PF1000 High-Energy Plasma Focus Device Operated With Neon as a Copious Soft X-Ray Source

Mohamad Akel, S. Ismael, S. Lee, S. H. Saw, and H. J. Kunze

***Abstract*— The measured current waveforms of PF1000 plasma focus operating in neon are first fitted to the computed currents using the Lee model for the pressures of 0.5 and 0.8 torr. The fitting fixes the model parameters. The code is then run to study and to optimize the soft X-ray yield from ($\sim$352 kJ) PF1000 device. The maximum characteristic soft X-ray (H-like and He-like lines) yield of 4.2 kJ is found to occur at the pressure of 0.85 torr, with the pinch duration of 207 ns and with an all-line yield of 4.8 kJ. Maximum compression (corresponding to smallest pinch radius) of 0.585 cm with the duration of 224 ns is obtained at 1 torr with the greatest all-line yield of 7.1 kJ but a lower characteristic soft X-ray yield of 3.2 kJ. Detailed computation results indicate that the maximum compression (minimum pinch radius) at 1 torr is attributed to two mechanisms: thermodynamics specific heat ratio effects and radiative losses.**

***Index Terms*— Lee model, measured current traces, neon gas, PF1000 device, soft X-ray.**

TABLE I

SUMMARY OF SOME STUDIES ON THE NEON PF AS X-RAY SOURCE

Experiment [ref.]	Storage energy E_0 (kJ)	X-ray yield (J/shot)	Wall plug efficiency (%E_0)
Wong et. al. [1]	3	140	5.6
Beg et. al. [4]	2	16.6	0.83
Zakaullah et. al. [8]	2.3	80	3.5
Liu et. al. [9]	2.9	6	0.2
Lee et. al. [2]	3	100	4
Lee et. al. [2]	1.9	18	1
Zhang et. al. [10]	3.3	8	0.25
Mohammadi et. al. [11]	3.3	7.9	0.24
Talebitaher et. al. [12]	2	77.5	3.9
Baghdadi et. al. [13]	3	2.8	0.094
Lee et. al. [14]	2.2	4	0.18

I. INTRODUCTION

X-RAY emitted from the plasma focus (PF) devices has multiple applications such as lithography [1], [2], microscopy [3], X-ray backlighter [4], radiography [5], [6], and micromachining [7]. The intensity and energy of X-ray could be controlled by suitable experimental conditions including storage energy (E_0), electric currents, electrode geometry, shape and material, gas type, and pressure. A summary of some earlier experimental studies involving neon as filling gas for different low-energy PF devices is shown in Table I. Burkhalter *et al.* [15] also studied the X-ray emission from neon plasma by varying the bank energy from 1 to 4 kJ (340–370 kA) and by changing the anode/cathode diameter. They estimated the X-ray yield up to 14 J. They observed the enhancement in the X-ray output by reducing the anode diameter and by increasing the bank energy. The time-resolved soft X-ray signals (but not the absolute yield) in the energy range of 0.7–15 keV were recorded with a silicon PIN detector by Kubes *et al.* [16] from PF1000 operated with pure neon and puffing deuterium. A considerable decrease was confirmed of the soft X-ray emission in comparison with shots without deuterium injection.

This decrease can be explained by the absence of the neon in the region of the compressed and hot plasma. Kubes *et al.* [17] studied also the soft X-ray emission from the PF1000 operated with deuterium and puffing neon. The intense soft X-ray emission shows the presence of neon in the central region of the pinch. However, no quantitative measurement of the neon yield is available for the PF1000 device. The results from low-energy PF operated with neon show that typically the required end axial speed is around 6–7 cm/μs (mean axial speed around 4 cm/μs) leading to a suitable final on-axis speed of $V_s = 21.4$ cm/μs (at 3.3 torr) and a pinch temperature of about 2×10^6 K; at which temperature 64% of the line radiation (soft X-ray) emissions are at 922 eV (He$_\alpha$) and 1022 eV (H$_\alpha$) and the rest 36% is essentially recombination [18], [19]. The high-energy neon PF is also introduced as a plentiful soft X-ray emitter and a scaling law versus the pinch current ($Y_x \sim I_{\text{pinch}}^{3.5-4}$) was proposed [20]. The low inductance NX2 PF is also extensively utilized for study and optimization of the X-ray yield. The measured X-ray yields with pressure are estimated and compared to the computed

