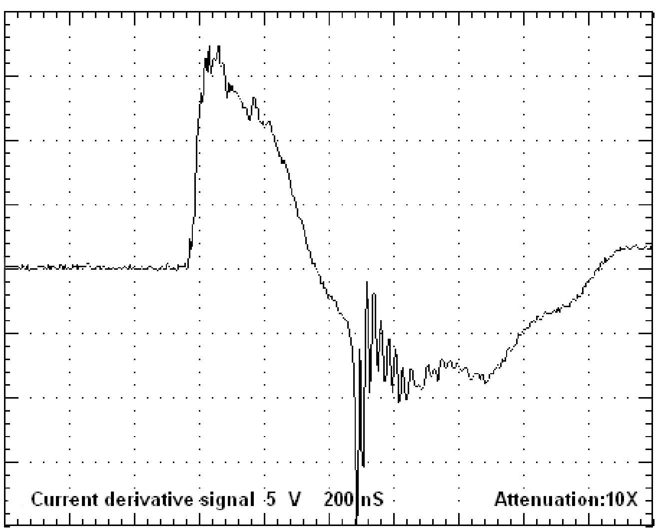

Figure 2. Typical trace of current derivative signal with deuterium at pressure of 5 mbar.

As aforementioned the neutron yield measurements were performed using *3He* detector in proportional counter mode. An analog signal corresponding to the current generated in the *3He* detector tube is registered through a preamplifier (CAEN A424A) whose output is directly connected to a digital oscilloscope. Typical oscilloscope trace of this signal is shown in Fig. 3.

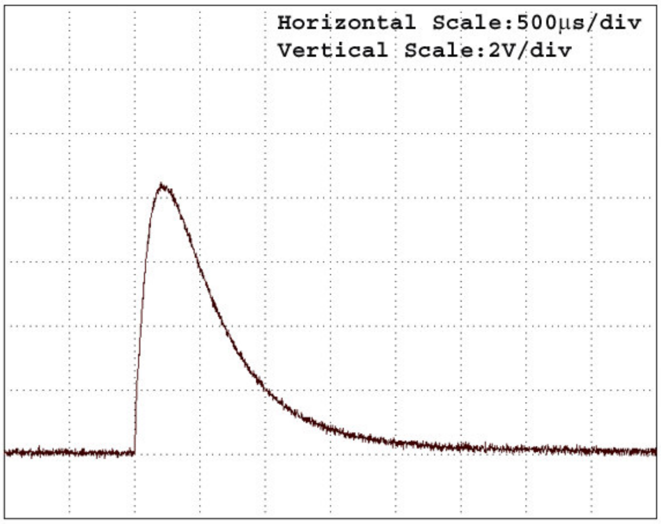

Figure 3. Time integrated oscilloscope trace of *3He* detector output through preamplifier

The time-integrated signal is the charge generated in the *3He* tube and it is proportional to the neutron yield. Time of integration is determined by the characteristics of the preamplifier and it is about some hundred of microseconds. No neutron background is detected during this temporal window. Signal registered on the oscilloscope is integrated using Yokogawa software, XViewer®. Area under the curve calculated in μVs, is then converted to neutron yield by multiplying with calibration factor *i.e.* 240 neutron/μVs (at bias setting of +650V). It worth's mentioning here that estimated calibration factor is specific to bias voltage setting and distance between the source and detector.

The pressure dependence of the neutron yield per pulse for pure deuterium discharges on 'FMPF-1' is shown in Fig. 4. As shown in the graph, maximum neutron yield of $1.23 \pm 0.18 \times 10^6$ neutrons/pulse was achieved at 5.5mbar (each point shown in the graph is the average of twenty shots at corresponding pressure).

