Electron Beam Properties Emitted From Deuterium Plasma Focus: Scaling Laws

M. Akel, S. H. Saw, and S. Lee

***Abstract*— The Lee model is extended to study and characterize the electron beams emitted from plasma-focus devices. It is then first applied to characterize the electron beams emitted from low and high-energy plasma focus operated with deuterium gas. The numerical experiments on NX2 device at 15 torr of deuterium give the following results: electron fluence = 5.7×10^{22} m^{-2}, electron flux = 16×10^{29} m^{-2} s^{-1}, the relativistic kinetic mean energy of the electron = 56 keV, electron number = 2×10^{16}, electron current = 91 kA, and damage factor = 2.7×10^{12} W $\cdot$ m^{-2}s$^{0.5}$. Then, the effect of pressure on the beam characteristics is studied. The energy of the beam at pinch exit changes from around 57 J (1.9% of the stored energy E_0) to 176 J (6%E_0) with maximum value of 180 J (6.1%E_0) at 15 torr, and these results are compared with the measured values 3.2%E_0 on NX2. Scaling trends are suggested for electron beam characteristics. The energy fluence and the power flow density (energy flux) have a variation $4.3 - 265 \times 10^7$ J $\cdot$ m^{-2} and $2.2 - 19 \times 10^{15}$ W $\cdot$ m^{-2}, respectively. The electron beam current ranges from 12 to 700 kA being 9%–35% of I_{peak}. The energy beam Y_{EB} scales on average as $Y_{\text{EB}} = 6.55 \times E_0^{1.45}$ at energies in the 1 to 500 kJ regions (Y_{EB} in J and E_0 in kJ), and $Y_{\text{EB}} = 1 \times 10^{-6} I_{\text{pinch}}^{3.53}$ and $Y_{\text{EB}} = 2 \times 10^{-6} I_{\text{peak}}^{3.14}$ ($I_{\text{peak}}$and I_{pinch} in kA and Y_{EB} in J). These results provide much needed benchmark reference values and scaling trends for electron beams of a plasma focus operated in deuterium gas.**

***Index Terms*— Deuterium gas, electron beam, Lee model, plasma focus, scaling law.**

I. Introduction

THE dense plasma-focus devices have been extensively used as a source of multiradiation such as neutron yield [1], soft [2] and hard [3] X-rays, ion beams [4], [5], and high-energy relativistic electrons [6], [7]. Different methods have been used to analyze the emissions of energetic relativistic electron beams from the dense plasma focus such as hard X-ray emission from a target (or the anode tip), Faraday cups, and magnetic spectrometers [8]–[13].

NX2 plasma-focus device operated with various gases is used for deposition of thin films using high-energy electron beams. It is measured that the efficiency of electron beam emission from NX2 is about 3.2% E_0 (E_0—the storage energy) [9]. Electron beam features have been investigated on a 2.2-kJ PF by using a charge collector for different conditions. The average electron beam current has an optimum value of 13.5 kA at 0.3 torr of nitrogen and the electron energy ranges from ~10 to 200 keV with a most probable distribution within 80 to 110 keV [13]. Tartari *et al.* [14] measured the X-rays (30–45 keV) emitted from a 7-kJ plasma-focus device due to the interaction of the relativistic electron beam with the electrode material. Electrons, ions, and X-rays emission from a 45-kJ plasma-focus facility are also simultaneously studied and discussed [15]. The relativistic electron beam was observed by employing a fast response Rogowskii coil in a 2-kJ plasma focus and correlated with the hard X-ray emission. The detected beam pulsewidth was around 10 ns and the energy is in the hard X-ray range [16]. Several electron emission features are also identified and correlated with the X-ray emission in different energy ranges on a 3-kJ Mather-type plasma-focus device operated in neon. The electron beam properties presents very strong correlation with the plasma focus and it is found that most of electron energies concentrating below 200 keV [17]. According to published works, it is evidence that measurements of electron beams from plasma focus have produced a wide variety of results and not giving any scaling laws. In earlier works, the Lee model [18], [19] has been modified based on the virtual plasma diode mechanism proposed by Gribkov *et al.* [20], [21] for studying of ion beams from plasma focus [22]–[24]. In this work, we further modify the Lee code to study and characterize the electrons beams emitted from deuterium plasma focus at various conditions. We discuss in some detail the results of many numerical experiments carried out using this modified code on different energy plasma-focus devices. So, the correlation between the plasma-focus parameters and produced electron beam properties could assist to understand the plasma surface interactions and to find the optimum conditions for hard X-ray generation.

