Simulation of physical processes

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THE EFFECT OF A GAS TYPE ON THE SOFT X-RAY YIELD FROM A PLASMA FOCUS

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Abstract. Using the Lee code version (RADPFV5.15de), we carried out a series of numerical experiments to find the parameters for the plasma focus and the soft X-ray yield for each of nitrogen gas (molecular) and neon gas (atomic) within an appropriate temperature range for PF400 dense plasma focus device. The results showed that the highest value of the soft X-ray yield in neon was 0.148 J at 3.2 Torr pressure, while for nitrogen it was 0.0634 J at 4.4 Torr. This is because of the higher atomic number and effective charge of neon as compared to nitrogen.

Keywords: plasma pinch, PF400 plasma focus device, soft X-ray yield, Lee model

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ВЛИЯНИЕ ТИПА ГАЗА НА ВЫХОД МЯГКОГО РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ ИЗ ПЛАЗМЕННОГО ФОКУСА

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Аннотация. Используя версию кода Ли RADPFV5.15de, мы провели серию численных экспериментов с целью определения оптимальных параметров плазменного фокуса и максимального выхода мягкого рентгеновского излучения путем их сравнения для газов азота (молекулярного) и неона (атомного) в пределах рабочего температурного диапазона устройства фокусировки плотной плазмы PF400. Согласно полученным результатам, наибольшее значение выхода указанного излучения составило для неона 0,148 Дж при давлении 3,2 Торр, тогда как для азота – всего 0,0634 Дж при 4,4 Торр. Анализ полученных результатов привел к заключению, что разница связана с более высоким атомным номером и эффективным зарядом неона, по сравнению с таковыми для азота.

Ключевые слова: плазменный пинч, устройство плазменной фокусировки PF400, мягкое рентгеновское излучение, модель Ли

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Introduction

Plasma focus is one of plasma magnetic confinement mechanisms developed in the early 60-s of the 20th century for nuclear fusion research by the two scientists: J. W. Mather in the USA and N. V. Filippov in the Soviet Union [1]. The plasma focus device is similar to a *Z*-pinch device, and it is qualified to produce plasma with a short life, high electron density and temperature ($T_e > 500$ eV), and the ability to emit short, high-intensity pulses of *X*-rays (the radiation spectrum of plasma focus in the *X*-ray spectrum covers a range from 1 keV to 500 keV), fast neutrons and charged particle beams (ions, electrons) [2, 3]. Plasma focus devices are considered as promising sources of soft *X*-ray pulses with durations ranging from units to hundreds of nanoseconds. The *X*-rays generated during a pulse from the *Z*-pinch devices are of higher energy than those generated from other sources [4].

The operating principle of plasma focus devices is based on transferring the electrical energy stored in a capacitor bank, which is quickly transferred to a group of electrodes by means of rapid triggering, so that the discharge current begins from the surface of the insulator surrounding the bottom of the anode and spreads to its end so the Lorentz force $J \times B$ formed from the effect of the self-magnetic induction field on the current passing through the plasma sheet accelerates it from the bottom of the anode to its end, and then the current sheet is compressed magnetically within a time of 50 ns. And there is a density of 10^{19} m^{-3} in the plasma column or what is known as pinch, and then the plasma column collapses due to the plasma instabilities [5, 6]. The plasma pinch is characterized by its ability to emit different types of radiation and particles, including hard, medium and soft *X*-rays, ultraviolet rays, neutrons, fast ions, and fast electrons [7]. These emissions are related to device engineering (its length and electrodes radii) as well as related to an operation gas type [9, 8]. For example, when neutrons producing deuterium gas is used, while noble gases are used to *X*-rays emission [6].

The Lee model

The first version of this model was issued in 1985, when it consisted of two stages, and after that it was used to describe and improve the plasma focus devices. Later it was developed in five stages in 2000, as it provided a realistic simulation of the characteristics of plasma focus, by linking the circuit parameters with properties of electrodynamics and thermodynamics of plasma and radiation emissions [10 – 12]. In this model, the plasma focus dynamics is divided into three basic phases: break-down one, axial one, and compression one, and the latter is divided into three secondary phases:

inward radial shockwave one,
outward reflected shockwave one,
and slow compression one [13].

