MULTI-RADIATION YIELDS SIMULATION AND OPTIMIZATION OF PLASMA FOCUS DEVICES

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To my beloved family and Xiu

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ABSTRACT

The plasma focus device is a potential source of multi-radiation emission. Numerical experiments were performed to study the multi-radiation emission of soft X-ray and neutrons from Mather type plasma focus devices with energies ranging from 1.4 kJ to 480 kJ operated in deuterium and argon gases. This device was chosen since it provides an open geometry with large possible collection angles operated over wide parameter ranges. However, the study of optimum gas pressure, current sheath speed, and pinch current is still required for a better understanding of the device. In this study, the Lee's Code version RADPF6.1b was used to perform the current profiles fitting process. The mass sweeping and current factors for axial and radial phase were used to accommodate the conditions encountered in the experiments. All gross properties including the radiations were realistically modelled once the computed and measured current profiles are well fitted. In the case of 1.4 kJ plasma focus device, the optimum computed neutron yield, Y_n was 2.9×10^7 neutrons/shot at 5.5 Torr deuterium pressure. The optimum computed Y_n of 1.447×10^8 neutrons/shot for 11.2 kJ plasma focus device was achieved at 4.1 Torr. For 28.8 kJ device, the optimum computed Y_n of 1.24×10^9 neutrons/shot was obtained at 2.2 Torr deuterium pressure at 20 kV. For the 480 kJ device, the optimum yield of 1.8×10^{11} neutrons/shot was obtained at pressure and charging voltage of 7.6 Torr and 27 kV respectively. Analysis of the results showed that the optimum neutron yields were achieved only at optimum operating conditions. It was also found that no soft X-rays were emitted from the 28.8 kJ plasma focus operated in argon gas due to the absence of Helium-like and Hydrogen-like ions at the recorded low plasma temperature of 0.094 keV and axial speed of 8.12 cm μs^{-1}. In conclusion, the current sheath speed is not a dominant factor for optimizing neutron yield in plasma focus devices.

ABSTRAK

Peranti tumpuan plasma adalah satu sumber berpotensi bagi perlepasan sinaran-pelbagai. Ujikaji berangka telah dijalankan untuk mengkaji pelepasan sinaran-pelbagai bagi sinar-X lembut dan neutron daripada peranti tumpuan plasma jenis Mather dengan julat tenaga daripada 1.4 kJ hingga 480 kJ yang beroperasi dalam gas deuterium dan argon. Peranti ini telah dipilih kerana ia menyediakan satu geometri terbuka dengan sudut pengumpulan yang besar dan boleh beroperasi dengan julat parameter yang luas. Walau bagaimanapun, kajian terhadap tekanan gas optimum, kelajuan sarung arus, dan cubitan arus masih diperlukan untuk pemahaman yang lebih baik terhadap peranti ini. Dalam kajian ini, Kod Lee versi RADPF6.1b telah digunakan untuk melaksanakan proses pemasangan profil arus. Faktor jisim sapuan dan arus bagi fasa paksian dan jejarian telah digunakan untuk menampung keadaan yang dihadapi dalam ujikaji. Semua sifat pukal termasuk dinamik sinaran telah diragakan secara nyata apabila profil arus yang dihitung dan diukur disesuaikan dengan baik. Dalam kes peranti 1.4 kJ, perlepasan neutron optimum yang dihitung, Y_n ialah 2.9×10^7 neutron/tembakan pada 5.5 Torr tekanan deuterium. Y_n optimum yang dihitung bagi 1.447×10^8 neutron/tembakan untuk peranti tumpuan plasma 11.2 kJ telah dicapai pada 4.1 Torr. Untuk peranti 28.8 kJ, Y_n optimum yang dihitung bagi 1.24×10^9 neutron/tembakan telah diperoleh pada 2.2 Torr tekanan deuterium pada 20 kV. Untuk peranti 480 kJ, Y_n optimum dihitung bagi 1.8×10^{11} neutron/tembakan telah diperoleh masing-masing pada tekanan dan penyecasan voltan 7.6 Torr dan 27 kV. Analisis terhadap keputusan menunjukkan bahawa sinar neutron optimum hanya dicapai pada keadaan operasi yang optimum. Didapati juga bahawa tiada sinar-X lembut yang dipancarkan daripada peranti tumpuan plasma 28.8 kJ yang dioperasi dengan gas argon disebabkan oleh ketidakhadiran ion seperti-Helium dan seperti-Hidrogen pada suhu plasma yang dicatatkan serendah 0.094 keV dan kelajuan paksian sebanyak 8.12 cm $\mu\mathrm{s}^{-1}$. Kesimpulannya, kelajuan sarung arus adalah bukan satu faktor dominan untuk mengoptimumkan hasil neutron dalam peranti tumpuan plasma.

