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Collaborative Research using the Small Plasma Focus

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COLLABORATIVE RESEARCH USING THE SMALL PLASMA FOCUS

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Abstract

A study of the body of experimental results as well as modelling indicates that all plasma focus machines big and small operate with the same energy density both in the axial and radial phases related to an almost constant current per unit radius for all machines. This results in operational speeds and compressed plasma temperatures which are the same for all machines. It is proposed that the existing network of 3 kJ machines may be the most efficient and effective way to produce a comprehensive experimental picture of the plasma focus, apart from 'large machine' effects such as the neutron 'saturation' effect. Operational benchmarks are established for these 3 kJ machines for the purpose of standardisation to increase the effectiveness of comparative studies using different measurements obtained from different, though nearly identical machines.

1. Introduction

The small plasma focus (1-10 kJ) is the most cost effective device to produce a high temperature (1 keV) and high density (10^{19} cm^{-3}) plasma. When operated with argon or xenon it produces large quantities of soft x-ray whilst with deuterium it produces a fusion plasma. Typical operation in a 3 kJ device in 3 torr deuterium produces a burst of 10^8 neutrons of 10^{-7} second duration giving peak emission rates in excess of 10^{15} n per second. The scaling law that neutron yield is proportional to the square of device energy ($Y \sim E^2$) has been experimentally established.

A careful comparison of data[1] produced by large (above 100 kJ), medium-sized (10 kJ-100kJ) and small plasma focus machines all over the world indicates that irrespective of size all installations produce plasmas of the same temperature within a small range of densities. This is a remarkable and useful characteristic for design purposes. This characteristic is closely related to a simple conventional design criterion that the current amplitude per cm of anode (I_o/a) is almost constant at about 300 kA per cm. This ensures for all machines the same value of drive magnetic field in the axial phase and the same compressed energy density in the focus phase leading to the same high temperature in all devices, large or small. On the other hand this energy density limit corresponding also to an axial drive speed limit of about 10 cm/μs is also suspected of limiting the neutron yield scaling law to $Y \sim I^4$ instead of a better scaling law of $Y \sim I^n$ where n could be as high as 8 if advantage is taken of the rapid increase of D-D fusion cross-section with temperature (power greater than 4) at the operating temperature of existing plasma focus machines.

The larger machines produce more neutrons. This increased neutron yield appears to be due only to a combination of the larger volume of focussed plasma with the consequent increase in lifetime of the focussed region. Any realistic modelling of the plasma focus will show that each linear dimension of the approximately cylindrical focus or pinch region is proportional to the anode radius. And since all plasma focus are designed conventionally with a constant I_o/a it follows that the volume of the focussed or pinched plasma is proportional to I_o^3. The period of plasma confinement is limited by the magnetohydrodynamic transit time, a function only of the smallest linear pinch dimension, and hence of I_o since the energy densities which control the relevant magnetohydrodynamic speeds are practically identical as discussed above. Combining these scalings of volume and confinement time gives immediately the experimentally observed scaling law of $Y \sim I^4$. However for large machines a neutron 'saturation' effect has been reported which appears to inhibit the production of neutrons to below that predicted by the 4th-power scaling law as the machine energy is pushed beyond the region around 200 kJ. The small plasma focus does not suffer from this difficulty. On the other hand it should be pointed out that the small plasma focus cannot be used to study this phenomenon of neutron 'saturation'.

2. The phases of plasma development

Breakdown phase: The device consists of an inner electrode and a coaxial outer electrode separated by a refractory insulator at the launching end. Capacitor C_o charged to voltage V_o is switched onto the inner electrode by switch S (Fig.1) so that a discharge occurs across the surface of the insulator between the electrodes. The **JXB** force on this axially symmetric surface current lifts the current off the insulator in an inverse pinch phase.

Axial acceleration phase: The current then flows radially outwards between the electrodes in a radially symmetric sheet canted in the forward direction at the inner electrode. The current sheet scooping up all the gas it encounters is accelerated down the tube. Detailed experimental work has shown that for a 1-D representation it is necessary to assume that the drive current is a fraction (typically 0.8) of the external circuit current whilst the mass swept-up is a fraction (typically 0.2) of the total mass encountered by the current sheet. This may be referred to as a current shedding and a mass shedding effect.

