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Abstract. Multiple double layers develop during expanding capacitive mode of RF discharge in a linear vacuum vessel in the absence of external magnetic field. Dynamics of multiple double layers have been studied through electric probe diagnostics in nitrogen RF plasma operated at 13.56 MHz frequency. The burst oscillations of the potential, fire tube formations and space charge formations suggest formations of complex structures during the discharge. Our first experimental results provide interesting information about the stability of plasma sheath and space charge effect on it. The visibly bright discharge transforms into multiple intensely coaxial luminous “Fire Tube” structures on increasing the input RF power in plasma.

1. Introduction

Fire tubes are Multiple Double Layer (MDL) plasma regions having multiple intensely luminous coaxial cylindrical structures of plasma, produced in laboratory. The RF power is applied across a cylindrical plasma source that consists of a coaxial stainless steel (SS) wire mesh with a central electrode, placed inside a linear SS vacuum vessel. The name “Fire Tube” owes to the MDL structures appearing as annular plasma cylinders of progressive intensity. Although the geometry of the plasma source used during the present study resembles that of a conventional Hall thruster, the presence of the semi-transparent cylindrical mesh type source allows the plasma sheath to simultaneously expand in radial as well as axial directions, resulting in the formation of an ambient capacitive RF plasma prior to the “Fire Tube” formation. These complex structures have been generated during a capacitive Radio Frequency (RF) plasma discharge \([1, 2]\). Despite being capacitive RF discharge with asymmetric electrodes, burst oscillations in the potential due to charge particle trapping, acceleration of the trapped charged particles, glowing spots formations, and space charge formation around the plasma source and existence of secondary electrons have been observed.

![Experimental setup and inset show a Fire Tube formation during the RF discharge.](image-url)

Figure1. Experimental setup and the inset show a Fire Tube formation during the RF discharge.
The experiments have been done in a linear vacuum vessel, described elsewhere in details [1] and shown in the schematic in figure 1. The current investigation has been carried out in Nitrogen plasma at a constant pressure of 0.075 Torr, within the range of coupled RF power PRF = (30–250) W, with a special emphasize on the discharge characteristics measured during higher coupled power (PRF ≥ 250W) to study the behavior of the trapped charged particles. The RF plasma has been formed using a semitransparent cylindrical mesh around a solid central cylindrical electrode. Although, in case of RF plasmas the discharge is not entirely dependent on the secondary electron population, in the present scenario the secondary electrons and the magnitude of the electric field intensity in the plasma plays a key role to the formation of multiple double layer structure in the expanding plasma. During RF power operational regime (>180W), a large number of secondary electrons generate inside the plasma source and simultaneously propagate along the axial as well as radial direction (through the mesh apertures). The secondary electrons that escape radially through the mesh spacing lead to formations of glowing spots on the mesh surface. The temporal variation electric field inside the semitransparent plasma source promotes the development of strong displacement current, providing strong basis for the formation of expanding RF plasma, which is observed first time in present scenario.

2. Burst Oscillation and Particle Trapping

In presence of applied RF power, the oscillating electric field couple with the electrode structure. The geometrical asymmetries between the central electrode and the coaxial cylindrical mesh leads to significant divergence of the electric field near the open end of the plasma source. During the capacitive discharge, the radial as well as an axial motion of charged particles, especially electrons, leads to formation of complex MDL structures during RF discharge in such a semi-transparent cylindrical plasma source due to pronounced electric field gradient in the system. The MDL formations are prominent in the range of PRF ~ (100 – 250) W RF power in present operational regimes. Variations of this setup and diagnostics have also been investigated but have been described elsewhere [1]. The burst oscillations obtained by the RF compensated Langmuir Probe (RFCLP) and the B-dot Probes are shown in figure 2(a), (b).