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LIST OF ABBREVIATIONS

PF	-	Plasma Focus
RADPF	-	Radiative Dense Plasma Focus
UNU-ICTP	-	United Nations University/International Centre for Theoretical Physics
PMT	-	Photomultiplier Tube
BIC	-	Baise Ion Collector
MCNPX	-	Monte Carlo Simulation Package
KSU	-	Kansas State University
HV	-	High Voltage
SXR	-	Soft X-ray
CCD	-	Charge Coupled Device
SDS	-	Small Disturbance Speed
JPEG	-	Joint Photographic Experts Group
xls	-	Microsoft Excel 2007 binary file

LIST OF SYMBOLS

L_o	-	Static Inductance
L	-	Plasma Inductance
L_a	-	Axial Phase Inductance
C_o	-	Capacitance
V_o	-	Charging Voltage
r_o	-	Stray Resistance
b	-	Radius of Circle Formed by Cathode Rods Surrounded the Central Anode
a	-	Anode Radius
z	-	Instantaneous Position
z_o	-	Anode Length
P_o	-	Gas Pressure
f_m	-	Axial Phase Mass Sweeping Factor
f_{mr}	-	Radial Phase Mass Sweeping Factor
f_c	-	Axial Phase Current Factor
f_{cr}	-	Radial Phase Current Factor
Y_{n}	-	Neutron Yield
Y_{th}	-	Thermonuclear Neutron Yield
$Y_{b\text{-}t}$	-	beam-target Neutron Yield
V_p^{max}	-	Maximum Voltage Drop During The Pinch
ΔE_p^{max}	-	Maximum Energy Transfer To The Pinch
ΔI	-	Change In Discharge Current Trace
I	-	Circuit current
I_o	-	Characteristic Current
I_{pinch}	-	Pinch Current
I_{peak}	-	Peak Current
E_o	-	Device’s Energy

RESF	-	Ratio Of Stray Resistance To Impedance
EINP	-	Work Done By The Radial Magnetic Piston
Si	-	Silicon
H	-	Hydrogen
H^2 or H^3	-	Hydrogen Isotopes
He	-	Helium
Cu	-	Copper
Al	-	Aluminum
Ti	-	Titanium
Ar	-	Argon
Ne	-	Neon
D_2	-	Deuterium Gas
H_2	-	Hydrogen gas
Be	-	Beryllium
Y_{sxr}	-	Soft X-ray Yield
c	-	b/a
$\vec{J}$	-	Current Density
$\vec{B}$	-	Magnetic Field
p	-	Momentum
m	-	Object's mass
r_s	-	Shock Front Position
r_p	-	Magnetic Piston Position
z_f	-	Pinch Length
v	-	Velocity
v_a	-	Characteristic Axial Current Sheath Speed
v_s	-	Radial Shock Front Speed
v_p	-	Radial Magnetic Piston Speed
v_r	-	Characteristic Radial Inward Shock Speed
ρ_o	-	Ambient Density
F	-	Magnetic Force
μ	-	Permeability
R or r	-	Plasma Resistance
τ	-	Time In Normalized Form