Radial implosion phase: When the current sheet reaches the end of the anode the end of the sheet which has been sliding along the anode in the axial direction begins to slide across the face of the centre electrode in the radially inward direction. The other end which has been sliding along the outer electrode in the axial direction continues in its motion. Because of the increasing drive magnetic force (inversely proportional to the square of radius) the current sheet or magnetic piston accelerates inwards driving an imploding shock wave ahead of it. The configuration is that of an elongating pinching layer of shock heated plasma (of length z_f) lying between the radially converging shock front at r_s and the radially driving piston at r_p.

When the shock front has imploded on-axis the magnetic piston continues converging on-axis driving the shock which reflects off-axis. The reflected shock soon hits the piston ending the dense phase. Whilst it lasts a dense plasma column sits on the axis of the focus tube just off the face of the anode. As a rule-of-thumb the radius and length of this dense plasma focus column (Fig.2) may be taken as 1/8 a and a respectively when operating in deuterium, and has a significantly smaller radius less than a when operating in argon or xenon due to thermodynamic effects[2]. Towards the end of this dense plasma phase instabilities mainly of the $m=0$ type set in. The dense column seems to explode in a manner more rapid and certainly more spectacularly chaotic than the relatively very well-behaved implosion phase. A large diameter turbulent plasma is rapidly formed.

The sequence of events from the implosion to the formation of the large diameter plasma has been presented in sequences of time-resolved Schlieren photographs correlated to the measured tube voltage, and x-ray and neutron signals (Fig.3)[3]. There is consistent evidence to show that the soft x-ray from the plasma is associated mainly with the dense plasma phase, the hard x-ray is more to be associated with the instability phase whilst the neutron emission peaks between the instability and the explosion phase.

3. Design parameters of the plasma focus

The electro-dynamical behaviour of the plasma focus may be described in each of the major phases by writing down the equations of motion coupled to an appropriate circuit equation.

In the axial phase adopting a snow-plow or thin-layer model results in a two-equation system[4] which on appropriate normalisation yields two scaling parameters determining the behaviour during this phase. These two parameters take the form of an impedance matching parameter, $\beta=L_{zo}/L_o$ defining the matching of L_{zo} the maximum tube inductance of the axial phase to the stray inductance L_o of the circuit and a time matching parameter, $\alpha=t_o/t_a$ defining the matching of t_o the characteristic electrical time of discharge to the characteristic axial transit time t_a where $t_a= Kz_o p_o^{1/2}/(I_o/a)$. K is a geometrical constant also incorporating the current shedding and mass shedding factors and p_o is the ambient density. This yields a characteristic axial speed of $u_a=z_o/t_a$ which assumes the form: $u_a \sim (I_o/a)/p_o^{1/2}$

Moreover[18] in both the axial and radial phases the characteristic speeds scale as (I_o/a) and inversely as $(p_o^{1/2})$.

There are 3 design criteria[5] arising out of the consideration of the axial phase. First, the value of α should be designed to be in the range 1-1.5. Second, β should not be too much less than 1. Third, all conventional machines seem to need to be adjusted to operate in a narrow range of axial speeds (just before radial collapse) of 8-12 cm/μsec, in order to achieve optimum neutron yield.

The 3 kJ plasma focus known as the UNU/ICTP PFF[5] has been designed with $C_o=30$ μF, $V_o=15$ kV and $L_o=110$ nH. This defines a current amplitude $I_o=250$ kA fixing a as 1 cm, t_o at 1.8 μsec so that risetime to peak current takes 2.8 μsec hence $z_o=16$ cm giving an average axial transit speed of 5.5 cm/μsec corresponding to a peak speed at the end of the axial phase of 9 cm/μsec. Taking $\alpha=1.2$, a current factor of 0.85 and a mass factor of 0.2 enables us to fix an operating pressure of 3 torr in deuterium. Computation[14] of a typical model yields current, voltage variation and also gives trajectories in the axial and radial phases.

