NUMERICAL EXPERIMENT OF RADIATION SELF-ABSORPTION AND RADIATION DYNAMICS IN THE DENSE PLASMA FOCUS USING LEE MODEL

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Dedicated to my beloved Parents
And Family

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ABSTRACT

Radial dynamics and plasma focus pinch were influenced in slow compression mode by optically thick plasma due to radiation self-absorption. In this study, the role of radiation self-absorption in Mather type dense plasma focus (DPF) device was investigated. The impact of opacity in slow compression phase and the behaviour of optically thick plasma towards radiation emission were explored. The numerical modelling of self-absorption effect on radiation dynamics, focusing, cooling, collapse and influence of self-absorption on the radiation emission was performed. Lee Model was used for numerical simulation. The model was developed incorporating the various energy balances including thermodynamics, kinematics, radiation dynamics and was capable of yielding the plasma structure and trajectories. The snowplow model describes the axial rundown phase and slug model in radial phase of pinch. Numerical simulations were performed for the absorption of radiation within dense and optically thick plasma. It was found that a steady state pinch with constant radius was only possible at the Pease–Braginskii (PB) current of 1.2 to 1.6 MA for hydrogen and deuterium DPF. For lower and higher values of input current as compared to PB current, the pinch expands and collapses respectively. This current was reduced for heavier gases like Neon (Ne), Argon (Ar), Krypton (Kr) and Xenon (Xe) due to the emission of significant amount of line radiation. For Ne, Ar, Kr and Xe gases with different DPF configurations more severe radiative collapse was observed as compared without the self-absorption factor. It was found that for Ar with no self-absorption, the pinch boundary collapsed in only a few nanoseconds to the radius of 0.1 mm set as cut-off in the model. The pinch does not attain the cut-off radius with self-absorption. In the case of Ne, there was no radiative collapse with self-absorption factor but radiative collapse occurs without self-absorption. A severe radiative collapse was also observed in both cases of Kr and Xe. It was inferred that the pinch radius collapses less when self-absorption was taken into account. The plasma opacity reduces the amount of radiation loss. Thus, self-absorption phenomenon was significant during the slow compression phase and needs to be considered in the design of a new DPF device.

ABSTRAK

Dinamik jejarian dan jepitan plasma fokus dipengaruhi dalam mod mampatan perlahan oleh plasma tebal secara optik disebabkan oleh swaserapan sinaran. Dalam kajian ini, peranan swaserapan sinaran di dalam peranti plasma fokus padat (DPF) jenis Mather diselidiki. Kesan kelegapan di dalam fasa mampatan perlahan dan tingkah laku plasma tebal secara optik terhadap pancaran sinaran diterokai. Permodelan berangka kesan swaserapan sinaran terhadap dinamik sinaran, pemfokusan, penyejukan, runtuhan dan pengaruh swaserapan terhadap pancaran sinaran dijalankan. Model Lee digunapakai untuk permodelan berangka. Model dibangunkan dengan menggabungkan pelbagai keseimbangan tenaga termasuk termodinamik, kinematik, dinamik sinaran dan mampu menghasilkan struktur plasma dan trajektori. Model bajak salji menghuraikan fasa paksi urutan acara dan model pasak di dalam fasa jejari jepitan. Simulasi berangka dijalankan untuk penyerapan sinaran di dalam plasma padat dan tebal secara optik. Jepitan keadaan mantap dengan jejari malar didapati hanya boleh dilakukan pada arus Pease-Braginskii iaitu 1.2 hingga 1.6 MA untuk DPF di dalam gas hidrogen dan deuterium. Pada arus yang lebih tinggi dan rendah daripada arus Pease-Braginskii, jepitan mengembang dan runtuh. Arus ini dikurangkan untuk gas yang lebih berat seperti Neon (Ne), Argon (Ar), Kripton (Kr) and Xenon (Xe) disebabkan oleh pelepasan sejumlah besar sinaran garis. Bagi gas Ne, Ar, Kr and Xe dengan konfigurasi mesin yang berbeza runtuhan sinaran lebih teruk diperhatikan tanpa faktor swaserapan. Sempadan jepitan runtuh dalam beberapa nanosaat kepada set jejari 0.1 mm sebagai pemutus di dalam model bagi gas Ar tanpa swaserapan. Jepitan tidak mencapai jejari pemutus dengan swaserapan. Runtuhan tidak berlaku dengan swaserapan tetapi berlaku apabila tiada swaserapan bagi gas Ne. Runtuhan sinaran yang lebih teruk turut diperhatikan bagi kedua-dua gas Kr dan Xe. Disimpulkan bahawa runtuhan sinaran jepitan berkurangan apabila swaserapan diambilkira. Kelegapan plasma mengurangkan amaun kehilangan sinaran. Oleh itu, fenomena swaserapan adalah penting semasa fasa mampatan perlahan dan perlu dipertimbangkan semasa merekabentuk peranti plasma fokus padat yang baru.

