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Final Technical Report
Pakistan Science Foundation Project

Project Title : Study of Plasma Focus Discharge

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Project Number : PSF/Res/C-QU/Phys(70)

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SUMMARY

Dense Plasma focus is a device whose operation is much simpler as compared to other plasma machines. The device consists of an anode rod of bigger diameter surrounded by six cathode rods of relatively smaller diameter forming a co-axial system. These rods are screwed to the anode and cathode base plates called anode and the cathode headers. An insulator sleeve usually a pyrex glass is used to provide the electrical isolation between the electrodes of the device. The operation of the device begins with the application of high voltage pulse (through a charged capacitor or by a capacitor bank) between the co-axial electrodes. As a result dielectric breakdown of the filling gas occurs between the central anode rod and the cathode base plate via insulator sleeve surface. During this process axially symmetric current sheath is developed which expands radially and moves towards the open end of the electrode assembly due to the magnetic pressure behind the current sheath. It is one of the basic requirements of the Plasmas Focus operation that, when the current sheath arrives at the tip of the central electrode the current through the device is maximum, so that the maximum energy stored is in the magnetic field which is indispensable for efficient compression. Experimentally this is achieved by synchronizing the current sheath arrival time from the base plate to the anode tip with the peak current time (rise time) of the capacitor. This in turn strongly depends upon the length of the anode, pressure and nature of the filling gas. Once this synchronization is achieved by adjusting these parameters, causing the radial collapse of the current sheath resulting, in the formation of hot and dense focused plasma just beyond the face of the central electrode. Experimentally this can be conformed by using a high voltage probe which is actually a resistor divider connected to anode and cathode headers. A sharp spike in the signal of the high voltage probe is an indication of strong pinching during the collapse phase of current sheath. Further when the device is operated with D_2

as the filling gas intense burst of neutrons and x-rays are emitted due to D-D fusion resulting from the pinching.

During the entire duration of the project we have performed a number of experiments on the dense plasma focus. Some of the significant findings in our research work on the device are as under :

a) In the laboratory, for the first time deterioration of neutron yield in a low energy plasma focus operated by a single 32μF, 15 kV (3.6 kJ) capacitor is observed. When sum of the discharged energy across an insulator sleeve approaches 1.6 MJ, the neutron yield from the device starts deteriorating. The insulator sleeve, when examined, is found to have a ~3 μm thick copper layer evaporated from the electrodes of the device. It is therefore concluded that the degradation of neutron yield in our low-energy device occurs due to Cu deposition on the sleeve surface.

b) We are the first in Pakistan who have successfully designed and developed a simple, low-inductance pressurized sparkgap for the plasma focus operation energized by a single 32 μF, 15 kV (3.6 kJ) capacitor. The sparkgap in capable of handling discharge current upto 200 kA with a rise time of less than 1 μsec.

c) A low inductance capacitor bank for the plasma focus operation is also designed and developed. The bank comprises three modules, each consisting of two 2 μF, 40 kV capacitors alongwith a field-distortion-type pressurized sparkgap. A peak current of about 250 kA has been estimated when the bank is charged at 18 kV

d) The behaviour of the current sheath in the presence of a target placed downstream of the anode is studied. The high voltage probe signal and the sequential bursts of the neutrons suggest the possibility of the plasma focus system to be used as a cascading device for the production of sequential bursts of x-rays and neutrons.

e) To enhance the efficiency of the plasma focus system we have studied the effects of anode length and insulator sleeve length variation on the pressure range of neutron emission. It is found that the proper choice of the two parameters broadens the pressure range for the high neutron yield and hence improves the shot-to-shot reproducibility of the system.

DETAILED REPORT

i) INTRODUCTION

Plasma focus is a simple functional device with high neutron and x-ray yields. It is speculated that if the neutron scaling $Y_n \sim E^2$, $Y_n \sim I^4$ holds upto bank energies of 30 - 50 MJ, the plasma focus will be of interest from the stand point of fusion power plants also. However some difficulties still persist with the operation of the plasma focus devices. For example shot-to-shot reproducibility of the plasma focus device is very poor. Even in machines which are regarded as highly reproducible one, a factor of two is common in the variation of neutron yield. It has been observed on the large plasma focus facilities that the neutron yield saturates or even decreases with increase in the discharge energy. This may prove a detrimmental constraint reducing the scope of the plasma focus in the context of fusion programme as well as other applications also. For example on POSEIDON (the biggest operational plasma focus in the world, situated at Stuttgard, Germany) the well known stagnation of the neutron yield at high bank energies (280 - 500 kJ) was studied. Measurements with magnetic and optical probes suggest that the saturation is due to a malfunction of the current sheath, particularly in the radial collapse phase, leading to inefficient compression. Impurities released mainly from the insulator may be responsible for this phenomenon. When the pyrex insulator was replaced by an alumina (ceramic) insulator, the operation of the plasma focus at high discharge energy was considerably improved since only partial saturation of the neutron yield was observed.

To examine the scope of the plasma focus in the fusion programme as well as its other applications, it seems essential that different machine parameters be investigated systematically and in a comprehensive manner. In the optimization of the plasma focus devices, different parameters are involved, such as geometry and structure of the inner and outer electrodes, the material and configuration of the insulator and the initial pressure. etc. These parameters are related in an intricate way and no general relation has been found so far. An attempt in this direction was made in our laboratory and noticed that there exist optimum choice of the sleeve length which is capable of developing an azimuthally symmetric current sheath and that any departure from this choice causes spokes formation on the sleeve surface. We have used a variety of different materials of the insulator sleeve, observed the neutron emission and found that a sleeve material with higher dielectric constant ε_r provides the neutron yield over a wider range of filling pressure and that the yield increases linearly with the product P x ε_r, where P is the filling gas pressure and ε_r is the dielectric constant of the insulator sleeve material. It is thus speculated that if some special insulators of higher dielectric constant are available, the neutron yield may be increased several times. A further investigation was made to study the behaviour of the system with the change in anode length. Regimes of high and low fluence anisotropy as well as high neutron yield were identified. In the report period we extended this work in a comprehensive manner for tuning of the lengths of the insulator sleeve and that of anode. We find that the proper choice of the two parameters broaden the pressure range of high neutron yield and hence improves the shot-to-shot reproducibility of the system.

As already mentioned the operation of the device begins with the application of high voltage between the electrodes of the system. This results in the dielectric breakdown of the filling gas and the formation of current sheath, after that it moves along the axial direction sweeping mass of the gas in its front until it collapses in the radial phase. When focusing occurs, a rapid compression of plasma takes place. The strong electro-mechanical action draws energy from the magnetic field, pumping the energy into the compressing plasma. This mechanism results in a distinct spike in the signal of high voltage probe and a dip in the rogawski coil signal. High spike/dip in the voltage/current signals are the indication of strong focusing. The typical oscillographs of voltage/current signals are given in figure 1.

ii. RESULTS

We have done our experimental work on plasma focus system of the electrodes assembly as shown in figure 2, while the various parameter of the system are given in Table1.

Table1

Parameter of the Plasma Focus Device

Capacitor bank	32 μF single
Charging voltage	12 kV
Discharge energy (W_o)	2.3 kJ
Peak discharge current	~200 kA
Length of inner electrode	160 mm
Radius of inner electrode	9 mm
Radius of outer electrode	25 mm
Short circuited external inductance	~80 nH
Focus tube inductance	~30.5 nH
Current rise time	~1 μsec
D_2 gas pressure for high neutron yield	
Optimum pressure (p_o)	3.0 mbar
Energy to gas ratio $\left(\frac{W_o}{p_o V}\right)\left(\frac{J}{\text{mbar cm}^3}\right)$	2.9

We have completed a number of experiments on the Plasma Focus operated by a single 32 μF, 15 kV capacitor. The electrode system consists of a 160 mm long Cu rod of 18 mm diameter as anode surrounded by six co-axial Cu rods of 10 mm diameter. Since the breakdown occurs initially between the electrodes via insulator sleeve surface. As a result the sleeve surface is gradually contaminated due to the copper coating, evaporated from the electrodes of the device and that causes the characteristics of the device to vary continuously. For example in our plasma focus system when a new insulator glass sleeve is installed, the breakdown is delayed by 100 - 150 ns compared to the normal time of 30 - 40 ns and no focusing is observed. During the next few shots, however, this delay lowers successively and high voltage probe indicates improvement in the focusing action. In figure 3 the signals of high voltage probe for an uncontaminated and for a relatively contaminated one are given. These observation indicate that some minimum coating level of the conducting material on the sleeve surface is essential for prompt breakdown and current sheath formation.

Another observation in our plasma focus system is that for a fresh glass sleeve, some shots observe single focusing spike while in others multiple focusing. After the glass sleeve has sustained some 100 shots multiple focusing spikes appear in almost every shot. Each focusing spike in the high voltage probe signal is accompanied with the corresponding neutron pulse, ion beam pulse and x-ray pulse. This phenomenon is depicted in figure 4.

A very interesting observation in our experimental work was that after about 700 shots i.e. when the total discharge energy across the glass sleeve surpassed 1.6 MJ, the neutron yield of the device started to exhibits deterioration. In figure 5(a) is shown the shot-to-shot behaviour and in 5(b) the average of 12 consecutive shots when the neutron yield from the device started to decline. As the neutron yield from the device started to decline, amplitude of the high voltage probe signal went down, indicating that energy available for pinching has been reduced some how.

To check whether the contaminated glass sleeve introduces higher or lower content of impurities in the focus plasma, we analyzed the optical plasma radiations for the contaminated glass sleeve as well as for a new one. A one-meter monochromator with 1200 lines/mm grating was employed to this end. The Pyrex glass is an alloy with different concentrations of silicon oxide, sodium oxide, potassium oxide, aluminum oxide and boron oxide etc. We detected the B_{II} (412.19 nm), B_{IV} (468.16 nm), K_{IX} (416.96 nm) and K_{IX} (590.96 nm) lines to access the plasma impurities content introduced from the insulator sleeve. For each line, twenty shots were recorded, ten shots for the contaminated insulator sleeve and ten for the case of new insulator sleeve. It is found that the plasma impurities content introduced from the insulator sleeve surface is relatively higher for a new sleeve as compared to the contaminated one with deteriorated neutron yield.

On examining the contaminated insulator glass sleeve, its surface was found to be coated with approximately 3 μm thin Cu layer evaporated from the electrodes of the device. We also made an arrangement to measure the resistance of contaminated glass sleeve which comes out to be about 30 GΩ, while the resistance of a brand new glass sleeve was almost infinity as we were not able to measure that.

We made an arrangement to study the effect of target on the focusing action and on the neutron emission. The target in our case was a Cu disc of 5 mm thick having diameter of 35 mm. The target was hanged from the top flange of the chamber with the help of two supporting rods. Our target insertion mechanism allows enough room to the current sheath to focus beyond the target. A dual channel 100 MHz oscilloscope was used for displaying the transient voltage.

In figure 6(a) average neutron counts versus the target distance from the anode tip is shown. It is clear from the figure that counts are almost independent of the target distance beyond 5 cm. However, placing the target closer to the anode decreases the neutron counts and a minimum is obtained at about 2 cm. The reduction of the neutron counts is due to the interference of the target with the deuterium beam accelerated downstream from the focus region. This phenomenon is confirmed by making a hole of diameter 2 mm in the center of the target. Figure 6(b) shows average neutron counts versus the target distance from the anode tip for the case of target having hole in the centre. It is interesting to note that by bringing the target at a distance of about 1-1.2 cm, the average neutron counts increases abruptly. At this distance two focusing spikes in the oscillograph of the high voltage probe signal and in the neutron pulse profile are the clear indication of a second focus after the target position. The second focus occurs about 1 μs later and the phenomenon is shown in the oscillograph depicted in figure 7. The second spike is relatively lower in amplitude, implying a weak focus. However, it proves that such a device can possibly be used as a cascading focus device to produce sequential bursts of neutrons and soft x-rays.

In the laboratory early experiments were performed using open air sparkgap which produce a huge acoustic noise. Now we have developed a pressurized sparkgap which works reliably and is quite reproducible one for capacitor charging of 10 - 13 kV. The schematic diagram of the pressurized sparkgap is given in figure 8. Its body is machined from a nylon rod of 100 mm diameter and the electrodes are developed from a 50 mm diameter copper rod. A motor bike spark plug has been used with slight modification as a trigger pin. Six brass bolts tightened coaxially outside the body of sparkgap provide a low inductance path for the current. A colour TV flyback transformer has been employed to step up a -2 kV trigger pulse generated from a krytson KN - 6B, for triggering the sparkgap. A discharge current of about 200 kA has been estimated at 12 kV charging. The system works reliably and reproducibly for argon, hydrogen and deuterium gases.

A capacitor bank has also been developed for the plasma focus operation. The capacitor bank consists of three modules each having two 2 μF, 40 kV capacitors along with a field distortion type pressurized sparkgap. The schematic diagram of the capacitor bank is given in figure 9 and a detailed design of the sparkgap is depicted in figure 10. The body of the sparkgap is machined from ertalon rod of 75 mm diameter, and the electrodes are developed from a 40 mm diameter copper rod. A circular disc of 12 mm thickness is employed to trigger the sparkgap. Six brass bolts tightened coaxially outside the sparkgap body provide low inductance path to the current. A 0.3 μF capacitor charged upto -20 kV is used to trigger the three sparkgaps. The parasitic external inductance of the capacitor bank is estimated about 50 nH, while a peak discharge current of 250 kA is recorded when the 12 μF capacitor bank is charged at 18 kV (2 kJ). The system has been used for the temporal correlation study of neutrons, ion beam, high voltage probe and rogowski coil signals. From a careful analysis of the data, the high voltage probe signal is found to coincide well with the rogowski coil signal, where as the ion beam and the neutron pulses are delayed by 20 - 30 nsec. A set of signals recorded by a four channel digital storage oscilloscope is given in figure 11.

iii) DISCUSSION

An experimental study of Mather-type plasma focus device is conducted with a view to understand the dependence on various parameters of the device. We find that the proper selection of the length of the anode and the insulator sleeve lowers the neutron fluence anisotropy and enhances the possibility of azimuthally symmetric and uniform current sheath.

The contamination of the insulator sleeve changes the characteristic of the device. However, a minimum level of contamination seems essential for prompt breakdown and good focusing action associated with the high neutron yield. As the contamination level grows, the current partition increases,which gives rise to multiple foci formation. Any further increase in sleeve contamination causes neutron yield deterioration.

It is found that the neutron emission from the focus region records maximum whenever the average current sheath velocity is around 6.5×10^4 m/sec. Any major departure from this value lowers the neutron yield. Furthermore, the neutron generation mechanism at play also seems to depend on the said velocity during the axial run.

v) CONCLUSIONS/NEED FOR ADDITIONAL RESEARCH

Proper adjustment of machine parameters and tuning of driver impedance with that of the accelerator enhances the neutron emission from the pinch filament and broadens the pressure range for high neutron emission. However, the study is far from complete. A more comprehensive and systematic study of the plasma focus characteristics using several diagnostics in parallel seems essential to fully understand the role of different parameters and the phenomena involved. The operational simplicity and easy-to-handle changes one can do in the machine parameters recommend the low energy devices for such investigations.

LIST OF PUBLICATIONS

1. Sausage Instability Threshold in a Low Energy Plasma Focus
M.Zakaullah, M.Nisar, F.Y.Khattak, S.Lee, G.Murtaza, X.P. Feng, H.U. Rehman and M.M.Beg.
Frontiers in Physics, Vol.4, p.306 Proceedings Fourth Symposium on Frontiers in Physics (15-19 April 1992).

2. Sequential Focussing in a Mather-Type Plasma Focus
M.Nisar, F.Y.Khattak, G.Murtaza, **M.Zakaullah,** and N. Rashid
Physica Scripta, **47** (1993)814.

3. Influence of Insulator Contamination by Copper Evaporation on Neutron Yield in a low Energy Plasma Focus.
M.Zakaullah, Imtiaz Ahmed, Nasir Rashid, M.M.Beg, and G.Murtaza.
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4. A Simple Pressurized Sparkgap for Plasma Focus Operation. '
M.Zakaullah, Samia Kausar, Imtiaz Ahmed, G.Murtaza and M.M.Beg
Mod. Phys. Lett. B7 (1993)835.

5. Characteristics of a Plasma Focus with Contaminated Insulator Sleeve
M.Zakaullah, Imtiaz Ahmed, S.Beg, M.M.Beg and G.Murtaza.
Proceedings of International Summer School and Workshop on
Nuclear Fusion and Plasma Physics (October 4-17, 1993) held at Hefei, China.

6. Effect of Insulator Sleeve Contamination on the Low Energy Plasma Focus Performance.
M.Zakaullah, Imtiaz Ahmed, G.Murtaza, M.Yasin and M.M.Beg
Fusion Engineering and Design, 23 (1993)359.

7. Pressure Range Broadening for a Plasma Focus Operation.
M.M.Beg, M.Shabbir .**M.Zakaullah** and G.Murtaza
Phys. Lett. A186 (1994)335.

8. Temporal Correlation of Electron, Ion Beam, and High Voltage Probe Signals in a Low Energy Plasma Focus
M.Zakaullah, Imtiaz Ahmed, Anwar Z. Shah, G.Murtaza and M.M.Beg.
Mod. Phys. Lett. B8 (1994)303.

9. Electron Temperature Measurement of Focus Plasma By Optical Radiation Emission Spectrum Analysis
M.Zakaullah, Samia Kausar, Imtiaz Ahmed, Shahid Qamar, M.M.Beg and G.Murtaza.
(Submitted)

10. Comparative Study of Low Energy Mather-Type Plasma Focus Devices.
M.Zakaullah, G.Murtaza, Imtiaz Ahmad, Farhat N.Beg, M.M.Beg, and M. Shabbir
(Submitted)

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3) Samia Kausar
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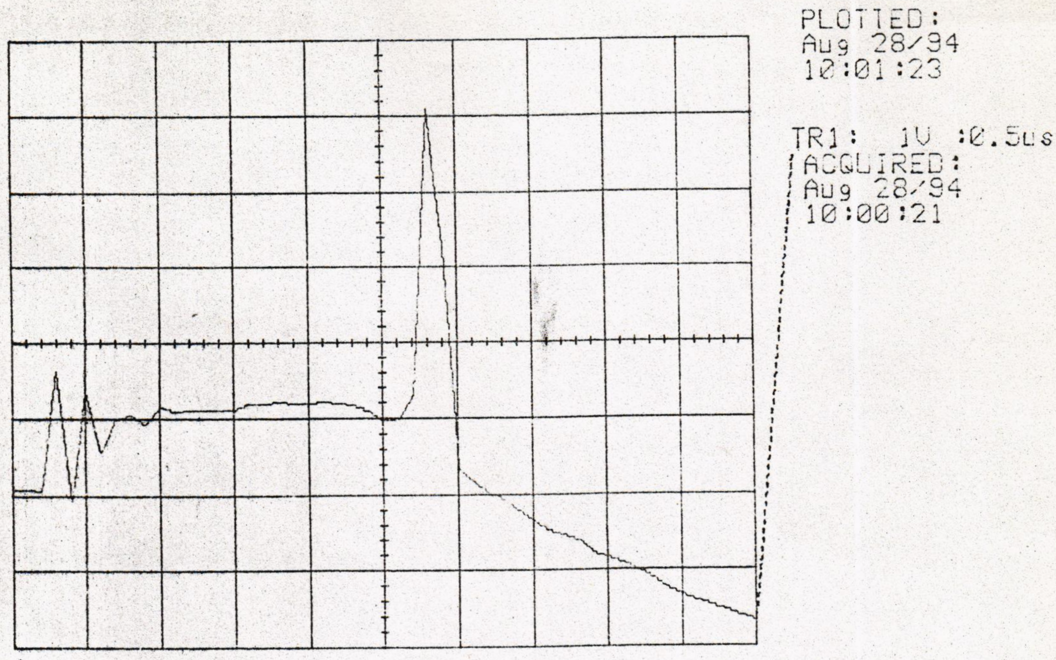
5) Muhammad Sharif
6) Abdul Majeed
7) Anisa Qamar
8) Salma Khanam
9) Qurrat-ul-Ain
10) Shehzad Mahmood
11) M. Asif
12) Shafique Hussain
13) Safadar Mahmood

M. PHIL. DEGREES AWARDED

S.No.	Name of Researcher	Year of Award	Title of Thesis
1.	Mr.Imtiaz Ahmed	1993	Effects of Parasitic Impurities on Neutron Emission from a Plasma Focus
2.	Mr.Nasir Rashid	1993	Multi-Channel X-rays Detector for Electron Temperature Measurement of the Focus Plasma
3.	Mr.Shahid Qamar	1994	X-ray Imaging of Low Energy Focus Plasma
4.	Miss Samia Kausar	1994	Optical Radiation Emission Spectrum Analysis of Low Energy Focus Plasma

LIST OF SCIENTISTS

		(Percentage of time devoted for the project)
1)	Dr.M.Zakaullah	~ 80%
2)	Prof.Dr.G. Murtaza	~ 10%
3)	Mr.M.Yasin ,SSO, PAEC	~ 5%
4)	Mr.M.Shabbir SSO,PAEC	~ 5%



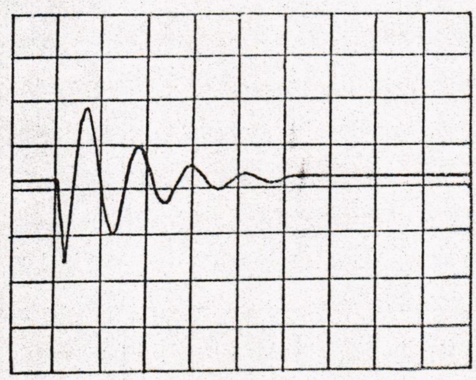


Fig. 1 : Typical high voltage probe (upper) and Rogowski coil (lower) signals. The Rogowski signal is displayed with 0.5 V/div, 10μsec/div.

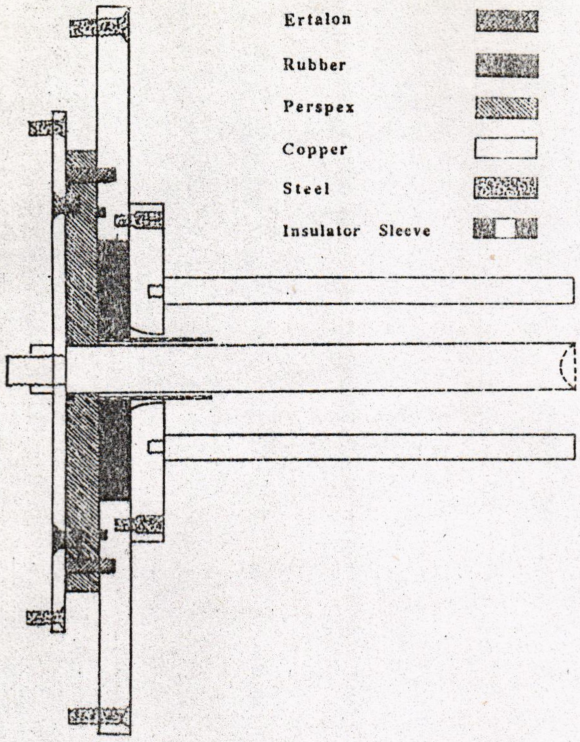


Fig. 2 The arrangement of plasma focus electrodes

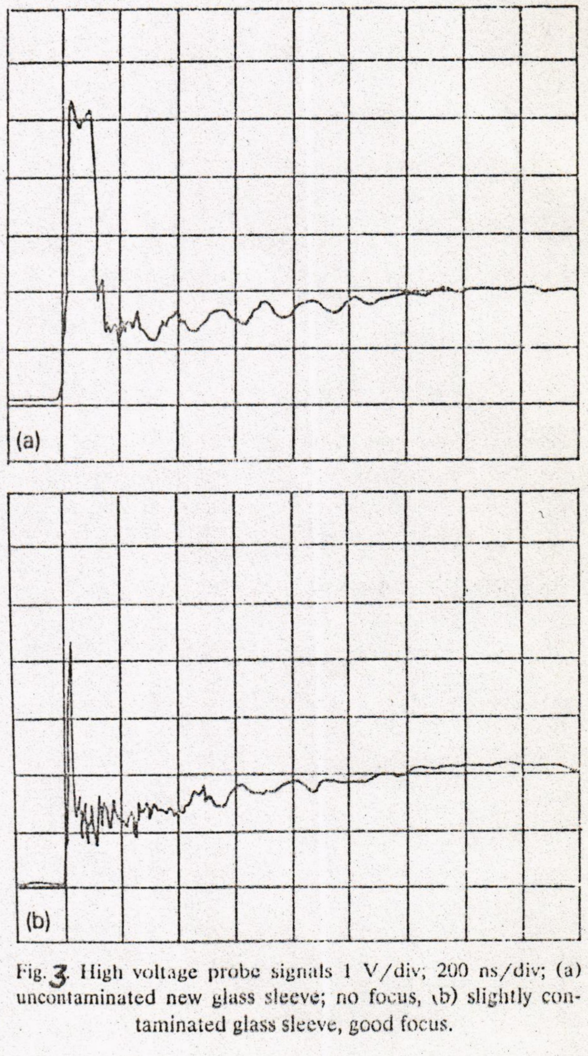


Fig. 3. High voltage probe signals 1 V/div; 200 ns/div; (a) uncontaminated new glass sleeve; no focus, (b) slightly contaminated glass sleeve, good focus.

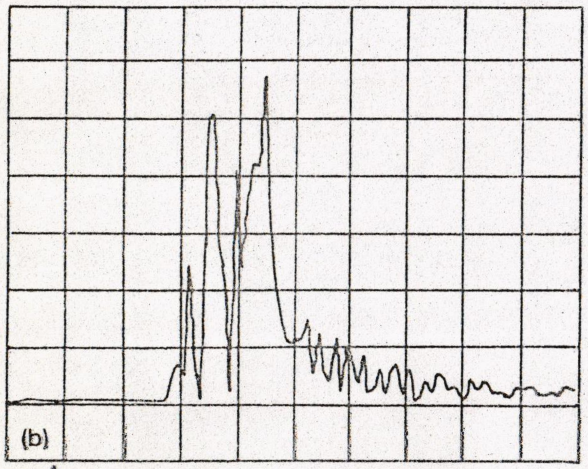


Fig. 4. Multiple foci formation; (a) HV probe signal: 2 V/div; 200 ns/div, (b) X-ray pulse detected by a pin-diode: 2 V/div; 200 ns/div.

