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ABSTRACT: Removing the speed (v) limitation of present generation plasma focus devices would improve the present scaling law of $Y \sim I^4$ to an ultimate $Y \sim I^8$. Some results of speed-enhanced experiments are reported indicating that the thermonuclear component $Y_{th} \sim I^4 v^4$.

1. INTRODUCTION

The plasma focus PF is important for generating fusion neutrons. An analysis of data for PF devices in their wide range of sizes from 1 kJ (small) to 1 MJ (large) shows the following **experimentally** observed features: (1) They follow the neutron yield Y scaling law with focus current I of $Y \sim I^4$ and (2) For neutron optimized operation they all (a) have the same limited axial speed v_a of 10 cm/μs and radial on-axis collapse speed v_f of 25 cm/μs driven by a standard value of undamped current per unit anode radius I_o/a =250 kA/cm (b) operate in a narrow range of pressures of several torr (D_2).

In this paper we propose that removing the speed limitation would result ultimately in a **vastly improved scaling of $Y \sim I^8$** which could enhance prospects of the PF as a fusion contender. We deduce the speed-enhanced scaling law as follows: First consider the thermonuclear component Y_{th} of the yield.

2. THERMONUCLEAR COMPONENT OF YIELD, Y_{th}

Operating in deuterium

$$Y_{th} = \frac{1}{2} n_f^2 \langle \sigma v \rangle \; (r_f^2 z_f) \tau_f \qquad \textbf{(1)}$$

n_f = PF number density. Experiments and theory agree that PF radius r_f, length z_f (Lee 1983), and lifetime τ_f of the PF column are each~a, the anode radius. Also PF radial speed v_f (Lee et el 1983, Lee 1990) is proportional to the current linear density (as is the axial speed v_{ax}). Factoring these in we have:

$$Y_{th} = c_x \frac{I_f^4}{v_f^5} \langle \sigma v \rangle \qquad \textbf{(2)}$$

where c_x is a constant. We note that (Glasstone & Lovberg 1960) in the range 1 - 5 keV, for the deuterium fusion reaction: $\langle \sigma v \rangle \sim T^{4.5}$. We note also an assumption that $T_f \sim v_f^2$. With these we have:

$$Y_{th} = c_y \; I_f^4 v_f^4 \qquad \textbf{(3)}$$

where c_y = a constant over the range of PF devices. From (10) it is seen that Y_{th} scales as I^4 since v_f is practically a constant in existing PF devices.

3. BEAM TARGET COMPONENT OF YIELD, Y_{b-g}

Next we consider the beam-gas component Y_{bg}. We assume a simple model in which $Y_{bg} \sim n_o N_b \sigma L$ where n_o is the number density of the target gas, N_b is the total number of ions in the beam, $\sigma(x)$ is the fusion cross section and L is the effective interaction length. In the range 100 to 1000keV which is the beam energy of relevance we may put $\sigma L \sim E_b^{3/2}$ where E_b is the beam energy. We further assume an inductive model for the beam acceleration voltage such that $E_b \sim v_f I_f$ and $N_b \sim a^3$. Then we have:

$$Y_{b-g} = C_z \frac{I_f^{4.5} \rho_o^{1/2}}{v_f^{3/2}} \tag{4}$$

Here c_z may be taken as constant. Eq 15 shows that $Y_{b-g} \sim I^{4.5}$ for operation at fixed density and v_f.

4. NEUTRON YIELD Y

The total neutron yield is $Y = Y_{th} + Y_{b-g}$ and Moo et al (1991) have shown that $Y_{b-g}:Y_{th}$ is of the order of 85:15. Thus Equations (10) and (15) are not inconsistent with the observed neutron yield scaling law of $Y \sim I^4$, noting that this scaling law is at best an indicative one based on many experiments conducted under diverse conditions.

5. SPEED-ENHANCEMENT FOR YIELD $Y \sim I^8$

Equations (10) and (15) also indicate that if experiments do not limit the speed of operation, then $Y_{th} \sim I^4 v_{ax}^4$ will increase above the I^4 scaling whilst $Y_{b-g} \sim I^{4.5}/v_{ax}^{1.5}$ will have a scaling law poorer than $Y_{b-g} \sim I^{4.5}$. In the limit keeping 'a' constant whilst increasing I, $v_{ax} \sim I$ so that in that limit (constant 'a'): $Y_{th} \sim I^8$ and $Y_{b-g} \sim I^3$. Since $v_f \sim v_{ax}$ (Lee 1990) these are used interchangeably in the consideration of proportionality.

From the above analysis the following conclusions are drawn:

Operation at increased speed (above v_{ax} of 10 cm/μs) should: (1) increase Y_{th} preferentially to Y_{b-g} and (2) make the scaling law more favourable than $Y \sim I^4$ with the most favourable scaling law being $Y \sim I^8$.

6. SPEED-ENHANCEMENT EXPERIMENTS

Following Mather's pioneering work (Mather 1965) all Mather-type plasma focus devices, big and small, have been designed for optimum operation around a standard value of I_o/a = 250 kA/cm. Experiments have shown that when pressure is varied good focusing is observed only in the limited v_{ax} range of 6 - 10 cm/μs (Lee 1990). The lower limit is easily understood in terms of poor coupling indicated by a low magnetic Reynolds Number R_m (Lee et al 1991), or low specific energy (Pouzo et al 1988). For the higher speed limit, it may be that the high R_m leads to an effective separation (Lee 1990) of MP from the driven plasma layer. The plasma layer then collapses radially whilst MP is still driving axially thus limiting the focusing efficiency.

