Neutron Yield Scaling With Inductance in Plasma Focus

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***Abstract*— Neutron yield is enhanced by reduction of the short-circuit plasma focus inductance L_0, which in turn increases the pinch current I_{pinch}. Numerical experiments are carried out to optimize the neutron production using the Lee model on small plasma focus devices (several kilojoules), such as UNU/ICTP PFF, NX2, and LDiana. The maximum neutron yield is obtained for each L_0 with a combination of gas pressure as well as anode length and radius (Y_n versus z_0, p_0 and a at fixed L_0). The numerical experiments confirm the limitation effect of I_{pinch}, and suggest an optimum L_0 in the range of 10–20 nH. Finally, the neutron yield is scaled with system inductance.**

***Index Terms*— Inductance, neutrons, plasma focus.**

I. Introduction

A DENSE plasma focus (DPF) is a device consisting of two coaxial electrodes with a high-voltage source at one end, typically a capacitor bank. In the presence of a low-pressure gas, the high-voltage source forms a plasma sheath at the end of the DPF. The early work on the DPF has shown that hot (≈1 keV) and dense ($\gg 10^{17}$ cm^{-3}) plasma is created with lifetime ∼50 ns in this device [1]. These results have indicated that a plasma focus device can be used as a fusion neutron source, when operated in deuterium, and also as a source of copious high energy electrons and ions, X-rays. A comprehensive review of the plasma focus with discussions of relevance to this paper particularly with regard to the effect of inductance on plasma focus performance had been made in [2]. Moreover, discussions on plasma focus inductance have also been made in a 1975 detailed parametric study by Trunk [3] and in a recent study of a impedance matching transformer applied to the plasma focus by Bures *et al.* [4].

The observed neutron yield for a 3-kJ device, the UNU/ICTP PFF, is typically as high as 10^8 per pulse [5]. The number of models for the neutron production mechanism has been proposed, which are mainly categorized under thermal and nonthermal mechanisms [6].

Two modes of neutron production have been proposed up to now: 1) a beam-target model and 2) moving boiler model. The measured characteristic of the emitted neutrons from various plasma focus devices indicate that neither model adequately explains the observed behavior. There do not appear to be any published results demonstrating nonthermonuclear modeling that may be applied to any particular machine to derive Y_n in a manner where such modeled data may be compared with specific experiments. Given that it is widely held that the neutron yield from the small plasma focus is predominantly from nonthermonuclear mechanisms [7].

The Lee model code was equipped with a beam-target mechanism that computes the Y_n for a wide range of plasma focus machines ranging from the sub-kilojoule PF-400 J to the megajoule PF1000. The comparison shows degrees of agreement between the laboratory measurements and the computed results [18].

The beam-target mechanism is derived using the following phenomenological neutron production process:

1) acceleration of deuterons by high transient electromagnetic fields (high voltages not only by fast varying inductance but also by anomalous resistivity);
2) interaction of those accelerated ions with the pinch plasma (gyration in the magnetic field experiencing mainly Coulomb collisions and some fusion reactions) [8].

Neutron production by the beam-target model [9], [10] is related to the number of ions in the beam, the ion speed, target density, and the beam–target interaction time. The beam–target interaction time is assumed proportional to the confinement time of the plasma column [11]–[13]. Given that the number of beam ions is proportional to the total beam energy that is related to the pinch current [13], the neutron yield is related to the pinch current [14], [15]. Its dependence on target (pinch plasma) density and pinch volume is given in (2).

The current in the pinch is maximum, if it occurs at the maximum discharge current. The main factors that affect the amplitude of discharge current are energy and inductance of the system. Some other factors are important to be considered in the pinch current such as pressure and anode length. The influence of these factors on neutron yield can be explained by their effect on the pinch current. The effect of gas pressure, the anode length, and bank energy have been studied by several groups in the world (see [1], [16]–[18]). Comparing the neutron yield of PACOa [19] (Argentina) and DPF-2.2 [20]

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(both are about 2 kJ) as well as Fuego Nuevo II (Mexico) [21] and GN1 [22] (both are about 5 kJ) shows that the reduction of inductance (to 15–20 nH) increases neutron yield by a factor of 3–4.

