Effect of atomic number and pressure on plasma pinch properties and characteristic soft x-ray emission in PF1000

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Abstract
In this study, the Lee code is used to compute the characteristics soft x-ray yield (Y_{sxr}) production for nitrogen (N₂), oxygen (O₂), neon (Ne), and argon (Ar) and bremsstrahlung radiation for hydrogen (H₂), deuterium (D₂), and helium (He) with pressure variation in PF1000 of 2.5–2.6 MA for D₂. In the calculation of characteristic soft x-ray, the corresponding temperature windows of the said gases are set into the code at which they are ionized to their H-like and He-like levels. The focus pinch parameters such as radius ratio (minimum radius of plasma pinch column/anode radius), ion density, specific heat ratio, pinch energy density, self-absorption correction factor, and maximum induced voltage are computed at the optimum pressure of each gas. The obtained pinch plasma temperature range (1.2–2.2) × 10⁶ K of H₂, D₂, and He is sufficiently high for fully ionized plasmas and the resulting bremsstrahlung radiation (14 J) for He is significantly larger than for H₂ (0.26 J) and D₂ (0.62 J). The optimum Y_{sxr} of Ne (~9314 J) at 0.51 Torr with pinch energy density (PED) (~26 × 10⁸ J m⁻³) is found to be the highest whilst for Ar (~7 J) at 0.019 Torr with (~1.2 × 10⁸ J m⁻³) is the lowest. It is found that the radius ratio (~0.05) of Ne is 3-fold smaller than that (~0.16) in Ar. This enhancement of compression in pinch of Ne increases the ion density significantly by a factor of 253 than in Ar gas. Thus, the results show a strong correlation of plasma pinch properties with Y_{sxr} for various gases.

1. Introduction

The study of pinch plasmas as a bright soft x-ray source is well established. Although it is simple to construct [1, 2] the dense plasma focus (DPF) emits x-ray emission efficiently when compared with other pinches including the X-pinch [3] and vacuum spark [4]. Applications in the x-ray spectrum range include spectroscopy [5], microscopy and microlithography [6], for pumping lasers [7], crystallography [8], medical and industrial radiography [9], for back-lighter [10], and for engineering micromachining [11]. A super-hot (~100s eV) and super-dense (~10¹⁸ cm⁻³) short-lived plasmas is concentrated in the focus pinch column by electromagnetic acceleration and compression [6]. During the intense pinch compression phase, high levels of ionization are attained with efficient transfer of energy into predominantly radiative recombination and line emission [12] in the soft x-ray wavelength region. It has been shown that the radius of the pinch may be determined by the operation of work-energy balance and magnetic-kinetic pressure balance [13].

The ratio of the minimum radius of plasma pinch column (r_{min}) to anode radius (a) is, to some extent dependent on temperature through the specific heat ratio (γ). The lower the value of γ, the greater the degree of freedom, hence the greater the compressibility in the pinch plasma column [14]. The lower atomic number gases (e.g. H₂, D₂, He) are fully ionized in the focus pinch and the dominant radiations are free-free bremsstrahlung. The high atomic number gases such as Ne to Xe are freely ionizing at the temperatures of the plasma focus pinch and emit predominantly line radiation [15]. The line radiation powers are orders of magnitude greater than...
bremssstrahlung power. The analysis [16, 17] shows that the line radiation powers are sufficient to cool the high atomic number pinch to the extent of the radiative collapse. On the other hand, the bremsstrahlung in (low atomic number) pinches is hardly sufficient to affect the pinch dynamics.

To optimise the x-ray yield, changes have been made to capacitor bank parameters including bank inductance and discharge current, electrode material, dimension and form [18, 19], insulator length and material [18], the gas its operational pressure [10]. Such optimizations are important for applications, especially for specialized material fabrication and modification of surface properties [20]. The Lee code combines the actual electric circuit with the effects of DPF dynamics. Its equations incorporate the thermodynamics and in the pinch phase couple to radiation. The code covers a wide range of gases [21]. The self-absorption of the radiation by the volume of the plasma is included to improve the realism of the code when the plasma becomes optically with sufficient density [15, 22].