This model is used to calculate soft *X*-rays yield and neutron emissions [14].

Results and discussion

The Lee code RADPFV 5.15 dec1 was used for PF400 plasma focus device according to the following characteristics:

capacitor bank parameters – inductance L_0 = 40 nH, capacitance C_0 = 0.95 μF, resistance r_0 = 10 mΩ;

geometric dimensions – cathode radius b = 1.6 cm, anode radius a = 0.6 cm, anode length z_0 = 1.7 cm;

operating parameters – energy E_0 = 0.4 kJ, voltage V_0 = 28 kV.

The soft X-ray yield is calculated using the following relation [6]:

$$dQ/dt = -4.6 \cdot 10^{-31} N_i Z_{eff} Z_n^4(\pi r_p^2) Z_f/T.$$

Notice that the yield dQ/dt is directly proportional the following quantities:

Z_{eff} is the number of effective charges, Z_n is the atomic number of gas, N_i is the ions density in the plasma pinch, $(\pi r_p^2)Z_f$ is the volume of the plasma pinch; and the yield dQ/dt is inversely proportional to T.

Using the Lee code, the plasma focus parameters and the soft X-rays yield for nitrogen and neon gases were found within a temperature range for soft X-ray emission. The results are presented in Table 1.

Table 1

The calculated dependence of the plasma focus parameters on the nitrogen pressure for the PF400 device

P	T_e	I_{pinch}	V_a	V_s	V_p	Y_{sxr}
Torr	10^6 K	kA	cm/μs			mJ
3.6	1.93	71	7.2	25.9	18.3	37.1
3.7	1.85	70	7.1	25.4	18.0	41.1
3.8	1.76	69	7.0	24.9	17.7	45.0
3.9	1.68	68	6.9	24.4	17.3	49.1
4.0	1.93	67	6.8	23.9	17.0	52.7
4.1	1.59	66	6.7	23.5	16.7	56.9
4.2	1.51	65	6.6	23.0	16.4	60.2
4.3	1.44	64	6.5	22.5	16.1	62.3
4.4	1.29	63	6.5	22.2	15.8	63.4
4.5	1.22	62	6.4	21.7	15.5	61.4
4.6	1.16	61	6.3	21.2	15.2	58.4

Notations: P is the pressure; T_e is the plasma temperature; I_{pinch} is the pinch current; V_a, V_s, V_p are the axial, shock and radial piston speeds, relatively; Y_{sxr} is the soft X-ray yield.

Footnote. The peak current I_{peak} is 127 kA for all pressure values, except P = 4.6 Torr, when it is 128 kA.

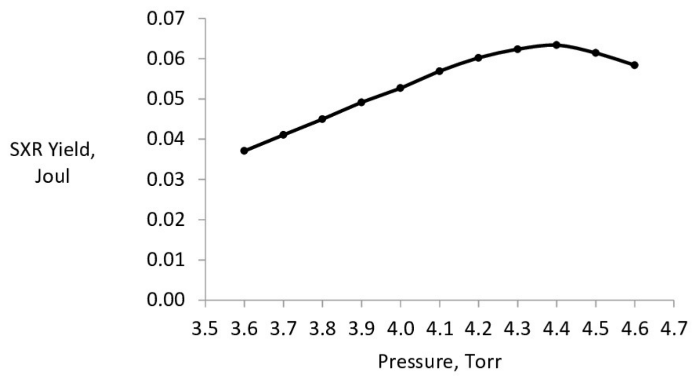

Fig. 1. A plot of the soft X-ray yield versus nitrogen pressure for the PF400 device

An analysis of the data in Table 1 allows us to state that the soft X-ray yield increased from 37.1 mJ at 3.6 Torr pressure to a maximum of 63.4 mJ at 4.4 Torr pressure and then decreased to 58.4 mJ at 4.6 Torr pressure (see Fig. 1), this is due to a decrease in speeds (the axial V_a, shock V_s, radial piston V_p) (see Fig. 2), which leads to a decrease in the plasma temperature to less than the temperature needed to emit soft X-rays (see Fig. 3).

