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Power supply and impedance matching to drive technological radio-frequency plasmas with customized voltage waveforms

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We present a novel radio-frequency (RF) power supply and impedance matching to drive technological plasmas with customized voltage waveforms. It is based on a system of phase-locked RF generators that output single frequency voltage waveforms corresponding to multiple consecutive harmonics of a fundamental frequency. These signals are matched individually and combined to drive a RF plasma. Electrical filters are used to prevent parasitic interactions between the matching branches. By adjusting the harmonics’ phases and voltage amplitudes individually, any voltage waveform can be approximated as a customized finite Fourier series. This RF supply system is easily adaptable to any technological plasma for industrial applications and allows the commercial utilization of process optimization based on voltage waveform tailoring for the first time. Here, this system is tested on a capacitive discharge based on three consecutive harmonics of 13.56 MHz. According to the Electrical Asymmetry Effect, tuning the phases between the applied harmonics results in an electrical control of the DC self-bias and the mean ion energy at almost constant ion flux. A comparison with the reference case of an electrically asymmetric dual-frequency discharge reveals that the control range of the mean ion energy can be significantly enlarged by using more than two consecutive harmonics. © 2015 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4921399]

I. INTRODUCTION

The manufacturing of many high technological products requires processing steps that involve a surface modification via plasma treatment, e.g., anisotropic dielectric etching of integrated circuits and the Plasma Enhanced Chemical Vapor Deposition (PECVD) of nano structures and of biocompatible surfaces.¹–¹⁰ The corresponding plasma sources are typically driven by a voltage oscillating in the MHz regime, which is supplied by a generator and applied to an electrode or a coil via an impedance matching network. Such single frequency capacitively and/or inductively coupled radio-frequency (RF) discharges are most frequently used in industry. The control and the optimization of the flux of the electrons, ions, and neutral radicals at the substrate surface as a function of energy are essential for these applications; thus, means of customizing the flux-energy distribution functions (FEDFs) of these species are strongly required.

In capacitively coupled radio frequency (CCRF) plasmas operated at a single frequency (e.g., 13.56 MHz), such control is strongly limited. For example, the shape of the ion FEDF at the substrate cannot be customized and independent control of the mean ion energy and flux is impossible. In traditional, single-frequency systems, an increase in the driving voltage amplitude results in a stronger electric field in the sheaths and, thus, an increase in the driving voltage amplitude increases the particle flux as well as the mean ion energy.¹¹ Dual-frequency plasmas operated at two substantially different frequencies (e.g., 2 MHz and 27 MHz) provide an improved control.¹¹–¹⁶ This approach is based on the idea that the charged particle generation, density, and fluxes mainly depend on the amplitude of the high-frequency component, whereas the energy gain of ions in the plasma-substrate sheath mainly depends on the amplitude of the low-frequency component. However, the control of the ion FEDF is again limited due to the effects of frequency coupling and secondary electrons¹¹,¹⁶–¹⁹ as well as the limited control of the voltage drop across the sheaths as a function of time.

An efficient way to realize an advanced control of distribution functions and to improve their lateral uniformity across large substrates is driving RF plasmas with customized voltage waveforms.²⁸–³⁰ The individual voltage drops across the plasma-electrode sheaths can be customized within the fundamental RF period, resulting in control of the ion and electron heating dynamics on a nanosecond time scale. Furthermore, this approach allows control of the symmetry of the discharge, which translates into a convenient method of tuning the mean ion energy at both the powered and the grounded electrodes. In general, such voltage waveforms, \( \tilde{b}(t) \), can be generated as a finite Fourier series consisting of multiple consecutive harmonics of a fundamental driving frequency

\[
\tilde{b}(t) = \sum_{k=1}^{N} \phi_k \cos(2\pi f_k t + \theta_k). \tag{1}
\]

Here, \( N \) is the total number of applied consecutive harmonics, \( f \) is the fundamental frequency, \( \phi_k \) is the amplitude of the \( k \)-th harmonic, and \( \theta_k \) is its phase. The total amplitude of the driving voltage waveform is \( \phi_{\text{tot}} = \sum_{k=1}^{N} \phi_k \). This waveform can be tailored by individually adjusting the harmonics’
amplitudes and phases. For a sufficient number of harmonics, any driving voltage waveform can be generated in this way.

