Diagnoses for the Dynamics of Power Dissipation in Technologically used Plasmas


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Abstract. Radio frequency (rf) discharges are widely used for technological applications. Despite this, power dissipation mechanisms in these discharges are not yet fully understood. The limited understanding is mainly caused by the complexity of underlying phenomena and very restricted experimental access. Recent advances in phase resolved optical emission spectroscopy (PROES) in combination with adequate modeling of the population dynamics of excited states allow deeper insight into underlying fundamental processes. This paper discusses the application of PROES in a variety of rf-discharges, such as: capacitively coupled plasmas (CCP), dual-frequency CCP (2f-CCP), inductively coupled plasmas (ICP), and magnetic neutral loop discharges (NLD).

Keywords: Low-temperature plasmas, radio-frequency discharges, power dissipation, plasma ionization, electron dynamics, electron heating, plasma diagnostics, phase resolved optical emission spectroscopy (PROES)

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INTRODUCTION

Non-equilibrium low temperature plasmas, in particular radio-frequency (rf) discharges, are widely used for technological applications. Increased demands on plasma technology, particularly from the micro-electronics industry, have resulted in the development of various types of discharges based on different power coupling mechanisms. Despite this, the complexity of these mechanisms is not yet fully understood. Insight into power dissipation requires temporal resolution on various time scales; in particular the dynamics within the rf cycle is of importance. Detailed investigations are, therefore, a challenge for diagnostics. Recent advances in phase resolved optical emission spectroscopy (PROES) provide a non-invasive access with excellent spatial and temporal resolution on a nano-second time scale [1-6].

The optical emission from rf discharges exhibits temporal variations within the rf cycle. These variations are particularly strong in capacitively coupled plasmas (CCPs), but also easily observable in inductively coupled plasmas (ICPs). Neglecting these variations in classical time averaged optical emission spectroscopy (OES), based on balance equations, can result in serious misinterpretation [1]. The effect of neglecting temporal changes is not as pronounced in ICPs as in CCPs [5]. However,
even these relatively small modulations can be exploited for insight into power dissipation. Using modeling of the dynamics of various excited states compared with phase resolved measurements of the optical emission yields detailed information on the electron dynamics.

**ANALYTICAL MODEL FOR THE POPULATION DYNAMICS OF EXCITED STATES**

In contrast to the standard corona model commonly used for OES of stationary low density plasmas, PROES requires a time dependent model based on rate equations to take into account the transient character of the exciting electrons.

The temporal modulations of the optical emission are caused by temporal changes in the electron energy distribution function (EEDF). Highly excited states in atoms or molecules are excited by electrons in the tail of the EEDF where the modulation is particularly strong. Temporal variations are, therefore, observable in the optical emission from these high electronically excited atoms or molecules.

Electron impact excitation out of the ground state is described by the excitation function $E_i(t)$. For an excited state $i$, not populated through cascade processes or step-wise excitation, the excitation function $E_i(t)$ can be determined directly from the measured number of photons per unit volume and unit time $\dot{n}_{ph,i}(t)$ [4]:

$$E_i(t) = \frac{1}{n_0 A_{ik}} \left( \frac{d\dot{n}_{ph,i}(t)}{dt} + A_{i} \dot{n}_{ph,i}(t) \right).$$  \hspace{1cm} (1)

Here, $\dot{n}_{ph,i}(t) = A_{ik} n_i(t)$ is given by the transition probability $A_{ik}$ of the observed emission and the population density of the investigated state $n_i(t)$; $n_0$ is the ground state density. The effective decay rate $A_i$ takes into account spontaneous emission, radiation trapping and quenching [2]:

$$A_i = \sum_k A_{ik} g_{ik} + \sum_q k_q n_q,$$  \hspace{1cm} (2)

where $g_{ik}$ is the so-called escape factor [7, 8] and $k_q$ the quenching coefficient with the species $q$ of density $n_q$.