It is evident from Table 2 that the soft X-ray yield increases from 35.0 mJ at 2.2 Torr pressure to a maximum value of 148.0 mJ at 3.2 Torr and then decreases to zero (see also Fig. 4). This is due to a decrease in the temperature below the one required to produce the soft X-rays. The pinch temperature behavior is given in Fig. 6. This is also due to a decrease in velocities (axial one V_a, shock one V_s, radial piston one V_p) with an increasing pressure (see Fig. 5).

A comparison of calculated results related to the soft X-ray yield versus nitrogen and neon pressures for the PF400 device is presented in Fig. 7. From this figure it follows that the soft X-rays yield is higher when using neon gas than in the case of using nitrogen one. Therefore, it is necessary to discuss the factors affecting the value of the soft X-rays yield as follows.

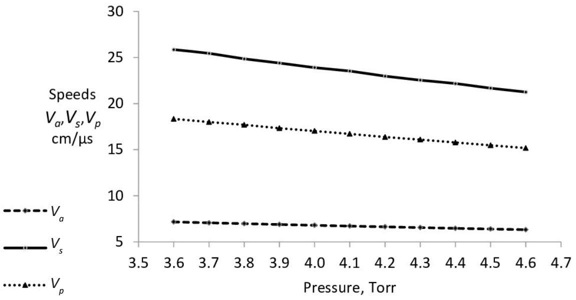

Fig. 2. A plot of the speeds versus nitrogen pressure for the PF400 device

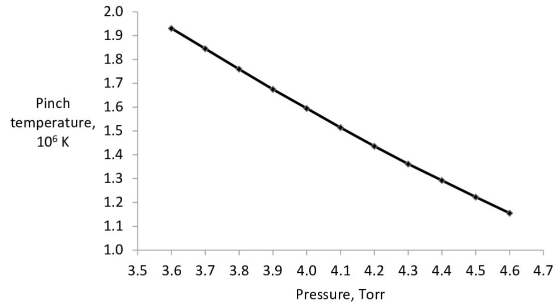

Fig. 3. A plot of the plasma temperature versus nitrogen pressure for the PF400 device

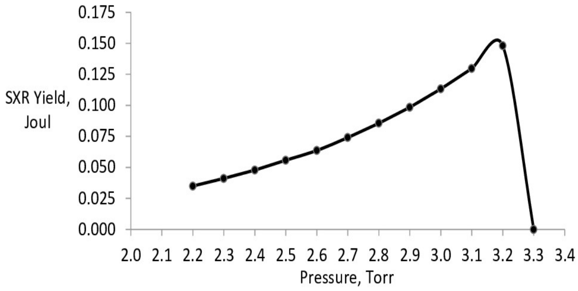

Fig. 4. A plot of the soft *X*-ray yield versus neon pressure for the PF400 device

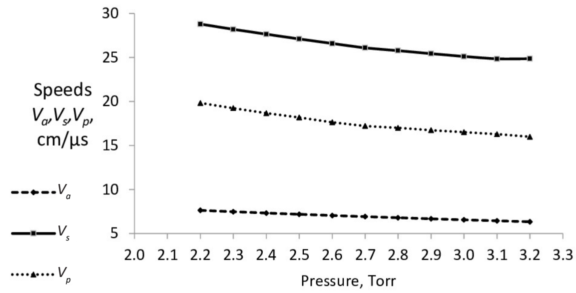

Fig. 5. A plot of the speeds versus neon pressure for the PF400 device

Table 2

The calculated dependence of the plasma focus parameters on the neon pressure for the PF400 device