The idea of voltage waveform tailoring is based on earlier work of Wendt et al. and Baloniak et al., who introduced unmatched customized low frequency (kHz) voltage waveforms as a substrate bias to control the shape of the ion FEDF in high density remote plasma sources. As many manufacturers cannot modify their capacitive RF plasma reactors to include remote plasma sources, however, this technology is not widely used in industry.

Previous works on RF voltage waveform tailoring without remote sources have demonstrated its enormous potential and advantages for process control compared to conventional methods. The recent discoveries of the Electrical Asymmetry Effect (EAE) and the slope asymmetry effect in CCRF discharges driven by customized voltage waveforms can be used to solve some of the most critical limitations of plasma processing such as the lack of separate control of the ion mean energy and the ion flux at the wafer as well as the failure to prevent lateral inhomogeneities of the ion flux across large substrates.

However, all these previous works suffered from strong technical limitations caused by the absence of a multi-frequency RF power supply and impedance matching for more than 2 consecutive harmonics. The first experimental works on the EAE made use of two consecutive harmonics combined with classical dual-frequency impedance matchings. While these experiments demonstrated the functionality of the EAE, its full performance—predicted to occur in the presence of multiple driving harmonics by simulations and models—could not be tested experimentally. This was later done by Lafleur et al. using multi-frequency waveforms without impedance matching. This simplified scheme facilitated fundamental investigations of the particle heating dynamics and the control of distribution functions in such multi-frequency plasmas. The absence of impedance matching, however, makes practical implementations in industrial applications impossible due to high reflected powers of about 90% and the restriction to low voltage amplitudes.

Here, we present a novel RF supply system with impedance matching that solves this important problem. It allows technological plasmas to be driven with customized voltage waveforms at low reflected powers and, therefore, allows RF voltage waveform tailoring to be used at an industrial level for the first time. Utilizing this system, we demonstrate that increasing the number of consecutive harmonics in a CCRF plasma significantly improves the performance of the EAE, i.e., the control ranges of the DC self-bias and the mean ion energy are increased significantly. This is examined by direct measurements of the DC self-bias, thereby probing the discharge asymmetry, and of the ion FEDF at the electrodes.

We show that by varying the relative phases of the applied harmonics for a given total voltage amplitude, the controllable ranges of the DC self-bias and the mean ion energy are increased if three instead of two consecutive harmonics are used, while the ion flux remains almost constant. These results agree with previous simulation and experimental results without impedance matching and prove the feasibility of this technology for the plasma processing industry.

The RF supply system, which is commercially available, is described in detail in Sec. II. There, we also provide a description of the plasma source and the diagnostics as well as the model of the EAE in CCRF plasmas. The results are presented and discussed in Sec. III, where first the measured and modeled DC self-bias and then the ion FEDF measurements are analyzed. Finally, conclusions are drawn in Sec. IV.

II. EXPERIMENTAL SETUP AND MODEL

A. Multi-frequency RF power supply and impedance matching

Figure 1 shows the novel multi-frequency RF power supply and impedance matching that allows technological plasmas to be driven with customized RF voltage waveforms with low reflected power for the first time. It can be combined with capacitive, inductive, or hybrid combinations of both reactor types. Existing reactors can be upgraded by adding this system without modifying the reactor itself. The multi-frequency system used in this work is designed to drive a CCRF discharge with 3 consecutive harmonics of 13.56 MHz with independent relative phase and voltage amplitude control for each harmonic. It is designed to provide a maximum degree of flexibility, i.e., it can be customized according to the requirements of a given application: the number of harmonics (1–8 harmonics), their absolute values (1 MHz–200 MHz), and maximum power levels are variable and can be customized. In principle, there is no upper power limit. This makes this RF supply system highly relevant for high power applications of CCRF discharges, where large surface areas are processed and the control of the ion FEDF at the substrate is crucial. For powers above 600 W per harmonic, the required electrical filters become larger and might not be integrated into the generator and matching unit. In this context, the particular system shown in Figure 1 corresponds to a prototype and serves as an example of a variety of design options.

The multi-frequency RF supply system consists of independent matching branches for each frequency. Each branch consists of a single-frequency RF generator, an impedance matching system shown in Figure 1 corresponds to a prototype and serves as an example of a variety of design options.

