

AUTOMATED NUMERICAL EXPERIMENTS TO OPTIMIZE TAPERED ANODE CONFIGURATION FOR SOFT X-RAY YIELD IN A LOW-ENERGY PLASMA FOCUS

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Abstract

Using the RADPF5.15 Lee model code, numerical experiments were conducted to study the effects of anode tapering configuration on the soft X-ray (SXR) yield (Y_{SXR}) of the 2.2 kJ EAEA-PF1 plasma focus device. Taper dimension parameters were investigated, including the taper start and end radius, variations in the initial pressure of argon gas (P_0), and the charging voltage (V_0). A comparison of SXR production in the plasma focus device with and without anode tapering revealed that the Y_{SXR} obtained using optimized tapered anode dimensions (550.5 mJ) was nearly 100 times greater than that without tapering (5.24 mJ). Additionally, the effects of the taper start and end radius on pinch duration, ion density, pressure, and Y_{SXR} were examined. The product of the plasma focus volume, pinch duration, and the square of the plasma density was identified as the dominant factor responsible for the enhancement in Y_{SXR} with the tapered anode compared to the untapered configuration. These results indicate that determining the optimal anode tapering dimensions is key to improving Y_{SXR} efficiency in plasma focus devices.

Keywords: Lee model RADPF5.15 K; Plasma focus; Soft X-ray yield; Tapering anode

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Introduction

Plasma focus (PF) devices belong to the family of dynamic z-pinches, self-constricted plasma configurations. These configurations are of interest in plasma physics due to their occurrence in space (e.g., current channels on galactic scales and solar flares) and on Earth (e.g., aurora borealis and lightning), as well as their significance in various applications (Scholz *et al.*, 2004). A dense plasma focus (DPF) is a device that generates, accelerates, and pinches plasma through electromagnetic forces. The short-lived pinched plasma is sufficiently hot and dense to enhance nuclear fusion reactions, even with high threshold energies (Al-Halim, 2010). A DPF produces abundant multi-radiation, consisting of a broad spectrum of photons and particles, which has been the subject of extensive studies and applications (Gautam *et al.*, 2015).

Extensive data and information have been gathered from numerous DPF devices and experiments. For a long period after the discovery of the DPF (Mather, 1963), most studies focused on hydrogen and its isotopes. In recent decades, significant potential applications of the DPF as an intense soft X-ray source (Kato *et al.*, 1988; Neff *et al.*, 1989) have been proposed and investigated, including its use in micro-lithography and X-ray microscopy. The X-ray yield and its dependence on plasma properties are crucial for DPF applications (Favre *et al.*, 1999; Liu, 2006).

While many recent experiments have focused on low-energy devices (Kato and Be, 1986; Bogolyubov *et al.*, 1998; Lee *et al.*, 1998) to develop repetitively pulsed sources, other studies have explored X-ray pulses from larger PF devices (Filippov *et al.*, 1996; 2002) extending into the megajoule regime. However, numerical experiments simulating X-ray pulses from PF devices have gained increasing interest in the public domain. For instance, the Institute of Plasma Focus Studies (Lee, 2014) organized an International Internet Workshop on Plasma Focus Numerical Experiments (Lee and Saw, 2011). At this conference, it was demonstrated that the Lee model code (Lee, 2014) computes realistic focus pinch parameters and absolute values of soft X-ray yield (Y_{SXR}), which are consistent with experimental measurements (Lee *et al.*, 1998; Lee *et al.*, 2009; Lee, 2014). A comparison for the NX2 machine (Lee *et al.*, 1998) showed good agreement between the computed and measured Y_{SXR} as a function of operational pressure (P_0) (Lee *et al.*, 2009; Lee, 2014), reinforcing confidence in the Lee model code's accuracy in computing Y_{SXR} .

Recently, the NX2 plasma focus device has been operated with a tapered copper anode to enhance and stabilize the X-ray yield (Wong *et al.*, 2005). The tapered anode reportedly produced higher current sheath speeds, which increased the temperature of the pinch column (Serban and Lee, 1998), leading to an improvement in neutron yield.

In this study, the Lee model code RADPF5.15 is used to conduct a series of numerical experiments to examine the role of inner electrode taper dimensions in optimizing the soft X-ray yield from a 2.2 kJ PF device, considering variations in P_0 using argon gas and the charging voltage (V_0).

