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ARTICLE

Neon Soft X-Ray Yield Optimization from NX2 Dense Plasma Focus Device

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Abstract: The aim of this research is to study soft x-ray emission from NX2 plasma focus device with neon filling gas using the Lee model code and find the maximum value of soft x-ray yield by using the standard parameters of the device and then find the optimum combination of pressure and anode dimensions that gives the maximum value of soft x-ray yield. Many numerical experiments were carried out and we obtained the maximum value of soft x-ray yield (Y_{sxr}) of (22.6 J) at a pressure of (2.9 Torr) by using the standard parameters of NX2 device. We found the optimum combination of pressure, anode length and anode radius (3 Torr, 2.1 cm and 2 cm), respectively, by reducing the anode length and increasing the anode radius. The soft x-ray yield increases to (26.01 J) with a corresponding efficiency of about 1.53%.
Keywords: Lee model code, NX2 device, Soft x-ray yield.

Introduction

Hot and dense plasma can be generated by compression and imploding cylindrical magnetized plasma, to form a hot, dense plasma pinch. This pinch is considered an important source for x-rays (soft and hard) and energetic beam ions. The plasma focus devices are the simplest in construction and provide the highest x-ray emissions compared to other devices of equivalent energy [1, 2]. These x-ray sources are used for various applications, such as lithography [3] and imaging [4].

The importance of this research lies in computing soft x-ray yield Y_{sxr} as a function of filling gas pressure (neon) and searching for the possibility of increasing the soft x-ray yield through modification of the anode's dimensions without the need to change the energy of capacitor bank by carrying out numerical experiments using the Lee model code, version (RADPFV5.15de.c1).

The Radiative Lee Model

The Lee model couples the electrical circuit with plasma focus dynamics, thermodynamics and radiation, enabling a realistic simulation of all gross focus properties. The basic model is described in [6]. The code has been used extensively in several machines, including UNU/ICTP PFF, NX2 and NX1. The 5 phases of Lee model are as follows:

1) Axial phase.
2) Radial inward shock phase.
3) Radial reflected shock (RS) phase.
4) Slow compression (quiescent) or pinch phase.
5) Expanded column phase.

A detailed description of these phases is found in [7].

In the code, neon line radiation Q_L is calculated as follows [8]:

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$$\frac{dQ_L}{dt} = -4.6\times10^{-31} n_i^2 Z Z_n^4 \left(\pi r_p^2\right) z_f \ /T$$

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

Hence, the SXR energy generated within the plasma pinch depends on the following properties: number density n_i, effective charge number Z, pinch radius r_p, pinch length z_f, temperature T and pinch duration. In our code, Q_L is obtained by integrating over 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 SXR yield.

Method

Numerical Experiments on Standard NX2 Device with Neon Filling Gas

The following bank, tube, operation and model parameters are used [9]:

1) Bank: static inductance L_0 = 15 nH, C_0 = 28 μF and stray resistance r_0 = 2.2 mΩ.
2) Tube: cathode radius b = 4.1cm, anode radius a =1.9 cm and anode length z_0 = 5 cm.
3) Operation: voltage V_0 = 11 kV, pressure P_0 = 3 torr Neon, MW=20, A=10, At-Mol=1.
4) Model: f_m=0.1, f_c=0.7, f_{mr}=0.12, f_{cr}=0.68.

Optimizing Soft X-ray Yield (Y_{sxr}) by Changing Anode Geometry

Numerical experiments using the Lee model code were carried out to determine the optimum configuration of anode that gives the highest value of soft x-ray yield (Y_{sxr}). The bank capacitor parameters were retained at (L_0=15 nH, C_0= 28 μF, RESF = 0.1) and the voltage was retained at (V_0 = 11 kV). The model parameters were also retained at (f_m = 0.1, f_c = 0.7, f_{mr} = 0.12, f_{cr} = 0.68). The value of the ratio of the outer to inner electrode constant (c=b/a) is kept constant at (2.2). The anode dimensions (length z_0 and radius a) and the pressure (P_0) were parametrically varied and results were tabulated in Table 2.

The following procedure was used [10]:

At each P_0, the anode length z_0 was fixed at a certain value.