P	T_e	I_{pinch}	V_a	V_s	V_p	Y_{sxr}
Torr	10^6 K	kA	cm/µs			mJ
2.2	4.95	75	7.6	28.8	19.8	35.0
2.3	4.64	74	7.5	28.2	19.2	41.1
2.4	4.35	72	7.3	27.6	18.7	47.8
2.5	4.07	71	7.2	27.1	18.2	55.8
2.6	3.82	70	7.1	26.6	17.6	63.6
2.7	3.57	69	6.9	26.1	17.2	74.0
2.8	3.33	67	6.8	25.8	17.0	85.6
2.9	3.11	66	6.7	25.4	16.7	98.5
3.0	2.89	64	6.6	25.1	16.5	113.3
3.1	2.70	63	6.4	24.9	16.3	129.7
3.2	2.51	61	6.3	24.9	16.0	148.0

Footnotes. 1. Here the notations are the same as those in Table 1.
2. The peak current I_{peak} is 127 kA for all pressure values, except P = 3.2 Torr, when it is 128 kA.

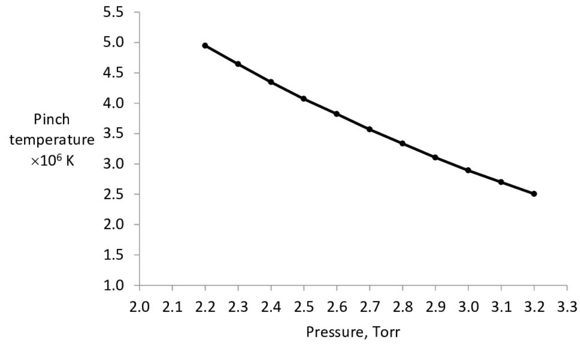

Fig. 6. A plot of the plasma temperature versus neon pressure for the PF400 device

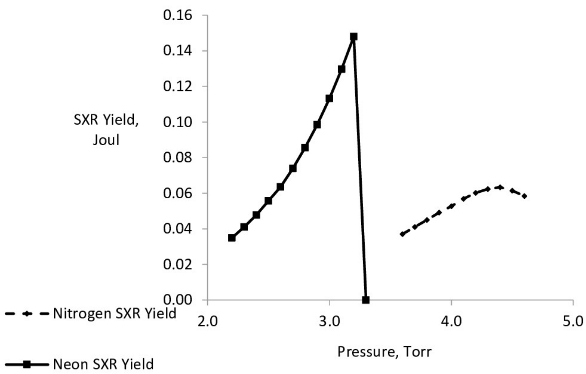

Fig. 7. A comparison of calculated results related to the soft *X*-ray yield versus nitrogen and neon pressures for the PF400 device

Table 3

A comparison of the dependencies of plasma parameters on the pressure of the two gases

<table>
<tr><th>P</th><th>Z_p</th><th>r_p</th><th>N_i</th></tr>
<tr><td>Torr</td><td colspan="2">cm</td><td>$10^{23}/m^3$</td></tr>
<tr><td colspan="4">Neon (Ne)</td></tr>
<tr><td>2.2</td><td rowspan="11">0.80</td><td rowspan="11">0.07</td><td>2.9</td></tr>
<tr><td>2.3</td><td>3.0</td></tr>
<tr><td>2.4</td><td>3.1</td></tr>
<tr><td>2.5</td><td>3.2</td></tr>
<tr><td>2.6</td><td>3.4</td></tr>
<tr><td>2.7</td><td>3.5</td></tr>
<tr><td>2.8</td><td>3.7</td></tr>
<tr><td>2.9</td><td>3.8</td></tr>
<tr><td>3.0</td><td>4.0</td></tr>
<tr><td>3.1</td><td>4.2</td></tr>
<tr><td>3.2</td><td>4.4</td></tr>
<tr><td colspan="4">Nitrogen (N_2)</td></tr>
<tr><td>3.6</td><td rowspan="4">0.90</td><td rowspan="2">0.06</td><td rowspan="2">4.3</td></tr>
<tr><td>3.7</td></tr>
<tr><td>3.8</td><td rowspan="4">0.07</td><td>4.4</td></tr>
<tr><td>3.9</td><td>4.5</td></tr>
<tr><td>4.0</td><td rowspan="7">0.80</td><td>4.6</td></tr>
<tr><td>4.1</td><td>4.7</td></tr>
<tr><td>4.2</td><td rowspan="5">0.06</td><td>4.9</td></tr>
<tr><td>4.3</td><td>5.0</td></tr>
<tr><td>4.4</td><td>5.1</td></tr>
<tr><td>4.5</td><td>5.3</td></tr>
<tr><td>4.6</td><td>5.4</td></tr>
</table>

Notations: P is the pressure; Z_p, r_p are the pinch length and radius; N_i is the plasma density.