Numerical experiments on the PF1000 plasma focus device have indicated [23, 241] that there exists an optimum L_0 for maximum pinch current and reducing L_0 will further increase neither I_{pinch} nor Y_n. This unexpected pinch current limitation effect was first observed by Lee and Saw [23]. Numerical experiments on the PF-SY1 plasma focus device [25], [26] with a capacitance of 25 μF for optimization of soft X-ray yield have confirmed that the pinch current limitation effect also extends to the limitation of soft X-ray yield. Hence, quantitative analysis of the inductance effect on the neutron yield and the determination of optimum inductance is crucial for designing a plasma focus device as a neutron source. In this paper, the effect of reducing the inductance of the system on the pinch current and consequently neutron yield on small plasma focus devices (several kilojoules) is studied using the Lee model [27], [28].

II. Numerical Experiments

The Lee model (open source [28]) couples the electrical circuit with plasma focus dynamics, thermodynamics, and radiation, enabling the simulation of all gross focus properties. The Lee model code is configured to work as any plasma focus by inputting:

1) energy storage capacitance C_0, short-circuit inductance L_0, and stray circuit resistance r_0;
2) electrode parameters b, a, and z_0;
3) operational parameters V_0 and P_0 and the fill gas.

The standard practice is to fit the computed total current waveform to an experimentally measured total current waveform using four model parameters representing the mass swept-up factor f_m, the plasma current factor f_c for the axial phase, and factors f_{mr} and f_{cr} for the radial phases.

In this paper, we kept the model parameters constant and ran numerical experiments for a particular device with specific energy. The numerical experiments were conducted using a constant value of a factor RESF $= r_0/(L_0/C_0)^{0.5} = 0.1$ (RESF = stray resistance/surge impedance. RESF < 0.2 is a typical value for capacitor banks used for plasma focus devices and it makes little difference to the main results of this paper if RESF is taken from 0.05 to 0.2). Also, at each L_0, the ratio ($c = b/a$) was kept constant. To optimize the neutron yield with deuterium gas, varying L_0, z_0, P_0, and a keeping c and RESF constant and axial speed is between 8 and 10 cm/μs. Finally, the best combination of L_0, P_0, z_0, and a that gives the best Y_n is achieved. Table I shows the bank parameters and model parameters of three PF devices.

III. Results and Discussion

Numerical experiments are carried out to enhance the influence of L_0 reduction on the pinch current trace using the Lee model on small plasma focus devices (less than 10 kJ), such as UNU/ICTP PFF, NX2, and LDiana. These machines were chosen because the model parameters are available for them [27]–[31]. At each L_0, anode length z_0, inner radius a, and pressure P_0 were adjusted to obtain the optimum neutron yield that corresponds closely to the largest I_{pinch}.

Fig. 1 shows the numerical results of L_0 reduction on the pinch current. It is seen that I_{pinch} increases with L_0 reduction and reaches a maximum of 10–20 nH, which limits the neutron yield. This pinch current limitation had been investigated earlier on PF1000 [23], [24].

TABLE I
Bank Parameters (Real) and Model Parameters of the Investigated Systems

	UNU/ICTP PFF[26]	NX2[27,28]	LDiana[29]*
Energy (kJ)	3.4	1.7	9.2
Capacitance (μF)	30	28	15
Inductance (nH)	110	20	320
Resistance (mΩ)	12	2.3	12
f_m	0.08	0.0635	0.168
f_c	0.7	0.7	0.7
f_{mr}	0.16	0.16	0.2
f_{cr}	0.7	0.7	0.7

*Private communications.