Numerical Experiments Using the Lee Model

The dynamics of PF discharges are complex. The Lee model integrates an electrical circuit with PF dynamics, thermodynamics, and radiation to investigate PF phenomena, enabling realistic simulation of gross focus properties (Saw and Lee, 2010; Lee and Saw, 2011). The Lee model code is configured to simulate any PF type by inputting bank parameters (L_0 and C_0), stray circuit resistance (r_0), tube parameters (b , a , and z_0), operational parameters (V_0 and P_0), and the fill gas. Standard practice is to fit the computed total current waveform to an experimentally measured total current waveform (Lee, 2014; Lee, 2008; Lee and Saw, 2008a; 2008b; Lee *et al.*, 2008a; 2008b) using four model parameters: the mass swept-up factor (f_m), the plasma current factor (f_c) for the axial phase, and the factors (f_{mr} and f_{cr}) for the radial phases.

For each studied PF device, fitted values of the model parameters are determined using the following procedure. The computed total discharge current waveform is adjusted to match the measured waveform by varying f_m , f_c , f_{mr} , and f_{cr} one by one until agreement is achieved (Al-Hawat *et al.*, 2011). The current-trace fitting results for a low-energy PF device, the EAEA-PF1, operating at 12 kV with an argon filling gas pressure of 0.8 Torr, are presented in Ahmed *et al.* (2019).

Soft X-Ray Yield at Different Charging Voltages with Regular Anode

The Lee model code has been successfully used to perform numerical experiments to compute

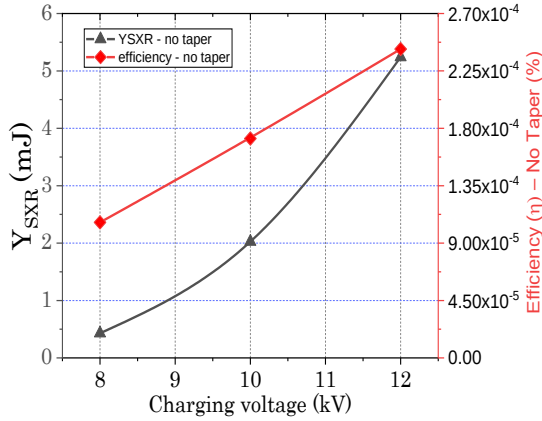


Figure 1. Variation of Y_{SXR} and efficiency with charging voltage for a regular anode

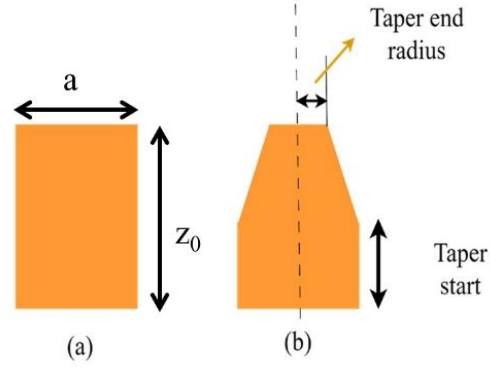


Figure 2. A schematic of the anode configuration: (a) without taper and (b) with a tapered anode

the argon soft X-ray (SXR) yield for the EAEA-PF1 device as a function of pressure. The SXR emission is calculated by subtracting plasma self-absorption from the generated SXR energy (line radiation), which primarily depends on temperature and density. This effect occurs when an emitted photon (in this case, the SXR) is reabsorbed by another plasma component before escaping the plasma region, resulting in a lower radiation yield (Ong *et al.*, 2014). The rate of argon line radiation can be calculated as follows (Lee, 2014):

$$\frac{dQ_L}{dt} = 4.6 \times 10^{-31} n_i^2 Z_{eff}^4 Z_n^4 (\pi r_p^2) Z_p / T \quad (1)$$

where n_i is the ion number density, Z_{eff} is the effective charge number, Z_n is the atomic number, r_p and z_p are the pinch radius and length, respectively, and T is the plasma pinch temperature. Q_L is obtained by integrating over the pinching period. The balance quantity, after accounting for self-absorption, is emitted as SXR. This effect is included in the model calculation (Lee, 2014) but is insignificant for operation in low-pressure argon (Akel *et al.*, 2012), meaning $Y_{SXR} = Q_L$.