4. Studies on the 3kJ plasma focus

Typical behaviour of the 3 kJ plasma focus may be observed from the signature current dip and voltage spike and by shadowgraphs of the current sheet in the axial and radial phases (Fig.4). These results establish that the electro-dynamical behaviour of the small plasma focus is no different from the larger plasma focus devices.

The 3 kJ plasma focus has been used to study ion beams[6] from the focussed plasma using a metal obstacle and deuterated target enabling the neutron emitting regions of the device to be mapped (Fig.5). Such experiments confirm the importance of the deuteron beams in the neutron production of the small plasma focus, no different from the case in bigger plasma focus devices.

X-ray emission characteristics in the 3 kJ plasma focus operating with H_2-Ar mixtures have also been reported[7]. Two main periods are observed in the x-ray emission corresponding to two successive compressions. X-ray emission arising from electron beam activity and dense plasma regions is identified and correlated to detailed features of the dynamics. Figure 6 shows temperature (T_e) evolution deduced from ratio of filtered signals.

Other studies using the 3 kJ plasma focus emphasise on neutron emission[8], influence of backwall insulator dielectric constant on neutron yield[9], instabilities as elaborated by shadowgraphy, materials modification[10] using ion beams from the focus, studies of the plasma focus as a source of high pressure[11], negative polarity plasma focus (Fig.4b) and focus implosion onto a axial wire target[12], studies of a cascading plasma focus system[13] with possibility of sequenced bursts of x-ray and neutrons[14] for cinematographic purposes and studies of chaos mechanisms and deterministic dynamics[15].

5. Network of 3 kJ plasma focus installations

There exists a large variety of phenomena occuring in sub-microsecond phases in the focus, including highly nonlinear and chaotic behaviour, hence each existing plasma focus facility only manages to study some aspects of the total behaviour. The collation of the total behaviour meets with a major difficulty in that each plasma focus is designed differently because of different emphasis. Thus the behaviour of each machine may be differently coloured by different machine effects or boundary conditions peculiar to that machine. Another approach for a comprehensive experimental picture may be to set up a network of identical machines on an international basis. This is not possible for big machines because of the question of cost.

On the other hand much of the physics that may be studied in large plasma focus installations (except for effects such as neutron 'saturation' as pointed out above) can be carried out much more cost-effectively on small plasma focus devices. There is considerable savings also in experimental turn-around time. More scientific manpower resources may be harnessed in a network including also small laboratories in small nations. Furthermore a network of 15 identical machines already exists in countries including Sierra Leone, Nigeria, Egypt, Italy, Pakistan, India, Thailand, Malaysia, Singapore, Indonesia and China. The research using this 3 kJ machine designated as the UNU/ICTP PFF (United Nations University/ International Centre for Theoretical Physics Plasma Fusion Facility)[5,17] is very diversified as already mentioned earlier. For example the machine in Pakistan is being used to look into a variety of problems[9] including 2-D modelling, dielectric effects and instabilities; one of the two in India is being used for materials modification[10]; that at the ICTP[15,16] in Trieste has been used for studies on chaos and deterministic dynamics, to bench-mark the performance of the device and to provide international training as have the ones in Malaysia which are also being used for neutron[6], x-ray[7] and basic studies, the one in Singapore for device development, cascading focus studies[14] and thermodynamic effects[2], the ones in Indonesia for neutrons[8] and aerospace applications[11] and the one in Shanghai is being planned for laser-focus interaction. Gradual upgrading of the scientific expertise and diagnostic systems will enable the diverse results of the network of identical machines to have an impact when collated and compared perhaps under the coordination of the Asian African Association for Plasma Training (AAAPT) which has taken a leading role in the establishment of this network of devices[17] as a network of the ICTP.