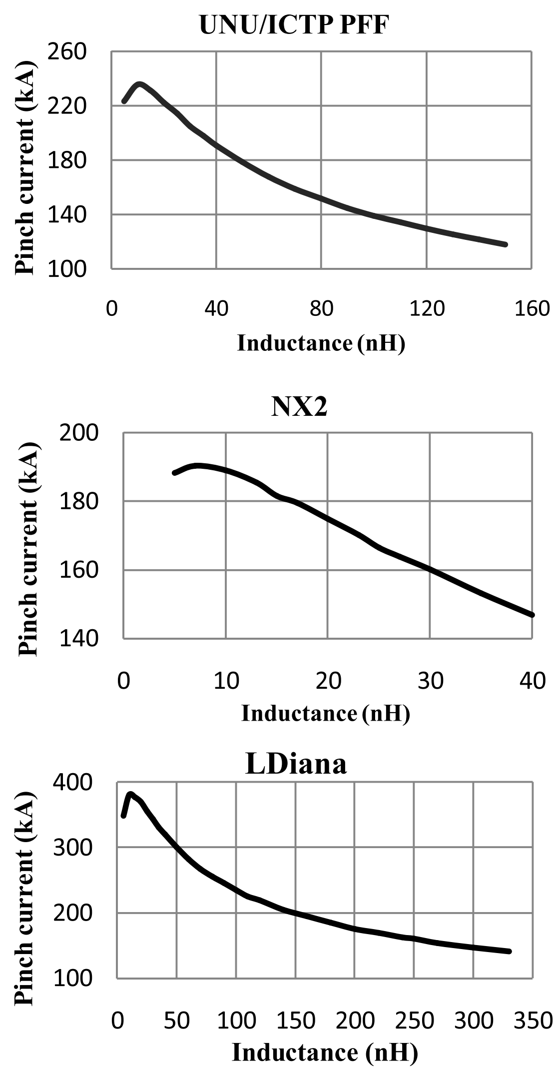

Fig. 1. Effect of L_0 reduction on the pinch current (computed) UNU/ICTP PFF, NX2, and LDiana, when operated with deuterium.

TABLE II
NEUTRON YIELD (COMPUTED) FOR EACH DEVICE AND THE OPTIMUM INDUCTANCE

	declared		Optimum		
	L_0 (nH)	Y_n ($\times 10^7$)	L_0 (nH)	I_{pinch} (kA)	Y_n ($\times 10^7$)
UNU	110	2	15	231.2	23
NX2	20	2.7	13	185.4	7
LDiana	320	2	10	380.7	125

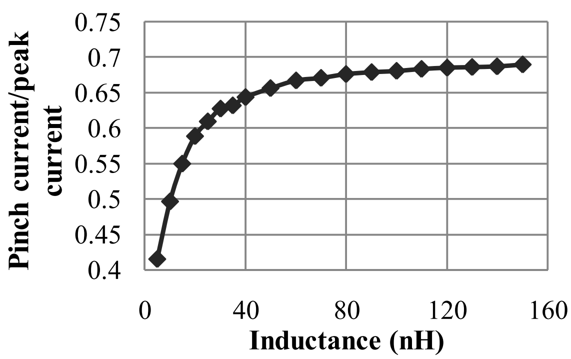

Fig. 2. Effect of L_0 reduction on current ratio (computed).

Several sets of experiments were conducted on the UNU/ICTP PFF, NX2, and LDiana. In every set, an optimum inductance was found to be around 10–20 nH.

It is shown in Table II that when L_0 is reduced, neutron yield of the LDiana is optimized from 2×10^7 at $L_0 = 320$ nH to 1.25×10^9 at $L_0 = 10$ nH. Reducing the inductance of the UNU/ICTP PFF and NX2 to the optimum inductance increases neutron yield from 2×10^7 and 2.7×10^7 to 2.3×10^8 and 7×10^7, respectively.

To explain this unexpected result, we examine the energy distribution in the system at the end of the axial phase right before the current drop from peak value I_{peak} and then again near the bottom of the almost linear drop to I_{pinch}. The energy equation describing this current drop is written as follows [23]:

$$0.5I_{\text{peak}}^2\left(L_0 + L_a f_c^2\right) = 0.5I_{\text{pinch}}^2\left(L_0/f_c^2 + L_a + L_p\right) + \delta_{\text{cap}} + \delta_{\text{plasma}} \quad (1)$$

where L_a is the inductance in the axial phase at full axial length z_0. δ_{plasma} is the energy imparted to the plasma as the current sheet moves to the pinch position and is approximately $0.5L_p I_{\text{pinch}}^2$. δ_{cap} is the energy flow into or out of the capacitor during this period of current drop.

