Power absorption in electrically asymmetric dual frequency capacitive radio frequency discharges

E. Schüngel, J. Schulze, Z. Donkó, and U. Czarnetzki
1Institute for Plasma and Atomic Physics, Ruhr-University Bochum, 44780 Bochum, Germany
2Research Institute for Solid State Physics and Optics, Hungarian Academy of Sciences, P.O. Box 49, 1525 Budapest, Hungary

(Received 13 October 2010; accepted 17 December 2010; published online 11 January 2011)

The symmetry of capacitive radio frequency discharges can be controlled via the electrical asymmetry effect by driving one electrode with a fundamental frequency and its second harmonic. In such electrically asymmetric discharges, the mean ion energies at both electrodes are controlled separately from the ion flux by tuning the phase angle $\theta$ between the harmonics at fixed voltage amplitudes. Here, the question why the ion flux is nearly independent of $\theta$ is answered by investigating the power absorbed by the electrons $P_e$ as a function of $\theta$ and time experimentally, by a particle in cell simulation, and an analytical model. The dynamics of $P_e$ is understood by the model and is found to be strongly affected by the choice of $\theta$. However, on time average, $P_e$ is nearly constant, independently of $\theta$. Thus, the ion flux remains approximately constant. In addition, it is shown that the absolute value of the individual voltages across the powered and grounded electrode sheath vary linearly with the dc self-bias. However, their sum remains constant. This yields, in combination with the constancy of the ion flux, a constant power absorbed by the ions and, in conclusion, a total power absorption that is independent of $\theta$.

I. INTRODUCTION

For many applications of capacitively coupled radio frequency (CCRF) discharges, separate control of ion energy and ion flux at a processing surface is of major importance. In “classical” dual frequency capacitive discharges operated at two substantially different frequencies this separate control is limited by the coupling of both frequencies and the effect of secondary electrons.

These limitations can be overcome by driving one electrode with a voltage waveform $\phi_0(t, \theta)$, which is the sum of a fundamental frequency $f$ and its second harmonic with fixed, but adjustable phase shift $\theta$ between the driving harmonics:

$$\phi_0(t, \theta) = \frac{1}{2}\phi_0[\cos(\omega_r t + \theta) + \cos(2\omega_r t)].$$

Here $\omega_r = 2\pi f$ and $\phi_0$ is the sum of the identical amplitudes of both harmonics. If such a driving voltage waveform is used, the electrical asymmetry effect (EAE) will allow to control the mean ion energies at the electrodes separately from the ion fluxes in an almost ideal way by tuning $\theta$ such as demonstrated experimentally and by a particle in cell (PIC) simulation.

In this work, we investigate and answer the question why the ion flux at each electrode is nearly constant at fixed $\phi_0$ regardless of $\theta$ in such electrically asymmetric discharges. The article is structured in the following way: In Sec. II, we introduce the methods used to investigate the power absorption, i.e., experiment, PIC simulation, and model. In Sec. III, the results are presented. This section is divided into four parts. First, the energy balances for electrons and ions in electrically asymmetric dual frequency discharges are discussed. Second, the power absorption by the electrons is analyzed based on the electron energy balance. Third, the power absorption by the ions is investigated based on the ion energy balance and the results for the electron power absorption. Fourth, the total absorbed power is discussed based on the results for the electron and ion power absorption. Finally, conclusions are drawn in Sec. IV.

II. METHODS

We investigate an electrically asymmetric CCRF discharge such as shown in Fig. 1. The discharge is geometrically symmetric, i.e., the surface areas of the powered and grounded electrode, $A_p$ and $A_g$, are equal. The electrode gap is $d$. One electrode is driven by the voltage waveform $\phi_0(t, \theta)$ with $f=13.56$ MHz to generate an argon plasma. In the experiment, the discharge is operated in a modified gaseous electronics conference (GEC) reference cell. The plasma is confined between the electrodes by a glass cylinder. The rf current is measured time resolved by a self-excited electron resonance spectroscopy (SEERS) sensor implemented into the grounded electrode. The square of this measured current is proportional to the time resolved power absorbed by the plasma electrons.