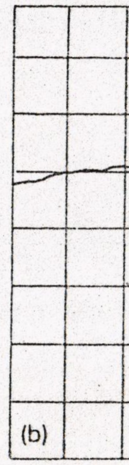
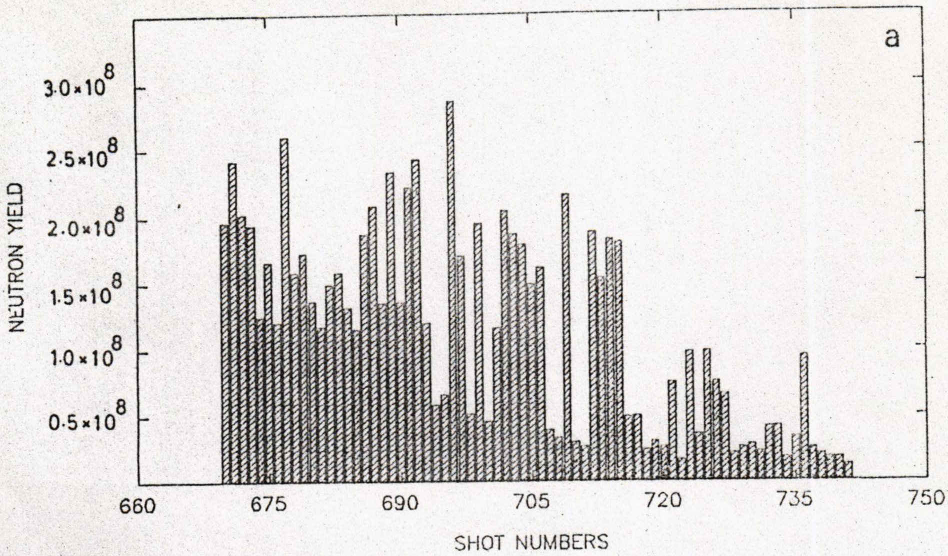


Fig. 4. Multip
200 ns/di



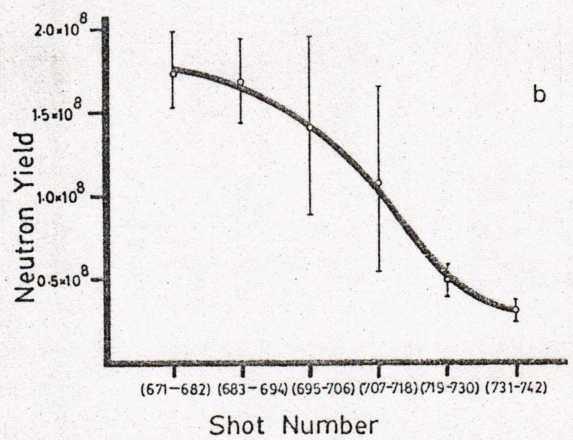
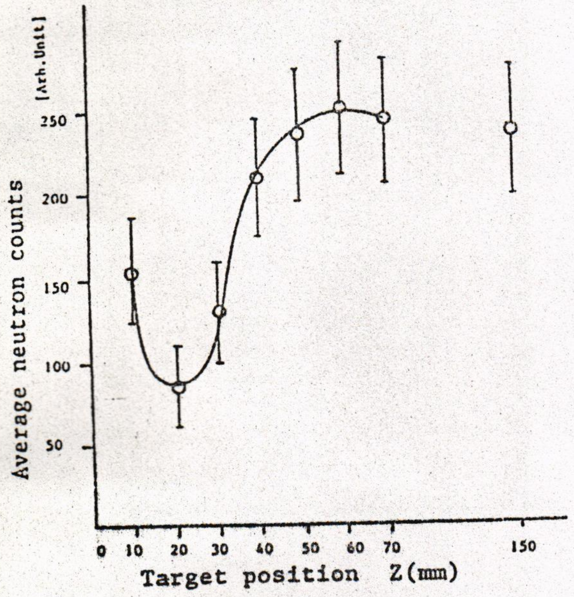
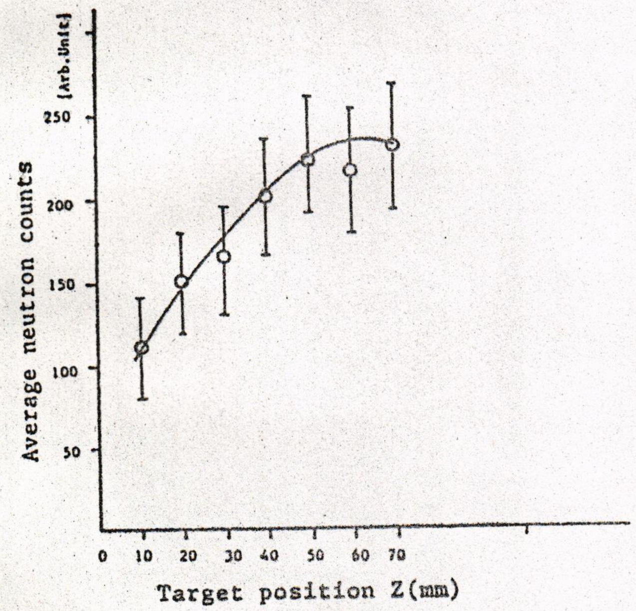


Fig. 5 Neutron yield versus shot number across an insulator sleeve when the device started to exhibit deterioration; (a) shot to shot variation, (b) average of 12 consecutive shots



(a)



(b)

Fig.6. Average neutron yield as a function of target distance from the tip of the anode, (a) without hole and (b) with a hole in the center of the target

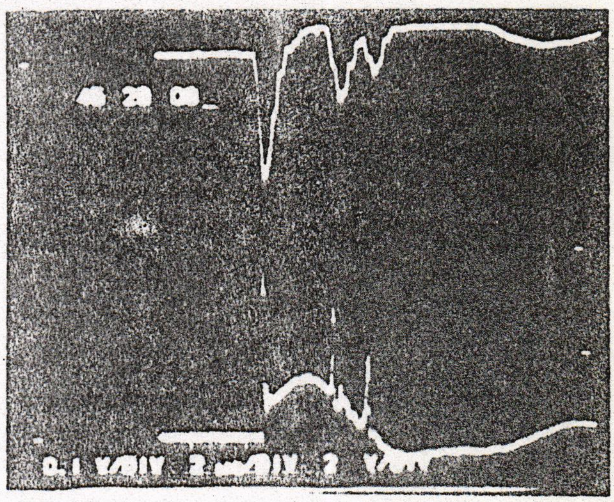


Fig. 7. A typical oscillogram of the voltage probe signal and the neutron pulse. The distance of the target from the tip of the anode is 1.0 cm, and the D2 pressure is 2.5 mb. The baseline time is 2 μs per division. The top signal is the neutron pulse and the bottom one shows the voltage probe signal

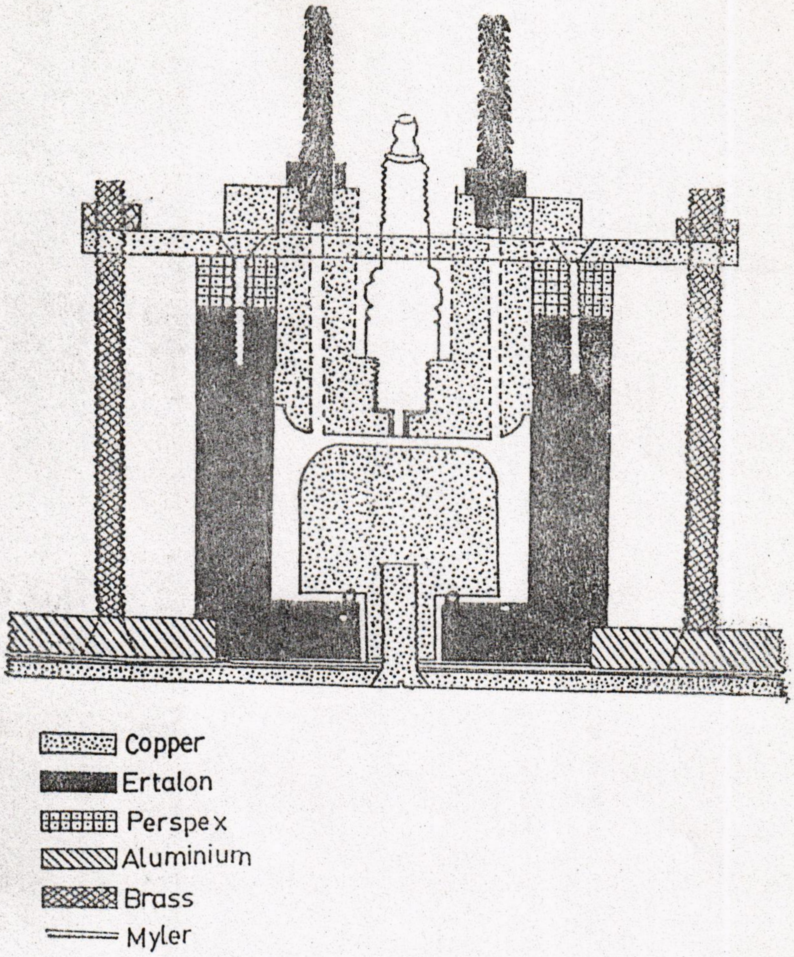


Fig. 8. A schematic diagram of pressurized sparkgap.

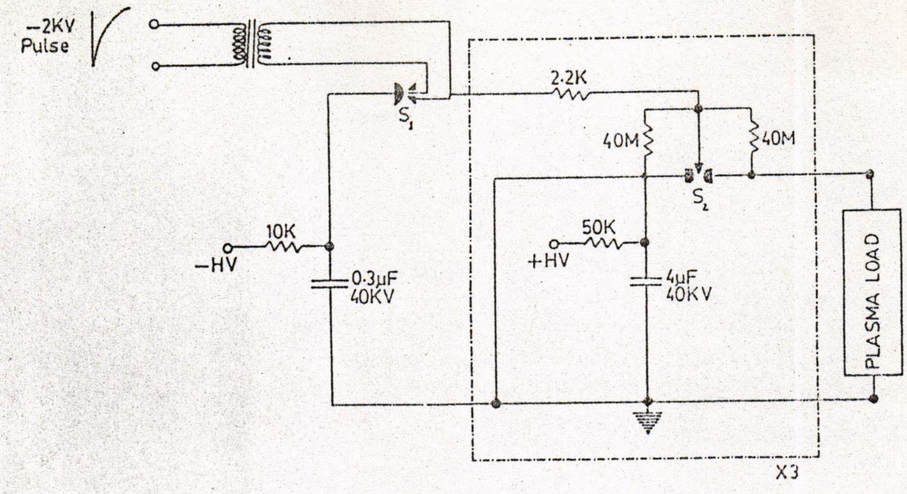


Fig. 9. The schematic arrangement of the capacitor bank.

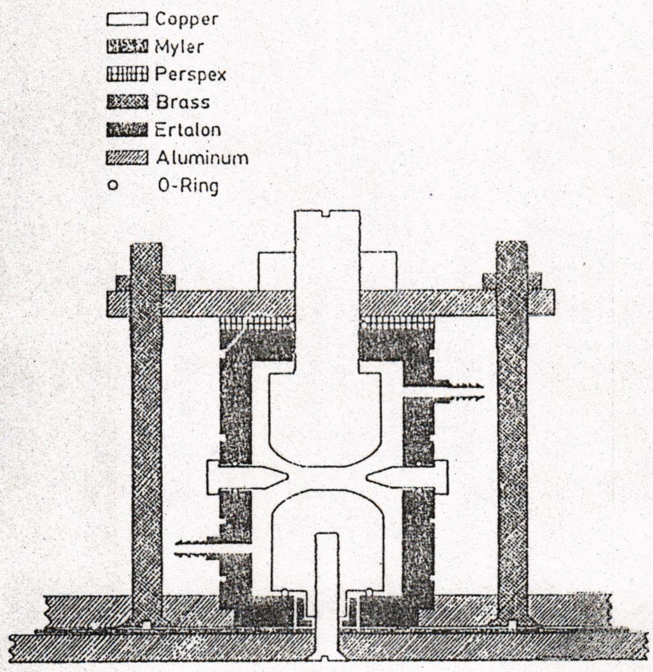


Fig. 10. The detailed sketch of field distortion type pressurized sparkgap.

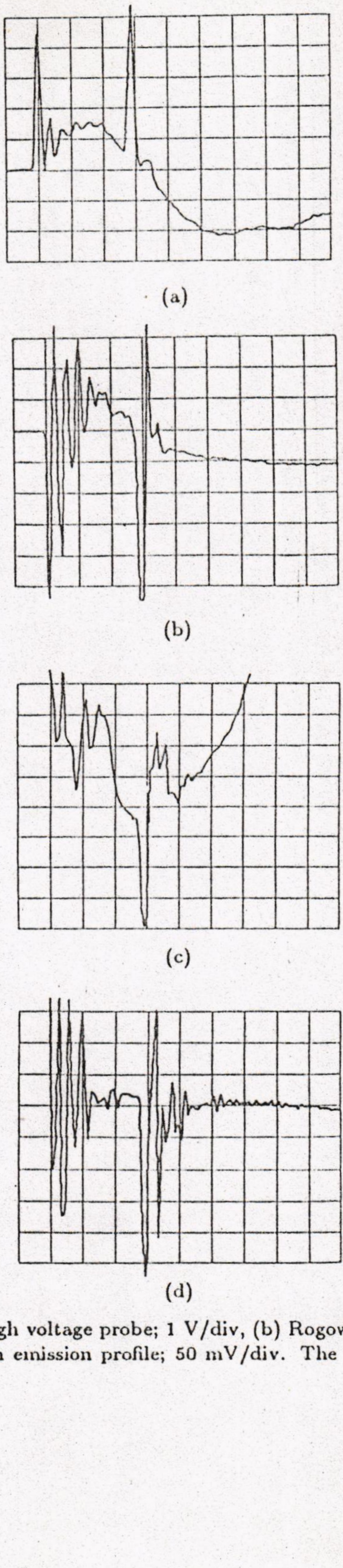


Fig.11. Oscillograms of (a) high voltage probe; 1 V/div, (b) Rogowski coil; 1 V/div, (c) ion beam pulse; 0.2 V/div, (d) neutron emission profile; 50 mV/div. The signals are recorded with time base 0.5 μsec/div.

SAUSAGE INSTABILITY THRESHOLD IN A LOW ENERGY PLASMA FOCUS

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ABSTRACT

Development of sausage instability (m = 0 mode) is studied in a small low energy Mather-type plasma focus. A shadowgraphic study of the current sheath has shown that the focused plasma necks off during the radial phase before the maximum compression. This may indicate the lowering of the instability threshold. Three hook-type structures are observed which may not be due to the multifoci formation. The bubble shape structure is observed to be developed in the expansion phase.

INTRODUCTION

Plasma focus[(1)] is a device whose operation is much simpler compared to other plasma machines. Hot and dense plasmas are produced in these devices. Such a plasma may act as a high intensity pulsed neutron and x-ray source. An ion beam is generated in the focus region due to sausage-type instabilities (m = 0 type). These instabilities give rise to

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the formation of some "micropinch" type structures or hot spots[2,3]. In this paper, we report on the behaviour of the m = 0 instability and the formation of hot spots in a low energy (3kJ) plasma focus device. We also present data showing some atypical behaviour of such plasmas.

Experiments were carried out in a Mather-type[4] device, energized by a single 32μF capacitor. An air gap made by a 1/2 inch thick copper plate was used to transfer the energy to the focus system. The electrodes system consisted of a central copper anode of 19 mm diameter and 160 mm length, with inner diameter of 64 mm. The outer cathode comprised of six copper rods screwed onto a copper plate with a knife edge near the anode. A 13 mm thick rubber disc with a hole at its centre is used to support the cylindrical pyrex glass sleeve, so that it could be positioned without touching the anode or the cathode. The length of the glass sleeve, from the cathode base plate is 25 mm. The parasitic inductance of the system including the capacitor, air gap, connecting cables and the electrodes headers is measured to be 100 nH.

The shadowgraphic setup is shown in Figure 1. A transversely excited atmospheric pressure nitrogen laser[5] ($\lambda \sim$ 340nm, $\tau \sim$ 3ns) is used as a light source. The expanded laser beam passes through the plasma focus chamber, scans the adjusted part of the rundown or radial collapse phase and falls on the objective lens. The image of the current sheath is focused at a small hole thorugh the stopper, and is then recorded by a time integrated camera. To screen the plasma and air gap stray light, a narrow band pass filter centered at 340 nm is mounted in front of the camera. A voltage probe,

(a)

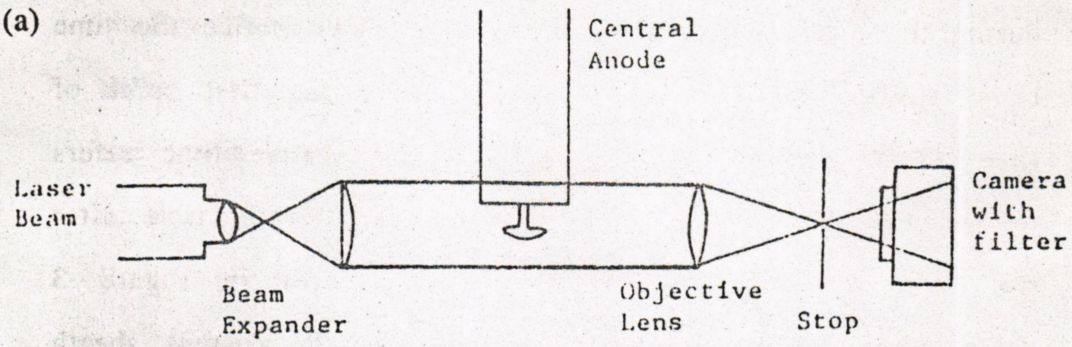


FIGURE 1. A schematic of the shadowgraphic arrangement.

(b)

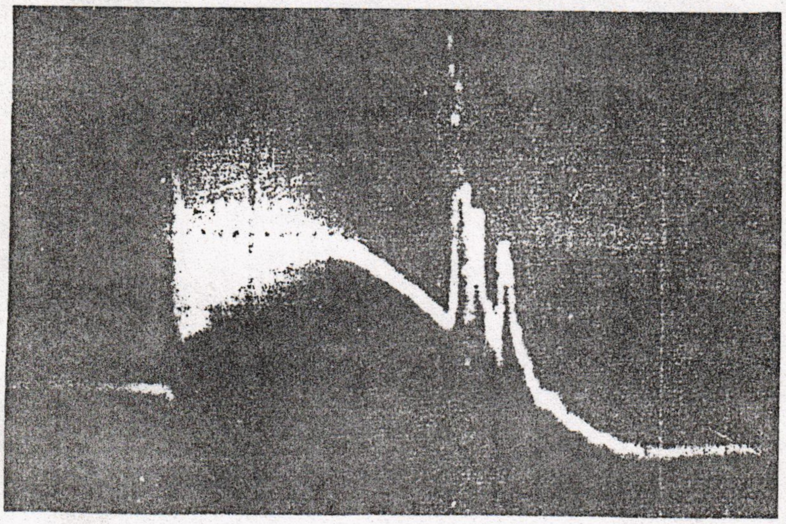
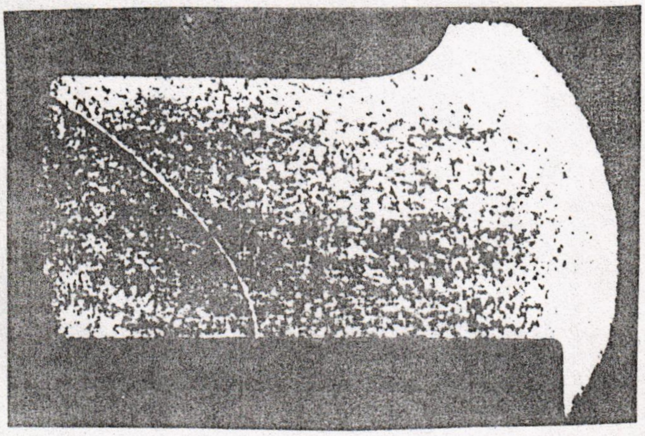


FIGURE 2. An oscillograph of the voltage signal. The first spike from the left is the breakdown spike. The second spike represents the focusing spike. The horizontal scale is 1μs/div.

which is a simple resistor divider having response time of 15 nsec, is used to monitor the voltage signal. It is connected across the anode and the cathode headers.

Figure 3 shows the shadowgraphs of current sheath during the axial run, down the accelerator. We define the time t = 0 when the laser pulse just coincides the first spike of the voltage probe signal (figure 2). The negative time refers to the time before the voltage probe spike, while time after the spike is considered positive. The pictures in Figure 3 depict no instability during the axial run. The current sheath across the electrodes, as observed by the earlier workers[6]

(a)



(b)

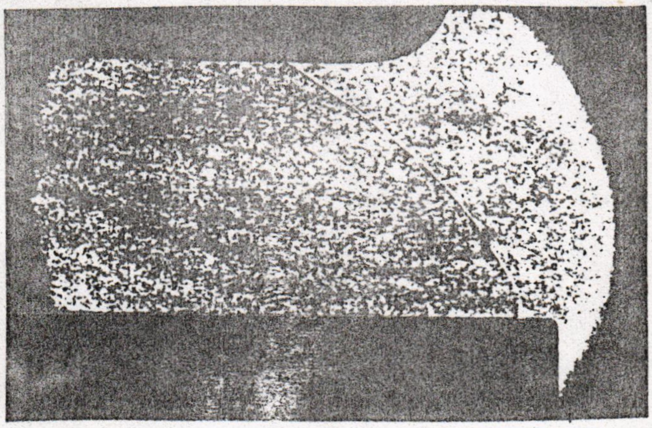


FIGURE 3. Shadowgraphs of the current sheath in the axial phase (a) time = -388ns (b) time = -180ns

is not planar. The sheath is canted backward from the anode to the cathode due to the radial dependence of the magnetic pressure gradient. The velocity of the current sheath during the axial run down the accelerator, estimated from the two shadow images, is about $6x10^6$ cm/sec. It is to be noticed that these two images are taken from two different shots at about the same discharge conditions. This demonstrates a typical accelerating phase, however, it touches the lower velocity limit[(1)].

In Figure 4, shadowgraphs of the current sheath during the radial collapse phase are presented. From these shadowgraphs, it is observed that the necking of focus plasma occurs well before (more than 12.5 ns) the maximum compression. This is atypical as compared to the other medium and high energy plasma focus devices[(7)]. In the latter devices, the m = 0 type instabilities are reported to be developed after the maximum compression. This may indicate that the lowering of the discharge energy reduces the instability threshold. However, no systematic study of the instabilities is carried out to conclude this result.

Some other interesting features can be observed from these shadowgrahps. Three hook-type structures can be clearly seen in the figure 4d, in the focus filament just before the maximum compression. We believe that these structures are not due to the multifoci formation observed by Shyam and Srinivasan[(8)]. In their case the multi foci formation was

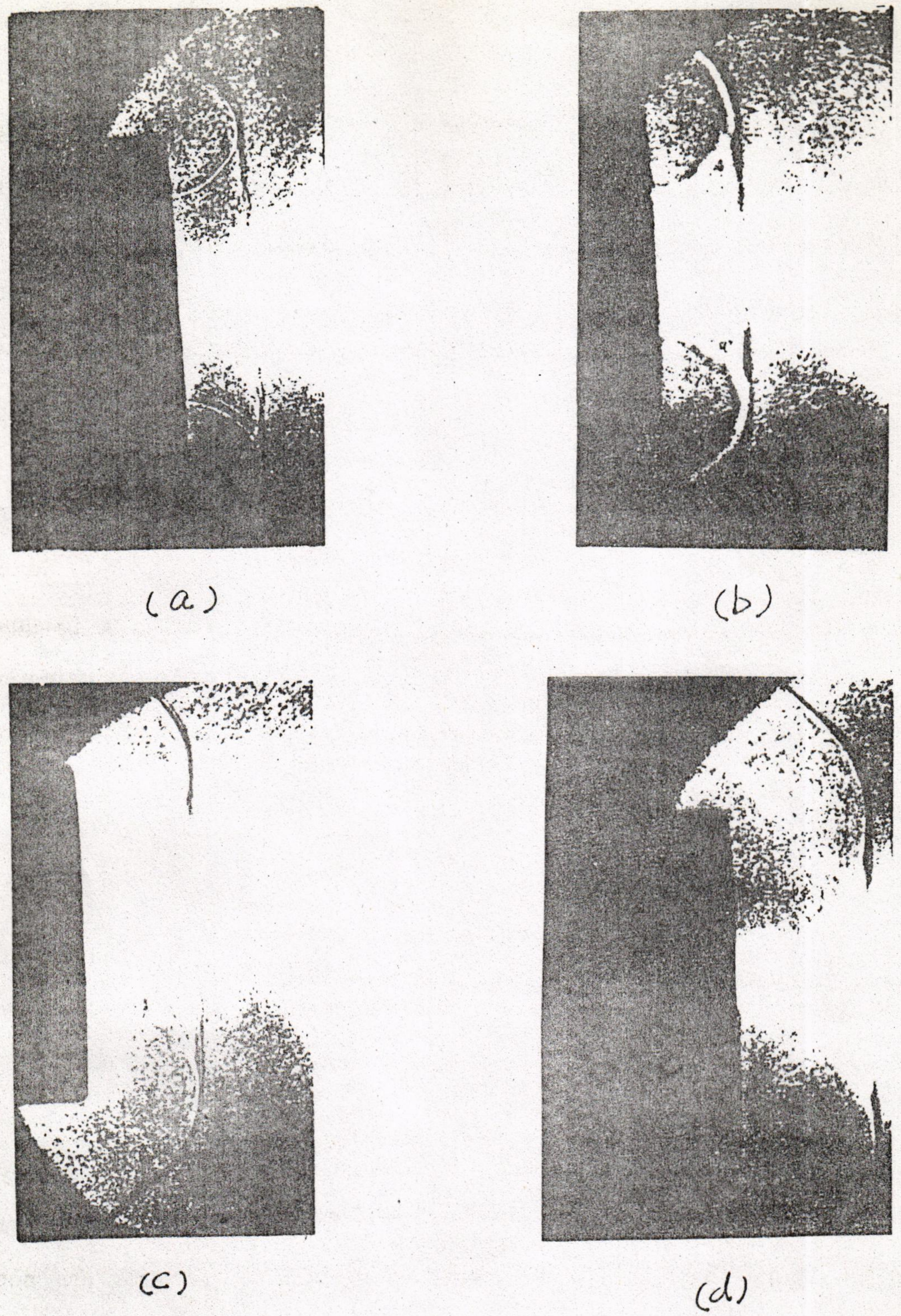


FIGURE 4. Shadowgraphs showing the current sheath in the radial phase. (a) time = -52ns, (b) time = -25ns, (c) time = -12.4ns, (d) time = -3.2ns.

observed after the radial phase and was argued to be due to the high pressure gas enclosed in the gap between the insulator and the anode. We observe these structures before the radial collapse not after the collapse.

Figure 5 shows a shadowgraph of the current sheath in the expansion phase. The formation of a bubble shape structure of the plasma sheath can be clearly seen. This structure is observed only in the expansion phase, unlike the one observed by Choi[9] in the presence of the focus filament. A more interesting feature of the observed bubble structure is the formation of a ring at its base. The physics of the ring formation is still under investigation.

To conclude, the sausage-type instabilities in a small 3 KJ Mather-type plasma focus are observed to be set in about 15 nsec prior to the maximum compression. Three hook-

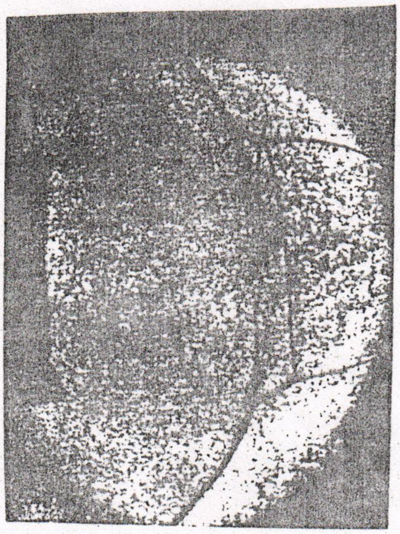


FIGURE 5. A shadowgraphic image showing the formation of the bubble shape in the expansion phase. This image is taken 65ns after the peak compression.

type structures are also appeared in the current sheath of the focus filament. The bubble formation is observed after the radial phase when there is no pinched plasma at all. This is in contrast with the observation in the medium as well as the high energy plasma foci wherein the sausage instability is found to develop only after the maximum compression of the pinch filament during the re-expansion phase and the bubble formation is observed in the presence of the radial pinch.