For quantitative investigations cascade processes can be substantial [9-12]. The population density $n_i(t)$ of the investigated state $i$ can be described by the following rate equation including cascades from state $c$:

$$\frac{dn_i(t)}{dt} = n_0 E_i(t) - A_i n_i(t) + A_{ic} n_c(t).$$  \hspace{1cm} (3)
The population density \( n_c(t) \) obeys a rate equation analogous to eq. 3, without cascade processes:

\[
\frac{d n_c(t)}{dt} = n_0 E_c(t) - A_c n_c(t).
\] (4)

These coupled differential equations for the investigated state \( i \) and the cascade state \( c \) can be solved in a general manner for the periodic boundary conditions of the rf discharge \( n_{i,c}(t) = n_{i,c}(t + T_{RF}) \):

\[
n_i(t) = n_0 \left( \frac{\tilde{E}_i(T_{RF}, A_i)e^{-A_i T_{RF}}}{1 - e^{-A_i T_{RF}}} + \tilde{E}_i(t, A_i) \right) e^{-A_i t} + \frac{n_0 A_{i,c}}{A_i - A_c} \left[ \left( \frac{\tilde{E}_c(T_{RF}, A_i)e^{-A_i T_{RF}}}{1 - e^{-A_i T_{RF}}} + \tilde{E}_c(t, A_i) \right) e^{-A_i t} - \left( \frac{\tilde{E}_c(T_{RF}, A_i)e^{-A_i T_{RF}}}{1 - e^{-A_i T_{RF}}} + \tilde{E}_c(t, A_i) \right) e^{-A_i t} \right]
\] (5)

Here, the substitution \( \tilde{E}_x(t, A_i) = \int_0^t E_x(t')e^{A_i t'} dt' \) has been used.

The time dependence of the excitation function, reflecting the electron dynamics, is strongly dependent on the power coupling mechanisms. These time dependencies are discussed for various types of rf discharges in the following.

**SET-UP FOR PHASE RESOLVED OPTICAL EMISSION SPECTROSCOPY**

The set-up for a typical PROES experiment using a fast, gate-able, intensified CCD camera (ICCD) is shown in fig. 1. A spectral filter or spectrometer allows for spectral discrimination of emission lines. The CCD camera is synchronized with a signal from the rf generator powering the discharge. Measurements with a defined gate width can be made, typically 2 ns for the used radio-frequencies. A variable delay between the camera gate and the rf voltage allows for phase resolved measurements within the rf cycle (fig. 1). The intensities measured in the camera gate time are integrated over many rf cycles, for a certain phase setting, to obtain good signal to noise ratio. Fainter emission lines can be integrated for longer. The ICCD camera allows spatially resolved measurements in the various discharge systems.
FIGURE 1. Typical experimental set-up for PROES measurements.

CAPACITIVELY COUPLED PLASMAS (CCP)

Single Frequency CCP

Single frequency CCPs are often considered as the simplest configuration for an rf discharge. The optical emission, however, exhibits a very pronounced and complex dynamics. The basic excitation mechanisms of a plan parallel CCP are discussed in the following. The electrode gap is 25 mm and the electrode diameter is 100 mm.

Fig. 2(a) displays the phase and space resolved optical emission from a hydrogen CCP (100 W, 142 Pa) with a small admixture (1%) of Neon as tracer gas. The observe Ne 2p$_1$ state is practically free of population through cascades [12]. The abscissa comprises one rf cycle and the transverse axis indicates the distance from the powered electrode.

Eq. 1 is used to determine the excitation dynamics (fig. 2(b)) from the measured phase resolved optical emission (fig. 2(a)). Different electron impact excitation processes can be clearly identified. The first process is caused by a field reversal across the space charge sheath, typical for hydrogen rf discharges. During this phase electrons are accelerated towards the powered electrode and induce a strong impact excitation. The second excitation process is due to sheath expansion heating of electrons moving to the plasma bulk, when the sheath potential becomes negative again. The third process results from secondary electrons created by ion impact. Due to the small mass of hydrogen ions they are able to follow the applied electric field. Thus, time dependent ion bombardment determines the creation of secondary electrons at the electrode surface. During the phase of maximum bombardment the high sheath potential of several hundred Volts results in an acceleration of electrons and electron multiplication through ionization. The high energetic directed electrons created in the sheath region also induce excitation when they enter the plasma bulk.
FIGURE 2. Phase and space dependent emission (a) and electron impact excitation (b) in a capacitively coupled hydrogen rf discharge. A small admixture of Neon is used as tracer gas.

