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The effect of phase difference between powered electrodes on RF plasmas

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Abstract

This paper presents the results of measurements carried out on plasmas created in five different RF discharge systems. These systems all have two separately powered RF (13.56 MHz) electrodes, but differ in overall size and in the geometry of both vacuum chambers and RF electrodes or antennae. The two power supplies were synchronized with a phase-shift controller. We investigated the influence of the phase difference between the two RF electrodes on plasma parameters and compared the different system geometries. Single Langmuir probes were used to measure the plasma parameters in a region between the electrodes. Floating potential and ion density were affected by the phase difference and we found a strong influence of the system geometry on the observed phase difference dependence. Both ion density and floating potential curves show asymmetries around maxima and minima. These asymmetries can be explained by a phase dependence of the time evolution of the electrode–wall coupling within an RF-cycle resulting from the asymmetric system geometry.

1. Introduction

Phase synchronization in RF dual-cathode plasma systems is commonly used in both manufacturing and scientific research in order to eliminate the low frequency beating effect when two or more RF sources with the same nominal frequency are used to power the same system. Although it is possible to eliminate the low frequency beating effect by using RF power supplies with very different frequencies, it is more convenient to use two standard 13.56 MHz (heating band) power supplies and synchronize them. It has been shown that a dual-cathode plasma excited by synchronized RF sources is affected by the phase difference between the two RF sources [1] for reasons that are not yet well understood. In this work, we explore the influence of the phase difference on the plasma parameters in five different RF systems. These systems all use two separately powered RF electrodes with a surrounding grounded vessel, where the relative phase can be set using a phase-shift controller. The systems differ in geometry and have electrodes or antennae of different shape and size.

2. Experimental set-up

A schematic of the generic experimental set-up is given in figure 1, which shows the common components of the five systems we studied. The two electrodes are powered by separate RF power supplies operating at 13.56 MHz connected to separate matching networks. The electrodes are synchronized by a phase-shift controller, which enables the phase of one RF supply to be varied relative to the other. Note that the phase difference at the electrodes immersed in the plasma is not the same as the phase difference at the generators, because of phase changes associated with the matching network and the cables. However, since in our experiments the frequency is constant, the cables have a fixed length and the matching network was operated with fixed settings in manual mode, the phase difference between the electrodes in the plasma differs only by a constant from the phase difference at the generators. We confirmed that the phase difference at the output of the matching networks differed by a constant amount from the phase difference at the output of

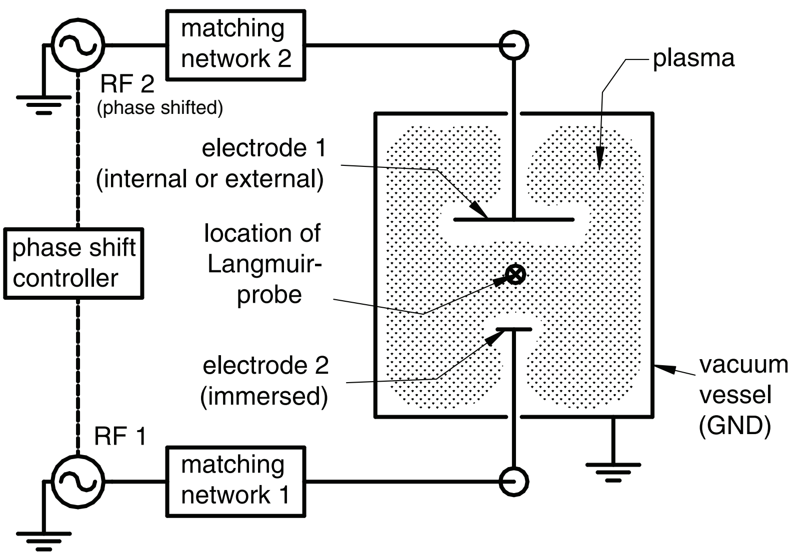

Figure 1. Schematic of a generic system fitted with two separately powered RF electrodes.