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results obtained using the Lee model giving a good agreement. The optimum yield was about 20.8 J (1.22% E_0) at 2.9 torr with $V_a = 5.8$ cm/μs and $V_s = 21$ cm/μs. This comparison gives confidence that the Lee model describes realistically the PF dynamics [21]. The Lee model calculations on UNU/ICTP PFF show that the highest soft X-ray yield ($Y_{\text{sxr}} = 9.5$ J) could be achieved by shortening of the length of anode from the basic 16–7 cm with increasing its radius to 1.2 cm [22] at 3.5 torr with $V_a \sim 5$ cm/μs and $V_s \sim 22$ cm/μs. Scaling laws for neon soft X-ray yield Y_{sxr} with a wide range of storage energies, pinch I_{pinch}, and total I_{peak} currents have been deduced by using the Lee model [23], [24]. The line radiation yield Q_{line} emitted from PF is computed using the Lee model as follows [25]–[28]:

$$\frac{dQ_{\text{line}}}{dt} = C_l N_i^2 Z_{\text{eff}} Z_n^4 \left(\pi r_{\text{pi}}^2\right) z_f / T \tag{1}$$

where $C_l = -4.6 \times 10^{-31}$, number density $= N_i$, effective charge number $= Z_{\text{eff}}$, atomic number of gas $= Z_n$, pinch radius $= r_{\text{pi}}$, pinch length $= z_f$, plasma temperature $= T$ (all quantities in SI units unless otherwise stated). The plasma self-absorption effect is incorporated in a subroutine in our calculations. For the estimation of the soft X-ray yield (Ysxr) from the PF operated with neon, in the Lee code, we take $Y\text{sxr} = Q_{\text{line}}$ at the following temperature range 160–500 eV suitable for generating H-like and He-like ions (or the soft X-ray) from neon plasma. It is known that in gases (like neon) emitting strongly in line radiation, the radiation-cooled threshold current for radiation-enhanced compression is considerably lowered and the Lee model code may be used to compute this lowering [28]–[31]. The code uses the following equation for the radiation-coupled piston position r_{pi}:

$$\frac{dr_{\text{pi}}}{dt} = \frac{-\frac{r_{\text{pi}}}{\gamma I}\frac{dI}{dt} - \frac{1}{\gamma+1}\frac{r_{\text{pi}}}{z_f}\frac{dz_f}{dt} + \frac{4\pi(\gamma-1)}{\mu\gamma z_f}\frac{r_{\text{pi}}}{f_c^2 I^2}\frac{dQ}{dt}}{\frac{\gamma-1}{\gamma}} \tag{2}$$

where f_c is the fraction of current flowing into the pinch, μ is the permeability, I is the total discharge current in the circuit, and γ is the specific heat ratio of the plasma. This equation indicates that a smaller γ, due to increased degree of freedom from ionization and excitation leads to a higher piston speed and increased compression, an effect which may be called "thermodynamically enhanced compression." The total power term *dQ/dt* includes Joule heating (which is a power gain term) and radiative loss (bremsstrahlung, recombination, line radiation) after appropriate reduction by plasma self-absorption. When the total power is negative, energy is lost from the plasma adding a negative component to dr_{pi}/dt which tends to reduce the radius r_{pi}. This causes radiatively enhanced compression which escalates to radiative collapse when the effect is severe. This effect is distinct from and additional to the thermodynamic effect. Recently, reduced Pease–Braginskii currents and the depletion times of pinch thermal energy by radiation in various gases are estimated, resulting in the conclusion that no radiative collapse may be expected in D_2 and He, while in Ne, significant radiative cooling and reduction in the radius ratio may be anticipated and in higher atomic gases (Ar, Kr, and Xe) radiative collapse may be expected [30]. Experimental studies of discharges in PF devices with neon filling and comparative numerical simulations employing the radiative Lee code are also reported from a small PF [32] as well as from a large PF [33]. The pinch currents exceed the Pease–Braginskii current and depletion times by radiation are significant, indicating that radiatively enhanced compressions should occur and was indeed observed. Crucial for the identification of such an effect were the parallel numerical simulations [33]. The Lee model code was run for different PF devices with various gases and demonstrated radiative cooling leading to radiative contraction. Six possible regimes each characterized by a combination of significant power terms affecting PF dynamics are found and discussed. Comparing the radius ratio versus pressure curves in each gas of the three devices, it is noticed that the operational, geometrical, and electrical parameters of the setup have an important role in determining the degree of radiative contraction and the operational regimes [31]. In this paper, the Lee model is used for study and optimization of the soft X-ray emitted from the high energy PF1000 operated with neon gas.

