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Numerical Experiments to Investigate the Interactive Effects of some key Pinch Plasma Properties with Pressure on Neon Soft x-ray Production in Inti Plasma Focus

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***Abstract---* The work on these numerical experiments was carried out using the Lee model code as a tool to compute the neon soft x-ray production in INTI plasma focus device. The computed pinch properties of plasma curves versus pressure are presented and discussed particularly in terms of the gross properties of the plasma focus including peak discharge current I_{peak}, pinch current I_{pinch}, minimum pinch radius a_{min}, maximum pinch density n_i, and plasma temperature at middle duration of pinch T_{pinch} are presented and the trends in variation of these are discussed to explain the peaking of soft X-ray (Y_{sxr}) at optimum pressure.**

Index Terms--- **Pinch plasma properties, soft x-ray production, plasma focus, Lee model code.**

I. INTRODUCTION

Plasma focus has been demonstrated as potential x-ray source for various medicobiological and industrial applications such as lithography [1-4], radiography [5, 6], microscopy [7, 8] and micromachining [9]. This has led to an interest in exploiting the plasma focus device as a viable intense X-ray source and also due to its advantages such as being relatively cheap, compact, and ease of construction. The x-ray emissions from plasma focus devices have been explored over the wide range of capacitor bank energies ranging from large mega joule and few hundred kilo joule banks [10] to sub-kilojoule banks of miniature sized focus devices [11, 12].

In recent years various efforts have been made for enhancing the x-ray yield by changing various experimental parameters such as bank energy [13], discharge current, electrode configuration (shape and material) [14, 15], insulator material and dimensions [14], gas composition, and filling gas pressure [5]. Thus, soft x-ray yield optimization studies on the plasma focus devices operating over the wide range of bank energies have been one of the actively pursued fields of plasma focus research owing to their possible applications. Presently used systematic trial and error experimental procedure to obtain the optimized conditions for maximum radiation yield is highly time-consuming. To overcome this, a quicker optimization of plasma focus device is highly desirable, which can be achieved if a reliable focus model and corresponding simulation code to predict the X-ray yields from plasma focus device is used.

In this work, we use the Lee model code [16] ver-13.6b to carry out the numerical experiments on INTI plasma focus device to compute its neon soft x-ray yield Y_{sxr} as a function of filling gas pressure. The INTI plasma focus is a 3.3 kJ plasma focus device. Its performance has been extensively studied, especially in regards to discharge currents and soft X-ray yield Y_{sxr}. In this paper, we have simulated the operation of INTI plasma focus device in numerical experiments which are designed to compare its currents, dynamics, and some plasma pinch properties at various pressures so as to examine the role played by various relevant interactive plasma properties on the way the Y_{sxr} peaks at the optimum pressure.

II. THE MODEL CODE FOR NUMERICAL EXPERIMENTS

The Lee model couples the electrical circuit with plasma focus dynamics, thermodynamics, and radiation, enabling realistic simulation of all gross plasma properties of plasma focus. Radiation-coupled dynamics was included in the five-phase code leading to numerical experiments on radiation cooling [17]. The code has been used extensively in several machines including UNU/ICTP PFF [4, 18, 20, 21], NX2 [4, 22], NX1 [4] and adapted for the Filippov-type plasma focus DENA [23]. The description, theory, code and a broad range of results of this Universal Plasma Focus Laboratory Facility is available for download from World Wide Web [24].

A brief description on the five phases [25] incorporated the Lee model code is a follows:

i. Axial phase: This phase is described by a snowplow model with an equation of motion which is coupled to a circuit equation. The equation of motion incorporates the axial phase model parameters: mass and current factors f_m and f_c. The mass swept-up factor f_m accounts for not only the

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porosity of the current sheath but also for the inclination of the moving current sheath-shock front structure and all other unspecified effects which have effects equivalent to increasing or reducing the amount of mass in the moving structure, during the axial phase. The current factor f_c accounts for the fraction of current effectively flowing in the moving structure due to all effects such as current shedding at or near the back-wall, current sheet inclination. This defines the fraction of current effectively driving the structure, during the axial phase.

ii. Radial inward shock phase: It is described by four coupled equations using an elongating slug model. The first equation computes the radial inward shock speed from the driving magnetic pressure. The second equation computes the axial elongation speed of the column. The third equation computes the speed of the current sheath, also called the magnetic piston, allowing the current sheath to separate from the shock front by applying an adiabatic approximation. The fourth is the circuit equation. Thermodynamic effects due to ionization and excitation are incorporated into these equations, these effects being important for gases other than hydrogen and deuterium. Temperature and number densities are computed during this phase. A communication delay between shock front and current sheath due to the finite small disturbance speed is crucially implemented in this phase. The model parameters, radial phase mass swept up, and current factors f_{mr} and f_{cr} are incorporated in all three radial phases. The mass swept-up factor f_{cr} accounts for all mechanisms which have effects equivalent to increasing or reducing the amount of mass in the moving slug, during the radial phase not least of which could be axial ejection of mass. The current factor f_{cr} accounts for the fraction of current effectively flowing in the moving piston forming the back of the slug (due to all effects). This defines the fraction of current effectively driving the radial slug.