The multi-frequency RF supply system consists of independent matching branches for each frequency. Each branch consists of a single-frequency RF generator, an impedance matching circuit, and electrical filters, for each frequency. In Figure 1, each band pass filter is represented by three stacked sine-waves. The middle wave is highlighted in blue to illustrate the fact that these filters are band-rather than high- or low-pass filters. Each filter is included in a generator or matchbox for a particular frequency and is designed to transmit the corresponding frequency. The topmost matching branch provides the 13.56 MHz signal, the middle branch provides the 27.12 MHz signal, and the lowest branch provides the 40.68 MHz signal. A signal generator provides phase-locked low amplitude RF signals at the respective frequency to each generator. By adjusting the relative phases between these RF signals via the signal generator, the phase control is realized. The signal generator also provides a trigger channel that can be used to synchronize external equipment. The output signals of all matching branches are combined and directly applied to an electrode located inside the plasma reactor. A band pass filter is installed at the output of each matching network to block signals from other matching branches. In this way,
parasitic coupling between the matching branches is minimized, ensuring the functionality of the automatic matching. The use of band pass filters rather than low or high pass filters for the fundamental and highest frequencies facilitates future extensions of the system to more frequencies (lower and higher frequencies).

Each matching network uses an L-type configuration. While most conventional matching networks employ phase–magnitude–detectors that measure the phase difference and magnitude of the RF current and voltage, we use directional couplers, which are more robust against signal distortion and are better suited to handle stray, reflected signals from the other matching branches. One directional coupler is located at the output of each generator behind the band pass filter. Another directional coupler is located at the input of each matching network. Altogether there are two directional couplers per matching branch. The directional coupler at the output of the generator measures the forward power and is used in a closed loop to adjust the generator’s output power to keep the forward power constant. The directional coupler at the input of the matchbox measures the reflected power as a basis for adjusting the matching to minimize the reflected power. As a result, parallel auto–matching remains functional when all RF sources are switched on simultaneously.

Frequency conversion products and instabilities can occur if signals from the various matching branches reach another RF generator. As the effect of such parasitic stray signals on the RF generator’s control system is more critical compared to their effect on the matching network, an additional band pass filter is placed between each RF generator and its matchbox.

The RF generators are driven by an external RF signal. Modern RF generators often provide this feature; however, these signals are usually fed to a Transistor to Transistor Logic (TTL) circuit. As such circuits would cause phase jitter, no TTL circuits were used here. Instead, the signal is amplified by linear RF stages where an analog RF attenuator is used as a correcting element for the control loop; thus, the dependence of the phase relationship between the output signal and the input signal on the output power level is minimized.

Ultimately, the phase response between the RF generator’s input and the matching network’s output for a given frequency is most important. Although the RF generator’s phase response is almost constant and independent of the amplitude, the matching network inserts a phase shift that depends on its capacitor settings. The final voltage waveform at the electrode surface is, therefore, determined by measuring the voltage waveform in front of the electrode by a high-voltage probe and by applying the calibration procedure described in Sec. II B.22 The amplitude and relative phases of each of the applied frequencies are adjusted iteratively to obtain the desired voltage waveform at the electrode surface.

The heart of the system is the signal generator and phase shifter. The signals are generated with a Direct Digital Synthesizer (DDS) chip. This integrated circuit provides four synchronized DDS channels with 14 bit phase resolution, very low phase noise, and independent control of frequency, phase, and amplitude. To provide eight channels (for up to 8 consecutive harmonics), two of these integrated circuits must be synchronized using a stable and identical clock signal produced by a dedicated integrated circuit with low phase noise. The signal generator and phase shifter can provide reliable signals up to 200 MHz.

The additional trigger channel provides a trigger signal at \( f/1000 = 13.56 \text{kHz} \) that can be used to synchronize plasma diagnostics such as a fast camera for Phase Resolved Optical Emission Spectroscopy (PROES) with the driving voltage waveform. Such diagnostics often require a phase-locked trigger at frequencies lower than the applied fundamental RF.
Although the output frequency is much lower than the lowest driving frequency, it is still synchronized to the RF signal. While the trigger channel is also based on the DDS chip, the voltage level must be adapted to drive logical circuits that standard equipment, e.g., cameras, requires. High speed circuits are used to avoid phase jitter.

The entire system is controlled by a LabVIEW control panel. It allows the relative phase and amplitude of each harmonic to be set separately and independently. It also allows independent control of the matching networks in each frequency branch.