6. Bench-marking the 3 kJ Plasma Focus

In order for the results of the network of 3 kJ plasma focus machines to be collated to form a comprehensive total body of evidence on the experimental behaviour of the plasma focus in all its aspects, identical design alone is not enough. The devices have to be compared at identical conditions of operation. With reference to the discussions of Section 3 above the axial phase dynamics is governed by the scaling parameters α and β. In identical machines (identical C_o, L_o, V_o, a, z_o) these scaling parameters are made identical when the ambient pressure is set to be identical for each gas used. A more detailed discussion[18] shows that even when the radial phase dynamical equations are considered the additional scaling parameters introduced remain identical for identical gas species and pressure. Thus bench-marking becomes a straight-forward procedure. Considering the large number of studies that have been carried out in the 3 kJ plasma focus[5-16] we propose the following bench-marks to ensure that the 3 kJ plasma focus is operated at optimum consistency with good production of neutrons (deuterium operation) and soft x-rays:

Deuterium : 5.5 mbar
Air : 0.9 mbar
Argon : 0.6 mbar
giving with better than 95% consistency the following:
Axial Transit time measured from start of current to time of voltage spike : 3.0 μs
Peak axial speed before focus : 9.0 cm/μs

The proposal is that every set of experiments carried out on each of the network of 15 identical 3 kJ plasma focus machines should comprise at least some discharges with the above bench-mark operating conditions. The results of these bench-mark shots should be carefully kept. This enables standardisation and interpolation, when necessary, of results for meaningful comparison.

7. Complementing International Cooperation in Plasma Focus Research

The scientific activity of this network can complement the envisaged role of the proposed ICDMP, International Centre for Dense Magnetized Plasma which plans to build within one centre a range of devices including one large (MJ) device, several medium energy devices and several small devices with two main objectives; firstly the consolidation and exchange of the scientific and technological expertise in pulse power technology and plasma focus technology on a world-wide basis and secondly the further development of scientific manpower in these areas by the provision of essential and integrated training combined with follow-up equipment. The Working Group of the ICDMP formed in Moscow in December 1990 has since met another 6 times in Warsaw, Paris, Stuttgart, San Diego, Ferrara and Beijing and London. It meets again in October in Buenos Aires. In the meantime the training and international exchange aspects of plasma focus research is already being carried out, made possible by the versatility, simplicity and richness in physical phenomena of the 3 kJ plasma focus. Moreover with proper bench-marked experiments results from the network of 3 kJ machines may produce a more comprehensive picture of plasma focus physics than otherwise possible.

References

1. "Plasma focus" World Survey of Activities in Controlled Fusion Research (1986 Ed), Nuclear Fusion Supplement, pg 201 (1986).
2. S.Lee, Australian J. Phys **35**, 891 (1983)
3. K.H.Kwek, Ph D Thesis, Universiti Malaya (1989)
4. S.Lee "Plasma Focus Model Yielding Trajectory and Structure" in Radiation in Plasmas, B.McNamara Ed. World Scientific pg 967-977 (1984).
5. S.Lee et al, Amer. J. Phys. **56**, 62-68 (1988).
6. S.P.Moo, C.K.Chakrabarty & S.Lee, IEEE Trans Plasma Sc **19**, 515 (1991).
7. M.Favre, S.Lee, S.P.Moo & C.S.Wong, Plasma Sources Science and Technology **1**, 122-125 (1992).
8. W.Usada, Suryadi & Agus Purwadi "Neutron burst of BATAN PFFF, to be published.
9. M.Zakaullah et al, Phys. Lett.A **39**, 137 (1989); Ph D Thesis, Quaid-I-Azam University. (1988)
10. M.P.Srivastava et al, to be published.
11. S.Mulyodrono, Ph D Thesis, Bandung Institute of Technology, Indonesia (1993).
12. S. Lee et al, J.Fiz. Mal. **11**, 1 (1990).
13. S. Lee et al, IEEE Trans Plasma Sc **18**, 1028 (1990).
14. S. Lee, IEEE Trans Plasma Sc **19**, 912 (1991).
15. J. Gratton, M.A.Alabrabra, A.G.Warmate and G.Giuudice "Deterministic Dynamics of Plasma Focus Discharges" Report IC/92/60 , ICTP Trieste (1992)
16. S. Lee, A. Serban & others "Report of Experimental and Diagnostic Working Group" ICTP Spring Coll on Plasma Phys, May-June 1991.
17. S.Lee "Training Prog for Research Transfer-Experience & Results" invited paper Internat Conf on Phys & Physicists for Development, 1990, Enschede, Netherland; Procs. pg 88-104.
18. S.Lee "Technology of the Small Plasma Focus" Invited Lecture at Spring Coll on Plasma Phys, Trieste Italy May-June 1989; pub in Procs. "Small Plasma Physics Experiments II" 114-169 (1990) World Scientific (Ed.S.Lee & P.H.Sakanaka)