II. Calculations of Electron Beam Properties Produced by Plasma Focus

For studying the electron beam characteristics generated in the pinch using Lee model, the corresponding equations are first deduced and it is then incorporated into the code.

We start from the electron beam flux formula: $J_{\text{eb}} = n_{\text{eb}} v_{\text{eb}}$ (electrons per m^{-2}s^{-1}), where n_{eb}—number of beam electron N_{eb} divided by volume of pinch plasma; and v_{eb}—electron speed (all quantities are expressed in SI units, except where otherwise stated).

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Then based on the kinetic energy of the beam electrons and pinch inductive energy concepts, the n_{eb} and v_{eb} are derived. The beam kinetic energy is (1/2) $N_{\mathrm{eb}} m_{\mathrm{e}} v_{\mathrm{eb}}^2$, where $\mathrm{m_e}$—the mass of the electron. And the pinch inductive energy equals (1/2) $L_{\mathrm{p}} I_{\mathrm{pinch}}^2$, where $L_{\mathrm{p}} = (\mu/2\pi)$ (ln[b/r_{p}])z_{p} is the inductance of the focus pinch; $\mu = 4\pi \times 10^{-7}$ Hm^{-1}; b—cathode radius; r_{p}—pinch radius; z_{p}—length of the pinch, and I_{pinch} is the pinch current. As the kinetic energy is imparted by a fraction f_{e} the pinch inductive energy, thus we write

$$(1/2) N_{\mathrm{eb}} m_{\mathrm{e}} v_{\mathrm{eb}}^2 = f_{\mathrm{e}} (1/2)(\mu/2\pi)(\ln[b/r_{\mathrm{p}}]) z_{\mathrm{p}} I_{\mathrm{pinch}}^2.$$

This gives

$$n_{\mathrm{eb}} = N_{\mathrm{eb}} / \left(\pi r_{\mathrm{p}}^2 z_{\mathrm{p}}\right) = (\mu/[2\pi^2 m_e])(f_{\mathrm{e}}) \left\{ (\ln[b/r_{\mathrm{p}}]) / \left(r_{\mathrm{p}}^2\right) \right\} \times \left(I_{\mathrm{pinch}}^2 / v_{\mathrm{eb}}^2\right). \quad (1)$$

Next, we proceed to derive v_{eb} from the accelerating voltage provided by the diode voltage U to an electron. Each electron is given kinetic energy of $E_{\mathrm{e}} = (1/2) m_e v_{\mathrm{eb}}^2$ by diode voltage U.

Thus

$$(1/2) m_{\mathrm{e}} v_{\mathrm{eb}}^2 = eU \quad (2)$$

where e is the electronic charge.

Now, we take (1) and combine with (2); and noting that $(\mu/[2.83\pi^2 \ (\mathrm{em_e})^{1/2}]) = 1.2 \times 10^{17}$, we have the flux equation as follows:

$$J_{\mathrm{eb}}(\text{electrons m}^{-2}\text{s}^{-1}) = 1.2 \times 10^{17} (f_{\mathrm{e}}) \left\{ (\ln[b/r_{\mathrm{p}}]) / \left(r_{\mathrm{p}}^2\right) \right\} \times \left(I_{\mathrm{pinch}}^2\right) / U^{1/2}. \quad (3)$$