This novel multi-frequency RF power supply reduces the reflected power from more than 90% (previous works) to about 5% of the total applied power or less. Most of the measured reflected power results from RF signals originating from other matching branches that penetrate into a given matching branch due to imperfect filters. It is the sum of the reflected powers at all frequencies in all matching branches divided by the total applied power (sum over all frequencies). In this sense, it is the frequency accumulated relative reflected power. The reduction of the reflected power from more than 90% to 5% is an enormous and extremely important improvement, since it allows to transfer the technology of RF voltage waveform tailoring to industrial applications, for which 90% reflected power are unacceptable. The reflected power could further be decreased by improving the RF filtering.

B. Plasma source and diagnostics

The experimental setup including the diagnostics is shown in Figure 2. A multi-frequency voltage waveform according to Eq. (1) is applied to the powered electrode of a modified Gaseous Electronics Conference (GEC) reference cell. Here, \( N = 3 \) consecutive harmonics of \( f = 13.56 \) MHz are used and the obtained results are compared to the dual-frequency reference case \( (N = 2 \) and \( f = 13.56 \) MHz). In both cases, a total voltage amplitude of \( \phi_{tot} = 120 \) V is used. The harmonics’ amplitudes are chosen according to the following criterion to maximize the electrical control range of the DC self-bias: \(^{27}\)

\[
\phi_k = \frac{2(N-k+1)}{N(N+1)} \phi_{tot}.
\]

Thus, in the triple-frequency case \( (N = 3) \), \( \phi_1 = 60 \) V, \( \phi_2 = 40 \) V, and \( \phi_3 = 20 \) V are used for the voltage amplitudes of the 13.56 MHz, the 27.12 MHz, and the 40.68 MHz RF signals, respectively. In the dual-frequency reference case \( (N = 2) \), \( \phi_1 = 80 \) V, \( \phi_2 = 40 \) V, and \( \phi_1 = 0 \) V are used.

The discharge is operated in argon at 5 Pa within the adjustable gap between two circular, stainless steel electrodes, with a diameter of 10 cm. The gap length, \( d \), has been set to 4 cm by adjusting the height of the top grounded electrode, while the position of the bottom powered electrode is fixed. A glass cylinder radially confines the plasma between the electrodes. Nevertheless, this discharge configuration is geometrically asymmetric due to the capacitive coupling between the glass cylinder and the grounded side wall of the vacuum chamber.\(^{22,45,46}\) This capacitive coupling effectively enlarges the grounded electrode surface area. Thus, a negative geometrically induced DC self-bias is present even if only a single driving frequency is used, since the grounded electrode surface area is effectively larger compared to the powered electrode surface area, although the powered and grounded surface areas inside the confinement cylinder are identical.

Two diagnostics are utilized to investigate this triple frequency discharge. First, a high voltage probe is attached to the cable connecting the combiner behind the matching branches with the powered electrode. The amplitudes and phases of the voltage waveforms corresponding to the three applied frequencies at the electrode surface are determined based on a calibration routine, which has been used on dual-frequency systems before.\(^{22}\) The chamber is vented and the high voltage probe is attached to the powered electrode surface. By comparing the voltage waveform at the measurement position (on the cable) with the voltage waveform at the electrode surface, calibration factors for the amplitudes and phases are determined for each of the individual harmonics. These calibration factors are system dependent and different for each applied frequency. Care has been taken both during the calibration procedure and during the actual measurements that any disturbance due to reflections of the applied power, i.e., due to an improper matching, is minimized.

Second, a Retarding Field Energy Analyzer (RFEA, Impedans Semion\(^{47}\)) is placed on the powered electrode surface. Ions and electrons enter the device through orifices facing the plasma. The RFEA basically consists of three grids and a collector plate. The first grid remains on the potential of the housing, i.e., the oscillating potential of the electrode, to prevent any disturbance of the plasma. The second grid is on a potential of about \(-60\) V with respect to the first grid to repel the electrons. The potential of the third grid is varied, thereby varying the minimum kinetic energy of the ions, which are detected at the collector plate. A voltage of about \(-60\) V is applied to this plate to attract all ions that have overcome the potential of the third grid. The first derivative of the ion current onto the plate as a function of the discriminator voltage (of the third grid) yields the ion flux-velocity distribution function, which is conveniently plotted in energy units.\(^{48}\) Details on the RFEA technique to measure this ion distribution function (ion FEDF) can be found elsewhere.\(^{47-50}\) The measured ion FEDF, \( f(e_i) \), is further analyzed by calculating the total ion flux, \( \Gamma_i \),
as well as the mean ion energy, \( \langle \epsilon_i \rangle \).\(^{22,25,26}\)

\[
\Gamma_i = \int_0^{\epsilon_{i,\text{max}}} f(\epsilon_i) d\epsilon_i,
\]

\( \langle \epsilon_i \rangle = \Gamma_i^{-1} \int_0^{\epsilon_{i,\text{max}}} \epsilon_i f(\epsilon_i) d\epsilon_i. \)

Here, \( \epsilon_{i,\text{max}} \) is the maximum energy of the ions.