II. NUMERICAL EXPERIMENTS ON PF1000: RESULTS AND DISCUSSION

A. Characterization of PF1000 With Neon Filling Gas

Many experiments are carried out on the ($E_0 \sim 352$ kJ) PF1000 device operated with neon gas at pressures of 0.5 torr (shots: 10120, 10095, 10095II, 10119, 10119I)–0.8 torr (shot: 10108I). Some of these had already been analyzed and reported in [33] and [34]. In this paper, we use the measured current traces of neon PF1000 to study the soft X-ray for different conditions using the Lee model. For this purpose, the Lee model code is operated as PF1000 device using the following fitted parameters [33]: bank parameters: $L_0 = 31$ nH, $C_0 = 1332$ μF, $r_0 = 3$ mΩ; tube parameters: $b = 16$ cm, $a = 11.55$ cm, $z_0 = 60$ cm; operating parameters: $V_0 = 23$ kV, $p_0 = 0.5$ torr, neon gas, where $L_0 =$ static inductance (nominal), $C_0 =$ storage capacitance (nominal), $r_0 =$ stray circuit resistance, $b =$ cathode radius, $a =$ anode radius, $z_0 =$ anode length, $V_0 =$ operating voltage, and $p_0 =$ operating initial pressure. The computed total current waveform is well fitted (Fig. 1) to an experimentally measured current, using four model parameters representing the mass swept-up factor [35] $f_m = 0.035$ and the plasma current factor $f_c = 0.7$ for the axial phase and the mass swept-up factor $f_{\text{mr}} = 0.15$ and the plasma current factor $f_{\text{cr}} = 0.6$ for the radial phases. This fit gives the following results: the end axial speed is $V_a = 19.5$ cm/μs, the on-axis shock speed of $V_s = 26.4$ cm/μs; the radial piston speed has a peak value of $V_p = 17.9$ cm/μs; and the speed factor (SF $= (I_0/\text{ap}_0^{1/2})$) is 182 kA/(cm/torr$^{1/2}$) [36]. The pinch is 1.55 cm in radius, and 17.3 cm in length, and the pinch life time is 148 ns. At these conditions, the Ysxr is estimated, to be 421 J, and the corresponding efficiency is 0.12% E_0. The total and pinch currents are 1485 and 610 kA, respectively, and the focus time is near 5.3 μs. The pinch energy (EINP) value is of 36 kJ (10% E_0) at 0.5 torr, while the pinch energy density (PED) value of 4.1×10^8 J/m^3.