iii. Radial reflected shock RS phase: In this phase when the shock front hits the axis, because the focus plasma is collisional, a RS develops which moves radially outwards, while the radial current sheath piston continues to move inwards. Four coupled equations are also used to describe this phase, these being for the RS moving radially outwards, the piston moving radially inwards, the elongation of the annular column and the circuit equation. The same model parameters f_{mr} and f_{cr} are used as in the previous radial phase. The plasma temperature behind the RS undergoes a jump by a factor nearly 2.

iv. Slow compression quiescent or pinch phase: In this phase when the outgoing RS hits the ingoing piston the compression enters a radiative phase in which for gases such as neon; the radiation emission may actually enhance the compression where we have included energy loss/gain terms from Joule heating and radiation losses into the piston equation of motion. Three coupled equations describe this phase; these being the piston radial motion equation, the pinch column elongation equation and the circuit equation, incorporating the same model parameters as in the previous two phases. Thermodynamic effects are incorporated into this phase. The duration of this slow compression phase is set as the time of transit of small disturbances across the pinched plasma column. The computation of this phase is terminated at the end of this duration.

v. Expanded column phase: In this phase to simulate the current trace beyond this point we allow the column to suddenly attain the radius of the anode, and use the expanded column inductance for further integration. In this last phase the snow plow model is used and two coupled equations are used similar to the axial phase above. This phase is not considered important as it occurs after the focus pinch.

III. METHODOLOGY

To start with the numerical experiments we selected a discharge current trace of the INTI plasma focus taken with a Rogowski coil. The selected measured waveform is of a shot at 2.9 Torr neon, near optimum Y_{sxr} yield. The following bank, tube, and operation parameters are used; bank: static inductance L_0=110 nH, C_0=30 μF, stray resistance r_0=12 mΩ; tube: cathode radius b=3.2 cm, anode radius a=0.95 cm, anode length z_0=16 cm; and operation: voltage V_0=15 kV, pressure P_0=2.9 Torr.

The computed total current waveform is fitted to the, measured waveform by varying model parameters: f_m, f_c, f_{mr} and f_{cr} one by one until the computed waveform agrees with the measured waveform. Then we proceed to fit the radial phase model factors f_{mr} and f_{cr} until the computed slope and depth of the dip agree with the measured data. In this process, the fitted model parameters are obtained: f_m=0.08, f_c=0.7, f_{mr}= 0.16 and f_{cr}=0.7. These fitted values of the model parameters are then used for the computation of all the discharges at various pressures. The code is used for each pressure, starting at 5 Torr. At this high pressure the computed results indicate a slow axial phase speed with the end of the axial phase starting much too late after the time of peak current. This is repeated each time lowering the filling neon pressure until a non-zero value of neon SXR is computed. It was decided that a range of neon operating pressures from 3.7 Torr down to 0.1 Torr is suitable to study the SXR yield as a function of pressure. Fig. 1 record the discharge current waveforms run. This is repeated each time lowering the filling neon pressure. Fig. 1 records the discharge current waveforms for some of the gross properties of INTI plasma focus for selected pressures.

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Table I. (a), (b): Computed plasma dynamics and pinch plasma parameters for different neon filling gas pressures by numerical experiments conducted on INTI plasma focus device using Lee model code.

P_0 (Torr)	I_{peak} (kA)	$I_{pinch\ start}$ (kA)	$T_{pinch\ max}$ (10^6)	$Peak_{va}$ (cm/us)	$Peak_{vs}$ (cm/us)	$Peak_{vp}$ (cm/us)	a_{min} (cm)
0.1	139.09	95.17	55.74	18.03	81.08	54.12	0.12
0.3	166.32	113.41	26.39	12.81	58.16	40.12	0.10
0.5	175.99	119.64	17.62	10.74	47.88	33.92	0.09
0.7	180.44	121.90	13.65	9.48	41.90	29.99	0.09
0.9	183.47	122.12	11.11	8.58	37.34	27.29	0.09
1.1	185.74	121.09	9.14	7.89	34.52	24.86	0.09
1.3	187.54	119.19	7.67	7.33	31.96	22.73	0.09
1.5	189.00	116.58	6.49	6.85	29.94	20.72	0.09
1.7	190.23	113.50	5.51	6.45	28.18	19.21	0.09
1.9	191.29	110.11	4.69	6.09	26.96	17.93	0.09
2.1	192.20	106.31	3.99	5.77	25.92	16.98	0.08
2.3	193.00	102.10	3.41	5.49	25.19	16.44	0.08
2.5	193.72	98.01	2.88	5.23	24.87	15.90	0.08
2.7	194.37	93.35	2.42	4.99	23.98	15.28	0.07
2.9	194.95	88.59	2.04	4.78	21.40	14.68	0.06
3.1	195.48	83.72	1.70	4.58	19.46	14.04	0.06
3.3	195.97	78.57	1.40	4.39	17.72	13.36	0.07
3.5	196.42	73.10	1.15	4.21	15.99	12.34	0.06
3.7	196.83	67.56	0.92	4.05	14.41	11.43	0.06

