Magnetic control of nonlinear electron resonance heating in a capacitively coupled radio frequency discharge

M Oberberg, D Engel, B Berger, C Wölfel, D Eremin, J Lunze, R P Brinkmann, P Awakowicz and J Schulze

1 Institute of Electrical Engineering and Plasma Technology, Ruhr University Bochum, Universitaetsstrasse 150, D-44801 Bochum, Germany
2 Institute of Theoretical Electrical Engineering, Ruhr University Bochum, Universitaetsstrasse 150, D-44801 Bochum, Germany
3 Institute of Automation and Computer Control, Ruhr University Bochum, Universitaetsstrasse 150, D-44801 Bochum, Germany
4 Department of Physics, West Virginia University, Morgantown, WV 26506, United States of America

E-mail: oberberg@aept.rub.de

Received 4 June 2019, revised 9 September 2019
Accepted for publication 1 November 2019
Published 27 November 2019

Abstract

In magnetized capacitively coupled radio frequency (RF) plasmas operated at low pressure, the magnetic asymmetry effect (MAE) provides the opportunity to control the discharge symmetry, the DC self-bias, and the ion energy distribution functions at boundary surfaces by adjusting a magnetic field, that is oriented parallel to the electrodes, at one electrode, while leaving it constant at the opposite electrode. This effect is caused by the presence of different plasma densities in regions of different magnetic field strength. Here, based on a balanced magnetron magnetic field configuration at the powered electrode, we demonstrate that the magnetic control of the plasma symmetry allows to tailor the generation of high frequency oscillations in the discharge current induced by the self-excitation of the plasma series resonance (PSR) through adjusting the magnetic field adjacent to the powered electrode. Experimental current measurements performed in an argon discharge at 1 Pa as well as results of an equivalent circuit model show that nonlinear electron resonance heating can be switched on and off in this way. Moreover, the self-excitation of the PSR can be shifted in time (within the RF period) and in space (from one electrode to the other) by controlling the discharge symmetry via adjusting the magnetic field.

Keywords: magnetic asymmetry effect, plasma series resonance, nonlinear electron resonance heating, DC self-bias voltage, magnetized plasma, capacitively coupled radio frequency discharge

1. Introduction

Plasma technology has significantly improved our modern life. The manufacturing of a high number of technological devices requires processing steps involving surface modification via plasma treatment, e.g. plasma enhanced chemical vapor deposition or anisotropic etching of integrated circuits [1]. For all of these applications the control and optimization of the flux-energy distribution functions of charged particles and neutral radicals at the substrate surface is essential. In capacitively coupled plasmas (CCPs) driven by a single frequency, however, the control of these distribution functions is strongly limited. Using two or more consecutive harmonics of a fundamental frequency to power the discharge instead allows for an electrical control of the symmetry, the DC self-bias, and the charged and
neutral particle distribution functions via the electrical asymmetry effect (EAE) by voltage waveform tailoring (VWT) [2–15].

Recently, the effects of an asymmetric magnetic field distribution, where the magnetic field is parallel to the electrodes and higher at one compared to the other electrode, on the discharge, called the magnetic asymmetry effect (MAE), have been explored. In 2013, Trieschmann et al. studied computationally the effects of a magnetic field on a dual-frequency, geometrically symmetric CCP. In their one-dimensional set-up, the magnetic field was set parallel to the powered electrode surface and decreased towards the grounded electrode. A strong influence of the magnetic field on the ion energy distribution function at both electrodes was observed [16]. In 2017 and 2018, Yang et al. published results on the MAE based on one-dimensional particle-in-cell simulations. They found that for a static magnetic flux density of 10 mT at the grounded electrode and an increasing magnetic flux density (1–10 mT) at the powered electrode, the DC self-bias changes from −50 V to 0 V in a single frequency argon discharge at 13.56 MHz and at a driving voltage amplitude of 150 V, i.e., they demonstrated that the discharge symmetry can be controlled magnetically. Furthermore, it was shown that the magnetic field strongly influences the potential, the electron density, and the ionization rate between the electrodes. A pressure variation revealed an attenuation of the MAE as a function of pressure [17, 18]. Joshi et al. investigated the electron series resonance in a magnetized geometrically symmetric CCP in argon at 13.56 MHz. A magnetic field parallel to the electrodes was used that is constant as a function of the distance from the powered electrode within the entire electrode gap, i.e., there is no magnetic asymmetry. By switching on the magnetic field, the series resonance and an increase of the inductive reactance in the plasma bulk were observed [19].

Also in 2018, the first experimental proof of the existence of the MAE was published. These investigations were performed in a CCP driven at 13.56 MHz in argon at 1 Pa with a static balanced magnetron-like magnetic field configuration at the powered electrode and almost no magnetic field at the grounded electrode. A controlled change of the magnetic flux density at the powered electrode was found to allow for a control of the symmetry, the DC self-bias, and the mean ion energy at boundary surfaces. The results were compared to results of an analytical RF sheath model, which reproduced the measured trends of the mean ion energy as a function of the driving voltage amplitude and the magnetic flux density. Increasing the magnetic field at one electrode was found to confine electrons locally and to increase the charged particle density in the magnetized zone. This effect was identified to lead to the observed asymmetry of the plasma density and to be the physical origin of the MAE [20]. Ultimately, the magnetic control of the DC self-bias, $\eta$, was explained based on an analytical model of Czarnetzki et al. [11] that yields the following expression for the DC self bias in a low pressure electropositive single frequency CCP driven by a sinusoidal voltage waveform with amplitude $\phi_0$:

$$\eta = -\phi_0 \frac{1 - \epsilon}{1 + \epsilon}. \quad (1)$$

Here, $\epsilon$ is the symmetry parameter:

$$\epsilon = \left| \frac{\phi_{sg}}{\phi_{sp}} \right| = \frac{A_p}{A_g} \frac{\bar{n}_{sp} I_g}{\bar{n}_{sg} I_p}. \quad (2)$$

where $\phi_{sg}$ and $\phi_{sp}$ is the maximum voltage drop across the sheath at the grounded and powered electrode, respectively. $A_p$ and $A_g$ are the surface areas of the powered and grounded electrode, $\bar{n}_{sp}$ and $\bar{n}_{sg}$ is the mean ion density in the respective sheath and $I_p$ and $I_g$ is the respective sheath integral defined according to [11]. The ratio of the sheath integrals is typically close to unity and, therefore, can be neglected in most cases. In equation (1) the voltage drop across the plasma bulk and the floating potentials at both electrodes are neglected.

The presence of a strong magnetic confinement of electrons at one of the electrodes leads to a local enhancement of the mean ion density, which is a function of the local magnetic field strength. Thus, by controlling this magnetic field the ratio of the mean ion densities at both electrodes, $\bar{n}_{sp}/\bar{n}_{sg}$, and, therefore, the discharge symmetry can be controlled, i.e., the symmetry parameter can be tuned.

Understanding and controlling the electron power absorption dynamics in CCPs is essential, since it strongly affects the plasma density, the ion flux to boundary surfaces, and energy distribution functions of charged particles in the volume and at the electrodes. Control of these plasma parameters is important for applications of these plasma sources. Different modes of operation of CCPs are known ranging from the $\alpha$-mode, where electrons are predominantly accelerated by interactions with the oscillating boundary sheaths [21–25], to the $\gamma$-mode, where ionization by secondary electrons emitted from boundary surfaces is important [26, 27].

Previous investigations of the electron power absorption dynamics in unmagnetized CCPs [28–35] have shown that high frequency oscillations of the discharge current at frequencies higher than the driving frequency can be generated. Their generation is explained by the self-excitation of the plasma series resonance (PSR) in asymmetric low pressure discharges, i.e., in scenarios where $\epsilon < 1$. Ultimately, this is caused by the fact that the nonlinearities of the charge-voltage relation of the sheaths at the powered and grounded electrode do not compensate each other in asymmetric CCPs, i.e., they do not cancel in the voltage balance of the discharge in the frame of equivalent circuit models [11]. The kinetic origin of such resonance phenomena in CCPs has recently been revealed by Wilczek et al. [36]. The presence of PSR oscillations of the current leads to high frequency oscillations of the sheath edge and to the generation of multiple electron beams during a single phase of sheath expansion at the electrode, where the maximum sheath voltage is high [37, 38]. In this way the self-excitation of the PSR enhances the electron power absorption in CCPs. This phenomena is called nonlinear electron resonance heating (NERH) and is
strongly pronounced at low pressure, at which the resonance is not damped efficiently by collisions. Mussenbrock et al [39] demonstrated NERH to enhance the ohmic and stochastic electron heating.

The discharge asymmetry (\(e \approx 1\)) required for the presence of NERH can be generated in different ways. One option is the presence of a geometric reactor asymmetry, i.e. \(A_p/A_g \approx 1\). Such a geometric asymmetry is present in many industrial plasma reactors, but cannot be controlled easily, since the reactor design typically cannot be changed. Another option to control the discharge symmetry is VWT and the EAE [2–11], which allows to control the discharge symmetry by customizing the driving voltage waveform. In contrast to the geometric reactor asymmetry, this electrical asymmetry can be controlled easily. Donko et al [40] demonstrated that tuning the driving voltage waveform in a geometrically symmetric low pressure CCP allows to change the symmetry parameter from values smaller than unity to values larger than unity. In this way, the PSR and NERH could be switched on and off electrically. Moreover, the electrode at which the PSR is excited during the local sheath collapse could be changed from the powered to the grounded electrode by controlling the driving voltage waveform.

In this work, we investigate the effects of controlling the discharge symmetry via the MAE on the self-excitation of the PSR and NERH. Based on experiments and an equivalent circuit model, we demonstrate that controlling the magnetic field at the powered electrode in a low pressure single frequency CCP operated in argon with a balanced magnetron magnetic field at the powered electrode allows to switch NERH on and off. We show that the symmetry parameter is a function of this magnetic field and can be changed from less than unity to values larger than unity magnetically. In this way and similar to the electrical tuning of the driving voltage waveform in previous studies, the self-excitation of the PSR can be shifted from one electrode to the other by adjusting the magnetic field at the powered electrode. We also show that this magnetic control of NERH has important consequences on the total power dissipation to electrons, which, in turn, is highly relevant for knowledge based optimization of plasma processing applications. While the equivalent circuit model reproduces the measurements qualitatively, it does not yield perfect quantitative agreement. This is caused by the fact that it is a simplified global model. Nevertheless, it reduces the complex scenario to its essence and reveals the physical reason why the MAE allows to control the PSR and NERH.