### C. Model of the electrical asymmetry effect

We compare the measured DC self-bias with the analytical model of the EAE, which has been introduced in Ref. 20 and extensively discussed in Ref. 23. In brief, the electrical circuit of the discharge is modeled by the voltage balance

\[
\bar{\phi} + \eta = \phi_p + \phi_b + \phi_g,
\]

where \( \bar{\phi}, \eta, \phi_p, \phi_b, \) and \( \phi_g \) are the applied voltage waveform, the DC bias self-developed by the plasma, and the individual voltage drops across the powered electrode sheath, the plasma bulk, and the grounded electrode sheath, respectively. Typically, the bulk voltage, \( \phi_b \), can be neglected in low pressure electropositive plasmas.\(^{23}\) Furthermore, it is assumed that both sheaths totally collapse at least once within the fundamental RF period. These collapses occur at the times of maximum, \( \phi_{\text{max}} \), and minimum, \( \phi_{\text{min}} \), applied voltage. Then, examining the voltage balance at these two specific times yields a simple equation for the DC self-bias, \( \eta \).\(^{20,23}\)

\[
\eta = -\frac{\phi_{\text{max}} + \epsilon \phi_{\text{min}}}{1 + \epsilon}.
\]

Hence, the DC self-bias depends on the global extrema of the applied voltage waveform, i.e., it can be controlled by tuning the phases between the applied harmonics and on the symmetry parameter, \( \epsilon \), which is defined as\(^{20,23}\)

\[
\epsilon = \frac{\phi_{\text{max}}}{\phi_{\text{sp}}} \approx \left( \frac{A_p}{A_g} \right)^2 \frac{n_{\text{sp}}}{n_{\text{sg}}},
\]

The symmetry parameter relates the maximum voltage drops across the powered and grounded sheaths, \( \phi_{\text{max}}^{\text{sp}} \) and \( \phi_{\text{max}}^{\text{sg}} \), to each other. In a good approximation, it can also be expressed as the product of the squared ratio of the powered and grounded electrode surface areas, \( A_p \) and \( A_g \), and the ratio of the mean ion densities in the respective sheaths, \( n_{\text{sp}} \) and \( n_{\text{sg}} \). Therefore, \( \epsilon \) provides further insights into the discharge asymmetry induced via the EAE. As already performed in Ref. 25, we determine the symmetry parameter in the experiment by rearranging Eq. (6) for \( \epsilon \) and using the measured values of \( \eta, \phi_{\text{max}}^{\text{sp}}, \) and \( \phi_{\text{min}}^{\text{sp}} \).

### III. RESULTS

#### A. Electrical control of the DC self-bias

Figure 3 shows the DC self-bias normalized by the total applied voltage amplitude, \( \phi_{\text{tot}} \), as a function of the phase of the second and third harmonics resulting from experiment and model. In the model, the symmetry parameter \( \epsilon = 0.63 \) is taken to be constant for all phase angles and is determined by averaging over \( \epsilon \) obtained from the experiment for each combination of \( \theta_2 \) and \( \theta_3 \) based on Eq. (6) using the measured phase resolved DC self-bias as well as the global extrema of the driving voltage waveform. In this way, the model is simplified. In reality, \( \epsilon \) varied by up to \( \pm 40\% \) around this averaged value as a function of the harmonics’ phases. We find good agreement between the experiment and the model of the DC self-bias. The overall shape is very similar and resembles the outcome of a previous simulation study on geometrically symmetric triple-frequency discharges.\(^{27}\) In contrast to these previous simulations, the measured DC self-bias and the model’s prediction of the DC self-bias are shifted towards negative values due to the geometric discharge asymmetry that was not accounted for in the simulation.\(^{27}\) This shift is caused by the deviation of the symmetry parameter from unity (see Eq. (7)) caused by the capacitive coupling between the glass cylinder and the grounded chamber walls.\(^{22,45,46}\) Moreover, the control range is slightly smaller in the experiment compared to the model assuming a constant symmetry parameter, independent of the phases. This is caused by the fact that the ratio of the mean ion densities in Eq. (7) and thus, the symmetry parameter vary as functions of \( \theta_2 \) and \( \theta_3 \) in the experiment, but are taken to be constant in the model calculations leading to Figure 3(b). The minimum DC self-bias is found at \( \theta_2 \approx 0^\circ \) and \( \theta_3 \approx 0^\circ \), while the maximum DC self-bias is found around \( \theta_2 \approx 180^\circ \) and \( \theta_3 \approx 0^\circ \). There are multiple ways to tune \( \eta \) between these extrema via phase control, but the easiest option is to set \( \theta_3 = 0^\circ \) and vary \( \theta_2 \), i.e., the phase of the second harmonic.\(^{27,28}\)
This is done in the following to control the DC self-bias and the mean ion energy at the electrodes.