This work was partially supported by the Pakistan Science Foundation Projects No.C-QU/Phys(69) and (70), NSRDB Project No.P-16, ICAC-QAU, PAEC, A.Q.Khan research laboratory and UGC project for Plasma Physics.

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Sequential Focusing in a Mather-Type Plasma Focus

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Abstract

The current sheath behavior in a small 3 kJ plasma focus device, in the presence of a target placed downstream of the anode is investigated. The voltage signal and the sequential bursts of neutrons give a clear indication of the occurrence of the sequential focusing.

1. Introduction

Plasma focus has been the subject of intensive research for decades due to its potential for high neutron yield under optimum conditions and this device can act as a source of intense pulsed X-rays. Recently interest has been shown in using the plasma focus device as a cascading focus device [1, 2] by placing a target downstream of the anode. Such a device may have practical applications for the production of sequential bursts of neutron and soft X-ray for various purposes like neutron radiography and soft X-ray cinematography.

After the breakdown in a Mather-type plasma focus, the current sheath moves along in the axial run down phase, sweeping the mass in its front until it collapses in the radial phase. When focusing occurs, a rapid compression of plasma takes place. The strong electro-mechanical action draws energy from the magnetic field, pumping the energy into the compressing plasma. This mechanism results in a distinctive current dip and a voltage spike. A bigger spike in the voltage signal and a dip in the current signal are indications of strong focusing. In the presence of the target, after the collapse, the current sheath climbs over the target which now acts as a second anode as shown in Fig. 1. Hence the sheath now runs along the second axial phase until it collapses. Moo *et al.* [3] have studied the effect of using metal obstacles and deuterated targets downstream the current sheath on the ion beam and neutron yield in a small plasma focus device. The behavior of the current sheath in the presence of the target was shadowgraphically studied by Lee *et al.* [1]. In their arrangement, the supporting rod with the insulating glass tube posed a problem to the cascade focusing beyond the target. In this paper we report on the experimental evidence of sequential focusing in a low energy focus device, with a unique target insertion mechanism, by the analysis of the high voltage signal and the neutron pulse.

2. Experimental arrangement

These experiments were carried out in a low energy (3 kJ) focus device [4] energized by a single capacitor. The electrodes system is comprised of the inner copper anode, having a diameter of 18 mm and length of 152 mm and the outer electrode, consisting of six copper rods. Figure 2 shows the hanging target and the electrodes system. The target, in our case, is a copper disc having a thickness of 5 mm and a diameter of 35 mm. The thickness of the target has a crucial role since the current sheath, after climbing the target, must have enough time to become uniform before reaching the subsequent focus event. The target is hanged from the top flange of the chamber with the help of two supporting rods. These supporting rods are 3 mm thick brass rods encapsulated in glass tubes. The target can then be placed at the floating potential at various axial positions from the end of the anode or be withdrawn to the rear of the chamber without interrupting the vacuum in the chamber. Our target insertion mechanism allows enough room to the current sheath to focus beyond the target.

A resistive voltage divider with a response time of 15 ns is strapped across the anode collector plate and the cathode collector plate to measure the voltage across the focus tube. A channel of a dual channel 100 MHz oscilloscope is used

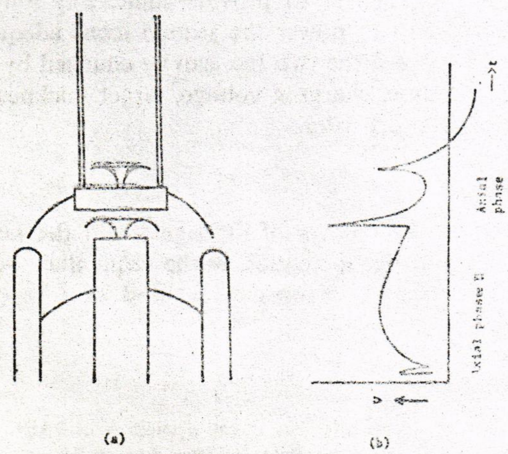

Fig. 1. Schematic layout of the sequential focusing event. (a) Cascading anode; (b) Sequential voltage spike

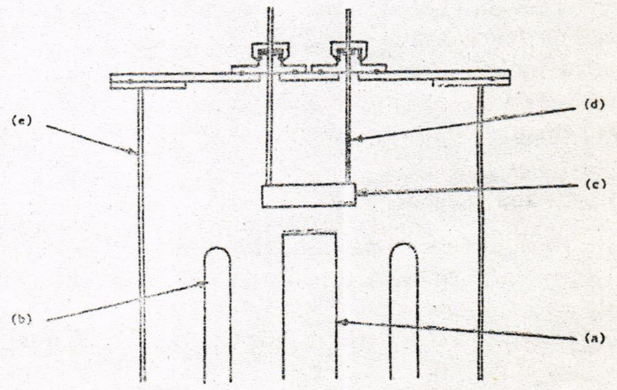

Fig. 2. Schematic diagram of the plasma focus electrodes and target. (a) Copper anode; (b) Copper cathodes; (c) Copper target, 3.5 cm dia.; (d) Supporting rods; (e) Chamber

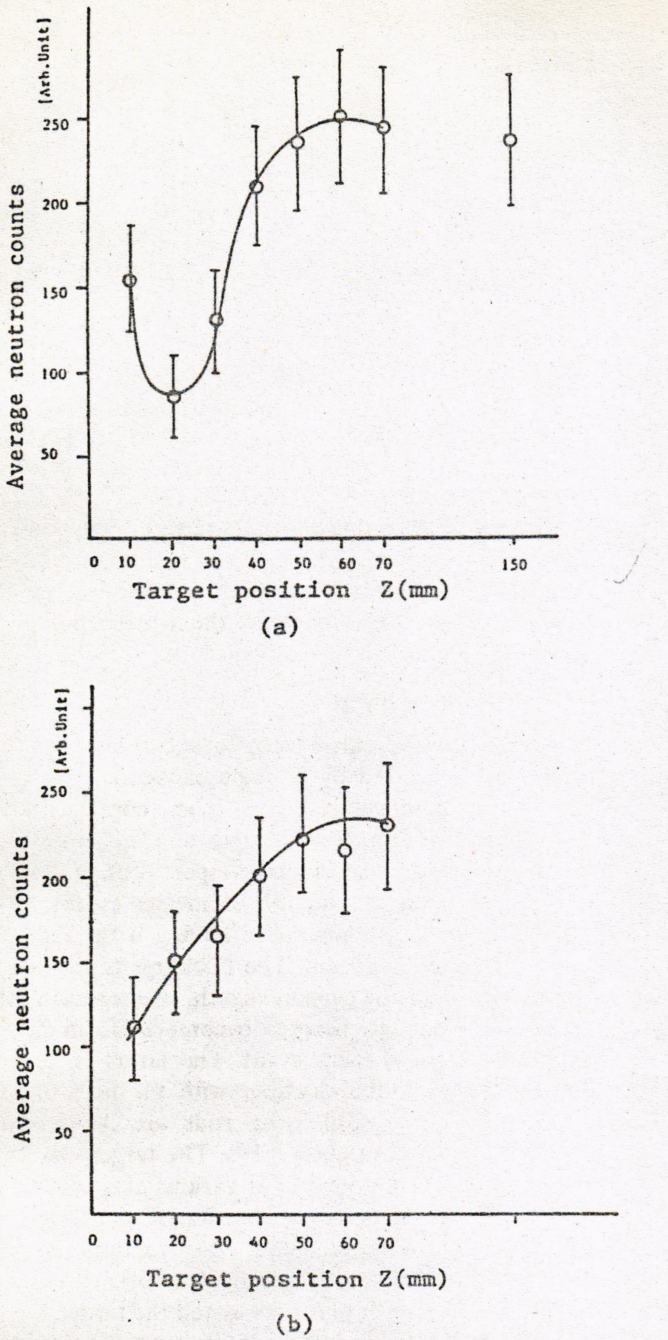

Fig. 3. Average neutron yield as a function of target distance from the tip of the anode, (a) without hole and (b) with a hole in the center of the target

for displaying and subsequently recording the signal. The average neutron yield from the plasma focus is measured by an indium foil activation detector. The neutron pulse was recorded by using the Integral Detector Assembly of NE Technology Limited [5] whose signal is monitored on the second channel of the oscillosope.

3. Results and discussion

Figure 3 exhibits the average neutron yield as a function of the target distance from the tip of the anode. It can be clearly seen that the neutron yield is independent on target distance beyond 5 cm. However, placing the target closer to the anode surface decreases the average number of neutron counts and a minimum is obtained at a distance of about 2 cm, which is in agreement with the results obtained by Moo *et al.* [3]. The reduction in the neutron yield, when

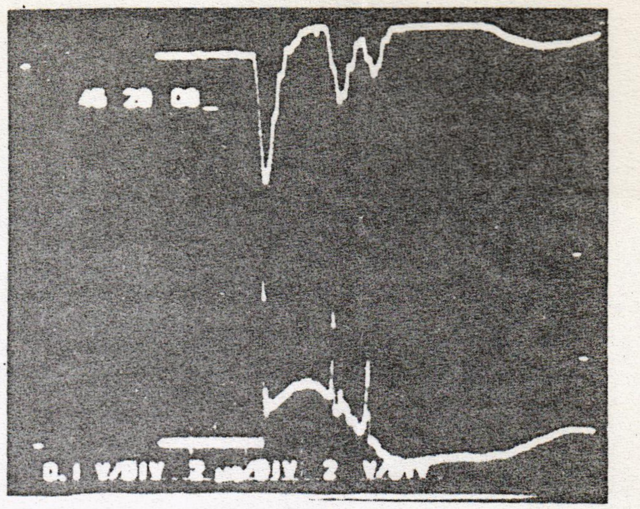

Fig. 4. A typical oscillogram of the voltage probe signal and the neutron pulse. The distance of the target from the tip of the anode is 1.0 cm, and the D2 pressure is 2.5 mb. The baseline time is 2 µs per division. The top signal is the neutron pulse and the bottom one shows the voltage probe signal

compared with the situation when no target is used, is due to the interference of the target with the deutron beam accelerated downstream outside the focus region. This is confirmed by replacing the target with a copper disc of the same size having a 2 mm hole at its center. Figure 3(b) shows the average neutron yield as a function of target distance (target with a hole at its center). The average neutron yield has increased significantly even for a distance of 2 cm. In this case the neutron beam generated in the focusing column due to the $m = 0$ instability passes through the hole and then, due to the target mechanism, appreciable neutrons are produced.

Interestingly it is observed that by bringing the target even closer to the anode, at a distance of about 1–1.2 cm, the average neutron yield increases abruptly. Moreover a second spike is also observed in the voltage signal and in the neutron pulse as can be seen in the oscillogram shown in Fig. 4. This second spike is a clear indication of a second focus after the target. The second focus is at about 1 µs interval from the first focus shown by the second spike in the two signals. The second spike is relatively low, implying a weak second focus. However, it proves that such a device can possibly be used as a cascading focus device to produce bursts of neutrons and soft X-ray. It is necessary to adjust the discharge parameters to provide sufficiently long sustaining current and to power the second focus adequately. The distance between the two foci can be changed by altering the gas pressure, charging voltage, target thickness and possibly the target diameter.

4. Conclusion

The analysis of the voltage of the signal and the neutron pulse provides a clear indication of the sequential focusing in our device. Such a device can be used as a cascading focusing device.

Acknowledgements

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Influence of insulator contamination by copper evaporation on neutron yield in a low-energy plasma focus

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Abstract. Deterioration of neutron yield in a low-energy plasma focus operated by a single 32 μF, 15 V, (3.6 kJ) capacitor is observed. When the cumulative discharge energy over successive shots across an insulator sleeve approaches 1.6 MJ, the neutron yield from the device starts deteriorating. The insulator sleeve, when examined, is found to have a ~3 μm thick layer of copper desposit. The contaminated sleeve surface appears rough with a grain-type structure. It is therefore concluded that the degradation of neutron yield in our low-energy device occurs due to Cu deposit on the insulator sleeve surface. The situation may improve if low-sputtering-rate conductors are employed for the electrodes of the device.

1. Introduction

In large plasma focus facilities, the neutron yield has been reported to saturate or even decrease with an increase in discharge energy (Herold *et al* 1989). This may prove a detrimental constraint, reducing the scope of plasma focus in the context of fusion programmes. Preliminary results on POSEIDON suggest that the impurity content in the plasma depends, among other factors, on the insulator sleeve material and can have a major impact on the final plasma ionization and compression efficiency leading to eventual reduction in neutron yield (Herold *et al* 1988). When the POSEIDON team replaced the glass insulator by a ceramic insulator, the situation seemed considerably improved since only partial saturation of the neutron yield was observed. Kaeppeler (1990) argued that the saturation was due to the appearance of current chopping instabilities. However, this interesting problem is not yet solved and may have several reasons for its origin. Beg *et al* (1992), investigating the effects of insulator sleeve material on neutron emission, reported that a sleeve with higher dielectric constant ε_r provides neutron yield over a wider range of filling pressure and that the neutron yield increases linearly with the product of pressure and the dielectric constant $p\varepsilon_r$. That suggests that the neutron yield may increase several times if some special insulators of higher dielectric constant are available. In this paper, however, we report the first evidence for neutron yield deterioration in a low-energy plasma focus.

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2. Experimental set-up

Our Mather-type plasma focus is energized by a single 32 μF, 15 kV (3.6 kJ) capacitor. The electrode system consists of a 160 mm long Cu rod of 18 mm diameter as anode, surrounded by six 10 mm thick Cu rods forming the cathode, with inner diameter of 50 mm. The cathode rods are screwed to a Cu plate with a knife edge near the anode. An insulator sleeve of Pyrex glass, 25 mm in length, is placed between the anode and the cathode at this end. The lengths of anode and the insulator sleeve are chosen from the experimental results reported previously (Beg *et al* 1992, Zakaullah *et al* 1989). A 13 mm thick rubber disc with a hole at its centre is used to support the cylindrical glass sleeve, so that it could be positioned without touching the anode or the cathode. The electrode system is enclosed in a cylindrical vacuum chamber of ~18 l volume, which may be evacuated up to 5×10^{-5} mbar. A swinging cascade-type air gap made of 1/2 inch (approx 13 mm) thick Cu plate is used as a switch. The external inductance of the system including the capacitor, conducting plates, switch, connecting cables and the cathode and the anode headers is measured to be 80 nH. The neutron detectors consist of Geiger–Muller tubes along with indium foils of thickness 0.1 mm immersed in paraffin wax cylinders with available moderating length of 80 mm. The neutron detectors were calibrated against an Am–Be standard neutron source. To analyse the plasma optical radiations from the focus region, 1 m Czerny–Turner-type monochromator is used. A photomultiplier tube coupled to the monochromator detects the optical signals. The output of the photomultiplier tube is recorded by a digital storage oscilloscope placed in a screened room. The status of the focus is observed with the help of a resistor divider connected to the cathode and anode headers.

3. Results and discussion

We operated the 32 μF capacitor at 12 kV charging with a discharge energy of 2.3 kJ per shot. After the glass sleeve had sustained some 700 shots, that is, the total discharged energy across the glass sleeve surpassed 1.6 MJ, the neutron yield of the device started to decline. Figure 1 describes the neutron yield versus the shots across the insulator sleeve, when the neutron yield from the device started to exhibit deterioration. To record these data, the system was operated with optimum deuterium filling pressure of 3.2 mbar. As the neutron yield deteriorated, the amplitude of the resistor divider signal went down. On examining the contaminated glass sleeve insulator it was found that the surface was coated with ~3 μm thick Cu film. The sleeve surface also exhibited change in its resistance. While the resistance of the new sleeve was almost infinity, the resistance of the contaminated sleeve was measured to be ~30 GΩ. When we repeated the experiment using a new insulator glass sleeve, the neutron yield became normal again, that is, about 1.5×10^8 neutrons per shot.

To investigate how the impurity content in the focus plasma varies with the contamination of the glass sleeve, we analysed the optical plasma radiations for both the contaminated glass sleeve and an uncontaminated one. A 1 m monochromator with a 1200 lines/mm grating was employed to this end. The Pyrex glass is an alloy with different concentrations of silicon oxide, sodium oxide, potassium oxide, calcium oxide, aluminium oxide and boron oxide (see, for example, *Van Nostrand's*

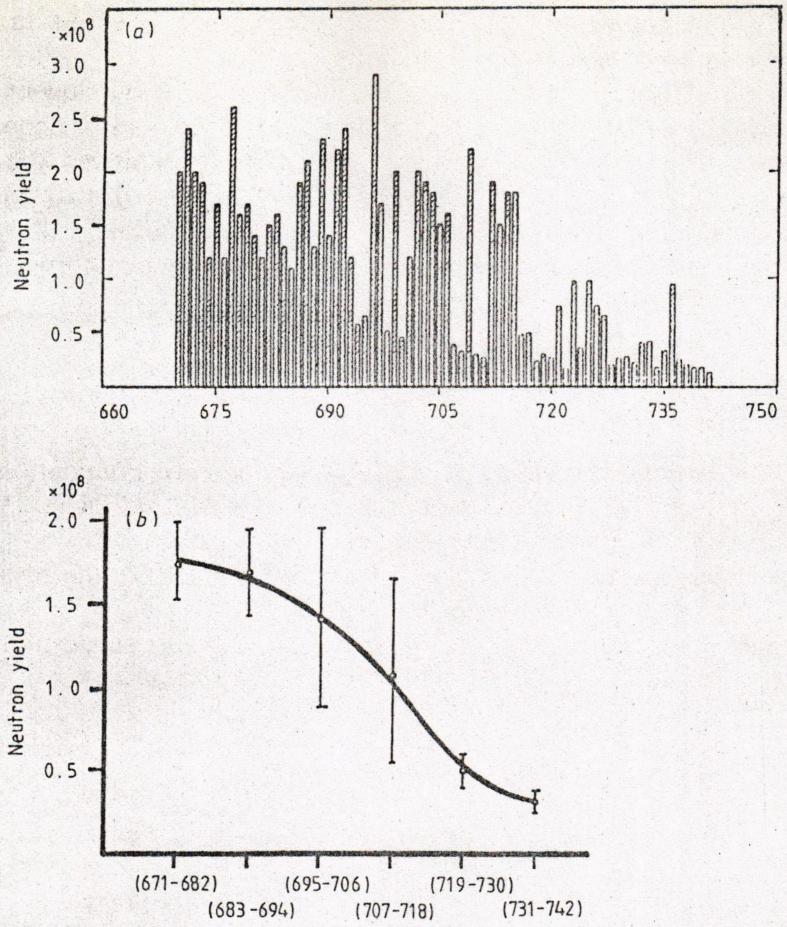

Figure 1. Neutron yield versus shot number across a sleeve, when the device started to exhibit deterioration. (*a*) Shot-to-shot variation; (*b*) average of 12 consecutive shots.

Scientific Encyclopedia 1968). We detected the B II (412.19 nm), B IV (468.16 nm), K IX (416.96 nm) and K IX (590.95 nm) lines to assess the plasma impurity content introduced by the insulator sleeve. For each line, 20 shots were recorded, 10 for the contaminated insulator sleeve and 10 for the uncontaminated one. We conclude that the plasma impurity content is relatively higher for the sleeve with less copper deposit.

Decker *et al* (1982), in an attempt to explain the polarity riddle of the plasma focus, noted that the radial electric field at the sleeve surface is of paramount inportance for prompt breakdown and plasma sheath formation. When the radial electric field was shielded by using a Cu foil, they observed a reduction of neutron yield for a positive anode and enhancement of neutron yield for a negative anode. The reduced neutron yield with shielded radial electric field for a positive anode was explained as being due to a bad breakdown environment. In our case, although we are observing deterioration of neutron yield due to surface contamination of the insulator by Cu evaporated from electrodes, the breakdown conditions as recorded by a high-voltage probe are rather improved. The breakdown delay is 20–30% lower in the case of a contaminated insulator sleeve, as compared to an uncontaminated one. Perhaps, the large Cu deposition increases the current partition which in turn reduces the available current during the pinch phase leading to a decrease in neutron yield. Further work using magnetic probes is in progress in this regard, which will be reported in a future publication.

In conclusion, neutron yield deterioration is observed in our low-energy plasma focus. It is found that the Cu evaporated from the electrodes is deposited on the sleeve surface. The contaminated sleeve, although it improves the breakdown conditions, deteriorates the neutron yield. It is speculated that neutron yield degradation arises due to increased current partition. Perhaps the use of low-sputtering-rate conductors for the electrodes of the device may improve the situation considerably.

Acknowledgments

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A SIMPLE PRESSURIZED SPARKGAP FOR PLASMA FOCUS OPERATION

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A simple, low-inductance, cost-effective pressurized sparkgap is developed for a low-energy plasma focus operation energised by a single 32 μF, 15 kV (3.6 kJ) capacitor. This sparkgap is capable of handling discharge current up to 200 kA with a rise time of less than one μsec. The system works reliably and is reproducible for capacitor charging of 10–13 kV.

The plasma focus device has received a considerable attention in the teaching of plasma dynamics and in the context of nuclear fusion.[1] It has proved a useful source for a variety of phenomena like $J \times B$ acceleration, pinch formation, and neutron and X-ray generation in hot plasmas. In recent years, a training programme on plasma and laser technology was organised under the auspices of the United Nations University and the International Centre for Theoretical Physics with a view to develop a simple and cost-effective plasma focus system powered by a single 30 μF, 15 kV (3.3 kJ) Maxwell capacitor and switched on by a simple parallel-plate swinging cascade type air gap. Low-cost features of the device made it popular in most of Asian and African countries. This simple machine has been used to study the effects of different parameters[2–5] on neutron yield.

In this letter, we report the fabrication of a pressurized sparkgap that replaces the parallel-plate air gap which generates huge acoustic noise, without increasing the system inductance.

As described in Fig. 1, the plasma focus electrode system consists of a 160 mm long Cu rod of 18 mm diameter as anode, surrounded by six 10 mm thick Cu rods forming the cathode, with internal diameter of 50 mm. The cathode rods were screwed to a Cu plate with a knife edge near the anode. An insulator sleeve of pyrex glass was placed between the anode and the cathode at this end. A 13 mm thick rubber disc with a hole at its center is used to support the cylindrical glass sleeve, so that it could be positioned without touching the anode or the cathode.

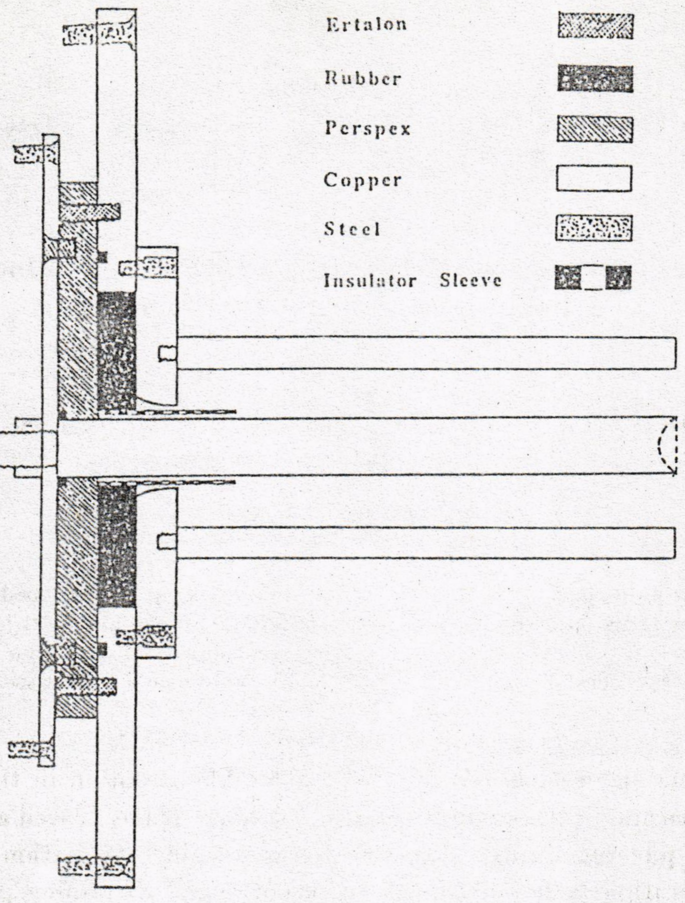


Fig. 1. Plasma focus electrodes arrangement.

The electrode system is enclosed in a vacuum chamber which may be evacuated up to 10^{-5} mbar within a period of one hour.

A schematic drawing of the pressurized sparkgap is given in Fig. 2. The sparkgap body is machined from a nylon rod of 100 mm diameter and the electrodes are developed from a 50 mm diameter copper rod. A motor bike spark plug with slight modification is used as a trigger pin. Six brass bolts tightened coaxially outside the sparkgap body provide a low-inductance path to the current. The TV flyback transformer is used to step up a −2 kV trigger pulse generated from a Krytron KN-6B, which triggers the sparkgap. A schematic diagram of the trigger arrangement is given in Fig. 3.

Figure 4 shows the discharge current characteristics as recorded by a Rogowski coil. A simple formula

$$I_0 = \frac{\pi C_0 V_0 (1+f)}{T}$$

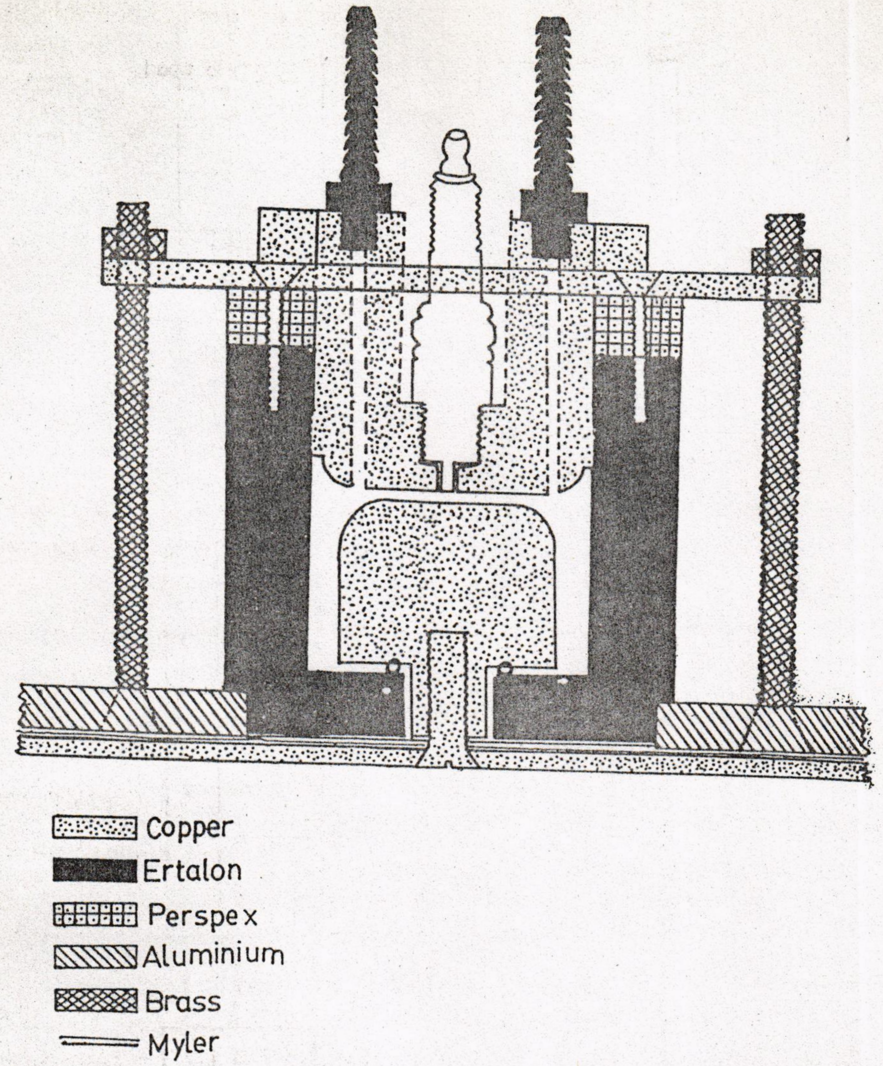


Fig. 2. A schematic diagram of pressurized sparkgap.

estimates discharge peak current of ~ 200 kA for 12 kV capacitor charging. The system works reliably and reproducibly for argon, hydrogen, and deuterium foci. Figure 5 contains a high-voltage probe signal indicating focussing action, along with neutron emission profile, detected by a photomultiplier tube + NE 102 plastic scintillator assembly. Figure 6 shows another signal of the same probe along with an ion beam detected by means of a simple Faraday cup. These figures correspond to different shots because of our being able to record only two signals at a time. Ion beam signal synchronizes with the high-voltage probe signal, while the neutron pulse appears a bit later.

