Low voltage operation of plasma focus

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Plasma foci of compact sizes and operating with low energies (from tens of joules to few hundred joules) have found application in recent years and have attracted plasma-physics scientists and engineers for research in this direction. We are presenting a low energy and miniature plasma focus which operates from a capacitor bank of 8.4 μF capacity, charged at 4.2–4.3 kV and delivering approximately 52 kA peak current at approximately 60 nH calculated circuit inductance. The total circuit inductance includes the plasma focus inductance. The reported plasma focus operates at the lowest voltage among all reported plasma foci so far. Moreover the cost of capacitor bank used for plasma focus is nearly 20 U.S. dollars making it very cheap. At low voltage operation of plasma focus, the initial breakdown mechanism becomes important for operation of plasma focus. The quartz glass tube is used as insulator and breakdown initiation is done on its surface. The total energy of the plasma focus is approximately 75 J. The plasma focus system is made compact and the switching of capacitor bank energy is done by manual operating switch. The focus is operated with hydrogen and deuterium filled at 1–2 mbar.
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I. INTRODUCTION

A simple neutron source to operate-with has always been a temptation for the users of neutron sources and it becomes one of the motivations for researchers for putting the efforts to develop tabletop fusion devices. Plasma focus was invented a long way back[1,2] and later when it was found that they can be scaled for lower energies in which the similar plasma parameters are generated as to that of high energy plasma focus, the terminology[3] of microfocus[4–14] and nanofocus evolved.[15] It was also found that the formation of good plasma focus requires a good initial breakdown occurrence to generate a technically beautiful plasma sheath, which means a plasma sheath symmetrically initiated on the insulator surface making possibility of z-pinch fusion. The reported lowest voltages for initiation of good surface breakdown and successful operation (producing neutrons) of plasma focus had never been below 6 kV.[12–15] We have made an effort to explore these voltage limits and experimentally found the possibility to operate the plasma focus at lower voltages such as 4.2 kV, which is the lowest reported voltage for the operation of any plasma focus. The strong dip observed in the dI/dt signal verifies the successful pinch compression.[6] The energies of the plasma focus are 74 J, which comes in the range of microfocus. The advantage of operating a plasma focus at these voltages is that solid-state switches can best be used for operating a plasma focus giving an operating simplicity to portable plasma foci systems.[12]

II. EXPERIMENTAL SETUP

The plasma focus consists of coaxial anode and cathode insulated in between by a coaxial insulator on a certain length of anode. The operation of plasma focus starts with switching the capacitive energy stored in a capacitor bank. A discharge on the surface of insulator takes place and is forced by $J \times B$ force density in forward direction. The first phase is called discharge phase and the second one is called acceleration phase. Then at the end of anode the radial compression of coaxial current sheath takes place and z-pinch takes place in small volume of plasma focus. The pinching generates the radiations such as neutrons and hard x-ray, etc., depending upon the gas filled in the plasma focus. Figure 1 shows a typical Mather type plasma focus with its three important phases shown with arrows and Fig. 2 shows our experimental arrangement of plasma focus setup.

(1) Compact capacitor bank: The capacitor bank is made of four capacitors of 2.1 μF each connected in parallel to give a total capacitance of 8.4 μF. The capacitors of capacitor bank can be charged up to 4.5 kV. Compacting the arrangement makes the low inductance circuit and a calculated 60 nH inductance is achieved which includes the inductance of plasma focus and capacitor bank circuit both. This way the system becomes capable of delivering >50 kA current in the plasma focus. At these currents and energies successful operation of plasma focus is previously reported.[9] Here the similar peak currents are achieved by a low voltage capacitor bank giving a discharge on plasma focus insulator surface and causing formation of a good focus evidenced by the dip in di/dt waveform. The capacitor bank assembly of four

