Soft x-ray yield from NX2 plasma focus

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The Lee model code is used to compute neon soft x-ray yield \( Y_{sxr} \) for the NX2 plasma focus as a function of pressure. Comparison with measured \( Y_{sxr} \) shows reasonable agreement in the \( Y_{sxr} \) versus pressure curve, the absolute maximum yield as well as the optimum pressure. This gives confidence that the code gives a good representation of the neon plasma focus in terms of gross properties including speeds and trajectories and soft x-ray yields, despite its lack of modeling localized regions of higher densities and temperatures. Computed current curves versus pressure are presented and discussed particularly in terms of the dynamic resistance of the axial phase. Computed gross properties of the plasma focus including peak discharge current \( I_{peak} \), pinch current \( I_{pinch} \), minimum pinch radius \( r_{min} \), plasma density at the middle duration of pinch \( n_{pinch} \), 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 \( Y_{sxr} \) at optimum pressure. © 2009 American Institute of Physics.

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I. INTRODUCTION

Plasma focus has been demonstrated as potential x-ray source for various medicobiological and industrial applications such as lithography1–4 (using ~0.9–1.5 keV photons), radiography,5,6 microscopy7,8 (using ~0.25–2.5 keV radiations), and micromachining9 (using ~4 keV photos). This has led to an increasing interest in exploiting the plasma focus device as a viable intense x-ray source due to some clear advantages such as being relatively cheap, compact, and easy of construction. The x-ray emissions from plasma focus devices have been explored over the wide range of capacitor bank energies ranging from large megajoule and few hundred kilojoule banks10 to medium sized kilojoule banks4,11–14 to subkilojoule banks of miniature sized focus devices.15,16 In the past few years various efforts have been made for enhancing the x-ray yield by changing various experimental parameters such as bank energy,17 discharge currents, dynamics, and some plasma pinch gross properties.18 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 vast possible applications. Currently used systematic trial and error experimental procedure to obtain the optimized conditions for maximum radiation yield is highly time-consuming. Hence, the quicker optimization of plasma focus device is highly desirable, which can be achieved if the reliable focus model and corresponding simulation code to predict the x-ray yields from plasma focus device can be developed and used. Obviously the computed yields need to be checked against corresponding measured yields. Further, if the computed soft x-ray yields are consistently reliable against measured values; then it is reasonable to use the computed gross plasma properties as indicative of what we can expect when these plasma properties are measured. In this way, a reliable model code cannot only be used to compute radiation yields, but also be used as a good indicative diagnostic tool for multiple gross plasma properties of the plasma focus.

In the present paper, we used the Lee model code version 13.6b to carry out the numerical experiments on NX2 plasma focus device to compute its neon soft x-ray yield \( Y_{sxr} \) as a function of filling gas pressure. The NX2 is a 3 kJ plasma focus originally designed to operate as a neon soft x-ray source with 20 J per shot at 16 shots/s with burst durations of several minutes.4 Its performance in repetitive mode has been extensively studied, especially in regards to its discharge currents and soft x-ray yield \( Y_{sxr} \). In this paper, we have simulated the operation of NX2 focus device in numerical experiments which are designed to compare its currents, dynamics, and some plasma pinch gross properties at various pressures so as to examine the role played by various relevant plasma properties on the way the \( Y_{sxr} \) peaks at the optimum pressure.

II. THE MODEL CODE USED FOR NUMERICAL EXPERIMENTS

The Lee model couples the electrical circuit with plasma focus dynamics, thermodynamics, and radiation, enabling realistic simulation of all gross focus properties. The basic model, described in 1984,19 was successfully used to assist several projects.14,19–21 Radiation-coupled dynamics was included in the five-phase code leading to numerical experiments on radiation cooling.22 The vital role of a finite small disturbance speed discussed by Potter in a Z-pinch situation was incorporated together with real gas thermodynamics and radiation-yield terms;24 this version of the code assisted