The fluence is the flux multiplied by pulse duration τ, where $f_{\mathrm{e}} \sim 0.14$ is equivalent to electron beam energy of 3%–4% E_0 for cases when the pinch inductive energy holds 20%–40% of E_0 as observed for low inductance plasma focus [9], [23]. From the above mentioned equations, it is noticed that the electron flux and fluence is $(2m_{\mathrm{p}}/m_{\mathrm{e}})^{1/2}$ ~60.6 of deuteron beam flux and fluence, where m_{p} is the mass of the proton. However, our experimental observations over the years show that the electron beam leaves a very fine footprint on a per shot basis with a diameter of the order of 0.1 mm when the ion beam is of the order of a mm for a plasma focus with radius of the order of 1 cm. These experimental observations seem consistent with a necessary assumption that the electron beam current be set to be approximately equal to the ion beam current. To implement this assumption in the code we take the radius of the electron beam as $(1/60.6)^{0.5}$ times the radius of the ion beam, which at the exit of the pinch is taken as the radius of the pinch. The kinetic energy of the relativistic electrons is estimated by $E_{\mathrm{rel}} = m_{\mathrm{e}} c^2 (\gamma - 1)$, where γ is the relativity factor $[(1/(1 - v_{\mathrm{eb}}^2/c^2)^{1/2})]$, c is the light speed ($c = 3 \times 10^8$ m/s), and $m_{\mathrm{e}} c^2$ is the rest mass energy of an electron ~511 keV. The diode voltage U is $U = 3$ $\mathrm{V_{max}}$ taken from data fitting in extensive earlier numerical experiments [22], where $V_{\max}$ is the maximum voltage induced by the current sheet collapsing radially toward the axis.

Once the flux is determined, the following quantities are also computed: energy flux or power density flow ($\mathrm{W \cdot m^{-2}}$), power flow (W), current density ($\mathrm{A \cdot m^{-2}}$), current (A), fluence (electrons $\mathrm{m^{-2}}$), energy fluence ($\mathrm{J \cdot m^{-2}}$), number of electrons in beam (electrons), energy in beam (J), damage Factor ($\mathrm{W \cdot m^{-2} s^{0.5}}$), magnetic Field (kG) ($B = 0.2 I_{\mathrm{pinch}/} r_{\mathrm{p}}^2$), larmor radii of electrons (μm) ($3.37(E_{\mathrm{rel}})^{0.5}$/B [20]), and electron beam charge (mC).

III. Numerical Experiments: Results and Discussion

A. Electron Beam Properties of NX2 Operated With Deuterium Gas

The modified Lee code (RADPFV5.15REB) is utilized to get some features of the electron beams emitted from NX2 plasma-focus device [25], [26]. The NX2 has the following bank and tube parameters.

Bank parameters: $L_0 = 20$ nH (fitted), $C_0 = 28$ μF, $r_0 = 2.7$ mΩ (fitted), tube parameters: $a = 1.55$ cm, $b = 3.8$ cm, $z_0 = 4.5$ cm, operating parameters: $V_0 = 14.5$ kV, $p_0 = 15$ torr, deuterium gas, together with the following fitted model parameters: $f_m = 0.11$, $f_c = 0.7$, $f_{\mathrm{mr}} = 0.38$, and $f_{\mathrm{cr}} = 0.7$. Here L_0 is the static inductance, C_0 is the storage capacitance, r_0 is the short circuited resistance, a is the anode radius, b is the cathode radius, z_0 is the anode length, p_0 is the operating initial pressure, while V_0 is the bank charging voltage ($V_{\max}$ is computed by Lee model code and of course it is depend on V_0 and other operational parameters as well).

The calculated properties of the electron beam are: fluence $= 5.67 \times 10^{22}$ m^{-2}, flux $= 1.6 \times 10^{30}$ m^{-2} s^{-1}, $E_{\mathrm{rel}} = 56$ keV, electron number $= 2 \times 10^{16}$, electron current $= 90.63$ kA, and damage factor $= 2.7 \times 10^{12}$ $\mathrm{W \cdot m^{-2}\ s^{0.5}}$. Then, for studying the effect of pressure on the beam characteristics, more numerical experiments were carried out with the above model parameters, but varying deuterium gas pressure from 1 to 19 torr (see Table I).

From Table I, it is noticed that the electron flux initially increases with the increase in gas pressure and reaches a maximum (1.6×10^{30} electrons m^{-2} s^{-1}) at a pressure of 14 torr. The electron number is proportionate with gas pressure and varies from 0.27×10^{16} (at 1 torr) to 2.4×10^{16} (at 19 torr) for NX2 device. The energy of the beam at pinch exit also changes from around 57 J (1.9%E_0) to 176 J (6%E_0) with maximum value of 180 J (6.1%E_0) at 15 torr and these results are consistent with the measured values 3.2% E_0 on NX2 [9]. The calculations reveal also the peak values of the power flow density of 1.98×10^{16} $\mathrm{W \cdot m^{-2}}$at 5 torr, and the highest damage factor of almost 3.1×10^{12} $\mathrm{W \cdot m^{-2} s^{0.5}}$ at a deuterium pressure of 8 torr. Table I also shows that for operation with high electron flux regime, pressures higher than 10 torr are needed, while for the maximum power flow and damage factor regimes around 5 and 8 torr are required, respectively.