To conclude, a simple, low-inductance, and cost-effective pressurized sparkgap has been developed and successfully employed in a low-energy plasma focus

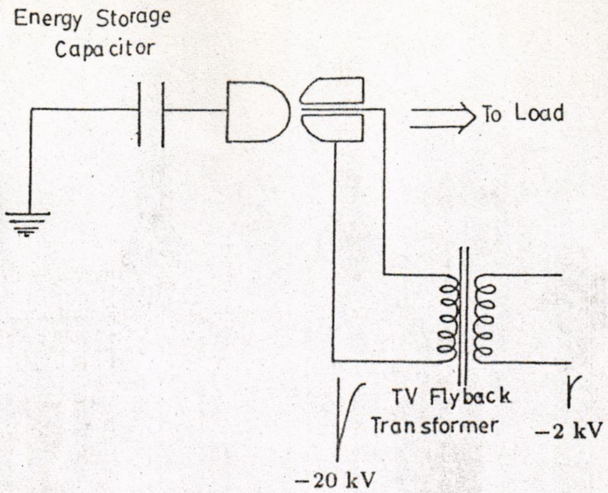
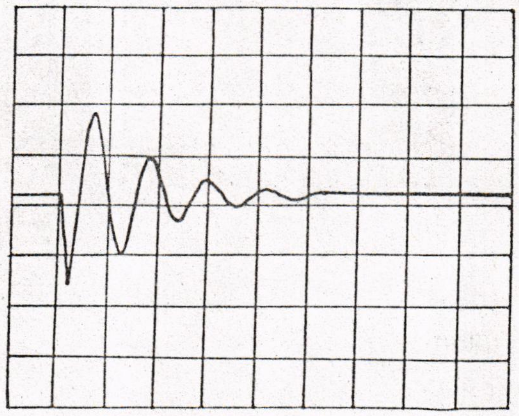
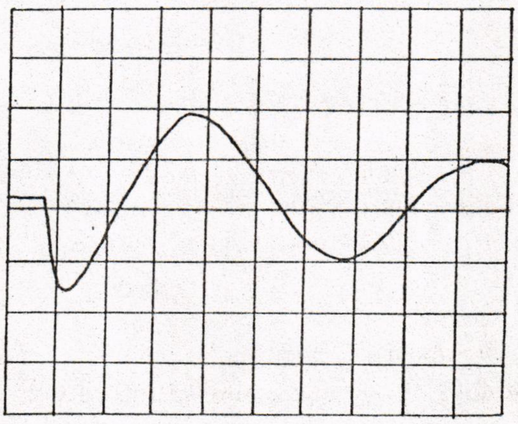


Fig. 3. Sparkgap trigger arrangement.



(a)



(b)

Fig. 4. Rogowski coil signal to record the discharge current: (a) 0.5 V/div; 10 μsec/div and (b) 0.5 V/div; 2 μsec/div (same signal with expanded time).

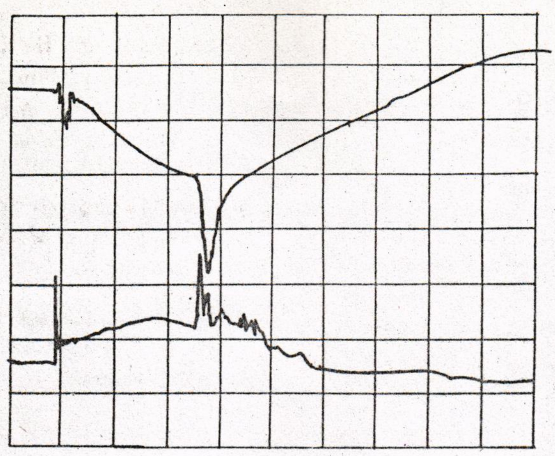


Fig. 5. High-voltage probe signal (lower) 2 V/div, along with corresponding neutron emission profile (upper) 50 mV/div, time base 1 μsec/div.

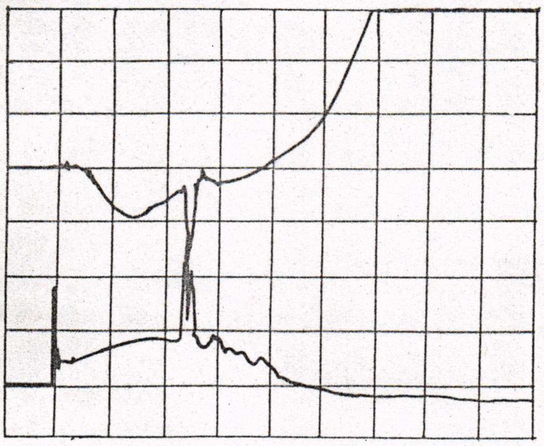


Fig. 6. High-voltage probe signal (lower) 2 V/div along with corresponding ion beam emission profile (upper) 1 V/div, time base 1 μsec/div.

operation energised by a single 32 μF, 15 kV capacitor. The sparkgap is capable of handling $\sim$ 200 kA current with a rise time of less than one μsec. The system has proved reliable and reproducible for focussing in argon, hydrogen, and deuterium plasmas.

Acknowledgements

This work was partially supported by The Pakistan Science Foundation Projects No. C-QU/Phys(69) and (70), NSRDB Project No. P-16, ICAC–QAU Project, UGC and PAEC Projects in Plasma Physics, and TWAS grants (RG MP 90-059, MP 90-072, and MP 91-018).

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CHARACTERISTICS OF A PLASMA FOCUS WITH CONTAMINATED INSULATOR SLEEVE

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The characteristics of a low energy (2.3 KJ) plasma focus of Cu electrodes is investigated. It is found that some minimum level of contamination is required for the generation of a well-behaved current sheath leading to good focussing action. When the contamination grows further, initially multiple foci are formed and then the system becomes less reproducible with pronounced shot-to-shot variations in neutron yield. Ultimately, the neutron yield deteriorates by an order of magnitude. The situation may however improve if low-sputtering-rate conductors are employed for the electrodes of the device.

In large plasma focus devices, the neutron yield is reported to saturate or even decrease with increase in discharge energy [1]. This may prove a detrimental constraint reducing the scope of Plasma Focus in the context of fusion programme. In fact, in the operation and optimization of a plasma focus, different parameters are involved, such as the geometry and structure of the inner and outer electrodes, the material and configuration of the insulator and the initial pressure. The parameters are interrelated in an intricate way and no general relationship has been found so far. We in this presentation report the performance of a low energy plasma focus vis-a-vis insulator sleeve contamination.

Our Mather-type plasma focus [2] is energized by a single 32 μF, 15 KV capacitor. Geiger-Muller tubes alongwith indium foils are employed to estimate the total neutron yield. A simple resistor divider with a response time of ~15 nsec is used to monitor the focusing of the plasma. A PMT+ NE 102 scintillator assembly records the time resolved neutron emission. Time-resolved X-ray emission is monitored by a pin-diode PBX-65 with slight modification. The safety glass cover of the diode was removed, and 9 μm thick aluminium foil was used to screen the visible light. A simple Faraday cup detects the ion beam generated during the focus phase. The results are summarized as under :

When a new insulator glass sleeve is installed, the breakdown is delayed 100-150 nsec compared to the normal time of 30-40 nsec and no focus is formed. During the next few shots however this delay lowers successively and the high voltage probe indicates improvement in focusing action. By now, a Cu thin film starts appearing on the insulator sleeve surface. These observations indicate that some minimum coating of a conducting material on the insulator sleeve surface is essential for prompt breakdown and current sheath formation.

We operated the device with a discharge energy of 2.3 KJ per shot. When a new glass sleeve is installed, a single focusing spike is observed in some shots while in others multiple focusing spikes are seen. After the glass sleeve had sustained some 100 shots, multiple focusing spikes appear in almost every shot. When the cumulative discharge energy across an insulator sleeve exceeds ~1MJ, the system becomes less reproducible and shot-to-shot variations in neutron yield become pronounced. After about 700 shots, that is when the total discharge energy across the glass sleeve surpassed 1.6 MJ, the neutron yield started to decline [3] Figure 1 describes the neutron yield from the device, when it started to exhibit deterioration. On examining the contaminated glass sleeve, it was found that the surface was coated with ~3 μm thick Cu film.

When the high voltage probe records multiple foci formation, X-ray, neutron and ion beam signals also exhibit multiple pulses. Neutron pulses almost coincide with the HV probe signal, however, the ion beam pulses occur a bit later. Every good focusing peak is

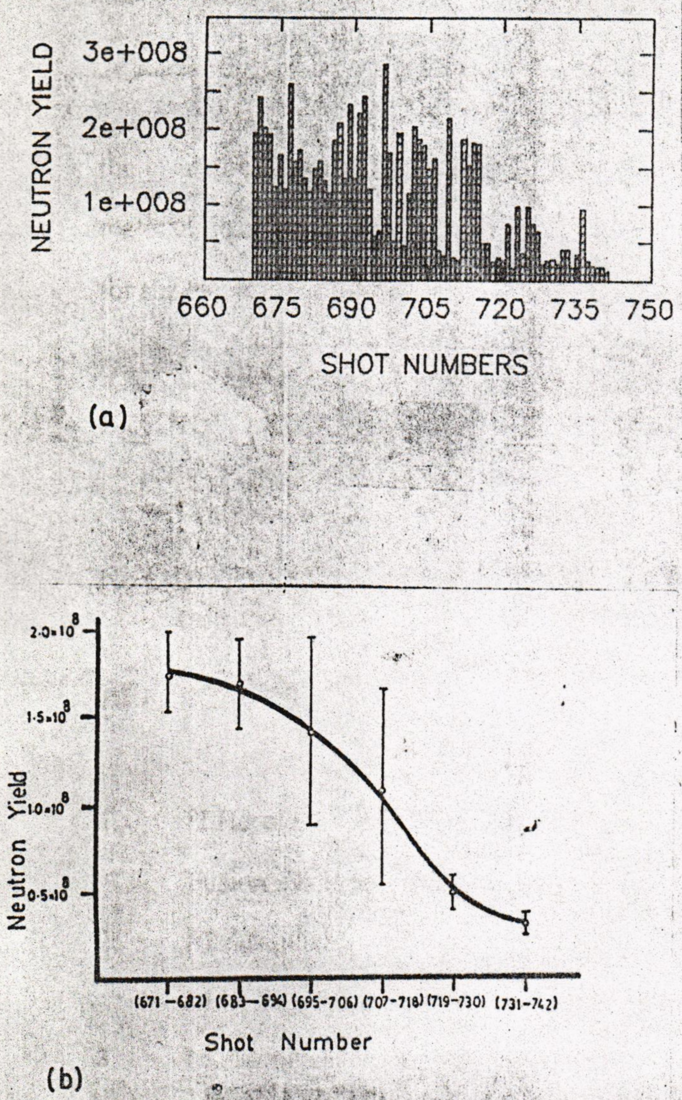

Figure 1: Neutron yield versus shot number across an insulator sleeve when the device started exhibit deterioration.
(a) Shot-to-shot variation.
(b) Average of 12 consecutive shorts

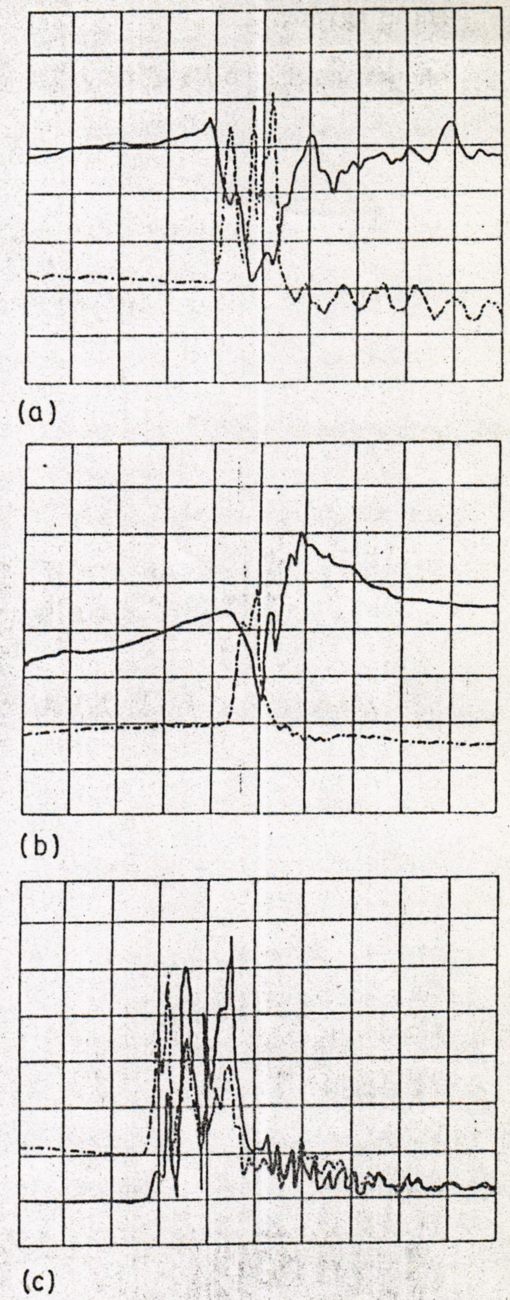

Figure 2: Multiple foci formation with time base 200 nsec./div; HV probe signal (dotted): 2V/div, (a) neutron pulse: 100 mV/div, (b) ion beam: 0.5 V/div, (c) X-rays: 2V/div

accompanied by X-ray and neutron pulses. The number of focusing peaks goes an increasing with the insulator sleeve contamination. Figure 2 depicts high voltage probe signals alongwith neutron pulse, ion beam pulse and X-ray pulse. These signals correspond to different shots because of our being able to record only two signals at a time.

To conclude, we have studied the performance of a low energy plasma focus with the insulator sleeve contamination. It is found that the Cu evaporated from the electrode-material deteriorates the neutron yield. Perhaps, the use of low sputtering-rate conductors for the electrodes of the device may arrest the deterioration considerably.

ACKNOWLEDGEMENTS :

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Technical note

Effect of insulator sleeve contamination on the low energy plasma focus performance

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The characteristics of a low energy plasma focus of copper electrodes operated by a single 32 μF, 15 kV (3.6 kJ) capacitor with an insulator sleeve contamination are studied. When the plasma focus is operated, the insulator sleeve is contaminated due to the deposition of copper evaporated from the electrodes. A slight contamination improves the system performance. When the cumulative discharge energy over successive shots across the insulator sleeve exceeds ~ 1 MJ, the copper deposition on the sleeve surface makes it rough with a grain-type structure, with as result that the system becomes less reproducible and shot-to-shot variations in neutron yield are pronounced. In addition, a high voltage probe records multiple foci formation, giving rise to multiple neutron pulses, multiple X-ray pulses as well as multiple ion beams. When the cumulative discharge energy approaches 1.6 MJ, the neutron yield starts deteriorating, and the resistor divider signal begins to indicate less compression. It is suggested that the neutron yield degradation occurs due to copper coating with grain structure on the sleeve surface, which decreases the resistance of the sleeve surface and may therefore increase the current partition and eventually lower the snowplow efficiency. The situation may improve if low-sputtering-rate conductors are employed for the electrodes of the device or the truncated end of the anode is lined with low sputtering rate material like molybdenum.

1. Introduction

The plasma focus is a simple functional device with high neutron and X-ray yields. It is speculated that if the neutron scaling $N \sim E^2$, $N \sim I^4$ holds upto bank energies of 30–50 MJ, the plasma focus will be of interest also from the standpoint of fusion power plants [1]. However, some difficulties remain with the operation of the plasma focus device. For example, the shot-to-shot reproducibility of the plasma focus devices has been observed to be poor. Even in machines which are regarded as highly reproducible, a shot-to-shot variation in neutron yield by a factor of two is common. Also the neutron yield has been reported to saturate or even decrease with the increase in discharge energy on large plasma focus facilities [2]. This may prove a detrimental constraint reducing the scope of the Plasma Focus in the context of a fusion programme. Results of POSEIDON, the biggest plasma focus in operation with a discharge energy upto 500 kJ, suggest that the impurity content in the plasma depends, among other factors, on the insulator sleeve material and can have a major impact on the final plasma ionization and compression efficiency leading to an eventual reduction in neutron yield [3]. When the POSEIDON team replaced the glass insulator by a ceramic insulator, the situation seemed considerably improved since only partial saturation of the neutron yield was observed.

To examine the scope of the plasma focus in the fusion programme as well as its other applications, it seems essential that different machine parameters be investigated systematically and in a comprehensive manner. As Herold et al. [2] state, in the optimization of plasma focus facilities, different parameters are involved, such as the geometry and structure of the inner and outer electrodes, the dimensions of these electrodes, the material and configuration of the insulator, and the initial pressure. These parameters are interrelated in an intricate way and no general relations have been found so far. Zakaullah et al. [4] were the first to investigate the effects of the insulator sleeve length. They emphasized that the length of the insulator sleeve plays an important role in the formation of azimuthally symmetric current sheath and also found that an optimum choice of the sleeve length gives a uniform current sheath and any departure from that value causes spokes on the sleeve surface. A detailed study to establish useful scaling laws is still uncomplete. Beg et al. [5] using different materials for the insulator sleeve, investigated their effects on neutron emission. They determined that an insulator sleeve with a higher dielectric constant ϵ_r provides a neutron yield over a wider range of filling pressure and that the neutron yield increases linearly with $p \times \epsilon_r$. Thus if some special insulators of higher dielectric constant are available, the neutron yield may increase several times. Zakaullah et al. [6] reported the neutron yield deterioration in a low energy plasma focus as well. The contamination of the insulator sleeve due to copper evaporated from the electrodes was found to cause the phenomenon.

In this paper, we report a detailed study of the performance of the machine vis-a-vis insulator sleeve contamination. We observe that the insulator sleeve is contaminated continuously with the system operation. Some contamination is essential for good focus formation. However, continuous deposition of electrode material on the sleeve surface deteriorates the neutron yield and consequently affects the system's reproducibility. In Section 2 the experimental arrangement and diagnostic equipment are described. Section 3 presents the results while Section 4 presents the conclusions.

2. Experiment and diagnostics

Our Mather-type plasma focus is energised by a single 32 μF, 15 kV (3.6 kJ) capacitor. The electrode system as described in Fig. 1, consists of a 160 mm long Cu rod of 18 mm diameter as anode, surrounded by six 10 mm thick Cu rods forming the cathode. The cathode rods are screwed to a Cu plate with a knife edge near the anode. An insulator sleeve of pyrex glass, 25 mm in length from the cathode base plate, is placed between the anode and the cathode at this end. The lengths of anode and the insulator sleeve are chosen from the experimental results reported previously [4,5,7]. A 13 mm thick rubber disc with a hole at its centre is used to support the cylindrical glass sleeve, so that it could be positioned without touching the anode or the cathode. The electrode system is enclosed in a vacuum chamber which may be evacuated upto 5×10^{-5} mbar. A swinging cascade type airgap made of

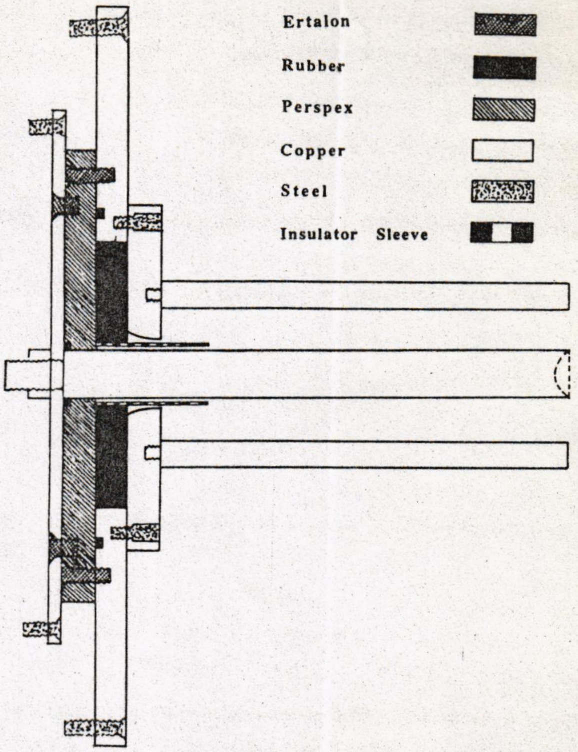


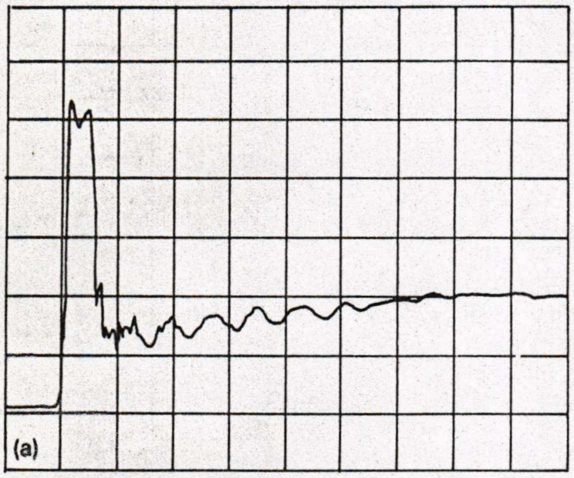
Fig. 1. The arrangement of plasma focus electrodes.

1/2 inch thick Cu plate is used as switch. The external inductance of the system including the capacitor, conducting plates, switch, connecting cables and the cathode and the anode headers is measured to be 80 nH.

The neutron yield is measured with detectors consisting of Geiger-Müller tubes alongwith indium foils of thickness 0.1 mm immersed in paraffin wax cylinders with an available moderating length of 80 mm. The neutron detectors were calibrated against an Am–Be standard neutron source. For time-resolved neutron measurements, a Thorn EMI photomultiplier tube 9956 optically coupled with 2 in. $\times$ 2 in. cylindrical plastic scintillator NE 102 is used. To record the current behaviour, a Rogowski coil along with an integrator is employed. A resistor divider with a response time of $\sim$ 15 ns is connected across the anode and the cathode headers, which monitors the voltage of the system during breakdown and radial collapse phases. The time-resolved X-ray emission is monitored by a pin-diode PBX-65 with slight modifications. The safety glass cover of the diode was removed, and a 9 μm thick aluminum foil was used to screen the visible light. A simple Faraday cup placed at a distance of 17 cm from the anode tip was employed to detect the ion beam generated during the focus phase.

3. Results

When the system is evacuated upto 5×10^{-5} mbar, 3.2 mbar D_2 pressure appears to be optimum for neutron yield. However, if the deuterium is filled by evacuating upto 10^{-2} mbar with a rotary pump, the optimum pressure shifts to a lower value of 2.5 mbar. Interestingly, no appreciable change in neutron yield is observed with the quality of vacuum. When a new insulator glass sleeve is installed, the breakdown is



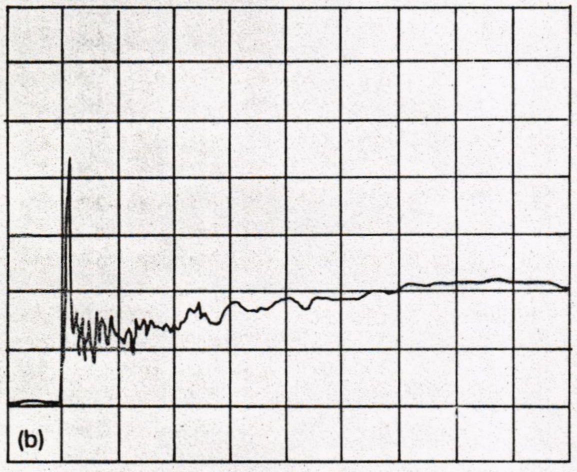
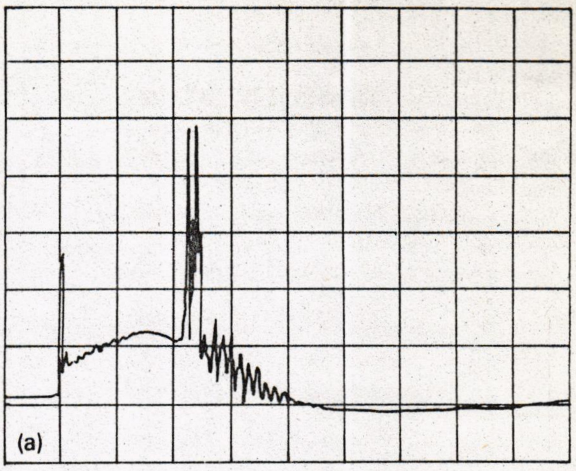


Fig. 2. High voltage probe signals 1 V/div; 200 ns/div; (a) uncontaminated new glass sleeve; no focus, (b) slightly contaminated glass sleeve, good focus.



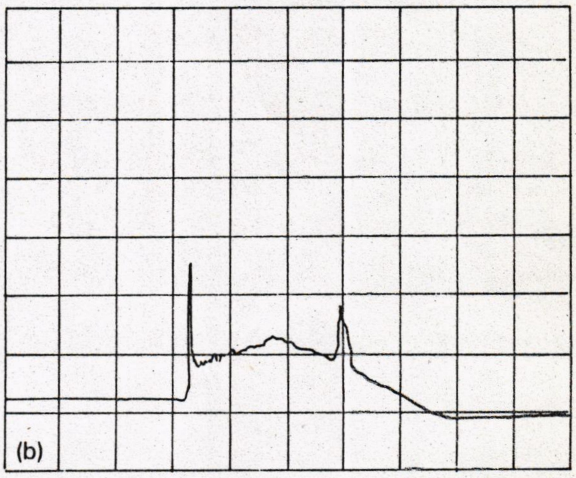


Fig. 3. (a) Good shot – higher axial velocity; 2 V/div, 1 μs/div; (b) bad shot – lower axial velocity: 2 V/div, 1 μs/div.

delayed 100–150 ns compared to the normal time of 30–40 ns and no focus is formed. During the next few shots, however, this delay lowers successively, and the high voltage probe indicates improvement in focussing action. By now, a Cu thin film starts appearing on the insulator sleeve surface. In Fig. 2, the signal of high voltage probe for an uncontaminated glass sleeve as well as for a relatively contaminated one are given. These observations indicate that some minimum coating of conducting material on the insulator sleeve surface is essential for prompt breakdown and current sheath formation, since the copper deposition on the sleeve surface will reduce its resistance as compared to the almost infinitly large resistance of the uncontaminated sleeve. The lower resistance of the sleeve surface in turn will help the breakdown and current sheath formation.