The code was widely used for the design and understanding of a number of machines including sub-kJ DPF devices [23], kJ machines FNII [24], the UBA [25] hard X-radiation source, the KSU plasma focus [26] and the cascading PF [27]. Information in the output includes trajectories and speeds for the dynamics of the axial and radial phases [28], focus pinch duration and dimensions, pinch properties including densities and temperatures, radiation yields, and characteristics including soft x-ray [28]. The code is used for the systematic optimization of plasma focus devices [28].

In NX2 plasma focus, this code verified the measured values of soft x-ray yield and variation of Ne pressure. The effect of operating pressure on radiation yield for various gases is studied in low-energy DPF device [28, 29]. As a megajoule DPF device, x-ray yield investigations in PF1000 are not very frequent since its prime object is to achieve fast neutron yield [30, 31]. A numerical experiment was performed for Ne gas with pressure variation in PF1000 [32] to find optimum yield conditions. In this present work, we extend the numerical investigation to study the effect of atomic number and P0 on radiations and characteristic soft x-ray in the standard PF1000. Radiation–enhanced compression in the focused plasma are studied in lighter (H2, D2, and He) and heavier (N2, O2, Ne, and Ar) gases through simulation work. The computed properties including pinch current, pinch duration, ion density, specific heat ration, radius ratio (radius of plasma pinch column/anode radius), pinch column length, energy (from capacitor bank) injected into the pinch plasma (EINP), and (PED) are correlated with radiations and characteristic soft x-ray at the optimum P0 for each gas in PF1000. Dividing EINP by the volume of the pinch column, PED is computed. The consequent effects of operating pressure and atomic number on radiations and characteristic soft x-ray emission are then discussed.

This paper is organized as follows: in the next section, we consider the procedure of numerical experiments to calculate x-rays and radiations configuring the Lee code with the standard parameters of PF1000 and the computed results of characteristics soft x-ray including bremsstrahlung radiations for different gases with pressure variation are shown in section 3. In section 4, we discuss our findings, and finally, section 5 concludes the present work.

2. Numerical experiments

2.1. x-ray calculation in the code

The Lee code has been adapted for various gases such as Ar, O2, and N2. Based on the corona model, the relevant temperature ranges (temperature window) for generating He-like and H-like ions in Ne, Ar, N2, and O2 plasmas are 200–500 eV (2.3 × 106 – 5 × 106 K), 1.4–5keV (16.3 × 106 – 58.14 × 106 K), 74–173 eV (0.86 × 106 – 2.01 × 106 K), and 119–260 eV (1.38 × 106 – 3 × 106 K), respectively [32]. The corresponding temperature window for each gas is set so that the PF is operating with the gas ionized to its H-like and He-like levels. Such radiation is referred to be termed the ‘characteristic’ soft x-ray of the particular gas rather than just the soft x-ray. The gas can also radiate soft x-ray outside the window, but the soft x-ray will not be its characteristic soft x-ray; meaning not from H-like and He-like levels. So, in the RADPF5.15 code, the line radiation yield (QL) is computed as the characteristic soft x-ray yield at the corresponding temperature window for each of these gases [32].

The line radiation is computed as follows:

\[
\frac{dQ_L}{dt} = -4.6 \times 10^{-31}N_e^2 Z_{\text{eff}} Z^4(\alpha T_{\text{min}}^2) \frac{Z_{\text{max}}}{T_{\text{max}}}
\]

Where, we take Y_{xxx} = Q_L, by operating in the correct temperature-window according to the gas. The radiation is integrated over the time of the pinch, the soft x-ray energy generated in the pinch depends on: effective ion charge (Z_{\text{eff}}), ion density (N_e) and temperature (T), pinch length (Z_{\text{max}}), and pinch radius, and atomic number (Z). This soft x-ray energy is emitted after reduction by self-absorption of the plasma which has dependence on temperature and density.
### Table 1

At optimum pressure, computed maximum radiation yields for H<sub>2</sub>, D<sub>2</sub>, and He with fixed \( V_0 = 27 \text{ kV}, f_m = 0.13, f_c = 0.7, f_{\text{sc}} = 0.35, \) and \( f_{\text{sc}} = 0.65 \) in PF1000.