B. Electron Beam Features of Deuterium Plasma Focus With a Range of Energies

In the same manner as described for the NX2, numerical experiments are investigated on each studied plasma-focus device operated with deuterium for various conditions using

TABLE I

VARIATION OF THE PROPERTIES OF ELECTRON BEAM EMITTED FROM NX2 PLASMA FOCUS OPERATING WITH DEUTERIUM GAS

p_0 (Torr)	Electron fluence ($\times 10^{22}$ m^{-2})	Electron flux ($\times 10^{30}$ m^{-2} s^{-1})	E_{rel} (keV)	Beam energy (J)	Electron number ($\times 10^{16}$)	Electron current (kA)	Power flow density ($\times 10^{16}$ Wm^{-2})	Damage factor ($\times 10^{12}$ Wm^{-2}s$^{0.5}$)
1	0.88	0.69	134.34	57.16	0.27	33.00	1.48	1.67
2	1.47	0.92	119.92	85.78	0.45	44.84	1.77	2.23
3	1.97	1.08	109.81	106.47	0.61	53.21	1.90	2.57
4	2.42	1.20	101.79	122.29	0.75	59.75	1.96	2.78
5	2.82	1.30	95.12	134.80	0.88	65.09	1.98	2.92
6	3.21	1.37	89.33	145.42	1.0	69.58	1.97	3.01
7	3.56	1.44	84.22	153.58	1.1	73.43	1.94	3.05
8	3.89	1.49	79.64	160.47	1.3	76.75	1.89	3.07
9	4.21	1.53	75.41	166.00	1.4	79.66	1.84	3.06
10	4.50	1.55	71.57	170.46	1.5	82.18	1.78	3.03
11	4.77	1.58	68.00	173.57	1.6	84.41	1.72	2.99
12	5.02	1.59	64.74	176.31	1.7	86.33	1.65	2.93
13	5.26	1.602	61.61	178.21	1.8	87.99	1.58	2.87
14	5.47	1.604	58.72	179.11	1.9	89.41	1.51	2.79
15	5.67	1.603	55.97	179.60	2.0	90.63	1.44	2.70
16	5.84	1.59	53.34	179.30	2.1	91.70	1.36	2.61
17	6.00	1.58	50.90	178.76	2.2	92.47	1.29	2.51
18	6.15	1.57	48.56	178.10	2.3	93.25	1.22	2.42
19	6.26	1.55	46.39	176.39	2.4	93.76	1.15	2.31

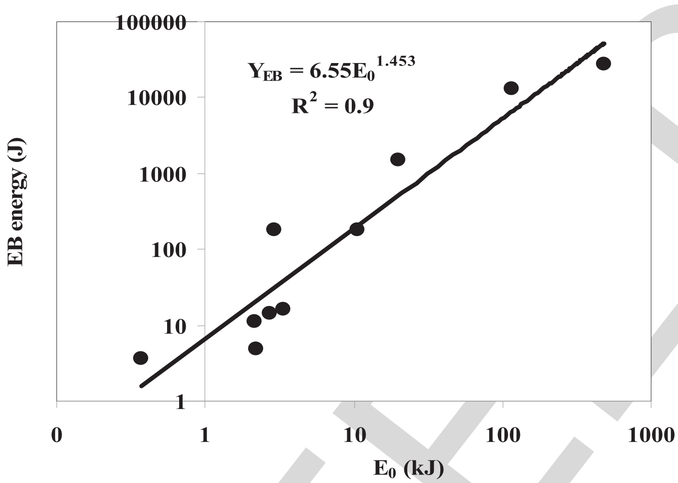

Fig. 1. Energy of the electron beam from deuterium plasma focus versus E_0.

