Numerical Experiments for Radial Dynamics and Opacity Effect in Argon Plasma Focus

Z. Ali[1,2], J. Ali[1], S. H. Saw[3,5], and S. Lee[4,5]

[1]Institute of Advanced Photonics Science, Nanotechnology Research Alliance
Universiti Teknologi Malaysia (UTM), Johor Bahru 81310, Malaysia
[2]Karachi Institute of Power Engineering, P. O. Box 3183, Karachi, Pakistan
[3]INTI University College, Nilai 71800, Malaysia
[4]Nanyang Technological University, National Institute of Education, Singapore
[5]Institute for Plasma Focus Studies, 32 Oakpark Drive, Chadstone VIC3148, Australia

Abstract— A z-pinch in its simplest form is a column of plasma in which current (J) is driven in the axial direction (z) by an electric power source producing an azimuthal (θ) direction magnetic field (B) that tends to confine plasma by ($J \times B$) force. One application of this configuration is Plasma Focus. Dense plasma focus (DPF) is essentially a pulsed electric gas discharge between coaxially arranged electrodes. DPF devices belong to the family of dynamic Z-pinches which are self-constricted plasma configurations. The Lee model code was developed to simulate the plasma dynamics in a DPF. The model incorporates the energy and mass balances equivalent, at least in the gross sense, with radiation-coupled dynamics to all the processes which are not even specifically modeled. It is a well known fact that radiation loss is an inevitable phenomenon in the final stage of pinch compression. The most obvious one is that of a focus or a Z-pinch. Plasma self-absorption is an important factor during the pinch compression. In this paper the effect of self absorption of line radiation was investigated in argon plasma by a series of numerical experiment considering both aspects, i.e., by including and excluding the self absorption term in Lee code. The results were compared for various parameters, i.e., Radial trajectories, pinch duration, pinch current, line radiation yield while changing pressure. The effect of radiation self absorption was observed in last few fractions of seconds (200–300 ns). Considering self absorption, the compression shows a value of radius of about 0.2 mm while a collapse (radiative collapse) was observed otherwise. The results illustrated that the radiation cooling becomes significant when the plasma is dense and turn to be opaque for radiation. Hence in real case we do not see a radiative collapse in argon PF as self absorption plays in real experiments. The results of pinch duration and pinch current also indicated that self absorption is essentially enhancing the pinch in terms of stability.

1. INTRODUCTION

A z-pinch in its simplest form is a column of plasma in which current (J) is driven in the axial direction (z) by a pulsed electric power source producing an azimuthal (θ) direction magnetic field (B) that tends to confine plasma by ($J \times B$) force. Dense plasma focus (DPF) is essentially a pulsed electric gas discharge between coaxially arranged electrodes. DPF devices belong to the family of dynamic Z-pinches which are self-constricted plasma configurations. Radiation collapse is known as a phenomenon of a sudden decrease in plasma temperature caused by an increase of radiation loss. It is a well known fact that radiation loss is an inevitable phenomenon in the final stage of pinch compression. The most obvious one is that of a focus or a Z-pinch.

Lee has proposed that current-stepping technique can significantly reduce the plasma pinch ratio. Therefore, this technique can enhance the pinch compression to a significant level which can play important role while designing high intensity soft x-ray sources using argon or xenon plasma [1]. Saw has developed current-stepped pinches [2] to confirm the predictions of the numerical experiments. Jalil et al has developed the model to explore the effects of radiation loss and elongation on the compression dynamics in a small size plasma focus [3]. Plasma focus machines have been studied as intense source of various radiations like soft x-rays (SXRs), electrons, neutrons etc. with potential applications [4, 5]. Whilst many recent experiments have concentrated efforts on low energy devices [4, 5] with a view of operating these as repetitively pulsed sources, other experiments have looked at x-ray pulses from larger plasma focus devices [6] extending to the megajoule regime. Numerical experiments simulating x-ray pulses from plasma focus devices are gaining more interest in the public domain. A comparison was made for the case of the NX2 machine [4], showing good agreement between computed and measured SXR yield (Ysxr) as a function of pressure [7, 8]. This gives confidence that the Lee model code gives realistic results in the computation of Ysxr.

