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Correlation of Pinch Properties with Minimum Pinch Radius in UNU/ICTP PFF for Different Pressure of Argon Gas

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ABSTRACT

In this present work, numerical experiments are performed using the Lee code to examine the correlation of minimum pinch radius (r_{min}) with pinch energy density (PED), ion number density (N_i), induced voltage (V_{max}), total radiation power (P_{rad}), and Joule heating power (P_{joule}) in UNU/ICTP PFF device when using argon gas at different pressure. The computed results show that at the optimum pressure of 1.0 Torr argon, PED (338×10^9 Jm^{-3}), N_i (123×10^{23} /m^3), V_{max} (245 kV), P_{joule} (114.48×10^8 W), and P_{rad} (173×10^8 W) reach to their maximum values whilst the r_{min} reaches to its lowest value of 0.01 cm. At this optimum condition, the strong radiation cooling effect is found and the excess (P_{joule} - P_{rad}) in radiative power of -58.51 $\times 10^8$ W (negative singe indicates the energy going out from pinch plasma) which is sufficiently enough to cause the radiative collapse in heavier argon pinch plasma. Hence, the excess radiation power would be another reason for the occurrence of radiative collapse beside the critical (Pease-Braginskii) current. The variation nature of pinch properties of this studies are compared with those of PF1000 plasma focus device that makes the consistent of the present research work.

Key words: Joule heating power, Lee code, Pinch radius, Plasma focus, Radiation power.

1. INTRODUCTION

A plasma focus (PF) is a system of generating high-dense and super-hot pulsed plasma through electric discharge into a co-axial electrodes (cathode and anode) separated by an insulator within an enclosed gas chamber powered by a high voltage capacitor bank (Lee et al., 2009). In 1960s, the model of PF was invented by Mather in USA (Mather, 1964) and Filippov in USSR (Filippov et. al., 1962). This device has a wide range of real life applications as a non-radioactive source of fusion neutron (~2.45-14 MeV) (Niranjan et al., 2018), soft (~ 0.1-10 keV) (Beg et al., 2000) and hard (~10-1000 keV) X-rays (Knoblauch et. al., 2018), ion beam (~0.01-100 MeV) (mohammadreza Seyedhabashi et al., 2019), and electron beam (~0.01–1 MeV) (Wang et al., 2008). Hence, active research and studies have been conducted on the effects of focus dynamics on neutron and X-ray yield, ion and electron beams emission for various gases in PF device. The formation and acceleration of plasma sheath (Habibi et al., 2010), the features of affecting discharge current and pinch current (El-Sayed et al., 2019), the sleeve length of electrodes separating the insulator (Lee and Saw, 2008), anode and cathode configurations (Koohestani et al., 2021), and filling gas types and pressures (Zulkiplee et al., 2021) are included in focus dynamics. The plasma pinch properties such as pinch length, radius, temperature, ion density, and pinch duration are directly influenced by the focus dynamics. Consequently, Joule heating and the radiations along with particles emission from pinched plasma in PF are strongly correlated with these pinch properties.

Due to electromagnetic compression pinch plasmas are staging onto the anode top producing high dense and hot plasma for very short time (few ns) which is the source of radiations (line and continuum radiations). Its collapse for instabilities leads to formation of accelerated electrons and ions beam in opposite directions for voltage works on the plasma pinch column. During this compression, plasma gains internal energy from Joule heating, requiring a bigger equilibrium radius of pinch column whilst it loses energy through radiations (line and bremsstrahlung) emission oppose this trend (Lee et al., 2015). The radiation power may exceed the power of Joule heating depending on various operating parameters especially discharge current and excess radiation power. In such condition, the magnetic piston produced by electric current continuously exerts a squeezing (pinching) force in radially inward direction whilst the excess radiation power (the total radiation power lose minus the Joule heating power gain) reduces the kinetic pressure (resisting) force. If this cooling effect due to radiation power is sufficiently large, then it leads to a very sharp drop in pinch radius (principal sign of radiative collapse) and it might be a very far lesser than envisaged in the case of just the electromagnetic compression (pinch) (Lee et al., 2015). The plasma density increases with decreasing pinch radius whilst the temperature drops due to radiation emission and hence, plasma self-absorption sets a limit of radiation and the radiation collapse will stop (Robson, 1989). This procedure places a lower limit of the plasma pinch radius in a PF.

