Influence of a phase-locked RF substrate bias on the E-to H-mode transition in an inductively coupled plasma

Article in Plasma Sources Science and Technology · July 2015
DOI: 10.1088/0963-0252/24/4/044006

5 authors, including:

Edmund Schüngel
Evatec AG
77 PUBLICATIONS  703 CITATIONS
SEE PROFILE

Julian Schulze
Ruhr-Universität Bochum
124 PUBLICATIONS  1,512 CITATIONS
SEE PROFILE

Tsanko Vaskov Tsankov
Ruhr-Universität Bochum
42 PUBLICATIONS  210 CITATIONS
SEE PROFILE

Uwe Czarnetzki
Ruhr-Universität Bochum
139 PUBLICATIONS  2,461 CITATIONS
SEE PROFILE

Some of the authors of this publication are also working on these related projects:

QuantemolDB View project
Influence of a phase-locked RF substrate bias on the E- to H-mode transition in an inductively coupled plasma

2015 Plasma Sources Sci. Technol. 24 044006
(http://iopscience.iop.org/0963-0252/24/4/044006)

View the table of contents for this issue, or go to the journal homepage for more
Influence of a phase-locked RF substrate bias on the E- to H-mode transition in an inductively coupled plasma

P Ahr1, E Schüngel2, J Schulze2, Ts V Tsankov1 and U Czarnetzki1

1 Institute for Plasma and Atomic Physics, Ruhr University Bochum, 44780 Bochum, Germany
2 Department of Physics, West Virginia University, WV 26506, USA

E-mail: philipp.ahr@rub.de

Received 26 February 2015, revised 14 April 2015
Accepted for publication 5 May 2015
Published 14 July 2015

Abstract

The effect of a capacitive radio frequency (RF) substrate bias on the E- to H-mode transition and electron-heating dynamics in a low-pressure inductively coupled plasma (ICP) operated in hydrogen is investigated by phase-resolved optical emission spectroscopy (PROES) and Langmuir probe measurements. The inductive and capacitive power sources are driven at the same frequency and operated in a phase-locked mode with fixed but adjustable phase between them, as well as without a phase lock. For both operations, when the discharge is in the E-mode, the plasma density is significantly influenced by the choice of capacitive power. This directly affects the mode transition power: already low values of bias power can substantially reduce the threshold for the E- to H-mode transition. This coupling between both power sources is strongly dependent on the adjustable phase between them and is attributed to a phase-sensitive confinement mechanism for the highly energetic electrons produced by the expanding sheaths at the substrate and at the ICP coil. At higher pressures the beam electrons do not interact with the opposing sheath and, consequently, the effect diminishes. Using phase-unlocked operation reduces the overall beam confinement and also results in less pronounced coupling effects. In contrast, by using electrodes with ring-shaped trenches the initial energy of the beam electrons is enhanced, increasing the influence of the RF bias on the operation of the ICP discharge.

Keywords: hybrid discharge, phase lock, E- to H-mode transition, electron beam confinement, structured electrodes, PROES

(Some figures may appear in colour only in the online journal)

1. Introduction

Inductively coupled plasmas (ICP) with radio-frequency (RF) substrate bias are frequently used for high-aspect-ratio plasma etching and sputtering of dielectrics as key process steps for semiconductor manufacturing [1, 2]. These plasma sources are basically combinations of an inductively and capacitively coupled plasma, therefore called hybrid discharges, that aim to utilize the advantages of both components. The ICPs are generally characterized by higher electron densities and lower ion energies at substrates compared to capacitively coupled plasmas (CCP) [1, 2]. The absence of high-voltage sheaths in the ICPs is the reason for the relatively low ion energies at the substrates and the high density is caused by a combination of Ohmic and stochastic heating [3, 4] that ensures efficient coupling of the RF power to the electrons, allowing high-density plasmas to be sustained. Typically these heating mechanisms are effective only at high plasma densities, i.e. high applied powers, $P_{\text{ICP}}$. In this case the discharge is said to operate in the H-mode. At low electron densities (low $P_{\text{ICP}}$) the discharge runs in the E-mode and behaves similarly to a capacitive discharge. The transition between the two
modes is usually abrupt and exhibits a hysteresis [5–11]. To maximize the process rate in applications, ICPs are usually operated in the H-mode where the ion and neutral radical fluxes to the substrate are higher than in the E-mode.