Numerical experiments were conducted using the Lee model to optimize the operation of the EAEA-PF1 device for optimal Y_{SXR} with a flat-top cylindrical (regular) anode. The variation of Y_{SXR} with operating pressure was studied at different charging voltages of 8, 10, and 12 kV while keeping z_0 , a , and b constant at 10.8, 2.25, and 4.5 cm, respectively. This analysis aimed to determine the optimal charging voltage and operating argon pressure for maximizing Y_{SXR} . Figure 1 illustrates the variation of Y_{SXR} and efficiency (η), defined as the percentage of

Y_{SXR} relative to input energy as a function of charging voltage for a regular anode (no taper).

Figure 1 shows that Y_{SXR} and η increase as the charging voltage increases. Specifically, Y_{SXR} increased from 0.43 mJ to 5.24 mJ, and η increased from 0.000045% to 0.00024% as the charging voltage increased from 8 to 12 kV. At a charging voltage of 12 kV, a Y_{SXR} of 5.24 mJ was obtained at an operating pressure of 0.115 Torr. For charging voltages of 10 and 8 kV, the optimum pressures were found to be 0.051 and 0.028 Torr, respectively.

Anode tapering was proposed to enhance the SXR yield, as shown in Figure 2. Previous experiments have demonstrated that a gradually tapered anode increases the SXR yield (Zakaullah *et al.*, 1996).

Numerical experiments were conducted using the Lee model on the proposed tapered anode to investigate the effect of tapering dimensions, including the taper start and end radius, on Y_{SXR} at different charging voltages and working pressures. This analysis determined the optimal charging voltage and operating pressure required to maximize Y_{SXR} .

Procedure of Tapered Anode Effect on Soft X-Ray Yield

The taper start varied from 3 to 10 cm in 1 cm increments. The end radius was adjusted from 0.4 to 1 cm for charging voltages of 8, 10, and 12 kV for each taper start value. The Y_{SXR} is numerically obtained using the code by varying the working pressure until the maximum Y_{SXR} is achieved. The procedure is as follows:

1. The parameters a , b , L_0 , C_0 , r_0 , z_0 , and model parameters were fixed, ensuring that the temperature window for argon gas remains within 1.4-5 keV (16.3×10^6 to 58.14×10^6 K) (Wong *et al.*, 2005).

2. The charging voltage was initially set to 8 kV.

3. The taper start was set to 3 cm, and the end radius was set to 0.4 cm.

4. The operating pressure was adjusted incrementally until the targeted temperature window was achieved.

5. The pressure was further varied in precise steps, and the Y_{SXR} value was recorded until the maximum was reached for an end radius of 0.4 cm.

6. The end radius was increased to 0.5 cm, and the pressure was adjusted until the highest Y_{SXR} was obtained.

7. Steps 5 and 6 were repeated for end radius values of 0.6, 0.7, 0.8, 0.9, and 1 cm. The end radius corresponding to the highest Y_{SXR} is selected as the optimal value for a taper start of 3 cm.

8. The taper start was then adjusted to 4, 5, 6, 7, 8, 9, and 10 cm, and steps 1-7 were repeated to determine the optimal end radius for each taper start.

9. Among the optimal end radius values obtained for each taper start, the one yielding the highest Y_{SXR} was selected as the best case for anode redesign.

10. Steps 1-9 were repeated for charging voltages of 10 and 12 kV. The charging voltage that produces the highest Y_{SXR} was identified as the optimal value for device optimization.

Soft X-Ray Yield Optimization with Tapered Anode

Figure 3 illustrates the variation of Y_{SXR} with end radius for different taper start values at charging voltages of 8, 10, and 12 kV. The figure reveals that for all taper start values considered, the maximum Y_{SXR} is achieved at end radius values of 0.6, 0.6, and 0.7 cm for charging voltages of 8, 10, and 12 kV, respectively. Additionally, the three best cases