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LIST OF ABBREVIATIONS

1-D	–	One Dimensional
2-D	–	Two Dimensional
DBD	–	Dielectric-barrier discharge
DPF	–	Dense Plasma Focus
GUI	–	Graphic User Interface
MHD	–	Magneto Hydrodynamic
PF	–	Plasma Focus
SPE	–	Snow Plow Energy Model
SPM	–	Snow Plow Model
UNU/ICTP PFF	–	United Nation University / International Centre for Theoretical Physics Plasma Fusion Facility
UV	–	Ultra violet

LIST OF SYMBOLS

A	–	Atomic Weight
a	–	Anode Radius
α_z	–	Fraction of Plasma that Ionized to the z^{th} Ionized State.
B	–	Magnetic Field
b	–	Cathode Radius
c	–	Ratio of Cathode to Anode Radius
c_s	–	Sound Speed
C_o	–	Capacitor Bank for Energy Storage
D	–	Departure Coefficient
dQ	–	External Input Energy
Ei	–	Initial Energy of Excited Electron
Ef	–	Final Energy of Excited Electron
Ek	–	Kinetic Energy of Plasma Sheath
E_z	–	Average Excitation Energy per z^{th} Ionized Atom
$EINP$	–	Energy Input into Plasma
$\mathrm{E_I}$	–	Energy Stored in the Tube Inductance
E_i	–	Ionization Energy
E_x	–	Excitation Energy
η	–	Spitzer Plasma Resistance
ζ	–	Normalized Axial Position
γ	–	Specific Heat Ratio
Γ	–	Shock Density Ratio
f_m	–	Axial Mass Factors
f_c	–	Axial Current Factors

f_{mr}	–	Radial Mass Factors
f_{cr}	–	Radial Current Factors
F_{z1}	–	Axial Force on Plasma Sheath
F_{z2}	–	Radial Force on Plasma Sheath
h	–	Focus Enthalpy
h	–	Plank's Constant
h_L	–	Leakage Resistance in the Plasma Tube
ι	–	Normalised Current
I	–	Discharge Current
I_P	–	Pinch Current
$Imax$	–	Peak Discharge Current
I_{PB}	–	Pease-Braginskii Current
I_z	–	Total Energy Required to Raise One Ion from its Unionized State to its zth Ionized State
J	–	Current Density
$j \times B$	–	driving Magnetic force
k_B	–	Boltzman Constant
keV	–	kilo electron volt
K_P	–	Normalised Magnetic Piston Position
K_s	–	Normalised Shock Front Position
l_v	–	Mean Free-Path
L_o	–	Fixed Circuit Inductance
L_p	–	Changing Plasma Tube Inductance
L_e	–	Plasma Inductance Spark Gap Inductance
Lo	–	External (stray) Inductance
M	–	Molecular Weight
M	–	Photonic Excitation Number
m_i	–	Mass of Atom or Ion.
n	–	Number Density of Ions and Electrons
ni	–	Ion Density (in the code)
N_i	–	Density of the Ions
N_e	–	Electron Density