Depending on the discharge conditions, the CCP—as the second power source in a hybrid discharge—can be operated in different electron heating modes, which strongly affect process-relevant plasma parameters such as electron and ion energy distributions: at low pressures and in electro-positive gases, CCPs are typically operated in the α-mode, where stochastic and ambipolar electron heating during the phase of sheath expansion [4, 12–24] and electron heating by electric field reversals during sheath collapse [25–30] dominate; at higher neutral gas pressures and/or driving powers the discharge operates in the γ-mode where the ionization is dominated by secondary electrons generated at boundary surfaces and multiplied by collisions inside the sheaths [23, 31]. In electronegative, dusty and/or high-pressure CCPs the electrical conductivity in the plasma bulk is reduced resulting in high drift electric fields and strong electron heating in the discharge centre. Moreover, strong ambipolar electric fields at the sheath edges can be generated and cause significant electron heating and ionization. This mode is called the drift-ambipolar heating mode [32–37]. In the α- and γ-modes, electrodes with trench-like structures were found to enhance the electron heating, the ionization rate and the plasma density inside and above the structures [38–48]. This increase in the excitation and ionization is attributed to a hollow cathode effect and faster sheath expansion inside the structures as well as enhanced electric fields around the sharp edges of the structures [48].

However, in a pure CCP the plasma density and ion flux to the substrate always remain significantly lower compared to conventional ICPs. On the positive side, there exist concepts that enable a separate control of the mean ion energy, $E_i$, and the ion flux, $I_i$. These rely on using multiple driving frequencies and can follow two different approaches: (i) classical dual-frequency CCPs operated at significantly different frequencies, e.g. 2 MHz and 27 MHz [49–53] and (ii) electrically asymmetric CCPs operated at multiple consecutive harmonics of a fundamental driving frequency [54–61]. Coupling mechanisms between both capacitive driving sources were found to limit the quality of this separate control significantly in classical dual-frequency CCPs [31, 62–66], while such parasitic effects are largely avoided in electrically asymmetric CCPs [54].

The same idea of a separate control is sought with the concept of a hybrid discharge but with the added gain of much higher values for $E_i$ in contrast to CCP concepts. The quality of this separate control is extremely important for applications, but recent investigations have demonstrated significant limitations of the hybrid concept: Lee et al [67, 68] and Sobolewski et al [69] found the ion flux to decrease as a function of the bias power at high ICP powers, while the opposite trend was observed at low ICP powers, i.e. the ion flux was not independent of $P_{ICP}$. Schulze et al [70] found the inductive power to affect the sheath voltage waveform at the substrate and, therefore, the ion flux-energy distribution function at fixed values of $P_{CCP}$. In order to understand and control these important coupling mechanisms between the capacitive and inductive RF sources, a detailed analysis of the simultaneous electron heating dynamics of both sources is required. Using phase-resolved optical emission spectroscopy (PROES) it was found that the capacitive power coupling in a hybrid discharge affects the spatio-temporal excitation dynamics significantly via sheath expansion heating even at high values of $P_{CCP}$, indicating an effect of $P_{CCP}$ on the plasma density and the ion flux [70]. However, in that work only the capacitive electron heating could be investigated in a time-resolved manner due to the absence of a phase lock between the driving sources. This made a parallel time-resolved study of the inductive electron heating and, thus, of the coupling effects between both driving sources on the electron heating dynamics impossible. Therefore, a phase-locked operation of the plasma is required.