Then, the anode radius (a) was smoothly varied, till the maximum soft x-ray yield (Y_{sxr}) was obtained for this certain value of z_0.

After that, we chose another value of z_0, by varying the value of (a) looking for the maximum of Y_{sxr}, until we found the optimum combination of z_0 and (a) for the best soft x-ray yield at the fixed P_0.

Then, we changed P_0 and repeated the above procedure to find the optimum combination of z_0 and (a) corresponding to this new value of P_0. We continued until we obtained the optimum combination of P_0, z_0 and (a) for the maximum soft x-ray yield (Y_{sxr}).There is an optimum temperature for optimum neon soft x-ray yield (2.3×10^6 K) [11].

Results and Discussion

From Table 1, we note that:

The pressure varies from 5 to 0.5 Torr. The soft x-ray yield (Y_{sxr}) increases with decreasing pressure until it reaches the maximum value (22.6 J) at (P_0=2.9 Torr) at a corresponding efficiency of about 1.329%, after which it decreases with lower pressure (see Fig. 1). This is due to the fact that as pressure increases, the speed (end axial speed v_a, inward shock speed v_s, radial piston speed v_p) decreases. The decrease in speed leads to lowering the plasma temperatures below the level needed for soft x-ray production (see Fig. 2). The pinch current (I_{pinch}) increases with decreasing pressure. This is due to the shifting of pinch time towards the time of peak current. On the contrary, the total discharge current (I_{peak}) decreases with decreasing pressure because of increasing the dynamic resistance due to increasing current sheath speed as the pressure decreases (see Fig. 3). The ion density in the middle of the pinch (n_{pinch}) increases as pressure decreases, peaking around 3 Torr and then dropping at lower pressures (see Fig. 4).

TABLE 1. Computed soft x-ray yield (Y_{sxr}) and pinch properties *versus* P_0 for standard parameters of NX2 at: L_0 = 15 nH, C_0 = 28 μF, r_0 = 2.2 mΩ, V_0 = 11 kV, ratio of stray resistance/bank surge impedance RESF = 0.1, c = b/a = 2.2, f_m = 0.1, f_c = 0.7, f_{mr} = 0.12, f_{cr} = 0.68, neon gas.

P (Torr)	I_{peak} (kA)	I_{pinch} (kA)	$T_{pinch}\times10^6$ (K^0)	V_a (cm/μs)	V_s (cm/μs)	V_p (cm/μs)
5			The code unable to run			
4.5			The code unable to run			
4	378	118	0.88	4.9	14.9	11.6
3.5	374	132	1.24	5.3	17.3	12.9
3	370	143	1.72	5.7	19.9	14.2
2.9	369	145	1.83	5.8	20.5	14.5
2.8	368	147	1.95	5.9	21.1	14.8
2.7	367	149	2.07	6	21.8	15
2.5	365	154	2.37	6.2	23.4	15.6
2	359	163	2.78	6.8	25.3	16.8
1.5	350	168	4.6	7.6	27.6	18.9
1	337	169	6.71	8.8	32	22.8
0.5	310	160	11.21	11.1	40.8	29

Table 1 (Continued)

P (Torr)	SF	a_{min} (cm)	z_{max} (cm)	Pinch duration (ns)	n_i ($\times10^{23}$) (m^{-3})	Y_{sxr} (J)	Efficiency %
5				The code unable to run			
4.5				The code unable to run			
4	99	0.21	2.7	42.5	4.9	3.66	0.215
3.5	105	0.20	2.7	35.7	4.6	10.5	0.617
3	113	0.16	2.8	30.9	5.8	21.9	1.288
2.9	114	0.16	2.8	30.2	5.7	22.6	1.329
2.8	116	0.16	2.8	29.9	5.4	22.1	1.3
2.7	118	0.17	2.8	29	4.7	19.4	1.141
2.5	122	0.19	2.8	26.8	3.4	12.3	0.723
2	134	0.24	2.7	23	1.8	3.89	0.228
1.5	151	0.25	2.8	21.7	1.2	1.48	0.087
1	178	0.25	2.8	18.7	0.8	0.42	0.024
0.5	231	0.25	2.8	15.1	0.4	0.05	0.003

