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Numerical Experiments in Plasma Focus Operated in Various Gases

Mohamad Akel, Sing Lee, and S. H. Saw

***Abstract*—We adapted the Lee Model code as a branch version RADPF5.15K to gases of special interest to us, namely, nitrogen and oxygen and applied numerical experiments specifically to our AECS PF-1 and AECS PF-2. We also generalized the numerical experiments to other machines and other gases to look at scaling laws and to explore recently uncovered insights and concepts. The required thermodynamic data of nitrogen, oxygen, neon, and argon gases (ion fraction, the effective ionic charge number, the effective specific heat ratio) were calculated, the X-ray emission properties of plasmas were studied, and suitable temperature range (window) for generating H- and He-like ions (therefore soft X-ray emissions) of different species of plasmas were found. The code is applied to characterize the AECS-PF-1 and AECS-PF-2, and for optimizing the nitrogen, oxygen, neon, and argon SXR yields. In numerical experiments we show that it is useful to reduce static inductance L_0 to a range of 15–25 nH; but not any smaller. These yields at diverse wavelength ranges are large enough to be of interest for applications. Scaling laws for argon and nitrogen SXR were found. Model parameters are determined by fitting computed with measured current waveforms in neon for INTI PF and in argon for the AECS PF-2. Radiative cooling effects are studied indicating that radiative collapse may be observed for heavy noble gases (Ar, Kr, Xe) for pinch currents even below 100 kA. The creation of the consequential extreme conditions of density and pulsed power is of interest for research and applications.**

***Index Terms*—Lee Model, plasmas focus (PF), radiative collapse, scaling law, soft X-ray.**

I. Introduction

SOFT X-ray sources of high intensity are required in diverse areas like X-ray spectroscopy [1], micro- lithography [2], X-ray microscopy [3], X-ray laser pumping [4], and X-ray crystallography [5]. Work is underway to develop such sources by employing geometries like Z-pinch [6], X-pinch [7], vacuum spark [8], and plasma focus (PF) [9]–[11]. The latter is the simplest in construction and yet provides the highest X-ray emission compared to other devices of equivalent energy [12], [13]. Efforts have been made for enhancing the X-ray yield by changing various experimental parameters such as bank energy [14], discharge current, electrode configuration (shape and material) [15], [16], insulator material and dimensions [15], gas composition, and filling gas pressure [17] owing to possible applications including in materials [18]–[31].

Moreover, numerical experiments are gaining much interest. For example, the Institute of Plasma Focus Studies (IPFS) [32] conducted an International Internet Workshop on Plasma Focus Numerical Experiments [33], at which it was demonstrated that the Lee Model code [34] computes not only realistic focus pinch parameters, but also absolute values of SXR yield $\mathrm{Y_{sxr}}$ consistent with experimental measurements [13], [33]–[35]. Numerical experiments are also carried out systematically by Lee *et al.* [14], [36] to determine the neon $\mathrm{Y_{sxr}}$ for optimized conditions with storage energy $\mathrm{E_0}$ from 1 kJ to 1 MJ. It is pointed out that the distinction of $\mathrm{I_{pinch}}$ from $\mathrm{I_{peak}}$ is of basic importance [37]–[39].

The Pease–Braginskii (P–B) current [40] is that current flowing in a hydrogen pinch which is just large enough for Bremsstrahlung to balance Joule heating. In gases emitting strongly in line radiation, the radiation-cooled threshold current is considerably lowered. Lee *et al.* showed that Lee Model code [34] may be used to compute this lowering [41], [42]. Ali *et al.* [43] reported that self absorption becomes significant when plasma is dense enough to be optically thick.

In this paper, we discuss the different states of X-ray radiative nitrogen, oxygen, neon and argon plasmas and their suitable working conditions in plasma focus. We discuss the laboratory measurements to determine model parameters. We discuss the comprehensive range of numerical experiments conducted to derive scaling laws on nitrogen and argon soft X-ray yield leading up the study of radiative collapse effect in the plasma focus.

II. Calculations of Plasma Parameters Using Corona Model

The X-ray radiation properties of plasmas are dependent on the plasma temperature, ionization states, and density. Plasma equilibrium model can be used to calculate the ion fraction α, the effective ionic charge number $\mathrm{Z_{eff}}$, the effective specific heat ratio γ and X-ray emission of the plasma at different temperatures. The ion fraction is defined as the fraction of the plasma which is ionized to the zth ionized: $\alpha_\mathrm{z} = \mathrm{N_z}/\mathrm{N_i}$ where: $\mathrm{N_z}$ is the zth ionized ion number density; $\mathrm{N_i}$ is the total ion number density. The effective ionic charge number $\mathrm{Z_{eff}}$ is the average charge of one ion [34], [44]–[47]. Based on the corona model, we obtained for nitrogen, that the suitable temperature range for generating H-like 1s-2p, $\mathrm{N_2}$: 24.784 $\mathrm{A^\circ}$ (500 eV), 1s-3p, $\mathrm{N_2}$: 21 $\mathrm{A^\circ}$ (592.92 eV) and He-like $1s^2$-1s2p, $\mathrm{N_2}$: 29 $\mathrm{A^\circ}$ (426 eV), $1s^2$-1s3p, $\mathrm{N_2}$: 24.96 $\mathrm{A^\circ}$ (496 eV) ions in