Here, we report on a series of numerical experiments to explain the dynamics of self absorption during the slow compression phase occurring in the last fractions of seconds of pinch. The X-ray radiation properties of plasma are dependent on the plasma temperature, ionization states and density. Recently Ar has been considered for micro-machining due to the harder characteristic line radiation [9].

2. SELF ABSORPTION AND RADIATIVE COLLAPSE IN LEE MODEL

The Lee Model code incorporates radiation dynamics [10] using the following equation:

$$\frac{dr_p}{dt} = \frac{-\frac{r_p}{\gamma I}\frac{dI}{dt} - \frac{1}{\gamma+1}\frac{\gamma_p}{z_f}\frac{dz_f}{dt} + \frac{4\pi(\gamma-1)}{\mu\gamma z_f}\frac{r_p}{f_c^2 I^2}}{\frac{\gamma-1}{\gamma}} \tag{1}$$

where r_p is piston radius γ is specific heat z_f focus length while f_c is current factor and I is discharge current.

The volumetric plasma self-absorption correction factor A is obtained in the following manner [10–12]:

$$A_1 = (1 + 10^{-14} n_i Z) \Big/ T^{35} \tag{2}$$

$$A_2 = 1/AB_1 \tag{3}$$

$$A = A_2^{(1+M)} \tag{4}$$

where M is photonic excitation number given by

$$M = 1.66 \times 10^{-15} r_p Z_n^{0.5} n_i \Big/ (ZT^{1.5}) \tag{5}$$

Transition from volumetric to surface emission occurs when the absorption correction factor goes from 1 (no absorption) down to $1/e$ ($e = 2.718$) when the emission becomes surface-like given by the expression:

$$\frac{dQ}{dt} = -\text{const} \times Z^{0.5} Z_n^{3.5} \left(r_p\right) z_f T^4 \tag{6}$$

where the constant const is taken as 4.62×10^{-16} to conform with numerical experimental observations that this value enables the smoothest transition, in general, in terms of power values from volumetric to surface emission. Where necessary another fine adjustment is made at the transition point adjusting the constant so that the surface emission power becomes the same value as the absorption corrected volumetric emission power at the transition point. Beyond the transition point (with A less than $1/e$) radiation emission power is taken to be the surface emission power [10, 11].

3. NUMERICAL EXPERIMENTS WITH ARGON FILLED NX2 PLASMA FOCUS

NX2 Plasma Focus was configured with Argon as filling gas at voltage of 11 kV and the tube and model parameters used for configuration are:

Table 1: Configuration Parameters for PF.

Electrical Bank Parameters	**Lo**	**Co**	**ro**	
	20 nH	28 µF	2.3 mΩ	
Geometrical Tube Parameters	**b**	**a**	**zo**	
	4.1 cm	1.9 cm	5 cm	
Model Parameters	**massf**	**currf**	**massfr**	**currfr**
	0.0635	0.	0.16	0.

A series of Numerical experiments had been performed after configuring the machine for both the cases, i.e., including the self absorption term and without accounting for it into the code. The radial trajectories were plotted against time at various pressures ranging from 0.1–2.0 Torr with a step of 0.1 Torr. Finally the results were compared for both the cases as shown in figure.

4. RESULTS & DISCUSSION

4.1. Radial Dynamics

Starting from Figs. 1 & 2 showing the radial position of piston and shock as well as focus length at 0.5 torr the radial shock of about 18 mm is driven to the axis by magnetic piston and hits after 120 ns. After hitting the axis of anode, a reflected shock (RS) moves out and hits the incoming magnetic piston after about 20 ns. At this point the plasma column initiates to be compressed and radiation emit out from the pinch making it cool. But to notice the effect of radiation cooling there should be equilibrium between energy gain by Joule Heating and energy loss due to Bremstrahlung and Line radiation emission. The situation is same for both cases when the numerical experiment was done with and without including the term of self absorption.