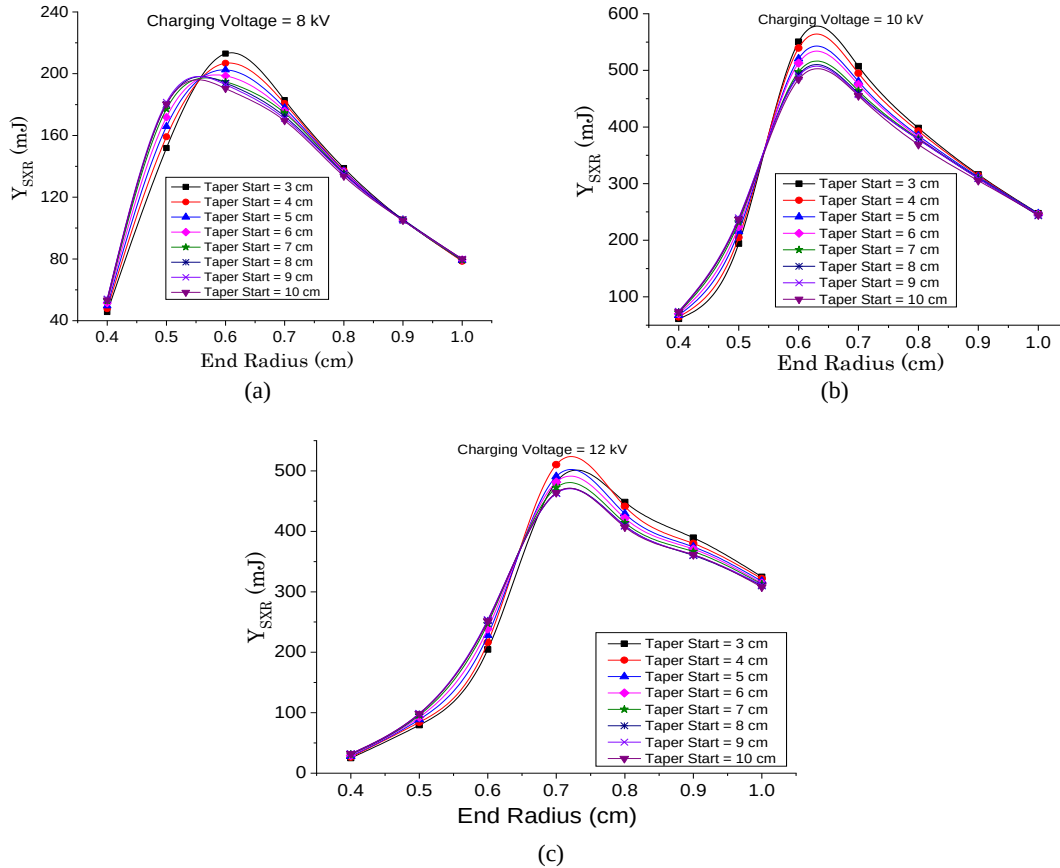


Figure 3. Variation of Y_{SXR} with end radius at different taper start values of (a) 8 kV, (b) 10 kV, and (c) 12 kV

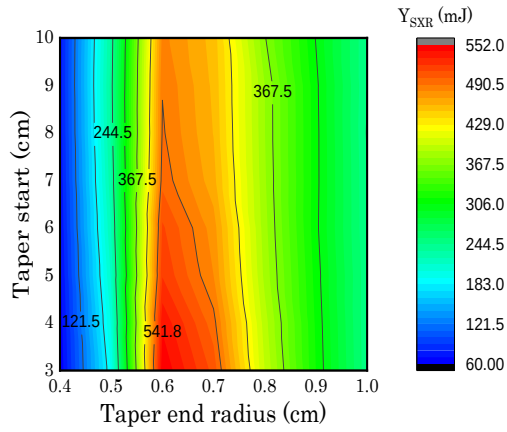


Figure 4. Two-dimensional contour plot of the X-ray profile at different taper dimensions (taper start and end radii) at a 10 kV charging voltage, where Y_{SXR} ranges from 60 to 552 mJ (color scale)

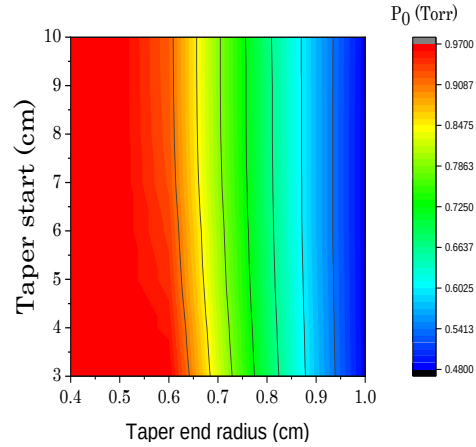


Figure 5. Two-dimensional contour plot of the pressure at the highest Y_{SXR} for different taper dimensions (taper start and end radii) at a 10 kV charging voltage, where the pressure ranges from 0.480 to 0.970 Torr (color scale)