| Gas   | \( P_0 \) (Torr) | \( I_{\text{peak}} \) (kA) | \( I_{\text{pinch}} \) (kA) | Pinch dur. (ns) | \( \gamma \) | \( r_{\text{max}}/a \) | \( Z_{\text{max}} \) (cm) | \( Y_{\text{sxr}} \) (J) | EINP \((\times 10^4)\) | PED \((\times 10^4)\) J m\(^{-3}\) |
|-------|-----------------|-----------------|-----------------|-----------------|----------|----------------|-----------------|-----------------|----------------|----------------|
| H<sub>2</sub> | 2.48 | 1609.36 | 737.94 | 177.21 | 1.67 | 0.19 | 18.79 | 0.26 | 4.53 | 1.63 |
| D<sub>2</sub> | 2.49 | 1768.98 | 803.49 | 230.55 | 1.67 | 0.19 | 18.79 | 0.62 | 5.53 | 1.97 |
| He    | 1.48 | 1699.57 | 757.61 | 187.75 | 1.62 | 0.17 | 18.82 | 14  | 5.13 | 2.15 |

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2.2. Configuring the Lee code for PF1000

The code is configured with the capacitor bank characteristics, tube dimensions and operating voltage and pressure of the standard PF1000 [7]:

Bank parameters: Static inductance \((L_0) = 33.5 \text{nH}\), Capacitance \((C_0) = 1332 \mu\text{F}\), Stray circuit resistance \((r_0) = 6.1 \text{m}\Omega\).

Tube parameters: radius of cathode \((b) = 16 \text{ cm}\), radius of anode \((a) = 11.55 \text{ cm}\), length of anode \((z_0) = 60 \text{ cm}\).

Operating parameters: Voltage \((V_0) = 27 \text{ kV}\), pressure \((P_0) = 3.5 \text{Torr}\).

Model (mass swept- up and effective current) parameters: for axial phase, \((f_m) = 0.13, (f_c) = 0.7\) and \((f_{\text{sc}}) = 0.35\) and \((f_{\text{sc}}) = 0.65\) in the radial phase. These model parameters have been obtained by fitting the computed and measured current waveforms at 3.5 Torr D<sub>2</sub> in PF1000 [7]. The experimental current trace for different gases in this device is not available. Though this set of model parameters is expected to vary considerably within a wide range of gases, even in a pressure range for a given gas, these are kept fixed throughout our present series of numerical experiments for different gases [4, 15, 17].

3. Results

3.1. PF1000 with hydrogen, deuterium, and helium

The effects of atomic number and pressure on pinch plasma properties are tabulated (see table 1). We found the temperature of pinch plasmas as \(1.15 \times 10^6 \text{ K}\) at 2.48 Torr H<sub>2</sub>, \(1.36 \times 10^6 \text{ K}\) at 2.49 Torr D<sub>2</sub>, and \(2.20 \times 10^6 \text{ K}\) at 1.48 Torr He. Since, H<sub>2</sub>, D<sub>2</sub>, and He are fully ionized in the PF pinch and hence the radiations for them are completely bremsstrahlung \((Y_{\text{sxr}})\).

The bremsstrahlung radiation from He plasma \((14 \text{ J})\) at optimum pressure of 1.48 Torr is considerably higher than from H<sub>2</sub> \((0.26 \text{ J})\) and D<sub>2</sub> \((0.62 \text{ J})\). This is because of the increased compression and the lower specific heat ratio in He. In He pinch plasma, (see table 1) the lesser values of \(r_{\text{min}}/a\) \((\sim 0.17)\), \(\gamma\) \((\sim 1.62)\) and larger \(Z_{\text{max}}\) \((\sim 18.82 \text{ cm})\), PED \((\sim 2.15 \times 10^4 \text{ Jm}^{-3})\) produce larger values of bremsstrahlung radiation in H<sub>2</sub> and D<sub>2</sub> plasmas.