A comparison of the DC self-bias in electrically asymmetric dual- and triple-frequency discharges is shown in Figure 4 under otherwise identical discharge conditions. In both cases, the control parameter for \( \eta \) is the phase of the second harmonic, \( \theta_2 (\theta_1 = \theta_3 = 0^\circ) \). Again, \( \eta \) is normalized by the total applied voltage amplitude. In a dual-frequency discharge \( (N = 2) \), the DC self-bias is negative for all phases due to the geometrical asymmetry and the control range is about 35\%, between \( \eta \approx -38\% \) at \( \theta_2 \approx 0^\circ \) and \( \eta \approx -3\% \) at \( \theta_2 \approx 180^\circ \). By adding the third frequency \( (N = 3) \), it is possible to tune the bias from a minimum of \( \eta \approx -46\% \) at \( \theta_2 \approx 0^\circ \) to a positive value of \( \eta \approx 4\% \) at \( \theta_2 \approx 180^\circ \); thus, the interval over which the DC self-bias can be controlled via the EAE is about 50\%. This means that the electrical control range of \( \eta \) is significantly extended by about 35\% by increasing the number of applied harmonics from \( N = 2 \) to \( N = 3 \). This is an important result, since it is the basis for a significantly broader range of ion energy control via the EAE such as described in Sec. III B.

### B. Electrical control of the ion energy

Figure 5 shows the ion FEDFs measured at the powered electrode as a function of the phase of the second harmonic \( \theta_2 (\theta_1 = \theta_3 = 0^\circ) \). Under our experimental conditions, the ion mean free path is smaller than the width of the powered electrode sheath. Therefore, the probability of collisions within the sheath is relatively high and, subsequently, the ion FEDFs exhibit a broad shape between \( \epsilon_i = 0 \) and \( \epsilon_i = \epsilon_i, \text{max}^{25,47-50} \). The mean ion energy as well as the shape of the ion FEDF can be controlled by tuning the phase of the second harmonic. At \( \theta_2 = 0^\circ \), the DC self-bias is most negative and, accordingly, the time averaged voltage drop across the powered electrode sheath is largest, whereas at \( \theta_2 = 180^\circ \), the DC self-bias is maximum and, accordingly, the time averaged voltage drop across the powered electrode sheath is smallest. Therefore, the ion FEDF is relatively broad for \( \theta_2 = 0^\circ \) and becomes narrower with increasing \( \theta_2 \). Meanwhile, for \( N = 2 \) (Figure 5(a)), the maximum ion energy changes from 108 eV to 58 eV. In agreement with the enlarged DC self-bias control interval discussed above, adding the 40.68 MHz component \( (N = 3) \), see Figure 5(b)) leads to a larger change of the ion FEDF as a function of \( \theta_2 \) at fixed total voltage amplitude. We find that the maximum possible ion energy is increased to \( \epsilon_i, \text{max} = 118 \) eV and the minimum width of the ion FEDF is decreased to \( \epsilon_i, \text{max} = 50 \) eV. Furthermore, the total ion flux becomes larger due to the enhanced electron heating in a triple-frequency discharge compared to a dual-frequency discharge\textsuperscript{27,28} and the ion flux fraction at relatively high energies becomes larger. This is due to the fact that the sheath width is reduced, as the plasma density increases as a function of \( N \) due to the enhanced electron heating dynamics at higher frequencies.\textsuperscript{27,28,38,39} Thus, the sheath gets less collisional and more ions hit the electrode at higher energies. This mechanism explains the change of the shape of the ion FEDF. For applications, these results mean that the mean ion bombardment energy at the substrate can be controlled over a larger range at higher ion flux (process rate) by adding a third harmonic without increasing the total driving voltage/power. Moreover, the shape of the ion FEDF can be controlled more effectively.