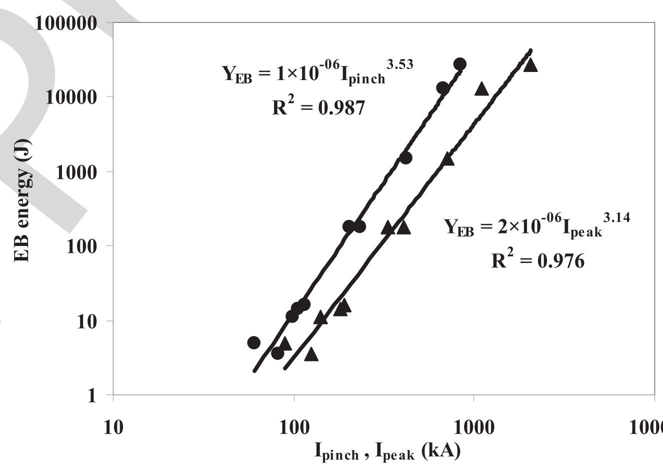

Fig. 2. Energy of the electron beam from deuterium plasma focus versus I_{pinch} and I_{peak}.

the modified Lee code (RADPFV5.15REB). For comparison, the electron beamproperties at optimum pressures for the maximum electron flux values are shown in Table II.

Table II shows that the electron energy ranges over 17–207 keV, and the electron fluence has no correlation with E_0 and varies by a factor of 8 through the whole range of E_0 from 10×10^{21} (for PF 400J) to 80×10^{21} electrons m^{-2} (for PF 115 kJ). Such a small variation of fluence over two and a half orders of magnitude of storage energy is likely related to the constancy of energy density that is one of the key scaling parameters of the plasma focus throughout its E_0 range of sub-kJ to sub-MJ [31]. The flux has a peak value of 19.8×10^{29} electrons m^{-2} s^{-1} for (3.4 kJ) INTI PF device, while the minimum value is about 1.6×10^{29} electrons m^{-2} s^{-1} for the (486 kJ) PF1000 device. It is noticed that the higher fluxes are for the small low-energy plasma-focus devices, and this is due to the dependence of pinch duration on the anode radius. The energy fluence and the power flow density (energy flux) have variations $4.3-265\times10^{7}$ J·m^{-2} and $2.2 - 19\times10^{15}$ W · m^{-2}, respectively. The electron number is 3.8×10^{14} for the PF 400 J and becomes 5000 times greater than that for the PF1000 device, with a strong correlation to E_0, modified by a dependence on I_{peak} (or L_0). The energies of the beam modify from 0.2% (for PF 2.2 kJ) to 11.5% (for PF 115 kJ) of E_0. The electron beam currents change between 12 kA (9% I_{peak}) for the lowest energy PF 400 J and 700 kA (35% I_{peak}) for highest energy PF1000 device. The damage factor has a range 2.9–67 $\times 10^{11}$ W · m^{-2}s$^{0.5}$. The Larmor radius of electron is also estimated to vary from 3.7 to 2318 μm. The charge

TABLE II
ELECTRON BEAM PROPERTIES OF A RANGE OF LOW AND HIGH STORAGE ENERGY PLASMA FOCUS OPERATED WITH DEUTERIUM GAS

Device	PF 400 J [22]	ICTP PF [27]	PF 2.2 kJ [10]	PF 2.7 kJ [28]	NX2 [25]	INTI [22]	PF 10 kJ [29]	NX3 [22]	PF 115 kJ [30]	PF1000 [22]
E_0 (kJ)	0.37	2.16	2.22	2.7	2.9	3.4	10.6	20	115.2	486
L_0 (nH)	40	121	330	70	20	110	120	47	120	33
V_0 (kV)	28	12	25	14	14.5	15	15	20	40	27
p_0 (Torr)	6.6	10	5	3	14	8	12	18	9	10
I_{peak} (kA)	126	140	90	182	405	190	333	711	1094	2059
I_{pinch} (kA)	81	98	61	106	234	115	204	418	672	843
z_p (cm)	0.8	1.4	1.53	1.7	2.5	1.4	2.92	4.7	10.4	18.7
r_p (cm)	0.09	0.14	0.15	0.16	0.26	0.13	0.29	0.48	0.94	2.32
τ (ns)	5.2	16	21.6	12	34	12.2	37	68	157	441
E - fluence ($\times 10^{21}$ m^{-2})	10	28.4	15.6	12.2	54.7	24	41.17	71	79.7	70
E - flux ($\times 10^{29}$ m^{-2} s^{-1})	19	17.65	7.2	10.5	16	19.8	11.3	11	5.1	1.6
E_{rel} (keV)	58.8	26.2	17	52	59	47	63	106	207	87
En fluence ($\times 10^{7}$ J m^{-2})	9.4	11.92	4.3	10.2	51.4	18	41.4	126	265	98.3
En flux ($\times 10^{15}$ Wm^{-2})	18	7.4	1.98	8.7	15	14.8	11.3	19	17	2.2
E- number ($\times 10^{14}$)	3.8	27	18	16.9	190	21.8	176	881	3987	19633
EB energy (J)	3.6	11.3	4.83	14	179	16.3	177	1500	13197	27437
EB energy (%E_0)	1	0.5	0.2	0.5	6	0.5	1.7	7.5	11.5	5.7
EB current (kA)	11.7	26.8	13	23.2	89.4	29	77.2	207	407	713
EB current (%I_{peak})	9.3	19	14.5	12.7	22.1	15	23.2	29	37	35
EB curr. den. ($\times 10^{10}$ A m^{-2})	30.6	28.2	11.56	16.8	25.7	31.6	18	17	8.2	2.6
Dam Fr ($\times 10^{11}$ Wm^{-2} s$^{0.5}$)	13	9.4	2.9	9.44	27.9	16.3	22	49	67	14.8
Magnetic Field (Tesla)	220.4	107.5	55.8	79.8	69.5	132.1	49.4	36.2	14.0	3.13
Larmor radius (μm)	3.7	5	7.9	9.6	11.7	5.5	17	30.44	110	318
EB charge (mC)	0.06	0.4	0.3	0.3	3	0.35	2.8	14.12	64	315

