# DYNAMICS OF MATHER TYPE PLASMA FOCUS WITH STEP ANODE CONFIGURATION

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*To my beloved parents & family*

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# ABSTRACT

The tube parameters are of importance to the dynamical properties of plasma as it undergoes the axial and the final pinch phase in a plasma focus. Neutron yield of the plasma focus is dependent on plasma dynamics. The study was aimed to investigate the plasma dynamical behaviour of deuterium gas in Mather type plasma focus with step anode configuration in order to enhance the neutron yield. The model is based on the Lee code version RADPFV5.15FIB under Visual Basic program. The equation of motion of the current sheath was derived for the step anode configuration based on snowplow model and slug model. In this numerical study, the modified Lee model was used to describe the dynamics of current sheath between the outer electrodes and inner electrode with step configuration based on momentum conservation of swept gas. The plasma inductance development from numerical analysis was found to be consistent with the plasma sheath motion across the coaxial tube which gives the total static inductance equal to 104.5 nH and the stray resistance equal to 8.5 mΩ. Numerical experiments has been carried out between the step anode configuration plasma focus system and the cylindrical anode configuration plasma focus system which showed that the step anode configuration system is able to enhance the plasma sheath speed by 42.4 % from the cylindrical anode configuration. The neutron yield from the cylindrical anode configuration system with the effective anode length of 173 mm showed an optimum values of neutron yield of $1.212\times10^{8}$ neutrons from various anode diameters at 3.3 mbar. It was found that due to the speed enhancement, the neutron produced from the step anode configuration system was also increased by 8.2 % at its optimum pressure. In conclusion, the neutron yield is significantly enhanced in step anode configuration of the Mather type plasma focus.

# ABSTRAK

Parameter tiub adalah sangat penting dalam sifat dinamik plasma semasa melalui fasa paksi dan fasa sempitan terakhir dalam plasma fokus. Hasil neutron plasma fokus ini adalah bergantung kepada dinamik plasma. Kajian ini bertujuan untuk menyiasat perilaku dinamik plasma gas deuterium dalam plasma fokus jenis Mather dengan tatarajah anod berinjak untuk meningkatkan hasil neutron. Model ini adalah berdasarkan kepada kod model Lee versi RADPFV5.15FIB di bawah program Visual Basic. Persamaan pergerakan bagi arus plasma telah diperoleh untuk tatarajah anod berinjak berdasarkan model pembajak salji dan model lintah bulan. Dalam kajian berangka ini, model Lee yang diubahsuai itu telah digunakan untuk menggambarkan dinamik sarung plasma di antara elektrod-elektrod luar dan elektrod dalam dengan tatarajah anod berinjak berdasarkan keabadian momentum gas tersapu. Perkembangan aruhan plasma daripada analisis berangka didapati konsisten dengan gerakan sarung plasma merentasi tiub sepaksi yang memberikan jumlah aruhan statik sama dengan 104.5 nH dan rintangan kesasar sama dengan 8.5 mΩ. Ujikaji berangka telah dijalankan antara sistem plasma fokus bertatarajah anod berinjak dan sistem plasma fokus bertatarajah anod silinder yang menunjukkan bahawa sistem tatarajah anod berinjak mampu meningkatkan kelajuan sarung plasma sebanyak 42.4 % berbanding sistem tatarajah anod silinder. Hasil neutron dari sistem tatarajah anod silinder dengan panjang anod berkesan 173 mm telah menunjukkan nilai hasil neutron yang optimum sebanyak 1.212 × 108 neutron dari pelbagai diameter anod pada 3.3 mbar. Didapati bahawa disebabkan peningkatan kelajuan, neutron yang dihasilkan dari sistem tatarajah anod berinjak juga telah meningkat sebanyak 8.2 % pada tekanan optimum. Kesimpulannya, hasil neutron meningkat secara ketara dalam tatarajah anod berinjak plasma fokus jenis Mather.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| PF | - | Plasma focus |
| RADPF | - | Radiative plasma focus |
| SPF | - | Spherical plasma focus |
| UNU-ICTP PFF | - | United Nation University—International Center for Theoretical Physics Plasma Focus Facility |
| NIE-SSC-PFF | - | National Institute of Education - School of Science – Plasma -Focus Facility |
| SF | - | Shock front |
| RP | - | Radial piston |
| SAC | - | Step anode configuration |
| CAC | - | Cylinder anode configuration |
| WOCM | - | Without corrected mass |
| WCM | - | With corrected mass |
| LR | - | Lower region |
| UR | - | Upper region |
| SR | - | Step region |
| OFHC | - | Oxygen-free high conductivity |
| VBA | - | Visual Basic for Application |
| SXR | - | Soft X-ray |
| HXR | - | Hard X-ray |
| MHD | - | Magneto-hydro-dynamical |
| ICF | - | Inertial confinement fusion |
| DXS | - | Diode x-ray spectrometer |
| HP | - | High pressure |