It is a common observation in plasma focus devices that some shots appear bad giving low neutron yield (see for example Herold et al. [2]). On our device we noticed that when the system is kept open for some time or has not been used for some days, few initial shots appear as bad shots. Besides initial operation, about 10 percent of the shots appear as bad shots. For such shots, the time interval between breakdown and focussing peak in our device is more than 2.5 μs while, in the case of good shots of high neutron yield, this interval reduces to about 2.2 μs. Thus, for good shots, the average current sheath velocity during the axial phase is $\sim 7.2 \times 10^4$ m/s, while for bad shots, the average current sheath velocity is less than 6.4×10^4 m/s. High voltage probe signals for a good shot and a bad shot are given in Fig. 3. We could not distinguish between their breakdown times. One may speculate that during the breakdown and current sheath formation, high-Z impurities somehow appear which increase the mass content in the current sheath and hence lower the velocity during the axial run.

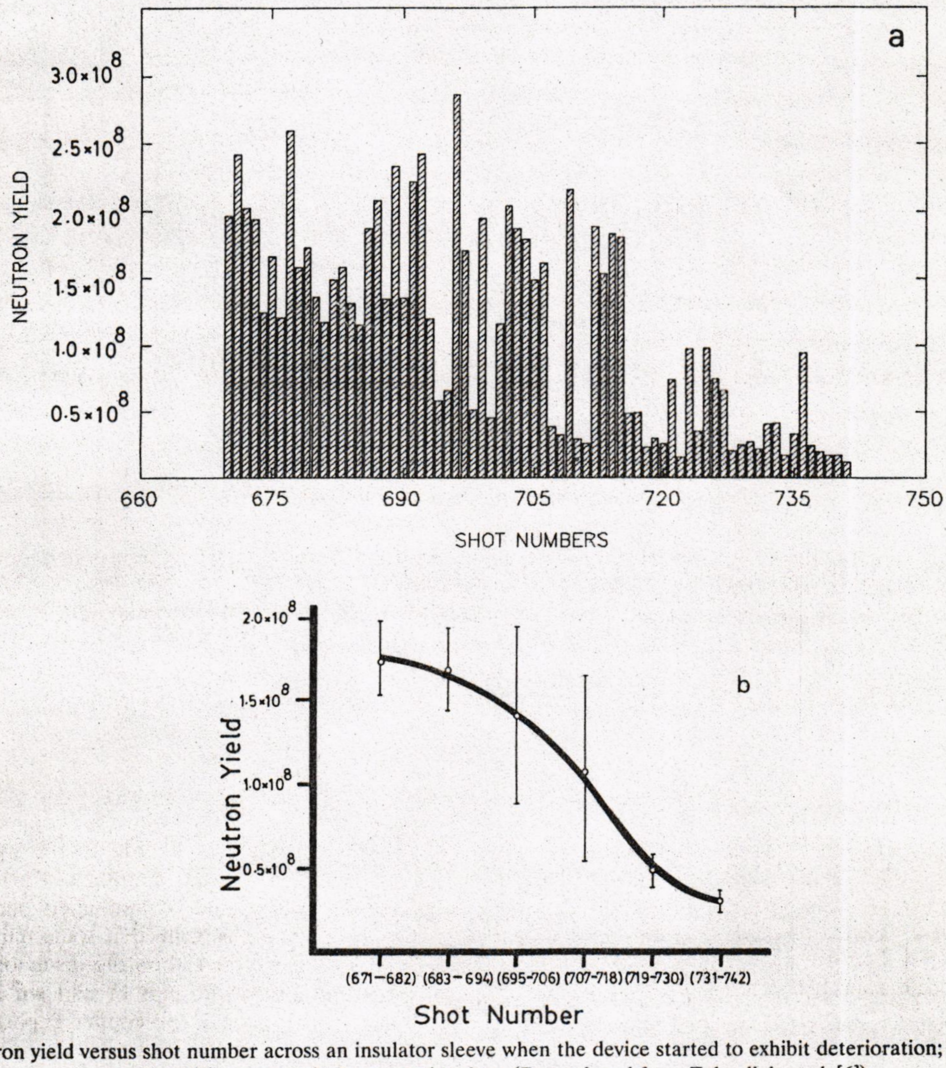


Fig. 4. Neutron yield versus shot number across an insulator sleeve when the device started to exhibit deterioration; (a) shot to shot variation, (b) average of 12 consecutive shots (Reproduced from Zakaullah et al. [6]).

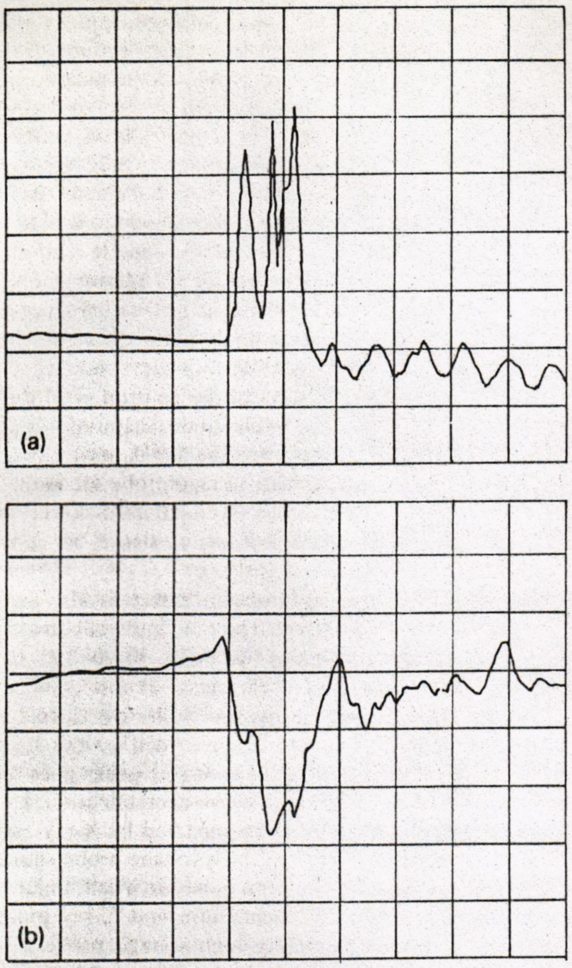


Fig. 5. Multiple foci formation (a) HV probe signal: 2 V/div; 200 ns/div; (b) neutron pulse: 100 mV/div; 200 ns/div.

We operated the 32 μF capacitor at 12 kV charging with a discharge energy of 2.3 kJ per shot. When a new glass sleeve is installed, a single focussing spike is observed in some shots while in others multiple focussing spikes are seen. After the glass sleeve had sustained some 100 shots, multiple focussing spikes appear in almost every shot. When the cumulative discharge energy across an insulator sleeve exceeds ~ 1 MJ, Cu deposition on the sleeve surface makes it rough with grain-type structure. It decreases the resistance of the sleeve surface which in turn may therefore increase the current partition and lowers the snowplow efficiency. The system becomes less reproducible and shot-to-shot variations in neutron yield become pronounced. An interesting observation in our experiment as reported earlier [6], was that after about 700 shots, that is, when the total discharge energy across the glass sleeve surpassed 1.6 MJ, the neutron yield of the device started to decline. Figure 4 describes the neutron yield versus the number of shots across an insulator sleeve, when the neutron yield from the device started to exhibit deterioration. To record this data, the system was operated with optimum deuterium filling pressure. As the neutron yield deteriorated, the amplitude of the resistor divider signal went down. On examining the contaminated glass sleeve insulator, it was found that the surface was coated with ~ 3 μm thick Cu film. The sleeve surface also exhibited change

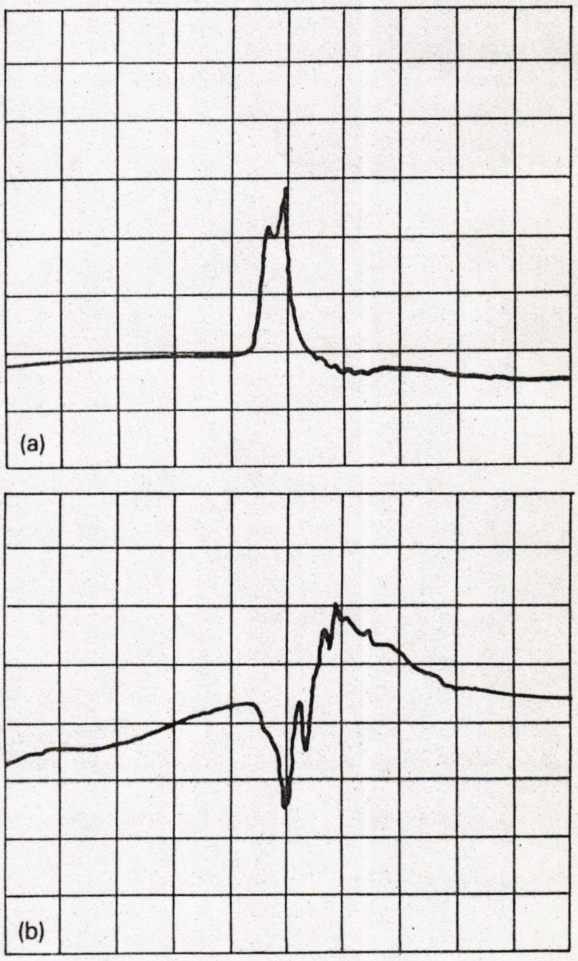


Fig. 6. Multiple foci formation; (a) HV probe signal: 2 V/div; 200 ns/div; (b) ion beam pulse detected by a Faraday cup: 0.5 V/div; 200 ns/div.

in its resistance. While the resistance of the new sleeve was almost infinity, the resistance of the contaminated sleeve was measured to be $\sim 30\ G\Omega$. When we repeated the experiment using a new glass sleeve, the neutron yield became normal again, that is, about 1.5×10^8 neutrons per shot. We cleaned the contaminated insulator sleeve mechanically using acetone and removed the grain structure of Cu deposit on the surface. When this sleeve was used again, the situation drastically improved, although the average neutron yield per shot was still lower by a factor of two as compared to the case with uncontaminated insulator sleeve.

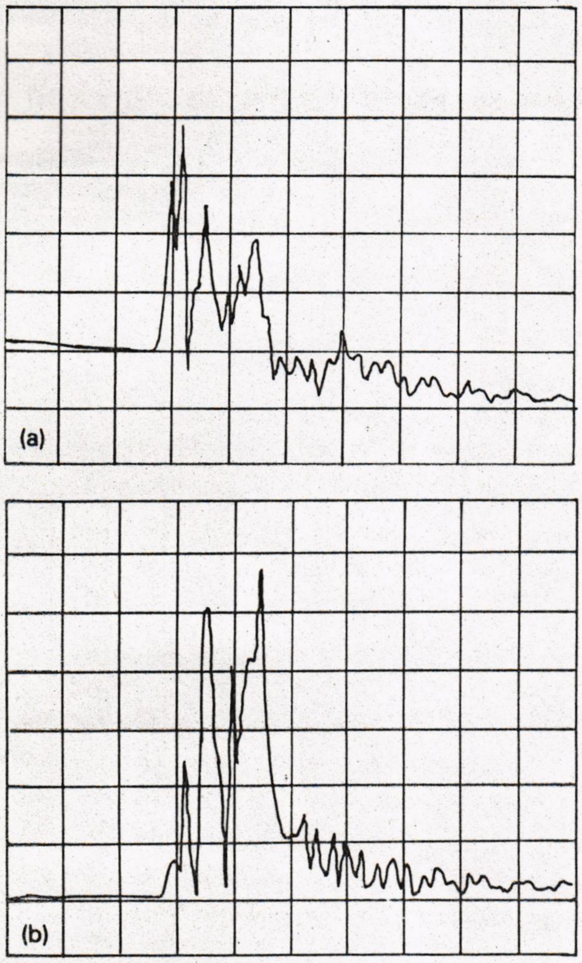


Fig. 7. Multiple foci formation; (a) HV probe signal: 2 V/div; 200 ns/div, (b) X-ray pulse detected by a pin-diode: 2 V/div; 200 ns/div.

Decker et al. [8], in an attempt to explain the polarity riddle of the plasma focus, (i.e., reduction of neutron and X-ray yield by several orders of magnitude when the central electrode is given reverse polarity) noted that the radial electric field at the sleeve surface is of paramount importance for prompt breakdown and plasma sheath formation. When the radial electric field was shielded by using a Cu foil, they observed a reduction of neutron yield for a positive anode and an enhancement of neutron yield for a negative anode. The reduced neutron yield with shielded radial electric field for the positive anode was explained due to the bad breakdown environment. In our case, though, we are observing a deterioration of the neutron yield due to coating of the insulator by electrodes material, which was Cu in our case. However, the breakdown conditions as recorded by the high voltage probe are rather improved. The breakdown delay is 20–30% lower in the case of a contaminated insulator sleeve, as compared to a less contaminated sleeve.

X-rays, neutrons and ion-beam detection also suggest multiple foci formation. The time interval between two consecutive focuses is recorded 30 to 150 ns. Neutron, X-ray and ion beam pulses almost coincide with the pulses recorded by HV probe. In different shots, 2–4 focussing peaks are recorded by the high voltage probe. The number of focussing peaks goes on increasing with the insulator sleeve contamination. Every good focussing peak is accompanied by X-ray and neutron pulses. In Fig. 5, the high voltage probe signal and the corresponding neutron pulse are given. Figures 6 and 7 depict the ion beam pulse and X-ray pulse alongwith the corresponding high voltage probe signals. These signals correspond to different shots because of our being able to record only two signals at a time.

4. Conclusions

The neutron yield in our low energy plasma focus is found to be almost independent of the background vacuum. However the low vacuum shifts the optimum deuterium pressure to the lower side. One may speculate that the condition of lower ambient gas pressure producing the highest neutron yield is due to the introduction of high-Z impurities, which lower the current sheath velocity during the axial run phase. However, one needs to check in detail, to what extent the impurities lower the ambient gas pressure, and what impurity level deteriorates the neutron yield.

As the insulator sleeve of our device contaminates heavily, breakdown conditions are found to improve though neutron yield deteriorates. The latter may be explained if the current partition is found to increase which in turn will reduce the available current during the pinch phase leading to decrease in neutron yield. Further work is in progress in this regard.

With the contamination, the number of current sheaths which develop across the insulator sleeve, goes on increasing. This phenomenon gives rise to multiple foci formation which is confirmed by high voltage probe, X-rays pin-diode detectors, time-resolved neutron detectors as well as ion-beam-pulses detected by a Faraday-cup.

To conclude, we have studied the performance of a low energy plasma focus with the insulator sleeve contamination. It is found that the Cu evaporated from the electrode-material and deposited on the sleeve surface improves the breakdown conditions. A small level of sleeve contamination by copper is found to be essential for good focussing action and high neutron yield. However, as the contamination is surpassed to some critical level, the neutron emission from the device is deteriorated. Perhaps, the use of low-sputtering-rate conductors for the electrodes of the device or lining the truncated end of the anode with low sputting rate material like molybdenum may arrest the deterioration of the neutron yield considerably.

Acknowledgements

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PHYSICS LETTERS A

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Pressure range broadening for a plasma focus operation

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Abstract

The effects of insulator sleeve length and anode length variation on the pressure range of neutron emission in a low energy plasma focus are investigated. It is found that the proper choice of the two parameters broadens the pressure range of the high neutron yield and hence improves the shot to shot reproducibility of the system. The experiment also demonstrates that the bulk of the neutrons are emitted from a region within 2 cm above the anode top and that, in turn, reflects on the nature of the dominant production mechanism.

A plasma focus is a device with the fame of being an intense pulsed neutron source. In material research for nuclear fusion reactors, a source of very large fluence, 10^{20} n/cm^2, is required, for which an obvious candidate is the plasma focus [1]. As Filippov [2] pointed out, there has so far been no systematic study of the simple question of how to determine the optimum length of the insulator at which a symmetric current sheath forms in the initial state of the discharge. It has also been noted that discharges at high initial pressure (near atmospheric) will be required to develop a fusion reactor based on plasma focus. Herold et al. [3] emphasized the role of various parameters, such as the geometry and structure of the inner and outer electrodes, the dimensions of these electrodes, the material and configuration of the insulator and the initial pressure, in the optimization of plasma focus facilities. These parameters are interrelated in an intricate way and no general relationship has been found so far.

An attempt in this direction was made by Zakaullah et al. [4] who noticed that there exists an optimum choice of the sleeve length which gives an azimuthally symmetric current sheath and that any departure from this choice causes spokes on the sleeve surface. Beg et al. [5], using a variety of different materials for insulator sleeve, observed the neutron emission and found that a sleeve material with higher dielectric constant ε_r provides the neutron yield over a wider range of filling pressure and that the yield increases linearly with $p\varepsilon_r$. Thus, if some special insulators of higher dielectric constant are available, the neutron yield may increase several times. A further investigation was done by Beg et al. [6] who studied the behaviour of the system with the change in anode length. Regimes of high and low fluence anisotropy as well as of high neutron yield were identified.

In this paper we report our results of tuning the length of the insulator sleeve and of the anode. We find that the proper choice of the two parameters broadens the pressure range of high neutron yield and hence improves the shot to shot reproducibility of the system.

Different parameters of the plasma focus system

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are described in Table 1. The system is assembled in a compact manner, anode rod and the capacitor bank common plate form the spark gap electrodes. In this way, the system parasitic inductance is drastically reduced and the current rise $dI/dt \sim 3\times10^{11}$ A/s is achieved. A simple resistor divider has been used to monitor the voltage across the cathode and the anode whereas a Rogowski coil is employed for measuring the discharge current from the capacitor bank to the focus tube. For 0.8 kJ discharge energy, a peak current of 190 kA was recorded. The neutrons emitted from the pinch filament were detected by a BF_3 neutron counter placed in a 2″ thick wax moderator, placed at 1.5 m from the focus point. The detector was calibrated using a neutron source of known strength. The neutron emission profile was recorded by employing a 2″×2″ cylindrical NE 102 plastic scintillator optically coupled to a XP2020 photomultiplier tube.

Various lengths of anode and insulator sleeve were tried. For three lengths of the glass sleeve, 21, 26 and 32 mm, keeping the anode length fixed at 98 mm, the variation of the neutron yield versus the deuterium filling pressure is shown in Fig. 1. Each data point in this and the following graphs corresponds to an average of 10 shots.

Since the inductance of the accelerator is $\simeq 2.15$ nH per cm, the length of the electrodes is varied between 7 and 10 cm to tune the focus tube inductance with the external one. A neutron yield of 6×10^6 is obtained for an anode length of 95 mm at a deuterium pressure of 3.75 Torr. Fig. 2 shows the deuterium pressure versus neutron yield for the 95 mm anode. As we increase the pressure, the neutron yield exhibits a sharp cutoff. When the pressure is raised by 50% of its optimum value, no neutron emission is observed.

On reducing the anode length, the focussing action at higher deuterium pressure is also observed. It is found that for a slightly mistuned length of the anode, the neutron emission peaks twice, one peak occurs around 3.5 Torr, while the other occurs at 7.0 Torr, as shown in Fig. 3. This type of observation was also reported earlier by Lee and Chen [7]. As we mistune the anode length further, the neutron yield

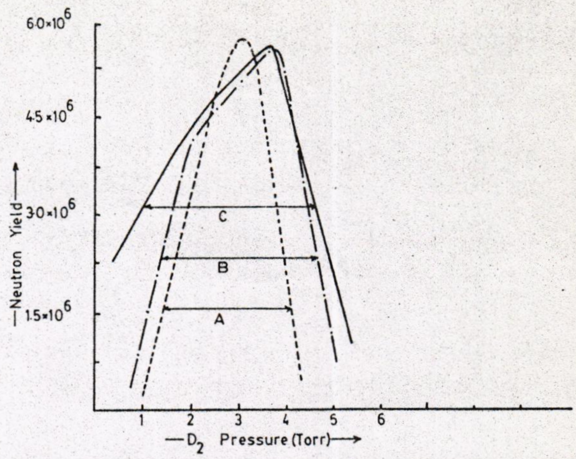

Fig. 1. Variation of the neutron yield with deuterium filling pressure for pyrex insulator sleeves of length (A) 21 mm, (B) 26 mm, (C) 32 mm; the anode length is 98 mm.

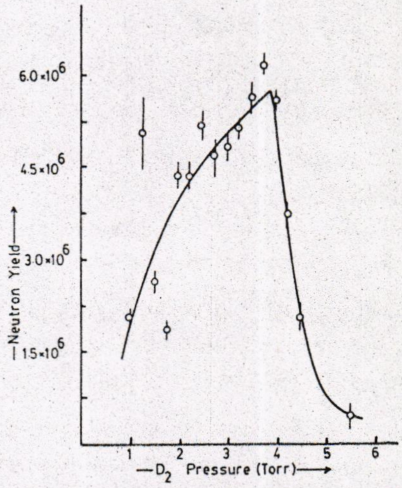

Fig. 2. Neutron yield versus deuterium filling pressure for a 95 mm long anode.

Table 1
Plasma focus parameters

capacitor bank	4×(3.3 μF)
discharge energy	0.6–0.8 kJ
charging voltage	9.5–11 kV
peak discharge current at 11 kV	190 kA
length of electrodes	8 cm
radius of inner electrode	0.82 cm
radius of outer electrode	2.45 cm
short circuit external inductance	22 nH
focus tube inductance	17.5 nH
current rise time	0.6–0.8 μs
oscillation time period	4.2 μs
D_2 gas pressure	2.5–9.0 Torr

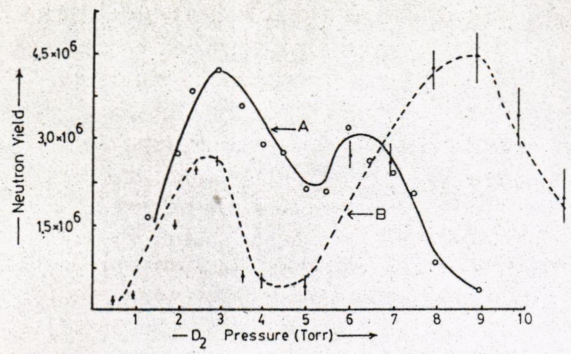

Fig. 3. Anomalous behaviour of the neutron emission versus deuterium filling pressure for anode lengths of (A) 80 mm, (B) 70 mm; the insulator sleeve length is 27 mm.

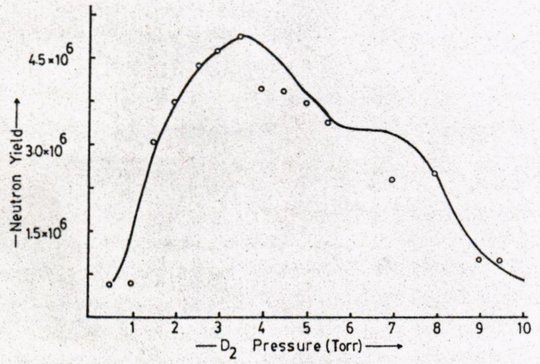

Fig. 4. Neutron emission versus deuterium filling pressure when the anode and insulator sleeve lengths are properly tuned.

at lower pressure is reduced, while the yield at a higher pressure of 7.0 Torr is increased. This effect was used to obtain a design advantage by adjusting the lengths of the anode and the insulator sleeve. An optimum combination provides a good neutron yield upto 9 Torr deuterium pressure, as shown in Fig. 4. When the system was operated with hydrogen gas, a good focussing action was observed even upto 18 Torr filling pressure.

When we installed a tritium target at a distance of 2–3 cm in front of the anode, the neutron yield doubled to 1.2×10^7 n/shot. With a deuterium–tritium gas mixture the neutron yield is expected to increase further by one order of magnitude.

Extensive work was done to determine the cathode shape effects. We tried three electrode configurations, a solid cylinder, a perforated cylinder and rod shaped electrodes. No appreciable difference in behaviour is observed for the solid cylinder and the perforated cylindrical cathode. However, for the case of a six-rods cathode, the operating pressure for the high neutron yield is broadened as compared with the perforated cylinder. The variation of the neutron yield with the deuterium filling pressure for two cathodes is shown in Fig. 5.

The neutron pulse profile is detected by a scintillator–photomultiplier tube arrangement. As given in Fig. 6, the profile has a rise time of a few nanoseconds. The main pulse has a full width at a maximum height of 50 ns, followed by a few more smaller pulses within about 250 ns, indicating multiple pinch formations. There is also a continuous production of

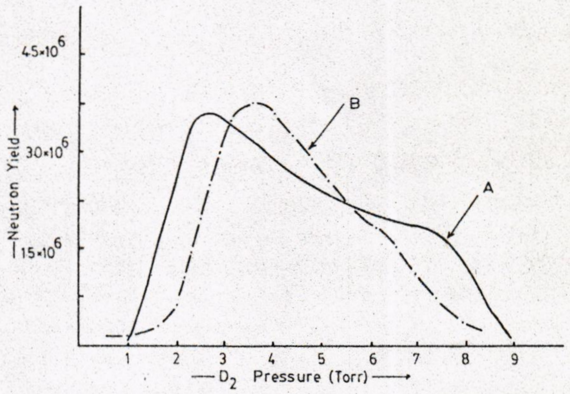

Fig. 5. Effect of the cathode shape on the pressure range for neutron emission, (A) the cathode is comprised of six Cu rods, (B) perforated cylindrical cathode.

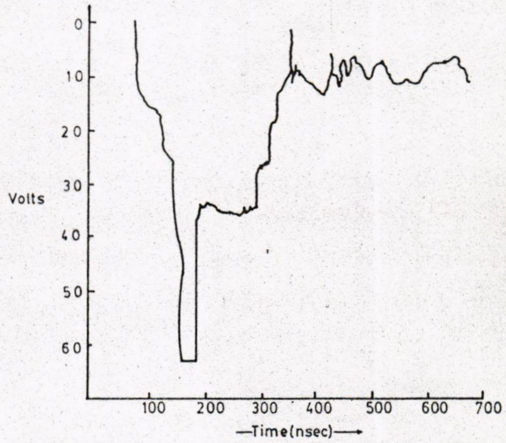

Fig. 6. Neutron pulse profile as detected by a NE102+PMT detector assembly.

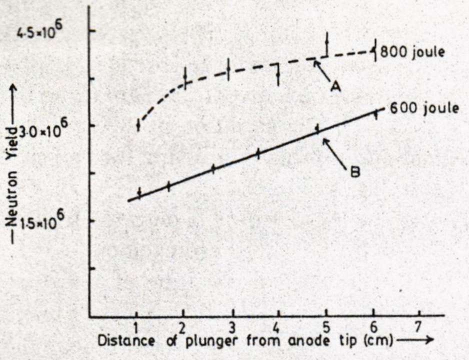

Fig. 7. Variation of the neutron yield with the plunger height from the anode tip at discharge energies of 0.6 and 0.8 kJ.

neutrons for a few hundred nanoseconds as the deutron jets emitted from the pinch stream through the gaseous deuterium. The maximum neutron emission duration is obtained when the anode and insulator sleeve lengths are properly tuned.

One generally believes that in plasma focus devices neutrons are produced by two different mechanisms. Firstly by the D–D reactions in the hot pinch region and secondly by the D–D reactions between the deutron ion beam emitted from the pinch region and the neutral gas in the chamber. The extent of neutrons produced by the two processes was estimated by performing a simple experiment. The neutron yield was measured by placing a plunger at various distances above the anode. The results are shown in Fig. 7. This experiment was carried out for discharge energies of 600 and 800 J. Our experiment demonstrates that about 70% of the neutrons are generated within 2 cm above the anode.

