SPEED ENHANCEMENT OF NEUTRON YIELD

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ABSTRACT: Removing the speed limitation of present generation plasma focus devices would improve the present scaling law of $Y \sim I^4$ to an ultimate $Y \sim I^8$. Speed-enhanced experiments are planned.

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

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

n_f = PF number density. Radius r_f, length z_f (Lee 1983), lifetime τ_f of the PF column are each~a, the anode radius. We thus write:

$$r_f = a\,k_f \quad (2) \qquad z_f = a(1-k_f) = 0.88a \tag{3}$$

where $k_f = r_f/a$ = radius ratio of 0.12 for the deuterium focus and

$$\tau_f = \frac{a}{c_1 (I_f/a)/\rho_o^{1/2}} \tag{4}$$

f_{en} = observed lifetime enhancement factor, μ = permeability and

$$where\ c_1 = \frac{\sqrt{\mu}}{2\pi f_{en} d_f}\left[(1/k_f)^2 + \frac{\gamma f_{rs}}{2}\right]^{1/2}$$

f_{rs} = reflected shock over-pressure ratio (Lee 1988). PF radial speed v_f (Lee et el 1988, Lee 1990) is proportional to the current linear density (as is the axial speed):

$$v_f = \frac{I_f/a}{\rho_o^{1/2}} c_2 \quad (5) \qquad where\ c_2 = \frac{\mu^{1/2}(1+\gamma)^{1/2}}{4\pi k_f}$$

$$Hence \qquad a = \frac{I_f}{v_f \rho_o^{1/2}} c_2 \tag{6}$$

Putting Eqs 2-6 into Eq 1 we have

$$Y_{th} = c_x \frac{I_f^4}{v_f^5} \langle \sigma V \rangle \tag{7}$$

$$where\ c_x = \tfrac{1}{2}(n_f/\rho_o)^2 k_f^2 (1-k_f)\, c_2^5 / c_1$$

From nuclear data (Glasstone & Lovberg 1960) we may fit, in the range 1 - 5 keV, for the deuterium fusion reaction:

$$\langle \sigma V \rangle_{D-D} = c_N T^{4.5} \tag{8}$$

where c_N = constant. From pressure balance we write the focus temperature T_f (Lee 1983) as:

$$T_f = c_3 \frac{(I_f/a)^2}{\rho_o} = c_4 v_f^2 \tag{9}$$

$$where\ c_4 = \frac{\mu}{4\pi^2} \frac{m}{k(1+Z)} f_{rs} / c_2^2$$

where m = mass of deuterium atom, k = Boltzmann constant and Z=charge. Put Eq 9 into Eq 8 and then Eq 8 into Eq 7 and we have:

$$Y_{th} = c_y I_f^4 v_f^4 \tag{10}$$

where $c_y = c_x c_N c_4^{4.5}$. We note that c_y may be taken to be 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, $Y_{b\text{-}g}$

Next we consider the beam-gas component Y_{bg}. We write:

$$Y_{bg} = n_o \int N_b\, \sigma(x)\, dx \approx n_o N_b \sigma L \tag{11}$$

where n_o is number density of target gas, N_b is total number of ions in the beam and $\sigma(x)$ is the fusion cross section, and σL represents the product of cross section and effective interaction length. From available nuclear data we may write

$$\sigma L = c_5 E_b^{3/2} \tag{12}$$

where E_b is the beam energy in the range 100 - 1000 keV. Assuming an inductive model for the beam energy we have

$$E_b = c_6 v_f I_f \tag{13}$$

We assume N_b depends on the number of particles in the plasma focus volume we write

$$N_b = c_7\ a^3\ \rho_o = c_8 \frac{I_f^3}{v_f^3\ \rho_o^{1/2}} \tag{14}$$

where $c_8 = c_7\ c_2^3\ (1 - k_f)$. Combining Eqs 11 - 14 we have

$$Y_{b\text{-}g} = c_z \frac{I_f^{4.5} \rho_o^{1/2}}{v_f^{3/2}} \tag{15}$$

where $c_z = c_5 c_6^{3/2} c_8\ n_o/\ _o$. Here c_z may be taken as constant. Eq 15 shows that $Y_{b\text{-}g} \sim I^{4.5}$ for operation at fixed density and v_f.

4. NEUTRON YIELD Y

The total neutron yield is $Y = Y_{th} + Y_{b\text{-}g}$ and Moo et al (1991) have shown that $Y_{b\text{-}g}:Y_{th}$ 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 $Y_{th} \sim I^4\ v_f^4$ will increase above the I^4 scaling whilst $Y_{b\text{-}g} \sim I^{4.5}/v_f^{1.5}$ will have a scaling law poorer than $Y_{b\text{-}g} \sim I^{4.5}$. In the limit keeping 'a' constant whilst increasing I, Eq (5) indicates $v_f \sim I$ so that in that limit (constant 'a'):

$$Y_{th} \sim I^8 \quad \text{and } Y_{b\text{-}g} \sim I^3$$

From the above analysis the following conclusions are drawn: Operation at increased speed (above axial speed of 10 cm/μs) should: (1) increase Y_{th} preferentially to $Y_{b\text{-}g}$ 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) it appears that 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 axial speed range of 6 - 10 cm/μs (Lee 1990). The lower limit is easily understood in terms of poor coupling of the magnetic piston MP with the driven plasma layer, indicated by a low magnetic Reynolds Number R_m (Lee et al 1991), or in terms of low specific energy (Pouzo et al 1988). For the higher speed limit, it appears 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. Such a large separation is not conducive to an intense focus.

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 (see Eq 5). 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. Other factors that need to be considered include the mean free path which increases with temperature. Also a fast rise current may enable the use of a shorter anode thus reducing separation. Experiments are designed and results will be reported shortly.

REFERENCES

GLASSTONE S. & LOVBERG R.H. 1960 *Controlled Thermonuclear Reactions, D Van Nostrand, New York*

LEE S. 1983 *Plasma Physics* **25,** 571

LEE S. 1988, *Laser and Particle Beams,* **6,** 597

LEE S., TOU T.Y., MOO S.P., EISSA, M.A., GHOLAP A.V., KWEK K.H., MULYODRONO S, SMITH A.J., SURYADI & ZAKAULLAH M., 1988, *Amer J. Phys.,* **56,** 62

LEE S. 1990 **Technology of a small plasma focus** in *Small Plasma Experiments II* Ed by S.Lee & P.H. Sakanaka, World Sci Pub Co Singapore

LEE S., SAW S.H., ELFETOURI A.A., SHENGHER A.N., SHUMMAKI E.O. & HASSAN N.A. 1991 *J. Fiz. Mal.,* **12,** 25.

MATHER J.W. 1965, Phys. Fluids 8, 366.

MOO S.P., 1991 *IEEE Trans. Plasma Sc.* **19,** 515.

POUZO J., CORTAZER D., MILANESE M., MOROSO R. & PIRIZ R, 1988 **Limits of Deuterium Pressure Range with Neutron Production in Plasma Focus Devices** in *Small Plasma Physics Experiments* Ed. S. Lee & P.H. Sakanaka, World Sci.

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