**American Journal of Modern Physics**
2019; 8(6): 86-89
http://www.sciencepublishinggroup.com/j/ajmp
doi: 10.11648/j.ajmp.20190806.12
ISSN: 2326-8867 (Print); ISSN: 2326-8891 (Online)

# Nitrogen Soft X-Ray Yield Optimization from UNU/ICTP PFF Plasma Focus Device

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**To cite this article:**
Walid Sahyouni, Alaa Nassif. Nitrogen Soft X-Ray Yield Optimization from UNU/ICTP PFF Plasma Focus Device. *American Journal of Modern Physics*. Vol. 8, No. 6, 2019, pp. 86-89. doi: 10.11648/j.ajmp.20190806.12

**Received**: September 25, 2019; **Accepted**: November 5, 2019; **Published**: January 4, 2020

**Abstract:** The aim of this research studying soft x-ray emission from United Nations University/International Centre for Theoretical Physics Plasma Fusion Facility (UNU/ICTP PFF) plasma focus device with nitrogen gas pressure changes and find the maximum value of soft x-ray yield by using the standard parameters of device and do optimization to obtain the combination of pressure and electrodes dimensions that gives the maximum value of soft x-ray yield. Many numerical experiments were carried out using Lee code and obtained the maximum value of soft x-ray yield 0.193J at pressure 1.9 Torr by using the standard parameters of device. We optimized the device and found the optimum combination of pressure and electrode dimensions (P0 = 0.5 Torr, z0 = 9 cm, a = 3.19 cm, b = 3.2 cm,) that gives the maximum value of soft x-ray yield Ysxr = 2.7 J without changing the energy of the device.

**Keywords:** Lee Code, UNU/ICTP PFF Device, Soft X-ray Yield

## 1. Introduction

The Plasma Focus is a compact powerful-pulsed source of multi-radiation [1]. Even a small table top sized 3 kJ plasma focus produces an intense burst of radiation with extremely high powers. For example when operated in neon, the X-ray emission power peaks at $10^9$ W over a period of tens of nanoseconds. When operated in deuterium the fusion neutron burst produces rates of neutron typically $10^{15}$ neutrons per second over burst durations of tens of nanosecond. The emission comes from a point-like source making these devices among the most powerful laboratory pulsed radiation sources in the world. These sources are plasma-based. There are two main types of plasma focus classified according to the aspect ratio of the anode. The Filippov type [2] has an anode with a radius larger than its length. The Mather type [3] has a radius smaller than its length.

The studied device (UNU/ICTP PFF) is a dense plasma focus device according to Mather-type that operates with operating energy 2.2 KJ. In this paper we carried out many numerical experiments to studied soft x-ray yield when used nitrogen gas and optimized to get the optimum combination that gives the maximum soft x-ray yield.

## 2. 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 [4-5]. 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 [6].

The Lee code is an important tool to study plasma focus phenomenon in general and the soft x-rays emissions in particular from different plasma focus devices [7-8-9] when using different gases such as oxygen [10], argon [11], nitrogen [12] and neon [13].

In this paper we carried out many numerical experiments to study soft x-ray yield form UNU/ICTP PFF device using nitrogen as operation gas and optimized this device to get optimum combination of pressure and electrode dimension that give the maximum value of soft x-ray yield.

# 3. Results and Discussion

Using Lee code (RADPFV5.15de. c1), a series of numerical experiments carried out on the UNU/ICTP PFF plasma focus device according to the following parameters [14]:

i. Capacitor bank parameters: $L_0$ = 110 nH, $C_0$ = 30 μF, $r_0$= 12 mΩ.
ii. Parameters of the plasma tube: b = 3.2 cm, a = 0.95 cm, $z_0$ = 16 cm.
iii. Operating parameters: $V_0$ = 12 kV.
iv. Model Parameters: $f_m$ = 0.06, $f_c$ = 0.7, $f_{mr}$ = 0.15, $f_{cr}$ = 0.7

*Soft x-ray yield changing with pressure changing using standard parameters for UNU/ICTP PFF plasma focus device:*

The soft x-ray yield from UNU / ICTP PFF device was studied as a function of nitrogen gas pressure with fixing of electrode dimensions (length and radius). The applied pressure was changed from 1.5 Torr to 2.13 Torr and within the appropriate temperature range for soft x-ray emission when using nitrogen gas (0.86 × $10^6$-2 × $10^6$K) [14].