Dual Frequency CCP

CCPs operated simultaneously with two radio-frequencies are used to achieve separate control of plasma density and ion impact energy onto the substrate [13-20]. The plasma density is expected to be mainly controlled by the higher frequency while the ion energy is determined by both the lower and higher frequency. Here, PROES with temporal resolution within the low frequency rf cycle is discussed.

The investigated plasma is a modified industrial dual frequency CCP (2f-CCP) etch-reactor (Exelan®, Lam Research). The gap between the two, plane, parallel plate, electrodes is 13 mm and the radius is 110 mm. The bottom electrode is powered with both frequencies (2 MHz and 27.12 MHz) simultaneously and the top electrode is grounded. Two quartz rings surrounding the electrode gap produce a symmetric discharge.

Fig. 3 shows the time and space resolved optical emission from a discharge operated at $P_{27} = 800$ W and $P_2 = 200$ W. The emission recorded is from the He $3^3S$-state at $\lambda = 706.5$ nm ($\tau = 36.1$ ns) in a He–O$_2$ discharge (1500 sccm He, 1000 sccm O$_2$ at 490 mTorr). The low frequency cycle is scanned with a resolution of 36.88 ns, averaging over the dynamics within the high frequency cycle. In fig. 3 the abscissa shows the phase of the 2 MHz cycle, whereas the ordinate corresponds to the distance between bottom ($y = 0$) and top ($y = 1$) electrode.
FIGURE 3. Space and phase resolved optical emission illustrating the electron dynamics within the low-frequency rf-cycle. The pronounced dynamics exhibits a strong coupling of both frequencies. The emission maxima indicated as 2 and 2’ scale with the 2 MHz power relative to the 27 MHz power, while the maxima indicated as 27 and 27’ scale vice versa.

The emission and corresponding excitation exhibit a pronounced dynamics within the low frequency cycle. The confined discharge is symmetric with similar excitation mechanisms occurring in front of both electrodes. Two double peak structures can be easily identified: two peaks (indicated as 2 and 27) at the bottom electrode at different phases in the rf cycle, and two peaks (indicated as 27’ and 2’) close to the top electrode at the same phases. The two peaks at each electrode are separated by half a low frequency cycle. Separate power variations of both frequency components show a ‘diagonal correlation’ of the peaks. With increasing 27 MHz power the peaks indicated as 27 and 27’ increase in relation to the other two peaks; and for increasing 2 MHz power the peaks indicated as 2 and 2’ increase correspondingly. These dependencies illustrate that the excitation mechanisms in front of both electrodes are of the same nature and hence 180° out of phase. The pronounced maxima around the sheath edge are typical for CCPs in α-mode, where energetic electrons are created in the rapidly moving sheath and penetrate into the plasma bulk [3].

The dynamics in the dual frequency discharge can be understood in the following picture. The rapid oscillations of the sheath-edge, determined by the high-frequency component, drive the energy gain of electrons. The velocity of these oscillations depends on the spatial movement of the sheath-edge and, therefore, on the local ion density. The spatial structure of the sheath is predominantly governed by the large low-frequency voltage. Thus, the position of the sheath-edge oscillation is strongly determined by the low-frequency. Ion flux conservation in the sheath results in a decrease of ion density towards the electrode. Depending on the phase of the low-frequency voltage, and the corresponding ion density in the vicinity of the sheath-edge, the same high-frequency voltage change results in different spatial movements of the sheath-edge. The lower the ion density the larger the spatial movement, resulting in higher sheath velocities and, hence, increased energy gain for electrons.

This explains the strong coupling of both frequencies. Maximum energy gain for electrons can be expected around the minimum voltage of the low-frequency
component, when the sheath-edge is close to the electrode, corresponding to low ion densities and extremely fast instantaneous sheath-edge velocities. Thus, the peaks 2 and 2', corresponding to minimum low-frequency sheath voltages, are strongly dependent on the 2 MHz power, which governs the spatial structure of the sheath. Excitation through energetic electrons, created during these phases, decreases with penetration through the plasma bulk. Additional energy gain and increased excitation can be observed close to the opposite electrode at maximum sheath extension (peaks 27' and 27). This energy gain, through high-frequency oscillations, is less dependent on the 2 MHz power since the spatial structure of the sheath is not as relevant.