Figures 3 & 4 at 1.0 torr is radiative collapse of the pinch as the radial shock of about 18 mm is driven to the axis by magnetic piston and hits after 155 ns at this pressure. After hitting the axis, the reflected shock (RS) hits the incoming magnetic piston after about 25 ns. Here the pinch shows clear signs of radiative collapse; and we can see the difference that without including self absorption the pinch collapses earlier than the case when Self Absorption is considered in the calculation. When self absorption was not included the radial shock collapse in shorter time in only a few ns to the radius of 0.1 mm set as cut-off in the model as the pressure increased, while the pinch duration and focus length has increased when radiation absorbed for instance after hitting the shock pinch duration is observed as 24 ns, 35 ns and 41 ns for pressures 1.0, 1.5 and 2.0 Torr respectively. In this case the pinch doesn't collapse but attains a minimum radius (See Figs. 5, 6, 7 & 8). It suggests that the pinch radius collapses less when self absorption is taken into account.

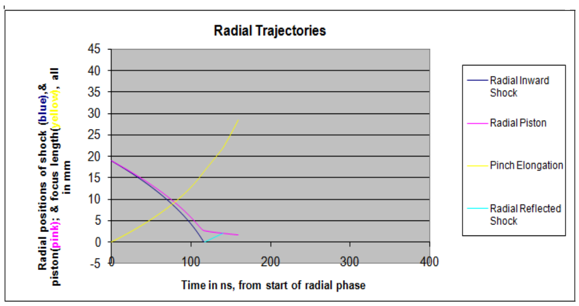

Figure 1: At 0.5 torr without self absorption.

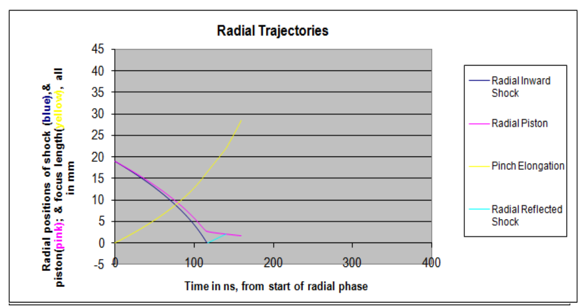

Figure 2: At 0.5 torr with self absorption.

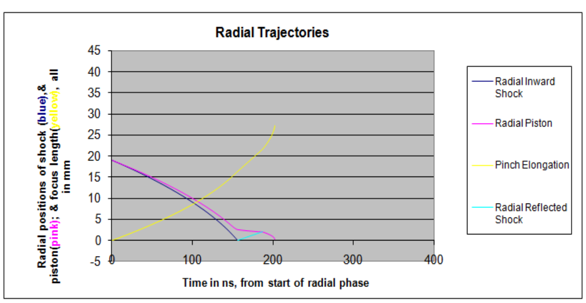

Figure 3: At 1.0 torr without self absorption.

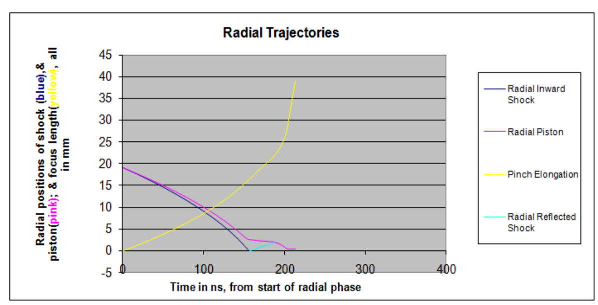

Figure 4: At 1.0 torr with self absorption.