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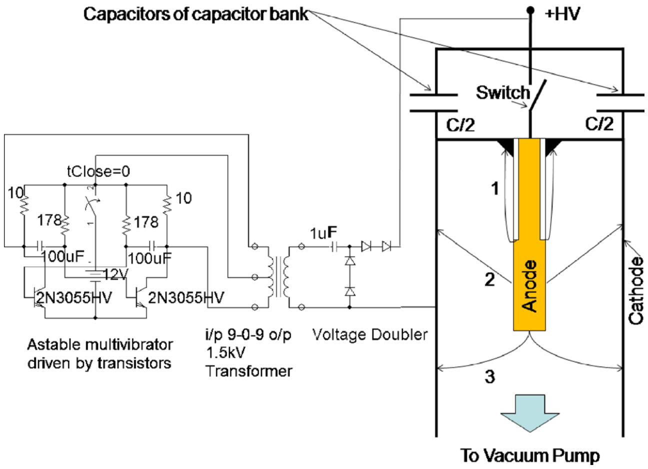

FIG. 1. (Color online) Schematic of Mather type plasma focus. 1: breakdown phase. 2: axial acceleration phase. 3: radial compression phase.

capacitors is lightweight (1 kg) and low cost (20 U.S. dollars) also. The capacitors are cylindrical in shape and axial threaded electrodes are available on the capacitors for further connections. The capacitor bank is made in coaxial geometry where the four capacitors are connected in the form of squirrel cage and the return path, which is the extension of copper anode, is coaxially located in this squirrel cage. The switching of capacitor bank energy to this plasma focus is done using a manually operating switch in which the metal block, which is tied on an end of long insulator rod, is manually pushed inside a gap between capacitor electrode (+ve) connecting plate and the anode rod placed close to it but their distance being such that without manual switch operation it does not close up to 5.0 kV.

(2) Battery driven power supply: To make the system portable and compact, we have made a battery driven power supply which is an astable-multivibrator driven by 12 V battery and its output connected to the input terminals of

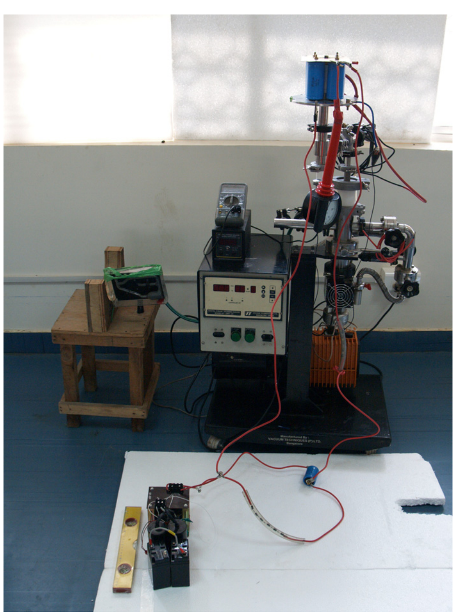

FIG. 2. (Color online) Experimental setup of plasma focus.

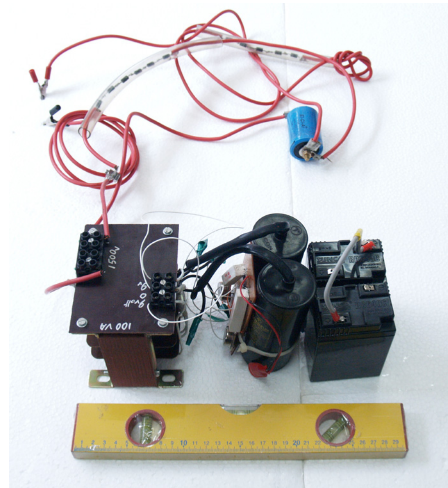

FIG. 3. (Color online) Battery driven compact power supply for plasma focus.