The manuscript is structured as follows: section 2 describes the experimental set-up followed by an introduction of the equivalent circuit model used to understand the self-excitation of the PSR in section 3. In section 4, our results are presented and discussed followed by conclusions in section 5.

2. Experimental set-up

The experimental set-up is shown schematically in figure 1 and consists of a cylindrical vacuum chamber with a height of 400 mm and a diameter of 318 mm. The powered electrode is made of aluminum and is mounted at the top of the chamber. It includes permanent magnets, which are located behind a cooling system. A grounded shield as well as a grounded mesh surround the lateral surface area of the electrode and prevent parasitic RF coupling to the reactor walls. This suppresses the ignition of parasitic discharges between the electrode and the grounded walls. The NdFeB permanent magnets are arranged in two rings inside the powered electrode and can be stacked to achieve different field strengths. This arrangement generates an azimuthally symmetric balanced magnetron-like magnetic field. As a reference, the maximum radial component of the magnetic flux density is measured at an axial distance of 8 mm from the powered electrode surface. Magnetic flux densities of 0 mT, 7 mT, 11 mT, 18 mT and 20 mT can be reached at this reference point by stacking different permanent magnets. A more detailed description of the configuration and measurements of the magnetic flux density can be found in [20]. This reactor can be used for RF magnetron sputtering. The grounded electrode is also made of aluminum and is located at a gap distance of 52 mm below the powered electrode.

The powered electrode is driven by a single RF voltage waveform at 13.56 MHz with an amplitude of \(V_0 = 300\) V. A VI-probe (Impedans Octiv Suite) is used to measure the driving voltage amplitude and the current. Additionally, the DC self-bias voltage is measured.

As shown in figure 1, a dielectric glass confinement is added to improve the geometrical symmetry of the reactor [20]. It consists of stacked glass rings with an inner diameter of 100 mm. Every second glass ring is thinner and has a larger inner diameter of 160 mm. In this way shortcuts between the powered and the grounded electrode due to the deposition of conducting coatings are prevented.
sheaths adjacent to the powered and grounded electrode, as well as the plasma bulk. The voltage source provides a driving voltage waveform \( \phi(t) = \phi_0 \cos(\omega_{RF} t) \), \( \phi_0(t) \) denotes the time dependent voltage drop across the external blocking capacitor. The DC self-bias, \( \eta \), corresponds to the time average of \( \phi_0(t) \), i.e. \( \eta = \langle \phi_0(t) \rangle \). The time dependent voltage drop across the sheath at the powered and grounded electrode, \( \phi_{sp,sg}(t) \), respectively, is obtained based on a matrix sheath model according to [43]. The result is the following quadratic dependence of the sheath voltage on the time dependent charge, \( Q_{sp,sg}(t) \), in the respective sheath:

\[
\phi_{sp,sg}(t) = \frac{Q_{sp,sg}^2(t)}{2 \epsilon_0 \epsilon n_{sp,sg} A_{sp,sg}^2},
\]

The current through each sheath is assumed to be the sum of three components, i.e. the constant ion current, the time dependent electron conduction current, which is only high during the local sheath collapse, and the displacement current. Thus, according to figure 2 each sheath is modelled as a parallel circuit consisting of a DC current source (ion current), a diode (electron current), and a nonlinear capacitor (displacement current).

The quasi-neutral plasma bulk is divided into a magnetized region of length \( l_m \) and an unmagnetized region of length \( l_B \). The latter is modelled as a series of an ohmic resistance representing electron-neutral collisions and an inductance representing electron inertia. In RF magnetrons, the sheath width, \( s_p \), at the powered electrode is typically small due to the high local plasma density. In unmagnetized low pressure CCPs, this sheath width is significantly larger. In the model, the sheath width at the grounded electrode, \( s_g \), is also taken into account. The length of the unmagnetized plasma bulk is \( l_B \approx d - l_m - s_p = s_g \), where \( d \) is the electrode gap. The voltage drop across the magnetized region of the plasma bulk is neglected due to the enhanced local plasma density. In the frame of this zero dimensional model, the plasma density in the magnetized region is equal to the mean ion density in the sheath at the powered electrode, \( n_{sp} \), while the plasma density in the unmagnetized plasma bulk is assumed to be \( n_{sg} = n_{sg} \), while \( n_{sp} > n_{sg} \). In combination with the experimentally determined electrode surface areas and the assumption that the ratio of the sheath integrals at both electrodes is unity, this density ratio determines the symmetry parameter, \( \epsilon \), according to equation (2).

Based on these assumptions and the work of Ziegler et al [43], the following set of equations is solved for the time dependent charges in both sheaths, \( Q_{sp,sg}(t) \), the voltage drop across the blocking capacitor, \( \phi_{sb}(t) \), and the total current in the discharge, \( j(t) \), according to Kirchoff's laws and based on the input parameters provided in table 1:

\[
\phi_0 \cos(\omega_{RF} t) = \phi_{sb} - \phi_{sp} + \phi_{sg} + \frac{l_B n_m}{n_B e^2} \left( \frac{d \phi_{sb}}{dt} + e \phi_{sb} \right)
\]