Generally, it was found that in classical dual frequency discharges, the matching quality can be affected by modulations of the discharge conditions. In our experimental study of an electrically asymmetric dual frequency discharge, care is taken to always reach very good matching conditions.
Only a small change of the voltage amplitudes as a function of \( \theta \) is observed and corrected. Therefore, it can be reasonably assumed that the idealized voltage waveform given in Eq. (1) is applied to the powered electrode. Similarly, matching effects are neglected in both the simulation and the model.\(^{21}\)

Such a discharge is also investigated by a one-dimensional (1D) PIC simulation complemented with a Monte Carlo treatment of collisions using the cross sections given in Refs. \(^{22}\) and \(^{23}\). At the infinite, planar, and parallel electrodes, secondary electrons are emitted with a probability of \( \gamma = 0.1 \). Details of the simulation can be found elsewhere.\(^{15}\) The power absorption of electrons and ions in such electrically asymmetric discharges is analyzed theoretically based on the analytical model of the EAE.\(^{14}\) The main part of this work is related to the analytical description of the power absorption, which is supplemented and verified by experimental and simulation results and finally yields the answer why the ion flux in electrically asymmetric CCRF discharges is constant as a function of \( \theta \).

### III. RESULTS

In this section, the power absorption of electrons and ions in electrically asymmetric dual frequency CCRF discharges is investigated. First, we discuss the energy balances for electrons and ions in such a discharge. Based on the electron energy balance, we investigate the time averaged electron power absorption as a function of \( \theta \) and its effect on the ion flux at the electrodes at different discharge conditions in Sec. III B. In Sec. III C, we analyze the ion power absorption based on the ion energy balance and the results for the electron power absorption. Finally, we discuss the total absorbed power in Sec. III D.

#### A. Energy balances for electrons and ions

Generally, the time averaged fluxes of electrons \( \langle \Gamma^{(e)}_p \rangle \) and ions \( \langle \Gamma^{(i)}_g \rangle \) have to balance each other at the electrodes of an electrostatic CCRF discharge.\(^{24,25}\) The ion fluxes at the powered and grounded electrode, \( \Gamma^{(i)}_p \) and \( \Gamma^{(i)}_g \), can be assumed to be temporally constant. Thus,\(^{2}\)

\[
\langle \Gamma^{(e)}_p \rangle = \Gamma^{(i)}_p, \tag{2}
\]

\[
\langle \Gamma^{(e)}_g \rangle = \Gamma^{(i)}_g. \tag{3}
\]

Here, \( \langle \ldots \rangle \) indicates the temporal average over one period of the fundamental frequency.

The ions gain energy dominantly due to the acceleration toward the electrodes by the voltage drop across the sheaths.\(^{1,26}\) There are different electron heating mechanisms in a CCRF discharge,\(^{1,5,7,9,16,19,27–36}\) e.g., Ohmic and stochastic heating. A detailed discussion of the different electron heating mechanisms is beyond the scope of this work.

The fluxes toward the electrodes are determined by the time averaged power absorbed by the electrons, \( \langle P_e \rangle \), and by the ions, \( \langle P_i \rangle \), via the energy balances\(^{1,24,25,29,30,32}\) for both species, i.e., the energy gain mentioned above has to be balanced by the losses in the steady state:

\[
\langle P_e \rangle = e \Gamma^{(i)}_p A_p [E^{(e)}_p + \langle \epsilon^{(e)}_p \rangle] + e \Gamma^{(i)}_g A_g [E^{(e)}_g + \langle \epsilon^{(e)}_g \rangle], \tag{4}
\]

\[
\langle P_i \rangle = e \Gamma^{(i)}_p E_p^{(i)} + e \Gamma^{(i)}_g E_g^{(i)}. \tag{5}
\]

Here, \( e \) is the elementary charge, \( E^{(e)} \) is the collisional energy loss per electron-ion pair created, and \( E_p^{(i)} \) and \( E_g^{(i)} \) are the energy loss per electron lost from the discharge at the powered and grounded electrode, respectively. \( E_p^{(i)} \) and \( E_g^{(i)} \) is the energy loss per ion lost from the discharge at the respective electrode. \( \Gamma^{(i)}_p \) and \( \Gamma^{(i)}_g \) is the ion flux at the respective electrode. In the following, we assume \( \Gamma^{(i)}_p = \Gamma^{(i)}_g = \Gamma^{(i)}_g = \Gamma^{(i)}_g = E^{(e)}_p = E^{(e)}_g \), \( E_p^{(i)} = \langle \phi_{p,i}(t) \rangle \), and \( E_g^{(i)} = \langle \phi_{g,i}(t) \rangle \), where \( \phi_{p,i}(t) \) and \( \phi_{g,i}(t) \) is the voltage drop across the sheath adjacent to the powered and grounded electrode. The approximations for \( E_p^{(i)} \) and \( E_g^{(i)} \) will only be valid if ionization inside the sheaths can be neglected, which is the case under all conditions investigated here. Note that \( E_p^{(i)} \) cannot be significantly different from \( E_g^{(i)} \) in electrically asymmetric discharges. Under these assumptions, the electron and ion energy balances in a geometrically symmetric discharge (\( A_p = A_g = A \)) are:

\[
\langle P_e \rangle = 2 e A \Gamma^{(e)} [E^{(e)} + \langle \epsilon^{(e)} \rangle], \tag{6}
\]

\[
\langle P_i \rangle = e A \Gamma^{(i)} [\langle \phi_{p,i}(t) \rangle + \langle \phi_{g,i}(t) \rangle]. \tag{7}
\]

Since \( E^{(e)} + \epsilon^{(e)} \) is constant independently of \( \theta \), the ion flux is directly proportional to \( P_e \). In the following, we demonstrate that \( \langle P_e \rangle \), and thus \( \Gamma^{(i)} \), is constant independently of \( \theta \) in electrically asymmetric dual frequency discharges.

#### B. Electron power absorption

We use the analytical model of the EAE (Ref. 14) to investigate the power absorption by the electrons in electrically asymmetric discharges theoretically. This model is based on the following voltage balance of a CCRF discharge:

\[
\phi_{-}(t) + \phi_{p} + \phi_{g} + \phi_{b}, \tag{8}
\]

Here, \( \eta \) is the dc self-bias and \( \phi_{b} \) is the bulk voltage. Using the quadratic charge voltage relation for the sheaths in CCRF discharges\(^{35}\) and neglecting \( \phi_{b} \) (Ref. 15) yields

\[
\phi_{-}(t) + \eta = -Q^2(t) + e[q_i \pm q(t)]^2, \tag{9}
\]

with \( q(t) = Q(t)/Q_0 \), where \( Q(t) \) is the space charge in the sheath at the powered electrode as a function of time and...
$Q_0 \approx A_p \sqrt{2e \varepsilon_0 \bar{n}_{sp} \phi_0}$ is a normalization constant. $\varepsilon_0$ is the dielectric constant and $\bar{n}_{sp}$ is the spatially averaged ion density in the sheath at the powered electrode. $^{14}$ $q_i$ is the total uncompensated charge in the discharge normalized by $Q_0$; it is assumed to be temporally constant. $^{18}$ $\bar{\phi}_+(t, \theta)$ is the applied voltage normalized by its amplitude $\phi_0$ and $\bar{n}$ is the dc self-bias normalized by $\phi_0$. The symmetry parameter $\varepsilon$ is defined as the ratio of the maximum sheath voltages that drop across the sheath at the grounded electrode, $\bar{\phi}_{sp}$, and powered electrode, $\bar{\phi}_{sp}$, (Ref. 14):

$$\varepsilon = \left| \frac{\bar{\phi}_{sp}}{\phi_{sp}} \right| = \left( \frac{A_p}{A_g} \right) \frac{2 \bar{n}_{sp}}{\bar{n}_{sg}}.$$

(10)

In a geometrically symmetric discharge, $\varepsilon$ depends only on the ratio of the mean ion densities $\bar{n}_{sp}$ and $\bar{n}_{sg}$ in both sheaths.

If the low floating potentials during the sheath collapse at both electrodes are neglected, the normalized dc self-bias $\bar{n}$ and the total charge $q_i$ are found to be $^{14}$

$$\bar{n} = -\frac{\bar{\phi}_{m1}(\theta) + \varepsilon \bar{\phi}_{m2}(\theta)}{\phi_0 (1 + \varepsilon)},$$

(11)

$$q_i = \sqrt{\bar{\phi}_{m1}(\theta) - \bar{\phi}_{m2}(\theta)}.$$

(12)

Here, $\bar{\phi}_{m1}(\theta)$ and $\bar{\phi}_{m2}(\theta)$ are the maximum and minimum of the applied voltage waveform, which are functions of $\theta$. They can be approximated in the range $0^\circ \leq \theta \leq 90^\circ$ as

$$\bar{\phi}_{m1}(\theta) \approx \frac{\phi_0 [1 + \cos(\theta)]}{2},$$

(13)

$$\bar{\phi}_{m2}(\theta) \approx \frac{-\phi_0 [1 + \sin(\theta)]}{2}.$$  

(14)