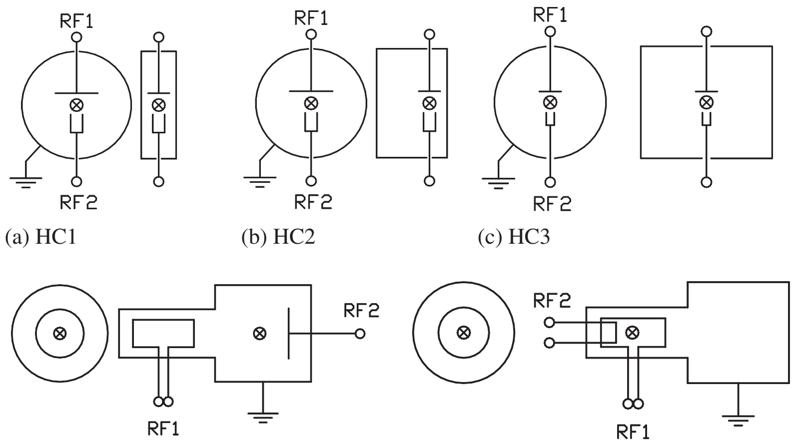

Figure 2. Schematics (front- and side-view) of the RF systems investigated. Three hollow cathode (HC) systems (*a*), (*b*), (*c*) and two helicon systems (*d*) and (*e*) are shown. The locations of the Langmuir probes are indicated by ⊗. (*a*) The vessel of HC1 has diameter 300 mm and depth 160 mm; (*b*) HC2 is identical to HC1, but the vessel has a depth of 340 mm; (*c*) HC3 has diameter 400 mm and depth 480 mm; (*d*) DINGO and (*e*) CHI KUNG both have 150 mm diameter and 300 mm long plasma source chambers attached to a 300 mm diameter and 300 mm long diffusion chamber.

the generators. The latter was recorded in the work described below.

Figure 2 gives simplified front- and side-views of the five systems showing the relative sizes and positions of vessels and electrodes. The respective locations of the Langmuir probes used to measure the plasma parameters are also indicated. The first three systems (HC1, HC2 and HC3, shown respectively in figures 2(*a*), (*b*) and (*c*)) have a similar electrode configuration—a planar electrode above a hollow cathode—inside vacuum vessels of different sizes. The HC1 and HC2 systems are identical except that HC2 has an extended vacuum chamber. Typical experimental parameters for HC1, HC2 and HC3 were: an argon pressure of 100 mTorr, 100 W RF power on the planar electrode (labelled RF1) and 50 W on the hollow cathode (labelled RF2).

The remaining two systems DINGO [2] and CHI KUNG [3], shown respectively in figures 2(*d*) and (*e*), use external helicon antennae (labelled RF1) with a second immersed antenna/electrode (labelled RF2) in contact with the plasma. Both systems have 15 cm diameter and 30 cm long plasma 'source' chambers attached to 30 cm diameter and 30 cm long 'diffusion' chambers. These two systems operate at lower pressures (typically a few mTorr) and at higher total RF power than the hollow cathode systems. In DINGO, the helicon antenna (RF1) was supplied with 800 W and in CHI KUNG with 700 W. The second electrode (RF2) was supplied with 20 W for both DINGO and CHI KUNG. However, as detailed in a previous publication [4], when a bare copper antenna is immersed into and in direct contact with the plasma, some sputtering of the antenna occurs. As the second antenna is immersed into the source of the helicon system in CHI KUNG, this sputtered copper induces a copper coating on the dielectric source tube, and consequently the power coupling efficiency between the helicon antenna and the plasma is reduced.

While scanning the phase shift, Langmuir probes were used to obtain the plasma density n_i, the electron