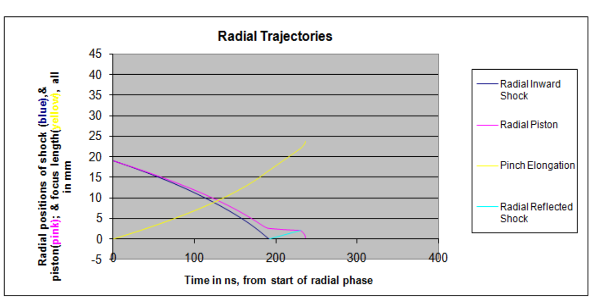

Figure 5: At 1.5 torr without self absorption.

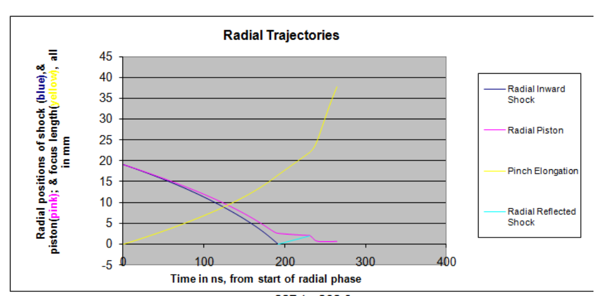

Figure 6: At 1.5 torr with self absorption.

This is because the self-absorption reduces the amount of radiation loss from the plasma.

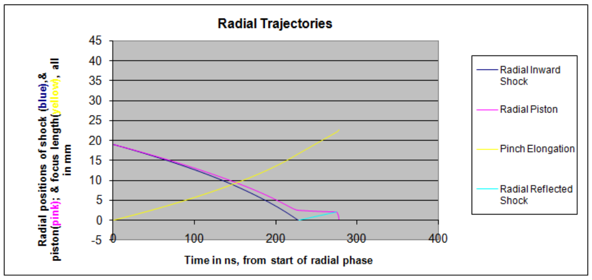

Figure 7: At 2.0 torr without self absorption.

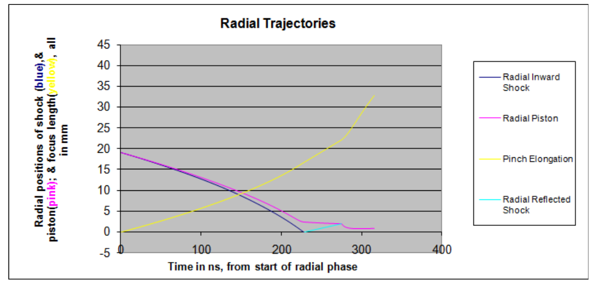

Figure 8: At 2.0 torr without self absorption.

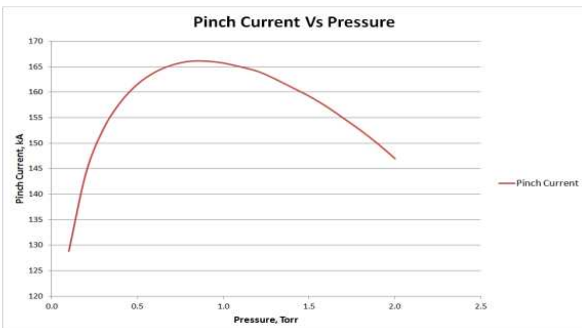

Figure 9: Pinch current vs pressure.

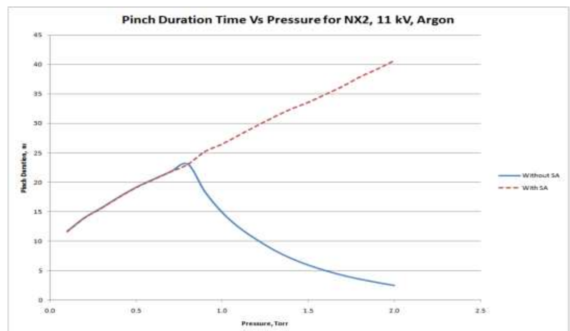

Figure 10: Pinch duration vs pressure.