Based on Eq. (11), a dc self-bias is generated via the EAE as an almost linear function of $\theta$ for $0^\circ \leq \theta \leq 90^\circ$, $^{13-15}$ which allows controlling the mean ion energies at the electrodes. $^{13-15}$

The balance (9) can be solved for $q(t)$:

$$q(t) = -\varepsilon q_i \pm \sqrt{\varepsilon q_i^2 - (1 - \varepsilon) \left[ \bar{n} + \bar{\phi}_{-(t)} \right]}.$$

(15)

Based on Eq. (15), the electron conduction current density $j_e(t) = -(Q_0/A_p) (\partial q/ \partial t)$ and, finally, the power absorbed by the electrons $P_e(t, \theta, \varepsilon) = [j_e(t)/\sigma] A_p l$ can be calculated. Here, $l$ is the bulk length and $\sigma \bar{n}_{sb}$ is the bulk conductivity. $^{13,20}$ for a given pressure, where $\bar{n}_{sb}$ is an effective plasma density in the bulk. Using Eqs. (11) and (12), the following result for $P_e(t, \theta, \varepsilon)$ is obtained:

$$P_e(t, \theta, \varepsilon) = P_{e,0} \frac{(1 + \varepsilon) \left[ \bar{\phi}_{-(t, \theta)} \right]^2}{4 \left[ \bar{\phi}_{m1}(\theta) + \varepsilon^2 \bar{\phi}_{m2}(\theta) - (1 - \varepsilon^2) \bar{\phi}_{-(t, \theta)} \right] \phi_0}.$$

(16)

FIG. 2. (Color online) Symmetry parameter $\varepsilon$ and $P_{e,0}$, i.e., $P_{e,0}$ normalized by its phase angle averaged value, as a function of $\theta$ at high pressure (100 Pa, $\phi_0=240$ V, $d=2$ cm) and at low pressure (2.66 Pa, $\phi_0=630$ V, $d=6.7$ cm) resulting from PIC simulations.

The dot represents the differentiation with respect to $\varphi=\omega_0 t$. $P_{e,0}=2 \phi_0 \omega_p e_0 e_0 \bar{n}_{sp} A_p l / \sigma \bar{n}_{sp} \bar{n}_p$ is approximately constant at high pressures and changes as a function of $\theta$ at low pressures (see Fig. 2), mainly due to the variation of $\bar{n}_{sp}(\theta)$. Based on Eq. (16), the time averaged value of $P_e(t)$ can now be calculated using $P_{e,0}$ and $\varepsilon$ as input parameters from the PIC simulation:

$$\langle P_e \rangle = P_{e,0} \varepsilon^2 / 5.8.$$

(17)

At high pressures in geometrically symmetric discharges, the symmetry parameter $\varepsilon$ is close to unity for all $\theta$ (Ref. 14) and $P_{e,0}$ is almost constant (see Fig. 2). In this case, the time averaged power absorbed by the plasma electrons is determined from Eq. (16) using $\langle \bar{\phi}_{-(t, \theta)} / \phi_0 \rangle = 5/8$:

$$\langle P_e \rangle = P_{e,0} \varepsilon^2 \text{ with } p_0(\theta) = \frac{\phi_0}{16} \left[ \bar{\phi}_{m1}(\theta) - \bar{\phi}_{m2}(\theta) \right].$$

(18)

At low pressures, $P_{e,0}$ and $\varepsilon$ are no longer constants, but change as functions of $\theta$. Nevertheless, an approximate value for the total power absorbed by the electrons can be calculated analytically by a linear expansion of Eq. (16) around $\varepsilon = 1$:

$$\langle P_e \rangle = P_{e,0} [p_0(\theta) + (\varepsilon - 1) p_1(\theta)] \text{ with } p_1(\theta) = \frac{5 \phi_0 [3 \bar{\phi}_{m1}(\theta) \bar{\phi}_{m2}(\theta) - 3 \phi_0^2 \cos(3\theta)]}{32 [\bar{\phi}_{m1}(\theta) - \bar{\phi}_{m2}(\theta)]^2}.$$  

(19)

Equation (19) will be a good approximation if $0.5 \leq \varepsilon \leq 1.5$. As shown in Fig. 2, $\varepsilon$ typically remains within these limits in geometrically symmetric electrically asymmetric dual frequency discharges. Although $p_0(\theta)$ and $p_1(\theta)$ are nominally functions of $\theta$, they are effectively constants ($p_0=0.2$ and...
by a small variation of the total charge by the ions can now be investigated by analyzing the absolute voltage amplitudes in electrically asymmetric dual frequency CCRF discharges.