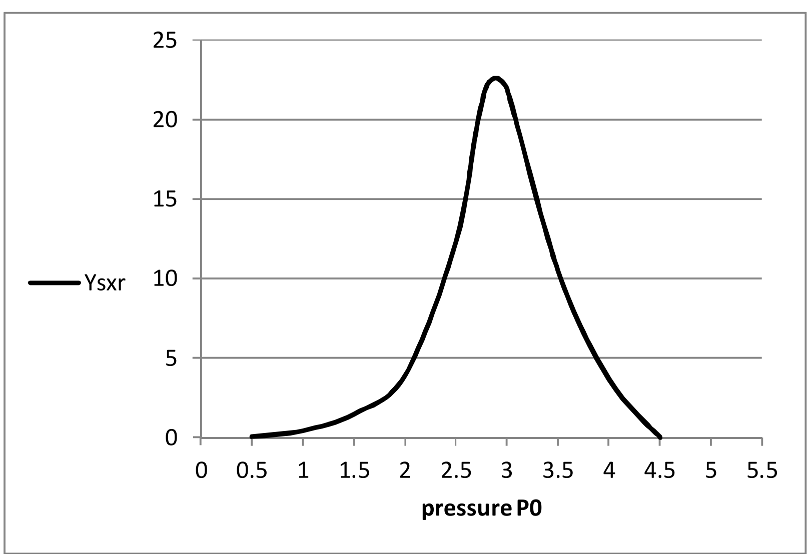

FIG. 1. Soft x-ray yield as a function of pressure.

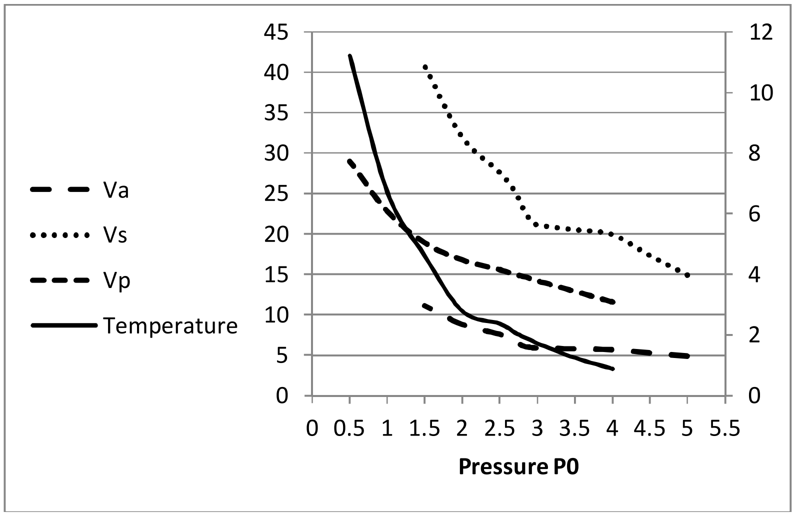

FIG. 2. Speeds and plasma temperature as functions of pressure.

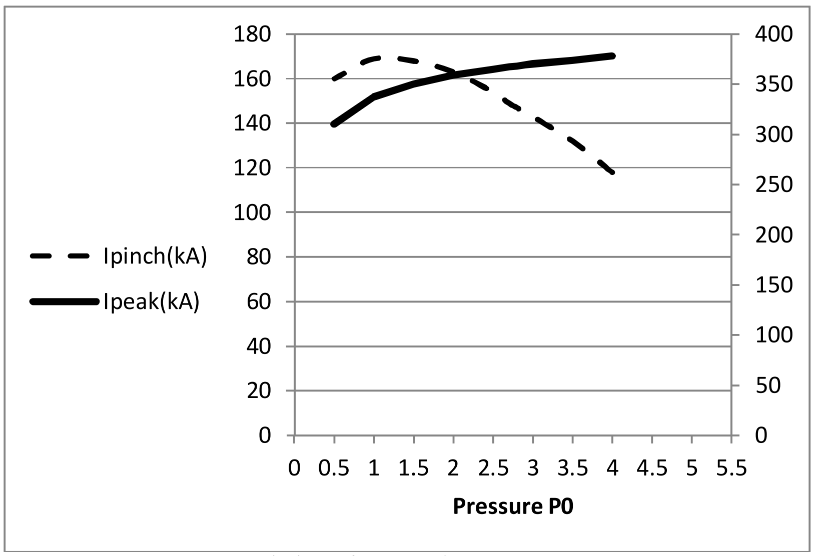

FIG. 3. Variation of I_{pinch} and I_{peak} *versus* pressure.