3.2. PF1000 with nitrogen, oxygen, neon, and argon

The computed maximum characteristic soft x-ray yields and pinch properties at optimum pressure for N<sub>2</sub>, O<sub>2</sub>, Ne, and Ar gases are recorded (see table 2). The operating pressure was varied in the range of 0.01 to 2.5 Torr. Through a series of numerical experiments, the obtained optimum pressure for each gas at which the maximum characteristic soft x-ray is presented here.

The computed total discharge currents rise to the peak values of 1978 kA at 6.60 \(\mu\text{s}\), 1906.4 kA at 6.48 \(\mu\text{s}\), 1773.5 kA at 6.23 \(\mu\text{s}\), and 1145.1 kA at 3.29 \(\mu\text{s}\) for N<sub>2</sub>, O<sub>2</sub>, Ne, and Ar, respectively (see figure 1). The current peaks come earlier and are lower because the dynamic loads \((0.5 \times dL/dt = 10^{-7} \times \ln (b/a) \times \text{axial speed})\) added in the circuit due to their axial motion of the current sheath. The peak axial current sheath speeds of N<sub>2</sub>, O<sub>2</sub>, Ne, and Ar are found 8.8 cm \(\mu\text{s}^{-1}\), 10.0 cm \(\mu\text{s}^{-1}\), 12.5 cm \(\mu\text{s}^{-1}\), and 28.2 cm \(\mu\text{s}^{-1}\), respectively (see table 2). Also, the pinch currents decreases and the dips arise earlier (see figure 1) due to the larger radial dynamic loads with higher magnetic piston speeds for high atomic number gases (see table 2).

Figures 2(a)–(d) show computed dynamics of the radial phases of the PF1000 at 27 kV, 0.93 Torr N<sub>2</sub>, 0.58 Torr O<sub>2</sub>, 0.51 Torr Ne, and 0.019 Torr Ar, respectively. The piston trajectories delineate the pinch radius after the reflected shock hits the piston. The pinch last 285.5 ns, 284.1 ns, 229.1 ns, and 81.1 ns in compressed N<sub>2</sub>, O<sub>2</sub>, Ne, and Ar plasmas, respectively. The code computes the radial trajectories and the minimum pinch radius is obtained. In the present numerical studies, the computed minimum pinch radii are 1.25 cm for N<sub>2</sub>, 0.83 cm for O<sub>2</sub>, 0.61 cm for Ne, and 1.82 for Ar which is marked by red arrows in figure 2.

In our optimization, we considered \(Q_L = Y_{\text{sxr}}\) within the corresponding temperature window for N<sub>2</sub>, O<sub>2</sub>, Ne, and Ar. The maximum characteristic soft x-ray for high atomic number gas is found at lower pressure compared to that of lighter gas (see figure 3). In this study, the maximum characteristic soft x-ray yield \((\sim 9314 \text{ J})\) is obtained.
Table 2. At optimum pressure, computed maximum characteristic soft x-ray yields for N2, O2, Ne, and Ar with fixed $V_0 = 27$ kV, $f_m = 0.13$, $f_e = 0.7$, $f_{mr} = 0.35$, and $f_{cr} = 0.65$ in PF1000.

| Gas | Tem. window (× 10^6 K) | $P_0$ (Torr) | $I_{peak}$ (kA) | $I_{pinch}$ (kA) | $v_s$ (cm/μs) | $v_p$ (cm/μs) | $v_e$ (cm/μs) | $r_{min}/a(k_{min})$ | $N_i (× 10^{23}/m^3)$ | Vmax (kV) | PED (×10^8 Jm⁻³) | $Y_{sxr}$ (J) |
|-----|------------------------|-------------|-----------------|------------------|--------------|--------------|--------------|---------------------|------------------|-----------|------------------|----------|
| N₂  | 0.86–2.01              | 0.93        | 1978.0          | 795.5            | 8.8          | 9.6          | 13.6         | 0.11                | 3.29             | 47.53     | 7.7              | 3879.93  |
| O₂  | 1.38–3.02              | 0.58        | 1906.4          | 766.3            | 10.0         | 12.3         | 18.1         | 0.07                | 4.69             | 60.86     | 16.2             | 6229.51  |
| Ne  | 2.32–5.80              | 0.51        | 1773.5          | 734.9            | 12.5         | 15.7         | 23.4         | 0.05                | 7.59             | 103.71    | 26.0             | 9314     |
| Ar  | 16.24–58.0             | 0.019       | 1145.1          | 504.5            | 28.2         | 35.9         | 50.5         | 0.16                | 0.03             | 96.57     | 1.2              | 6.69     |
at $P_0 \sim 0.51$ Torr Ne with consequent pinch temperature $T_{\text{pinch}} \sim 2.46 \times 10^6$ K and shock speed, $v_s \sim 23.4$ cm $\mu$s$^{-1}$.