The radial trajectories and tube voltage, pinch temperature, radiations, and ion density for different pressure were studied numerically including and excluding self-absorption term for argon, krypton, and xenon gases (Akel & Lee, 2013). The soft X-ray yield, pinch energy density (stored capacitor energy injected into the pinch column divided by its volume), and minimum pinch radius were correlated with pressure variation in PF1000 for nitrogen and oxygen gases using Lee code (Akel et al. 2017).

In this paper, we extend the study and obtain the correlation of minimum pinch radius with pinch energy density, maximum induced voltage, Joule heating power, and radiation power at different argon gas pressure through numerical experiments using the Lee code in UNU/ICTP PFF device. The radiative cooling and collapse is also consider here for this heavier gas.

2. WORKING PROCEDURE

2.1 UNU/ICTP PFF PLASMA FOCUS

The UNU/ICTP PFF (United Nations University/International Center for Theoritical Physics Plasma Fusion Facility) is a 3.3 kJ small PF device driven by a single 15 kV, 30 μF Maxwell capacitor bank which is switched by a simple parallel plate swinging cascade air gap. The UNU/ICTP PFF devise is designed and constructed for teaching plasma dynamics and nuclear fusion especially for developing countries where such facilities are rarely available (Lee et al., 1998).

2.2 THE LEE CODE

The electrical circuit and plasma focus dynamics, thermodynamics, radiations are linked by the Lee code. It can be used in experimental interpretation and design of a Mather-type plasma focus (Lee et al., 1988). The plasma sheath speeds in axial and radial phases, pinch duration and dimensions (pinch length and radius), pinch plasma temperature and density are traced out from the simulation with this code. It enables to compute and optimize realistic neutron and radiation yields, ion beam fluence, flux, and energy for various gas compositions at various pressure in a PF. This code is one of the famous programmes to explain the experimental results and design of a new plasma focus device. In this present studies, we configure the code with the standard parameters of UNU/ICTP PFF (Table 1).

Table 1 The device parameters of the standard UNU/ICTP PFF filling with argon at 1.4 Torr.

Bank parameters:	Static inductance (L_0)	110 nH
	Capacitance (C_0)	30 μF
	Stray resistance (r_0)	12 mΩ
Tube parameters:	Cathode radius (b)	3.2 cm
	Anode radius (a)	0.95 cm
	Anode length (z_0)	16 cm
Operating parameters:	Charging voltage (V_0)	14 kV
	Gas pressures (P_0)	1.4 Torr
Model parameters:	Mass swept- up factor axial phase (f_m)	0.05
	Effective current factor axial phase (f_c)	0.7
	Mass swept- up factor radial phase (f_{mr})	0.22
	Effective current factor radial phase (f_{cr})	0.7

By matching the computed current wave trace with the measured one, the mentioned model parameters have been obtained at 1.4 Torr argon in UNU/ICTP PFF (Lee, 2011). Though, these model parameters may varied slightly with pressure change for a given gas (Al-Hawat et al., 2012), they are kept unchanged in our present numerical studies for argon gas. The following power equations are considered in the Lee code to compute the total radiation power (line, bremsstrahlung, and radiative recombination) and Joule heating power (all quantities in SI units unless otherwise stated):

Bremsstrahlung radiation power (P_{br}):

$$P_{br} = -1.6 \times 10^{-40} N_i^2 Z_{eff}^3 (\pi r_{min}^2) Z_{max} T^{0.5} \quad (1)$$

Line radiation power (P_{ln}):

$$P_{ln} = -5.92 \times 10^{-35} N_i^2 Z_{eff}^5 (\pi r_{min}^2) Z_{max} / T^{0.5} \quad (2)$$

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Radiative recombination power (P_{rec}):

$$P_{rec} = -4.6 \times 10^{-31} N_i^2 Z_{eff} Z_n^4 (\pi r_{min}^2) Z_{max}/T \quad (3)$$

Total radiation power (P_{rad}):

$$P_{rad} = P_{rec} + P_{ln} + P_{rec} \quad (4)$$

Joule heating power (P_{joule}):

$$P_{joule} = 1300 \times \frac{Z_{eff} \times Z_{max}}{\pi r_{min}^2} I^2\, T^{-1.5} \quad (5)$$

Where, number density of ion (N_i), effective charge number (Z_{eff}), atomic number of gas (Z_n), minimum pinch column radius (r_{min}), pinch column length (Z_{max}), pinch plasma temperature (T), pinch current (I) are strongly correlated with plasma emission in a PF device.