We propose to limit this force field, flow field separation by a stepped anode structure. The first part of the axial phase uses a regular anode designed for standard I_o/a = 250 kA/cm, but shorter than required to match the discharge peak. The regular anode is attached to a stepped-down anode of smaller radius to increase the speed by an increase of I_o/a. This speed-enhanced section should be long enough to increase the speed significantly above 10 cm/μs, but short enough to limit force field, flow field separation. In this manner the speed increase is achieved by an increase in I_o/a at constant optimum pressure rather than by the usual method of reduced pressure.

EXPERIMENTAL SET-UP

The following configurations (3.3 kJ plasma focus, Lee et al 1988) are used:

One-piece anode: (a cylindrical electrode of uniform radius)

SPF 165/19 -standard starting configuration
(165mm long, 19 mm diameter, see Fig 1a)
MPF 175/17.5 -optimized one-piece anode
MPF 180/17 and MPF 185/15 -one piece anode, diameter reduced

Composite anode: (anode with second section having reduced diameter, Fig 1b)
MPF-103/19+70/15; MPF- 93/19+80/15; MPF- 95/19+90/14; MPF- 65/19+120/15 and MPF- 45/19+140/15.

Simultaneous measurements (see Fig 2) were made of current I, dI/dt, soft x-rays, axial speed v_{ax}, just before the radial collapse phase, hard x-ray and neutron pulses taken with PM-scintillator system placed at 3.5m and 6.1m, and also total neutron yield Y_n using an Indium foil activation counter. Shadowgraphs of the axial phase just before the radial collapse phase were also taken for some of the configurations.

RESULTS

1. A speed range (axial speed, just before radial collapse) of 7-14.8 cm/μs was achieved. (speed measurement accurate to 4%)
2. Neutron TOF measurements yielded the following conclusions:

(a) energy of neutrons E_n= 2.47 Mev (using a peak-to peak method of analysis)

(b) the neutron pulse detected by the far detector is broader than that detected by the near detector

(c) total neutron yield optimized at 4.5 mbar varies with va_x from $1.11x10^8$, averaged over 100 shots (SPF-165/19) at v_{ax}=8.3 cm/μs to $1.8x10^8$ (MPF-103/19+70/15) at v_{ax}=11.7 cm/μs.

(d) estimate of the proportion of thermonuclear neutrons to the total neutron yield Y_n was made by considering the area of the TOF detector output from the start of the n pulse to the start of the hard x-ray pulse to be purely thermonuclear. This method is found to underestimate the number of thermonuclear neutrons by a factor of 2. Nevertheless this underestimate shows a clear trend of 6-9 % of thermonuclear neutrons at v_{ax} of 8-9 cm/μs increasing significantly to 12-16% at v_{ax} of 10.5-11.5 cm/μs.

(e) The thermonuclear yield component was found to fit the relationship:

Y_{th}= $2.1x10^{-6}I^4v_{ax}^4$; I, measured peak current in kA and v_{ax} in cm/μs.

(f) Laser shadowgraphy indicated that the average canting of the current sheath increases from $40-45^0$ at 8-9 cm/μs to $55-60^0$ at 10-12 cm/μs.

CONCLUSION

A theory is presented indicating that in the present range of operation of the plasma focus:

Y_{th} should increase with speed, keeping all other parameters constant; and that Y_{th} should scale as I^4v^4. In this paper this is designated as the mechanism of speed-enhancement of thermonuclear neutron yield.

A set of experiments have been designed using composite anodes to increase the operational speed of the plasma focus by increasing the driving current density and to inhibit separation of the force-field flow-field that in normally operated plasma focus devices apparently tend to become significant at speeds higher than 10 cm/μs.

The results are indicative that the speed-enhancement mechanism has been observed in the limited axial speed range of 8- 14 cm/μs.

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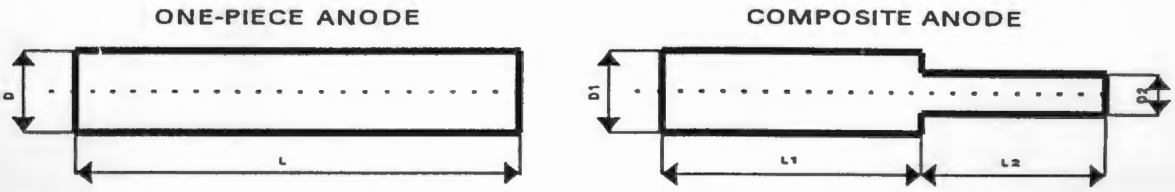

a

Fig. 1

b

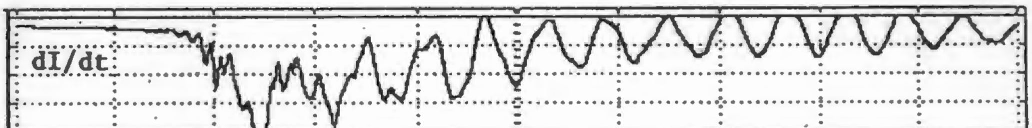

Fig. 2

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