(a)

P_0 (Torr)	Z_{max} (cm)	Pinch dur (ns)	V_{max} (kV)	n_i pinch max	EINP (%)	$T_{axialend}$ (us)	Y_{line} J
0.1	1.39	3.21	49.97	0.13	1.26	1.52	0.00
0.3	1.38	4.27	46.76	0.46	1.85	2.06	0.00
0.5	1.39	5.11	42.66	0.86	2.10	2.38	0.00
0.7	1.40	5.78	39.22	1.28	2.21	2.63	0.01
0.9	1.40	6.39	36.02	1.72	2.24	2.84	0.02
1.1	1.39	6.83	32.86	2.10	2.19	3.02	0.05
1.3	1.39	7.30	30.34	2.50	2.13	3.18	0.09
1.5	1.39	7.81	27.46	2.94	2.05	3.33	0.15
1.7	1.38	8.15	25.33	3.42	1.94	3.48	0.23
1.9	1.37	8.41	23.58	3.93	1.83	3.61	0.34
2.1	1.35	8.54	22.05	4.58	1.71	3.73	0.49
2.3	1.34	8.49	20.95	5.39	1.59	3.85	0.70
2.5	1.32	8.30	20.05	6.45	1.46	3.97	0.99
2.7	1.29	7.86	19.16	8.03	1.34	4.09	1.35
2.9	1.33	9.15	18.65	11.93	1.32	4.19	2.40
3.1	1.33	9.88	17.06	12.71	1.22	4.30	2.31
3.3	1.30	10.71	15.57	11.44	1.05	4.41	1.02
3.5	1.28	11.82	13.66	13.52	0.89	4.51	0.09
3.7	1.26	13.02	11.74	15.48	0.75	4.61	0.00

(b)

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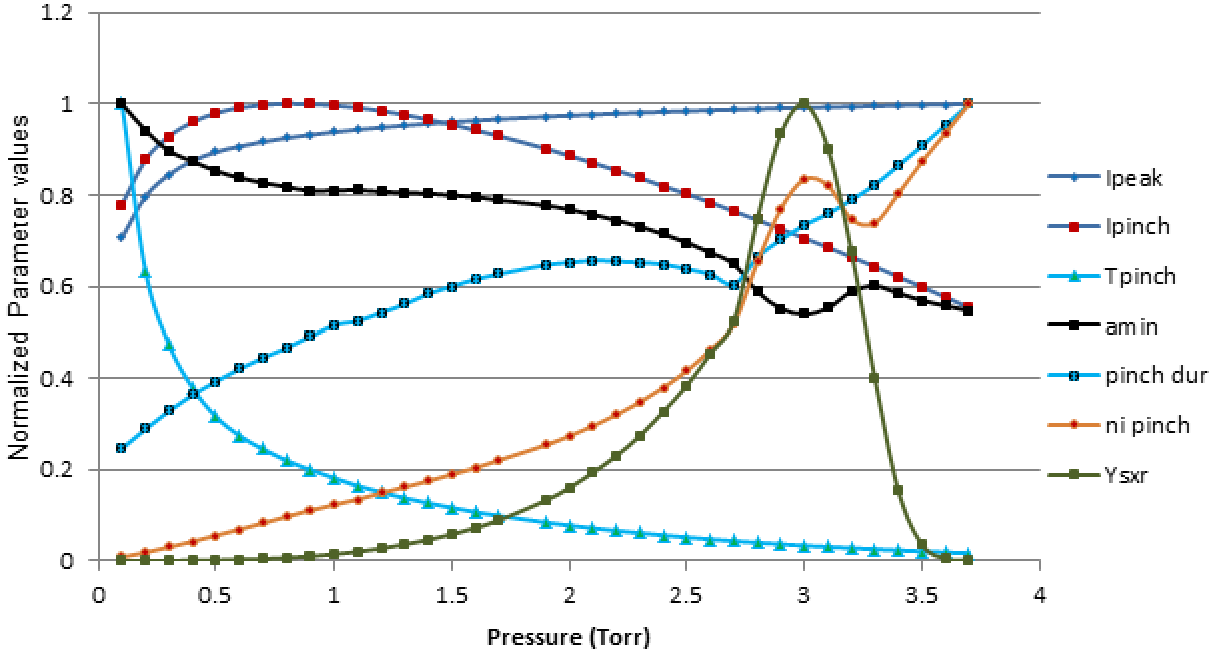

Fig. 1: Effect of operating gas pressure on some key pinch plasma parameters all normalized using value at optimum operating pressure of 2.9 Torr

IV. RESULTS AND DISCUSSION

Some properties of the dynamics and the pinch plasma as functions of the pressure as computed by numerical experiments are shown in Table I.