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other research projects\textsuperscript{4,25,26} and was web-published in 2000\textsuperscript{27} and 2005.\textsuperscript{28} Plasma self-absorption was included in 2007 (Ref. 27) improving soft x-ray yield simulation. The code has been used extensively in several machines including UNU/ICTP PFF,\textsuperscript{4,14,21,25,29} NX2,\textsuperscript{4,26} NX1,\textsuperscript{4} and adapted for the Filippov-type plasma focus DENA.\textsuperscript{30} A recent development is the inclusion of the neutron yield $Y_n$ using a beam-target mechanism,\textsuperscript{31–34} incorporated in the present version\textsuperscript{35} of the code RADPFV5.13, resulting in realistic $Y_n$ scaling with pinch current $I_{\text{pinch}}$.\textsuperscript{31,32} The versatility and utility of the model is demonstrated in its clear distinction of pinch current $I_{\text{pinch}}$ from peak discharge current $I_{\text{peak}}$ (Ref. 36) and the recent uncovering of a plasma focus pinch current limitation\textsuperscript{31,33} as well as elucidation of neutron scaling laws to multimega-Joule facilities.\textsuperscript{34} 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.\textsuperscript{35}

A brief description, however, of the five phases incorporated in the Lee model code is as follows.

(1) Axial phase: the axial 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 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.

(2) 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 $f_m$ and $f_c$ are incorporated in all three radial phases. The mass swept-up factor $f_m$ 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 $f_c$ 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.

(3) Radial reflected shock (RS) 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 $f_m$ and $f_c$ are used as in the previous radial phase. The plasma temperature behind the RS undergoes a jump by a factor nearly 2.

(4) Slow compression (quiescent) or pinch 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.

(5) Expanded column 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 final 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.

We note that in radial phases 2, 3, and 4, axial acceleration and ejection of mass caused by necking curvatures of the pinching current sheath result in time dependent strongly center-peak density distributions. Moreover the transition from phase 4 to phase 5 is observed in laboratory measurements to occur in an extremely short time with plasma/ current disruptions resulting in localized regions of high densities and temperatures. These center-peak density effects and localized regions are not modeled in the code, which consequently computes only an average uniform density and an average uniform temperature which are considerably lower than measured peak density and temperature (we thank a Reviewer for his comments regarding this point). 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.

III. X-RAY EMISSIONS IN PLASMA FOCUS AND ITS INCORPORATION IN MODEL CODE

The focused plasma, with electron temperature of a few hundreds of eV to about keV and high enough electron density, is a copious source of x rays. The plasma focus emits both soft (thermal) as well as hard (nonthermal) x rays but for the scope of this paper, we will concentrate only on soft thermal x rays. The plasma focus emits soft thermal x rays by three processes, namely: bremsstrahlung (free-free transition) from the Coulomb interactions between electrons and ions; recombination radiation (free-bound transition) emitted by an initially free electron as it loses energy on recombination with an ion; and de-excitation radiation (bound-bound transition) when a bound electron loses energy by falling to a lower ionic energy state. The first two processes give rise to the continuum of the x-ray spectrum, while the third process produces the characteristic line radiation of the plasma. The relative strengths of the continuum and line emissions depend on how the plasma was formed; typically, for a plasma formed from a high-Z material continuum emission dominates, while for a low-Z material line emission can be stronger. The calculation of the power emitted by processes within the plasma depends on assumptions made about the state of the plasma. Following the spectral data obtained by Mahe and Liu et al. for the soft x rays from neon operated plasma focus device, it was found that 64% of soft x-ray emission can be attributed to line radiations at 922 eV (Ly-α) and 1022 eV (He-α) and the remaining 36% by the rest, mainly recombination radiation, for optimized operations. For NX2 plasma focus device, Zhang reported the contribution of line radiation yield, i.e., $Q_{\text{L}} = Q_{\text{L}}$, to be comparable with measured values. In this case, the following fitted model parameters are used: bank: static inductance $L_0 = 15$ nH, $C_0 = 28$ μF, stray resistance $r_0 = 2.2$ mΩ; tube: cathode radius $b = 4.1$ cm, anode radius $a = 1.9$ cm, anode length $z_0 = 5$ cm; and operation: voltage $V_0 = 11$ kV, pressure $P_0 = 2.6$ Torr.