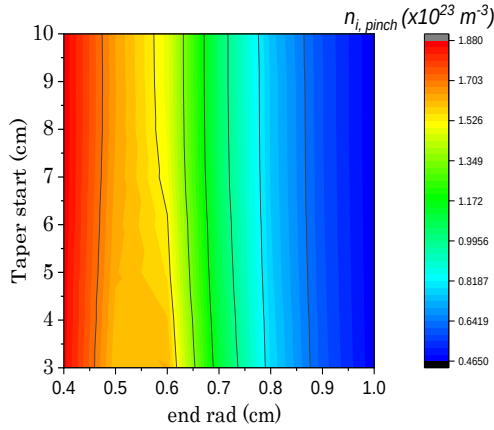


Figure 6. Two-dimensional contour plot of the ion density at the highest Y_{SXR} for different taper dimensions (taper start and end radii) at a 10 kV charging voltage

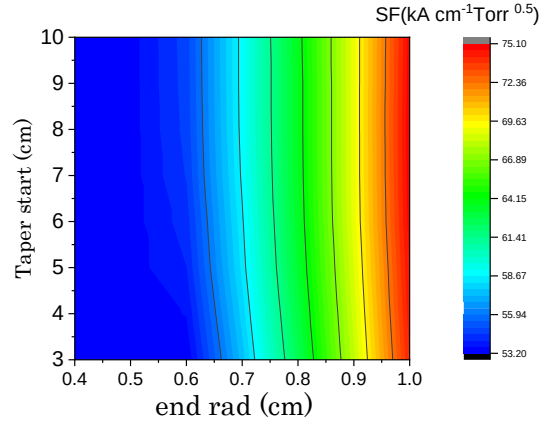


Figure 7. Two-dimensional contour plot of the speed factor at the highest Y_{SXR} for different taper start and end radii at a 10 kV charging voltage

yielding maximum Y_{SXR} values of 213, 550.5, and 510.33 mJ correspond to taper start values of 3, 3, and 4 cm for charging voltages of 8, 10, and 12 kV, respectively. The highest Y_{SXR} was obtained at 10 kV, indicating this as the optimum charging voltage. Consequently, plasma parameters were analyzed at this voltage.

Figure 4 presents a two-dimensional contour plot of the SXR yield at a charging voltage of 10 kV for different taper start and end radius values. Notably, the maximum Y_{SXR} occurs between end radius values of 0.6 and 0.7 cm for nearly all taper start values.

At a charging voltage of 10 kV and the maximum Y_{SXR} , the operating argon pressure is plotted in Figure 5 as a function of the end radius for all taper start values and as a function of taper start for all end radius values to determine the optimum pressure. Figure 5 shows that the optimum pressure remains constant at 0.9689 Torr for end radius values of 0.4 and 0.5 cm. Then, the pressure decreased incrementally as the end radius increased to 1 cm for all taper start values.

Figure 6 presents the variation of ion density (n_i) as a function of the end radius for all taper start values and as a function of taper start for all end

radius values at a charging voltage of 10 kV. The figure confirms that n_i gradually decreases as the end radius increases. A similar trend is observed for all taper start values, indicating that changes in taper start do not significantly affect n_i . This suggests that end radius is the predominant parameter influencing n_i in this study. Additionally, the highest n_i value ($\sim 1.87 \times 10^{23} \text{ m}^{-3}$) was obtained at an end radius of 0.4 cm.

The effect of all taper start values and end radii under the same conditions on the speed factor (SF) is illustrated in Figure 7. SF remained nearly constant for small end radius values and then

increased rapidly as the end radius increased. Additionally, increasing the taper start did not significantly affect SF.

A comparison of the simulated traces generated by the code for an argon EAEA-PF1 device fitted with and without a tapered anode and operated at charging voltages ranging from 8 to 12 kV is presented in the next section.

Figure 8 illustrates the variation of maximum Y_{SXR} and its relative efficiency at different charging voltages with and without anode tapering. Y_{SXR} for the tapered anode is approximately 100 times greater than that for the regular anode, highlighting