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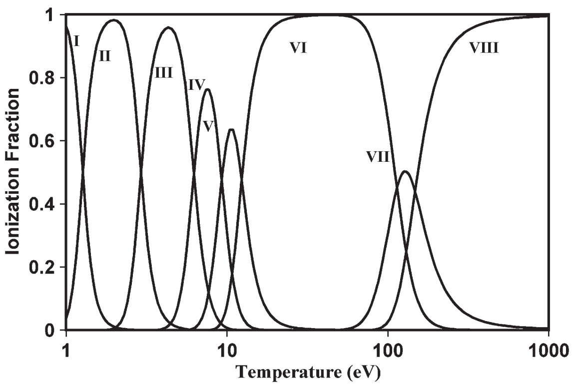

Fig. 1. Nitrogen ionization fractions as a function of temperature, where VIII indicates the ion N^{+7}[46].

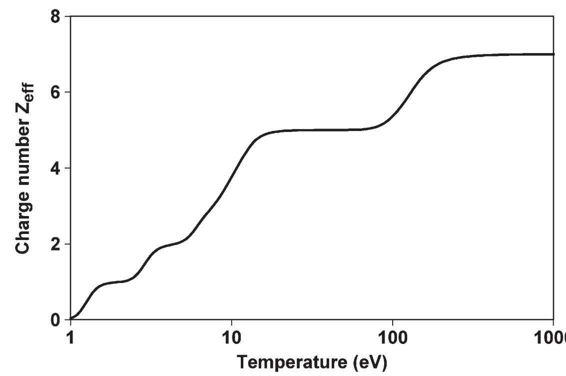

Fig. 2. Effective charge number Z_{eff} of N_2 calculated from Fig 1.

nitrogen plasma (therefore, generating soft X-ray emission) is 74–173 eV $(0.86 \times 10^6 - 2 \times 10^6$ K) [46], [48]. It is also noticed that the nitrogen atoms become fully ionized around 800 eV to 1000 eV.

The suitable temperature range for generating H-like 1s-2p, O_2: 18.97 A° (653.68 eV), 1s-3p, O_2: 16 A° (774.634 eV) and He-like $1s^2$-1s2p, O_2: 21.6 A° (573.947 eV), $1s^2$-1s3p, O_2: 18.62 A° (665.615) ions in oxygen plasma (therefore, soft X-ray emissions) has been calculated to be between 119 and 260 eV $(1.38 \times 10^6 - 3 \times 10^6$ K) with full ionization at around 2000 eV to 3000 eV [47].

For neon, a temperature window of 200 eV to 500 eV $(2.3 \times 10^6 - 5 \times 10^6$ K) is suitable for generating H-like 1s-2p, Ne: 12.132 A° (1022 eV), 1s-3p, Ne: 10.240 A° (1211 eV) and He-like $1s^2$-1s2p, Ne: 13.447 A° (922 eV), $1s^2$-1s3p, Ne: 11.544 A° (1074 eV) ions in neon plasma (therefore neon soft X-ray emissions) [45], [49]–[51].

From the reported experimental results [44], [52], [53], the X-ray emissions from argon plasma are mainly He-like alpha line (He_α ($1s^2$-1s2p, Ar: 3.9488 A° (3140 eV)), $1s^2$-1s3p, Ar: 3.365 A° (3684 eV)) and H-like alpha line (Ly_α (1s-2p, Ar: 3.731 A° (3323 eV)), (1s-3p, Ar: 3.150 A° (3936 eV)) lines. So, the most intense characteristic emissions of argon plasma are Ly_α and He_α lines. The corresponding X-ray emitters in the argon plasmas are mainly H- and He-like ions. For argon, a focus pinch compression temperature of 1.4 keV to 5 keV $(16.3 \times 10^6 - 58.14 \times 10^6$ K) is suitable for generating H- and He-like ions. An example of these calculations is shown in Figs. 1 and 2.

Based on the above work we take the soft X-ray yield (H- and He-like ions) from nitrogen, oxygen, neon and argon to be equivalent to line radiation yield i.e., $Y_{sxr} = Q_L$ at a suitable different temperature ranges (T windows) for each gas as follows: 74–173 eV for nitrogen [46], 119–260 eV for oxygen [47], 200 to 500 eV for neon [49], [51], and for argon is 1.4 keV to 5 keV [44], [52]–[54].