To conclude, a compact low energy Mather type plasma focus operated by a 0.6–0.8 kJ capacitor bank is developed. Attention is paid to match the focus tube inductance with that of the external inductance L_0. With the proper tuning of the insulator sleeve length and the anode length, the operating pressure range is broadened to 1.5–9.0 Torr deuterium, and the neutron pulse width is increased. On placing a tritium target in front of the anode, the neutron yield is doubled, that is, from 6×10^6 n/shot to 1.2×10^7 n/shot. One can speculate that the impedance matching of the focus tube with that of the external one and the proper tuning of the electrode length with the insulator sleeve length enhances the pinch filament stability. That in turn enhances the neutron production from the hot pinch region.

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TEMPORAL CORRELATION OF NEUTRONS, ION BEAM, AND HIGH VOLTAGE PROBE SIGNALS IN A LOW ENERGY PLASMA FOCUS

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A simple, low inductance (~ 50 nH) capacitor bank is developed for plasma focus operation. The bank comprises three modules, each consisting of two 2μF, 40 kV capacitors along with a field distortion type pressurized sparkgap. The system is employed to investigate the temporal correlation of neutrons, ion beam, high voltage probe, and Rogowski coil signals. From a careful analysis of the data, the high voltage probe signal is found to coincide well with the Rogowski coil signal, whereas the ion beam and the neutron pulses are delayed by 20–30 nsec. These observations suggest that in low energy plasma foci, ion beam generation and neutron emission occur after the maximum compression has taken place and the pinch filament has started to break, most probably due to the onset of sausage type instability.

The plasma focus device has received considerable attention in the teaching of plasma dynamics and nuclear fusion.[1] The device has proved an effective tool to investigate a variety of phenomenon like JAB acceleration, pinch formation, ion beam generation, and neutron and X-ray generation in hot plasmas. It has been speculated that if the neutron scaling $N \sim E^2$ and $N \sim I^4$ holds up to bank energies of 30–50 MJ, the plasma focus would be of interest from the standpoint of fusion power plant also.[2] However, the neutron yield has been reported to saturate or even decrease with the increase of discharge energy.[3] This may prove a detrimental constraint reducing the scope of plasma focus in the context of fusion programme. Plasma focus of course has vast applications. For example, it has been employed as soft X-ray source for X-ray lithography and microscopy.[4] The high neutron yield from the device and possible generation of multiple neutron pulses[5] may find applications in neutron radiography, as well as provide an intense neutron source for material deterioration research. Recently, the plasma focus has been successfully used to crystallize the as-grown rf-sputtered amorphous thin film of lead zirconate titanate (PZT).[6]

To explore the scope of plasma focus in fusion as well as its other applications, it seems essential that different machine parameters are investigated in a systematic and comprehensive manner. Since the low energy devices are much simpler to operate than the bigger machines, we have chosen the small plasma focus device at Quaid-i-Azam University, Islamabad, for such an investigation. Some of the aspects have been discussed in our earlier communications.[7–11] In this paper, we report on the design and development of a low energy capacitor bank with a rise time of $\sim 0.5\ \mu$sec, which is employed to investigate the temporal correlation of neutrons, ion beam, high voltage probe, and Rogowski coil signals.

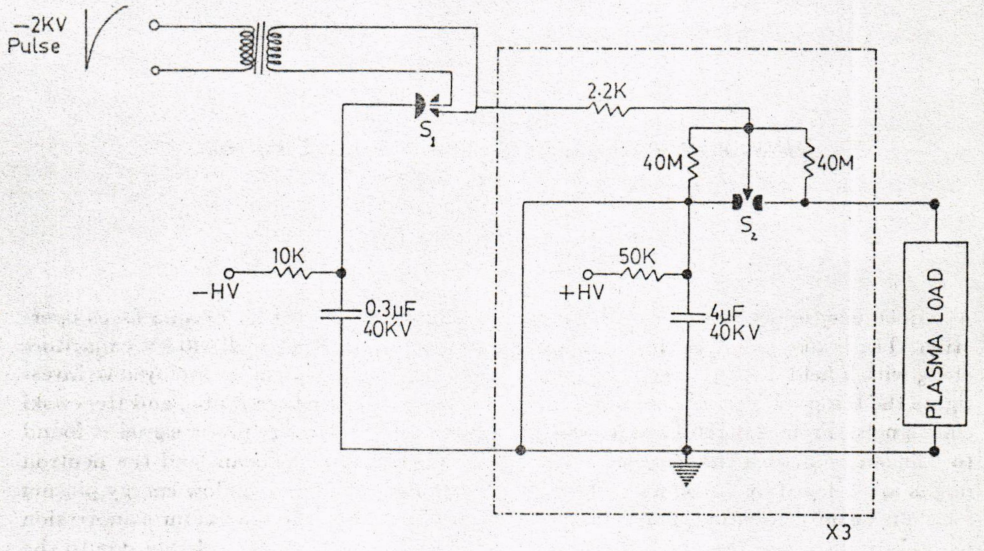

Fig. 1. The schematic arrangement of the capacitor bank.

Our plasma focus electrode system has been reported earlier.[9,12] In the present experiment, the anode rod length is reduced to 110 mm. The capacitor bank consists of three modules, each having two 2μF, 40 kV capacitors along with a field distortion type pressurized sparkgap. The schematic arrangement of the capacitor bank is given in Fig. 1 and the detailed sketch of the sparkgap in Fig. 2. The sparkgap body is machined from ertalon rod of 75 mm diameter, and the electrodes are developed from a 40 mm diameter copper rod. A circular disc of 12 mm thickness serves to trigger the sparkgap. Six brass bolts tightened coaxially outside the sparkgap body provide low inductance path to the current. A $0.3\,\mu$F capacitor charged up to −20 kV is used to trigger the three sparkgaps. Car trigger cables, each of about 2.2 kΩ resistance, are used to keep the sparkgaps isolated and to join the trigger capacitor to the trigger plates of the sparkgaps. A triggertron type sparkgap is

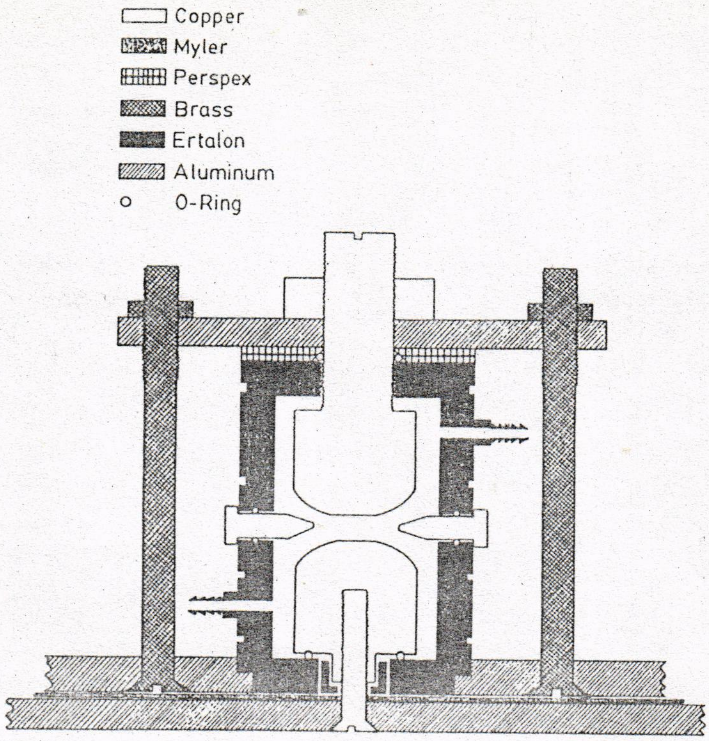

Fig. 2. The detailed sketch of field distortion type pressurized sparkgap.

employed with the 0.3 μF trigger capacitor. The parasitic inductance of the capacitor bank is estimated at about 50 nH, while a peak discharge current of 250 kA is recorded when the 12 μF capacitor bank is charged to 18 kV (2 kJ). The system has been found to work reliably and reproducibly for argon and deuterium plasmas.

Figure 3 contains a high voltage probe indicating focusing action, along with a Rogowski coil signal, ion beam signal as detected by a simple Faraday cup, and the neutron emission profile detected by a photomultiplier tube + NE 102 plastic scintillator assembly. The data was recorded by a 4-channel GOULD 4074A digital storage oscilloscope. The time integrated (GM tube + In foil) neutron detectors record neutron yield of $\sim 10^8$ neutrons at 2.25 mbar deuterium filling pressure. A careful analysis of the data shows that the high voltage probe signal coincides well with the Rogowski coil signal, whereas the ion beam and neutron pulses are delayed by 20–30 nsec. These observations suggest that in low energy plasma foci, ion beam generation and neutron emission occur after the maximum compression, during the breakup of the pinch filament, probably due to sausage type instability.

In this experiment, we used an uncontaminated new insulator glass sleeve. In most of the shots, a single focusing spike in high voltage probe signals is seen. Associated with a single focusing spike, a single dip in Rogowski coil signal and

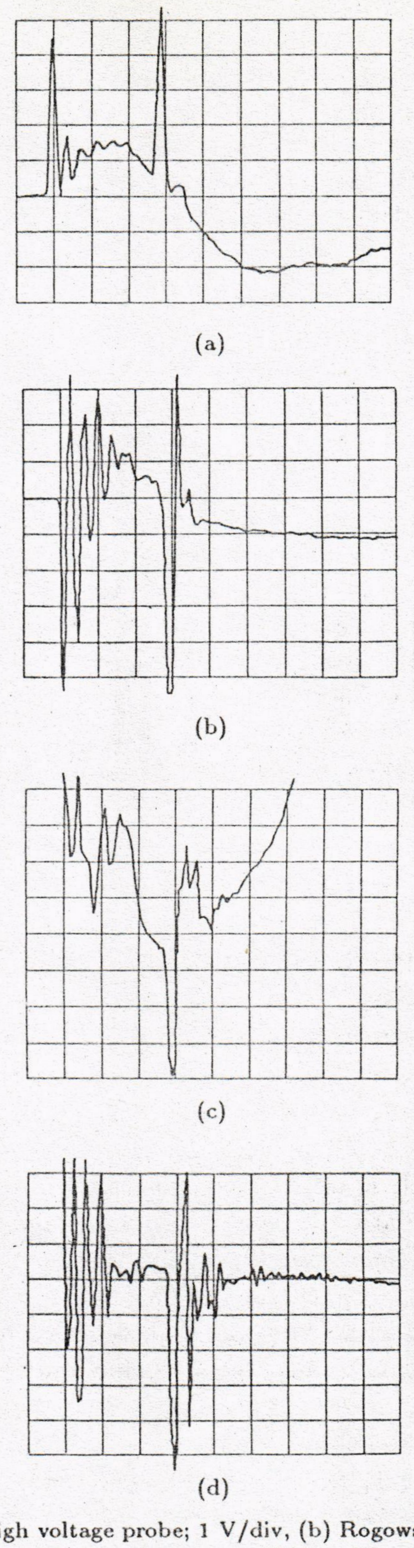

Fig. 3. Oscillograms of (a) high voltage probe; 1 V/div, (b) Rogowski coil; 1 V/div, (c) ion beam pulse; 0.2 V/div, (d) neutron emission profile; 50 mV/div. The signals are recorded with time base 0.5 μsec/div.

single neutron and ion beam pulses appear. These observations confirm our earlier results,[11] that is, when an insulator sleeve is contaminated due to the deposition of Cu evaporated from the electrodes, a high voltage probe records multiple foci formation, giving rise to multiple neutron pulses, multiple X-ray pulses, as well as multiple ion beams. The multiple foci formation is attributed to current partition, therefore, the use of low sputtering rate conductors seems essential for the electrodes of the device.

To conclude, a simple and low inductance 3-module capacitor bank operated by field distortion type pressurized sparkgaps has been developed and successfully employed in a plasma focus operation. For 18 kV (2 kJ) charging, a peak discharge current of 250 kA is recorded with a rise time ~ 0.5 μsec. The system has proved reliable and reproducible for focusing in argon and deuterium plasmas. Analysis of data reveals that high voltage probe signal coincides well with the Rogowski coil signal, whereas the ion beam and neutron pulses are delayed by 20–30 nsec. These observations suggest that in low energy plasma foci, ion beam generation and neutron emission occur after the maximum compression has taken place and the pinch filament has begun to break. One speculates that the latter is probably due to the onset of sausage type instability.

Acknowledgements

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ELECTRON TEMPERATURE MEASUREMENT OF FOCUS PLASMA BY OPTICAL RADIATION EMISSION SPECTRUM ANALYSIS

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ABSTRACT

The optical/near ultraviolet (6000Å-2000Å) radiations from a low energy (3 kJ) Mather-type plasma focus are detected by a photomultiplier tube coupled with a 1-m monochoromator. Comparing the radiation spectrum with the Planck's radiation law, the plasma temperature is estimated to be (0.84 ± 0.1) keV

1. INTRODUCTION

To achieve thermonuclear fusion in laboratory, one requires to confine high density plasma at sufficiently high temperature for a sufficiently long time. Evidently the plasma temperature measurement is one of the fundamental diagnostic requirements. Jahoda et al. [1] measured the electron temperature by recording X-ray continuum transmission through metal foils of different thicknesses and then by comparing the experimental curves with theoretical predictions. This method of measurement though requires lengthy computations, has attracted much attention of different workers. Donaldson [2] developed some formulae and tables based on the idea of foil absorption technique, which facilitate the analysis of X-ray spectrum and eventually the determination of the plasma electron temperature.

Measurements of electromagnetic radiations in the visible and near ultraviolet are the easiest one, because a wide selection of monochromators/spectrographs and detectors are available with the required spectral resolution. A typical emission spectrum from a plasma consists of bremsstrahlung continuum, recombination continuum and line radiations. However, the contribution from the recombination continuum is rather small at high temperature while the line radiation can be avoided by a judicious choice of the wave length. Regarding bremsstrahlung, one knows that, towards long wavelength,the absorption increases with sequare of the wavelength. As a result, the plasma becomes optically thick thus the emission spectrum approaches that of a blackbody radiator. If we compare the radiance of spectrum with Planck's law, the plasma temperature can be estimated [3], though the results are not very accurate since, in the visible spectral region, the dependence on temperature is rather weak as given by the formula

$$\varepsilon_b(\lambda) \sim \frac{1}{\lambda^2} \frac{n_e^2}{\sqrt{kT_e}}$$

Where $\varepsilon_b(\lambda)$ is the bremsstrahlung power loss, λ is the wavelength, n_e is the electron density, k is the Boltzman constant and T_e is the electron temperature.

In this paper, we present the measurement of electron temperature in a low energy Mather-type plasma focus by comparing the optical/near ultraviolet (6000Å-2000Å) radiation spectrum with that of a blackbody radiator. We believe that this is the first reporting of the this technique employed for focus plasma electron temperature measurement.

2. *EXPERIMENTAL ARRANGEMENT*

The experiment is carried out in a low energy (3 kJ) plasma focus device [4,5] energized by a single 32 μF, 15 kV capacitor. The plasma focus electrode system consists of a 160 mm long Cu rod of 18 mm diameter as anode surrounded by six 10 mm thick Cu rods forming the cathode, with internal diameter of 50 mm. The cathode rods are screwed to a Cu plate with a knife edge near the anode. An insulator sleeve of pyrex glass is placed between the anode and the cathode at this end. A 13 mm thick rubber disc with a hole at its center is used to support the cylindrical glass sleeve, so that it could be positioned without touching the anode or the cathode. A triggertron type pressurized sparkgap is used as a switch. The optical radiations emitted from the focus plasma are detected by EMI-9781B side window photomultiplier tube coupled to a 1-meter McPherson 2061, Czerny-Turner type scanning monochoromator with plane diffraction grating of 1200 lines/mm. It provides a linear dispersion of 8.33 Å/mm. The signal was recorded by a 100 MHz digital storage oscilloscope.

3. *RESULTS AND DISCUSSION*

We scanned the wavelength from 6000 Å- 2000 Åwith a step of 50 Å. For each selected wavelength, a set of five signals was recorded, monitored on the oscilloscope and then transferred to a 286 AT computer system through IEEE-488 interface port.. The signal intensity versus wavelength is given in figure 1. The spectrum is compared with Planck's law, assuming that the focus plasma is optically thick in this wavelength region and behaves as a blackbody radiator. The non-linear curve fitting technique is employed for the comparison. For this purpose a software in TurboPascal for windows is developed, capable of fitting the theoratical curve with experimental data points. As our detection system is not calibrated against some standerd radiation source, so we have to calculate the calibration factor, which accounts the solid angle sutended by the detector relative to source and calibration of the detector. This software calculates the two unknown parameters i.e. kT and calibration factor through non-linear least square curve fitting method and finally it displays the experimental data points and theoratical calculated curve. This comparison given in figure1 enables us to estimate the electron temperature, which is (0.84 ± 0.1) keV. Previously, such measurements were performed using relative X-ray transmission through thin foils, [6]. These measurements are, rather lengthy and time consuming, but, of course, the temperature estimates are fairly accurate.

To conclude, we have reported a method of estimating the electron temperature in a low energy Mather-type plasma focus by comparing the optical/near ultraviolet radiation spectrum with Planck's radiation law. The temperature is estimated to be (0.84 ± 0.1) keV.

ACKNOWLEDGEMENTS

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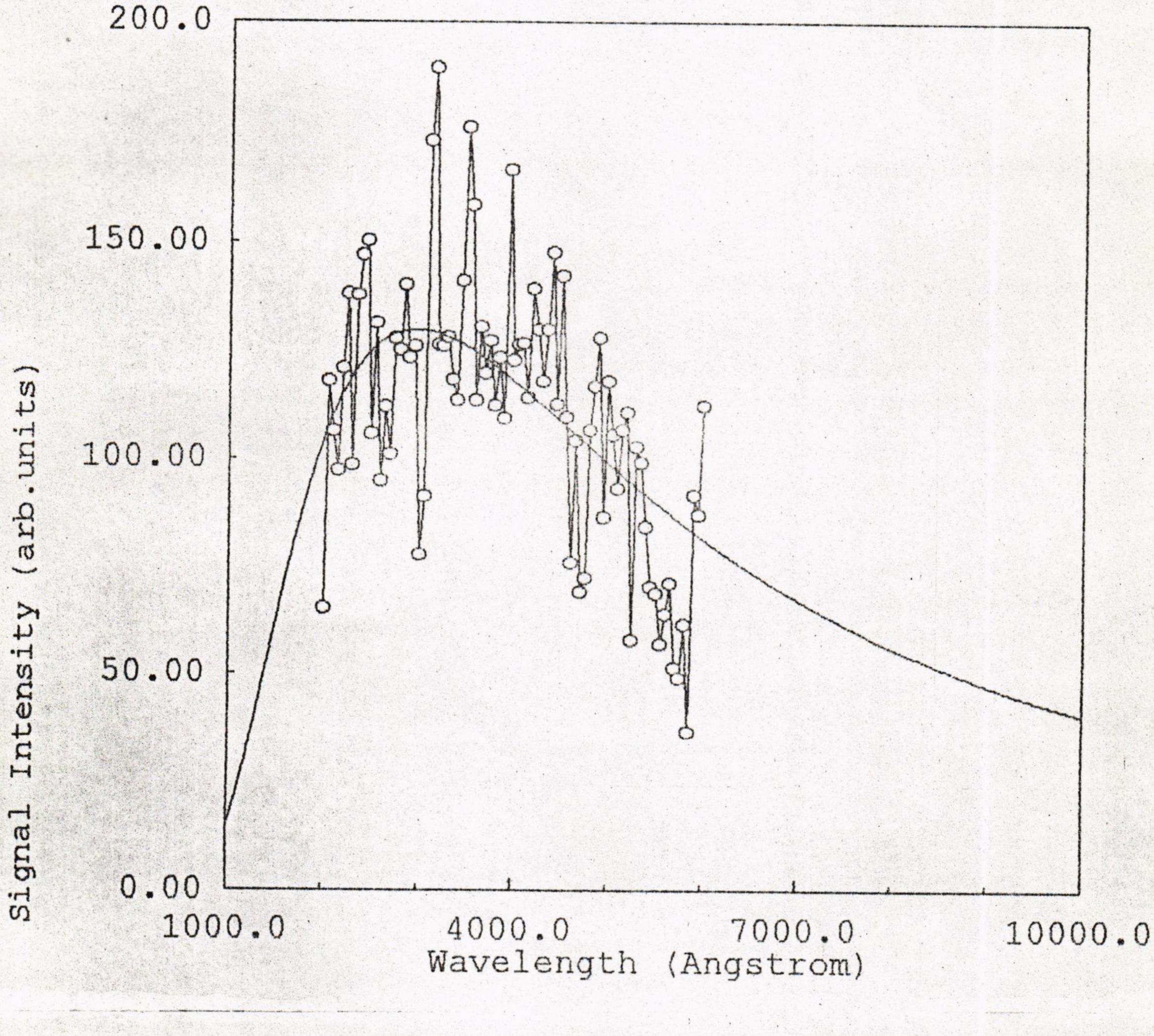

Figure 1: Focus plasma radiation intensity variation versus wavelength, the superimposed curve represents Planck's law.

COMPARATIVE STUDY OF LOW ENERGY MATHER-TYPE PLASMA FOCUS DEVICES

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The characteristics of three different low energy Mather-type plasma foci are investigated and compared. The effects of anode length and insulator sleeve length on neutron yield and on fluence anisotropy are studied. It is found that proper tuning of the focus tube inductance with that of the driver enhances the neutron emission from the focus region, increases the neutron pulse width and broadens the deuterium pressure range for high neutron yield. The insulator contamination which occurs due to Cu evaporated from the electrodes drastically changes the device characteristic. The possibility of using the device as a multi-pulse neutron generator is also examined.

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I - INTRODUCTION

The low energy plasma focus device has received considerable attention in the teaching of plasma dynamics and the study of the nuclear fusion [1]. The device has proved an effective tool to investigate a variety of phenomena like JxB acceleration, pinch formation, neutrons and X-rays generation. In spite of its short lived plasma due to the fast growing magnetohydrodynamic instabilities, plasma focus is amongst the few devices of thermonuclear fusion research that give high neutron and X-ray yield. Soft X-ray sources employing plasma focus have been developed for X-ray lithography and microscopy [2]. The high neutron yield from the device and possible generation of multiple neutron pulses [3] may find applications in neutron radiography and intense neutron sources for material deterioration research. Recently, the plasma focus has also been used to crystallize the as-grown rf-sputtered amorphous thin film of lead zirconate titanate (PZT) [4]. Not withstanding these successes, a number of difficulties persist in plasma focus facilities that may prove a detrimental constraint, reducing the scope of their use. For example, the neutron yield has been reported to saturate or even decrease with an increase in discharge energy [5]. This may be due to impurity present in the plasma which depends, among other factors, on the insulator sleeve material affecting the final plasma ionization and compression efficiency and thus leading to eventual reduction in neutron yield. When the POSEIDON team [5] in Stuttgart, Germany replaced the glass insulator by a ceramic insulator, the neutron yield showed only partial saturation. In any case, this problem is not yet fully resolved. Similarly, the simple question of how to determine the optimum length of the insulator at which a symmetric current sheath would form in the initial stage of the discharge remains unresolved, as pointed out by Filippov [6] in 1983. In fact, the various parameters, such as the geometry and structure of the inner and outer electrodes, the dimensions, the material and the configuration of the electrodes and the insulator and the initial pressure are all interrelated in an intricate way and no general relationship has been found so far.

In this paper, we present the comparative study of three low energy Mather-type devices in our laboratory with a view to investigate the effects of different machine parameters on neutron/X-ray emission. Specifically, the variation of neutron yield versus anode length and insulator sleeve length, deuterium filling pressure, impedance matching and insulator sleeve contamination is investigated. The possibility of using the device as a multi-pulse neutron generator is also examined. In Section II the parameters of different devices and the diagnostic equipment employed are described. Section III presents the experimental results and their discussion while Section IV summarises the conclusions.

II - DEVICES AND DIAGNOSTICS

Table I summarises the parameters of the three plasma foci under study. A simple resistor divider was used to monitor the voltage across the cathode and the anode headers whereas a rogowski coil was employed for measuring the discharge current from the capacitor bank to the focus tube. Neutron yield from PF I and PF II was measured with detectors consisting of Geiger-Muller tubes alongwith indium foil of thickness 0.1 mm immersed in paraffin wax cylinders with available moderating length of 80 mm. Neutron yield from PF III was detected by a BF_3 neutron counter placed in a 50 mm thick wax moderator, placed at 1.5 meter from the focus point. The neutron detectors were calibrated against an Am-Be standard neutron source. For time-resolved neutron measurements, a Thorn EMI (Electron Multiplier Intensifiers) photomultiplier tube 9956 optically coupled with 50 x 50 mm cylindrical plastic scintillator NE 102 was used. For some shots on PF III, a photomultiplier tube XP2020 alongwith 50x50 mm cylindrical plastic scintillator NE (Neuclear Enterprises) 102 was employed. Time resolved X-ray emission was monitored by a pin-diode PBX-65 with slight modifications. The safety glass cover of the diode was removed and 9 μm thick aluminium foil alongwith (1+35) μm thick aluminized myler was used to screen the visible light. A simple Faraday cup placed at a distance of 17 cm from the anode tip was employed to detect the ion beam generated during the focus phase.

III - RESULTS AND DISCUSSION

We have tried a set of ten anode lengths of 107, 114, 122, 136, 148, 156, 164, 175, 186 and 206 mm respectively in PF I, measured from cathode base plate to the anode tip [7]. Figure 1 describes the maximum neutron yield, optimum deuterium filling pressure, and neutron fluence anisotropy (axial neutron flux/radial neutron flux) against anode length variation for this system. The results predict high neutron yield in a certain domain of the anode length. The optimum pressure (for maximum neutron yield) records the highest value for the shortest anode and decreases as the anode length increases. However, for some anode lengths, the optimum pressure is higher than that expected from the smooth curve. More interesting part of this experiment is the observed change in the fluence anisotropy with the change in anode length. That perhaps is a reflection on neutron production mechanism at play in plasma foci. Large anisotropy suggests the possibility of ion beam generation which leads to neutron emission via beam-plasma interactions. Since enhanced anisotropy appears in a particular range of anode lengths, one can identify anode dimensions for efficient ion beam production. We have compared our results with those reported by Rapp [8] who studied the variations in neutron emission due to change in discharge energy E_o, anode length ℓ, and optimum pressure p for high neutron yield and obtained the following scaling law

$$\frac{p_1 \ell_1}{p_2 \ell_2} = \frac{E_{o1}}{E_{o2}}$$

We find that our results are in agreement with the above scaling law for anode lengths of 148, 156 and 164 mm, that is, in the domain of high neutron yield. For smaller anode lengths, the product 'pℓ' is enhanced and for larger anode lengths, it is lowered. This implies that agreement with the scaling law holds only within a narrow range of anode lengths corresponding to high neutron yield. The deviation of 'pl' parameter from the scaling law may be explained as follows. When the anode length is too short, the filling pressure must be high enough to obtain synchronization of current rise time (to its maximum) with the traversal time of the current sheath. On the other hand when the anode is elonggted, the filling pressure needs to reduce sufficiently, to obtain synchronization and to avoid possible breakup of the current sheath during the prolonged transit along the accelerator.