3. RESULTS AND DISCUSSION

The discharge current trace is one of the most significant indicators to simulate and analyze the gross performance of a plasma focus.

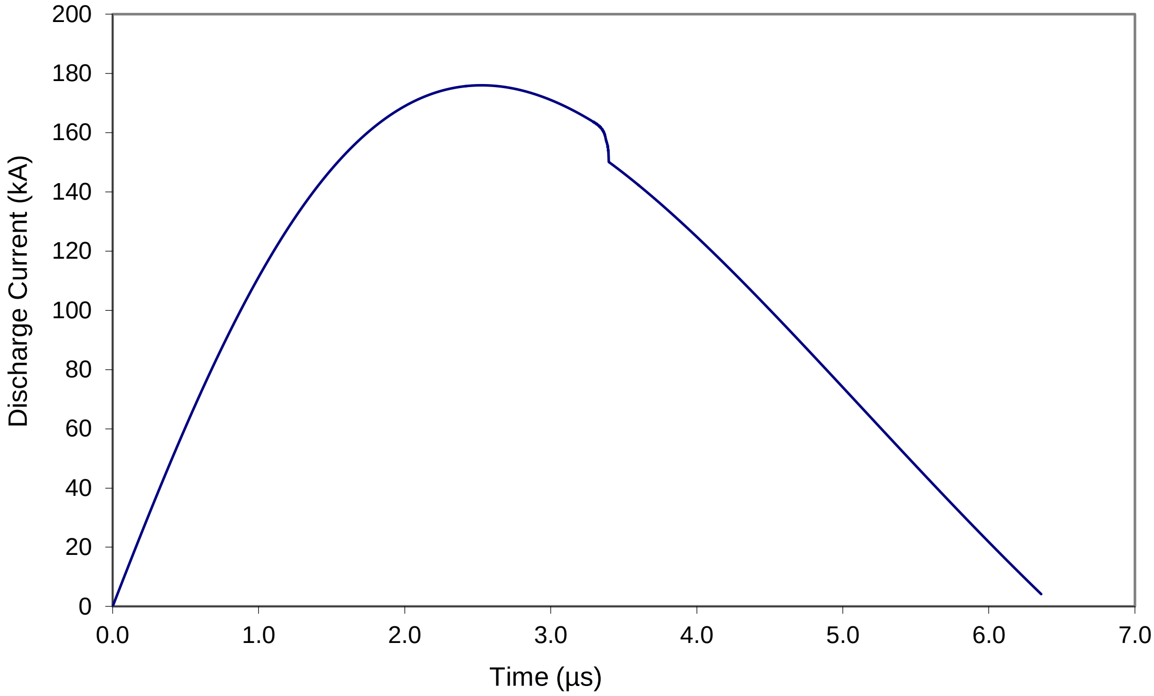

Fig. 1: The discharge current waveform at 1.0 Torr argon gas.

The axial and radial phase dynamics, thermodynamics, electrodynamics, and radiation emission in a PF can be traced out quickly from the discharge current flow through the plasma sheath (Lee, 2014). Using the Lee code, when the computed discharge current waveform is fitted with the measured one, the computed outputs of the code provide the realistic data of the dynamics and energy in each phases, geometry of pinch column, densities, and temperatures, radiations, neutron yields, and ion beam. The discharge current wave trace is taken at the operating pressure of 1.0 Torr because at which the plasma pinch column radius is reached to its smallest value of 0.014 cm. In the Lee code, this current wave trace is taken from the starting (closing the switch) of capacitor bank discharge to its ending (Fig. 1) where the peak value of discharge current is found 176 kA at 2.5 µs. In this present studies, the operating pressure is varied in the pressure range of 0.1 to 2.4 Torr and the corresponding results are tabulated (Table 2).

The computed results are plotted as function of pressure (Fig. 2) and from this figure we notice the following points: The r_{min} decreases with increase in pressure from 0.1 cm at 0.1 Torr until a minimum value of 0.014 cm at 1.0 Torr and then start to increase gradually with further increase in pressure.

Table 2: The computed r_{min}, N_i, V_{max}, PED, P_{rad}, and P_{joule} with P_0 for argon gas in UNU/ICTP PFF at 14 kV.