III. Numerical Experiments Using Lee Model

A. *Soft X-Ray Yield Versus Pressure*

The dynamics of plasma focus discharges is complicated; for this purpose, to investigate the plasma focus phenomena, the Lee Model couples the electrical circuit with plasma focus dynamics, thermodynamics and radiation, enabling realistic simulation of all gross focus properties [34]–[36]. In the radial phases, axial acceleration and ejection of mass are caused by necking curvatures of the pinching current sheath result in time-dependent strongly center-peaked density distributions. Moreover, laboratory measurements show that rapid plasma/current disruptions result in localized regions of high densities and temperatures particularly in the heavy gases like xenon. We point out that these center-peaking density effects and localized regions are not modeled in the code, which computes only an average uniform density and an average uniform temperature which are considerably lower than measured peak density and temperature. However, because the four-model parameters are obtained by fitting the computed total current waveform to the measured total current waveform, the model incorporates the energy and mass balances equivalent, at least in the gross sense, to all the processes which are not even specifically modeled. Hence, the computed gross features such as speeds and trajectories and integrated soft X-ray yields have been extensively tested in numerical experiments for several machines and are found to be comparable with measured values. Thus the code provides a useful tool to conduct scoping studies, as it is not purely a theoretical code, but offers means to conduct phenomenological scaling studies for any plasma focus device from low energy to high energy machines.

The Lee Model code has been successfully used to perform numerical experiments to compute neon soft X-ray yield for the NX2 as a function of pressure with reasonable degree of agreement in (1) the Ysxr versus pressure curve trends, (2) the absolute maximum yield, and (3) the optimum pressure value. The only input required is a measured total current waveform. This reasonably good agreement, against the background of an extremely complicated situation to model, moreover the difficulties in measuring Ysxr, gives confidence that the model is sufficiently realistic in describing the plasma focus dynamics and soft X-ray emission for NX2 operating in Neon.

In the code, line radiation Q_L is calculated as follows:

$$\frac{dQ_L}{dt} = -4.6 \times 10^{-31} N_i^2 Z_{eff} Z_n^4 (\pi a_{min}^2) Z_{max}/T$$

where for the temperatures of interest in our experiments we take $Y_{sxr} = Q_L$.

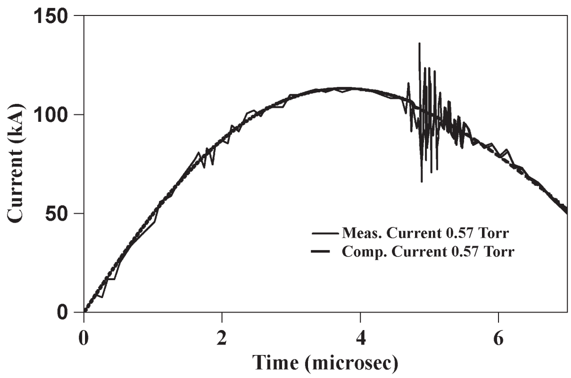

Fig. 3. Comparison of the computed current trace (smooth line) with the experimental one (solid line) of the AECS-PF-2 at 15 kV, 0.57 torr neon.

Hence, the SXR energy generated within the plasma pinch depends on the following properties: number density $\mathrm{N_i}$, effective charge number Z_{eff}, atomic number of gas $\mathrm{Z_n}$, pinch radius $\mathrm{a_{min}}$, pinch length $\mathrm{Z_{max}}$, plasma temperature T and the pinch duration. This generated energy is then reduced by the plasma self-absorption which depends primarily on density and temperature; the reduced quantity of energy is then emitted as the soft X-ray yield.

As an example, in the modified Lee Model code version, we take the nitrogen soft X-ray yield to be equivalent to line radiation yield i.e., $\mathrm{Y_{sxr}} = \mathrm{Q_L}$ at the following temperature range 74–173 eV. In any shot, for the duration of the focus pinch, whenever the focus pinch temperature is within this range, the line radiation is counted as nitrogen soft X-rays. Whenever the pinch temperature is outside this range, the line radiation is not included as nitrogen soft X-rays.

For the plasma column, using Spitzer form for resistivity, and the Bennett distribution we obtain a relationship between T (temperature) and I as follows):

$$\mathrm{T} = b\frac{I^2}{\left(n_i r_p^2\right)\left(1+Z_{eff}\right)}$$
$$\text{where} \quad b = \frac{\mu}{8\pi^2 k}.$$

Here μ = Permeability, k = Boltzmann constant; and all variables in the temperature equation refer to their appropriate values within the pinch during the time of pinch. Numerical experiments have been investigated systematically using Lee Model to characterize various low energy plasma focus devices operated with different gases (nitrogen, oxygen, neon, argon) and plasma focus parameters.

For each studied plasma focus device, fitted values of the model parameters were found using the following procedures: The computed total discharge current waveform is fitted to the measured by varying model parameters $\mathrm{f_m}$, $\mathrm{f_c}$, $\mathrm{f_{mr}}$ and $\mathrm{f_{cr}}$ one by one until the computed waveform agrees with the measured waveform [55].

For example, experiments have been investigated on the AECS-PF-2 with Ne at wide range of pressures to get experimental current traces with good focus effect [63] from 0.25 to 1.25 torr. To start the numerical experiments we select a discharge current trace of the AECS-PF-2 taken with a Rogowski coil at 0.57 torr (Fig. 3).