of electron beam is calculated to be from 0.06 to 315 mC. The range of machines considered in this work is wide not just in terms of range of stored energies but also in terms of some stand-out characteristics. For example, the NX3, NX2, and PF-400J may be considered to be the more typical plasma-focus devices with static inductance L_0 in a good performance range of 20–50 nH, operating voltage between 14 and 30 kV, and the capacitor banks being lightly damped. The ICTP PF and INTI PF have a single-capacitor configuration, hence a rather large L_0 of 110 nH. Such large L_0 machines (Type 2) have a significantly different pre- and postfocus energy distribution characteristics compared with the more “typical” higher performance (Type 1) L_0 range of 20–50 nH. From the data of Table II, we also first plot the energy of the electron beam Y_{EB} against E_0, I_{peak} and I_{pinch} as shown in Figs. 1 and 2.

From Fig. 1, we find that Y_{EB} scales on average as $Y_{EB} = 6.55 \times E_0^{1.45}$ at energies in the 1 to 500 kJ regions (Y_{EB} in J and E_0 in kJ), while Fig. 2 shows that $Y_{EB} = 1 \times 10^{-6} I_{pinch}^{3.53}$ and $Y_{EB} = 2 \times 10^{-6} I_{peak}^{3.14}$ (I_{peak} and I_{pinch} in kA and Y_{EB} in J). The plasma-focus devices considered in this work have a wide range of stored energies, static inductance, total and pinch currents. With this method, electron beam parameters may be computed for any Mather-type plasma focus operating with deuterium gas.

IV. CONCLUSION

The Lee code is extended to compute the electron beam features emitted from the plasma-focus pinch. Then it is utilized to characterize the electron beam of NX2 device operated with deuterium versus pressure. The electron flux initially increases with the increase in gas pressure and reaches a maximum (1.6×10^{30} electrons m^{-2} s^{-1}) at a pressure of 14 torr. The energy of the beam at pinch exit has a maximum value of 180 J (6.1% of the stored energy E_0) at 15 torr. The peak power flow density is about 2×10^{16} W $\cdot$ m^{-2} at 5 torr, and the highest damage factor of almost 3.1×10^{12} W $\cdot$ m^{-2}s$^{0.5}$ at a deuterium pressure of 8 torr. Many numerical experiments are also carried out for a wide range of plasma-focus storage energies. The results reveal that the variation of fluence is dependent on the static inductance L_0 and it is independent of E_0. The electron fluence is 10–80 $\times 10^{21}$ electrons m^{-2} and the electron flux has a range of 1.6–20 $\times 10^{29}$ electrons m^{-2} s^{-1} being greater for the smaller devices. The energy fluence has a variation $4.3 - 265 \times 10^7$ J $\cdot$ m^{-2}. The energy flux varies over the range 2.2–19 $\times 10^{15}$ W $\cdot$ m^{-2}. The number of electrons in the beam increases with E_0 being 3.8×10^{14} for the 0.37 kJ PF-400 J and 5000 times greater than that for the PF1000. The energy of the beam at pinch exit varies from 0.2% to 11.5% of E_0. The electron beam current ranges from 12 to 700 kA being 9%–35% of I_{peak}. The damage factor is 2.9–67 $\times 10^{11}$ W $\cdot$ m^{-2}s$^{0.5}$ across the whole range of machines. The Larmor radius of electron ranges from 3.7 to 2318 μm. The electron beam charge ranges from 0.06 to 315 mC. Scaling laws on the energy of the electron beam, in terms of storage energies E_0, peak discharge current I_{peak} and focus pinch current I_{pinch}