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P_0 (Torr)	I_{peak} (kA)	I_{pinch} (kA)	T_{pinch} (10^6 K)	r_{min} (cm)	z_{max} (cm)	V_{max} (kV)	N_i (10^{23} m^{-3})	PED ($10Jm^{-3}$)	P_{joule} (10^8Js^{-1})	P_{rad} (10^8Js^{-1})
0.10	138.70	94.98	26.13	0.10	1.44	38.48	0.22	3.35	0.06	0.01
0.20	154.40	105.42	16.09	0.10	1.39	39.20	0.51	5.08	0.17	0.07
0.30	162.01	110.28	11.74	0.08	1.40	40.39	0.98	7.47	0.39	0.26
0.40	166.04	112.70	9.20	0.08	1.41	39.66	1.59	9.80	0.72	0.71
0.50	168.70	113.72	7.49	0.07	1.42	37.88	2.31	12.00	1.17	1.56
0.60	170.75	113.83	6.46	0.07	1.44	35.55	3.20	14.31	1.80	3.10
0.70	172.41	113.32	5.78	0.06	1.44	33.20	4.36	17.15	2.67	5.74
0.80	173.79	112.25	5.27	0.05	1.47	39.45	6.49	22.63	4.38	11.46
0.90	174.97	110.82	4.80	0.04	1.52	63.97	12.54	38.99	9.42	29.28
1.00	**175.98**	**109.09**	**4.36**	**0.01**	**1.73**	**245.11**	**123.37**	**338.08**	**114.48**	**172.99**
1.20	177.67	104.83	3.66	0.02	2.14	159.89	107.48	204.50	106.30	104.95
1.30	178.37	102.44	3.32	0.02	2.12	132.37	88.80	154.01	82.48	81.02
1.50	179.59	97.06	2.73	0.02	1.95	93.01	59.61	91.18	47.47	45.94
1.70	180.61	91.12	2.24	0.03	1.77	66.38	39.08	54.55	26.75	25.33
1.80	181.07	87.90	2.02	0.04	1.68	55.97	31.17	41.87	19.87	18.57
2.00	181.88	81.35	1.64	0.05	1.54	48.14	17.29	21.56	9.74	8.73
2.20	182.58	74.08	1.28	0.07	1.44	23.41	11.11	12.77	5.64	4.87
2.40	183.21	66.52	0.97	0.08	1.35	8.40	8.79	9.48	3.56	2.35

At this pressure point, the radial phase starts at 3.292 µs and ends at 3.397 µs, i. e. it lasts for 0.106 µs. Here, the argon plasmas are confined within the pinch column for very short period of time as 9.092 ns.