We configure the Lee Model code (version RADPF5.15K) to operate as the AECS-PF-2 plasma focus. To obtain a reasonably good fit the following parameters are used:

Bank parameters: static inductance $\mathrm{L_0} = 280$ nH, capacitance $\mathrm{C_0} = 25\ \mu$F, stray resistance $\mathrm{r_0} = 25\ \mathrm{m}\Omega$,

Tube parameters: cathode radius $\mathrm{b} = 3.2$ cm, anode radius $\mathrm{a} = 0.95$ cm, anode length $\mathrm{z_0} = 16$ cm,

Operating parameters: voltage $\mathrm{V_0} = 15$ kV, pressure $\mathrm{p_0} = 0.57$ torr, Ne gas, together with the following fitted model parameters:

$$\mathrm{f_m} = 0.1, \mathrm{f_c} = 0.7, \mathrm{f_{mr}} = 0.2 \text{ and } \mathrm{f_{cr}} = 0.7.$$

With these parameters, the computed total current trace agrees reasonably well with the experimental trace (Fig. 3).

These fitted values of the model parameters are then used for the computation of all the discharges at pressures from 0.1 to 2.1 torr [63]. The results (Table I) show that the $\mathrm{Y_{sxr}}$ attains an optimum value of 0.42 J at 1.12 torr (efficiency 0.015%, end axial speed $\mathrm{V_a} = 4.2\ \mathrm{cm}/\mu\mathrm{s}$, speed factor (SF) is 113.4 kA/cm per $[\text{torr of Ne}]^{1/2}$) [11].

It is evident from Table I that the peak value of total discharge current $\mathrm{I_{peak}}$ decreases with decreasing pressure. This is due to increasing dynamic resistance (rate of change of tube inductance, dL/dt gives rise to a dynamic resistance equal to 0.5 dL/dt [36]) due to increasing current sheath speed as pressure is decreased. On the contrary, the current $\mathrm{I_{pinch}}$ that flows through the pinched plasma column increases with decreasing pressure until it reaches the maximum. This is due to the shifting of the pinch time towards the time of peak current as the current sheet moves faster and faster. As the pressure is decreased, the increase in $\mathrm{I_{pinch}}$ may be expected to favor $\mathrm{Y_{sxr}}$; however there is a competing effect that decreasing pressure reduces the number density. The interaction of these competing effects will decide on the actual yield versus pressure [49], [51]. The Lee Model code was also applied to characterize the UNU/ICTP PFF Plasma Focus, finding a maximium argon soft X-ray yield (Ysxr) of 0.039 J [63].

B. Soft X-Ray Yield Versus Electrode Geometry

We next optimize $\mathrm{Y_{sxr}}$ from various plasma focus devices with different gases. More numerical experiments were carried out; varying $\mathrm{p_0}$, $\mathrm{z_0}$ and "a" keeping $\mathrm{c} = \mathrm{b/a}$ constant. The pressure $\mathrm{p_0}$ was slightly varied. The following procedure was used [46], [47], [49], [51], [52], [55]. At each $\mathrm{p_0}$, the anode length $\mathrm{z_0}$ was fixed at a certain value; then the anode radius "a" was varied, till the maximum $\mathrm{Y_{sxr}}$ was obtained for this $\mathrm{z_0}$. This was repeated for other values of $\mathrm{z_0}$, until we found the optimum combination of $\mathrm{z_0}$ and "a" at the fixed $\mathrm{p_0}$. Then we changed $\mathrm{p_0}$ and repeated the above procedure; until finally we obtained the optimum combination of $\mathrm{p_0}$, $\mathrm{z_0}$ and "a".

The optimized results for each value of $\mathrm{p_0}$ showed that as $\mathrm{p_0}$ is increased, "a" has to be decreased to maintain the required speeds so that the argon pinch remains within the required temperature window. The $\mathrm{Y_{sxr}}$ attains an optimum value of 0.0035 J at $\mathrm{p_0} = 1.8$ torr as shown in Fig. 4 which also shows corresponding optimum end axial speed as with

TABLE I
VARIATION AECS-PF-2 PARAMETERS WITH PRESSURE AT: $L_0 = 280$ nH, $C_0 = 25\ \mu$F, $r_0 = 25$ mΩ, $V_0 = 15$ kV, RATIO OF STRAY RESISTANCE/BANK SURGE IMPEDANCE RESF = 0.24, c = b/a = 3.37, $f_m = 0.1$, $f_c = 0.7$, $f_{mr} = 0.2$, $f_{cr} = 0.7$, NEON GAS [63]