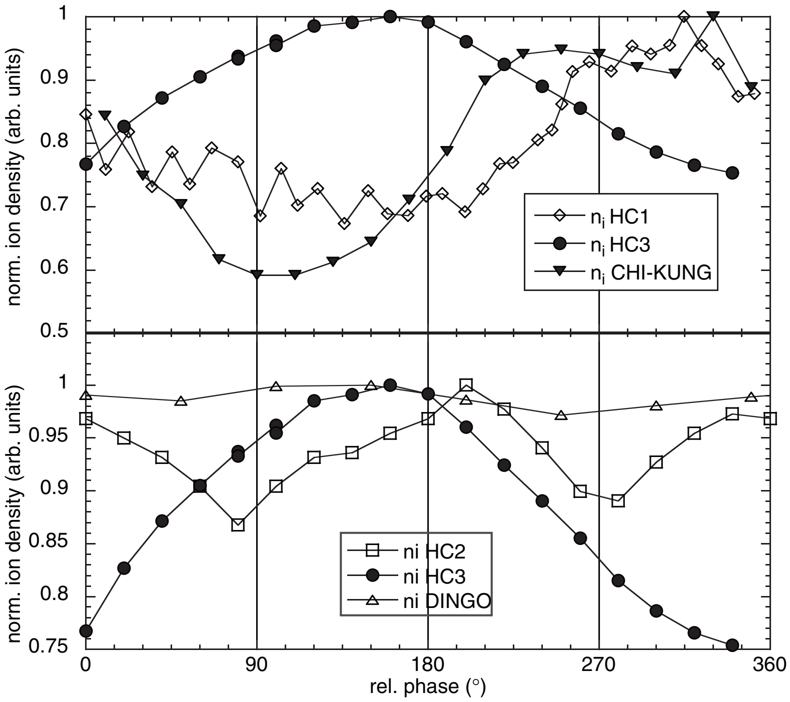

Figure 3. Ion densities (n_i) for the five different RF systems as a function of relative phase difference between electrodes. The maximum ion density for each system has been normalized to unity. In all cases, the phase given is relative to the first maximum of V_f.

temperature T_e, and the floating potential V_f. For the three hollow cathode systems, a commercial RF-compensated electrostatic probe [5] was used for the data collection and least squares fitting was used for the data analysis. The Langmuir probe data acquisition and analysis used for the two helicon systems has been reported in detail previously [1, 4].

It is convenient to present experimental results as functions of the floating potential of the probe rather than the plasma potential. The difference Φ between the plasma potential and the floating potential can be estimated from the relation [6]

$$\Phi = T_e \ln\left[\left(\frac{M}{2\pi m}\right)^{1/2}\right], \tag{1}$$

where M is the mass of the ions and m is the electron mass. For all systems in this work, the electron temperature is approximately 3 eV.

Optical plasma emission from the HC1 system was measured by taking digital images of the electrode set-up through a glass window using a digital still camera (exposure time: 1/8 s, f-stop: *f*/4.8, focal length: 21 mm). The intensity values (8-bit greyscale) of different regions of the image were determined using the image processing software *ImageJ* [7].

3. Results and discussion

We observed a reproducible dependence of ion density on the phase difference between driven electrodes in all five RF systems. Figure 3 shows the normalized ion density at a point between the electrodes as a function of the *relative phase difference*, which as explained above differs only by a constant from the true phase difference between the electrodes. For clarity, the maximum ion density for each system has been normalized to unity. The average ion densities of these measurements are 3.5×10^{16} m^{-3} for HC1, 2.0×10^{16} m^{-3} for HC2, 3.5×10^{16} m^{-3} for HC3, 5×10^{17} m^{-3} for DINGO and 2.9×10^{17} m^{-3} for CHI KUNG.

In the case of an RF-powered electrode-pair far away from the grounded vessel walls, the electric field amplitude between electrodes will be strongest when the phase difference is 180° and weakest when the phase difference is zero. Since the electric field drives the ionization process, the ion density should follow the electric field amplitude. Assuming there is no harmonic content in the RF signals, only one maximum and one minimum in the ion density, between 0° and 360° phase difference, are expected. The ion density of the experimental set-up closest to this situation, HC3, clearly behaves in this way (figure 3). There is a notable deviation from this simple behaviour in cases where the electrode-pair is closer to the grounded vessel wall as in HC1 and HC2. The only geometric difference between the two helicon systems DINGO and CHI KUNG is the position of the second RF electrode (RF2). Since the power in RF1 is much higher than that in RF2, it is the RF1 electrode that is responsible for the main plasma generation. In DINGO the immersed electrode RF2 is located well away from the plasma generation region and, therefore, little effect of the phase difference between RF1 and RF2 is seen on the plasma density. In CHI KUNG, however, the immersed electrode (RF2) is very close to the helicon antenna (RF1), and situated inside the source chamber; hence, its effect on the electric field in the region of plasma generation is much stronger. However, it is weakly coupled to the wall and, therefore, a single maximum is expected for a phase difference of 180° between powered electrodes RF1 and RF2. The density variations in CHI KUNG can, therefore, be of the same order as the variations in the HC systems.