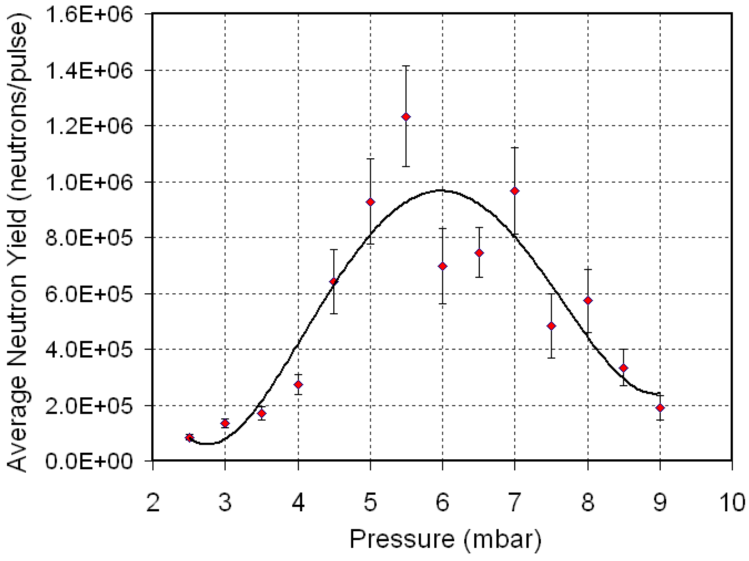

Figure 4. Experimentally measured values of neutron yield as a function of the deuterium filling gas pressure.

Time resolved measurements of neutrons were performed using scintillator-photomultiplier (PMT) detector located in side-on position, 0.7m away from the focus in order to distinguish the hard x-ray pulse from neutron pulse. Both time resolved signals: current derivative and scintillator-photomultiplier are registered simultaneously in fast digital oscilloscope DL9140; both channels were triggered at the same time and similar lengths of cables have been used for both diagnostics for signal transport. Fig. 5 shows the neutron time of flight (TOF) oscilloscope trace for a shot at 6mbar deuterium gas pressure.

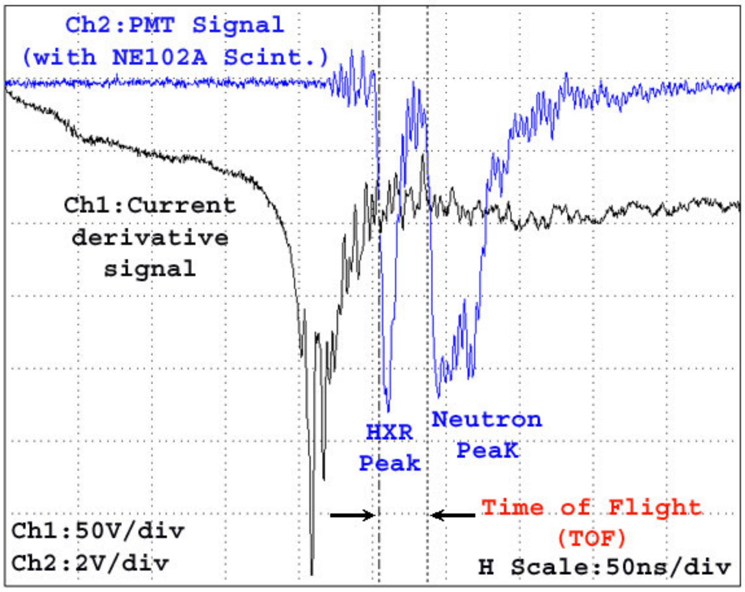

Figure 5. Current derivative signal trace with hard x-ray and neutron signal recorded with a side-on photomultiplier tube coupled with NE102A scintillator at position of 0.7m from the pinch- in radial direction.

The first peak of scintillator photomultiplier signal (Ch2) is due to non-thermal hard x-rays produced by the interaction of energetic electrons with the copper 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. The energy of neutron with time of flight *t* over distance *d* is given as $-E = 1\ 2 \times m(d\ t\ )^2$ [17]. Since x-rays travel with velocity of light *i.e.* 3×10^{10}cm/sec, 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 through the average time delay of ~32ns was registered between the HXR and neutron pulse. From the FWMH of the signals, the duration of HXR and neutron irradiation is obtained about 12ns and 35ns respectively.

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. But 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 [18]. Hence, 50keV is the lower energy threshold in our hard x-ray measurements.

5. Conclusion

In the recent years, growing interest in field applications of pulsed neutron sources for non-invasive interrogations has led the momentum in development of compact and portable machines. In similar context, development of a miniature PF device based pulsed neutron source has been reported here. The FMPF-1 device produced maximum yield in the order of 10^6 neutrons/pulse with pulse duration of 30-40ns. This is more than the yield suggested by empirical scaling law as a function of peak discharge current i.e. $Y \sim 7.73 \times 10^{-5}\ I^{4.82}$ (with I in kA) [4]. The precisely engineered device construction and judiciously chosen electrode parameters made this yield enhancement possible.