As L_0 is reduced, the ratio $I_{\text{pinch}}/I_{\text{peak}}$ drops progressively. Fig. 2 shows the effect of the reduction of L_0 on the ratio $I_{\text{pinch}}/I_{\text{peak}}$.

IV. Neutron Yield Scaling With Inductance

As previously mentioned, it has been found from neutron emission characteristics that most of the fusion reactions are

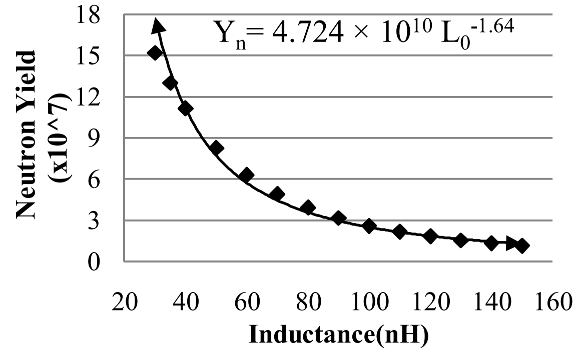

Fig. 3. Neutron yield scaling with inductance for UNU/ICTP PFF derived from the numerical experiments.

from the beam-target mechanism. The beam-target yield is written as

$$Y_{b-t} = C_n n_i I_{\text{pinch}}^2 z_p^2 (\ln(b/r_p))\sigma / V_{\max}^{\frac{1}{2}} \quad (2)$$

where n_i is the ion density in the plasma, I_{pinch} is the current flowing through the pinch at the start of the slow compression phase, r_p and z_p are the pinch dimensions at the end of that phase, σ is the cross section of the D–D fusion reaction, n-branch, and b is the cathode radius. $V_{\max}$ is the maximum voltage induced by the current sheet collapsing radially toward the axis. Here, C_n is a constant, which had been calibrated with an experimental point in practice [13]–[15], [27], [28].

Numerical experiments on small plasma focus devices are carried out, with deuterium gas for reducing the values of L_0 before it approaches the limiting value which in the case of UNU/ ICTP PFF is at L_0 smaller than 30 nH according to the numerical experiments. Fig. 3 shows the results of neutron yield optimization using the Lee model on UNU/ICTP PFF at 15 kV.

Neutron scaling with system inductance has been derived from the numerical experiments on UNU/ICTP PFF, which is

$$Y_n = 4.724 \times 10^{10} L_0^{-1.6} \quad (L_0 \text{ in nH}). \quad (3)$$

The above power law is obtained by fitting all data points of Fig. 3 with log–log axes using Excel power law selection for the trendline identification. The resulting coefficient of determination is $R^2 = 0.99$, indicating a very good fit for (3). Neutron scaling for plasma focus devices of tens of kilojoules is known to follow the scaling law $Y_n \sim E_0^2$ [32]. We then write (3) as

$$Y_n = 4 \times 10^9 E_0^2 L_0^{-1.64} \quad (4)$$

where the inductance of the system (L_0) is in nanohenry and energy of the system (E_0) is in kilojoules. This scaling rule is applicable for all inductances down to 20 nH. Below 20 nH, the scaling rule has to be applied carefully with the necessity of determining the optimum L_0 (Fig. 1 and Table II) for the device. As L_0 is reduced and the optimum L_0 is approached, scaling rule (4) starts to be no longer applicable. Our numerical experiments show that generally this rule applies down to 20 nH.

