Chapter 1

Introduction

Plasma exists can be produced by gas discharge. Examples of plasma used in daily activities are the fluorescent lights, arcs, welding and sterilization of medical products. Whilst lightning strikes is a natural discharge phenomenon that causes the air molecules to ionized and become plasma. Plasma technology has been applied in material and semiconductor processing industries, especially in surface treatment of polymers [Arefi et al., 1992], plasma immersion ion implantation (PIII) for ion nitriding of metal components [Rossi et al., 2001, Ueda et al., 2003], plasma etching in electronic circuits or integrated circuits [Bogaerts, 1999] and sputtering of indium tin oxide onto polymeric materials [Wakeham et al., 2009], and plasma pyrolysis of medical waste [Nema and Ganeshprasad, 2002].

The interest in controlled fusion discerned further when it was found that magnetized plasma can be confined and heated to so high temperature that thermonuclear energy could be released and be used as a substitute of energy supplied by burning of fossil fuel. A fusion reactor burning just 1 kg of fuel could produce a sustained power output of 1 GW. One way to do this is to use a tokamak. A tokamak is a device which confines plasma in the shape of a torus with the presence of a helical magnetic field. Another relatively simpler and low cost device that could be used to demonstrate nuclear fusion processes is the small plasma focus device.

Recently, the research on the compact plasma focus devices has attracted the attention of the plasma research community. The small-scale plasma focus facilities use capacitor bank of tens to hundreds of joules and are usually operated in repetitive mode for a frequency in the regime of Hz to kHz. When deuterium or deuterium–tritium mixtures are used as the operating gas in a plasma focus device, fusion reactions occur during the pinch phase, generating intense pulses of neutrons with a neutron yield about 2×10^{11} n per pulse [Mather, J. W., 1965, Gribkov et al., 2007]. The pulsed neutron produced from plasma focus discharge can be used for various applications [Gribkov, V. A., 2008].

Besides neutron yield, a wide spectra of radiation emission which ranging from visible light up to hard x-rays was observed in plasma focus discharges [Casanova et al., 2005]. The plasma focus devices generate radiation output that can be used in a number of industrial applications [Moreno, C., 2002] such as tailored soft x-ray sources [Zakaullah et al.,2000, Lee et al., 1998], hard x-ray radiography of metallic manufacture [Hussain et al., 2004, Moreno et al., 2001] and neutronic detection of hydrogen by neutron scattering [Moreno et al., 2000].

The operation of a plasma focus device is usually divided into three phases that are the initial break-down, the axial rundown and the radial compression phases. Due to the high current pulse discharge, a current sheath (a dense plasma layer) is formed upon the insulator surface during the initial break down phase.

The coupling of the current density and the self-generated magnetic field produces a $J\times B$ electromagnetic force which will drive the current sheath to accelerate down the electrode ends. The length of the electrodes can be chosen such that the transit time matches the capacitor rise time. During this axial rundown phase, the rising capacitor current drives the current sheath axially down the electrode at a suitable speed until the current sheath reaches the end of the electrode.

After reaching the electrode ends the current sheath undergoes radial collapse towards the z-axis and it forms a dense plasma column. This radial compression phase is very intense because it starts at a very large current, usually at the peak of the discharge current.

In this project, the dynamics of the current sheath during the axial acceleration phase is simulated by using the Snow-plow Model. The parameters fitted are based on a 600 joules small Mather-type plasma focus device, which is in operation in the Plasma Technology Research Center in University of Malaya.

1.1 Literature review

1.1.1 Current sheath dynamics of plasma focus

Current sheath dynamic is an important parameter for good focusing in a plasma focus (PF) device. The structure of the current sheath from breakdown to the pinching phase has been studied in a small scale (50-160J) plasma focus facility by employing the time-integrated optical imaging method [Hassan et al., 2006]. The pinching is seen to occur at 380 ns and the current sheath buildup time is around 80 to 110 ns after the initial breakdown of gas. The evidence of pinching was observed as a bright spot in the time-integrated image. Images of bright plasma column have been registered at different gas filling pressures. The size of the bright spot varies with the filling gas pressure and it is becomes minimum at 12 mbar gas filling pressure. The size of the bright spot was measured to be around 1 mm at this condition.

A very small plasma focus device has been designed and constructed by Soto et al. (2002). The plasma focus operates in the limit of low energy (160 nF capacitor bank, 65 nH, 20−40 kV, 32−100 J). Experiments have been performed using H_2 at pressures over the range 0.1 to 2.0 mbar. The diagnostics used in the experiments include current derivative, voltage monitor, and plasma image using an ICCD camera gated at 5 ns. The umbrella-like current sheath running over the end of the coaxial electrodes and the pinch after the radial collapse can be clearly observed in the photographs taken by an ICCD camera gated at 5 ns of exposure time. The velocity of the radial collapse is of the order of 10^5 m/s.