**INDUCTIVELY COUPLED PLASMAS (ICP)**

The rf inductively coupled plasma (ICP) is an electrodless discharge type. The planar coil configuration is the most commonly used for material processing. The rf power is coupled into the plasma by means of an induction coil through a dielectric window so that the plasma is not in contact with the antenna. The power coupling mechanism is analogous to a transformer, whereby the antenna acts as the primary coil of the transformer and the plasma as the secondary coil. The oscillating currents in the antenna generate a time dependent magnetic field. This time varying magnetic field induces an electric field in the plasma, according to Faraday’s law.

However, the antenna can also act as an electrode. Therefore, both inductive and capacitive power coupling mechanisms can coexist in ICPs. Capacitive coupling drives the discharge at low plasma densities and is referred to as E-mode. During plasma ignition and at low rf powers the discharge is capacitive. As the plasma density increases, and the discharge can support the induced currents, a transition to inductive mode occurs, referred to as H-mode. The transition from capacitive mode to inductive mode, known as the E-H transition, can often be identified by an obvious increase in luminosity of the plasma.

Investigations of an ICP have been carried out in a modified GEC reference cell. Fig. 4 shows PROES measurements under a power variation in a hydrogen ICP operated at 10 Pa. Two rf cycles are resolved, with a 2 ns gate width in steps of 1 ns. The absolute intensity of the measured Hα-emission varies over orders of magnitude while the discharge transits from capacitive to inductive power coupling. The plotted modulation, however, is normalized to the time averaged intensity at each power. The normalized modulation clearly illustrates the capacitive coupling at low powers and inductive coupling at higher powers. The capacitive coupling is characterized by a pronounced modulation, with one emission maximum per rf cycle, while the inductive mode exhibits smaller modulation amplitude with twice the rf frequency.
Fourier-components in H-mode and E-mode

Electrons in rf discharges acquire energy from the oscillating electric field and lose energy through elastic and inelastic collisions with the background gas. The electron energy distribution function can be described by the Boltzmann equation. In rf discharges the EEDF shows time dependent modulations. In capacitive discharges the electrons gain energy mainly due to the sheath dynamics. The electrons are accelerated into the plasma bulk region, and thus gain energy, once in every rf cycle. Thus, the EEDF is modulated with a frequency corresponding to the rf frequency. While, in ICPs the electrons gain energy due to the induced electric current. This current oscillates forward and backward in one rf cycle. Since the direction does not matter, electrons gain energy twice in each rf cycle. Therefore, in ICPs, the EEDF time dependence is with twice the rf frequency. The modulation in inductively coupled plasmas is not as pronounced as in capacitively coupled plasmas.

The time dependence of the EEDF in rf discharges can be observed in the optical emission. The different power coupling mechanisms exhibit different signatures in the temporal modulation of the emission, as could be already identified in fig. 4. A Fourier-analysis of the optical emission allows one to distinguish between these mechanisms. The correlation of the various Fourier-components gives insight into electron motion and heating in the discharge.

As discussed above, the EEDF and optical emission in ICPs are modulated by the induced electric field, and thus with twice the rf frequency. Fig. 5 shows a 2d-spatially resolved measurement of the second harmonic component of $H_\alpha$-emission ($\lambda = 656$ nm). It shows maxima close to the quartz at around two-thirds the antenna radius, where the induced electric field has its maximum.

As discussed above, capacitive coupling can be identified through the $1\omega$-component. However, in capacitive mode, the mechanisms are more complex than in inductive mode. A variety of power coupling mechanisms can be present in capacitive plasmas; these different mechanisms are then overlapped in the $1\omega$-Fourier component of the emission. The field reversal present in hydrogen plasmas and the sheath
expansion are determined by the non-linear sheath dynamics and thus exhibit, in addition to a $1\omega$-component, also higher harmonics. Secondary electrons are determined by ion bombardment and also the subsequent acceleration of electrons produced by secondary emission. These processes follow a $(\cos \omega t + 1)^2$ function [3]. Thus secondary electrons can be expected in both the first and second harmonic component. Fig. 6(a) and 6(b) show the first and fourth harmonic of the space resolved emission, respectively. The first harmonic is a combination of a variety of capacitive power coupling mechanisms, thus making it difficult to distinguish individual processes. However, the fourth harmonic reveals detailed insight into power dissipation in capacitive-mode. Two distinct excitation mechanisms can be identified. The field reversal, at the quartz can be clearly observed and distinguished from the sheath expansion, at a position further into the plasma at maximum sheath extension.