1. The number of effective charges for neon is greater, namely, $Z_{eff/\mathrm{Ne}} \approx 9$, $Z_{eff/\mathrm{N}} \approx 6$.
2. The pinch dimensions (the length and radius) were found to be those given in Table 3; comparing the pinch size, we notice that they are almost the same, and therefore there is no noticeable effect of the pinch sizes on the difference in the soft *X*-rays yield.
3. The plasma density values were compared (see Table 3); we can notice that the density values of nitrogen ions are higher, but this factor alone is not sufficient for the nitrogen yield to be higher.
4. From the temperature range suitable for the soft *X*-rays emission, we note that the temperature required in neon is lower, which leads to an increase in the yield value.
5. The atomic number of neon is greater, which leads to an increase in the yield.

Conclusions

We have found that using a high-atomic-number gas such as neon in the PF400 dense plasma focus device can significantly increase the yield of soft *X*-rays (0.037 %) compared to using a lower-atomic-number gas like nitrogen (0.015 %).

This improvement in the soft *X*-ray yield is due to the higher effective charge and atomic number of neon. Additionally, the lower temperature range suitable for the soft *X*-ray emission in neon contributes to the increased yield. The size of the plasma pinch does not affect the soft *X*-rays yield.

REFERENCES

1. **Lee S.,** Plasma focus radiative model: Review of the Lee model code, J. Fusion Energy. 33 (4) (2014) 319–335.

2. **Al-Havat Sh., Saloum S.,** Characterization of 2.8 kJ small plasma focus using a five-phase radiative model, Contrib. Plasma Phys. 49 (1–2) (2009) 5–14.

3. **Liu M.,** Soft X-rays from compact plasma focus. A thesis for degree of PhD, School of Science Nanyang Technological University, Singapore, Dec. 1996.

4. **Al-Havat Sh., Saloum S.,** Characterization of 2.8 kJ small plasma focus using a five-phase radiative model, Contrib. Plasma Phys. 49 (1–2) (2009) 5–14.

5. **Zakaullah M., Alamgir K., Shafiq M., et al.,** Enhanced copper *K*-alpha radiation from a low-energy plasma focus, Appl. Phys. Lett. 78 (7) (2001) 877–879.

6. **Sahyouni W., Nassif A.,** Nitrogen soft X-ray yield optimization from UNU/ICTP PFF plasma focus device, Am. J. Mod. Phys. 8 (6) (2019) 86–89.

7. **Akel M.,** Numerical experiments on plasma focus for soft X-ray yield scaling laws derivation using Lee model (Rep. No. AECS-PH/RSS–993). Damascus (Syrian Arab Republic): Atomic Energy Commission, Dep. of Physics, 2012.

8. **Al-Hawat Sh., Akel M., Wong C. S.,** X-ray emission from argon plasma focus contaminated with copper impurities in AECS PF-2 using five channel diode spectrometer, J. Fusion Energy. 30 (6) (2011) 503–508.

9. **Akel M., Salo S.,** Numerical study of radiation from a plasma focus (Rep. No. AECS-PH/RSS –1046). Damascus (Syrian Arab Republic): Atomic Energy Commission, Dep. of Physics, 2013.

10. **Behbahani R. A., Aghamir F. M.,** Anomalous resistivity effect on multiple ion beam emission and hard X-ray generation in a Mather type plasma focus device, Phys. Plasmas. 8 (10) (2011) 03302.

11. **Aghamir F. M., Behbahani R. A.,** Current sheath behavior and its velocity enhancement in a low energy Mather-type plasma focus device, J. Appl. Phys. 109 (4) (2011) 043301.

12. **Lee S., Saw S. H.,** Neutron scaling laws from numerical experiments, J. Fusion Energy. 27 (4) (2008) 292–295.