# LIST OF SYMBOLS

A - Atomic Weight

$a$ - Anode Radius

$a_1$, $a_2$ - Step anode radius

B - Magnetic Field

b - Cathode Radius

$b_p$ - Radial position

c - Ratio of Cathode to Anode Radius

$c_s$ - Sound speed

$C_o$ - the Capacitor bank for energy storage

dQ - External Input Energy

EINP - Energy input into plasma

$E_I$ - The energy stored in the tube inductance

$E_i$ - Ionization energy

$\gamma$ - Specific Heat Ratio

$\Gamma$ - Shock density ratio

$f_{m1}$ - Axial mass factors

$f_c$ - Axial current factors

$f_{m2}$ - Radial mass factors

$f_d$ - surface coefficient

$f_L$ - Inductance factor

$f_{cr}$ - Radial current factors

$F_d$ - Drag force

$F_{z1}$ - Axial Lorentz force on plasma sheath

$F_{zr}$ - Radial force on plasma sheath

$F_m$ - Magnetic force

h - Focus enthalpy

$h_t$ - Total enthalpy

$h$ - Plank’s Constant

$h_L$ - leakage resistance in the plasma tube

$I$ - Discharge Current

$I_p$ - Plasma Current

$I_{pinch}$ - Pinch current

$I_{max}$ - Peak Discharge Current

$J$ - Current Density

$J \times B$ - driving magnetic force

$\mathrm{k_B}$ - Boltzman Constant

$\mathrm{k_eV}$ - kilo electron volt

$l_{Ins}$ - Length of the insulator

$l_v$ - The mean free-path

$L_o$ - The fixed circuit inductance

$L_{pr}$ - Effective inductance

$L_p$ - Changing plasma tube inductance.

$L_o$ - External (stray) Inductance

$M$ - Molecular weight

$m_i$ - The mass of atom or ion.

$m$ - Atomic mass of the filling gas

$n$ - Number density of ions and electrons

$n_i$ - Ion Density (in the code)

$n_0$ - Atomic number density of the filling gas

$n_b$ - Number of beam ions per unit plasma volume

$N_i$ - Ion number density

$N_e$ - Electron number density

$N_b$ - number of beam ions

$\rho$ - Shocked gas density

$\rho_\mathrm{o}$ - Ambient gas density

$P_B$ - Magnetic pressure

$P_p$ - Piston pressure

$P_J$ - Rate of Joule heating

$P_0$ - Ambient gas pressure

$P$ - Shocked gas pressure
$Q$ - Total electric charge
$q_o$ - Speed of the shocked gas
$q$ - Speed of the ambient gas
$R_s$ - Particle position
$RC$ - Integration time constant
$r_p$ - Slug external radius
$r_s$ - Slug internal radius
$r$ - The boundary radius of curvature
$r_c$ - Critical radius
$R_o$ - The circuit resistance
$Ro$ - Universal gas constant
$R_p$ - Plasma resistance
$T$ - Shock temperature
$t_{p-s}$ - Transmission time
$t_a$ - Characteristic axial run down time
$\tau$ - Confinement time
$T$ - Plasma temperature
$T_e$ - Electron temperature
$\mu_o$ - Permeability of Free Space
$V_o$ - Capacitor voltage
$V_{Slug}$ - Volume of plasma slug
$V$ - Plasma volume