9–0–9 V (rms voltages) to 1.5 kV rms high voltage transformer. A voltage-doubler circuit connected to the output of high voltage transformer doubles the peak voltage output of the transformer connected in its input. This high voltage output is rectified by high voltage diode chain arrangement consisting of more than five 1 N5408 diodes (1000 V, 1 A) in series. The schematic of the whole power supply is shown in Fig. 1. The capacitor bank charges in 1 min. The peak voltage of nearly 4.5 kV is applied at the capacitor bank and bank charges to this voltage. For controlling the voltage at capacitor bank, the timings of battery switching to the astable-multivibrator are controlled. This compact power supply is shown in Fig. 3.

(3) Plasma focus parameters: The plasma focus is made of copper anode, which is flat at its end and has a diameter of 12 mm. A length of 10 mm of this copper anode is left uncovered by the insulator. The insulator is in the form of quartz glass tube, which has an outer diameter of 12 mm and an inner diameter of 10 mm. The free length of insulator inside the focus chamber is 6 mm. For the initiation of good surface breakdown at low voltages the cathode portion has a sharp edge as shown in Fig. 1. The cathode of the plasma focus chamber is made of stainless steel. The insulator tube and cathode are vacuum-sealed using Wilson seal whereas Teflon tape layers seal the anode and insulator interface. The inner diameter of cathode is 25 mm.

(4) Diagnostics: We have used various diagnostics, as mentioned under, to record different parameters of plasma focus. For di/dt observation a small B-dot loop is used. For measurement of currents passing through the plasma focus we have used current transformer coupled with electronic integrator. For measurement of voltage at the capacitor discharge we have connected a high voltage probe at the two ends of capacitor bank. For neutron/hard x-ray (HXR) time-of-flight measurement fast plastic scintillator (2 ns rise time) with photomultiplier tube (PMT) is used in combination. For soft x-ray (SXR)

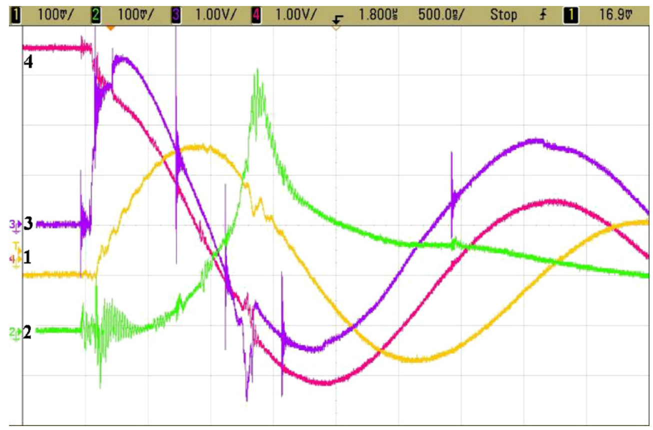

FIG. 4. (Color online) H_2 plasma focus. 1: current (5 mV/kA). 2: photodiode output. 3: dI/dt. 4: voltage (1 V/kV); horizontal axis 500 ns/div.

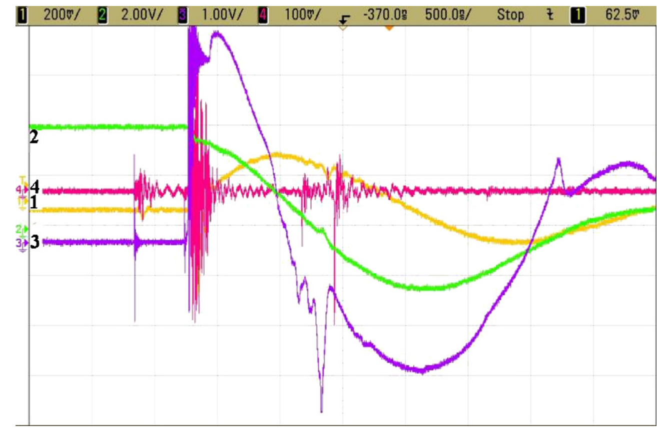

FIG. 5. (Color online) Double pinch in D_2 plasma focus. 1: current (5 mV/kA). 2: voltage (1 V/kV). 3: di/dt. 4: PMT output; horizontal axis 500 ns/div.