\[
j = \frac{\epsilon_0}{d_{sb}} \frac{d \phi_{sb}}{dt}
\]
Driving voltage amplitude \( \phi_0 = 300 \text{ V} \)
Driving frequency \( \omega_{\text{RF}} = 2\pi \cdot 13.56 \text{ MHz} \)
Surface area of powered electrode \( A_p = 78.5 \text{ cm}^2 \)
Surface area of grounded electrode \( A_g = 2.4 \cdot A_p = 188.4 \text{ cm}^2 \)
Electrode gap of bias capacitor \( d_{\text{bias}} = 2.5 \cdot 10^{-5} \text{ m} \)
Electrode gap \( d = 5.2 \text{ cm} \)
Electron temperature \( T_e = 3 \text{ eV} \)
Electron temperature \( n_B = n_{\text{B}} = 3 \cdot 10^{19} \text{ m}^{-3} \)
Sheath width at powered electrode (unmagnetized case) \( s_p = 0.58 \text{ cm} \)
Sheath width at grounded electrode (unmagnetized case) \( s_g = 0.18 \text{ cm} \)
Magnetized bulk length (unmagnetized case) \( l_m = 0 \text{ cm} \)
Unmagnetized bulk length (unmagnetized case) \( l_B = 4.44 \text{ cm} \)
Sheath width at powered electrode (magnetized case) \( s_p = 0.3 \text{ cm} \)
Sheath width at grounded electrode (magnetized case) \( s_g = 0.4 \text{ cm} \)
Magnetized bulk length (magnetized case) \( l_m = 1 \text{ cm} \)
Unmagnetized bulk length (magnetized case) \( l_B = 3.5 \text{ cm} \)
Ratio of plasma densities in the magnetized and unmagnetized regions \( y = n_m / n_B = 1 - 35 \)

\[
\begin{align*}
  j &= -\frac{1}{A_p} \frac{dQ_{\text{eq}}}{dt} - \bar{e} n_B \left( \frac{A_g}{A_p} \right)^2 \frac{T_e}{m_i} \nu_{\text{eff}} \\
  &+ \bar{e} n_B \left( \frac{A_g}{A_p} \right)^2 \frac{T_e}{2\pi m_e} \exp \left( -\frac{e\phi_{\text{eq}}}{T_e} \right),
\end{align*}
\]

\[
\begin{align*}
  j &= -\frac{1}{A_p} \frac{dQ_{\text{eq}}}{dt} - \bar{e} n_B \frac{T_e}{m_i} + \bar{e} n_B \frac{T_e}{2\pi m_e} \exp \left( -\frac{e\phi_{\text{eq}}}{T_e} \right)
\end{align*}
\]

Here, \( d_{\text{eq}} \) is the electrode gap of the external blocking capacitor and \( \nu_{\text{eff}} = \nu_m + \frac{s}{l_m + h} \) is the effective electron neutral collision frequency. \( \nu_m \) is the electron neutral momentum transfer collision frequency and \( \bar{e} = \sqrt{\frac{s t_e}{\pi m_e}} \).

Equation (4) corresponds to the voltage balance, while equations (5)–(7) describe the current flow through the external blocking capacitor (5), through the sheath at the powered electrode (6), and through the sheath at the grounded electrode (7), respectively. The ion current is modelled as Bohm flux and the electron current in the sheath is modelled based on a Maxwellian electron energy distribution function and the Boltzmann factor for the electron density inside the sheath as a function of the respective sheath potential taken from equation (3). A more detailed explanation of this system of equations can be found in [43].

The input parameters used for the model are listed in table 1. Generally, the electron temperature, \( T_e \), and the plasma density in the unmagnetized bulk, \( n_B \), are not obtained self-consistently from the model, but values typically obtained in low pressure CCPs [30] are used as input. The effect of the magnetic field is included in two ways: (i) The widths of both sheaths and of the unmagnetized bulk are shortened and a magnetized bulk region of length \( l_m \) is introduced. The exact choice of the respective dimensions is obtained from the experiment. (ii) While keeping the plasma density in the unmagnetized bulk region fixed, the plasma density in the magnetized region is increased by a factor \( y = n_m / n_B \). This factor is changed systematically in the model and corresponds to a change of the magnetic field in the experiment. In this way and for fixed electrode surface areas, the symmetry parameter \( \eta \) is changed as a function of the magnetic field according to equation (2). The model is solved for the DC self-bias, \( \eta \), and for the time dependent discharge current, \( j(t) \), as a function of \( y \), i.e. for different magnetic field strength. Based on a comparison to measured current waveforms, the model can reveal the physical origin of the self-excitation of PSR oscillations of the current and the control of NERH as a function of the magnetic field.

4. Results

Figure 3(a) shows the measured DC self-bias and the symmetry parameter calculated based on equation (1) and measured values for \( \eta \) as well as \( \phi_0 \) as a function of the magnetic field at the reference distance of 8 mm from the powered electrode surface and at a lateral position, where the radial component of \( B \) is maximum. The driving voltage amplitude is measured by a VI probe and is kept constant at 300 V. The argon neutral gas pressure is 1 Pa. Figure 3(b) shows the DC self-bias and the symmetry parameter obtained from the equivalent circuit model as a function of \( n_m / n_B \) at the same driving voltage amplitude and pressure as used in the experiment. In the model, the ratio of the mean ion densities at the powered electrode and in the unmagnetized bulk region is an input parameter. It is varied systematically in order to reflect the effect of changing the magnetic field on the plasma. Thus, figures 3(a) and (b) can be compared to each other. Good qualitative agreement is found between the experimental and the model results. As shown in [20], the DC self-bias voltage increases as a function of the magnetic field and its sign changes from negative to positive at a magnetic flux density of about 11 mT. Thus, the symmetry parameter...
Figure 3. (a) Experiment: DC self-bias voltage and symmetry parameter as a function of the magnetic flux density measured at a distance of 8 mm from the powered electrode surface at a lateral position, where the radial component of $\mathbf{B}$ is maximum. (b) Model: DC self-bias voltage and symmetry parameter as a function of $n_{ip}/n_B$. Discharge conditions in experiment and model: the driving voltage amplitude is $V_0 = 300$ V and the pressure is $p = 1$ Pa.