![Figure 2 (a, b)](image)

**Figure 2 (a, b).** The charged particle oscillations observed during the floating potential measurements using RFCLP (a) and dB/dt measurement done close to the mesh using azimuthal B-dot probe (b)

The burst oscillations in the above floating potential signal indicate the temporal oscillations of space charge potential, which can be described from the sheath capacitance, given as
For $C_s$ is the sheath capacitance, $V_p$ is the plasma potential. The profiles taken by the B dot probes are shown in figure 2(a). The bursts oscillations obtained by the B-dot probe starts with a first strong burst (concurrently with the first overshoot obtained in the RFCLP signal) following the interval with weak burst significantly reduces in amplitude than that of the first burst similar to the fishbone burst. Such burst oscillations obtained by both the RFCLP and B dot a probe indicating towards the strong dependence of displacement current [2]for mesh type plasma source and also the accumulation of charged particles, which form the particle bursts in the system. The signals also indicating towards the trapping of charged particles and the plasma medium also acts as an efficient transformer which accelerates the charged particles [3,4]. The burst oscillations as well as the charged particle trapping lead to the formation of MDL structures in the present experiment. The MDL structures occurs in this named as a Fire tube due to its coaxial hollow cylindrical formations. Evidence for the MDL along radial and axial direction due to the trapping of charged particles is shown in the contour profiles in figure 3(a),(b), which are indicate the propagation of MDL structures in space along axial and radial directions simultaneously.

\[ I = C_s \left( \frac{dV_p}{dt} \right) \]  

Equation (1)

Figure 3 (a, b) Axial distribution of density at PRF ≈ 50W, 100W and 250W respectively (a) and The contours of the floating potential profiles measured on various axial locations shows the MDL formations (b)

3. Theoretical Discussions

Although the plasma is macroscopically quasi-neutral in equilibrium state, the present experimental results can be elucidated using the two fluids Magnetohydrodynamic (MHD) model [5], separately for electron and ion motions. The electrons in plasma are separated spatially from the massive ions applying high frequency oscillating electric field, thus causing a charge imbalance in the perturbed region.

\[ n(m_i \frac{du_i}{dt} + m_e \frac{du_e}{dt}) = j \times B - \nabla P_{pe} \]  

where $m_i$, $m_e$ are the electron and ion masses, $n$ is the common number density of electrons and ions ($ni \approx ne \approx n$), $u_i$ and $u_e$ are the ion and electron fluid velocities in the laboratory frame, $j = ne(u_i - u_e)$ is the current density and B is representing the induced magnetic field.

Equation (2) finally reduces to the Lorentz force term $j \times B$, along with the pressure gradient contribution. In the present case, the plasma source is used to form a capacitive plasma discharge, where MDL structures form and drive the charged particles in the plasma like a propulsion system using such phenomena, simultaneously. Which can be described by the axial electric field variations,
which results in RF multiple double layer propagation by accelerates the charged particles to higher velocities while retaining them into bunches. The RHS terms in the equation (2) show the combination of an electromagnetic drift and a pressure gradient term, which is responsible for a expansion of RF plasma and acceleration of the charged particles during the present experiment.

4. Conclusion
A novel RF plasma source has been designed, using a semi-transparent mesh coaxially fitted around a short central electrode, in order to form and study the dynamics complex structures in a linear vessel. The mechanism and experimental study of formation and dynamics of the annular cylindrical Fire Tube structure in the vessel has been discussed in details to establish the charged particle trapping mechanism during present operational regime. The discharge obtained using the plasma source developed, has the following characteristics:

- Formation of the ion-electron sheath at the mesh opening and the initial axial motion of the charged particles due to the electric - field gradient are critical for the formation of MDL structure during present operational regime.

- The parametric behavior of the MDL structure formations during the RF discharge, experimentally investigated using RF compensated Langmuir probe, gives useful information about the charge particle trapping in the MDL sheath.

- The axial motion of the MDL structures in the system may also result in the acceleration of the trapped charged particles during the present operational regime, this part needs further detailed investigation.

The radial and axial motion of the charged particles during the RF discharge in the present case for this type of cylindrical plasma source might be useful for present day research in plasma accelerator, plasma propulsion system and plasma sputtering system, which is very helpful for the modern scientific research in medical and nanoscience.

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