measurement aluminum filter and BPX65 photodiode is used.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The experiments were conducted using two different gases. One gas was hydrogen and other was deuterium. A pinch was recorded by the dI/dt probe mentioned above at the capacitor charging voltage of 4.2 kV and hydrogen gas fill pressure of 1.6 mbar. The soft x-ray emission was observed by a BPX-65 photodiode reversed biased at 9 V and a 458 Ω resistor was sampling its photocurrent. The photodiode is kept in axis of plasma focus opposite to the capacitor direction. One 11 μm aluminum foil was kept before BPX-65 photodiode glass window in order to filter out the visible light. The results are presented in Fig. 4. The photodiode signal is showing maximum photocurrent at the time of pinch as is being shown by the waveform of voltage output of photodiode. The current peak value, which is passed through the plasma focus, was 52 kA in this experiment. The pinch formation is clearly evidenced by the peaks in dI/dt signal and photodiode outputs.

The plasma focus was later filled with deuterium for the production of neutrons and hard x-ray at 1.6 mbar. The capacitor bank was charged to 4.3 kV. The current through the plasma focus were nearly 53 kA during discharge. Formation of double pinch is observed in the dI/dt probe waveform shown in Fig. 5. When the current is in the second half of the current waveform cycle, a dip in the direction opposite to that of the first pinch is seen. This second dip is weaker than the first dip observed in the di/dt waveform. A fast-scintillator (6 in. diameter) coupled PMT kept behind a 3 in. thick lead wall has recorded the neutron pulse radiated during the pinch of plasma focus.

In Fig. 6 we have recorded the outputs of two PMTs one (with 6 in. diameter scintillator) at 1 m distance (PMT2) and other (with 2 in. diameter scintillator) at 0.75 (PMT1) meter from plasma focus. In this case no lead block was used to attenuate the x-rays emanating at the time of pinch. The first pulse in photodiode signal corresponds to the x-ray and the second one corresponds to the neutron emission. This time the plasma focus was filled at 1.0 mbar and the charging voltage of the capacitor bank was 4.3 kV. Both the waveforms show two peaks: one corresponding to hard x-ray emission from plasma focus and other corresponding to neutron emission from plasma focus. The noncoincidence between hard x-ray pulses between two outputs is because of delay in internal electronics of the two PMT outputs, which are of different dimensions.

This plasma focus, when optimally designed for the production of neutrons, is expected to deliver more than 10^4 neutrons per shot as is suggested by various scaling laws that had evolved and had been presented by various plasma focus research scientists.[11,16–18] The repeatability of strong di/dt shots is also satisfactory. A maximum of eight good shots (with strong dI/dt dip) are observed in ten sequential shots taken nearly after 3–4 min.

IV. CONCLUSION

A successful operation of plasma focus at the lowest voltages, i.e., down to 4.2 kV has been experimentally achieved and demonstrated. It could have been achieved because of symmetric breakdown initiation on insulator surface even at these low voltages. The further optimization of plasma focus parameters will certainly lead to higher neutron