were deduced. Finally, we believe that the Lee model could be a useful tool for characterization of the electron beams emitted from plasma focus, leading to selection of the suitable plasma-focus parameters for desired electron material processing applications and hard X-ray generation suitable for X-ray radiography.

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REFERENCES

[1] R. Verma *et al.*, "Neutron emission characteristics of NX-3 plasma focus device: Speed factor as the guiding rule for yield optimization," *IEEE Trans. Plasma Sci.*, vol. 40, no. 12, pp. 3280–3289, 2012.

[2] N. K. Neog and S. R. Mohanty, "Anode length optimization in a modified plasma focus device for optimal x-ray yields," *J. Appl. Phys.*, vol. 99, no. 1, p. 013302, 2006.

[3] F. Castillo-Mejia, M. M. Milanese, R. L. Moroso, J. O. Pouzo, and M. A. Santiago, "Small plasma focus studied as a source of hard X-ray," *IEEE Trans. Plasma Sci.*, vol. 29, no. 6, pp. 921–926, Dec. 2001.

[4] M. Hassan, A. Qayyum, R. Ahmad, G. Murtaza, and M. Zakaullah, "Nitriding of titanium by using an ion beam delivered by a plasma focus," *J. Phys. D, Appl. Phys.*, vol. 40, no. 3, pp. 769–777, 2007.

[5] S. R. Mohanty, N. K. Neog, H. Bhuyan, R. K. Rout, R. S. Rawat, and P. Lee, "Effect of anode designs on ion emission characteristics of a plasma focus device," *Jpn. J. Appl. Phys.*, vol. 46, no. 5, pp. 3039–3044, 2007.

[6] A. Patran *et al.*, "Spectral study of the electron beam emitted from a 3 kJ plasma focus," *Plasma Sour. Sci. Technol.*, vol. 14, no. 3, p. 549, 2005.

[7] P. Lee, X. Feng, G. X. Zhang, M. H. Liu, and S. Lee, "Electron lithography using a compact plasma focus," *Plasma Sour. Sci. Technol.*, vol. 6, pp. 343–348, Aug. 1997.

[8] K. Hirano, I. Kaneko, K. Shimoda, and T. Yamamoto, "Method for measuring electron energy distribution in a plasma focus," *Jpn. J. Appl. Phys.*, vol. 29, no. 6, pp. 1182–1188, 1990.

[9] T. Zhang *et al.*, "Optimization of a plasma focus device as an electron beam source for thin film deposition," *Plasma Sour. Sci. Technol.*, vol. 16, no. 2, pp. 250–256, 2007.

[10] S. R. Mohanty, H. Bhuyan, N. K. Neog, R. K. Rout, and E. Hotta, "Development of multi Faraday cup assembly for ion beam measurements from a low energy plasma focus device," *Jpn. J. Appl. Phys.*, vol. 44, no. 7, pp. 5199–5205, 2005.

[11] M. Z. Khan, L. K. Lim, S. L. Yap, and C. S. Wong, "Imperative function of electron beams in low-energy plasma focus device," *Pramana-J. Phys.*, vol. 85, no. 6, pp. 1207–1219, 2015, doi: 10.1007/s12043-015-0951-6.

[12] M. Z. Khan, Y. S. Ling, I. Yaqoob, N. N. Kumar, L. L. Kuang, and W. C. San, "Low-energy plasma focus device as an electron beam source," *Sci. World J.*, vol. 2014, Jul. 2014, Art. no. 240729. [Online]. AQ:2 Available: http://dx.doi.org/10.1155/2014/240729

[13] N. K. Neog and S. R. Mohanty, "Study on electron beam emission from a low energy plasma focus device," *Phys. Lett. A*, vol. 361, pp. 377–381, Feb. 2007.