*This paper has also been presented (S.Lee) in substantially the same form at the Changsa Conference on Plasma Physics 4-14 May, 1993.

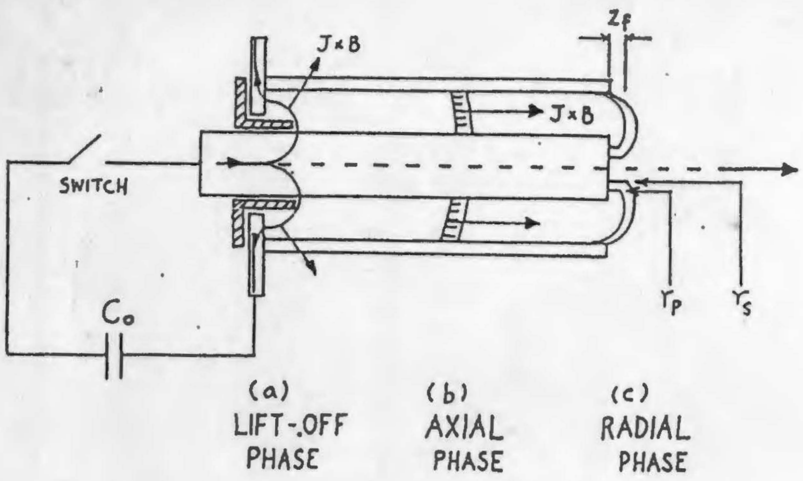


Fig.1 : Modelling the plasma focus:
(a) breakdown and lift-off phase
(b) axial acceleration phase
(c) Radial implosion focus phase; the **JxB** force during this phase implodes the plasma layer radially inwards, at the same time elongating the pinching column.

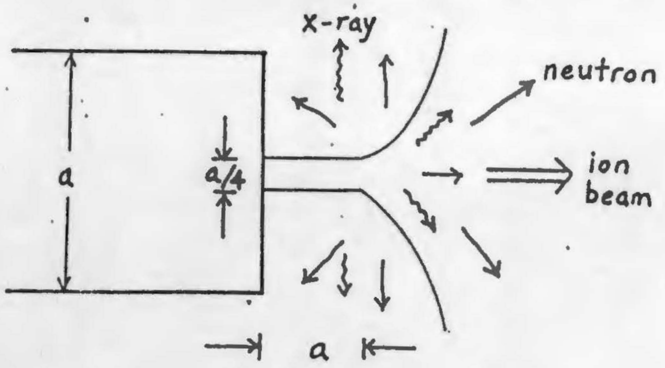


Fig.2 : Dimensions of the dense plasma focus column, at the end of the implosion phase.