The following results were obtained:

***Table 1.*** *Change soft x-ray yield when gas pressure changes.*

| $P_o$ Torr | $T_{pinch}$ 10^6 (K) | $v_a$ cm/μs | $v_s$ cm/μs | $v_p$ cm/μs | $Y_{line}$ J | Efficiency % |
|---|---|---|---|---|---|---|
| 1.5 | 1.98 | 5.3 | 18.2 | 12.9 | 0.084 | 0.0038 |
| 1.55 | 1.87 | 5.2 | 17.7 | 12.6 | 0.097 | 0.0044 |
| 1.6 | 1.76 | 5.1 | 17.3 | 12.2 | 0.111 | 0.005 |
| 1.65 | 1.65 | 5 | 16.8 | 11.9 | 0.127 | 0.0057 |
| 1.7 | 1.56 | 4.9 | 16.3 | 11.6 | 0.143 | 0.0065 |
| 1.75 | 1.45 | 4.8 | 15.9 | 11.3 | 0.158 | 0.0073 |
| 1.8 | 1.37 | 4.7 | 15.5 | 11 | 0.174 | 0.079 |
| 1.85 | 1.28 | 4.6 | 15 | 10.7 | 0.187 | 0.0085 |
| 1.9 | 1.2 | 4.6 | 14.6 | 10.4 | 0.193 | 0.0087 |
| 1.95 | 1.12 | 4.5 | 14.2 | 10.2 | 0.189 | 0.0085 |
| 2 | 1.04 | 4.4 | 13.7 | 9.9 | 0.17 | 0.0077 |
| 2.05 | 0.97 | 4.3 | 13.4 | 9.6 | 0.171 | 0.0077 |
| 2.1 | 0.9 | 4.3 | 13 | 9.4 | 0.13 | 0.0059 |
| 2.11 | 0.89 | 4.2 | 12.9 | 9.3 | 0.123 | 0.0055 |
| 2.12 | 0.87 | 4.2 | 12.8 | 9.3 | 0.116 | 0.0052 |
| 2.13 | 0.86 | 4.2 | 12.7 | 9.2 | 0.11 | 0.005 |

From these results we note:

1. Soft x-ray yield increases from 0.084 J at 1.5 Torr and reaches the highest value of 0.193 J at 1.9 Torr at an efficiency equal to approximately 0.009% of the energy stored in the capacitor bank and then decreases to 0.11 J at 2.13 Torr see Figure 1.
2. When the pressure is increased, the velocity values (axial $v_a$, radial $v_s$, velocity of the magnetic piston $v_p$) decrease and this decrease in velocities causes the plasma temperature to fall below the temperature required to produce soft x-rays as mentioned in table 1.

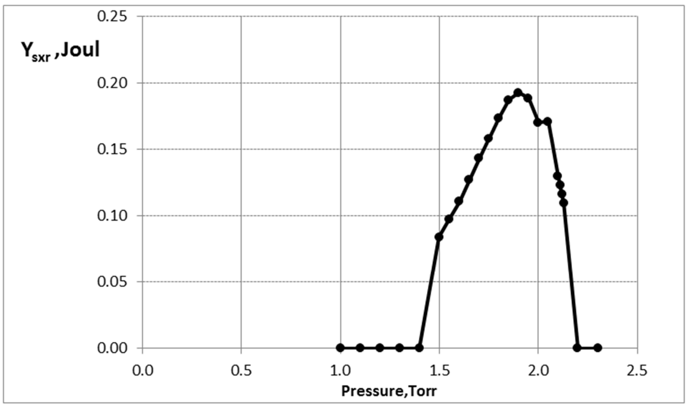


***Figure 1.*** *Change soft x-ray yield when gas pressure changes.*

Optimization soft x-ray yield when changing pressure and anode radius:
used the following method [15]:

1. Choose a value for pressure ($P_0$), fix the length of the anode ($z_0$) and the radius of the cathode (b) at the original values and change the radius of the anode (a) until the highest yield is achieved.