$V_{max}$ - Maximum voltage induced by the current sheath
$U$ - Internal energy
$U$ - disruption-caused diode voltage
$\upsilon_{Ti}$ - The thermal velocity of ion
$\upsilon_s$ - shock front speed
$v_p$ - piston speed
$v_b$ - beam ion speed
$Y_{th}$ - Thermonuclear term
$Y_{b-t}$ - Beam-target yield
$Z$ - Atomic number

$z$ - Instantaneous current sheath position

$Z_{eff}$ - Effective (average) charge number of one ion

$z_o$ - Length of anode

$z_f$ - Radial elongation pinch length

$Z_i$ - Effective charge

$Cp$ - Specific heat capacity at constant pressure

$Cv$ - Specific heat capacity at constant volume

$D$ - Dissociate number of the singular gas particle or one neutral atom

$\eta_\perp$ - Spitzer resistivity

$\sigma$ - Cross-section of the D–D fusion reaction

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background of Study

Plasma focus (PF) devices is a electrical pulsed discharge between filled gas coaxial electrodes which is one of the dynamic Z-pinches category that are self-constricted plasma configurations [1, 2] In the early 1960s, the Mather type and the Filippov type PF device were originally developed independently by USA [3]and the former Soviet Union [4] respectively. The discharge tube of Filippov type PF device is configured with 2R/L >1, while the Mather type PF device is configured with 2R/L <1, where R and L represent the anode radius and length, correspondingly. Currently, some development of PF device have been investigated [3, 4] using small PF devices operating at low capacitor bank energy which give to a range of tens to hundreds of joules alternatively to the high energy device range in kilojoule to megajoule. As pulsed plasma generators, the PF devices operating relatively in simple principle by utilize a self-generated magnetic field, for compressing the plasma to a very high temperatures (1–2 keV) and high densities ($\approx 10^{25}$–$10^{26}$ $m^{-3}$) which is dependent to the energy bank that provided to the system. There are also has been historically known as fusion devices, which is due to its capabiltity to produced intense neutrons bursts with deuterium gas filled. However, the PF devices are not only limited to its capability as fusion neutrons source [7] but also able to generates fast ion beam [8], relativistic electrons [9] and copious amount of hard X-ray (HXR) and soft X-ray (SXR) [8–11].

Previously, Zakaullah *et al.* [14] have studied the anode configuration effect on the energy of argon X-ray as well as Bhuyan *et al.* [13] on nitrogen and hydrogen SXR energy for Mather-type PF. Serban [15] had investigated anode configuration geometry and focus characteristic experimentally using the National Institute of Education - School of Science - Plasma -Focus Facility (NIE-SSC-PFF). In this study, the effect of anode configuration on the plasma focus neutron yield is investigated based on numerical modelling. Numerical modelling plays an important role where it can be used to compare the developed physical theories with experimental data. The process and physical properties related to PF which includes the energy transfer processes, the electrical properties, the shock wave interactions and the thermodynamic properties are know to be complex. Nevertheless, with a suitable equation applied describing the processes and physical properties involved, numerous physical models have been developed which able to simulate the plasma temperature, plasma dynamics and along with the emission of electromagnetic radiation and high energy particle from a PF device from a contructive reasoning. The dynamical model can be from a simple 1D snowplough model to a slightly complex 2D magnetohydrodynamic (MHD) model [16]. The thesis is focus on the numericals study of Mather type PF device with step anode geometry and cylindrical anode geometry. The plasma dynamic dependency on the anode geometrical shapes is investigated using modified Lee Model Code.

