Influence of Electrical Properties on Radiation and Emission to Pinch Radius Thermal Plasma Device

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Abstract. Plasma focus (PF) generation has advanced the development of high-density, high-temperature plasma that emits intense radiation. The radiation output and emission spectra depend on the operating parameters of the PF device. The ability to focus plasma governs the pinch radius and electrical properties at the truncated end of the PF device. In this study, the simulation system RADPF 5.15 FIB was used to investigate the pinching properties of the neon ion beam generated using an AECS PF-1 device. The pinch radius was the dominant factor affecting the current density produced.

1. Introduction
Over the last two decades, plasma focus (PF) devices have advanced the development of energy systems by producing a strong interaction between electrons and ions in the plasma. Moreover, PF is known as a clean, safe and sustainable energy source [1]. Thus, there have been many experimental and numerical studies on fundamentals, diagnostics and simulations of PF. These studies have reported on the system set-up, dynamics of radiation, radiative collapse and industrial applications of PF [2], including coating technology [3], ion implantation [4], material technology [5,6], microelectronic lithography [7] and medical devices [8].

PF system dynamics can be optimised to produce an ion beam suitable for a wide range of applications. For medical devices, the ion beam was tailored to penetrate the body to a certain depth, quickly release high energy to the surrounding area, and then extinguish [8]. The ion beam can be adjusted so that less energy is dissipated, and intense energy is released over a localized area. Research has shown that the ion beam can deliver radiation to a cancerous focal point, achieving better treatment results than X-ray therapy [8]. In traditional therapy, side effects are related to the field of irradiation, with a wider (narrower) field resulting in more severe (milder) side effects. The PF ion beam minimises side effects by delivering radiation to a highly focussed area.

PF devices are well recognized as ion beam sources that produce characteristic radiation already used in numerous applications. These devices use the principles of electromagnetic compression and confinement, in which the Lorentz force acts on electrical current flowing in the plasma. If the magnetic pressure exceeds the pressure of the particle, a focusing effect known as pinch
occurs [9]. High-quality focus emits intense pinch radiation, as illustrated in Fig. 1. PF devices have been shown to produce energetic ion beam emission. This study aimed to observe and report data on the pinch radius profiles and their relationship to current density. This information would be a significant contribution to the advancement of medical applications.

Figure 1. Schematic of radiation from the plasma focus (PF) device.

Bhuyan [10] characterized a neon ion beam using a 2.2-kJ Mather-type PF powered by a 7.1-μF high-energy storage capacitor with a charging voltage of 25 kV. In that study, neon ion beam emission was highly dependent on pressure. The optimal pressure of 0.3 Torr resulted in beam energy that ranged from 18 to 1000 keV. The maximum ion density was achieved at $5 \times 10^{19} \text{m}^{-3}$, and higher ion populations occurred below 180 keV. A pressure of 0.3 Torr is sufficient for PF discharge dynamics that produce strong pinching. At this pressure, the maximum current discharge was achieved, thus transferring maximum energy to the plasma. Increasing the pressure above 0.3 Torr decreased the current sheath velocity due to a greater sheath mass; thus, the focusing was weaker, and the ion beam emission was less intense.

2. Theoretical Consideration: Electrical Discharge and Pinch Radius Profiles

It is important to understand the production of the ion beam to characterise the properties of the ions emitted from PF devices. A plasma diode is located at the instant acceleration gap (Fig. 2), where a beam of fast deuterons is generated by the diode. The beam interacts with the hot, dense plasma of the focus pinch column, producing fusion neutrons. According to Gribkov [6], the ion beam can be described by calculating the neutron yield, $Y_n$.

$$Y_n = Y_{n-1} = C_n n_i I_{\text{pinch}}^2 \left( \ln \left( \frac{b}{r_p} \right) \right) \sigma / \sqrt{U}$$

The calibration constant for the neutron is $C_n = 8.54 \times 10^8$. This constant was obtained from a graph of all available measured $Y_n$ data at an experimental point of 0.5 MA. $n_i$ is the pinch ion density, $I_{\text{pinch}}$ is the current through the pinch, $r_p$ and $z_p$ are the final pinch radius and length, respectively, $b$ is the cathode radius, $r_p$ is the cross-section of the D–D fusion reaction branch, and $U$ is the disruption-induced diode voltage [12]. Instabilities during pinching cause a strong electric field and accelerate the ion beam. Lee [13] defined the beam passing through a plasma target as having a cross-section equal to the reaction rate (i.e. beam ion number flux times number of target particles). Thus, by the definition of the beam cross-section, Equation 1 can be rewritten as

$$Y_{b-1} = (n_i) \left[ n_i \pi r_p^2 z_p \right] \sigma = (J_b \pi \sigma) \pi r_p^2 z_p$$
From Equations 1 and 2, the beam kinetic energy and pinch inductive energy can be used to determine the number of beam ions per unit plasma volume traversed, $n_b$, and the beam ion speed, $v_b$. These parameters are represented by Equations 3 and 4 [11].

\[
\begin{align*}
    n_b &= \frac{N_b}{\pi r_{p,\text{pinch}}^2 z_p} \left( \frac{\mu f_e}{2\pi^2 m_p M} \right) \left( \frac{\ln(b / r_p) I_{\text{pinch}}^2}{r_p^2 v_b^2} \right) \\
    v_b &= \left( \frac{2eZ_{\text{eff}} U}{m_p M} \right)^{1/2}
\end{align*}
\]  