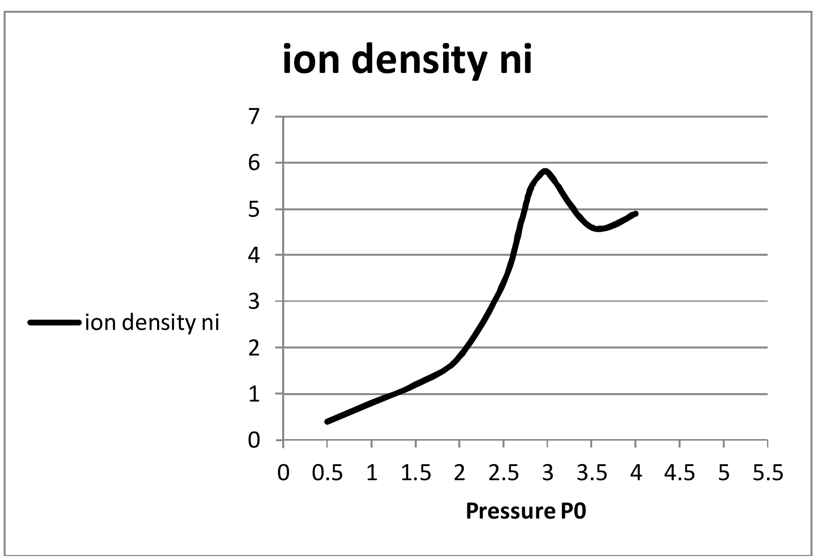

FIG. 4. Variation of ion density *versus* pressure.

Table 2 shows that as P_0 increases, anode length z_0 increases and inner radius 'a' decreases with each increase in P_0, while the soft x-ray yield slightly increases with increasing P_0 until it reaches a maximum value of 26.01 J at P_0 = 3 Torr and the corresponding efficiency is about 1.53%, then Y_{sxr} decreases with further pressure increase.

Fig. 5 shows x-ray yield as a function of P_0, with the plasma focus operated at the optimum combination of z_0 and (a) corresponding to each P_0.

Fig. 6 shows that both total current (I_{peak}) and pinch current (I_{pinch}) slightly increase with increasing pressure (P_0).

From our numerical experiments for, NX2 with L_0=15 nH, C_0= 28 μF, r_0 = 2.2 mΩ, V_0 = 11 kV, we find the optimum combination of P_0, z_0 and a for neon Y_{sxr} as 3 Torr, 2.1 cm and 2 cm, respectively, with the outer radius b = 4.4 cm. This combination gives Y_{sxr}= 26.01 J. We notice that the optimum soft x-ray yield from NX2 becomes higher (about 3.4 J).

TABLE 2. X-ray yield optimization from NX2 for each value of P_0 varying z_0 and (a) for filling neon gas at: L_0 = 15 nH, C_0 = 28 μF, r_0 = 2.2 mΩ, V_0 = 11 kV, ratio of stray resistance/bank surge impedance RESF = 0.1, c = b/a = 2.2, f_m = 0.1, f_c = 0.7, f_{mr} = 0.12, f_{cr} = 0.68.

P (Torr)	z_0 (cm)	a (cm)	b (cm)	I_{peak} (kA)	I_{pinch} (kA)	v_a (cm/μs)	v_s (cm/μs)	v_p (cm/μs)	Y_{sxr} (J)	Efficiency %
0.5	1.1	3.78	8.32	300	135	4.5	22.2	15.2	9.11	0.535
1	1.2	2.92	6.42	311	147	4.5	22.2	15.1	13.4	0.788
1.5	1.4	2.54	5.59	327	157	4.6	22.2	15.1	17.4	1.023
2	1.5	2.29	5.04	335	163	4.6	22.3	15.1	21.3	1.252
2.5	1.7	2.13	4.68	347	169	4.6	22.3	15.1	24.2	1.423
3	2.1	2	4.40	362	175	4.9	22.5	15.2	26.01	1.530
3.5	3	1.85	4.10	372	176	5.2	22.9	15.3	23.6	1.388
4	3.1	1.74	3.83	373	178	5.2	23.2	15.4	22.2	1.305