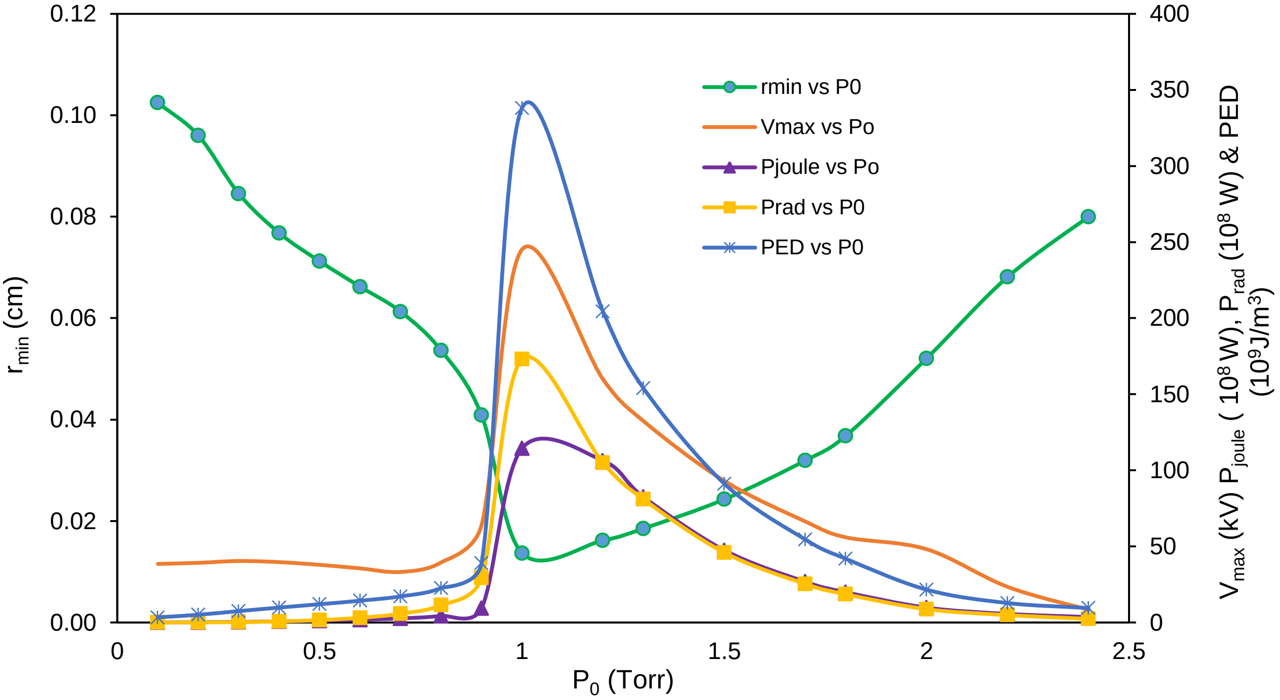

Fig. 2: The variations of r_{min}, V_{max}, Y_{line}, P_{rad} and PED with pressure change of argon in UNU/ICTP PFF at 14 kV.

During this time, the ion density and temperature of pinch plasma reach to their maximum values of 123 × 10^{23} m^{-3} and 4.36 × 10^6 K, respectively.

The induced voltage remains almost unchanged with pressure increase up to 0.8 Torr and then sharply rises to the peak value of 245 J at 1.0 Torr at which r_{min} is the lowest. After this pressure point, V_{max} exponentially decreases with further increases in pressure. The reason of this is to be the maximum dynamic inductive resistance due to the smallest cross-sectional area of the pinch column whilst pinch current gets almost in its maximum value (~109 kA).The values of pinch energy density and total radiation power also reach to their peak values of 173 ×10^8 W and 388 × 10^9 J/m^3, respectively at 1.0 Torr with the lowest value of r_{min}. At this lowest pinch radius (0.01 cm), the density of ions in pinch column reaches to its utmost value of 123 × 10^{23} /m^3 and

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it reduces in both higher and lower pressure than 1.0 Torr along with r_{min}. Because, at this lowest r_{min} the compression of pinch column as well as stagnation of ions are maximum.

This is one of the reasons for which the P_{rand} and PED get their largest values. The Joule heating power reaches to the peak value of (~114.48 ×10^8 W) at the same optimum pressure of 1.0 Torr with the lowest r_{min} = 0.01 cm. The nature of variation of P_{joule} with pressure is similar to other pinch parameters discussed previously but its value drastically jump from ~9.42 ×10^8 W at 0.9 Torr to the peak value. The radiation power is dominated by line radiation yield (Y_{line}). This power begins to excess (0.39 × 10^8 W) from Joule heating power gradually at 0.5 Torr and it goes to the peak value of -58.51 × 10^8 W sharply at the optimum pressure of 1.0 Torr (Table 2). So, at this pressure point the radiative collapse of pinch column occurs due to the strong radiative cooling effect. Then, the Joule heating power gets higher value from radiation power with pressure increase up to 2.4 Torr.
The computed soft X-ray yield (SXR), PED for nitrogen and oxygen gases with pressure variation in PF1000 device were correlated with pinch properties (Akek et al. 2017). In his study, it was found that SXR, PED were maximum whilst the minimum pinch radii reached to their lowest values at the corresponding optimum pressures. Hence, the variation nature of pinch properties with pressure change for argon gas of UNU/ICTP PFF in both studied devices are very similar in nature. Therefore, it may be concluded that the obtained numerical results from our present studies are consistent that increases the validation of this research work.

4. CONCLUSION

In the plasma focus operation, the energy of accelerated ions and electron beams depend on the induced voltage across the electrodes during the pinching time. In this studies we find that the V_{max} gets its peak value (245 kV) at the optimum pressure of 1.0 Torr whilst the minimum pinch radius reaches to the lowest value of 0.01 cm. The pinch energy density (338 × 10^9 Jm^{-3}), ion density (123 × 10^{23} /m^3) consequently radiation power (~ 173 × 10^8 W) and Joule heating power (114.48 × 10^8 W) show their peak values at the optimum r_{min} (0.01 cm) and P_0 (1.0 Torr). At this optimum combination, due to the strong radiatiove cooling effect the excess radiative power (-58.51 × 10^8 W) is responsible to the sharp drop of pinch column radius that cause radiative collapse. The variation trend of pinch properties with change in pressure of UNU/ICTP PFF are very similar in nature with those of PF1000 device that increases the validation of the results.

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