To make this device further useful for 'transient activation analysis' applications, efforts are undergoing to increase the time averaged fluence of neutron yield by running this device in repetition mode up to 10Hz at similar energy.

Acknowledgement

The authors are grateful to the National Institute of Education/Nanyang Technological University, Singapore, for providing the AcRF grant RP 3/06/RSR. The authors also wish to express their gratitude to Cecelia M. N. Selvam for her assistance in this work. One of us, RV, would like to thank NIE/NTU for providing the research scholarship and parent organization Institute for Plasma Research, Gandhinagar, Gujarat, India for providing study leave to pursue Phd Programme.

References

[1] J. W. Mather, Phys. Fluids, vol. 8, pp. 366, 1965.
[2] R. Petr, A. Bykanov, J. Freshman, D. Reilly, J. Mangano, M. Roche, J. Dickenson, M. Burte and J. Heaton, Rev. Sci. Instrum., vol. 75, pp. 8, 2004.
[3] L. Soto, Plasma Phys. Control. Fusion, vol. 47, pp. A361, 2005.
[4] L. Soto, P. Silva, J. Moreno, G. Silvester, M. Zambra, C. Pavez, L. Altamirano, H. Bruzzone, M. Barbaglia, Y. Sidelnikov and W. Kies, Braz. J. Phys., vol. 34, pp. 1814, 2004.
[5] H. Schmidt, A. Kasperczuk, M. Paduch, T. Pisarczyk, M. Scholz, K.Tomaszewski and A. Szydłowski, Phys. Scr. vol. 66, pp. 168, 2002.
[6] M. Zakaullah, I. Akhtar, A. Waheed, K. Alamgir, Anwar Z. Shah and G. Murtaza, Plasma Sour. Sci. Tech. vol. 7, pp. 206, 1998.
[7] M. Zakaullah, A. Waheed, S. Ahmad, S. Zeb and S. Hussain, Plasma Sour. Sci. Tech., vol. 12, pp. 443, 2003.
[8] M. A. Mohammadi, R. Verma, S. Sobhanian, C. S. Wong, S. Lee, S. V. Springham, T. L. Tan, P. Lee and R. S. Rawat Plasma Sour. Sci. Tech., vol. 16, pp. 785, 2007.
[9] P. Silva, J. Moreno, L. Soto, L. Birstein, R. E. Mayer and W. Kies, Appl. Phys. Letters, vol. 83, pp. 3269, 2003.
[10] M. Milanese, R. Moroso and J. Pouzo, Eur. Phys. J. D, vol. 27, pp. 77, 2003.
[11] S. R. Mohanty, T. Sakamoto, Y. Kobayashi, I. Song, M. Watanabe, T. Kawamura, A. Okino, K. Horioka, and E. Hotta, Rev. Sci. Instrum., vol. 77, 043506, 2006.
[12] http://www.intimal.edu.my/school/fas/UFLF/File7RADPF05.13.9b.xls
[13] R. Verma, P. Lee, S. V. Springham, T. L. Tan and R. S. Rawat, Rev. Sci. Instrum., vol. 78, 086107, 2007.
[14] http://fas.org/sgp/othergov/doe/lanl/lib-www/la-pubs/00326408.pdf
[15] M. Mathuthu, T. G.. Zengeni and A. V. Gholap, Rev. Sci. Instrum., vol. 68, pp.1429, 1997.
[16] F. C. Meja, M. Milanese, R. Moroso and J. Pouzo, J. Phys. D: Appl. Phys., vol. 30, pp. 1499, 1997.
[17] R. L. Gullickson and H. L. Sahlin, J. Appl. Phys., vol. 49, pp. 1099, 1978.
[18] T. D. Donnelly, M. Rust, I. Weiner, M. Allen, R. A. Smith, C. A. Steinke, S. Wilks, J. Zweiback, T. E. Cowan and T. Ditmire, J. Phys. B: At. Mol. Opt. Phys., vol. 34, pp. L313,