N	–	Line Density
ρ	–	Mass Density
ρ_o	–	ambient gas density
P_K	–	Kinetic Pressure
P_B	–	Magnetic Pressure
P_p	–	Piston Pressure
P	–	Rate of Radiation Loss
P_J	–	Rate of Joule heating
P	–	Pressure
P_{max}	–	Maximum Pressure
P(x,t)	–	The pressure distribution
P_l	–	Line Radiation Power Density
Q	–	Total Electric Charge
$\mathrm{r}_{\mathrm{min}}$	–	Minimum Pinch Radius
q_o	–	Speed of the Shocked Gas
q	–	Speed of the ambient gas
Q_{rad}	–	Radiation energy
Q_s	–	Radiation loss per unit length
R_s	–	Particle Position
RC	–	Integration Time Constant
r_p	–	Slug external radius
r_s	–	Slug internal radius
r	–	Boundary Radius of Curvature
r_c	–	Critical radius
R_o	–	Circuit Resistance
R_{o}	–	Universal gas constant
R_p	–	Plasma Resistance
T	–	Shock Temperature
$t_{p\text{-}s}$	–	Transmission Time
t_{a}	–	Characteristic Axial Run Down Time
$\boldsymbol{\tau}$	–	Confinement time

τ	–	Normalised Time
T	–	Plasma Temperature
T_e	–	Electron temperature
μ_o	–	Permeability of Free Space
V_o	–	Capacitor Voltage
V_{Slug}	–	Volume of Plasma Slug
V	–	Plasma Volume
U	–	Internal Energy
v_{T_i}	–	The Thermal Velocity of Ion
v_s	–	The Shock Front Speed
ω_g	–	Statistical weight of the ground state of the ion
W	–	Total de-excitation rate could be
W_e	–	Collisional de-excitation rate
Y_X	–	X-ray yield
Z	–	Atomic Number
z	–	Instantaneous Current Sheath Position
Z_{eff}	–	Effective (average) charge number of one ion
z_o	–	Length of anode
z_r	–	Radial Compression Length
Z_i	–	Effective Charge

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CHAPTER 1

INTRODUCTION

1.1 Overview

Since the discovery of the plasma focus in early 1960's, it was studied as a fusion device. The research was much focused on improvising the neutron generation while using deuterium as the working gas, intense x-rays production by the admixture of argon or other heavy noble gases with deuterium plasma. In fusion research area, the main concentration of earlier researches in plasma focus was to achieve thermonuclear fusion in a controlled manner. However, there is a growing interest in experimental area of research on X-ray bursts emitting out of plasma focus devices. Later this research was directed to study the powerful electrical discharges. In discharges driven by high power, the magnetic confinement and the Joule heating is achieved by the electro dynamical forces. To obtain fusion grade plasma, fusion devices have been scaled up to very large sizes. Hence there are still a lot of elementary principles and processes that are not intelligible so far. Therefore to have a better understanding there is a need to scale down the experiments so that important principles and mechanism of plasma physics and technology can be studied.

Strongly ionized plasma is broadly used in the scientific investigations and industrial applications. Therefore plasma focus is a potential source of radiations for soft x-ray, hard x-ray, electron, ion beams and fusion neutron. The plasma concepts and phenomena involved in the focused pinch are too complex to be understood by real experiments due to very short time of their occurrence. It is an appropriate approach to simulate the plasma formation on the basis of theoretical models to study the mechanisms involved in the process and to monitor their effects. Thus numerical experiments through computational models complement the experimental work. This provides the opportunity to get a better understanding of the concepts regarding plasma within plasma focus for research purpose.

1.2 Background of Research

Z-pinch was introduced in late 1950's to distinguish the self-constriction due to axial current from the compression by the azimuthal (along θ) direction. The basis behind the idea was heating deuterium-tritium mixture adiabatically in a Z-pinch and sustaining this system in equilibrium state to cause a fusion reaction for energy release. However, this approach couldn't get much attraction due to instabilities in the Z-pinches. Hence, this area of research eventually was not continued until early 1980's. Mather (1965) explained the creation of plasma focus by high-density deuterium also hot and dense plasma in a compressed non-cylindrical z-pinch was reported independently in early 1960's by Filippov *et al.* (1962).

Z-pinches regained importance when development of pulsed power technology grew in 1980's. Many aspects of the radiative collapse model were interpreted. Plasma points and bright spots appear to be related, and insight in plasma points could become useful in understanding bright spots. It should be emphasized that the plasma point is, by its very nature a dynamic phenomenon with constantly changing parameters. For example, during its development the temperature of the plasma point changes from tens to several kilo electron volts. The size and density of the plasma point also change significantly, e. g., from 1 mm to less than 10 pm and from 10^{19}/cm^3 to 10^{23}/cm^3. Moreover, the plasma point must have spatial gradients in temperature and density that cannot always be resolved experimentally (Vikhrev *et al.* 1982). The x-ray spectrum contains information about the plasma in the plasma point (Koshelev *et al.* 1994).