We briefly discuss the physics that give rise to (4). The first point we note is that as L_0 is reduced below small

TABLE III
COMPUTED NEUTRON YIELD USING (4) AND THE EXPERIMENTAL RESULTS FOR SEVERAL SMALL PLASMA FOCUS DEVICES

Device	Energy (kJ)	Inductance (nH)	Y_n (experimental)	Y_n (Computed)
PACOa	2	47	2.00E+8	0.29E+8
DPF-2.2	2.2	67	5.14E+7	1.95E+7
FN II	4.8	54	1.2E+8	1.3E+8
GN1	4.7	39	3.00E+8	2.2E+8

values such as 20 nH, I_{peak} continues to rise while the rise of I_{pinch} has practically stopped. We need to look at how the rise of I_{peak} is affected by the continued reduction of L_0 to vanishingly small values. We first note that even if L_0 were reduced to vanishing values, the value of I_{peak} would not approach infinity because with $L_0 = 0$ although the bank impedance is zero, the dynamics of the plasma focus constitutes an impedance, which then becomes the dominant load to limit the value of I_{peak}. In other words, as L_0 becomes small enough, I_{peak} would assume an asymptotic value. This effect alone would be enough to indicate that in every plasma focus, there is a value of L_0 below which there is no gain to be made. Furthermore, if we look at the energy distributions and the requirement to adjust the anode length and the radius, the situation requires that as L_0 is reduced, the ratio of $I_{\text{pinch}}/I_{\text{peak}}$ reduces (Fig. 2). Moreover, as L_0 is decreased to very small values, the capacitor bank becomes more and more immediately coupled to the pinch. These three mechanisms produce the combined effect that limits the I_{pinch} and Y_n to an optimal value defined by (4).

We compute the neutron yield using the above formula for small plasma focus devices with relatively small L_0 (less than 100 nH), such as PACOa [19], DPF-2.2 [20], FN II [21], and GN1 [22]. In Table III, computed neutron yield using (4) is compared with the experimental results. Computed Y_n for FNII and GN1 are close to the experimental results. For PACO, the difference between the computed and measured Y_n is larger than typically observed in comparing the computed Y_n from the Lee code to the measured values in other machines. However, we note that in a detailed study of the neutron yield of PACO, Castillo *et al.* [21] specifically pointed out in their conclusion that the neutron yield of PACO widely varied from shot-to-shot when compared with the FN-II, quoting representative figures for PACO such as 363 $\pm$ 214 (in representative units). The same paper measured the total yield of PACO more exhaustively than the typical practice of single-station counting by including both isotropic and anisotropic components. They obtained three values of total yield Y_n of $1.26 \pm 1.04 \times 10^8$, $1.62 \pm 1.01 \times 10^8$, and $0.45 \pm 0.43 \times 10^8$. Noting their range of variation it is not surprising that the computed value of Y_n differs so atypically (1/7) from the claimed experimental value of PACO of 2×10^8; which in any case might need to be reduced to a value closer to 10^8 in view of their exhaustive 2003 study [21]; given the three Y_n values they obtained for PACO as shown above.

In the case of FN II, found in the same exhaustive study by Castillo *et al.* [21] to be more consistent in Y_n, the agreement between (4) and their experimental value is good. The comparison with the other two machines DPF-2.2 and GN1 shows that the computed values have a tendency to be on the lower side of the measured values with a factor better than 0.4. We note that shot-to-shot fluctuations of Y_n by a factor of 3 are typical even in a machine found to be consistent such as the FN II [21].

The numerically derived scaling law with inductance is important for planning and designing a plasma focus as neutron source.

V. CONCLUSION

The Lee model code was applied to optimize the plasma focus device as a neutron source. The effect of reducing the inductance of system L_0 on the neutron yield on small plasma focus devices (several kilojoules) is studied for the first time. The numerical experiments confirm the limitation effect of I_{pinch} and consequently neutron yield. Hence, there exists an optimum L_0 in the range of 10–20 nH. The numerical experiments show that typically at 20 nH, the pinch current and the neutron yield are already more than 90% of the optimum values, so that practically 20 nH is low enough for the planning of any device. Such an inductance of 20 nH has been demonstrated in several machines notably the NX2. Finally, the neutron yield is scaled with system inductance that is important for planning and designing a plasma focus as neutron source.

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