Whilst for Ar, it requires much higher pinch temperature ($\sim 16.5 \times 10^6$ K) to reach its optimum characteristic soft x-ray emission regime since need to reach the 16th and 17th ionized level. That’s why we need to go to such low pressure ($\sim 0.019$ Torr) so as to get to high shock speeds ($\sim 50.5$ cm $\mu$s$^{-1}$). But such high temperature gives low overall line radiation ($\sim 6.69$ J) in Ar, particularly when we need to go to such low

**Figure 1.** Computed total discharge current waveforms with time at corresponding optimum pressure of 0.93 Torr N$_2$, 0.58 Torr O$_2$, 0.51 Torr Ne, and 0.019 Torr Ar filling gases at 27 kV of the PF1000.

**Figure 2.** (a) Radial Trajectories at 0.93 Torr N$_2$, (b) Radial Trajectories at 0.58 Torr O$_2$, (c) Radial Trajectories at 0.51 Torr Ne, and (d) Radial Trajectories at 0.019 Torr Ar.
pressures. So, operating PF in Ar to radiate its characteristic soft x-ray is not conducive to much radiation and we do not get radiative collapse, not even radiative cooling.

When we find Ar data over a range of pressures (~0.1–0.35 Torr) there is immense line radiation (~21780 J at 0.14 Torr, \(r_{\text{min}}/a \approx 0.009\), \(T_{\text{pinch}} \sim 5 \times 10^6\) K (NOT characteristic radiation) and that is the range when radiative effects on dynamics including radiation collapse is observed in Ar. It was found for N$_2$, O$_2$, and Ne (see table 2), a smaller radius ratio than typical and that is radiation enhancing compression (also to lesser expect \(\gamma\) effects). Especially Ne, we are close to its most compressed state due to radiative enhancement of compression.

Figure 4 shows the optimum characteristic soft x-ray yield increases with the high atomic number up to Ne\((Z = 10)\) and then reduces drastically for Ar\((Z = 18)\). The optimum characteristic soft x-ray yield for Ne\((\sim 9314\) J) was the highest whilst it was minimum in Ar\((\sim 6.69\) J).

Through a series of numerical experiments, we find an inequality relation in radius ratio \((k = r_{\text{min}}/a)\):
\[k_{\text{min}}(\text{Ar}) > k_{\text{min}}(\text{N}_2) > k_{\text{min}}(\text{O}_2) > k_{\text{min}}(\text{Ne})\]. It is clear that a reduction in the specific heat ratio leads to a corresponding reduction in the radius ratio. This reduction in \(k_{\text{min}}\) leads to an increase in the characteristic soft x-ray emission. Within the corresponding temperature window, the \(\gamma(\text{Ne}) \sim 1.49\), the \(r_{\text{min}}(\text{Ne}) \sim 0.61\) cm gives \(k_{\text{min}} \sim 0.05\) at optimum \(P_0 = 0.51\) Torr whereas the \(\gamma(\text{Ar}) \sim 1.57\), the \(r_{\text{min}}(\text{Ar})\) of 1.82 cm, \(k_{\text{min}} \sim 0.16\) and at optimum \(P_0 = 0.019\) Torr. The \(k_{\text{min}}(\text{Ne})\) is a more than 3-fold reduction from \(k_{\text{min}}(\text{Ar})\) gives an increase in plasma density \(N_{\text{e}}(\text{Ne}) = 7.59 \times 10^{23}\) m$^{-3}$ to \(N_{\text{e}}(\text{Ar}) = 0.03 \times 10^{23}\) m$^{-3}$; an increase in pinch density by 253 times. This enhanced pinch density is conducive to greater production of characteristic soft x-ray yield in Ne from Ar.
In the notation of the code, AB (self-absorption correction factor) = 1 when self-absorption is zero. When AB reaches 1/e, meaning substantial self-absorption of its emission, the radiation mode is considered to transition from volume to surface radiation [17]. We find within the temperature regime, $Z_{\text{eff}} = 16$ consequently AB(Ar) $\sim 1.0$ and in the case of Ne, $Z_{\text{eff}} = 8.2$ consequently AB(Ne) $\sim 0.98$. This higher value of AB(Ar) reduces its characteristic soft x-ray emission from other gases Ne.