It is also known that many complex and rich phenomena are occurring within plasma focus (Ali, 1990, Lee *et al.* 2009a, Rosenbluth *et al.* 1954). A plasma focus not only emits copious amount of soft X-rays but also acts as a ready source of hot dense plasma and fusion especially when operated with high-*Z* gases (Lee, 1984, Lee *et al.* 2009). This distinct feature enables plasma focus to be a prime candidate for many applications such as x-ray lithography (Dubrovsky *et al.* 2001, Rafique *et al.* 2010).

Lee *et al.* (2008) and Lee and Saw (2008b) has reported numerical experimentation and found out that below a certain value of optimum inductance, total current increases progressively while pinch current and neutron yield of plasma focus decrease.

A more global scaling law was developed than already available laws (Lee and Saw, 2008, Saw and Lee, 2010). A mid-range point is obtained from data to calibrate neutron generation process. Numerical experiments using Lee Model code have been carried out in order to study the plasma focus and in general fast electrical discharge.

The plasma focus device has been widely investigated as neutron generator (Conrads, 1990, Hagerman and Mather, 1958), with its probability to play important role in nuclear fusion. Vikhrev and Korolev (2007) depicted in their report that when deuterium is present in Z-pinch, these dense and high temperature bunches can become a source of strong neutron radiation. It was also researched not only for basic plasma studies, but also for other important applications (Bernard *et al.* 1977). Conception, design, construction and study of devices and diagnostics suitable for each application have been made on basis of developed criteria (Milanese and Team, 2006).

Gribkov *et al.* (2002) have reported reasonable soft X-ray yield from the regimes such as hot spots, plasma pinch, and plasma compression by a “heavy shell” by using the pure argon and mixtures of argon with deuterium or krypton as operating gas.

In the past, many attempts have been made for intensifying the x-ray production by varying different experimental parameters e.g. bank energy (Burkhalter *et al.* 1992), discharge current, electrode dimensions (Bhuyan *et al.* 2004, Zakaullah *et al.* 2002), electrode configuration (Al-Hawat *et al.* 2011), insulator material and shape (Zakaullah *et al.* 2002), gas constituents and pressure at which operating gas is filled (Darestani Farahani *et al.* 2011). Therefore, the research to gain an optimum yield of soft x-ray from the dense plasma focus machines working with capacitor banks of an ample range of storage energies has been an active area to study plasma focus research leading to the variety of potential applications. It is a complicated and lengthy process to achieve the values of appropriate parameters for the optimized maximum yield experimentally. For that reason, there is a need to work out some efficient and quick procedure to accomplish this task that can be attained by using a reasonably reliable model for plasma focus and a numerically simulated program based on that model to estimate the x-ray output from plasma focus device. Nevertheless, it is also desired that these computed yields should be verified against the equivalent measured yields. In such scenario if the computed observations are substantiated by measured values then it is realistic enough to accept the obtained plasma properties by computation process equivalent to the measured values. Hence, a reliable numerical model not only acts as a tool to calculate the radiation outputs, but also suggests the diagnostics for number of combined plasma properties regarding plasma focus.

To represent the physical concepts and phenomena within plasma focus during the pinching of plasma, its radiative properties are essentially important for simulation of the radiation dynamic. Such simulation enables the researchers to illustrate the physical picture of real time microscopic concepts that must be reasonably as close to real scenario as possible to acquire a better understanding.

The major development in this field, in last two decades, opened the new ways to explore a lot of complex and sophisticated aspects of physical phenomena with the help of numerical experiments which were not possible by real experiments. The constraints involved to perform such experiments for the radiative aspect of plasma were both from the very short time intervals of those mechanisms as well as the complexities of real time modification of various plasma parameters that is comfortably achieved through a numerical experiment.

On the basis of above overview, it was found that there is not a greater insight of dynamical behaviour of plasma during the slow compression phase regarding its radiation self-absorption aspect within Plasma Focus Devices.