TABLE II
VARIATION OF PF1000 NEON PF PARAMETERS VERSUS PRESSURE

p_0 (Torr)	I_{peak} (kA)	I_{pinch} (kA)	V_a cm/μs	V_s cm/μs	V_p cm/μs	r_{pi} (cm)	Z_{max} (cm)	SF	Pinch dur. (ns)	PED ($\times 10^9 Jm^{-3}$)	Yline (J)	Ysxr (J)	Effi. %E_0
0.4	1420	586	20.8	27.7	19.2	1.604	17.311	194	142.6	0.35	222.25	222.25	0.06
0.5	1484	609	19.5	26.4	17.9	1.546	17.281	182	148.0	0.41	420.75	420.75	0.12
0.60	1536	627	18.5	25.5	17.1	1.469	17.240	172	151.1	0.49	723.53	723.53	0.21
0.80	1619	651	16.9	24.5	16.3	1.053	18.081	157	185.6	1.13	2823.28	2823.28	0.80
0.85	1637	655	16.6	24.3	16.1	0.798	18.813	154	207.3	2.10	4776.31	4202.60	1.19
0.90	1653	660	16.4	24.2	15.9	0.656	19.311	151	216.9	3.28	6210.89	3947.22	1.12
1.00	1684	668	15.8	23.0	15.5	0.585	19.903	146	223.8	4.36	7091.61	3236.92	0.92
1.30	1759	689	14.6	20.8	14.6	0.660	19.405	134	218.8	3.66	6417.10	643.30	0.18
1.40	1780	694	14.3	20.2	14.3	0.697	19.190	130	220.6	3.33	6022.91	0.00	0.00
1.8	1849	712	13.2	18.4	13.4	0.855	18.463	119	233.9	2.32	4246.96	0.00	0.00
2.0	1876	719	12.7	17.7	13.0	0.924	18.172	115	239.4	2.02	3452.78	0.00	0.00
3.0	1978	742	11.1	15.1	11.5	1.116	17.565	99	269.5	1.50	1256.87	0.00	0.00
4.0	2057	752	10.0	13.2	10.2	1.198	17.389	89	302.3	1.37	535.40	0.00	0.00

TABLE III
SOFT X-RAY YIELDS CORRELATED WITH SPEEDS IN LOW-ENERGY AND HIGH-ENERGY PF DEVICES

Device (ref.)	E_0 (kJ)	p_0 (Torr)	a (cm)	c= b/a	γ	V_a cm/μs	V_s cm/μs	V_p cm/μs	SF	Ysxr (J)	Effi. %E_0
PF1000 [33*]	352.3	0.85	11.55	1.4	1.48	16.6	24	16	154	4203	1.2
NX2 [21]	1.7	2.9	1.9	2.16	1.4	5.8	21	15	114	20.8	1.22
ICTP PFF [22]	2.94	3.3	0.95	3.4	1.4	5.4	21.4	14.7	104	3.92	0.13

* - this work

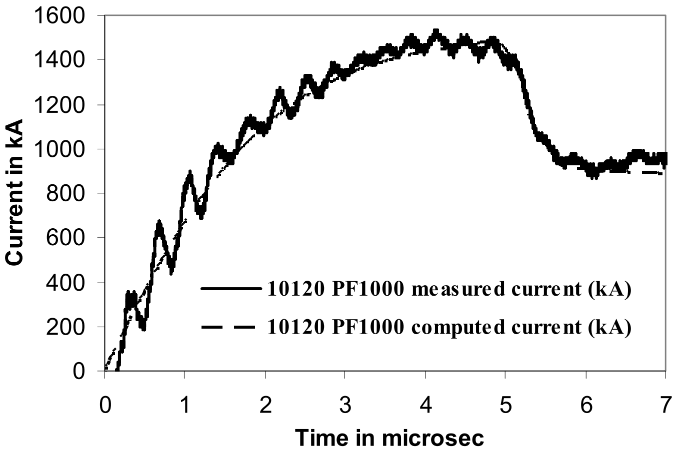

Fig. 1. Computed and measured currents of the PF1000 at 23 kV, 0.5 torr of neon.

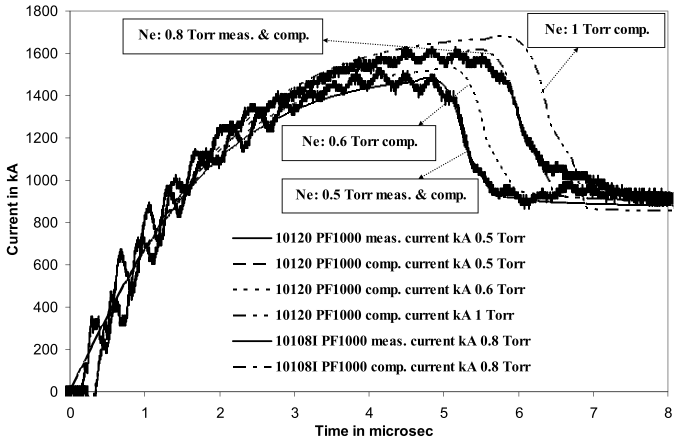

Fig. 2. Calculated and measured current traces versus neon pressures (0.5–1 torr) for the PF1000 at 23 kV.

