

**PhD Thesis Title:** Development of Diagnostics for Characterizing Electron Heating Mechanisms in Low-Pressure RF Discharges

**Name:** Arti Rawat

**Entry Number:** 2014ESZ8088

**Department of Energy Science and Engineering (DESE)**

**Supervisors Name:** Prof. Ramesh Narayanan & Prof. Ashish Ganguli (DESE)

---

## ***ABSTRACT***

Low pressure, Capacitively Coupled Discharges (CCDs) have drawn great attention for their enormous relevance in various fields of industrial applications, like deposition, etching, surface treatment, etc. In spite of being used extensively, both in industry as well as in scientific investigations, a thorough understanding of the RF power coupling to electrons in capacitive discharges, is still lacking. This lacking pertains not only to the theoretical models and simulations, but also to the experiments.

In this regard the work in this thesis is concerned with characterizing RF power absorption mechanisms in parallel plate capacitive discharges. At low to moderate pressures and low RF powers, the two competing mechanisms are the stochastic mechanism and the Ohmic mechanisms. Of these, the former is a nonlinear process that is most efficient at low pressures whereas the latter is effective mainly at high pressures (up to  $\sim 1000$  mTorr). While the nonlinear stochastic process is expected to take place at the sheath at the powered electrode where the RF fields are strong, the Ohmic mechanism is expected to occur in the plasma bulk. Thus one has two kinds of variations here. The first is concerned with the changes in power absorption with increasing pressure (from

low to high). The second is the shift in the nature of power absorption as one scans power absorption along the length of the system from the powered electrode into the plasma bulk. It is one of the aims of the thesis to undertake profiling of fundamental RF power absorption along the system length with respect to the pressure.

Now, because the stochastic mechanism is nonlinear, it is capable of producing harmonics of the applied RF frequency. Thus one may use the frequency and power spectrum of the harmonics as a tool to characterize, understand and fine-tune the models and simulations pertaining to the stochastic process, since this process is not fully understood even today. Thus the changes in the frequency and power spectrum harmonics would reflect correspondingly, the changes in the stochastic process. As a consequence, a second goal of this thesis is to develop techniques for the accurate determination of the frequency and power spectrum of the harmonics.

Considerable insight into harmonic characterization may be gained from *an RF equivalent circuit for harmonics, represented as a lumped RF voltage source  $V_{\text{RF}}^{\text{pl}}$  that is connected via its internal impedance to the load in the external RF circuit. Therefore, to characterize the harmonics one needs to characterize the voltage source, its internal impedance, as well as determine how much power the source can deliver into the external circuit.* For undertaking such characterization one needs to *measure harmonic power from both within and outside the discharge.* The measurements within the discharge would help *identify the regions of harmonic production by the stochastic process and the regions of their absorption by the Ohmic mechanism.* On the other hand, the measurements of harmonic power in the external RF circuit complement those in the plasma interior. Together, the two measurements would enable one to determine the total harmonic power spectrum across a wide range of pressures. It is to consolidate these ideas and illustrate the efficacy of the suggested measurements that this thesis undertakes a detailed investigation of Capacitively and

Directly Coupled (parallel plate) Discharges using a novel set of diagnostics and a simple analytical model.