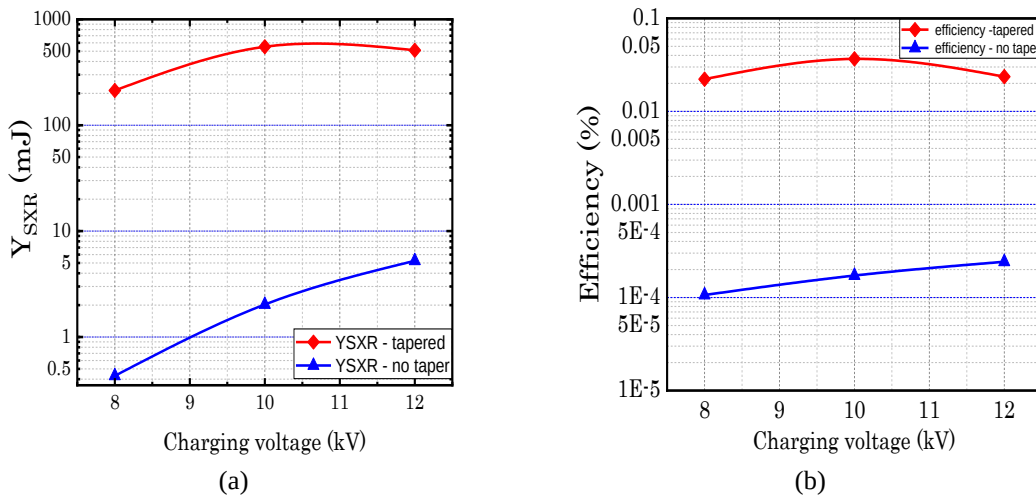


Figure 8. Logarithmic scale of the maximum YSXR and its relative efficiency at different charging voltages with and without a tapered anode

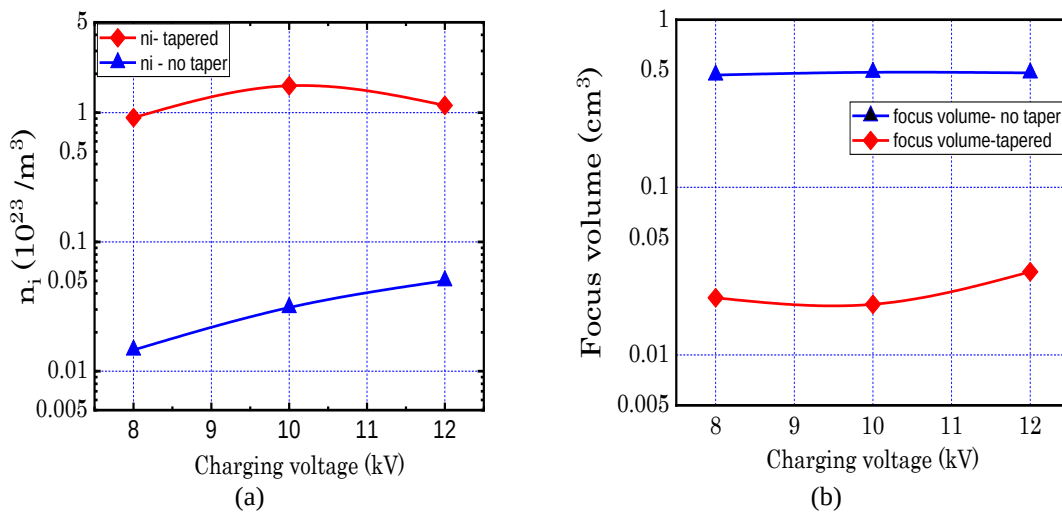


Figure 9. Logarithmic scale of (a) ion density and (b) focus column volume at the highest YSXR at different charging voltages with and without a tapered anode

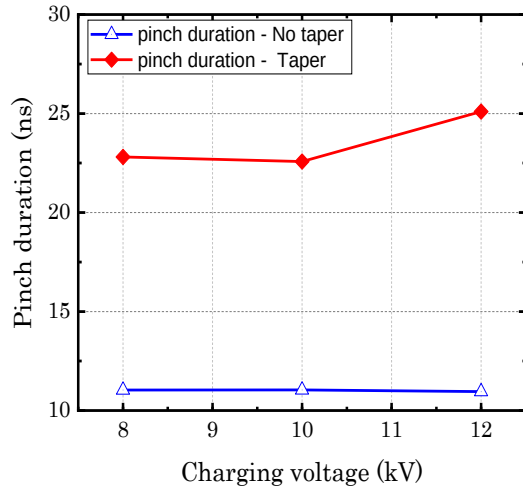


Figure 10. Variation of pinch duration at the highest Y_{SXR} at different charging voltages with and without a tapered anode