2. Choose a new pressure value and repeat the procedure to find the anode radius value corresponding to the new pressure value ($P_0$).
3. Continue this way until we get the optimal set of ($P_0$, a) that gives the highest yield of soft x-rays.

The following results were obtained:

***Table 2.*** *Change soft x-ray yield when gas pressure and anode radius change.*

| Pressure | Anode Length | Anode Radius | Cathode | Pinch Length | Pinch Radius | Ion Density | Soft X-ray Yield |
|---|---|---|---|---|---|---|---|
| $P_o$ | $z_o$ | a | Radius | $z_{max}$ | $a_{min}$ | $n_i$ | $Y_{line}$ |
| Torr | cm | cm | b | cm | cm | $(10^{23})/m^3$ | J |
| 0.16 | 16 | 3.19 | 3.2 | 4.6 | 0.34 | 0.2 | 0.08 |
| 0.36 | 16 | 3.19 | 3.2 | 4.5 | 0.33 | 0.6 | 1.35 |
| 0.5 | 16 | 2.79 | 3.2 | 3.9 | 0.29 | 0.8 | 1.62 |
| 0.8 | 16 | 2.07 | 3.2 | 2.9 | 0.21 | 1.4 | 0.89 |
| 1.3 | 16 | 1.45 | 3.2 | 2 | 0.14 | 2.4 | 0.4 |
| 1.7 | 16 | 1.16 | 3.2 | 1.6 | 0.11 | 3.2 | 0.21 |
| 2.2 | 16 | 0.92 | 3.2 | 1.2 | 0.09 | 4.3 | 0.1 |
| 3.1 | 16 | 0.6 | 3.2 | 0.8 | 0.06 | 5.8 | 0.07 |

Note the following:

1. Anode radius (a) decreases with increasing pressure ($P_0$).
2. Pinch dimensions (pinch radius $a_{min}$, pinch length $z_{max}$) have the highest value at the lowest pressure value where the anode radius is the highest value and therefore the anode radius is an important factor to control the pinch dimensions and thus yield's value.
3. The soft x-ray yield increases with increasing pressure to a maximum value of 1.62 J at 0.5 Torr and then decreases as the pressure increases as shown in Figure 2.
4. The optimum combination was obtained:
5. $P_0$ = 0.5 Torr, $z_0$ = 16 cm, $a_0$ = 2.79cm, b = 3.2 cm, $Y_{sxr}$ = 1.62 J
6. Note that the value of soft x-ray yield exceeds its value when using the standard dimensions, when increasing anode radius only.

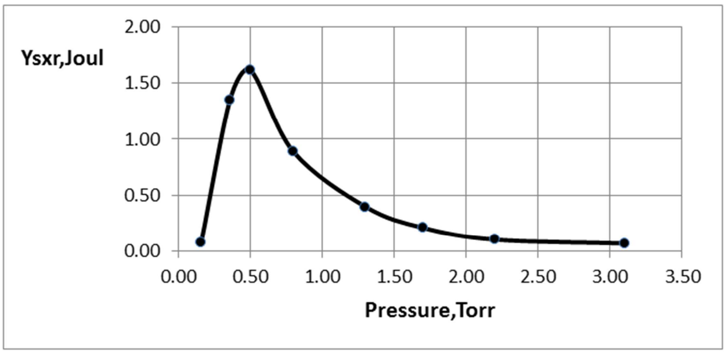


***Figure 2.*** *Change soft x-ray yield when gas pressure and anode radius change.*

*Optimization soft x-ray yield when changing pressure and anode length, radius:*

At this stage we install the cathode radius at the original value (b = 3.2 cm), and we change both the length of the anode and the radius with the change of nitrogen pressure.

