Chapter 2 The Plasma Focus

2.1 Introduction

Dense plasma focus (DPF) is capable in producing pinched plasma that is hot and dense that it becomes a copious multi-radiation source. Formation of the pinched plasma depends on the discharge dynamics.

The DPF discharge is initiated upon transfer of the stored energy in a capacitor bank to the coaxial electrodes. Breakdown and current sheath are formed at the backwall of the electrodes. The current sheath lifts off at the backwall due to the Lorentz force. This electromagnetic force due to the interaction of the current density and its self-induced magnetic field accelerates the current sheath axially toward the open end of the electrodes. Strong magnetic compression occurs at the end of the electrodes where a dense plasma column is formed. Upon onset of instabilities, the plasma column is disrupted. Intense radiation and particle beams are emitted during the pinching and disruption of the plasma.

The whole process of pinching takes tens to hundreds of nanoseconds for a several hundred joules DPF and around a microsecond for a mega joules DPF.

2.2 Plasma Focus Tube Design

The essential part of the plasma focus device is the plasma focus tube consisting of the electrode system. Figure 2.1 shows the schematic of the plasma focus tube. The set of coaxial electrodes has a length of 60.00 mm (z). The inner electrode is surrounded by six symmetrically arranged copper rods acting as the outer electrodes with radius of 23.75 mm (b). The radius of the inner electrode is 4.75 mm (a); while the radius of each of the six copper rods forming the outer electrodes is 3.00 mm. The cathode plate has a knife-edge profile to ease the current breakdown. The minimum distance between the anode and the cathode plate is 10 mm. In addition, a set of twelve coaxial plasma guns is employed to enhance the current sheath formation between the electrodes. The plasma focus tube is enclosed in a stainless steel vacuum chamber.

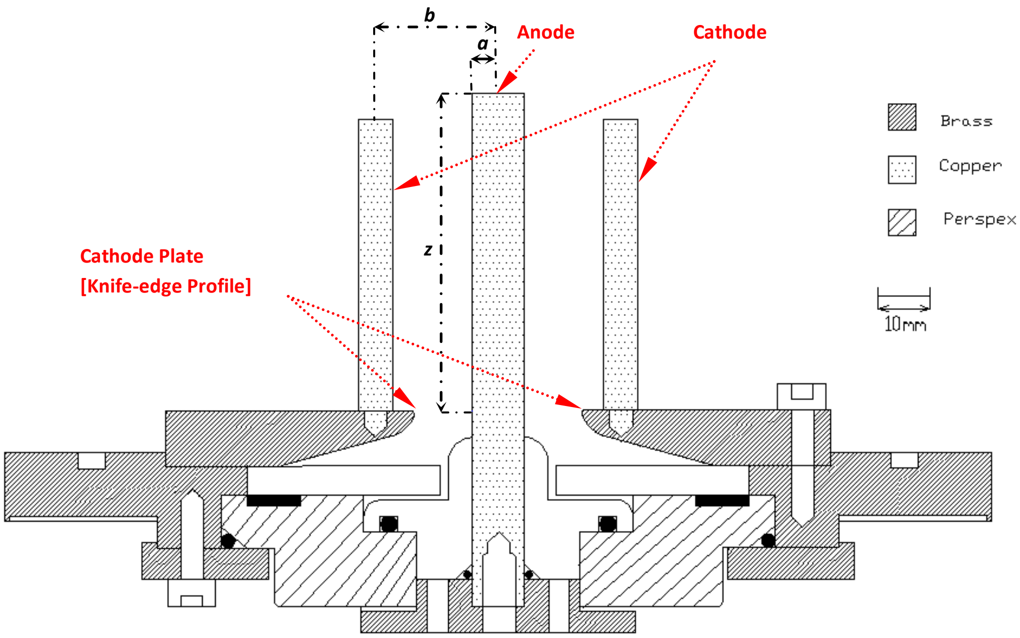

Figure 2.1 The cross section of a plasma focus electrodes set.