Thus, an advanced customization of the driving voltage waveform results in a significant improvement of the control over the ion properties at the surface. The enhanced control can be quantified in terms of the mean ion energy, \( \langle \epsilon_i \rangle \), and the total

![Figure 4](image-url) Normalized DC self-bias as a function of the phase of the second harmonic for two \( (N = 2) \) and three \( (N = 3) \) applied consecutive harmonics resulting from the experiment \( (\theta_1 = \theta_3 = 0^\circ) \). Discharge conditions: Ar, 5 Pa, \( d = 4 \) cm, \( \phi_{\text{tot}} = 120 \) V, harmonics’ amplitudes according to Eq. (2).

![Figure 5](image-url) Ion flux-energy distribution functions measured at the powered electrode as a function of the phase of the second harmonic for (a) two \( (N = 2) \) and (b) three \( (N = 3) \) applied frequencies \( (\theta_1 = \theta_3 = 0^\circ) \). Discharge conditions: Ar, 5 Pa, \( d = 4 \) cm, \( \phi_{\text{tot}} = 120 \) V, harmonics’ amplitudes according to Eq. (2).
The heating of electrons by their interaction with the electric field adjacent to the powered electrode is largest. Thus, at this phase, due to the enhancement of the electron heating dynamics by enhanced ion energy control at a greater number of applied frequencies, the plasma density and the particle fluxes are smaller for \( \theta_2 = 180^\circ \) compared to the \( \theta_2 = 0^\circ \) case. A very similar behavior has been observed before in a geometrically and electrically asymmetric discharge. It is important to keep in mind the strongly non-linear dependence of the ionization rate on the electron heating, which itself shows a complex dependence on the sheath dynamics. Based on the findings reported in Refs. 22, 25, and 26, this effect on the total ion flux occurs only at the powered electrode of electrically asymmetric discharges, which exhibit an additional geometrical asymmetry due to the electrode configuration, and vanishes for electrically asymmetric but geometrically symmetric discharges.

In the latter cases, variations in \( \Gamma_i(\theta_2) \) of less than \( \pm 10\% \) have been achieved experimentally in dual-frequency plasmas as well as in simulations of CCRF plasmas driven by multiple consecutive harmonics.

IV. CONCLUSIONS

A novel RF supply system including impedance matching is presented that allows technological RF plasmas to be driven with customized multi-frequency voltage waveforms and without high reflected powers for the first time. This allows the transfer of this technology from fundamental research to applications on an industrial level and to use its enormous advantages for process control to optimize a variety of applications ranging from plasma etching to PECVD and RF sputtering. These are only a few examples for the diverse potential applications of this multi-frequency supply system. Its commercial availability also fosters further fundamental research in the field of low temperature plasma physics, since it demonstrates that this technology is applicable on industrial levels.

Here, we used the prototype of this novel multi-frequency RF supply system to demonstrate that the Electrical Asymmetry Effect is strongly enhanced by using three instead of two consecutive harmonics of 13.56 MHz in a CCRF plasma. For a given total voltage amplitude and neutral gas pressure, we demonstrated that the DC self-bias and the mean ion energy as well as the shape of the ion FEDF at the substrate can be controlled over a much larger range by tuning the harmonics’ phases in triple- compared to dual- frequency discharges. The results are in agreement with model results and previous computational and experimental investigations (performed without impedance matching) of the EAE in multi-frequency capacitive discharges.

The RF supply system can be extended to more than three consecutive harmonics, other fundamental driving frequencies, and higher RF powers depending on the application of interest.
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Matthias Barthel is the CEO of Barthel HF. Dr. Schulze’s research group at West Virginia University developed the prototype of this novel multi-frequency RF power supply and impedance matching together with this company. This manuscript presents this scientific instrument based on scientific grounds. It allows to transfer the technology of RF voltage waveform tailoring to industrial applications (plasma etching, sputtering, PECVD, etc.) for the first time. The multi-frequency RF power supply and impedance matching are offered by Barthel HF.


See http://www.barthel-hf.de for information about the multi-frequency RF power supply and impedance matching system.