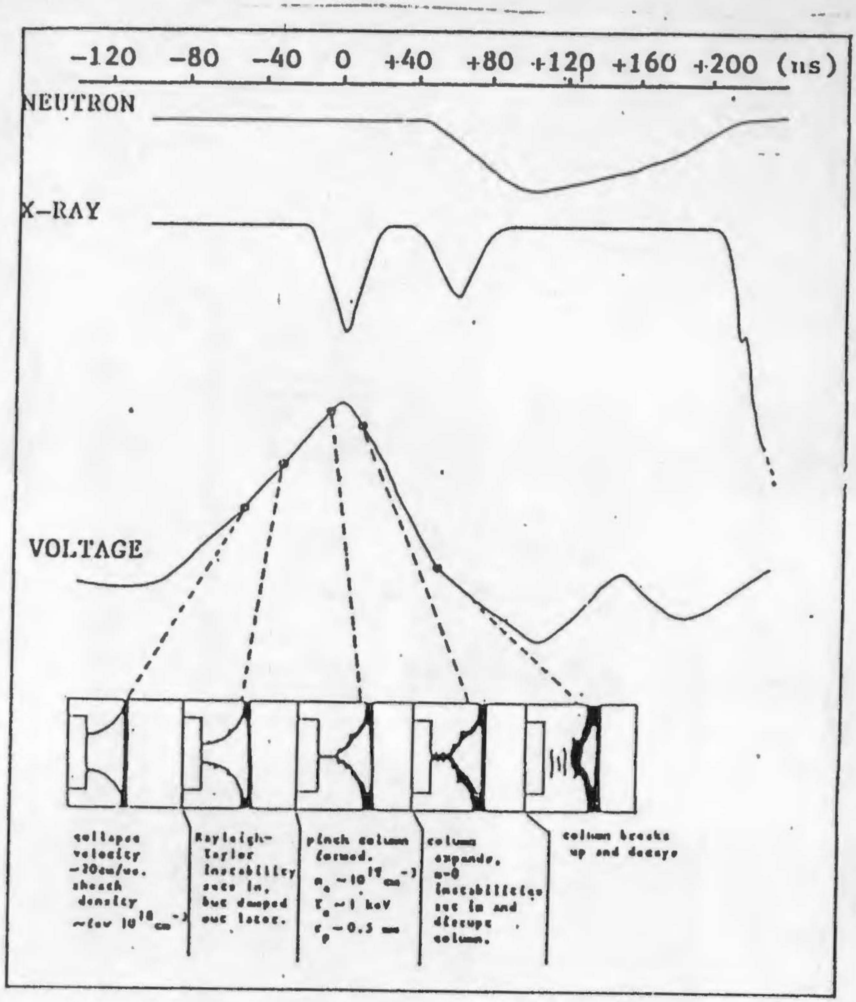


Fig.3 : Summary of the temporal development of the radial implosion process

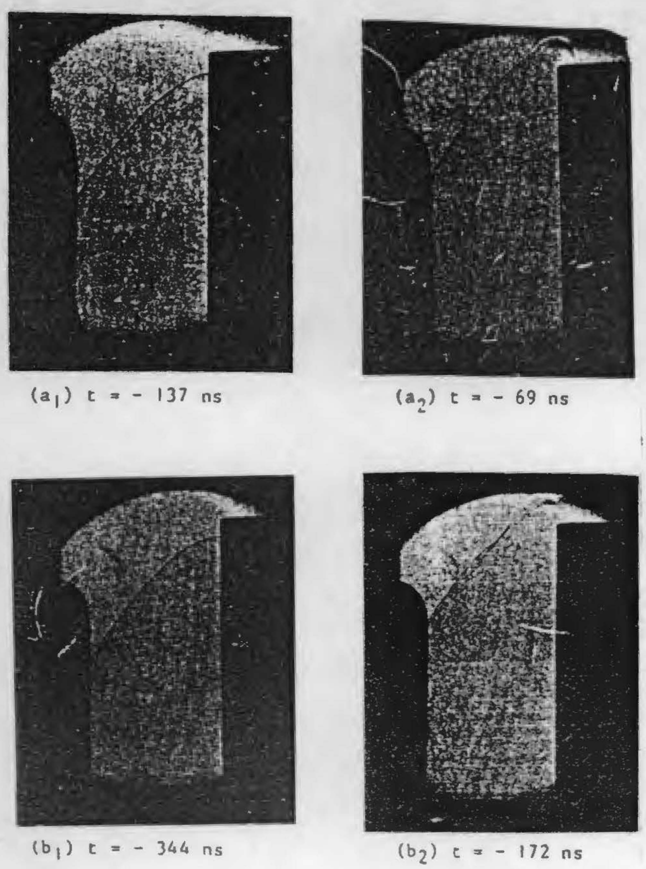

(a₁) t = - 137 ns
(a₂) t = - 69 ns
(b₁) t = - 344 ns
(b₂) t = - 172 ns

Fig.4 : Shadowgraphs comparing axial phase and start of radial phase for normal positive polarity versus negative polarity focus ;

(a_1) positive polarity end of axial phase
(a_2) positive polarity start of radial phase
(b_1) negative polarity end of axial phase
(b_2) negative polarity start of radial phase

In each shadowgraph, the anode is on the right and the cathode is on the left. Axial motion is upwards.