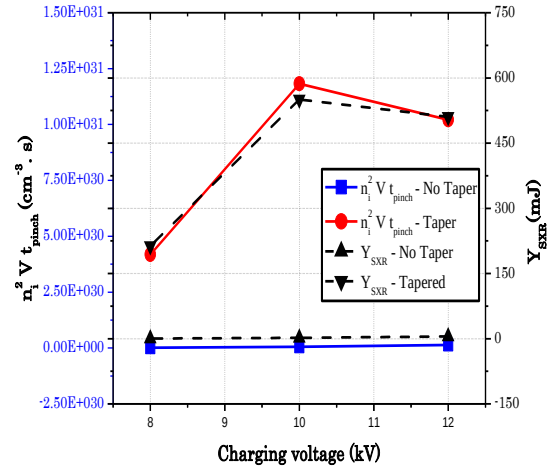


Figure 11. Variation of pinch duration at the highest Y_{SXR} at different charging voltages with and without a tapered anode

the significant role of anode tapering in enhancing Y_{SXR} . The efficiency, defined as the ratio of emitted Y_{SXR} to the energy stored in the capacitor bank, was generally higher.

Figure 9 illustrates the variation of ion density and focus column volume (V_{pf}) with maximum Y_{SXR} at different charging voltages with and without a tapered anode. The figure shows that ion density is significantly higher with a tapered anode than without, which is expected given that, as seen from Equation 1, the SXR energy generated within the plasma pinch depends on ion density. In contrast, the focus column volume exhibited the opposite behavior, decreasing in the case of a tapered anode.

Figure 10 illustrates the variation of pinch duration time (t_p) at maximum SXR yield for the charging voltage values under consideration, with and without a tapered anode. Without a tapered anode, t_p remained nearly constant across all charging voltages. In contrast, for the tapered anode case, t_p was constant at 8 and 10 kV but increased at 12 kV. Overall, t_p was significantly higher with a tapered anode than without.

Integrating Equation 1 over the pinch duration time, $Y_{SXR} = Q_L$, and assuming Z_{eff} and Z_n as constants in both cases (with and without a tapered anode) and $T = 16.3 \times 10^6$ K (as a constant) that yields the highest Y_{SXR} (Ahmed *et al.*, 2019), Equation 1 can be rewritten as:

$$Y_{SXR} = const. \times Q_L \propto n_i^2 V t_{pinch} ; V = (\pi a_{min}^2) Z_{max} \quad (2)$$

where $const. = 4.6 \times 10^{-31} \times Z_{eff} \times Z_n / T$ and V is the volume of the plasma focus column.

The product of the plasma focus volume, pinch duration, and the square of the plasma density, along with Y_{SXR} , is plotted as a function of the charging voltage in Figure 11 for both cases (with and without a tapered anode). This figure shows that the behavior of this product and Y_{SXR} is the same in both cases. This suggests that the product of the plasma focus volume, pinch duration, and the square of the plasma density is the primary factor and reason for the nearly 100-fold enhancement in Y_{SXR} with a tapered anode compared to without.

This product and Y_{SXR} were plotted as a function of the taper end radius at a charging voltage of 10 kV, as shown in Figure 12. The same profiles for the product and Y_{SXR} were observed, confirming the assumption that this product is the dominant factor in Y_{SXR} enhancement in the tapered anode case.

Figure 13 compares the pressure ranges at maximum Y_{SXR} for different charging voltages with and without a tapered anode. The results indicated that the pressure range yielding maximum Y_{SXR} was broader in the case of a tapered anode. Additionally, with a tapered anode, the model-optimized SXR pressure range (0.75-1.17 Torr) aligns more closely with the experimental pressure range for optimal focus with a regular anode (Lashin *et al.*, 2019).

A comparison of the device configuration and Y_{SXR} yield between our optimized device with and without a tapered anode, as obtained from the Lee model, is presented in Table 1.

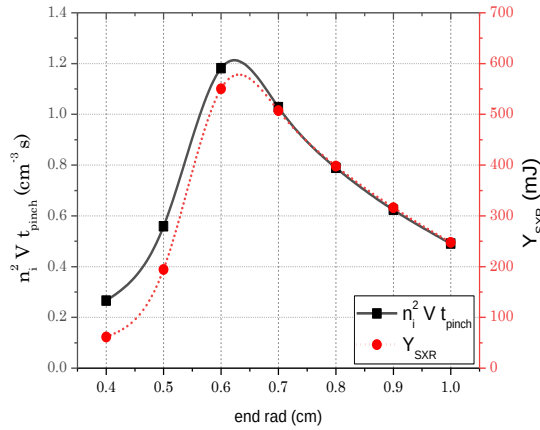


Figure 12. Product of the plasma focus volume, pinch duration, and the square of the plasma density, as well as Y_{SXR} , as a function of the taper end radius at a charging voltage of 10 kV