[14] A. Tartari, A. Da Re, C. Bonifazzi, and M. Marziani, "Energy spectra measurements of X-ray emission from electron interaction in a dense plasma focus device," *Nucl. Instrum. Methods Phys. Res. Section B, Beam Interactions Mater. Atoms*, vol. 213, pp. 206–209, Jan. 2004.

[15] L. Jakubowski and M. J. Sadowski, "Hot-spots in plasma-focus discharges as intense sources of different radiation pulses," *Brazilian J. Phys.*, vol. 32, no. 1, pp. 187–192, 2002.

[16] J. Pouzo, H. Acuna, M. Milanese, and R. Moroso, "Relativistic electron beams detection in a dense plasma focus," *Eur. Phys. J. D-Atomic, Mol., Opt. Plasma Phys.*, vol. 21, no. 1, pp. 97–100, 2002.

[17] A. Patran *et al.*, "A magnetic electron analyzer for plasma focus electron energy distribution studies," *J. Fusion Energy*, vol. 25, no. 1, pp. 57–66, 2006.

[18] S. Lee, "Plasma focus radiative model: Review of the Lee model code," *J. Fusion Energy*, vol. 33, no. 4, pp. 319–335, Aug. 2014.

[19] S. Lee. (2016). [Online]. Available: http://www.plasmafocus.net AQ:3

[20] V. A. Gribkov *et al.*, "Plasma dynamics in the PF-1000 device under full-scale energy storage: II. Fast electron and ion characteristics versus neutron emission parameters and gun optimization perspectives," *J. Phys. D, Appl. Phys.*, vol. 40, no. 12, pp. 3592–3607, 2007.

[21] V. A. Gribkov, "Physical processes taking place in dense plasma focus devices at the interaction of hot plasma and fast ion streams with materials under test," *Plasma Phys. Controlled Fusion*, vol. 57, no. 6, p. 065010, 2015.

[22] S. Lee and S. H. Saw, "Plasma focus ion beam fluence and flux-scaling with stored energy," *Phys. Plasmas*, vol. 19, no. 11, p. 112703, 2012.

[23] S. Lee and S. H. Saw, "Plasma focus ion beam fluence and flux-for various gases," *Phys. Plasmas*, vol. 20, no. 6, p. 062702, 2013.

[24] M. Akel, S. A. Salo, S. H. Saw, and S. Lee, "Ion beam features produced by two plasma focus machines operated with different gases," *IEEE Trans. Plasma Sci.*, vol. 42, no. 9, pp. 2202–2206, Sep. 2014.

[25] S. H. Saw *et al.*, "Comparison of measured neutron yield versus pressure curves for FMPF-3, NX_2 and NX_3 plasma focus machines against computed results using the lee model code," *J. Fusion Energy*, vol. 34, no. 3, pp. 474–479, 2015.

[26] S. Lee *et al.*, "High rep rate high performance plasma focus as a powerful radiation source," *IEEE Trans. Plasma Sci.*, vol. 26, no. 4, pp. 1119–1126, Aug. 1998.

[27] M. A. I. Elgarhy, "Plasma focus and its applications," M.S. thesis, Al-Azhar Univ., Cairo, Egypt, 2010. AQ:4

[28] B. Shirani, F. Abbasi, and M. Nikbakht, "Production of ^{13}N by ^{12}C(d,n)^{13}N reaction in a medium energy plasma focus," *Appl. Radiat. Isotopes*, vol. 74, pp. 86–90, Apr. 2013.

[29] S. M. S. Kiai *et al.*, "Preliminary results of is plasma focus as a breeder of short-lived radioisotopes ^{12}C(d,n)^{13}N," *J. Fusion Energy*, vol. 30, no. 2, pp. 111–115, 2011.

[30] S. F. Haghani *et al.*, "Theoretical study of the endogenous production of N-13 in 115 kJ plasma focus device using methane gas," *J. Fusion Energy*, vol. 32, no. 4, pp. 480–487, 2013.

[31] S. Lee and A. Serban, "Dimensions and lifetime of the plasma focus pinch," *IEEE Trans. Plasma Sci.*, vol. 24, no. 3, pp. 1101–1105, Jun. 1996.

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