It is found the PED and $V_{\text{max}}$ increase gradually from $N_2$ (PED $\sim 7.7 \times 10^8$ J m$^{-3}$, $V_{\text{max}} \sim 47.53$ kV) to Ne (PED $\sim 26 \times 10^8$ J m$^{-3}$, $V_{\text{max}} \sim 103.71$ kV) and then reduce in Ar (PED $\sim 1.2 \times 10^8$ J m$^{-3}$, $V_{\text{max}} \sim 96.57$ kV).

4. Discussions

The energy and intensity of radiations in a DPF device can be controlled by experimental conditions that include operating energy, electric current, electrode geometry, type of gas, and pressure. The lighter gases, H$_2$ and D$_2$ are fully ionized at 0.464 $\times$ 10$^5$ K (40 eV) and He is fully ionized at 1.856 $\times$ 10$^5$ K (160 eV) [2]. In this present paper, the pinch plasma temperatures are found as 1.15 $\times$ 10$^5$ K, 1.36 $\times$ 10$^5$ K, and 2.20 $\times$ 10$^5$ K for H$_2$, D$_2$, and He, respectively. Here, all the obtained temperatures are within the range of fully ionization temperature and hence the radiations for these gases are completely bremsstrahlung. This study presents that the optimum bremsstrahlung radiation increases with high atomic number gases.

In the energy range of 0.7–15 keV, the time-resolved soft x-ray signals (not absolute yield) were measured by Si-PIN detector from PF1000 device operating with pure Ne in the injection of D$_2$ and without puffing D$_2$ [33]. It was observed that the soft x-ray emission decreases considerably from this device in operation with Ne without injection of D$_2$. Also, the soft x-ray emission from this PF1000 device was studied operating with D$_2$ and puffing Ne and the intense soft x-ray emission was measured in presence of Ne at the central region of the pinch [34]. However, no quantitative measurement of soft x-ray yield from PF1000 is available for Ne and other gases.

The radiation that come from H-like and He-like ions of an atom is equivalent to K-shell radiation ($Y_k$) or characteristics soft x-ray. In Z-pinch, K-shell radiation yield follows the scaling law as $Y_k \sim I_{\text{peak}}^f$ for low current and $Y_k \sim I_{\text{peak}}^f$ for high current [35, 36], whilst in PF-pinch, it follows the scaling law as $Y_{\text{oxr}} \sim I_{\text{peak}}^f$ for low 0.1 to 2.4 MA current [37]. Also, experimentally it is observed that the K-shell radiation from the Z-pinch increases with decreasing pinch radius along with increasing peak current [37]. In our numerical studies using Lee code, we also found a similar trend in dependency of characteristic soft x-ray yield on peak discharge current as well as pinch radius. For example, in Z-pinch with argon gas it was experimentally measured that $Y_k = 440$ J with $I_{\text{peak}} = 1600$ kA and $r_{\text{min}} = 0.17$ cm [38], whilst in our numerical studies we obtained that $Y_k = 6.69$ J with $I_{\text{peak}} = 1145$ kA and $r_{\text{min}} = 1.82$ cm for argon gas. Here, the peak discharge current of our studies is lower (~455 kA), whilst the pinch radius is very high (~1.65 cm) compared to the K-shell radiation in Z-pinch [38]. Due to these lower peak current and larger pinch radius, our optimum $Y_k$ with argon is too smaller than that from Z-pinch. Again, for neon gas K-shell radiation from Z-pinch plasma has been measured as [39]: $Y_k = 4000$ J with $I_{\text{peak}} = 1450$ kA and $r_{\text{min}} < 0.2$ cm whilst in our numerical studies we obtained as $Y_k = 9314$ J with $I_{\text{peak}} = 1773.5$ kA and $r_{\text{min}} = 0.61$ cm. Here, the peak discharge current of our studies is higher (~323.5 kA) though the pinch radius is slightly higher (~0.41 cm) compared to those of K-shell radiation in Z-pinch [39]. In addition, experimentally it was observed that the K-shell radiation yield for argon was 800–1000 J whilst for neon it was 4000–5000 J from the same Z-pinch plasma system [40]. That means the H-like and He-like radiations for neon are higher than that of argon which is similar in nature to our numerical studies. For the other two gases (nitrogen and oxygen) the variation trend of soft x-ray yield with peak current and pinch radius like K-shell radiations in Z-pinch. Therefore, we may conclude that our computed results are justified with those from Z-pinch.