The following results were obtained:

***Table 3.*** *Change soft x-ray yield when gas pressure, anode radius and length change.*

| Pressure | Anode Length | Anode Radius | Cathode Radius | Pinch Length | Pinch Radius | Ion Density | Soft X-ray Yield |
|---|---|---|---|---|---|---|---|
| $P_o$ | $z_o$ | a | b | $z_{max}$ | $a_{min}$ | $n_i$ | $Y_{line}$ |
| Torr | cm | cm | cm | cm | cm | $(10^{23})/m^3$ | J |
| 0.1 | 6 | 3.19 | 3.2 | 4.6 | 0.32 | 0.2 | 0.03 |
| 0.4 | 8 | 3.19 | 3.2 | 4.5 | 0.31 | 0.8 | 1.41 |
| 0.5 | 9 | 3.19 | 3.2 | 4.5 | 0.31 | 1 | 2.7 |
| 0.9 | 9.5 | 2.52 | 3.2 | 3.5 | 0.25 | 1.6 | 2.1 |
| 1.2 | 10 | 2.11 | 3.2 | 2.9 | 0.21 | 2.2 | 1.2 |
| 1.5 | 10.5 | 1.8 | 3.2 | 2.5 | 0.18 | 2.8 | 0.75 |
| 2 | 12 | 1.36 | 3.2 | 1.9 | 0.13 | 3.8 | 0.33 |
| 2.5 | 12.3 | 1.12 | 3.2 | 1.5 | 0.11 | 4.8 | 0.19 |
| 3 | 12.6 | 0.94 | 3.2 | 1.3 | 0.09 | 5.9 | 0.11 |
| 4 | 13 | 0.69 | 3.2 | 0.9 | 0.06 | 8 | 0.05 |

The following figure shows the sequence of soft x-ray yields of nitrogen pressure when changing the length and radius of the anode at each pressure value.

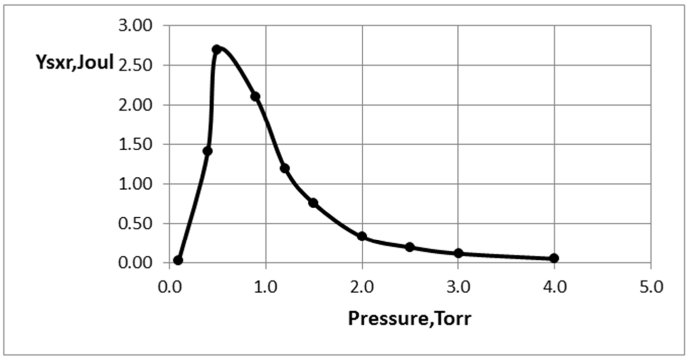


***Figure 3.*** *Change soft x-ray yield when gas pressure, anode radius and length change.*

Note the following:

1. Increase in the value of soft x-ray yield when changing the dimensions of the anode with the change of gas pressure to reach a maximum value and then decreases as the pressure increases.
2. The optimum combination that gave the highest yield was obtained:
3. $P_0$ = 0.5 Torr, $z_0$ = 9 cm, a = 3.19 cm, b = 3.2, $Y_{sxr}$ = 2.7 J
4. observed decreasing pinch dimensions with increasing gas pressure due to decreasing radius of anode Table 3.

# 4. Conclusion

Lee code used to study variations of soft x-ray yield from UNU/ICTP PFF device when used nitrogen gas. The results showed the yield value was found as a function of gas pressure when using the basic dimensions of the electrodes (length and radius), where the maximum yield value ($Y_{sxr}$ = 0.193 J) was obtained at pressure ($P_0$ = 1.9 Torr) with efficiency (0.009%). We studied soft x-ray yield with changing radius of the anode with change of pressure, the results showed that anode radius needs to increase from its original value (a = 0.95 cm) to the value (a = 2.79 cm), which led to an increase soft x-ray yield to the value ($Y_{sxr}$ = 1.62 J) at pressure ($P_0$ = 0.5 Torr) with efficiency (0.07%) and the size of the formed plasma pinch increased. And when both length and radius of anode changed to the values ( $z_0$ = 9 cm, a=3.19 cm) the soft x-ray yield increased to the value ($Y_{sxr}$ = 2.7 J) at pressure ($P_0$ = 0.5 Torr) with efficiency (0.122%).

The optimum combination at which we obtain the highest yield of soft X-rays from UNU / ICTP PFF can be written when using nitrogen gas for both pressure and electrode dimensions as follows:

$P_0$ = 0.5 Torr, $z_0$ = 9 cm, a = 3.19 cm, b = 3.2, $Y_{sxr}$ = 2.7 J

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