Equations 3 and 4 are discussed using neon gas properties. The interrelation of beam kinetic energy and pinch inductive energy are governed by $f_e$, the fraction of energy converted from pinch inductive energy to beam kinetic energy. These equations also include the effective charge, $Z_{\text{eff}}$, mass number, $M$, mass of a proton, $m_p$, charge of an electron, $e$, and diode voltage, $U$. For neon, the mass number of an ion is 20, and $m_p$ is $1.673 \times 10^{-27}$ kg. Lee [11] performed extensive data fitting to equate diode voltage and maximum induced voltage of the pre-pinch radial phase, $U = V_{\text{max}}$. The number of beam ions, $n_b$, and the beam ion speed, $v_b$, are well characterized; thus, these properties can be correlated to give the definition of ion beam flux, $J_b$. Equations 3 and 4 are combined to give Equation 5, where $J_b$ has units of current density for quantity of ions m$^{-2}$s$^{-1}$.

\[
J_b = n_b v_b
\]  

The ion beam cross-section is similar to that of the pinch, with a small divergence of about $3^\circ$. The narrow beam exits along the pinch axis and is considered the post-pinch of a shock wave. This estimation of the plasma at the exit point allows the ion beam to be characterized by the number of ions per unit cross-section, described by the flux, $J_b$, and fluence, $J_b \tau$ [11–13].

\[
\begin{align*}
    J_b &= (2.75 \times 10^{15}) \left( \frac{f_e}{MZ_{\text{eff}}} \right)^{1/2} \left( \frac{\ln(b / r_p) I_{\text{pinch}}^2}{r_p^2 \sqrt{U}} \right) \\
    J_b \tau &= (2.75 \times 10^{15}) \left( \frac{f_e}{MZ_{\text{eff}}} \right)^{1/2} \left( \frac{\ln(b / r_p) I_{\text{pinch}}^2}{r_p^2 \sqrt{U}} \right) \tau
\end{align*}
\]
3. Methodology

Neon was used in the RADPF5.15 FIB with an AECS PF-1 as the working chamber. The PF device configuration is described in Table 1. The current densities and pinch radius were plotted against pressure. Four applied voltage values were used: 14, 15, 16 and 17 kV. The discharge current signal comprises the system dynamics and the information on properties of multi-radiation, so, it was identified as the points of reference. The profiles of the discharged currents start from the breakdown phase until the end of pinch phase; and along the phases, it will signify the Joule heating, radiative emissions, and the expended column current flow that abruptly transited from the narrow pinch. In instance, when the computed current profile was fitted with the measured current profile, the system ready to be run for detailed experimental calibration. The numerical experiments conducted gives significant pattern on the results in the RADPF5.15 FIB. The data obtained were then accumulated by using Microsoft visual basic.

| Table 1. Plasma focus device configuration used in the RADPF 5.15 FIB simulation |
| PF Device Parameter | AECS PF-1 |
|---------------------|----------|
| Energy, E (kJ)      | 2.8      |
| Voltage, V (kV)     | 13–17    |
| Inductance, L₀ (nH) | 1600     |
| Capacitor, C₀ (µF)  | 25       |
| Resistance, r₀ (mΩ) | 77       |
| Cathode radius, b (cm) | 3.2     |
| Anode radius, a (cm) | 0.95    |
| Length of anode, z₀ (cm) | 16      |

![Figure 3](image-url) Correlation between current density and pinch radius in a neon-filled chamber

4. Results and Discussion

The current densities and pinch radius correlated closely. The pinch radius reached a maximum when the current density was at its minimum. This was true for all the applied voltages used in the system. The smallest pinch radius for an applied voltage of 14 kV was 0.7 mm (0.5 Torr), resulting in the
highest current density of $1.7 \times 10^9$ Am$^{-2}$. However, at 0.85 Torr, the pinch radius increased rapidly, causing the current density to decrease. The smallest pinch radius for an applied voltage of 15 kV was 0.7 mm (0.6 Torr), and the current density was $2.0 \times 10^9$ Am$^{-2}$. At 16 and 17 kV, the pinch radius was also 0.7 mm, and the current density was $2.1 \times 10^9$ and $2.4 \times 10^9$ Am$^{-2}$, respectively. Interestingly, the smallest pinch radius for all the applied voltages was 0.7 mm. The current density varied with pressure and applied voltage. These results indicate that energy savings can be achieved by operating at lower voltages. In other words, there is no need to use a higher voltage when the same pinch radius occurs at a lower voltage.

![Figure 4](image)

**Figure 4** Correlation between current density and applied voltage at three pinch radius values for the neon-filled chamber of an AECS PF-1 device

To obtain a better understanding of the current density behaviour, the data for current density and pinch radius were correlated for applied voltages of 14–17 kV. The tabulated data show a clear trend of decreasing current density with increasing pinch radius (Fig. 3). It is notable that current density was fairly consistent at a given pinch radius, even for different applied voltages. Thus, it was expected that pinch radius would significantly affect current density, and the applied voltage can be used to optimise the pinching phenomenon. The pinch radius was observed for the AECS PF-1 operated with Neon (Fig. 4).

The results show that the variation in current density was small over the applied voltage range, for all of the selected pinch radius values. Thus, pinch radius can be used to achieve the desired current density, regardless of the applied voltage. These results also confirm that Lee’s model can successfully simulate ion beam dynamics in an AECS PF-1 device.

5. Conclusion

The numerical simulation method using Lee’s code is an effective tool for investigating electrical discharge properties in PF devices based on theoretical calculations. RADPF5.515 FIB showed considerable variation in ion beam behaviour as a function of pressure, as evidenced by the range of pinch radius values produced under various conditions. The numerical data obtained for the AECS PF-1 system provide insight into the correlation between pinch radius and current density.
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