ζ	-	Current Sheath Axial Position in Normalized Form
ι	-	Current In Normalized Form
Z_o	-	Surge Impedance
t	-	Time
t_o	-	Characteristic Discharge Time
t_a	-	Characteristic Current Sheath Travelling Time In Axial Phase
t_r	-	Characteristic Current Sheath Travelling Time In Radial Phase
D	-	Incremental Time
P_m	-	Magnetic Pressure
P	-	Shock Pressure
γ	-	Specific Heat Ratio
Z_{eff}	-	Effective Charge Number
dV	-	Pinch Slug Volume
κ_s	-	Shock Front Position In Normalized Form
κ_p	-	Magnetic Piston Position In Normalized Form
ζ_f	-	Pinch Length In Normalized Form
Δt	-	Time Lapse Between The Shock Front And Magnetic Piston
D_c	-	Departure Coefficient
k_B	-	Boltzmann's constant
m_p	-	Proton Mass
R_o	-	Universal Gas Constant In SI Units
T	-	Shock Plasma Temperature
Q_J	-	Joule Heating Energy
Q_B	-	Bremsstrahlung Energy
Q_{rec}	-	Recombination Energy
Q_L	-	Line Radiation Energy
N_i	-	Ion Number Density
N_o	-	Ambient Number Density
Z_n	-	gas atomic number
A	-	self-absorption corrected factor

M	-	photonics excitation number
V_{max}	-	induced voltage
T_{pinch}	-	Pinch Temperature
r_{min}	-	Minimum Pinch Radius
z_{max}	-	Maximum Pinch Length
Xmin	-	Minimum Value of X-axis
Xmax	-	Maximum Value of X-axis
Ymin	-	Minimum Value of Y-axis
Ymax	-	Maximum Value of Y-axis
$t_{\text{p-dur}}$	-	Pinch Duration

CHAPTER 1

INTRODUCTION

1.1 Background

In general, the plasma focus (PF) device has a structure which comprises a set of metal rods acting as the electrodes, located inside a stainless steel chamber and filled with gas at low pressure. In the early 1960s, the research on plasma focus device was initiated by Mather [1] and also independently by Flippov [2]. This high-voltage high-current pulse-powered discharge device consists of a capacitor bank, charger, high-voltage high-current switch, master trigger and discharge chamber [3]. A high voltage pulsed discharge between the electrodes through the selected gas medium produces a column of hot dense plasma, i.e. current sheath, which then axially driven by a *Lorentz* force and leads to the strong electromagnetic compression of the plasma at truncated end of the anode [4]. The electromagnetically compression of plasma column results in hot and dense plasma pinch. As a consequence of the very fast plasma compression attained in this device, multi-radiation such as neutron yield [5], soft [6] and hard [7] X-rays, high energy electrons [8], and ions beams [9] are emitted.

Plasma focus device has been studied over the past few decades as a copious source of multi-radiation [10]. Scientists have put their effort on continuous studies of multi-radiation of this particular device especially in neutron and soft X-ray yields [6, 11-15]. In the numerical aspects, the Lee's code, consists of the combination of snow plow model and slug model, has been used for comprehensive studies on modeling of plasma focus [9, 16-19]. From previous works, its found that the careful selection of suitable experimental parameters can enhance the radiation yields in the plasma focus device. In this chapter, the problem statement, objectives, scope and the significant of the research are presented.

1.2 Problem Statement

The plasma focus device is an ideal multi-radiation source as it can generate ions, electrons, X-ray and neutron in a single shot. Over the past several years, the pulsed discharge plasma focus device as a potential multi-radiation source for numerous potential applications has been extensively studied such as material modifications [20], non-destructive industrial, medical or security examination [7, 21, 22] surface micro-machining [23], microelectronics lithography [24], thin film deposition [25] and etc.. The discharge voltage signal of the device has been widely used to study the system’s dynamics, in order to understand the radiation yield mechanisms and other phenomenon. This device was chosen since it provides an open geometry with the largest possible collection angles operated over wide parameter ranges.