Three lengths of pyrex glass insulator sleeve, that is 16, 22 and 30 mm were tried [9] on PF I. Figure 2 depicts the variation in the neutron yield and the optimum pressure against change in the insulator sleeve length. The neutron yield is relatively low whenever the insulator sleeve length deviates from the optimum value. The optimum insulator sleeve length provides neutron yield over a wide range of pressure 1.5-10 mbar whereas for other sleeve lengths, the pressure range of interest appears relatively narrow. The optimum pressure for best neutron yield is the highest for optimum insulator sleeve length. When sleeve length deviates from the optimum value, spokes are observed on the sleeve surface. The spokes are more prominent on the surface of shorter length. For optimum sleeve length, the sleeve surface appears symmetric and homogeneous all around, predicting azimuthally symmetric current sheath which in turn leads to higher neutron yield. The optimum insulator sleeve length reduces the neutron fluence anisotropy also. In this experiment, when we extended the cathode rods and terminated them by a Cu plate in analogy with the Filippov geometry, the neutron yield was reduced by an order of magnitude. It is not clear whether neutron production via beam-taeget mechanism is dominant in low energy Mather-type devices, or the current sheath behaviour is changed with the addition of ceiling. This phenomenon needs further investigation.

The insulator sleeve region in our system is found to possess some inductance, of the order of 0.6 nH/cm. When the energy storage capacitor is fired, a voltage $-L\frac{dI}{dt}$ is developed across the insulator. As a result, the applied voltage is clipped momentarily to some extent. The optimum insulator sleeve length corresponds to the conditions for uniform discharge development and its take off across the insulator sleeve surface. When the sleeve is too long, the increased inductance causes the current sheath to remain at the sleeve surface for a longer period of time. When the sleeve is too short, the rapid current sheath development causes spokes formation. As a result when the insulator sleeve is not of appropriate length, the current sheath no longer remains uniform, and the so called filaments or spokes are developed. This feature of current sheath structure is observed in other devices also [10,11]. Kies [10] reported that the filaments in the current sheath can be avoided by conditioning the sleeve surface.

In PF II, we investigated the effects of insulator sleeve material on neutron emission [12]. The dielectric constants of different insulators [13] which were tried during the experiment are given in Table 2. The different insulator sleeves used in the experiment had identical thickness (2.0 mm) and length (25.0 mm) from the copper base plate, to which cathode rods were screwed. Figure 3 shows the variation of the neutron yield with the deuterium filling pressure. An insulator with higher dielectric constant ε_r provides neutron yield over a wide range of filling pressure. As depicted in Figure 4, the maximum neutron yield is found to increase quite linearly with the product $p \times \varepsilon_r$, where p is the deuterium filling pressure and ε_r the dielectric constant of the insulator used. The filling pressure and the dielectric constant seem to conspire to create favourable conditions for the focusing phenomena leading to a new scaling law for maximum neutron yield. An insulator sleeve of high dielectric constant will generate steep electric field gradient across the sleeve surface, which would cause rapid acceleration of the electrons towards sleeve. That is why an insulator sleeve of higher dielectric constant makes the device operational for a wide pressure range, enhances the optimum pressure, and may help to increase the current sheath uniformity. This leads to neutron yield scaling with $p \times \varepsilon_r$. We may recall here the earlier results regarding the effects of the sleeve lengths and the sleeve material. Donges et al. [14] and Krompholz et al.[15] who investigated the breakdown phase and the formation of current sheath, noted that an increase in the insulator sleeve length shifts the pressure range for gliding discharge to lower values and vice versa. They also noted the effects of the sleeve material on the pressure range. The formation of a homogeneous and azimuthally symmetric current carrying plasma layer was found to be an essential condition for obtaining maximum energy density. Our investigation which is much more comprehensive and systematic in this regard suggests that a proper optimization of the of the insulator sleeve length is a must to obtain wider filling pressure range for high neutron yield.

The parasitic external inductance of PF I and PF II is much larger than the focus tube inductance of the corresponding systems. Due to this impedance mismatching, the energy may not transfer efficiently to the focus plasma. That necessitated developing a compact low inductance (~22 nH) system PF III [16]. Different anode lengths were tried in this system to study the impedance matching effects. For anode length of 10 cm, the focus tube inductance equals the external inductance of the system. Figure 5 describes the variation of neutron yield with the deuterium pressure for this case. When the pressure is increased beyond the optimum value for the highest neutron yield, a sharp cutoff in the neutron emission is observed. PF I also showed almost same behaviour. As we cut short the anode length so as to reduce the focus tube inductance, the focusing action at higher deuterium pressure is also observed. The neutron emission peaks twice, first around 4.0 mbar and then at 8 mbar, as shown in Figure 6. As we reduced the anode length further, the neutron yield is reduced at lower pressure and increased at higher pressure (of 12 mbar). This effect was exploited by adjusting the lengths of the anode and the insulator sleeve. An optimum combination provides good neutron yield upto 12 mbar of deuterium pressure as shown in Figure 7. When the system was operated with hydrogen, good focusing action upto 24 mbar of the filling pressure was observed. Gratton et al. [17] studied this problem operating on a 1 KJ plasma focus of accelerator inductance 20 nH, while the parasitic external inductance of the system was 51, 43 and 33 nH. They found the optimum deuterium pressure for high neutron yield to be 2.0, 2.6 and 3.1 mbar respectively. The behaviour of neutron yield versus deuterium pressure they found was analogous to our result depicted in Figure 5, when the two inductances "widely mismatch". They also noted the optimum pressure to rise as the external inductance was decreased. These results show that the coupling of the driver energy with the focus plasma improves as the driver inductive impedance approaches the inductive impedance of the accelerator. Lee and Chen [18] reported the behaviour of Mather-type plasma focus and their observation was analogus to our result shown in figure 6 for the slight-mismatch case.

With the optimum arrangement of the anode length and the insulator sleeve length, the neutron pulse width is broadened and about 70% neutrons are found to be emitted from the region within 2 cm above the anode top. The same was confirmed by placing a plunger at various distances above the anode. As given in Figure 8, the neutron emission profile recorded by XP2020 + NE102 plastic scintillator has a rise time of a few nanoseconds. The main pulse has a full width at maximum height of 50 nsec followed by a continuous background for a few hundred nanoseconds. It represents continuous neutron production as the deutron jets emitted from the pinch stream through the gaseous deuterium. These observations indicate that matching of external parasitic inductance with cumulative inductance of the focus tube and the focus plasma region enhances the neutron emission within the pinch region, and perhaps also stabilizes the pinch.

Table I lists the various parameters of the three plasma focus devices. We note that the optimum pressure for PF II small which is due to the asynchronisation of the three spark gaps. We further note that the systems PF I and PF II have almost the same discharge energy, identical external inductance, and almost the same current rise time, but the energy-to-gas ratio is different by a factor of three. The anomalously large energy-to-gas ratio of PF II may be attributed to our not being able to exactly synchronize the three sparkgaps. Indeed careful observation of the rogowski coil signal suggests that the the three sparkgaps asynchronize by a few tens of nsecs. The neutron yield in PF II is found (10-20) % lower than in PF I for the same discharge energy. However, that may well be within the error bars. The question therefore arises whether this small reduction in neutron yield due to asynchronization of sparkgaps can become important for high energy systems and as a consequence be a contributory factor for the observed neutron yield saturation/deterioration.

When a new insulator glass sleeve is installed, the breakdown is delayed by 100 - 150 nsec compared to the normal time of 30 - 40 nsec and no focusing is observed. During the next few shots however this delay lowers successively and the high voltage probe indicates improvement in focusing action. By now, a Cu thin film starts appearing on the insulator sleeve surface. These observations indicate that some minimum coating of a conducting material on the insulator sleeve surface may be essential for a prompt breakdown and current sheath formation, leading to good focusing action and high neutron yield.

For a fresh glass sleeve, some shots observe single focusing spike while others multiple focusing. After the glass sleeve has sustained some 100 shots, multiple focusing spikes appear in almost every shot. When the cumulative discharge energy across an insulator sleeve exceeds 1 MJ, Cu deposition on the sleeve surface makes it rough with a grain-type structure. The system becomes less reproducible and shot-to-shot variations in neutron yield become pronounced. An interesting observation [19,20] in our experiment PF I was that after about 700 shots, that is, when the total discharge energy across the glass sleeve surpassed 1.6 MJ, the neutron yield of the device started to decline. Figure 9 describes this behaviour. On examining the contaminated glass sleeve, it was found that the surface was coated with nearly 3μm thick Cu film. The sleeve surface also exhibited change in its resistance. While the resistance of the new sleeve was almost infinity, the resistance of the contaminated sleeve was measured to be about 30 GΩ. Although we observe deterioration of neutron yield due to surface contamination of the insulator by Cu evaporated from electrodes, the breakdown conditions as recorded by a high-voltage probe are rather improved. The breakdown delay is 20-30% reduced in the case of a contaminated insulator sleeve. Perhaps, the large Cu deposition increases the current partition which in turn reduces the available current during the pinch phase leading to a drop in neutron yield.

In PF I, we also studied the amplitude of neutron signal pulse as detected by Thorn EMI photomultiplier tube 9956 + NE102 plastic scintillator, of ion beam signal detected by a simple Faraday cup, neutron yield and average current sheath velocity vis-a-vis deuterium filling pressure. The results are described in Figure 10. The total neutron yield as well as the neutron emission from the pinch region and ion emission become maximum when the average current sheath velocity of 6.5×10^4 m/sec is attained. When we increase the deuterium pressure, all the four quantities, namely, current sheath velocity, ion beam current, neutron yield and the neutron emission from the focus region seem to decrease. However, it is not certain whether the ion beam current really decreases. The reduced signal perhaps merely reflects the inability of the ions to arrive at the Faraday cup due to increased background gas pressure. Our results predict that if the current sheath velocity stays within the optimum range, the neutron emission from the focus region reaches its highest value. We may therefore speculate that the neutron generation mechanism at play is dependent on the value of the current sheath velocity.

We also used the PF I system as a cascading device to generate sequential neutron and X-ray pulses [21]. A Cu disc having a thickness of 5 mm and a diameter of 35 mm was placed downstream of the anode, supported by two brass rods encapsulated in glass tubes, from the top flange of the chamber. Our target insertion mechanism allows enough room to the current sheath to focus beyond the target. When the separation between the anode and the target is 1-1.2 cm, two spikes separated by ~1 μsec are observed in the voltage probe as well as the PMT+ scintillator neutron detector. These results suggest the possibility of plasma focus to be used as a cascading device to produce bursts of neutron and X-rays by adjusting the discharge parameters for sufficiently long sustaining current. A typical oscillogram of the voltage probe signal alongwith the associated neutron pulse is given in Figure 11.

IV - CONCLUSIONS

We have conducted a comparative study of three low energy Mather-type plasma focus devices in our laboratory with a view to understand their characteristics and the dependence thereof on various parameters of the device. We find that the proper selection of the lengths of anode and the insulator sleeve lowers the neutron fluence anisotropy and enhances the possibility of azimuthally symmetric and uniform current sheath. If the external parasitic inductance is small enough and matches with the cumulative inductance of the focus tube and the pinch region, the deuterium pressure range as well as the neutron pulse width is broadened while the energy-to-gas ratio is greatly reduced. Under such conditions, one expects that nearly 70% neutrons will be emitted within a length of 2 cm above the anode top.

The use of multiple sparkgaps in capacitor banks increases the energy-to-gas ratio and reduces the optimum deuterium pressure by a factor of three. That in turn leads to a decrease in neutron yield by 10-20%, which is within the error bars. We speculate that this reduction may be due to asynchronization of different sparkgaps.

The contamination of the insulator sleeve changes the characteristics of the device. However, a minimum level of contamination seems essential for prompt breakdown and good focusing action associated with high neutron yield. As the contamination level grows, the current partition increases which gives rise to multiple foci formation. Any further increase in sleeve contamination causes neutron yield deterioration.

We make another important observation that the neutron emission from the focus region records a maximum whenever the average current sheath velocity is around 6.5×10^4 m/sec. Any major departure from this value lowers the neutron yield. Furthermore, the neutron generation mechanism at play also seems to depend on the said velocity during the axial run.

By placing a disc downstream of the anode, the device may also be used to generate sequential neutron and X-ray pulses.

To conclude, proper adjustment of machine parameters and tuning of driver impedance with that of the accelerator enhances the neutron emission from the pinch filament and broadens the pressure range for high neutron emission. However, the study is far from complete. A more comprehensive and systematic study of the plasma focus characteristics using several diagnostics in parallel seems essential to fully understand the rôle of different parameters and the phenomena involved. The operational simplicity and easy-to-handle changes one can do in the machine parameters recommend the low energy devices for such investigations.

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TABLE 1

Parameters of three plasma focus devices

	PF I	PF II	PF III
Capacitor bank	32 μF single capacitor	3x(7.7) μF three sparkgaps	4x(3.3 μF) single sparkgap
Charging voltage	12 KV	14 KV	(9.5-11) KV
Discharge energy(W_o)	2.3 KJ	2.26 KJ	0.8 KJ at 11 KV
Peak discharge current	~200 KA	~200 KA	~190 KA at 11 KV
Length of inner electrode	152 mm	148 mm	80 mm
Radius of inner electrode	9 mm	9 mm	8.2 mm
Radius of outer electrode	25 mm	25 mm	24.5 mm
Short circuited external inductance	~80 nH	~80 nH	~22 nH
Focus tube inductance	~30.5 nH	~30.3 nH	~17.5 nH
Current rise time	~1 μsec	~1 μsec	~0.8 μsec
D_2 gas pressure for high neutron yield	(1.5-5)mbar	(0.5-2)mbar	(1.5-14)mbar
Optimum pressure (p_o)	3.0 mbar	1.2 mbar	4.5 mbar
Energy to gas ratio $\left(\frac{W_o}{p_o V}\right)\left(\frac{J}{\text{mbar cm}^3}\right)$	2.9	7.5	1.3

TABLE 2

Dielectric constants of different insulators used

Alumina	4.5 - 8.4
Pyrex	4.5 - 6.0
Nylon	3.55
Perspex	2.76-3.12
Teflon	2.04

FIGURE CAPTIONS

Figure 1: Variation of maximum neutron yield, neutron fluence anisotropy and optimum filling pressure versus anode length in PF I.

Figure 2: Variation of highest neutron yield and optimum pressure with change in insulator sleeve length.

Figure 3: Neutron yield versus deuterium pressure with different insulator sleeve materials in PF II.

Figure 4: Maximum neutron yield versus the product of deuterium gas pressure and insulator sleeve dielectric constant.

Figure 5: For 95 mm long anode, neutron yield vis-a-vis deuterium filling pressure in PF III.

Figure 6: Anomalous behaviour of neutron emission vis-a-vis deuterium filling pressure for anode lengths of A:80 mm; B = 70 mm, insulator sleeve length 27 mm.

Figure 7: Neutron emission versus deuterium filling pressure, when the anode and insulator sleeve lengths are properly tuned.

Figure 8: Neutron pulse profile as detected PMT XP 2020 + NE 102 detector assembly.

Figure 9: Neutron yield versus shot number across a sleeve, when the device started to exhibit deterioration (a) Shot-to-shot variation; (b) average of 12 consecutive shots.

Figure 10: With the change in deuterium gas pressure, variations in : (a) neutron signal intensity; (b) ion beam intensity; (c) neutron yield; (d) average current sheath velocity.

Figure 11: A typical oscillogram of the voltage probe signal and the neutron pulse. The distance of the target from the tip of the anode is 1.0 cm and the deuterium pressure is 2.5 mbar. The base line time is 2 μsec/division. The top signal is the neutron pulse and the bottom one shows the voltage probe signal.

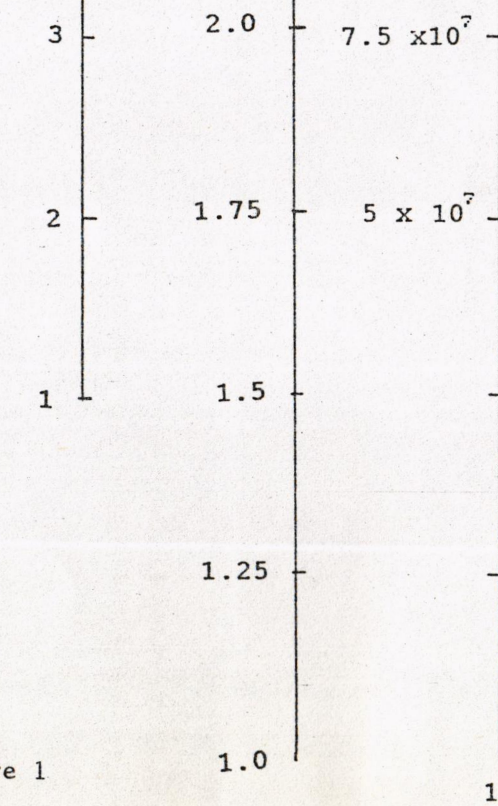


Figure 1

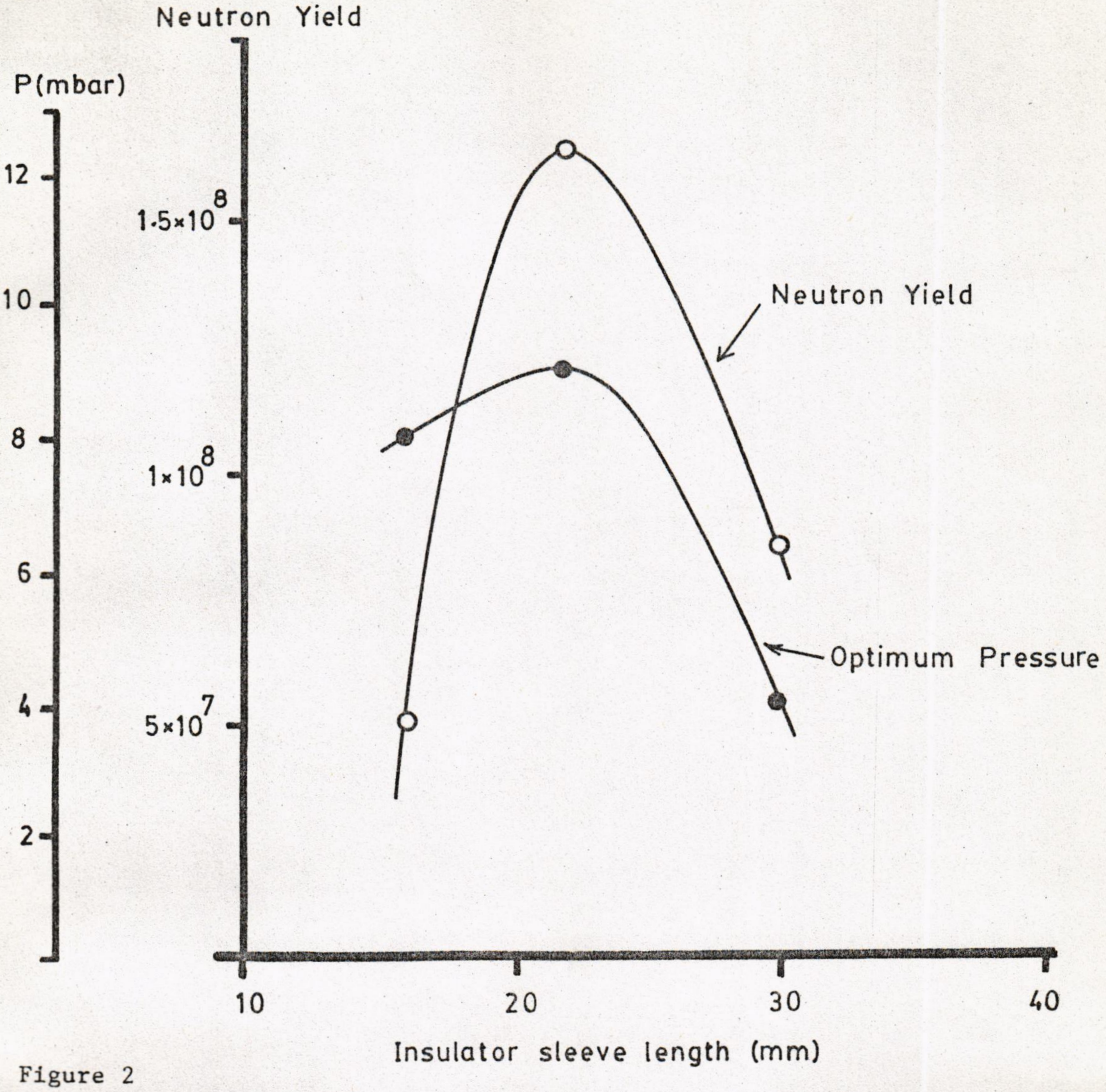
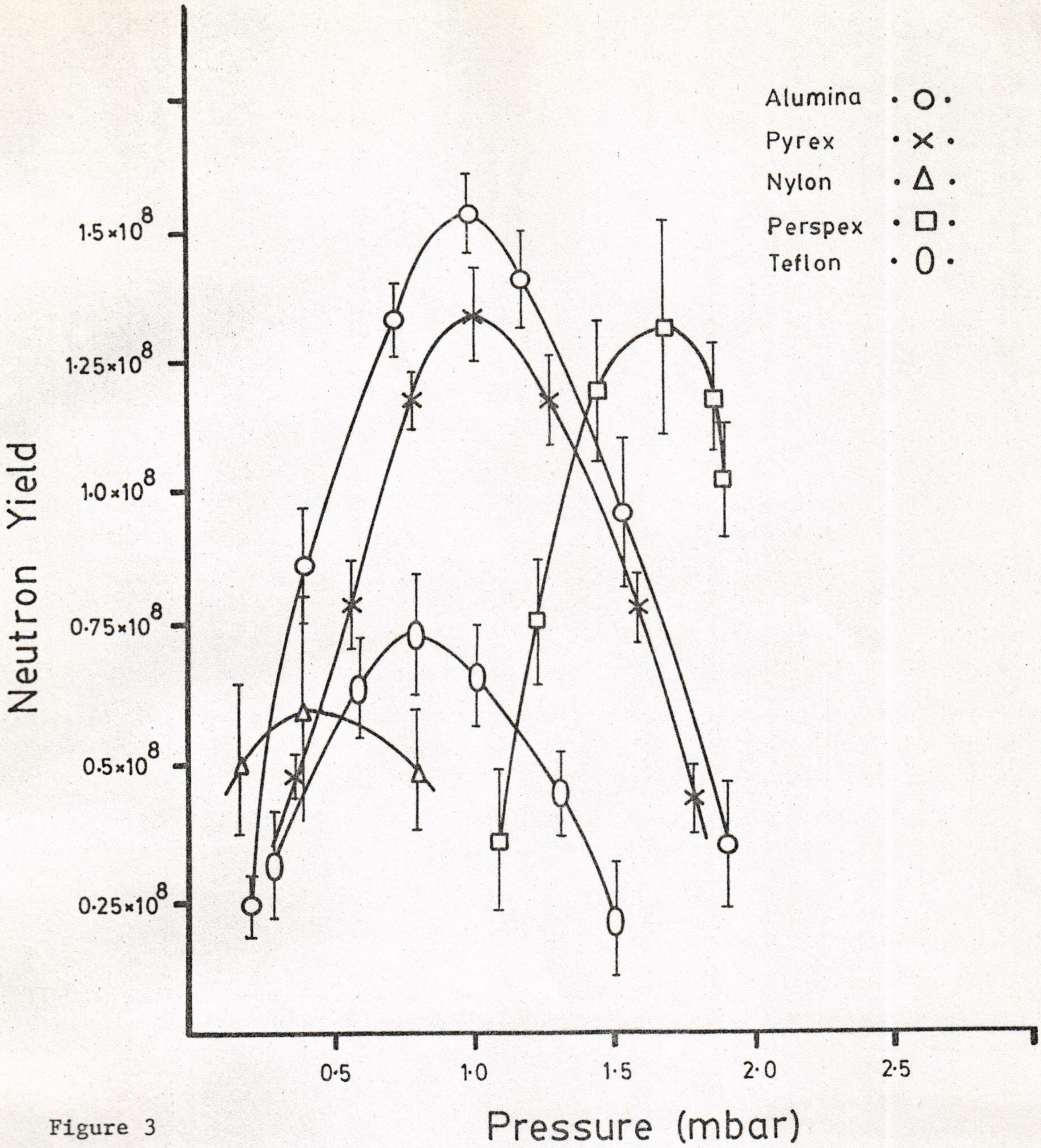

Neutron Yield
P(mbar)
12
10
8
6
4
2
1.5×10^8
1×10^8
5×10^7
Neutron Yield
Optimum Pressure
10
20
30
40
Insulator sleeve length (mm)

Figure 2



Alumina
Pyrex
Nylon
Perspex
Teflon
1·5×10^8
1·25×10^8
1·0×10^8
0·75×10^8
0·5×10^8
0·25×10^8
Neutron Yield
0·5
1·0
1·5
2·0
2·5
Pressure (mbar)

Figure 3

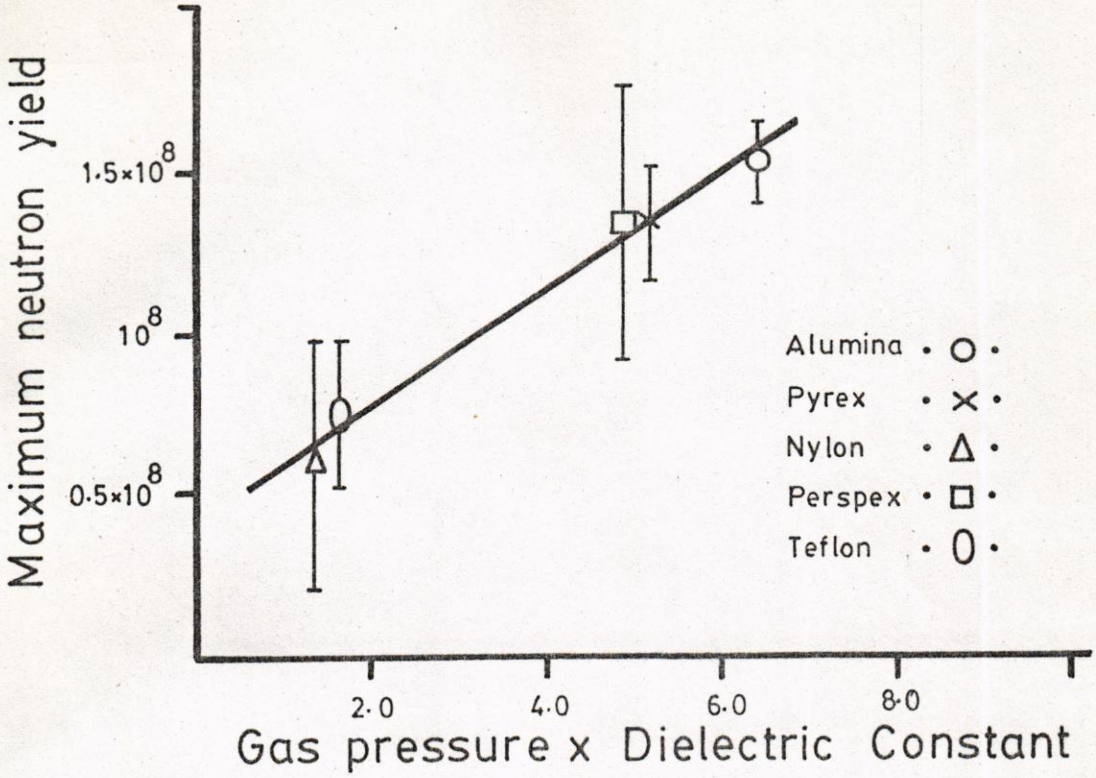

Maximum neutron yield
1.5×10^8
10^8
0.5×10^8
Alumina • O •
Pyrex • × •
Nylon • Δ •
Perspex • □ •
Teflon • 0 •
2.0
4.0
6.0
8.0
Gas pressure x Dielectric Constant