p_0(Torr)	I_{peak}(kA)	I_{pinch}(kA)	V_a (cm/μs)	V_s(cm/μs)	V_p(cm/μs)	SF	Pinch duration(ns)	Ysxr(J)	Efficiency (%)
2.1	The code unable to run								
1.30	114.4	61.9	3.88	19.9	14.2	105.6	9.2	0.000	0
1.20	114.2	64.4	4.06	21.5	14.7	109.7	8.6	0.000	0
1.15	114.1	65.6	4.16	22.5	15.0	112.0	8.2	0.000	0
1.12	114.0	66.3	4.22	23.2	15.2	113.4	8.0	0.418	0.015
1.10	114.0	66.8	4.27	23.7	15.3	114.4	7.7	0.355	0.013
1.00	113.8	69.0	4.49	24.9	15.8	119.8	7.9	0.247	0.009
0.80	113.2	72.8	5.03	25.8	16.9	133.2	8.2	0.114	0.004
0.70	112.8	74.4	5.36	26.8	17.8	141.9	8.2	0.075	0.0026
0.57	112.2	75.9	5.87	28.7	19.6	156.4	7.9	0.039	0.0014
0.50	111.7	76.4	6.21	30.1	20.9	166.3	7.6	0.026	0.0009
0.40	111.0	76.5	6.80	32.8	23.4	184.7	7.0	0.013	0.0005
0.30	109.5	75.7	7.59	35.9	26.2	210.3	6.5	0.005	0.0002
0.20	105.6	73.2	8.78	41.7	30.0	248.5	5.7	0.001	0.000036
0.10	96.2	66.8	11.04	52.7	36.8	320.1	4.6	0.000	0

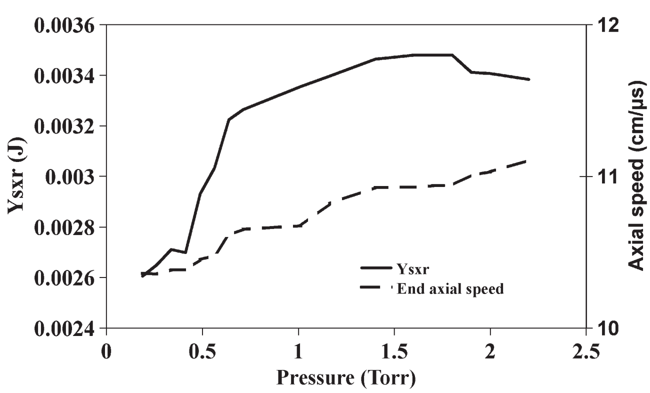

Fig. 4. Y_{sxr} and end axial speed of AECS-PF-2 in Ar (Y_{sxr} versus p_0, optimized z_0 and "a" for each point) [52].

TABLE II
FOR EACH L_0, THE OPTIMIZED COMBINATION OF z_0 AND "a" WERE FOUND AND ARE LISTED HERE. $L_0 = 280$ nH, $C_0 = 25\ \mu$F, $r_0 = 25$ mΩ; c = b/a = 3.37; MODEL PARAMETERS: $f_m = 0.1$, $f_c = 0.7$, $f_{mr} = 0.2$, $f_{cr} = 0.7$; 2.8 torr Ne, $V_0 = 15$ kV

L_0 (nH)	z_0 (cm)	a (cm)	b (cm)	I_{peak} (kA)	I_{pinch} (kA)	a_{min} (cm)	Z_{max} (cm)	V_a (cm/μs)	Y_{sxr} (J)
280	8.00	0.727	2.45	115	79	0.05	1.0	3.45	0.94
200	7.00	0.842	2.84	135	92	0.06	1.2	3.52	1.66
100	4.50	1.125	3.79	186	125	0.08	1.6	3.57	5.16
50	4.00	1.400	4.73	256	158	0.10	2.0	4.02	11.62
25	2.80	1.640	5.52	340	190	0.14	2.4	4.50	18.72
20	2.50	1.693	5.70	369	198	0.16	2.5	4.72	20.35
15	2.40	1.732	5.83	410	205	0.17	2.6	5.15	21.77
10	2.00	1.760	5.93	464	212	0.20	2.7	5.71	21.40
5	1.97	1.749	5.89	556	214	0.25	2.7	7.12	16.14
3	1.96	1.705	5.74	608	211	0.26	2.6	8.16	13.19

the plasma focus operated at the optimum combination of z_0 and "a" corresponding to each p_0. We thus found for the AECS-PF-2 the optimum combination of p_0, z_0 and "a" for argon Y_{sxr} as 1.8 torr, 24.3 cm and 0.26 cm, respectively, with the outer radius $b = 0.9$ cm. This combination gives $Y_{sxr} = 0.0035$ J with $I_{peak} = 102$ kA, $I_{pinch} = 71$ kA, and end axial speed is of 11 cm/μs [52].

Practically, it is technically difficult to change "b"; unless the whole electrode and input flange system is completely redesigned. So, for practical optimization, we wish to [49], [52], [63] keep $b = 3.2$ cm and compute the optimum combinations of (p_0, "a"), (p_0, z_0) and (p_0, z_0, "a") for the maximum Y_{sxr}. This gives us a practical optimum configuration of $b = 3.2$ cm, $a = 1.567$ cm, $z_0 = 9$ cm, giving a practical optimum yield of 0.924 J at 0.58 torr for Ne [63].