However, the extension of performance and the characteristic of such device on the multi-radiation emission of neutrons and soft X-ray in different discharging parameters have not yet been fully understood, the contributions to the group of knowledge are significant. The current discharge signal which has important information as compared to the voltage discharge signal has not been studied comprehensively. Also the attainment of optimum condition for the device needed extensive studies for the wider range of applications. Due to the project cost and time required for the experimental optimization processes, the numerical modelling can reveal essential output parameters before the real work on the fabrication can begin.

1.3 Objectives of the Research

1.3.1 General Objective

The general objective of this research is to numerically investigate the physics for the multi-radiation emission from the plasma focus devices.

1.3.2 Specific Objectives

The specific objectives of this research are:

- To determine using Lee's code the multi-radiation emission of neutron and soft X-ray from the plasma focus devices with different performance parameters.
- To optimize using Lee's code the neutron emissions of plasma focus for specific gas pressure.
- To determine the relationship of the plasma focus dynamics and the multi-radiation emissions of plasma focus devices.

1.4 Scope of the Research

The present research are mainly focused on the determination of neutron and soft X-ray emission from the plasma dynamics of Mather type plasma focus devices by numerical methods against experimental results. The hot and dense plasma pinch produced during the plasma compression has its radius of 1 – 25 mm and length of 10 – 190 mm and last for tens of nanoseconds to several hundreds of nanoseconds. The numerical experiments results were obtained using the 6-phase Lee Model Code, Version RADPF6.1b. The code was configured for the plasma focus devices with energies ranging from 1.4 kJ – 480 kJ, using the published parameters such as inductance, L_o, capacitance, C_o, charging voltage, V_o stray resistance, r_o, radius of the cathode, b, anode radius, a, anode length, z_o, gas pressure, P_o and the molecular weight and atomic number of filling gas. The current profiles fitting between the computed against experimental were performed. The mass sweeping factors (f_m and f_{mr}) and the current factors (f_c and f_{cr}) for axial and radial phase were used as the fitting coefficient. Then, optimizations of yields were conducted numerically as a function of pressure.

1.5 Significance of the Research

The significance of this work is to access numerically the plasma focus device as a multi radiation source. Previously the emphasis was on discharge voltage signals of the device and not the current signals, which also consists of important information. This work however, was fully focused on the investigation of current discharge signals to determine the neutron and soft X-ray emissions. The plasma focus device possessed potential applications, which allow the area of studies beyond basic plasma that can contribute significant impact in the scientific world. Design, construction, conception, diagnostics and research of the devices for different applications have been made based on the standard developed procedures. The potential applications of the neutron and soft X-ray from the plasma focus have been demonstrated [20-28]. The plasma focus device as a neutron source, including its possibility to generate nuclear fusion particles or radiation, is essential for the research dealing with the global energy security issue.

1.6 Thesis Outline

This thesis report on the numerical determinations of neutron and soft X-ray emissions from Mather-type plasma focus devices using the Lee’s code. The contents have been presented in six separated chapters according to the research flow.

- Chapter 1 describes the research background, problem statement, objectives and the scope of research.

- Chapter 2 consists of the literature reviews on the plasma focus devices and experimental and numerical studies of neutron and soft X-ray emission.
- Chapter 3 explains the theory of the plasma focus device dynamics, working principle, and the Lee's code computation.
- Chapter 4 illustrates the research methodology of experimental data extraction, current profiles fitting, and radiation yield optimization.
- Chapter 5 presents the results and discussions of the current profiles fitting between the computation and experiment current signals and the comparison of the numerical experiments radiations from the plasma focus devices.
- Chapter 6 concludes the whole research work by summarizing from the observations and findings.

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