1.3 Problem Statement

Despite of extensive research to increase the X-ray yield and its applications there is nominal study in the area of plasma radial dynamics regarding its self-absorption aspect. Since this effect may influence the X-ray yield as well as other important parameters that play vital role at the time of designing a new plasma focus device hence it seems reasonable to develop some correlation for this parameter with other parameters which is unavailable so far. This current study comprises the analysis of the plasma radial dynamics within plasma focus devices to look into the phenomenon of radiation self-absorption and its influence on various parameters in a Mather type dense plasma focus. The problem addressed in this research is stated as:

"How opacity of plasma pinch and radiation self-absorption of emitted radiation influenced the plasma dynamics in slow compression phase and what is its effect on the focus pinch. What is the correlation of self-absorption parameter with the radius of the focused pinch and hence with the other radiation emission parameter."

1.4 Objectives of Research

The objectives of this study are as follows.

- To analyse the radiative collapse effects on pinch dynamics considering dense hot plasma column while it becomes opaque for emitting radiation during the slow compression phase in a Plasma focus.
- To utilize the Lee Model for studying the effect of characteristic X-rays emission on reduction of current while a high Z operating gas is used.
- To correlate the radiation self-absorption effect with parameters of the focus with the emission parameters to identify the suitable conditions for enhanced emission of radiation.

1.5 Scope of Research

This study covered Numerical Experimentation on configured Dense Plasma Focus (DPF) machines. This current project comprises the study of plasma dynamics on theoretical basis and numerical experiments. Modelling of role of self-absorption in radiation yield during slow compression mode from a plasma focus operated in neon and argon was also included in the scope. This study contains description of plasma focus mechanism, Pinch Effect (radiation emission mechanism and its contributions to the radiation yield). Role of Self-Absorption in radiation yield in dense plasma focus has been observed. Numerical experiments has been conducted to study the effects of self-absorption by comparing the results obtained in hypothetical case in which numerical experiments in which self-absorption term has been excluded.

1.6 Significance of the Research

The plasma focus has been widely studied for the purpose of conception, design, construction and physics of various phenomena operating in the devices and appropriate diagnostics techniques required for each application. However, without incorporating the concepts of self-absorption it is not possible to get realistic design and is hard to probe into the physical phenomena of radial dynamics i.e. radiation cooling. This study contributes the understanding of concept of self-absorption by demonstrating the numerical experiments and unfolding the uncovered aspects of this phenomenon.

The model has been used for various applications, for example, in designing cascade plasma focus device, in calculating amount of soft x-ray output to develop a soft X-ray source for lithographic applications in microelectronics. It is also recently utilised in uncovering a pinch current limitation effect, throwing new light on neutron scaling laws and as a simulated experimental technique to compute focus pinch current from a measured discharge current waveform. This study will add to the parameters in consideration which are yet to be explored.

It acts as an X-rays source and charged particles as well as emits neutrons (using deuterium gas). An on-going research depicts the demonstration of potential applications such as soft X-ray source for microelectronics of next-generation. Surface micromachining, lithography, pulsed X-ray and neutron source for medical and security inspection applications and materials modification, among others. In addition to that, these devices have applications in simulating nuclear explosions for the purpose of testing electronic equipment. These devices also act as intense neutron source of small dimension contactless inspection and discovery of nuclear materials such as uranium and plutonium. A potential application of plasma focus research is focus fusion in which researchers are interested and involved actively.

1.7 Thesis Organization

This thesis is arranged in six chapters as following:

Chapter 1: The introductory description is covered in the first chapter with the introduction of the thesis, brief history of the plasma focus research providing the background followed by the problem statement, objectives of the research, scope of the research and its contribution to the current research.

Chapter 2: The review of pinch dynamics and various models used in plasma focus research are discussed comprehensively in this chapter regarding the literature review.

Chapter 3: The theoretical aspects of plasma generation and Plasma Focus devices are covered in this chapter including sheath evolution, pinch formation and microscopic concepts of instabilities.

Chapter 4: The computational model used in numerical experiments along with the proposed modification in the existing model is presented in this chapter. In addition, this chapter presents the procedures employed for numerical experiments in detail.

Chapter 5: The chapter is devoted for the presentation of results of the numerical experiments in graphical and tabulated form and depict an elaborated discussion by interpreting the obtained data.

Chapter 6: This chapter concludes the research findings. It acts as a summary of the whole thesis. In addition to that it also suggests some aspects to be considered for future investigations in this area of research of the plasma focus devices.

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