2.3 Dynamics of the Plasma Focus Discharge

The dynamics of the plasma focus discharge can be divided into four distinct phases:

1. Breakdown Phase
2. Axial Acceleration Phase (Axial Rundown Phase)
3. Radial Compression Phase (Radial Collapse Phase)
4. Disruption Phase

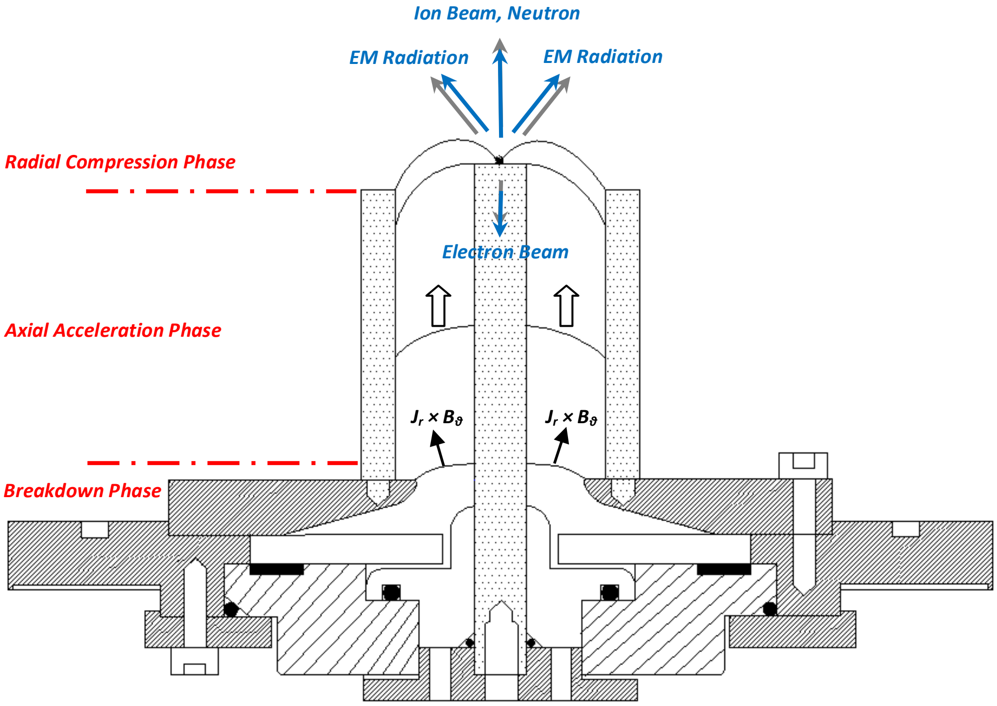

Figure 2.2 The plasma focus tube. Current sheath in the breakdown phase, axial acceleration phase and radial compression phase is indicated at the respective position. Emission from the plasma pinch is also schematically indicated.

In the current setup, the duration from the breakdown to complete disruption of the plasma takes about 1 μs. The dynamics of the four phases are explained in the following sections.

2.3.1 The Breakdown Phase

Once the high voltage is applied between the electrodes of the plasma focus device, stray electrons are accelerated by the electric field. Upon collision with neutral particles, ionization occurs and more electrons are produced. The number of free electrons is increased rapidly that avalanche will lead to the formation of the current sheath. In this work, stray electrons are purposely generated by using a set of twelve coaxial plasma guns inside the plasma focus chamber. The guns function to ease the breakdown and enhance the formation of the current sheath. Practically, a few hundred nanoseconds of time delay are observed before the voltage breakdown.

A dense, uniform, thin and quasi-homogeneous initial current sheath is formed near the backwall. Current flows from the anode to the cathodes and the Lorentz force is in the upward direction. The current sheath is accelerated up near the anode but remain at the knife-edge near the cathode. The breakdown phase ends when the current sheath near the knife-edge reaches the cathode rods.