4.2. Pinch Current & Pinch Duration

It is also notable in Fig. 9 that as the pressure was increased pinch current first increases upto 166 kA and then after 1.0 Torr it reduces gradually until 2.0 Torr where it is at its minimum value of 147 kA. At that point pinch radius collapses to 0 in case of no self absorption while it collapses and maintains to 0.1 mm if self absorption is considered in play as an evidence that radiation self absorption retards pinch collapse and gives a denser and hot pinch with high yield of radiation

Observing Fig. 10 it is apparent that pinch duration is decreasing as we increased the pressure in case of no absorption and it continues increasing while there is absorption. This indicates that due to higher pressure the density of plasma column increases which in turn causes the radiation to be absorbed due to opacity of the column and hence delaying the pinch collapse.

5. CONCLUSIONS

The self absorption effect of line radiation was determined in argon plasma by changing the pressure of gas in steps. After comparing the results of Numerical Experiment considering both aspects, i.e., by including and excluding the self absorption term in Lee code, the effect of radiation self absorption was observed in the slow compression phase. Considering self absorption, the compression shows a value of radius of about 0.2 mm while without including this term of self absorption a collapse (radiative collapse) was observed due to radiative cooling. This comparison indicates that the radiation cooling becomes significant when the plasma is dense enough to become opaque for radiation. The same effect was corroborated further in the pinch duration in both the cases. Hence in argon numerical experiments indicate that radiative collapse does occur (Figs. 4, 6, 8) but not as severely as the case when we neglect self absorption (Figs. 3, 5, 7) The consideration of self absorption is playing a significant role in this case leading to realistic results. Otherwise the radiative collapse may become overestimated by excluding the power absorbing in the plasma due to reabsorbed radiation.

ACKNOWLEDGMENT

We are deeply indebted to Dr. Lee Sing for his assistance in providing the understanding of code and Universiti Teknologi Malaysia for its generous support.

REFERENCES

1. Lee, S., "A current-stepping technique to enhance pinch compression," *Journal of Physics D: App. Phys.*, Vol. 17, No. 4, 733, 1984.
2. Saw, S. H., S. Lee, and C. S. Wong, "A current-stepping technique to enhance pinch compression — An experimental study," *AIP Conf. Proc.*, Vol. 195, No. 1, 500–506, 1989.
3. Ali, J., *Development and Studies of a Small Plasma Focus*, Universiti Teknologi Malaysia, Skudai, 1990.
4. Lee, S., et al., "High rep rate high performance plasma focus as a powerful radiation source," *IEEE Trans. on Plasma Sci.*, Vol. 4, No. 26, 1119–1126, 1998.
5. Bogolyubov, E. P., et al., "A powerful soft X-ray source for X-ray lithography based on plasma focusing," *Physica Scripta*, Vol. 57, No. 4, 488, 1998.
6. Filippov, N. V., et al., "Filippov type plasma focus as intense source of hard X-rays $E_x \sim 50\,\mathrm{keV}$) plasma science," *IEEE Transactions*, Vol. 24, No. 4, 1215–1223, 1996.
7. Lee, S., et al., "Soft x-ray yield from NX2 plasma focus," *Journal of Applied Physics*, Vol. 106, No. 2, 2009.
8. Haines, M. G., "The Joule heating of a stable pinched plasma," *Proceedings of the Physical Society*, Vol. 76, No. 2, 250, 1960.
9. Gribkov, V. A., et al., "Operation of NX2 dense plasma focus device with argon filling as a possible radiation source for micro-machining," *IEEE Trans. on Plas. Sci.*, Vol. 30, No. 3, 1331–1338, 2002.
10. *Plasma Focus*, 2010 Updated: 19 October 2010, [cited 2011 4 Oct 2011]; Available from: http://www.intimal.edu.my/school/fas/UFLF/
11. Khattak, N. A. D., *Plasmafocus.net*, 2007, [cited 2009 7 October]; Available from: http://www.plasmafocus.net/IPFS/modelpackage/File3Appendix.pdf.
12. Robson, A., "Lower hybrid ddrift instability and radiative collapse of a dense z pinch," *Phys. Fluids B*, Vol. 3, No. 6, 1461, 1991.