The computed total current waveform is fitted to the measured waveform by varying model parameters $f_m$, $f_c$, $f_{\text{mr}}$, and $f_{\text{e}}$, one by one until the computed waveform agrees with the measured waveform. First, the axial model factors $f_m$ and $f_c$ are adjusted (fitted) until the computed rising slope of the total current trace and the rounding off of the peak current as well as the peak current itself are in reasonable (typically very good) fit with the measured total current trace (see Fig. 1, e.g., 2.6 Torr measured trace and computed trace). Then we proceed to adjust (fit) the radial phase model factors $f_{\text{mr}}$ and $f_{\text{e}}$ until the computed slope and depth of the dip agree with the measured. In this case, the following fitted model parameters are obtained: $f_m = 0.1$, $f_c = 0.7$, $f_{\text{mr}} = 0.12$, and $f_{\text{e}} = 0.68$. 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 high pressure (about 10,000 Torr, which is not an issue in numerical experiments although we would not use such pressures in “hardware” experiments) so that the discharge current stayed at the backwall with hardly any motion and hence can be treated as short circuit discharge. The discharge current then resembles that of a simple L-C-R discharge, which is a damped sinusoid. The pressure is then lowered for another

![FIG. 1. Fine tuning of Lee model parameter by fitting of computed total current waveform of numerical experiment conducted at 2.6 Torr to that of experimentally measured waveform at same 2.6 Torr of neon. Plots of discharge current waveforms from numerical experiments performed over wide range of neon filling gas pressures are also shown for comparison.](https://jap.aip.org/jap/DOI.png)
TABLE I. Computed plasma dynamics and pinch plasma parameters for different neon filling gas pressures by numerical experiments conducted on NX2 device using Lee model code. [Parameters used in the table are: \( I_{\text{peak}} \) is the peak value of the total discharge current; \( I_{\text{pinch}} \) is the pinch current, taking its value at the start of the pinch phase; peak \( v_z \) =peak axial speed, typically end axial speed; \( S \) =speed parameter (in kA/cm/Torr\(^2\)); peak \( v_x \), \( v_y \) =peak radial shock and piston speeds, respectively; \( r_{\text{min}} \)=minimum radius or focus pinch radius at maximum compression; \( r_{\text{max}} \)=maximum length of focus pinch at time of maximum compression (note that the anode is hollow); \( T_{\text{pinch}} \)=plasma temperature at middle of pinch duration; \( n_i \)=pinch density at the middle of pinch duration; \( Z \)=effective charge of the neon plasma at middle of pinch duration; and EINP=work done by the dynamic resistance during radial phase expressed as \% of \( E_{\text{pinch}} \).]

<table>
<thead>
<tr>
<th>( P_0 ) (Torr)</th>
<th>( I_{\text{peak}} ) (kA)</th>
<th>( I_{\text{pinch}} ) (kA)</th>
<th>Peak ( v_x ) (cm/( \mu )s)</th>
<th>Peak ( v_y ) (cm/( \mu )s)</th>
<th>( r_{\text{min}} ) (cm)</th>
<th>( r_{\text{max}} ) (cm)</th>
<th>Pinch duration (ns)</th>
<th>( T_{\text{pinch}} ) (10(^6) K)</th>
<th>( n_i ) pinch (10(^{23}) ions/m(^3))</th>
<th>EINP (%)</th>
<th>( Y_{\text{sxr}} ) (J)</th>
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run. This is repeated each time lowering the filling neon pressure. Figure 1 records the discharge current waveforms for some of the selected pressures covering a wide range of neon operating pressures from 5 Torr down to 0.5 Torr. The Fig. 1 also includes the simulated waveform for high pressure shot and measured waveform at 2.6 Torr. It may be noticed that computed total current waveform at 2.6 Torr numerical experiment is almost identical to the measured total current waveform for the 2.6 Torr actual experiment conducted by Zhang indicating an extremely good fine tuning of Lee model parameters, i.e., \( f_m, f_r, f_{\text{mx}}, \) and \( f_{\text{es}} \). Similarly we compute a peak on-axis RS \( Y_{\text{sxr}} \) values from numerical experiments fit the experimental data in Fig. 2(b) is taken from Fig. 6b of Ref. 4 and also from Fig. 6.7b on page 206 of Ref. 37, and hence the numerical experiments were performed for NX2 device with 5 cm long anode with the device being operated at 11.5 kV. It is evident from Fig. 2(b) also from Table I that the \( Y_{\text{sxr}} \) values from numerical experiments fit the experimentally measured yields reasonably well. It is also necessary to point out here that our computed \( n_i \) (being an averaged uniform value) is considerably lower than values measured experimentally. From shock theory we compute for this case (2.6 Torr neon in NX2) a peak on-axis RS value of 2.63 \( \times 10^{23} \) ions/m\(^3\). Similarly we compute a peak on-axis RS temperature of 2.7 \( \times 10^8 \) K. This illustrates that consideration of density and temperature distributions can allow more realistic estimation of these quantities and even their spatial and temporal distributions. Hence, though our model gives only mean values of the key plasma parameters (such as that of \( n_i \) and \( T \)) and is unable to trace their evolution with an accuracy that probably can be achieved by modern diagnostics technique, but at the same time we also point out that our average methods allow us to compute realistic gross quantities such as trajectories, speeds, and soft x-ray yields.
sure is reduced toward 3 Torr, the increasing 
min at around 3 Torr. This shows that as the operating pres-