An advantage of a miniature device is that it can be operated in repetitive mode from Hz to kHz. Neutron yield of $10^4 - 10^5$ neutron per pulse is expected and is observed in a 400 J plasma focus discharge operated with deuterium. Whereby, the neutron yields measured are in the range of $10^7 – 10^{12}$ per shot with plasma focus energy ranges 1 kJ – 1000 kJ [Soto et al., 2003].

The effects of the argon gas pressure, charging voltage and anode shape on the current sheath dynamics in a low energy (4.9 kJ) Mather type plasma focus (PF) were investigated [Behbahani et al., 2010]. The radial magnetic probe measurements showed a rather constant current sheath velocity near the insulator, which was more sensitive to the variations of the gas pressure than the charging voltage. The current sheath did not lose its uniformity when expanding away from the insulator during the break-down phase. In the case where a stepped anode is used instead of a cylindrical one the results found from the axial magnetic probe signals also revealed a higher current sheath velocity inside the step region of the step anode [Behbahani et al., 2010].

The physical properties and processes, such as the electrical characteristics, shock wave interactions, the thermodynamic properties and the energy transfer processes, associated with the plasma focus are complex. Several models have been developed to study the plasma focus discharge, includes those based on the 2D magneto-hydro-dynamical (MHD) model [Garanin and Mamyshev, 2008] and the simple 1D snow plow model [Lee, 1998]. These models can be used to reasonably predict the plasma dynamics, the plasma temperature and the subsequent emission of particles and radiation.

Lee (1998) has developed a Lee Model, which is a dynamic model for plasma focus. In this model the axial phase is computed using a snow-plow model and the radial phase is computed using a slug model [Lee, 1998]. Wong et al. (2007) have refined and used the code of Lee Model to simulate the 4 phases of NX2, 3 kJ plasma focus device. The simulation shows that the axial velocity and the radial velocity of the current sheath are both proportional to the drive parameter $(I_o/a)/\rho^{1/2}$, where I_o is the peak current driving the plasma sheath, a is the anode radius and ρ is the ambient gas density. The result of the simulation agreed well to the experimental result after making adjustments to the inductance of the circuit, the mass factor and the current factor. [Wong et al., 2007].

Casanova et al. (2005) presented a finite-elements approximation of plasma focus discharges, which reproduced precisely the evolution of the current sheath. The current sheath was modeled with attributes of the mass, position, velocity, acceleration, density and internal energy of the plasma.

Garanin and Mamyshev (2008) introduced the MHD into the plasma focus model, which takes into account the anomalous resistivity. This Magnetohydrodynamic (MHD) codes where spatially resolved and detailed description (for example, the calculations of the ion velocity, the ion density, the ion and electron energies, the electron and ion thermal conductivities, the electric conductivity and the distributions of the magnetic and electric field, the neutron generation rate and the radiative losses) of plasma properties is calculated. They presented a method for numerical simulations of the dynamic of the current sheath that showed the acceleration of the current sheath, its collapse on the axis, followed by the formation of a pinch. The model is based on a set of two-dimensional MHD Euler equations with a single nonzero magnetic field component. This model which involving accelerated ions is proposed to estimate the contribution from the acceleration mechanism to the neutron yield. A scheme for calculating the yield of neutrons generated via the acceleration mechanism is described. With allowance for these neutrons, the calculated total neutron yield differs from the measured one by a factor of less than 2 [Garanin and Mamyshev, 2008].

In 2009, González et al. have presented a lumped parameter model of plasma focus without surrounding cathode containing the radial expansion of the current sheath [González et al., 2009]. This model which was based on the snow-plow approximation was applied to calculate the voltage during the formation of the plasma pinch in a small 300 J plasma focus device. The calculation showed good agreement with the experiments.

Although there are many models proposed to simulate the various properties of a plasma focus device (included the dynamics), however, the 1-D snow plow model is the simplest and yet accurate to simulate the axial phase of a plasma focus device.

1.2 The Objective of the Research Project

The main objective of this project is to simulate the dynamics of the current sheath during the axial acceleration phase. The physical parameters of the plasma focus used are based on the 600 J plasma focus device in the Plasma Research Lab. The Snow-plow model is used in the computation for the axial phase.

1.3 The layout of the project

In Chapter 1, a brief introduction of plasma focus device is given. The different phases in a plasma focus discharge are described. A literature review on some works on the current sheath simulation and theoretical studies is presented. The objective of the project is also stated.

In Chapter 2, a detail description of the Snow-plow model is presented. Besides, the Slug-model which is useful to predict the radial compression phase is discussed. In Chapter 3 the computational results are presented as well as the calculations to obtain the axial rundown speed of the current sheath are performed. The outcome of the project is summarized in Chapter 4.