Here, we investigate the electron heating dynamics and the E- to H-mode transition in a hybrid ICP/CCP discharge operated in hydrogen in a phase-locked mode with fixed and adjustable phase between the capacitive and inductive driving voltage waveforms for the first time and compare the results obtained with plasma parameters measured without a phase lock. In contrast to previous works, this allows us to study the coupling effects of both driving sources on the electron heating and excitation dynamics directly and completely by PROES, since both the capacitive and inductive RF periods are resolved temporally. Moreover, we study the effects of $P_{CCP}$ and $P_{ICP}$ on the plasma density by Langmuir probe measurements.

It is found that the addition of an RF bias strongly influences the E- to H-mode transition, changing its character from a sudden jump in the plasma parameters (electron density and excitation) to a continuous transition. A criterion based on the excitation dynamics obtained solely by the optical diagnostic method PROES is introduced to define the transition power during this continuous transition. Using the criterion it is found that the addition of a substrate bias power significantly lowers the inductive power, $P_{ind}$, needed for a transition to the H-mode. It is shown that the phenomenon is related to the interaction of the high-voltage sheaths adjacent to both the ICP coil and the RF-biased substrate with the beams of highly energetic electrons launched by the opposite sheaths during their expansion phases. Higher pressures or phase-unlocked operation weaken the effect, while phase variation or suitable choice of substrate structuring allow for its enhancement. This can be of benefit for the application of these hybrid plasma sources, since the high-density H-mode is reached at lower $P_{ICP}$, thereby reducing production costs.

The paper is structured in the following way: in section 2, the experimental setup and the applied diagnostics are introduced. Section 3 contains the results divided into three parts. First, the effects of $P_{CCP}$ on the E- to H-mode transition are discussed for the cases without and with a phase-lock at a fixed phase. In the second part, the changes in the spatio-temporal excitation dynamics and the total plasma emission at different phases are clarified. Finally, the effect of using structured electrodes on the E- to H-mode transition in the
phase-locked method of operation is analysed. Conclusions are drawn in section 4.

2. Experimental setup and diagnostics

The experimental setup, including all diagnostics and the synchronization between the inductive and capacitive power sources, is shown in figure 1. All experiments are performed in a modified Gaseous Electronics Conference (GEC) reference cell [71]. The inductive power coupling is realized by driving a three-turn double-spiral antenna at 13.56 MHz via an RF power generator and an impedance matching. The antenna is located at the top of the reactor, its diameter is 12 cm and it is separated from the plasma by a dielectric quartz cylinder. The side walls of the cylinder have a thickness of 0.5 cm and its bottom is closed by a quartz disc of 1 cm thickness. The capacitive power coupling is realized by driving a planar stainless steel electrode (denoted as RF electrode henceforth) at the same frequency (13.56 MHz). A multichannel frequency generator supplies a reference frequency for the RF power generator providing the inductive power coupling. In this way the inductive and capacitive power sources can be operated phase-locked, where the phase between the driving sources can be adjusted via the frequency generator. For phase-unlocked operation the frequency generator is disconnected from the ICP RF power generator. In this mode of operation the relative phase between the two generators is stochastically distributed during the measurements which typically extend over hundreds of seconds. For the relative phase to remain stable during such a time period, both generators would need to have frequency stability and a frequency difference of less than $10^{-2}$ Hz. This stringent requirement is not fulfilled by the generators used here and, therefore, the measurements in the phase-unlocked mode represent an average over all possible phases. The measured reflected power for both generators was below 10%, but it was not always possible to achieve a perfect matching. Therefore, some of the measured voltage waveforms are not perfectly sinusoidal.