By comparing our results of numerical simulation with the research results [4, 32], both the characteristics soft x-ray and PED increase with the increase in atomic number ($N_2$, O$_2$, and Ne) of used gases due to two factors: radius ratio and the effective ion charge while in our study we continue the increase in atomic number (Ar) of gas. We also focus on the effect of induced voltage, absorption correction factor, and ion density on the characteristics soft x-ray as it is found that both $Y_{\text{oxr}}$ and PED increase for high atomic number gases ($N_2$, O$_2$, and Ne) and then sharply reduce for Ar gas because the radius ratio and hence the number of ions inside the pinch of Ar plasma reduces significantly.

5. Conclusion

In this paper, the effect of atomic number and pressure on pinch properties, characteristic soft x-ray (for $N_2$, O$_2$, Ne, and Ar) and bremsstrahlung (for H$_2$, D$_2$, and He) radiations are studied using the modified Lee code in PF1000. The results show the optimum characteristic soft x-ray emission for high atomic number gas is obtained at lower pressure with high pinch temperature. A large enhancement of soft x-ray yield within the temperature window is found when the radius ratio could be reduced to a small value. In these present numerical studies, the
emission of the optimum characteristic soft x-ray increases from 3879.93 J (N₂) to 9314 J (Ne) then drastically falls to 6.69 J (Ar).

Also, the various pinch properties are obtained for Ne: \( k_{\text{min}} \approx 0.05 \), \( \gamma \approx 1.49 \), \( N_0 \approx 7.59 \times 10^{23} \text{ m}^{-3} \), PED \( \sim 26 \times 10^{6} \text{ J m}^{-3} \), \( V_{\text{max}} \approx 103.71 \text{ kV} \), and AB \( \sim 0.98 \) at optimum \( P_0 = 0.51 \text{ Torr} \) whilst for Ar: \( k_{\text{min}} \approx 0.16 \), \( \gamma \approx 1.57 \), \( N_0 \approx 0.03 \times 10^{23} \text{ m}^{-3} \), PED \( \sim 1.2 \times 10^{6} \text{ J m}^{-3} \), AB \( \sim 1.0 \) at optimum \( P_0 = 0.019 \text{ Torr} \). The Ar plasma pinch temperature is noticed too high \( \sim 16.5 \times 10^4 \text{ K} \) to reach its optimum characteristic soft x-ray (H-like and He-like) emission regime at very low pressure to get too high shock speeds \( \sim 50.5 \text{ cm s}^{-1} \).

The pinch temperatures of \( \text{H}_2, \text{D}_2, \) and He plasmas are found to be sufficiently high for fully ionized plasmas and emit completely bremsstrahlung radiations. The radiation from He plasma \( (14 \text{ J}) \) at optimum pressure of 1.48 Torr is considerably higher than from \( \text{H}_2 \) \( (0.26 \text{ J}) \) and \( \text{D}_2 \) \( (0.62 \text{ J}) \).

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Conflicts of Interest

On behalf of all authors, I, the corresponding author declare that there is no conflict of interest.

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