## 1.2 Problem Statement

A dynamical model with two main phase; axial phase based on snowplough model and radial phase based on a slug model has been numerical design by Lee [12–16] for the PF device. In the radial phase, the model considered that pinch plasma concurrently elongated further from the tip of anode while the plasma confined between the shock front and the $\boldsymbol{J}\times\boldsymbol{B}$ force. Thus, the model have shown it’s competent in providing a realistic pinch minimum radius. The Lee model is developed based on the law of conservationof energy. The model parameter introduced in the Lee model accounted from the energy losses of the total input plasma energy. The model parameter have been significantly important to this area of research which give the simulated result to be realistic to the experimental observation. The current versions of the Lee model are already capable of simulating various PF devices around the globe although it is still limited to the standard cylindrical electrode configuration. There are only few numerical studies were conducted for the past decades regarding to the step anode which only give us little information regarding how this actual could bring a significant effect to the dynamics of plasma sheath during axial phase and neutron yield.

## 1.3 Research Objectives

The general objective of this research is to investigate the dynamic phase and the circuit model of Mather type plasma focus with step anode configuration (SAC) using the Lee Model. The specific objective are as follows

- To determine the total static inductance, stray resistance profile and plasma inductance development from numerical analysis of discharge current traced and tube voltage signal.
- To improve the precision of current profile fitting by considering the impedance development in the modified Lee code
- To examine the dynamics of the PF for both axial and radial phases for cylindrical anode and step anode geometry.
- To evaluate numerically on the neutron yield from the cylindrical and step electrode configuration.

## 1.4 Research Scope

This project is focuses on developing the current Lee Model Code for simulating a PF device with various step anode configurations. Numerical experiments will be conducted using modified Lee model version RADPFv5.15FIB to compute step configured electrode plasma focus. The static inductance and stray resistance profile of the NIE-SSC-PFF device [15] will be firstly determined from discharge current trace and voltage signal which then will be used to acquire the inductance development. The model current trace will be fitted with the experimental result as a baseline to calibrate the numerical simulation in order to make it realistic. Neutron generation from fusion reaction when using deuterium filling gas is computed for step anode and compared with the standard cylindrical electrode in this numerical investigation.

## 1.5 Significance of Research

The significance of this study is to expand the potential of the Lee Model Code which enable it to compute more than just a standard tube parameter of cylindrical electrode configuration. The improvement of the Lee model will give us a significant control variable and this will open a new area in optimizing the DPF device for SXR yield and neutron yield. The new optimize value achieve from computing with various configuration electrode will give us a new understanding on how we could design the electrode that satisfactory for a specific used of the DPF devices. The determination of static inductance and stray resistance profile from numerical analysis can be contributed to new understanding of plasma discharge in the plasma focus device. Temporal inductance evolution of the PF device determined from both current trace and voltage signals can be used as a tool for understanding the dynamic of the plasma sheath in PF discharges.

## 1.6 Thesis outline

This thesis report on the numerical investigations of plasma dynamics and neutron yield from step configured electrode plasma focus devices using the modified Lee model code. The contents have been presented in six separated chapters according to the research flow. In chapter 1, the introductory description is covered with the background, brief history of the plasma focus research, followed by the problem statement, objectives of research, scope of research and its significance to the current research. The following chapter 2, will reviewing on the historical background of a plasma study, the dense Z-pinch, different phases in plasma focus operation, dynamics of current sheath in plasma focus, various configuration of electrodes and experimental and numerical studies of neutron yield. In chapter 3, the theory of the different phases of plasma focus device, dynamics and electrical properties of step configured electrode and working principle of plasma focus device is elaborated. In this report, chapter 4 will illustrates the research methodology of experimental data extraction, static and dynamic of inductivity and resistivity of the PF device, current profile fitting, and computation procedure for numerical simulation. Chapter 5 presents the results of the determination of inductance and resistance, current profiles fitting between the computation and experiment current signals and the comparison between step and cylindrical configured electrode on neutron yield radiations from the plasma focus devices numerically and is thoroughly discussed. The whole research work research is concluded in chapter 6 from the observations and findings.

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