C. Soft X-Ray Yield Versus Inductance

We investigated the effect of reducing L_0 down to 3 nH [38], [39], [48], [49], [52], [63], [64] for different plasma focus devices operated with various gases. For example, it was found that reducing L_0 increases the total current from $I_{peak} = 115$ kA at $L_0 = 280$ nH to $I_{peak} = 410$ kA at $L_0 = 15$ nH for AECS-PF-2 with neon gas [63] (see Table II).

As L_0 was reduced, I_{peak} increased; "a" is necessarily increased leading to longer pinch length (z_{max}), hence a bigger pinch inductance L_p. At the same time because of the reducing current drive time, z_0 needed to be reduced. The geometry moved from a long thin Mather-type to a shorter fatter one. Thus while L_0 and axial section inductance L_a reduced, the pinch inductance L_p increased due to increased pinch length [38], [48], [63].

While I_{peak} increases with each reduction in L_0 with no sign of any limitation, I_{pinch} reaches a maximum of 214 kA at $L_0 = 5$ nH, then it decreases with each reduction in L_0. From Table II it can be seen, that as L_0 decreased, Y_{sxr} increases until it reaches a maximum value of 22 J at $L_0 = 15$ nH; beyond which Y_{sxr} does not increase with reducing L_0. This confirms the pinch current and Y_{sxr} limitation effect in Ne plasma focus.

Based on the results of these numerical experiments on various devices with different gases, to improve Y_{sxr}, L_0 should

TABLE III
OPTIMIZED CONFIGURATION FOUND FOR EACH E_0; $L_0 = 10$ nH, $V_0 = 15$ kV, 1 torr ARGON; f_m, f_c, f_{mr}, f_{cr} ARE FIXED AT 0.05, 0.7, 0.15 AND 0.7 RESPECTIVELY, v_a IS THE PEAK AXIAL SPEED

E_0 (kJ)	C_0 (μF)	a (cm)	z_0 (cm)	I_{peak} (kA)	I_{pinch} (kA)	v_a (cm/μs)	Y_{sxr} (J)	Efficiency (%)
1.1	10	0.70	4	251.4	148.8	13.60	0.05	0.0045
2.8	25	0.90	6	329.5	193.1	13.98	0.13	0.0046
4.5	40	1.01	8	370.7	217.1	14.08	0.22	0.0048
5.6	50	1.07	9	390.4	229.0	14.08	0.26	0.0046
11.3	100	1.24	15	448.8	264.3	14.03	0.52	0.0046
22.5	200	1.41	23	503.5	300.1	13.79	1.01	0.0045
45.0	400	1.58	37	551.9	333.6	13.46	1.85	0.0041
67.5	600	1.68	43	578.3	354.5	13.30	2.52	0.0037
90.0	800	1.74	57	594.5	366.1	13.11	3.15	0.0035
112.5	1000	1.80	61	607.3	377.2	13.03	3.72	0.0033
450.0	4000	2.07	133	669.8	432.4	12.48	7.67	0.0020
900.0	8000	2.18	177	692.4	454.9	12.30	9.66	0.0010
1012.5	9000	2.20	209	695.7	457.8	12.24	10.03	0.0001

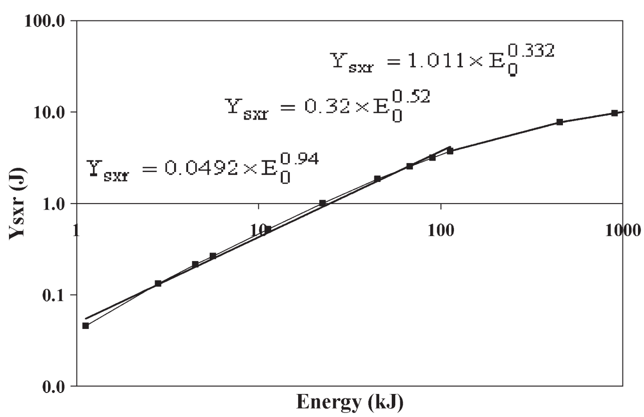

Fig. 5. Y_{sxr} versus E_0. The parameters kept constants are: RESF $= 0.337$, $c = 3.37$, $L_0 = 10$ nH, $p_0 = 1$ torr Argon and $V_0 = 15$ kV and model parameters f_m, f_c, f_{mr}, f_{cr} at 0.05, 0.7, 0.15 and 0.7, respectively [53].

be reduced to a value around 15–25 nH, which is an achievable range incorporating low inductance technology, below which I_{pinch} and Y_{sxr} would not be improved.