Figure 4. Experiment (a)–(e): Current density measured at the center of the grounded electrode normalized by its maximum for each magnetic field as a function of time within two RF periods for different magnetic flux densities measured at a distance of 8 mm from the powered electrode surface at a lateral position, where the radial component of $\mathbf{B}$ is maximum. Model (f), (g): Calculated current density normalized by its maximum for each ration of $n_{ip}/n_B$ as a function of time within two RF periods for two different magnetic flux densities represented by different plasma density ratios, $n_{ip}/n_B$. A driving voltage amplitude of $V_0 = 300$ V and a pressure of $p = 1$ Pa is used in the experiment and in the model.
becomes equal to unity and higher than unity for higher magnetic flux densities. This is caused by a local enhancement of the plasma density at the powered electrode as a function of the magnetic field. This finding is reproduced well and, thus, verified by the equivalent circuit model.  

The symmetry parameter is known to affect the self-excitation of high frequency PSR oscillations of the RF current and NERH, since it determines the extent to which the quadratic nonlinearities of both sheaths compensate each other [11]. For \( \epsilon = 1 \), these nonlinearities cancel in the voltage balance of CCPs and no PSR oscillations are self-excited, while they do not cancel for \( \epsilon > 1 \) and PSR oscillations are self-excited.  

The normalized RF current as a function of time within two RF periods obtained experimentally and from the model under the same discharge conditions is shown in figure 4 for different magnetic flux densities. In the experiment, the SEERS sensor is located at the center of the grounded electrode, i.e. the RF current is measured at this position. Depending on the discharge symmetry, represented by the symmetry parameter, high frequency PSR oscillations of the RF current are self-excited, when the sheath collapses at the electrode where the larger voltage drop across the local sheath occurs compared to the other electrode [11, 40]. For \( \epsilon < 1 \) the PSR is excited during the sheath collapse at the powered electrode, while it is excited during the sheath collapse at the grounded electrode for \( \epsilon > 1 \).  

During the time of sheath collapse at one of the electrodes the sign of the current reverses, i.e. the sheath collapses are marked by the zero-crossings of the current in figure 4. Here, the sheath at the powered electrode is collapsed, when \( I = 0 \) A and \( \delta I/\delta t < 0 \) A s\(^{-1}\). Shortly later, this sheath expands. Without magnetic field \( (B = 0 \) mT), the experimental (figure 4(a)) and the model results (figure 4(i)) show strong high frequency oscillations of the current, when the sheath at the powered electrode expands, i.e. NERH is present and the PSR is self-excited during this sheath collapse at the powered electrode. This is caused by the strong discharge asymmetry \( (\epsilon < 1 \) or, see figure 3) under these conditions. Correspondingly, high frequency oscillations of the current are observed, when the current is negative. Increasing the magnetic field at the powered electrode affects the discharge symmetry via the MAE, i.e. \( \epsilon > 1 \) for high magnetic fields (see figure 3). This change of the discharge symmetry causes high frequency PSR oscillations of the current to be self-excited, when the sheath is collapsed at the grounded electrode, when \( I = 0 \) A and \( \delta I/\delta t > 0 \) A s\(^{-1}\). Thus, high frequency oscillations of the current are observed, when the current is positive. This magnetic control of the PSR and NERH is observed experimentally and in the model (see figure 4(b)–(e), (g)). The model clearly shows that the physical origin of this magnetic control of the PSR and NERH is the local enhancement of the plasma density at the powered electrode induced by increasing the local magnetic field, i.e. the MAE. While the model can reproduce the general shape of the measured current waveform as well as the fact that the self-excitation of high frequency oscillations of the current happens at different times within the RF period at different magnetic field strengths, it cannot reproduce more detailed characteristics, e.g. the strong damping of the PSR oscillations in the experiment. This is caused by the strong simplifications made in the frame of the global model, which does not include any spatial dependencies. For instance, the presence of different currents paths and regions of different plasma densities and fields in the experiment, is not captured by the model explicitly. We find that the amplitude of the current increases as a function of the magnetic field due to the enhanced plasma density (not shown). This magnetic control of NERH is somewhat similar to the electric control of NERH via VWT [40]. Due to the significant enhancement of electron heating by NERH [39] and the fact that the magnetic field is an external control parameter, which can be changed and plays an important role for plasma source design, this effect is expected to be highly relevant for RF magnetron sputtering and other plasma processes in magnetized discharges.  