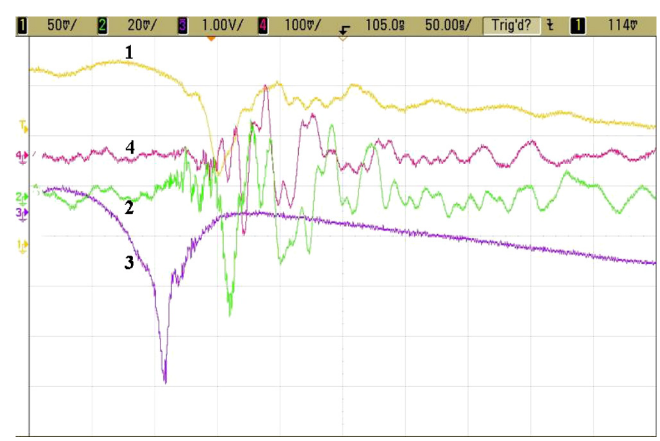

FIG. 6. (Color online) Time-of flight signal of neutron and hard x-ray in D_2 plasma focus,. 1: current (5 mV/kA). 2: PMT1 output. 3: di/dt. 4: PMT2 output; horizontal axis 50 ns/div.

yields. Moreover the device may now be realistically thought of being run by single solid-state switch making the plasma focus very much user friendly.

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[1] J. W. Mather, Phys. Fluids **7**, S28 (1964).
[2] N. V. Filippov, T. I. Filipova, and V. P. Vinogradov, Nucl. Fusion Suppl. **2**, 577 (1962).
[3] L. Soto, Plasma Phys. Controlled Fusion **47**, A361 (2005).
[4] R. K. Rout, P. Mishra, A. M. Rawool, L. V.Kulkarni, and S. C. Gupta, J. Phys. D: Appl. Phys. **41**, 205211 (2008).
[5] A. V. Dubrovski, V. A. Gribkov, Y. P. Ivanov, P. Lee, S. Lee, M. Liu, and V. A. Samarin, Nukleonika **46**, S107 (2001).
[6] R. Verma, M. V. Roshan, F. Mallik, P. Lee, S. Lee, S. V. Springham, T. L. Tan, M. Krishnan, and R. S. Rawat, Plasma Sources Sci. Technol. **17**, 045020 (2008).
[7] S. M. Hassan, T. Zhang, A. Patran, R. S. Rawat, S. V. Springham, T. L. Tan, D. Wong, W. Wang, S. Lee, V. A. Gribkov, S. R. Mohanty, and P. Lee, Plasma Sources Sci. Technol. **15**, 614 (2006).
[8] M. Milanese, R. Moroso, and Z. Pouzo, Eur. Phys. J. D **27**, 77 (2003).
[9] P. Silva, L. Soto, W. Kies, and J. Moreno, Plasma Sources Sci. Technol. **13**, 329 (2004).
[10] L. Soto, P. Silva, J. Moreno, M. Zambra, W. Keis, R. E. Mayor, A. Clausse, L. Altamirano, C. Pavez, and L. Huerta, J. Phys. D: Appl. Phys. **41**, 205215 (2008).
[11] A. Shyam and M. Srinivasan, Appl. Phys. (Berlin) **17**, 425 (1978).
[12] R. Petr, D. Reilly, J. Freshman, N. Orozco, D. Pham, L. Ngo, and J. Mangano, Jpn. J. Appl. Phys., Part 1 **39**, 607 (2000).
[13] R. K. Rout, A. M. Rawool, L. V. Kulkarni, T. C. Kaushik, and S. C. Gupta, Proceedings of 16th Annual Conference of Indian Nuclear Society, 2005.
[14] A. Shyam and P. K. Pal, Atomkernenerg./Kerntech. **41**, 23 (1982).
[15] L. Soto, C. Pavez, J. Moreno, M. Barbaglia, and A. Clausse, Plasma Sources Sci. Technol. **18**, 015007 (2009).
[16] S. Lee and S. H. Saw, J. Fusion Energy **27**, 292 (2008).
[17] G. Decker, L. Flemming, H. J. Kaeppeler, T. Openlander, G. Pros, P. Scilling, H. Schmidt, M. Shakhatre, and M. Trunk, Plasma Phys. **22**, 245 (1980).
[18] A. Bernard, P. Cloth, H. Conrads, A. Coudeville, G. Gourlan, A. Jolas, Ch. Maisonneer, and J. P. Rager, Nucl. Instrum. Methods **145**, 191 (1977).