D. Scaling Laws for Soft X-Ray Yield of Argon and Nitrogen Plasma Focus

Following above stated procedures numerical experiments were investigated on AECS-PF-2 like argon plasma focus at different operational gas pressures (0.41, 0.75, 1, 1.5, 2.5, and 3 torr) for two different static inductance values L_0 (270 and 10 nH) and then after systematically carrying out more than 3000 numerical runs, the optimized conditions are obtained. Table III shows optimized configuration found for each E_0 for 10 nH at gas pressure of 1 torr. From this data, we also plot Y_{sxr} against E_0 as shown in Fig. 5 to obtain scaling law: $Y_{sxr} = 0.05E_0^{0.94}$ in the 1 to 100 kJ regions. The scaling deteriorates as E_0 is increased to $Y_{sxr} = 0.32E_0^{0.52}$, and then to $Y_{sxr} = 1.01E_0^{0.33}$ at high energies towards 1 MJ. The requirement of a temperature window for the pinch fixes the axial speed within a narrow range of values. This fixes the axial dynamic resistance to a value around 7 mΩ for a plasma focus of any size. However, as E_0 is increased by increasing C_0, the bank surge impedance

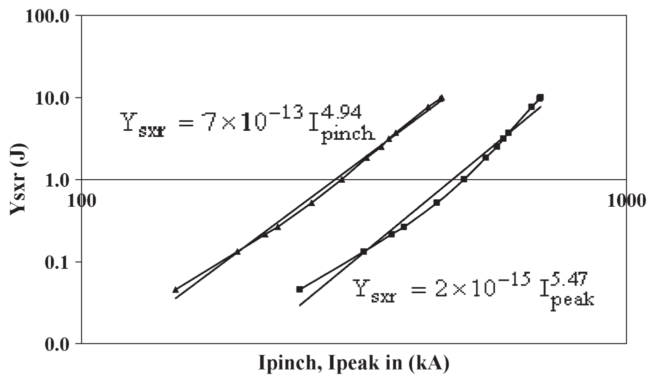

Fig. 6. Y_{sxr} versus I_{pinch}, I_{peak}. The parameters kept constants are: RESF $= 0.337$, $c = 3.37$, $L_0 = 10$ nH, $p_0 = 1$ torr Ar and $V_0 = 15$ kV and model parameters f_m, f_c, f_{mr}, f_{cr} at 0.05, 0.7, 0.15 and 0.7 [53]

$Z_0 = (L_0/C_0)^{0.5}$ ranges from 30 mΩ (for 1 kJ) to 1 mΩ (for 1 MJ). Thus at 1 kJ the plasma focus current is dominated by the bank impedance while at 1 MJ the bank impedance hardly affects the discharge current. At 1 kJ quadrupling C_0 (hence E_0) would double I_{peak}; but at 1 MJ quadrupling C_0 would increase I_{peak} by only some 7%. This is what causes the deterioration of current scaling with respect to E_0.

This is consistent with the deterioration of scaling with increasing E_0 in the case of neutron yield attributed to reduction of current rise due to the increasingly dominant effect of the dynamic resistance [65], [66]. Our results indicate that such yield deterioration with increasing E_0 is a general effect applicable to not just neutrons but also to SXR yields. We then plot Y_{sxr} against I_{peak} and I_{pinch} and obtain Fig. 6 which shows $Y_{sxr} = 7 \times 10^{-13} I_{pinch}^{4.94}$ and $Y_{sxr} = 2 \times 10^{-15} I_{peak}^{5.47}$[53].

Scaling laws for N_2[67] and Ne soft X-ray yields [14], [36], in terms of storage energies E_0, were found to be best averaged as $Y_{sxrN} = 1.93E_0^{1.21}$ and $Y_{sxrNe} = 11E_0^{1.2}$ (yield in J, E_0 in kJ), respectively at energies in the 2 to 400 kJ regions. By comparing our recent results for N_2 plasma focus with Ar and Ne soft X-ray yields over this studied storage energy ranges, it is seen that the Ne soft X-ray yield of plasma focus is the most intense one (Fig. 7). The plasma focus is a powerful source of X-rays with wavelengths which may be suitably selected for microlithography, micromachining and microscopy simply by selecting the working gas (Ne or Ar or N_2 correspondingly) and choosing corresponding design and operating parameters of the device.

E. Model Parameters Versus Gas Pressure in Two Different Plasma Focus Devices Operated in Argon and Neon

Using the Lee Model, the computed and measured current are fitted varying the pressure, with the purpose to find the proper model parameters versus pressure for AECS-PF-2 and INTI PF devices operated with Ar and Ne, respectively. The results show a value of $f_m = 0.05 \pm 0.01$ over the whole range of pressure 0.2–1.2 torr in Ar; and $f_m = 0.04 \pm 0.01$ over 0.7–4.1 torr in Ne. The value of $f_c = 0.7$ was fitted for all cases. Combining these results with those published for several other small machines, where measured current waveforms are

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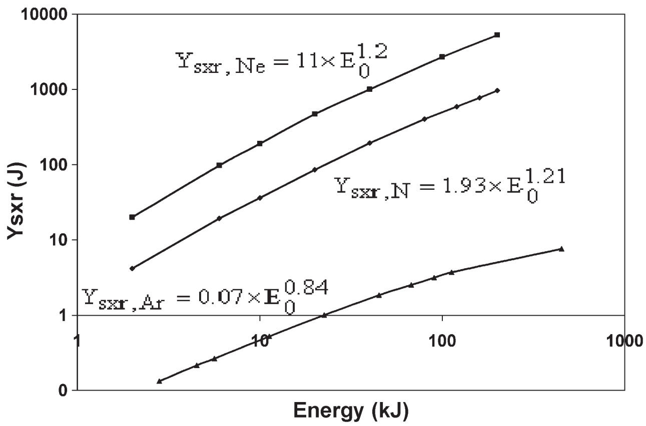

Fig. 7. Soft X-ray yields versus storage energy for Ne, N_2 and Ar plasma focus [67].