Here, all voltages are normalized by the constant applied voltage amplitude $V_0$, i.e., $\tilde{\phi}_{m}(t) = \phi_{m}(t)/V_0$ and $\tilde{\phi}_{n}(t) = \phi_{n}(t)/V_0$, The dc self-bias corresponds to the sum of the time averaged sheath voltages under the assumption of a negligible voltage drop across the plasma bulk, as can be seen by taking the time average of Eq. (8). Therefore, the following relation between the normalized self-bias $\bar{\eta}$ and the function $f(\eta)$ is valid:

$$ \langle \hat{\phi}_n(t) \rangle = f(\bar{\eta}), \quad \langle \hat{\phi}_m(t) \rangle = f(-\bar{\eta}). $$

Without loss of generality, $f(\bar{\eta})$ can be expressed by a power expansion:

$$ f(\bar{\eta}) = \sum_{n=0}^{\infty} a_n \bar{\eta}^n. $$

C. Ion power absorption

Based on Eq. (7) and $\Gamma(\theta) = \text{const}$, the power absorbed by the ions can now be investigated by analyzing the absolute values of the time averaged sheath voltages $|\langle \hat{\phi}_m(t) \rangle|$ and $|\langle \hat{\phi}_n(t) \rangle| > 0$. For symmetry reasons, they can be expressed as functions of the dc self-bias $\eta$ in the following way:

$$ |\langle \hat{\phi}_m(t) \rangle| = f(\bar{\eta}), \quad |\langle \hat{\phi}_n(t) \rangle| = f(-\bar{\eta}). $$

Figure 4 shows $P_{e}(t, \theta)$ resulting from the experiment, the PIC simulation, and the analytical model [Eq. (16)] at high pressure ($\varepsilon = 1\forall \theta$). According to the four extrema of $\phi_{m}(t, \theta)$, each plot shows four maxima. While the heights of the first and third maximum remain almost constant for all $\theta$, the second and fourth maxima vary oppositely in the range $0^\circ \leq \theta \leq 90^\circ$.

As a result of this compensation, $\langle P_{e} \rangle$ remains almost constant for all $\theta$ [see Fig. 5(a)]. The slight decrease at $\theta = 45^\circ$ in comparison to $\langle P_{e} \rangle$ at $\theta = 0^\circ$ and $\theta = 90^\circ$ is caused by a small variation of the total charge $q_{m}(\theta)$ due to a variation of $(\tilde{\phi}_{m}(t) - \tilde{\phi}_{m}(t))$ as a function of $\theta$ [Eq. (12)]. Also at low pressures, $\langle P_{e} \rangle$ is approximately constant [Fig. 5(b)]. Based on Eq. (6), these results demonstrate why the ion flux at both electrodes is constant as a function of $\theta$ using fixed applied voltage amplitudes in electrically asymmetric dual frequency CCRF discharges.

FIG. 3. (Color online) $\tilde{\phi}_{m}(\theta)/\phi_0$ [Eq. (13)], $\tilde{\phi}_{n}(\theta)/\phi_0$ [Eq. (14)], $p_0$ [Eq. (18)], and $p_1$ [Eq. (19)] as a function of $\theta$ calculated by the model.

FIG. 4. (Color online) Power absorbed by the electrons as a function of $\theta$ and time within one low frequency period. The color scale shows the relative power in percent of the maximum value. (a) Experiment, 100 Pa, $d=1$ cm, $\phi_0=100$ V; (b) PIC simulation, 100 Pa, $d=2$ cm, $\phi_0=240$ V; and (c) analytical model, $\varepsilon=1$.
FIG. 5. (Color online) Time averaged power absorbed by the electrons as a function of $\theta$ resulting from experiment, simulation, and model under several conditions. For all $\theta$, the period averaged absorbed power is normalized by the mean value. (a) High pressure and (b) low pressure $[P_{\phi,0}(\theta)$ and $\epsilon(\theta)$ from the PIC simulation are used as input parameters in the model].