Figure 4

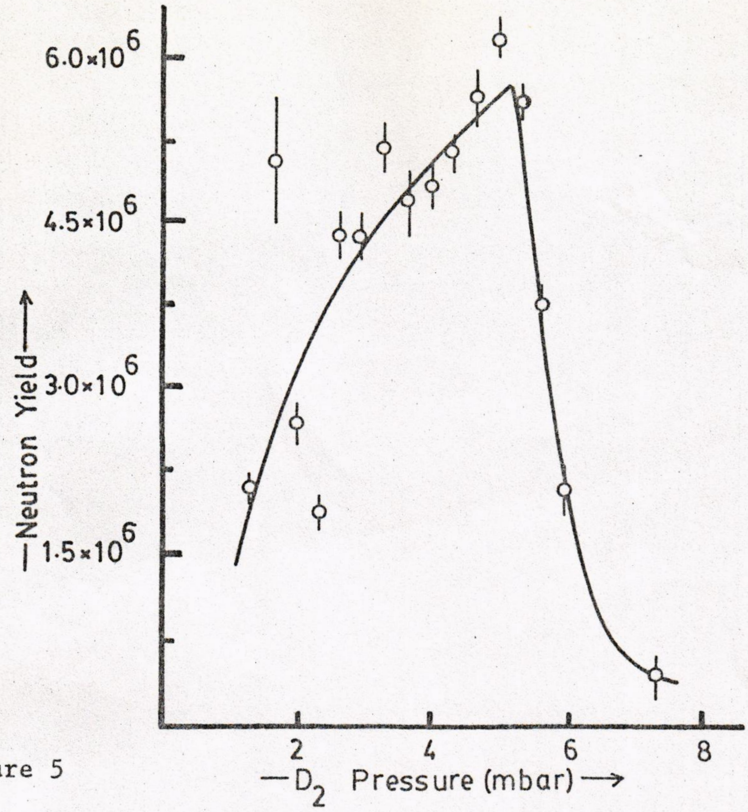


Figure 5

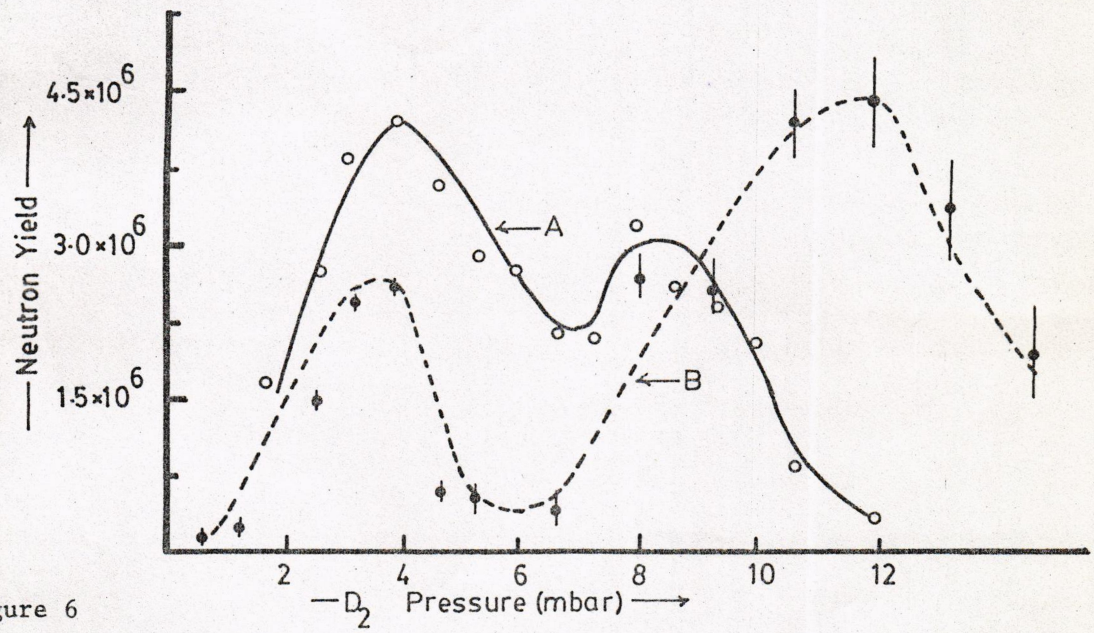


Figure 6

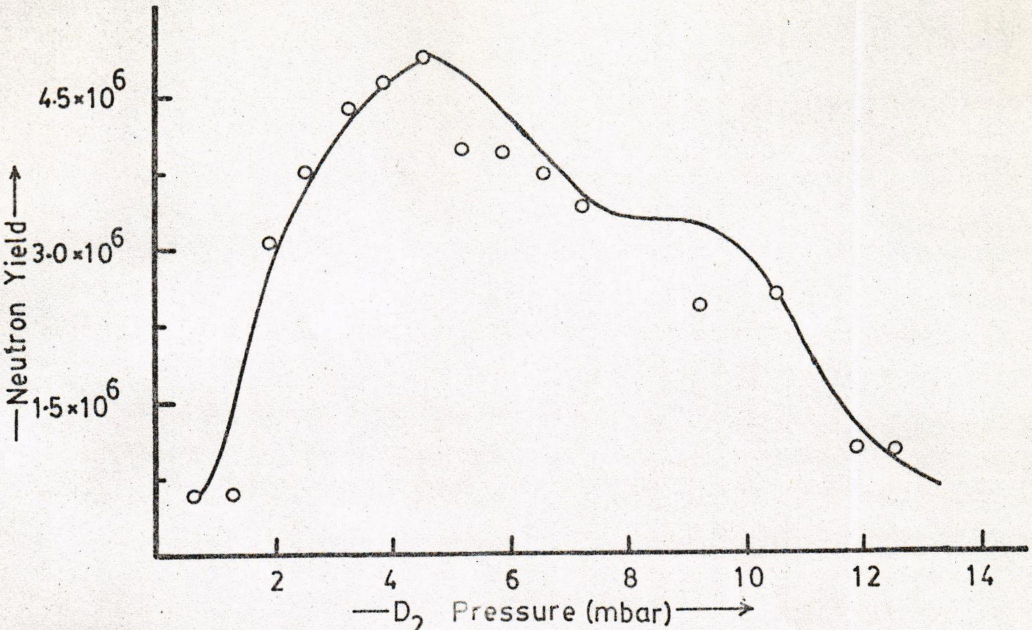

4.5×10^6
3.0×10^6
1.5×10^6
—Neutron Yield→
2
4
6
8
10
12
14
—D2 Pressure (mbar)→

Figure 7

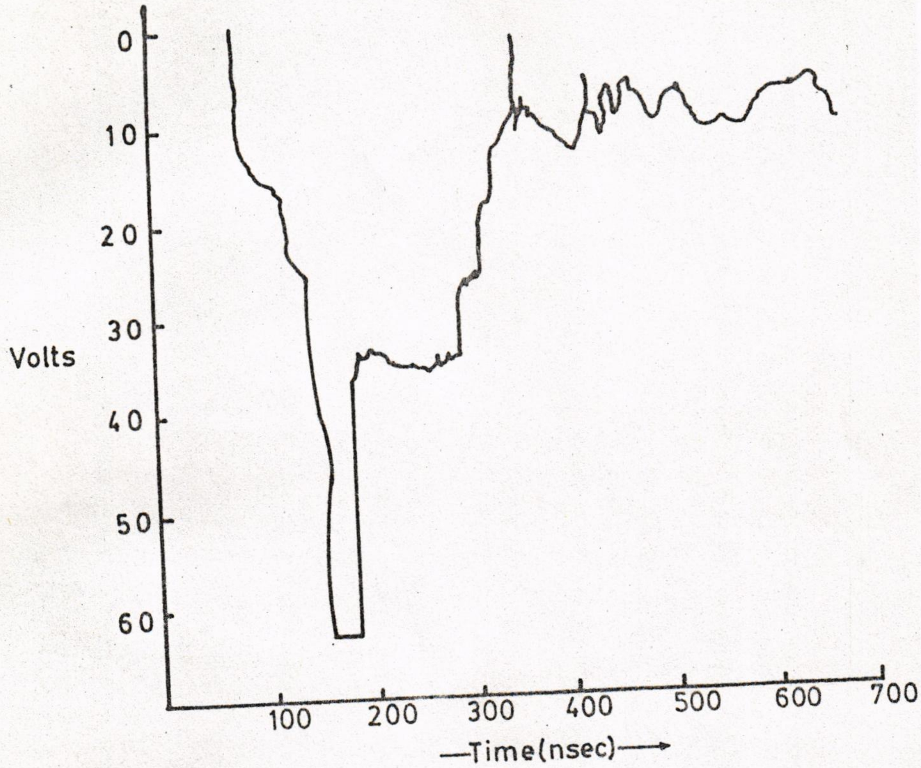
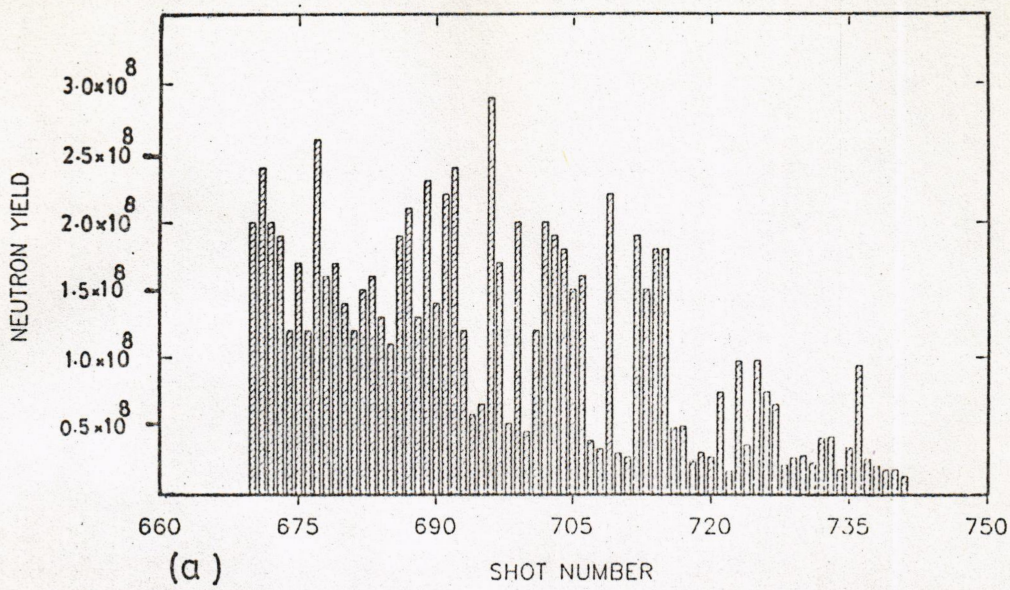


Figure 8


NEUTRON YIELD
3·0×10^8
2·5×10^8
2·0×10^8
1·5×10^8
1·0×10^8
0.5×10^8
660
675
690
705
720
735
750
(a)
SHOT NUMBER

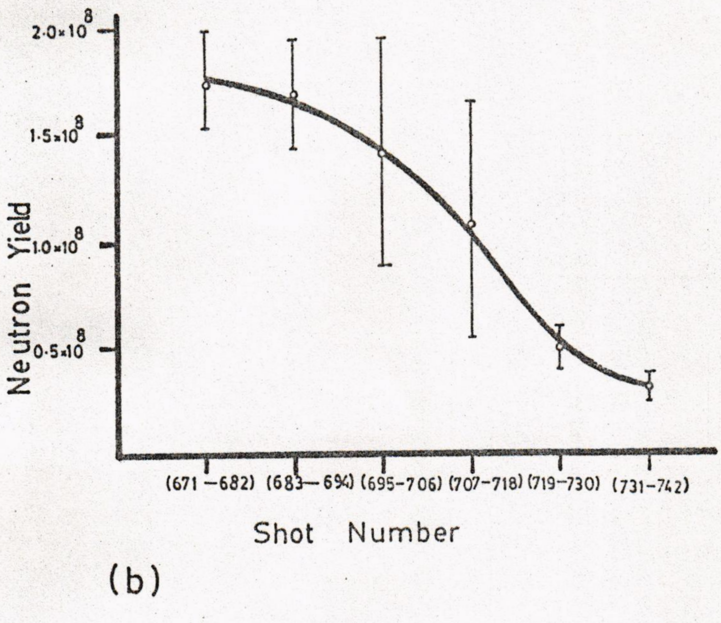

Neutron Yield
2·0×10^8
1·5×10^8
1.0×10^8
0·5×10^8
(671 −682) (683−694) (695−706) (707−718) (719−730) (731−742)
Shot Number
(b)

Figure 9

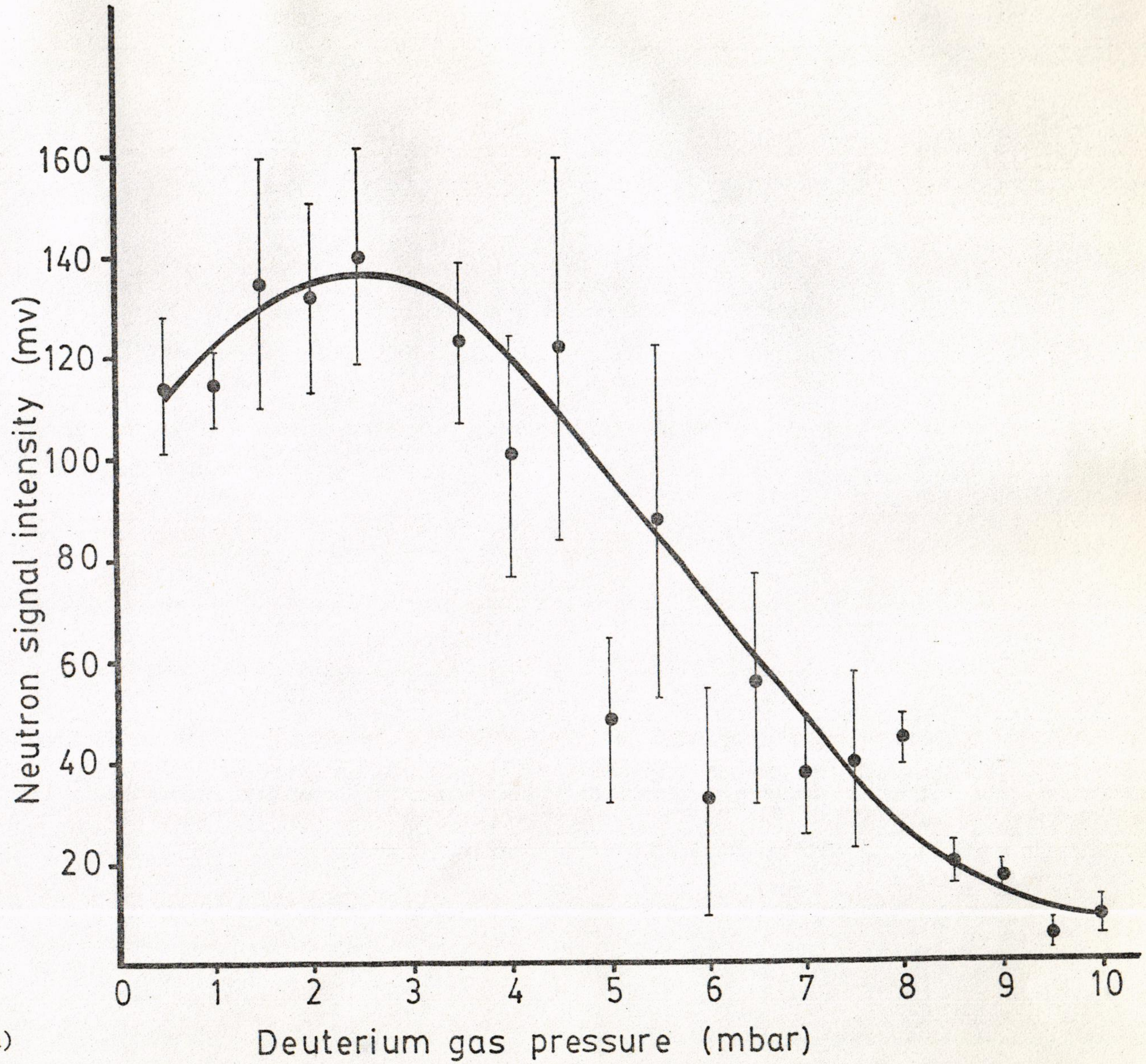

Neutron signal intensity (mv)
160
140
120
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
Deuterium gas pressure (mbar)

Figure I0(a)

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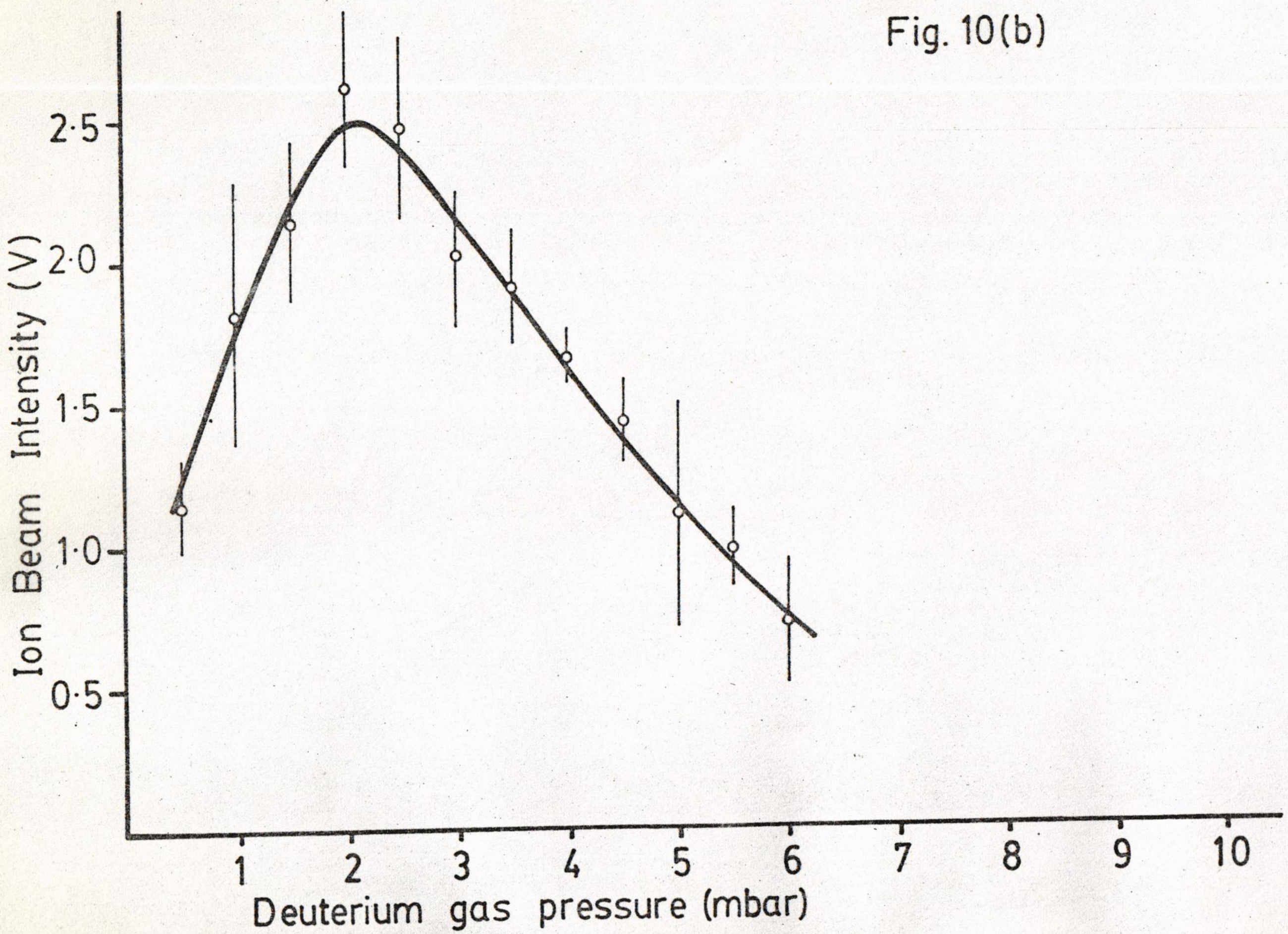
Fig. 10(b)



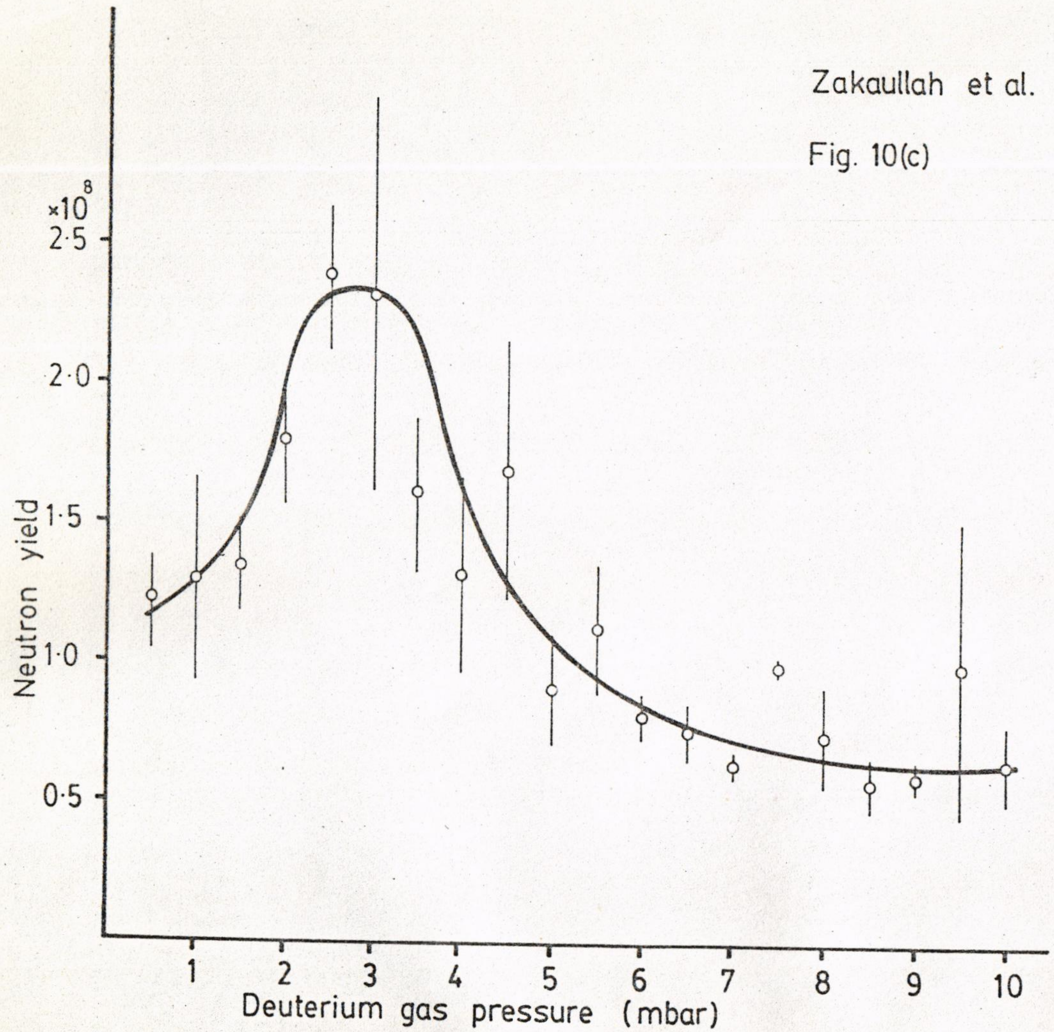


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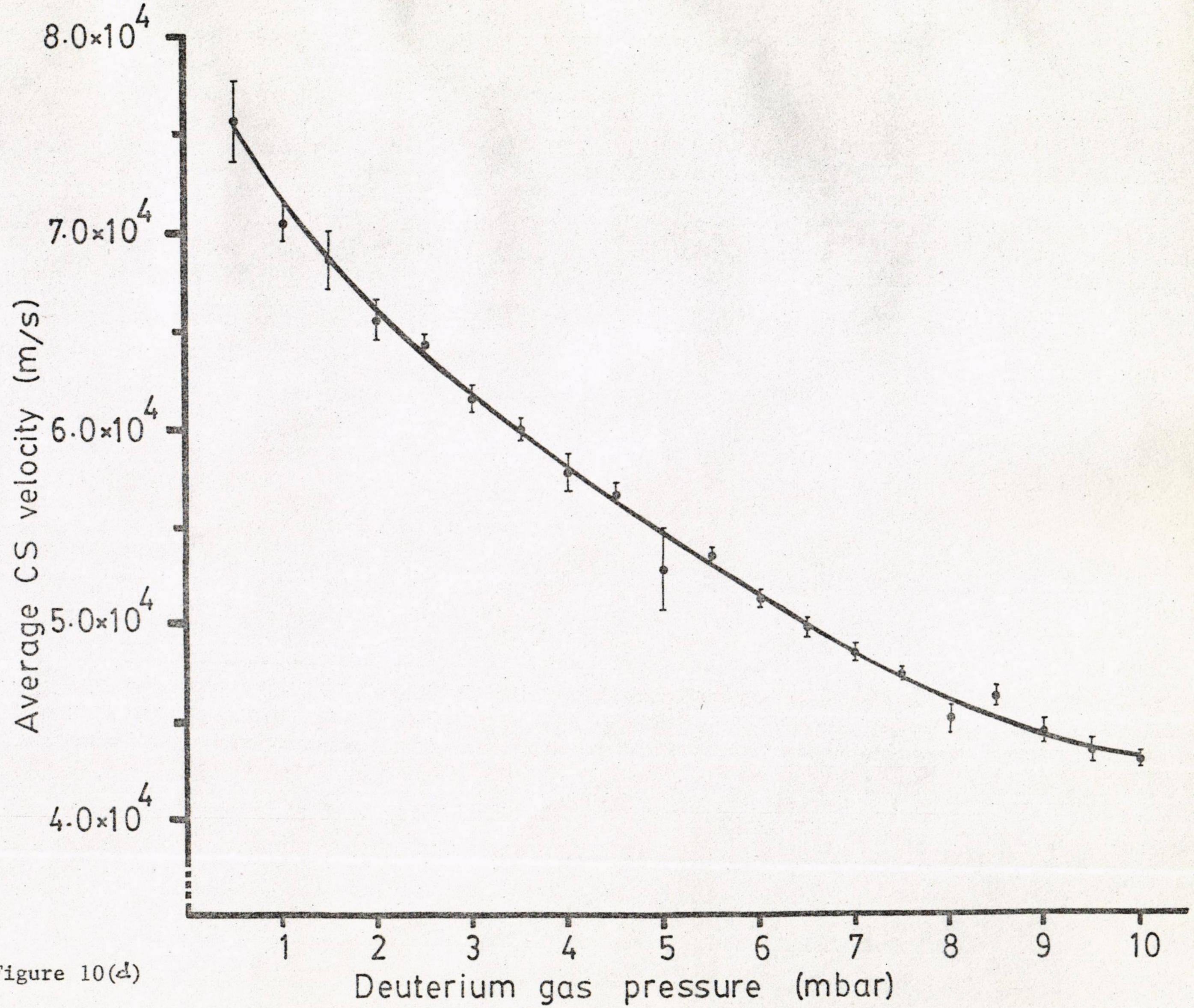
Fig. 10(c)



8.0×10^4
7.0×10^4
6.0×10^4
5.0×10^4
4.0×10^4
Average CS velocity (m/s)
1
2
3
4
5
6
7
8
9
10
Deuterium gas pressure (mbar)

Figure 10(d)

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Fig. 11