B. Soft X-Ray Yield Versus Neon Pressure

The neon pressure was changed from 0.4 to 4 torr for finding the optimum pressure needed for the superior value of soft X-ray. From Fig. 2, it is shown that the computed and measured current traces at 0.8 torr are well fitted using the same model parameters obtained for the shot at 0.5 torr. These good fits and comparison confirm that our numerical results are realistic and describe the PF dynamics well. From Table II, it is also manifest that the Ysxr enhances with pressure until it reaches the peak value near 4.2 kJ (1.2% E_0) at $p_0 = 0.85$ torr, with $V_a = 16.6$ cm/μs and $V_s = 24.3$ cm/μs. The pinch is 0.8 cm in radius, and 18.8 cm in length, and the pinch life time is 207 ns. With the higher pressure, the speeds reduce and consequently the temperature values decrease until at 1.4 torr the temperature is below that required for emission of neon characteristic (H-like and He-like ions) soft X-rays. Table II shows that the pinch radius decreases with increasing pressure until it reaches a minimum value of 0.585 cm with the pinch duration of 224 ns at 1 torr. A careful study of the results (dynamic power versus radiation power terms) indicate that this enhanced contraction of the pinch radius is due to thermodynamics specific heat ratio effects and the maximum radiative losses [see (2)]. Although the characteristic soft X-ray yield has reduced to 3.2 kJ at this pressure, the all-line yield reaches a maximum value of 7.1 kJ. This is a significant 15% of the pinch thermal energy radiated away, leading to substantial radiative cooling and radiatively enhanced compression [30], [31]. At this operational point the pinch length and the PED have the maximum values of 19.9 cm and 44×10^8 J/m^3, respectively. A comparison of our recently computed results on high-energy PF1000 with low-energy NX2 [21] and UNU/ICTP PFF [22] is summarized in Table III. It shows that for the maximum soft X-ray yield from all three devices; the values of the final on-axis (21–24 cm/μs) speeds have a small variation, while the axial speeds have a much larger variation from 5.4 to 16.6 cm/μs. These variations are explained as follows: for a given gas the ratio of characteristic radial and axial speeds (V_s/V_a) depends on the geometrical ratio ($c = b/a$) and the heat specific ratio γ and it is computed using the following relation [27], [28]: $(v_s/v_a) = [((c^2-1)(\gamma+1)/4\ln c)]^{0.5}$. This ratio is higher for a small machine like 2.94-kJ ICTP PF ~2.3 compared with the high energy device 352-kJ PF1000 ~1.3. Thus for the narrow range (21–24 cm/μs) of radial on-axis shock speeds, the end axial speed of the ICTP PF needs to be around 5–6 cm/μs, whereas the PF1000 requires end axial speed of about 17 cm/μs to get the needed axis shock speed (of 24 cm/μs). The drive parameter has practically the same value for all the experimentally optimized machines listed (104–154 $\text{kA} \cdot \text{cm}^{-1} \cdot \text{torr}^{-1/2}$). Finally, with the present geometry we expect the PF1000 to achieve 1.2% efficiency in generating 4.2 kJ of characteristic neon soft X-rays at 23 kV and it would be interesting and useful to measure the characteristic soft X-ray yield of the existing PF1000 to confirm such a large yield.

III. CONCLUSION

The PF1000 PFoperating in neon is simulated by the Lee model after fitting the code computed current with measured current traces to confirm the model parameters. The computed pinch parameters and line radiation versus pressure are studied and discussed. The peak value of soft X-ray yield was computed in the existing device to be 4.2 kJ, merely by changing the operating pressure. This paper shows that the pinch radius drops with increasing operating pressure to a minimum value of 0.59 cm at 1 torr, with contribution from a ionization-reduced specific heat ratio increasing the compressibility of the pinched plasma column and a greater contribution from radiatively enhanced compression resulting from the 7.1 kJ of all-line radiation; although the characteristic soft X-ray yield has reduced to 3.2 kJ. At this point, the pinch length and the PED have the maximum values of 20 cm and 44×10^8 J/m^3, respectively. These numerical experiments present the neon PF as a strong soft X-ray source suitable for several applications.

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Authors’ photographs and biographies not available at the time of publication.