It is evident from Fig. 1 that the peak value of total discharge current I_{peak} decreases with decreasing pressure. This is attributed to increasing dynamic resistance i.e. increasing rate of change of plasma inductance, dL/dt due to the increasing current sheath speed as pressure is decreased. On the contrary, the current I_{pinch} that flows through the pinched plasma column increases with decreasing pressure from 4 Torr. At 4 Torr in neon the axial speed is slow and the end of the axial phase comes long after the discharge current peaks. Thus the current that is available to drive the pinch is at low value. As the pressure is reduced below 4 Torr, the axial speed increases and there is a shift of the pinch time toward the time of peak current until the pressure nears 1.0 Torr. As the pressure is decreased below 1.0 Torr, the I_{pinch} starts to decrease as the pinch time now occurs before current peak time. The high value of I_{pinch} is conducive to good SXR yield [26, 27, 28, 29]. Thus 1.0 Torr is the pressure at which the highest I_{pinch} occurs and this is the best pressure to operate as far as the I_{pinch} is concerned. However there are other factors to consider.

The T_{pinch}, which is the temperature at the middle of the pinch, keeps increasing as pressure is decreased. The n_{ipinch}, which is the ion density at middle of the pinch, increases as pressure decreases peaking around 3 Torr and then dropping at lower pressures. The r_{min}, which is the minimum radius of the pinch, has a complementary trend with a minimum at around 3 Torr. This shows that as the operating pressure is reduced toward 3 Torr, the increasing I_{pinch} increases the compression sufficiently so that despite the drop in ambient number density, the pinch density *is* still able to reach a good value at 3 Torr. As the operating pressure is reduced below 3 Torr, the increase in I_{pinch} does not appear to be sufficient to further increase n_i or indeed even to compress the pinch to a smaller radius than at 3 Torr. To clarify this situation we briefly explain the plasma dynamics during the radial collapse phase.

The radial phase uses a slug model with an imploding cylindrical shock wave forming the front of the slug, driven by a cylindrical magnetically driven current sheath piston at the rear of the slug. Between the shock wave and the current sheath is the shock heated plasma. When the shock front implodes on to the tube axis, because the plasma is collisional, a reflected shock RS develops. The RS front moves radially out wards into the inwardly streaming particles of the plasma slug leaving behind it stationary doubly shocked plasma with a higher temperature and density than the singly shocked plasma ahead of it. When the RS reaches the incoming current sheath, typically the magnetic pressure exceeds the doubly shocked plasma pressure, in which case the current sheath continues inwards in a further slow compression, until the end of this quasi equilibrium phase. The duration of this slow compression phase may be defined by the transit time of small disturbances. For well-designed and operated plasma focus there is a slow compression throughout this whole duration and the pinch radius reaches its minimum r_{min} at the end of the phase. The radiation yield depends on: the absolute density (which depends on the ambient density and the compression of which r_{min} is a measure, the smaller r_{min}/a where a is the anode radius, the greater the compression). The temperature depends on the implosion speeds so that the lower the operating pressure, the higher the imploding speeds. The shocked temperature depends on the square of the shock speeds and the further compression. The duration of the slow compression phase scales inversely as the square root of the pinch temperature. Thus, in this particular example, as the operating pressure is reduced below 3 Torr, although I_{pinch} still increases, speeds also increase, increasing the temperature, which tends to oppose the severity of the compression during the slow compression phase, although the decreased ambient number density tends to work in the opposite direction. The interactions of all these factors are taken care of in the code and manifests in a peak of n_i at 3.1 Torr and the minimum value of r_{min} at 2.9 Torr (which is further enhanced by a radiative cooling effect [30].

Moreover, as can be seen in Table 1, the pinch duration progressively reduces, as the temperature increases with lowering pressure; while the radiating plasma volume reaches a minimum around 2.9 Torr. The interactions of all the behavior of r_{min}, ni, and T_{pinch}, pinch duration and plasma volume all contribute to the peak in Y_{sxr} as a function of operating pressure. Looking at the Table I and Fig. 1, 1it does appear that the peaking of ni_{pinch} at 3.1 Torr is a prominent factor for the peaking of Y_{sxr} at 2.9 Torr.

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