Figure 5 shows the fast fourier transformation (FFT) spectrum of the RF current normalized by the amplitude of the fourier term at the lowest driving frequency and obtained from the experiment and the model for different magnetic flux densities. For all magnetic fields, the 13.56 MHz peak of the driving frequency is dominant. In case of no magnetic field, additional strong peaks at higher frequencies can be identified, particularly around about 200 MHz in the experiment and in the model. This corresponds to a typical FFT spectrum of a CCP, where the PSR is self-excited. By increasing the magnetic flux density, these peaks are shifted to lower frequencies. Based on the work of Czarnetzki et al [29] and Wilczek et al [36], we know that there is no single PSR frequency. Instead an entire frequency spectrum is excited. This is also observed in figures 4 and 5 of this manuscript. Ultimately, at the kinetic level this is caused by the fact that electrons can only react on timescales of the inverse local plasma frequency to changes of the local electric field. When the sheath expands, electrons on the bulk side of the expanding sheath edge need to react to an increase of the local electric field. If they cannot react due to their inertia, local space charges are formed that cause high frequency oscillations of the RF current [36]. As the sheath expands into regions of higher plasma density as a function of time within the RF period, the local electron plasma frequency on the bulk side of the sheath edge increases and electrons can react more quickly. Thus, the frequency of the high frequency oscillations is not constant as a function of time within the RF period. Under the conditions studied here, these mechanisms result in the self-excitation of hf oscillations of the RF current within a frequency spectrum around about 200 MHz–100 MHz depending on the magnetic field, which affects the plasma density and its profile.  

According to Ziegler et al [44] the time dependent accumulated power dissipated to electrons, \( \tilde{P}_e(t) \), is:

\[
\tilde{P}_e(t) = \frac{1}{T} \int_0^T R_o I_e^2(t') \, dt' \propto \int_0^T j_e^2(t') \, dt'.
\]  

Here, \( R_o \) is the ohmic resistance of the plasma, which is assumed to be time independent. Based on equation (8), the accumulated power dissipated to electrons can be calculated from the time dependent current obtained from the experiment and from the model for different magnetic fields at the powered electrode. The time resolved results are shown in figure 6 within one RF period for a driving voltage amplitude of 300 V and a neutral gas pressure of 1 Pa. The results are shown in arbitrary units, since no absolute calibration of the current measurement...
Figure 5. Experiment (a)–(e): Fourier spectrum of the current measured at the center of the grounded electrode normalized by the amplitude of the Fourier term at the lowest driving frequency for different magnetic flux densities measured at a distance of 8 mm from the powered electrode surface at a lateral position, where the radial component of $\mathbf{B}$ is maximum. Model (f), (g): Fourier spectrum of the calculated current normalized by the amplitude of the Fourier term at the lowest driving frequency for two different magnetic flux densities represented by different plasma density ratios, $n_{ni}/n_{i0}$. A driving voltage amplitude of $V_0 = 300$ V and a pressure of $p = 1$ Pa is used in the experiment and in the model.

Figure 6. Time resolved accumulated power dissipated to electrons for different magnetic flux densities (measured at a distance of 8 mm from the powered electrode surface at a lateral position, where the radial component of $\mathbf{B}$ obtained experimentally (a)–(e) and from the model (f) and (g). $n_{ni}/n_{i0} = 1$ corresponds to the unmagnetized case, while $n_{ni}/n_{i0} = 35$ corresponds to a strong magnetic field. The driving voltage amplitude is $V_0 = 300$ V and the pressure is $p = 1$ Pa.
was performed in the experiment. Nevertheless, valuable information on the time dependence of $P_e$ can be obtained. Based on the good agreement between experimental and model results, the power dissipation to electrons can now be understood as a function of the magnetic field at the powered electrode. At the beginning of the RF period ($t = 0$) the sheath is collapsed at the grounded electrode and is fully expanded at the powered electrode. This situation is reversed after half an RF period, i.e. at $t \approx 37$ ns. In the unmagnetized case ($\epsilon < 1$, see figures 6(a) and (l)), a steplike dependence of $P_e$ on time is observed primarily during the second half of the RF period, when the sheath expands at the powered electrode, while a steplike dependence of $P_e$ on time is observed during the first half of the RF period for high magnetic fields at the powered electrode ($\epsilon > 1$, see figures 6(e) and (g)). As this steplike increase is caused by the self-excitation of PSR oscillations of the current and the presence of NERH [44], these results clearly show that the self-excitation of the PSR can be controlled magnetically and can be shifted from one electrode to the other by adjusting the magnetic field at the powered electrode. For a magnetic flux density of 7 mT, the discharge is almost symmetric ($\epsilon \approx 1$) and, thus, NERH is greatly attenuated. In the middle of the RF period ($t \approx 37$ ns), a plateau is observed, i.e. electrons are not heated at this time around the sheath collapse at the powered electrode. The level of this plateau corresponds to the accumulated power dissipation to electrons during the first half of the RF period. Clearly, we observe an increase of this value as a function of magnetic field at the powered electrode, since at low magnetic fields almost no NERH is present during the first half, while strong NERH is present during the first half at high magnetic fields. This is again caused by the magnetic control of the PSR and NERH, which are generated at different times within the RF period for different magnetic fields at the powered electrode.