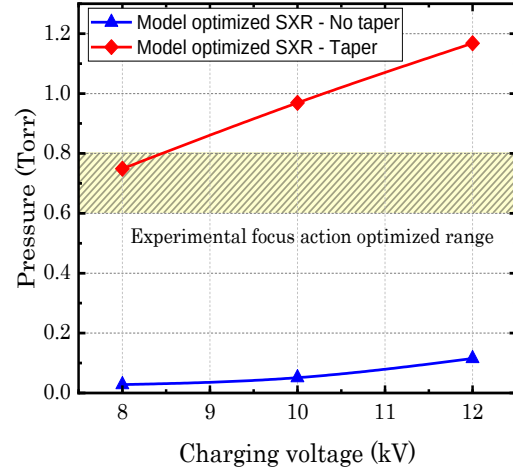


Figure 13. Variation of pressure at the highest Y_{SXR} as a function of charging voltage for both cases, with and without a tapered anode

Table 1. Comparison of the device configuration and Y_{SXR} yield between our optimized device with and without a tapered anode

#	Taper Start (cm)	End Radius (cm)	V_0 (kV)	P_0 (Torr)	Y_{SXR} (mJ)	Efficiency (%)
EAEA-PF1 optimized (without taper)	--	--	12	0.115	5.24	0.00024
EAEA-PF1 optimized (with taper)	3	0.6	10	0.969	550.5	0.0367

Conclusions

A series of numerical experiments were conducted on a low-energy 2.2 kJ Mather-type PF device. The Lee model code RADPF5.15K was used to compute the argon SXR yield as a function of gas pressure at charging voltages ranging from 8 to 12 kV while keeping the values of z_0 , a , and b constant. Using a regular anode, a Y_{SXR} of 5.24 mJ was obtained at an operating pressure of 0.115 Torr and a charging voltage of 12 kV. When the anode was tapered (with an anode taper start of 4 cm and an end radius of 0.7 cm), significantly higher Y_{SXR} levels, nearly 100 times greater than those obtained with a regular anode, were achieved.

Moreover, the SXR yield obtained at a 10 kV charging voltage for different taper start and end radii values indicated that the maximum Y_{SXR} was achieved at an end radius between 0.6 and 0.7 cm for almost all taper start values. Changing the taper start did not significantly affect the pinch density, n_i , suggesting that the end radius is the predominant parameter influencing n_i in this study. The highest n_i value ($\sim 1.87 \times 10^{23} \text{ m}^{-3}$), approximately 37 times greater than that of an anode without a taper, was

obtained at a 10 kV charging voltage for a tapered anode end radius of 0.4 cm. This corresponds to a maximum obtainable SXR yield of $\sim 0.5 \text{ J}$, generated within the plasma pinch depending on ion density. However, the focus column volume for a tapered anode was drastically compressed to only 4% of its volume compared to a regular anode. This reduction in pinch size was greater than expected, as the pinch dimensions generally scale with the anode radius, with the final tapered end radius reduced to only 30% of a regular anode radius.

On the other hand, the SF remained nearly constant for small end radius values. SF increased rapidly for larger end radius values despite the increase in end radius, indicating a greater variation in peak discharge current. Increasing the taper start did not significantly affect SF. Regarding pinch duration (t_p), it remained nearly constant at all charging voltages for a regular anode. For a tapered anode, t_p was nearly constant at charging voltages of 8 and 10 kV but increased at 12 kV.

It can be concluded that the product of $n_i^2 V t_{\text{pinch}}$ is the dominant factor contributing to

the approximately 100-fold increase in Y_{SXR} observed with a tapered anode compared to a regular anode. Further scaling of this product with energy, inductance, and I_{pinch} , among other parameters, is required for a more comprehensive understanding of its effect on Y_{SXR} .

Our findings indicated that the operating pressure range for maximum SXR yield shifts toward higher pressures (0.75-1.17 Torr) with a tapered anode. This range is closer to the experimentally optimized pressure range for optimal focus action using a regular anode. This shift may be attributed to the expected rise in axial and radial velocities of the plasma current sheath and the resulting increase in pinch temperature due to a tapered anode.

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