**FIGURE 5.** 2d-spatially resolved measurement of the $2\omega$-component of the normalized modulation in H-mode.

**FIGURE 6.** 2d-spatially resolved measurement of the $1\omega$-component (a) and $4\omega$-component (b) of the normalized modulation in E-mode.
MAGNETIC NEUTRAL LOOP DISCHARGES (NLD)

The NLD concept utilizes an inhomogeneous static magnetic field configuration, with a neutral loop (NL) region where the magnetic field vanishes [21]. An inductive radio-frequency electric field is superimposed on this magnetic NL. Three coaxial coils, of different diameters, surrounding the chamber produce the desired magnetic field configuration. The current in the top and bottom coil flow in the same direction and the current in the middle coil is opposite in direction to the other two. This arrangement produces a quadrupole magnetic field configuration bent into a torus structure with a magnetic null along a ring in the torus - the so called NL. The magnetic null ring, with relatively strong magnetic field gradients, is located just below the planar ICP antenna for efficient plasma production. An oscillating rf electric field is induced along the NL. The antenna is operated at 13.56 MHz and separated from the plasma by a quartz dome. The discharge can also be operated as a conventional ICP, without magnetic fields.

Such a discharge allows operation at significantly lower pressures than conventional ICPs due to electron confinement and more efficient collisionless electron heating. Low process pressure decreases ion scattering through collisions in the sheath, in front of the substrate, resulting in better etch anisotropy. In addition uniform plasma surface treatment over large areas can be achieved by varying the diameter of the NL radius.

FIGURE 7. Normalized time dependent optical emission in an ICP (a) and NLD (b) as a function of rf power.

The phase resolved Ne 2p\textsubscript{1} emission (λ = 585.2 nm) from a pure Neon plasma at 1 Pa for varying powers is observed. Fig. 7(a) shows the modulation of the emission measured in pure ICP mode of the discharge without magnetic fields. The optical modulation is normalized to the time averaged intensity. Modulation with twice the rf frequency is clearly visible. Fig. 7(b) shows the modulation measured with magnetic field in the center of the NL under the same conditions as in fig. 7(a). Compared to pure ICP, two differences are apparent: The modulation in the NLD is significantly
lower and the two peaks within one rf cycle become asymmetric with increasing power, producing a first harmonic component. Fig. 8(a) and 8(b) show the spatially resolved measurement of the first and second harmonic components, respectively, in NLD-mode at 2000 W.

FIGURE 8. 2D-image of the 2ω-amplitude (a) and 1ω-amplitude (b) using a Fourier analysis of the normalized time dependent emission in a NLD.

In NLD-mode the power dissipation in the discharge is more complex than in pure ICP-mode, with no magnetic fields. In contrast to ICP-mode a first harmonic component dominates the modulation of the emission. The comparatively small second harmonic component shows similar structures as in ICP-mode (fig. 5). The main difference is that the observed structures representing the induced electric field are closer and more confined to the quartz surface. This can be attributed to the higher plasma densities in NLD-mode.

The structure of the first harmonic component in fig. 8(b) is complex. It shows features around the NL region as well as along the separatrices. A structure along the separatrix can be observed close to the bottom of the plot where electrons following the separatrix move towards the observation window. The first harmonic component in the modulation of the optical emission can be correlated to a time independent drift component of electrons coupling with the induced electric field.

CONCLUSIONS

Recent developments in PROES have made detailed experimental investigations of electron dynamics and power coupling mechanisms in rf plasmas possible. The application of PROES in various rf plasmas based on different power coupling mechanisms has been discussed. The basis is a time dependent model for the population dynamics of excited states within the rf cycle. Characteristic signatures of different power coupling mechanisms in Fourier-components of the measured temporal modulation have been shown and understood. Despite the already achieved success, PROES is still a relatively new diagnostics technique which gives a lot of promise for future developments.
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