5. Conclusion

In a single frequency driven CCP operated at 13.56 MHz at 1 Pa in argon, the effect of adjusting the magnetron-like static magnetic field at the powered electrode on the RF current, the self-excitation of high frequency PSR oscillations of the current, and NERH was investigated experimentally and by an equivalent circuit model. Despite its simplicity, the model reproduces the experiment qualitatively and reveals the physical origin of the effects of magnetic field on current waveform observed experimentally. Based on this good qualitative agreement between experiment and model, adjusting this magnetic field was shown to change the discharge symmetry and to allow switching NERH on and off. In the unmagnetized case, the discharge is geometrically asymmetric ($A_2 > A_0$) and nonlinear PSR oscillations are self-excited during the sheath collapse at the powered electrode. Increasing the magnetic field at the powered electrode leads to an increase of the plasma density adjacent to the powered electrode relative to that at the grounded electrode and, thus, changes the discharge symmetry. This overcompensates the geometric reactor asymmetry and causes PSR oscillations to be self-excited during the sheath collapse at the grounded electrode at a different time within the RF period. At intermediate magnetic fields the discharge is symmetric and essentially no PSR oscillations are excited, i.e. NERH is switched off. The model clearly shows that the local enhancement of the plasma density induced by the magnetic field is the physical origin of this magnetic control of NERH. This effect is somewhat similar to the electrical control of NERH by VWT [40] and is expected to be of high relevance for fundamental and applied research on magnetized low pressure RF plasmas, since NERH strongly contributes to electron power absorption and is, thus, relevant for knowledge based process optimisation.

Acknowledgments

This work was funded by the German Research Foundation in the frame of the project ‘Plasmabasierte Prozessfuehrung von reaktivten Sputterprozessen’ (No. 417888799). The authors thank Thomas Mussenbrock and Jan Trieschmann for discussions and their valuable input.

ORCID iDs

M Oberberg https://orcid.org/0000-0002-8170-0628
B Berger https://orcid.org/0000-0001-7053-2545
R P Brinkmann https://orcid.org/0000-0002-2581-9894
J Schulze https://orcid.org/0000-0001-7929-5734

References

[1] Lieberman M A and Lichtenberg A J 2005 Principles of Plasma Discharges and Materials Processing 2 edn (New York: Wiley)
[2] Heil B G, Czarnetzki U, Brinkmann R P and Mussenbrock T 2008 On the possibility of making a geometrically symmetric rf-ccp discharge electrically asymmetric J. Phys. D: Appl. Phys. 41 165202
[3] Heil B G, Schulze J, Mussenbrock T, Brinkmann R P and Czarnetzki U 2008 Numerical modeling of electron beams accelerated by the radio frequency boundary sheath IEEE Trans. Plasma Sci. 36 1404–5
[4] Donkó Z, Schulze J, Heil B G and Czarnetzki U 2008 PIC simulations of the separate control of ion flux and energy in CCRF discharges via the electrical asymmetry effect J. Phys. D: Appl. Phys. 42 025205
[5] Schulze J, Schüngel E and Czarnetzki U 2009 The electrical asymmetry effect in capacitively coupled radio frequency discharges—measurements of dc self bias, ion energy and ion flux J. Phys. D: Appl. Phys. 42 092005
[6] Korolov I, Donkó Z, Czarnetzki U and Schulze J 2012 The effect of the driving frequencies on the electrical asymmetry of dual-frequency capacitively coupled plasmas J. Phys. D: Appl. Phys. 45 465205
[7] Schulze J, Schüngel E, Donkó Z and Czarnetzki U 2011 The electrical asymmetry effect in multi-frequency capacitively coupled radio frequency discharges Plasma Sources Sci. Technol. 20 015017
[8] Derzi A, Korolov I, Schüngel E, Donkó Z and Schulze J 2013 Electron heating and control of ion properties in capacitive discharges driven by customized voltage waveforms Plasma Sources Sci. Technol. 22 065009
[9] Berger B, Brandt S, Franek J, Schüngel E, Koepke M, Mussenbrock T and Schulze J 2015 Experimental investigations of electron heating dynamics and ion energy distributions in capacitive discharges driven by customized voltage waveforms. J. Appl. Phys. 118 223302

[10] Brandt S et al 2016 Electron power absorption dynamics in capacitive radio frequency discharges driven by tailored voltage waveforms in CF4 Plasma Sources Sci. Technol. 25 045015

[11] Czarnetzki U, Schulze J, Schüngel E and Donkó Z 2011 The electrical asymmetry effect in capacitively coupled radio-frequency discharges Plasma Sources Sci. Technol. 20 024010

[12] Schüngel E, Schulze J, Donkó Z and Czarnetzki U 2011 Power absorption in electrically asymmetric dual frequency capacitive radio frequency discharges Phys. Plasmas 18 013503

[13] Lafleur T, Delattre P A, Johnson E V and Booth J P 2012 Separate control of the ion flux and ion energy in capacitively coupled radio-frequency discharges using voltage waveform tailoring Appl. Phys. Lett. 101 121404

[14] Delattre P-A, Lafleur T, Johnson E and Booth J-P 2013 Radio-frequency capacitively coupled plasmas excited by tailored voltage waveforms: comparison of experiment and particle-in-cell simulations J. Phys. D: Appl. Phys. 46 235201

[15] Lafleur T 2015 Tailored-waveform excitation of capacitively coupled plasmas and the electrical asymmetry effect Plasma Sources Sci. Technol. 25 013001

[16] Trieschmann J, Shihab M, Szeremley D, Elgindy A E, Gallian S, Eremín D, Brinkmann R P and Mussenbrock T 2013 Ion energy distribution functions behind the sheaths of magnetized and non-magnetized radio frequency discharges J. Phys. D: Appl. Phys. 46 084016

[17] Yang S, Zhang Y, Wang H, Cui J and Jiang W 2017 Magnetic asymmetry effect in geometrically and electrically symmetric capacitively coupled plasma Plasma Process. Polym. 14 1700087