2.3.2 The Axial Acceleration Phase (The Axial Rundown Phase)

The axial acceleration phase of the current sheet begins when the current sheath formed in the breakdown phase begins to accelerate along the coaxial electrodes. The current sheath is canted naturally due to the dependence of the azimuthal magnetic field on the radial position. The magnetic field is strongest at surface of anode but weakest at cathode, thus the current sheath is accelerated in the canted profile by the Lorentz force. The Lorentz force is resulted by the current density, J_r with its self induced magnetic field, B_θ. The direction of this force is parallel to the electrode axis.

In this axial acceleration phase, the current sheath sweeps the neutral gas particles inside the focus tube and heats them to form plasma which grows in density. This increase in mass is counteracted by increase in the driving force due to the increase in the current. After a short period, the current sheath tends to move with a roughly constant axial velocity along the tube. Generally the axial velocity of the current sheath is in the range of 1.7 to 15.0 cm/μs. In this setup, the average axial velocity of the current sheath is about 10 cm/μs.

The axial acceleration phase plays an important role in the formation of the hot and dense plasma. The length of the electrodes allows the uniform, thin and quasi-homogeneous current sheath to reach the end of the electrodes at a time near to the peak of the discharge current at quarter time. This is to ensure maximum energy transfer to the pinch plasma.

2.3.3 The Radial Compression Phase (The Radial Collapse Phase)

When the current sheath reaches the end of the anode, the current sheath near to the anode is now accelerated radially inward by the Lorentz force. The other end of current sheet near the cathode continues its axial motion. This is the beginning of the radial compression phase.

Radial acceleration of the current sheath leads to the formation of a plasma column at the open end of the electrodes. The electron density of the plasma column reaches a maximum of about 10^{19} cm^{-3} and the size of the plasma column is less than 1 mm in diameter with electron temperature of several keV.

The minimum radius of the plasma column depends on the anode radius of the plasma focus machine [Lee et al. (1996)] and the gas trapped in the focused plasma is estimated at about 10% of the corresponding to the total volume swept through by the current sheath [Filippov (1965)]. This plasma column is temporary stable for few tenths of nanoseconds in small energy DPF to hundreds of nanoseconds in a large DPF facility.

The plasma column begins to expand in both radial direction and axial direction after it is compressed to the minimum radius. The radial expansion is hindered by the confining magnetic pressure, while the axial expansion is unhindered due to the current sheath's geometrical structure. Rayleigh-Taylor instability is onslaught before the end of this phase and it will be damped out when the radial velocity is diminishing. At the end of this phase the magnetohydrodynamic (MHD) $m=0$ instability induces a gradual disruption of the plasma column due to increasing electron temperature. The pinch lifetime, t_p can be defined as the time between the first compression and the instant when the MHD $m=0$ instability occurs.

Towards the end of this phase, the diffusion of magnetic field into the plasma column started and it will lead to an anomalous high plasma resistance. The system inductance is also increased due to the small radius of the conducting plasma column. Owing to the large surge of the plasma impendence, the sharp voltage spike and the current dip in the discharge signals are observed. Consequently the electric field in the plasma column induced by the rapid growth of plasma inductance will accelerate the ions and the electrons in opposite axial direction.

2.3.4 The Disruption Phase

The disruption phase starts when the well formed plasma column begins to be disrupted due to the MHD *m=0*, the *m=1* and Rayleigh-Taylor instabilities set in. In the disruption phase, rich phenomenon including Rayleigh-Taylor instability are believed to be responsible for the emission of soft and hard x-ray emission and high energy particles.

Owing to the bombardment of accelerated electrons at the anode tip, anode material is injected into the plasma column. The disruption phase prolongs until the whole plasma column breaks up completely. The plasma density drops below 10^{17} cm^{-3}. From the measurement of the Bremsstrahlung radiation in large machine the electron temperature increases up to 4 ~ 5 keV [Castillo et al. (2000)].