Experimental Characterization and Two-Zone Global Modeling of ECR Produced Hydrogen Plasma for Moderately Large Volume Applications

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Abstract

This thesis focusses on the characterization of electron cyclotron resonance (ECR) based hydrogen plasmas for its potential utility in plasma-based applications. The mechanism of ECR power coupling is well known in literature to be one of the most energy efficient processes for plasma applications. The experiments in this thesis work are undertaken in a cylindrical vacuum chamber (diameter = 48.2 cm, length = 75 cm), called Medium Volume Plasma System (MVPS), with an indigenously developed ECR plasma source mounted onto one end of the cylindrical MVPS chamber. The source section uses two different magnetic field configurations (MF1 and MF2), which are demarcated as Compact ECR Plasma Source (CEPS) and Noncompact ECR Plasma Source (NEPS), with the former having a more complex magnetic field configuration (MF1) than the latter (MF2). It is noted that the utility of developing and characterizing new configurations of hydrogen plasma sources is still of relevance in the current era because, depending on the operating conditions, hydrogen plasma can exist in multiple constituent species of hydrogen (H_2, H, H^+, H_2^+, H_3^+ and H^-) with varying ratios which enables it to be used for a wide array of applications in various fields of science and technology *viz.*, impurity removal from metals, passivation of semiconductor material, enhancement of growth rate of diamond films and surface treatment to protect from corrosive effects, plasma ion implantation and hydrogenation of polysilicon thin-film transistors, ion projection lithography and neutral beam injection (NBI) system for fusion devices to name a few.

This extensive range of hydrogen plasma applications along with some recent experiments using the patented CEPS, developed by the Plasma Lab at IIT Delhi, which has demonstrated the CEPS to be a generic source suitable for various applications provided a motivation for the work on ECR-based hydrogen plasmas using the CEPS and NEPS carried out in this thesis. The CEPS is a permanent magnet based ECR plasma source weighing only about ≈ 14 kgs (including the NdFeB permanent ring magnets), with length ≈ 60 cm and comprises of the waveguide microwave launcher, dual directional coupler (for forward and reflected power measurement), triple stub impedance matching unit, rectangular-to-circular waveguide transition and the plasma source section (PSS) all integrated into a single unit. Both the CEPS and the NEPS use the same microwave line except for the set of NdFeB permanent ring magnets of the CEPS being replaced by another combination of NdFeB permanent ring magnets and electromagnet coils in the NEPS. The magnetic field configuration (MF1) of CEPS as well

as the alternate or second magnetic field configuration (MF2) of NEPS generate suitable ECR fields within the PSS but which are still distinctly *different* from each other.

A series of experiments were performed for different operating parameters in both magnetic field configurations. The primary diagnostics used in this work are a set of radial and axial Langmuir Probe (LP) along with a Retarding Field Energy Analyser (RFEA); all diagnostics being fabricated in-house. The axial LP data for MF1 were recorded from $z \approx 4$ cm to $z \approx 50$ cm, measured from the source mouth, due to the complex field configuration of MF1. It may be mentioned that *two electron populations* are always present in the expansion chamber (*i.e.* for $z \geq 4$ cm) in MF1: a *high density bulk population* (n) with a *low electron temperature* (T_e) and a *low density warm population* ($n_w << n$) with *relatively high electron temperature* ($T_w >> T_e$). LP measurements reveal high-density hydrogen plasma ($\approx 10^{11}$ cm^{-3}), with high bulk electron temperatures ($T_e \approx 8$ eV) and plasma potentials ($V_p \approx 50$ V) at very modest microwave power ($P \approx 600$W) over a wide range of pressures ($p \approx 1$ to 8 mTorr) close to the source mouth. Ion energy analysis using RFEA shows nearly mono-energetic ion beams with beam energy $E_b \approx 98$ eV in front of the CEPS at 1mTorr pressure. As pressure increases, the ion beam energy decreases, such that at 8 mTorr the ion beam energy is $E_b \approx 17$ eV in front of CEPS.

One the other hand, due to the less harsh environment in MF2 one is able to probe deeper in to the source which reveals that the plasma starts with a *single* electron population originally and later splits into two electron population with the low temperature, bulk electron population showing a relative density enhancement than that observed upstream before the onset of splitting and is also co-existing with a higher temperature but relatively lower density warm electron population. The point at which splitting occurs can vary from well inside the source to outside the source. LP measurements reveal high-density hydrogen plasma ($n \approx 10^{11}$ cm^{-3}), with high bulk electron temperatures ($T_e \approx 7$ eV) and plasma potentials ($V_p \approx 30$ V) at microwave power ($P \approx 650$ W) over a wide range of pressures ($p \approx 1$ to 8 mTorr) in front of NEPS in the expansion chamber. One also observes a significant drop within the source near to the exit and the resulting ambipolar field help to accelerate the escaping ions from the PSS. RFEA also shows nearly mono-energetic ions with beam energy $E_b \approx 63$ eV, in front of the source at 1 mTorr pressure. As pressure increases the measured energy of the ion beam decreases, such that at 8 mTorr, $E_b \approx 7$ eV in front of the NEPS mouth.

Based on the results obtained from the experiments undertaken with NEPS, a model is proposed to explain the observation of a transition from a single-to-two electron population. The model identifies that the resonating electrons gain energy from the ECR field and then traverses a distance of a few meters, equivalent to the electron-neutral ionization mean free path (λ_{en}), along a helical trajectory but is effectively displaced from the ECR layer only by a distance of a few centimeters towards the expansion chamber. This displacement has been found to be well correlated with the distance from the ECR layer to the point of splitting, suggesting this to be the distance that is required for the energetic electrons emanating from the ECR zone to trigger an avalanche ionization process. Thereafter the bulk density is found to follow a n/B scaling initially for about 4-5 cms and then the density is found to decay much slower than that of the magnetic field. This scaling has been identified to be the distance over which the parallel diffusion coefficient ($D_{\|}$) is significantly dominant over the perpendicular diffusion coefficient ($D_\perp$). The proposed model was also able to provide an insight into the mechanism of the plasma generation within the CEPS and provide the plausible reason for generation of such high plasma potential drops across or near to the source mouth that explains the observation of relatively higher ion beam energies, making it a very harsh environment for probe studies.

In order to predict the presence of ion beams in the expansion chamber and to describe the plasma behaviour in expanding geometry, an unmagnetized, zero dimensional, 2-zone global model has been developed where zone-1 and zone-2 represent the source section and expansion chamber respectively. Separate particle and power balance equations were setup for the two zones that take into account particle and power flow across the two zones, wall losses, current balance across the interconnecting opening, etc. The results of the two zone global model obtained in this thesis are compared with the experimental results both inside and outside the source of the NEPS and are found to have a reasonable match between them. The unmagnetized zero-dimensional model was also able to predict the presence of a potential jump in the expanding field geometry. This implies that the expanding geometry contributes to the generation of potential drops across the source mouth which can be further enhanced by suitable tuning of the magnetic field configuration within the PSS leading to potential applications in the near future. The details of these investigations and inferences are presented in this thesis work.