[18] Yang S, Chang L, Zhang Y and Jiang W 2018 Magnetic asymmetry effect in capacitively coupled plasmas: effects of the magnetic field gradient, pressure, and gap length Plasma Sources Sci. Technol. 27 035008

[19] Joshi J K, Binwal S, Karkari S K and Kumar S 2018 Electron series resonance in a magnetized 13.56 MHz symmetric capacitively coupled discharge J. Appl. Phys. 123 113301

[20] Oberberg M, Kallihn J, Awakowicz P and Schulze J 2018 Experimental investigations of the magnetic asymmetry effect in capacitively coupled radio frequency plasmas Appl. Phys. Lett. 69 3818–20

[21] Turner M M 1995 Pressure heating of electrons in capacitively coupled rf discharges Phys. Rev. Lett. 75 1312–5

[22] Schulze J, Donkó Z, Lafleur T, Wilczek S and Brinkmann R P 2018 Spatio-temporal analysis of the electron power absorption in electropositive capacitive RF plasmas based on moments of the boltzmann equation Plasma Sources Sci. Technol. 27 055010

[23] Popov O A and Godyak V A 1985 Power dissipated in low-pressure radio-frequency discharge plasmas Sov. J. Plasma Phys. 2 78

[24] Popov O A and Godyak V A 1985 Power dissipated in low-pressure radio-frequency discharge plasmas J. Appl. Phys. 57 53–8

[25] Kaganovich I D, Kolobov V I and Tsendin L D 1996 Stochastic electron heating in bounded radio-frequency plasmas Appl. Phys. Lett. 69 3818–20

[26] Turner M M 1995 Pressure heating of electrons in capacitively coupled rf discharges Phys. Rev. Lett. 75 1312–5

[27] Schulze J, Donkó Z, Lafleur T, Wilczek S and Brinkmann R P 2018 Spatio-temporal analysis of the electron power absorption in electropositive capacitive RF plasmas based on moments of the boltzmann equation Plasma Sources Sci. Technol. 27 055010

[28] Popov O A and Godyak V A 1985 Power dissipated in low-pressure radio-frequency discharge plasmas Sov. J. Plasma Phys. 2 78

[29] Popov O A and Godyak V A 1985 Power dissipated in low-pressure radio-frequency discharge plasmas J. Appl. Phys. 57 53–8

[30] Kaganovich I D, Kolobov V I and Tsendin L D 1996 Stochastic electron heating in bounded radio-frequency plasmas Appl. Phys. Lett. 69 3818–20

[31] Turky M M 1995 Pressure heating of electrons in capacitively coupled rf discharges Phys. Rev. Lett. 75 1312–5

[32] Schulze J, Donkó Z, Lafleur T, Wilczek S and Brinkmann R P 2018 Spatio-temporal analysis of the electron power absorption in electropositive capacitive RF plasmas based on moments of the boltzmann equation Plasma Sources Sci. Technol. 27 055010

[33] Wilczek S, Trieschmann J, Schulze J, Donkó Z, Brinkmann R P and Mussenbrock T 2018 Disparity between current and voltage driven capacitively coupled radio frequency discharges Plasma Sources Sci. Technol. 27 125010

[34] Miller P A, Barnat E V, Heuber G A, Paterson A M and Holland J P 2006 Spatial and frequency dependence of plasma currents in a 300 mm capacitively coupled plasma reactor Plasma Sources Sci. Technol. 15 889

[35] Wilczek S et al 2016 Kinetic interpretation of resonance phenomena in low pressure capacitively coupled radio frequency plasmas Phys. Plasmas 23 063514

[36] Wilczek S, Trieschmann J, Schulze J, Schüngel E, Brinkmann R P, Derzsi A, Korolov I, Donkó Z and Mussenbrock T 2015 The effect of the driving frequency on the confinement of beam electrons and plasma density in low-pressure capacitively discharges Plasma Sources Sci. Technol. 24 025002

[37] Berger B, You K, Lee H-C, Mussenbrock T, Awakowicz P and Schulze J 2018 Observation of the generation of multiple electron beams during a single sheath expansion phase in capacitive RF plasmas Plasma Sources Sci. Technol. 27 12LT02

[38] Mussenbrock T, Brinkmann R, Lieberman M, Lichtenberg A and Kawamura E 2008 Enhancement of ohmic and stochastic heating by resonance effects in capacitive radio frequency discharges: a theoretical approach Phys. Rev. Lett. 101 085004

[39] Wilczek S, Schulze J, Czarnetzki U and Luggenhölscher D 2009 Self-excited nonlinear plasma series resonance oscillations in geometrically symmetric capacitively coupled radio frequency discharges Appl. Phys. Lett. 94 131501

[40] Klick M 1996 Nonlinearity of the radio-frequency sheath J. Appl. Phys. 79 3445–52

[41] Ziegler D, Mussenbrock T and Brinkmann R P 2008 Nonlinear dynamics of dual frequency capacitive discharges: a global model matched to an experiment Plasma Sources Sci. Technol. 17 045011

[42] Ziegler D, Trieschmann J, Mussenbrock T, Brinkmann R P, Schulze J, Czarnetzki U, Semmler E, Awakowicz P, O’Connell D and Gans T 2010 The influence of the relative phase between the driving voltages on electron heating in asymmetric dual frequency capacitive discharges Plasma Sources Sci. Technol. 19 045001