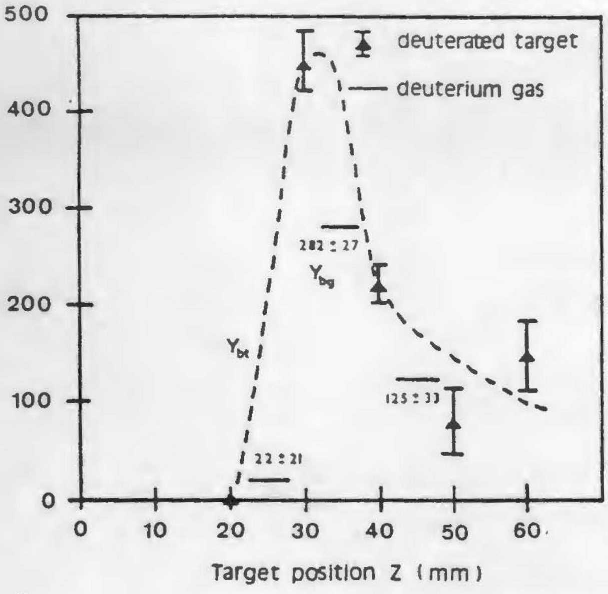
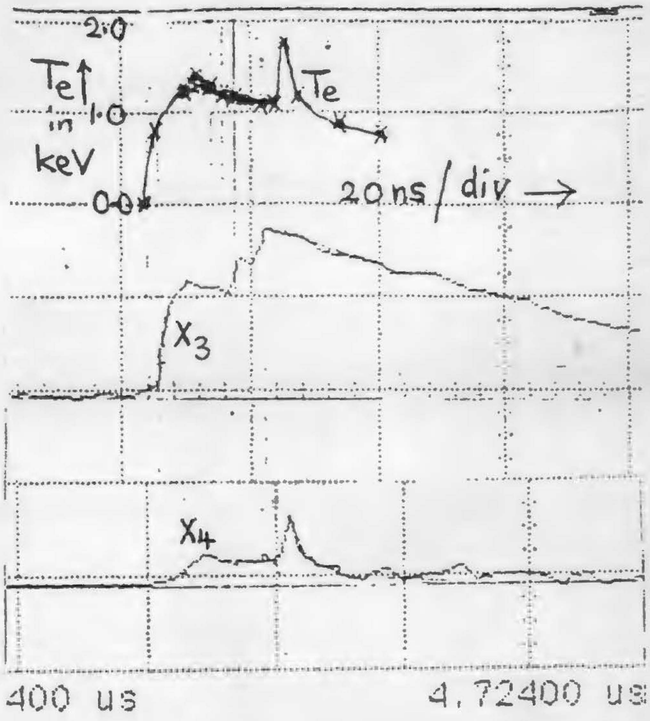


Fig.5 : Variation with position of the neutron counts (single shot) due to deuterated target alone (Y_{bt}) and due to the per cm of deuterium gas in the chamber (Y_{bg}).



20 ns/div

	Sensitivity	Offset
X_3	5.00 V/div	0.00 V
X_4	2.00 V/div	6.00 V

Fig.6 : Single shot x-ray emission in 0.6 torr Ar.

X_3 : aluminised mylar filter (24 μm)
X_4 : aluminised mylar filter (24 μm) + 10 μm copper filter
(X_4 trace has been displaced 4 ns to compensate for difference in cable lengths)

T_e : electron temperature T_e in keV as a function of time deduced from the ratio of the signal amplitudes of X_3/X_4