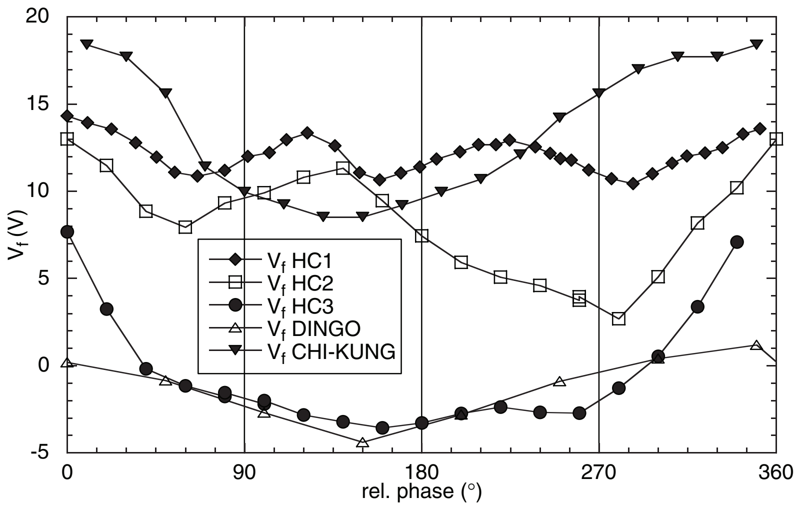

Figure 4. Floating potential (V_f) for the five different RF systems as a function of phase. The phase is identical to the one used in figure 3.

This could explain the stronger dependence of ion density on phase difference seen in CHI KUNG compared to DINGO. Note that the power coupling efficiency of the helicon antenna in CHI KUNG is reduced due to copper re-deposited on the source wall adjacent to the helicon antenna; this is believed not to affect the plasma density during the time it takes to acquire one set of measurements [5]. Hence, the effective RF power applied to the helicon antenna in CHI KUNG might be of the order of the power applied to the RF1 electrodes in the HC systems and not to the helicon antenna in DINGO.

Figure 4 shows the floating potentials for the systems as functions of the relative phase difference as used in figure 3. The behaviour of the floating potential is affected by the proximity of the vessel wall. For system HC3 the floating potential shows one minimum as expected for systems with remote walls. CHI KUNG also shows a single minimum and a strong variation between maximum and minimum. Both the systems, CHI KUNG and HC3, have a strongly coupled electrode-pair, in which each electrode interacts weakly with the wall. In the case of DINGO, the electrode-pair interacts much more weakly as the distance between the electrodes is large, so that each electrode behaves like an independent source, as shown in both the figures for ion density and floating potential. This explains why the system is relatively insensitive to the phase shift. For system HC1 the floating potential shows three minima. We interpret this as resulting from the closest distance of the electrode-pair to the walls so that it has the strongest coupling effect with the walls. For system HC2, the distance between the two electrodes is the same as that in HC1 but the distance of the electrode-pair to part of the wall is much larger, resulting in two minima in both figures 3 and 4. These results suggest that the grounded vessel walls will play an important role in the phase dependence when the electrode-pair is not far away from the grounded vessel wall.

In order to test the hypothesis that when the grounded vessel wall is close to the electrode-pair it plays a significant role in the behaviour of the phase dependence between the electrodes, we studied the optical emission close to the wall and between the electrodes as a function of the relative phase difference. Figure 5 shows the light emission intensity as a function of the relative phase difference for the two different plasma regions of HC1 (see schematic inset), where the walls are close to the electrode-pair. The relative phase difference is approximately equal to the actual phase difference for the electrodes in HC1, as the cable lengths were matched. Optical signal 1 (OS-1) is the intensity of light viewed along one line of sight, at a point close to the vessel wall. This light intensity is minimum for a phase difference of 180°. For 180° phase difference, the electric field is maximum between the electrode-pair and minimum far from the electrode-pair. This means that the electric field and hence the plasma density at points close to the vessel wall is minimum. Optical signal 2 (OS-2) is the average of the light emission intensity over four lines-of-sight, separated by approximately 1 cm, viewing the plasma between the two electrodes (see schematic inset in figure 5). The light signal collected from between the electrodes (OS-2) shows three maxima with less variation overall.