$\bar{\eta} = -\langle |\bar{\phi}_{sp}(t)| + |\bar{\phi}_{sg}(t)| \rangle$, \hspace{1cm} (22)

$= -\sum_{n=0}^{\infty} a_n \bar{\eta}^n + \sum_{n=0}^{\infty} a_n (-\bar{\eta})^n$, \hspace{1cm} (23)

$= -2 \sum_{n=0}^{\infty} a_{2n+1} \bar{\eta}^{2n+1}$. \hspace{1cm} (24)

Here, only odd powers contribute. Equation (24) is only fulfilled if $a_1 = -1/2$ and $a_{2n+1} = 0 \forall n \geq 1$.

With the symmetry considerations made above, we can assume a symmetric discharge at $\epsilon = 1$ and $\bar{\eta} = 0$. This means, that the absolute value of the mean sheath voltages in front of the powered and grounded electrode are the same: $|\langle \bar{\phi}_{sp}(t) \rangle| = |\langle \bar{\phi}_{sg}(t) \rangle|$ due to Eq. (22). Therefore, we can find $f(\bar{\eta}) = a_0$ analytically by solving Eq. (9) in the case of symmetry

$a_0 = |\langle \bar{\phi}_{sp}(t) \rangle| = |\langle \bar{\phi}_{sg}(t) \rangle| = 0.29 + 0.5 \bar{\eta}$, \hspace{1cm} (25)

Here, $\langle \bar{q}_s^2(t, \theta) \rangle = 1/4 \forall \theta$ is used. As mentioned above, the total charge $q_s(\theta)$ depends weakly on $\theta$ [see Eq. (12)].

In case of $\epsilon = 1$, the dc self-bias is expected to vanish at $\theta = 45^\circ$ due to Eq. (11). With the approximations of the maximum $\bar{f}_{n1}/f_0$ and minimum $\bar{f}_{n2}/f_0$ of $\bar{\phi}$ shown in Fig. 3, we find $q_s^2(\theta = 45^\circ) = (1 + \sqrt{2})/2.2$. This yields $a_0 = 0.29$. Therefore, the normalized sheath voltages are analytically found to be:

$\langle \bar{\phi}_{sp} \rangle \approx -0.29 + 0.5 \bar{\eta}$, \hspace{1cm} (27)

$\langle \bar{\phi}_{sg} \rangle \approx 0.29 + 0.5 \bar{\eta}$. \hspace{1cm} (28)

The linear functions of Eqs. (27) and (28) are compared to results of the PIC simulation in Fig. 6. The slope is very well reproduced. The model predicts $a_0 = 0.29$, which is slightly smaller than the value $a_0 = 0.33$ found in the simulations. This might be caused by small temporal variations of $q_s$, which are neglected in the model.\hspace{1cm} (28)
D. Total power absorption

The time averaged total power absorbed in the discharge $\langle P_{\text{abs}} \rangle$ is the sum of the powers absorbed by electrons and ions

$$\langle P_{\text{abs}} \rangle = \langle P_e \rangle + \langle P_i \rangle. \quad (29)$$

Based on Eq. (29) and the results of Secs. III B and III C for the power absorbed by electrons and ions, respectively, the total absorbed power is also approximately constant as a function of $\theta$. This might be important for practical purposes, since usually the power supplied by the generator rather than the voltage applied to the electrode is monitored.

IV. CONCLUSIONS

We investigated the power absorption by electrons and ions in electrically asymmetric dual frequency capacitively coupled radio frequency discharges experimentally, by a PIC simulation, and by an analytical model. Based on the analytical model of the EAE, we have shown that the power absorbed by the electrons is nearly constant as a function of the phase shift $\theta$ between the driving harmonics at high and low pressures. These theoretical results have been verified experimentally and by PIC simulations. Based on the energy balance for the electrons, we have demonstrated that a constant electron power absorption causes the ion flux at the electrodes to remain constant as a function of $\theta$. In this way, the questions why the ion flux is approximately constant as a function of $\theta$ and why the ion energy can be controlled separately from the ion flux in an almost ideal way in electrically asymmetric dual frequency discharges have been answered. Based on the ion energy balance and an analysis of the time averaged sheath voltages, we have found that a constant electron power absorption, i.e., a constant ion flux, causes the power absorption of the ions to remain constant, too. Thus, the total power absorbed in the discharge is also nearly constant as a function of $\theta$.

ACKNOWLEDGMENTS

The support by the Hungarian Fund for Scientific Research (Grants OTKA K77653 and OTKA-IN-85261), the Alexander von Humboldt Foundation, and the Ruhr-University Research Department Plasma are gratefully acknowledged.