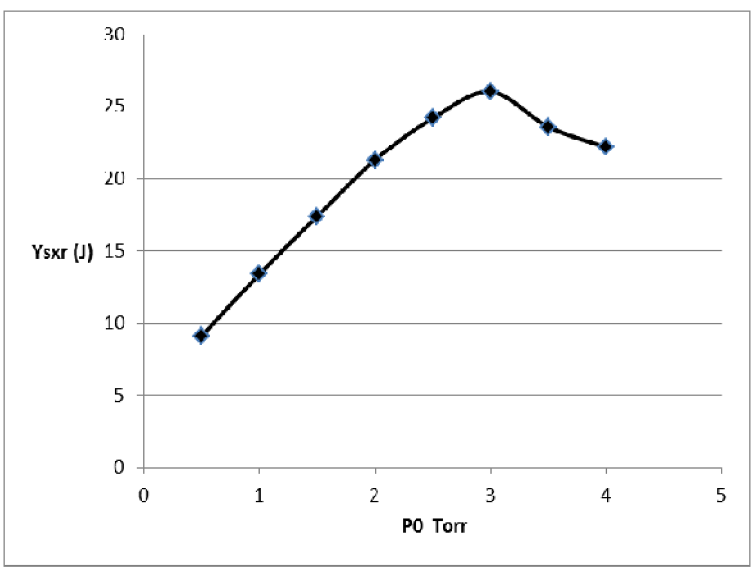

FIG. 5. Soft x-ray yield as a function of pressure, anode length and inner radius.

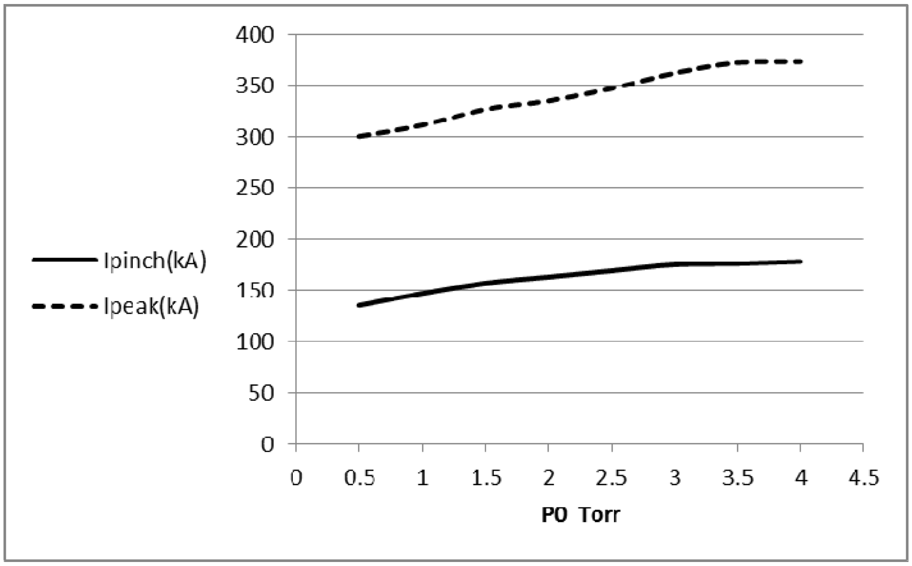

FIG. 6. Effect on total current (I_{peak}) and pinch current (I_{pinch}) as P_0 is increased from 0.5 to 4 Torr.

Conclusion

The Lee model code was applied to calculate the soft x-ray yield from NX2 plasma focus device by using standard parameters. We obtained the maximum value of Y_{sxr} as 22.6 J at a pressure of 2.9 Torr. We also used the Lee model code to run numerical experiments on NX2 device with neon gas for optimizing soft x-ray yield by reducing the anode length and increasing the radius of the anode. The neon soft x-ray yield optimum combination of NX2 was found to be at (pressure P_0= 3 Torr, anode length z_0=2.1 cm and anode radius a= 2 cm). The optimum soft x-ray yield was (Y_{sxr}= 26.01 J).

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