For most cases, the curves for both V_f and n_i are not symmetrical around their maxima and minima, especially for V_f and n_i in HC2 and CHI KUNG, respectively. This indicates that it is important which electrode is leading in time. For the ideal situation where the electrode-pair is far away from the grounded wall, no such asymmetry is expected, as the electric field strength between the electrodes would be the same independent of which electrode is leading. The situation changes when a vessel wall is relatively close. In cases where the system geometry is not symmetric, the coupling of the two electrodes to the vessel wall is not equal and the time evolution of the plasma depends on which electrode is leading in time. Existing electrical models using static values for sheath capacitances and resistances [8,9] will fail in modelling systems under these circumstances because the time evolution of the plasma cannot be described by any combination of lumped circuit components. To our knowledge, there is no model yet that can predict the dependence of the phase between two individually powered electrodes as described in this paper. Detailed models of RF plasma sheaths in front of a biased electrode immersed into an inductively coupled plasma source exist [10–12]. Such a model would also be applicable for any other plasma source sustained by microwaves or helicon waves.

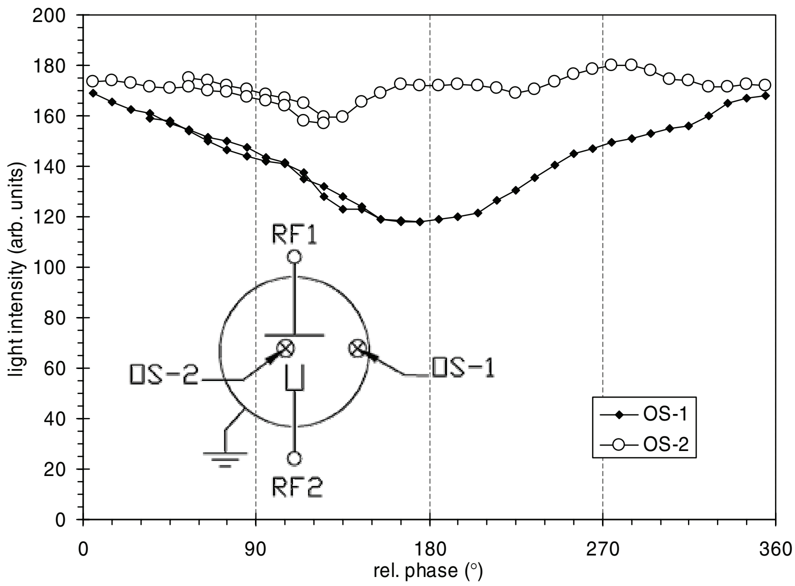

Figure 5. The light emission signals as functions of relative phase for two different plasma regions of HC1. The locations of the optical signals OS-1 and OS-2 are indicated in the overlaid schematic.

However, these models do not yet take into account the effect of the phase between the individually powered electrodes in the system. Rauf and Kushner [9, 11] modelled the effect of RF plasma processing reactor circuitry on the plasma parameters and showed that the external electrical circuit strongly influences the performance of the reactors by generating harmonics of significant amplitude. This model may be useful to simulate our systems, if it could be extended to include two powered electrodes with specified phase difference.

4. Conclusion

The plasma condition inside an RF system with two powered electrodes operating at the same frequency (13.56 MHz) inside an earthed vessel (third electrode) is dependent on the relative phase between the two synchronized RF sources. We observed changes in floating potential and ion density with the relative phase shift. Furthermore, we found a strong influence of the system geometry on the observed effect. The behaviour of the simple case of an electrode-pair far away from the grounded vessel walls can be understood qualitatively by considering the electric field between the electrodes. However, the closer the vessel wall is to the electrode set-up, the more the phase-shift effect deviates from this ideal case due to the electrodes interacting with the grounded wall. This is in agreement with optical emission measurements of the plasma. The importance of the vessel wall on the phase effect was shown by comparing three systems with similar electrode configurations but different clearances to the grounded wall. The comparison of two basically identical helicon systems with a second RF-powered electrode immersed into the source chamber and into the diffusion chamber of the helicon system showed the importance of the distance between the two powered electrodes relative to the distance to the wall. The asymmetry of both ion density and floating potential around maxima or minima can be explained by a phase dependence of the time evolution of electrode–wall coupling within an RF cycle on the asymmetric system geometry.

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