13. **Zhang T., Rawat R. S., Hassan S. M., et al.,** Drive parameter as a design consideration for Mather and Filippov types of plasma focus, IEEE Trans. Plasma Sci. 34 (5) (2006) 2356–2362.

14. **Kaastra J. S., Paerels F. B. S., Durret F., et al.,** Thermal radiation processes (Chapter), In book: J. S. Kaastra, A. M. Bykov, S. Schindler, et al. (Eds.) “Clusters of galaxies: Beyond the thermal view”. Springer, New-York, USA (2008) 155–190.

СПИСОК ЛИТЕРАТУРЫ

1. **Lee S.** Plasma focus radiative model: Review of the Lee model code // Journal of Fusion Energy. 2014. Vol. 33. No. 4. Pp. 319–335.

2. **Al-Havat Sh., Saloum S.** Characterization of 2.8 kJ small plasma focus using a five-phase radiative model // Contribution to Plasma Physics. 2009. Vol. 49. No. 1–2. Pp. 5–14.

3. **Liu M.** Soft X-rays from compact plasma focus. A thesis for degree of PhD. School of Science Nanyang Technological University, Singapore, December 1996. 225 p.

4. **Al-Havat Sh., Saloum S.** Characterization of 2.8 kJ small plasma focus using a five-phase radiative model // Contribution to Plasma Physics. 2009. Vol. 49. No. 1–2. Pp. 5–14.

5. **Zakaullah M., Alamgir K., Shafiq M., Hassan S. M., Sharif M., Waheed A.** Enhanced copper *K*-alpha radiation from a low-energy plasma focus // Applied Physics Letters. 2001. Vol. 78. No. 7. Pp. 877–879.

6. **Sahyouni W., Nassif A.** Nitrogen soft X-ray yield optimization from UNU/ICTP PFF plasma focus device // American Journal of Modern Physics. 2019. Vol. 8. No. 6. Pp. 86–89.

7. **Akel M.** Numerical experiments on plasma focus for soft X-ray yield scaling laws derivation using Lee model (Report No. AECS-PH/RSS–993). Damascus (Syrian Arab Republic): Atomic Energy Commission 49. No. 1–2. Pp. 5–14.

8. **Al-Hawat Sh., Akel M., Wong C. S.** X-ray emission from argon plasma focus contaminated with copper impurities in AECS PF-2 using five channel diode spectrometer // Journal of Fusion Energy. 2011. Vol. 30. No. 6. Pp. 503–508.

9. **Akel M., Salo S.** Numerical study of radiation from a plasma focus (Report No. AECS-PH/ RSS –1046). Damascus (Syrian Arab Republic): Atomic Energy Commission, Department of Physics, 2013.

10. **Behbahani R. A., Aghamir F. M.** Anomalous resistivity effect on multiple ion beam emission and hard X-ray generation in a Mather type plasma focus device // Physics of Plasmas. 2011. Vol. 18. No. 10. P. 03302.

11. **Aghamir F. M., Behbahani R. A.** Current sheath behavior and its velocity enhancement in a low energy Mather-type plasma focus device // Journal of Applied Physics. 2011. Vol. 109. No. 4. P. 043301.

12. **Lee S., Saw S. H.** Neutron scaling laws from numerical experiments // Journal of Fusion Energy. 2008. Vol. 27. No. 4. Pp. 292–295.

13. **Zhang T., Rawat R. S., Hassan S. M., Lin J. J., Mahmood S., Tan T. L., Springham S. V., Gribkov V. A., Lee P., Lee S.** Drive parameter as a design consideration for Mather and Filippov types of plasma focus // IEEE Transactions on Plasma Science. 2006. Vol. 34. No. 5. Pp. 2356–2362.

14. **Kaastra J. S., Paerels F. B. S., Durret F., Schindler S., Richter P.** Thermal radiation processes (Chapter) // J. S. Kaastra, A. M. Bykov, S. Schindler, et al. (Eds.) "Clusters of galaxies: Beyond the thermal view". New-York (USA): Springer, 2008. Pp. 155–190.

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