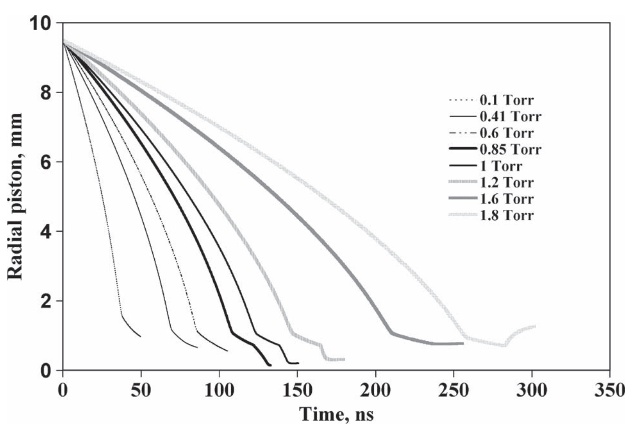

Fig. 8. Variations of radial piston trajectories on AECS-PF-2 for different Ar pressure [68] showing a regime of radiative collapse.

not available, a good compromise would be to take a guideline value of $f_m = 0.05$ and $f_c = 0.7$ for both Ar and Ne [55].

F. Radiative Collapse in Plasma Focus Operated With Heavy Noble gases

Numerical experiments have been investigated on plasma focus device to study radiative collapse phenomena.

Fig. 8 shows variations of radial trajectories versus pressures on AECS-PF-2 device. At 0.85 torr and a pinch temperature of 190 eV with a pinch current of just under 66 kA, radiative collapse is obvious with the radius collapsing in a few ns to the cutoff radius of 0.1 mm set in the model. At lower pressures such as 0.41 torr and higher pressures such as 1.6 torr clearly the pinch compression is far less. The range of 0.85 to 1.2 torr is when the radiation is maximum due to both factors of high pinch density as well as sufficiently large pinch current. Above 1.2 torr the pinch is coming too late in the discharge cycle and although the density is higher the current is already too low to cause sufficient radiation to lead to radiative collapse.

Finally, based on obtained results by five phase Lee Model, we can say that gas type and pressure of the plasma focus play an important role in radiative collapse creation. This phenomenon produces an extreme increase in tube voltage and generates huge line radiations in the plasma focus [68].

IV. Conclusion

The Lee Model code has been adapted to N_2 and O_2. We applied the numerical experiments specifically to our AECS-PF-1 and AECS-PF-2. Numerical experiments have been generalized to other machines and other gases to look at scaling and scaling laws and to explore recently uncovered insights and concepts. The required thermodynamic data of N_2, O_2, Ne and Ar gases at different temperatures were calculated, the X-ray emission properties of plasmas were studied and suitable temperature range (window) for generating H- and He-like ions in the various gases.

The Lee Model code version RADPF5.15K is used to characterize the AECS-PF-1 and AECS-PF-2, and for optimizing the N_2, O_2, Ne, and Ar SXR yields.

Numerical experiments show the big influence of L_0 for improving the soft X-ray yield; that it is useful to reduce L_0 to a range of 15–25 nH; but not any smaller since further reduction produces no yield benefit and would be a futile expensive exercise. For our machines, reduction of L_0 would give the optimum soft X-ray yields from N_2, O_2, Ne and Ar of 6 J, 10 J, 22 J, and 0.1 J, respectively. These yields at diverse wavelength ranges are large enough to be of interest for applications ranging from microelectronics lithography to micro-machining and microscopy of biological specimens.

Scaling laws for SXR of Ar and N_2 plasma focus, in terms of energy, peak and focus pinch current were found.

Numerical experiments were carried out on different plasma focus devices with different filling gases to show that radiation cooling and radiative collapse may be observed for heavy noble gases (Ar, Kr, Xe) for pinch currents even below 100 kA. The results show that the line radiation emission and tube voltages have huge values near the radiative collapse regime. The creation of the consequential extreme conditions of density and pulsed power is of interest for research and applications. Current waveforms and SXR measurements in krypton [41] are being evaluated to study such radiative conditions.

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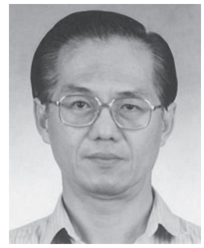

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