Towards the above goal, the plasma parameters were measured and preliminary characterization of RF harmonics was undertaken over a wide pressure range (0.6 – 1000 mTorr at 10 W RF power) using a compensated LP (CLP), Capacitive Probe (CP), and an Uncompensated Floating LP (UFLP). The CLP was used for plasma parameter measurement whereas the CP and UFLP were used for measuring the oscillations at the RF fundamental and its harmonics (at 13.56, 27.12, and 40.68 MHz). To correlate these to the stochastic ( $P_{\text{Stoch}}$ ) and Ohmic ( $P_{\text{Ohm}}$ ) power absorption mechanisms, an effective power  $P_{\text{eff}} = P_{\text{Stoch}}^{\rho} \times P_{\text{Ohm}}^{1-\rho}$  ( $\rho$  is a pressure dependent parameter), was defined. It is possible to tune  $\rho$  so as to match  $P_{\text{eff}}$  closely with the normalized profiles of  $n_e$  with the pressure. *Knowing  $P_{\text{eff}}$ , it is possible to determine the relative contributions of the stochastic versus Ohmic mechanisms towards plasma production at a given pressure.* Results show that plasma production is entirely due to stochastic mechanism at low pressures, whereas at higher pressures it is a mix of both mechanisms. A similar technique was applied for the analysis of the RF voltages. The analysis reveals, for instance, that for the 2<sup>nd</sup> and 3<sup>rd</sup> harmonics, the stochastic mechanism dominates almost exclusively up to  $\approx 5$  mTorr, while for higher pressures (above  $\approx 200$  mTorr) both Ohmic and stochastic mechanisms are present in roughly equal measure. At low pressures, where the stochastic mechanism operates almost exclusively, the contribution to the harmonics comes from the intrinsic nonlinearity of the stochastic mechanism, acting via the sheath at the powered electrode. *It may be noted though, that since the sheath at the powered electrode is present even at high pressures, harmonic production at these pressures can also proceed due to the stochastic mechanism, with the Ohmic mechanism serving to absorb the harmonic power.*

While the probes used for the above work give an insight into the correlations between power absorption and harmonics (and plasma production), these cannot determine the harmonic power produced and absorbed within the plasma. Therefore, in accordance with the program outlined above, two separate diagnostics were developed.

The first is a new diagnostic technique based on novel use of dual directional couplers (DDCs). It was developed and used to determine the harmonic (and fundamental) power in the external RF circuit. It turns out that a DDC placed between the matching network and the plasma load can detect with ease not only the fundamental, but also the harmonics produced by the plasma. The results *reveal that highest harmonic power in the external circuit is available in the 3<sup>rd</sup> harmonic and not the 2<sup>nd</sup>*, as is usually reported in various measurements. In addition, *another important result is the emergence of the 6<sup>th</sup> harmonic as the second most important harmonic in terms of power over a wide pressure range (below ~ 200 mTorr)*. Apart from these results on the measurement of harmonic power in the external circuit, it is possible to compute various other quantities of interest like the plasma impedance, VSWR, plasma reflection coefficients, etc.

To investigate and generate profiles of RF power absorption of the fundamental and to determine harmonic generation and absorption in a capacitive discharge, a new and novel probe, the *J.E* probe, was developed from scratch. Various aspects of the probe, like its design, fabrication, calibration, and limitations were resolved before it was used for obtaining axial profiles of power absorption for the fundamental (13.56 MHz) and the 2<sup>nd</sup> harmonic (27.12 MHz). A detailed analysis of the results, shows that *even for systems with large electrode gaps, i.e., plasmas with long bulk plasma regions, practically all the fundamental power is absorbed in a narrow edge region near the powered electrode, irrespective of the pressure*. In the context of harmonics, the first point to notice is that both harmonic production and absorption take place close to the powered electrode. Harmonic

production can be seen most clearly at low pressures where one observes a region of *monotonically decreasing absorption* as one approaches the powered electrode, indicating harmonic generation. On the other hand, the absorption profile for collisional absorption mimics that of the fundamental. Absorption is high near the RF electrode since the RF fields peak in this region.

Combining the complementary features of the harmonic power absorbed in the plasma and that available in the external circuit, one finds that the stochastic mechanism is able to generate harmonics over a wide range of pressures indicating that it *is a highly ubiquitous mechanism in CCDs*. The cause for its ubiquitousness stems from the fact that *it is basically a sheath phenomenon and is most easily triggered when the nonlinear sheath at an electrode (like the powered electrode in a CCD) is penetrated by strong RF fields, even at high pressures, where sheath widths are small*.

To summarize, this thesis provides several new insights for unraveling the RF power coupling mechanisms in capacitive discharges, so as to enhance present understanding of these mechanisms and to guide the development of more elaborate and accurate theoretical models. It is also believed that the new diagnostic methods developed in this work would help to generate more accurate models and pave the way for a more precise control and process optimization in applications of capacitive discharges.