radius of the pinch, has a complementary trend with a mini-
bient number density, the pinch 
the compression sufficiently so that despite the drop in am-

creasing rate of change of plasma inductance, 

This is due to increasing dynamic resistance 

We note that, on the contrary, the current 

the increasing current sheath speed as pressure is decreased. 

As the pressure is decreased below 1.2 Torr, the 

ting pressure. This is due to the shifting of the pinch time 

through the pinched plasma column, increases with decreas-

inversely as the square root of the pinch temperature 

below 3 Torr, the increase in \( I_{\text{pinch}} \) 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 shocked heated plasma. When the shock front 
implodes onto the tube axis, because the plasma is collis-

tional, a RS develops. The RS front moves radially outwards 
into the inwardly streaming particles of the plasma slug, 
leaving behind it a stationary doubly shocked plasma with a 
higher temperature and density than the singly shocked 
plasma ahead of it. When the RS reaches the incoming cur-

current sheath, typically the magnetic pressure exceeds the dou-

The radial phase continues inwards in a further slow compression, until 
the end of this quasiequilibrium phase. The duration of this 
slow compression phase may be defined by the transit time of small disturbances. For a well-designed and operated 
plasma focus there is a slow compression throughout this 
whole duration and the pinch radius reaches its minimum 
r_{\text{min}} at the end of the phase. These various phases/phenomena 
can be seen in Fig. 3. The radiation yield depends on: (a) the 
absolute density (which depends on the ambient density and 
the compression of which \( r_{\text{min}} \) is a measure, the smaller 
r_{\text{min}}/a \) where \( a \) is the anode radius, the greater the compression), 
(b) the temperature (which depends on the imploding speeds [the lower the operating pressure, the higher the im-

the square of the shock speeds 

\( n_{\text{pinch}} \), 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 \( r_{\text{min}} \) which is the minimum 
radius of the pinch, has a complementary trend with a mini-
mum at around 3 Torr. This shows that as the operating pressure 
is reduced toward 3 Torr, the increasing \( I_{\text{pinch}} \) increases the compression sufficiently so that despite the drop in am-

ambient number density, the pinch \( n_i \) is still able to reach a 
higher value at 3 Torr. As the operating pressure is reduced
to work in the opposite direction. The interaction of all these factors are taken care of in the code and manifests in the peaking of $n_i$ at 3.1 Torr and the minimum value of $r_{\text{min}}$ at 2.9 Torr. Moreover, as can be seen in Table I, 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 $r_{\text{min}}$, $n_i$, and $T_{\text{pinch}}$ pinch duration and plasma volume all contribute to the peak in $Y_{\text{sxr}}$ as a function of operating pressure. Looking at the Table I and Fig. 2(a) it appears that the peaking of $Y_{\text{sxr}}$ at 3.1 Torr is a notable factor for the peaking of $Y_{\text{sxr}}$ at 2.9 Torr.

The Fig. 2(b) shows reasonable agreement the results of numerical experiments and experimentally measured; in terms of absolute value of $Y_{\text{sxr}}$ at optimum pressure (about 20.8 J by numerical experiment, refer Table I, and about 16.1 J as experimentally measured\textsuperscript{4,39}) as well as the optimum pressure value itself. The computed curve falls off more sharply on both sides of the optimum pressure. This agreement validates our views that the fitting of the computed total current waveform with the measured waveform enables the model to be energetically correct in all the gross properties of the radial dynamics including speeds and trajectories and soft x-ray yields despite the lack of fine features in the modeling.

VI. CONCLUSIONS

To conclude, 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 (i) the $Y_{\text{sxr}}$ versus pressure curve trends, (ii) the absolute maximum yield, and (iii) 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 $Y_{\text{sxr}}$ gives confidence that the model is sufficiently realistic in describing the plasma focus dynamics and soft x-ray emission for NX2 operating in Neon. This encourages us to present Table I and to present the above views regarding the factors contributing to the peaking of $Y_{\text{sxr}}$ at an optimum pressure.