The RF electrode is located at a distance of 5 cm below the quartz surface separating the ICP antenna from the plasma. Pure hydrogen plasmas are investigated in order to avoid parasitic sputtering of the electrode, which is observed if heavier gases such as argon are used and which leads to impurities that can complicate the analysis of the observed phenomena. Moreover, hydrogen allows us to use the Balmer-$\alpha$ emission originating from the $n = 3$ state which has a short lifetime of 22.7 ns [72]. For the PROES diagnostics this permits high enough temporal resolution to resolve the inductive and capacitive RF periods (about 74 ns at 13.56 MHz). The neutral gas pressure is varied from 3 Pa to 40 Pa to investigate relatively collisionless nonlocal regimes (low pressure) and more collisional local regimes (highest pressure). $P_{\text{CCP}}$ and $P_{\text{ICP}}$ are varied from 0 W to 80 W and from 50 W to 400 W, respectively. Also, the phase of the capacitive power source relative to the inductive one is varied.

The effect of structured electrodes with ring-shaped trenches on the E- to H-mode transition is investigated by placing discs made of stainless steel with a height of 2 cm on top of the RF electrode. Three different types of discs are used: (i) a plate with a ring-shaped vertical trench of width 1.0 cm and depth of 1.0 cm located at 2/3 of the radius of the ICP antenna (i.e. at a radial position of 4 cm). This structure is used to locally enhance the generation of energetic electron beams [43–48] and to shoot a high number of energetic electrons into the region of maximum induced electric field located at 2/3 of the coil radius [73, 74]; (ii) a disc with a central hole with a diameter and depth of 1.0 cm in order to shoot a high number of energetic electrons towards the ICP antenna outside the region of high inductively induced electric field; and (iii) a planar disc as a reference case. In all three cases placing the discs onto the electrode reduces the distance between the RF electrode and the quartz cylinder surrounding the ICP antenna to 3 cm.

Without the presence of structured electrodes and a distance of 5 cm between the RF electrode and the quartz, the
plasma density is measured by a Langmuir probe [75]. 2.5 cm above the RF electrode and at a radial distance of 4 cm from the discharge centre. Moving the probe further into the plasma was found to disturb the discharge significantly. The probe measurements are performed at the same position under all conditions and the plasma density is determined by integrating the electron energy distribution function determined by the Druyvesteyn method [75].

With and without structured electrodes, the plasma emission at 656.28 nm corresponding to the Balmer-α line is measured space- and time-resolved within the RF period of the capacitive and inductive RF sources based on the phase-locked method of operation by an ICCD (intensified charge-coupled device) camera (Roper Scientific) equipped with an interference filter. The camera is synchronized with both the inductive and the capacitive driving voltage waveforms via the frequency generator. Due to the phase locking of both RF sources the electron heating and excitation dynamics can be studied time-resolved in both RF periods with a time resolution of 2 ns. All images are binned radially and the spatial resolution in axial direction is about 1 mm. From the measured spatio-temporal emission the electron impact excitation rate from the ground state into the upper energy level of the Balmer-α transition is calculated with one-dimensional spatial resolution in the axial direction and nanosecond time resolution in the RF periods based on a simplified rate equation model to eliminate the influence of the lifetime of the observed level [76].

Two high-voltage probes are used to monitor the phase locking of both RF sources during plasma operation by measuring the voltage at the output of the inductive matchbox and in front of the RF electrode, respectively.

An absolute calibration of the phase between the voltage waveforms at the ICP antenna and the RF electrode is performed based on the PROES measurements as shown in figure 3: in the E-mode, characteristic excitation maxima are observed at the RF electrode (0 cm) and the quartz surface below the ICP antenna (5 cm). These maxima are caused by electric field reversals in hydrogen and are known to occur at the instants of local sheath collapse [26]. In this way the times of sheath collapse at the quartz surface, \( t_{\text{coll,ICP}} \), and at the RF electrode, \( t_{\text{coll,CCP}} \), marked by vertical lines in figure 3, can be determined. The phase shift between the inductive and capacitive voltage waveforms, \( \Delta \varphi \), can be obtained from the difference between \( t_{\text{coll,ICP}} \) and \( t_{\text{coll,CCP}} \). In this way \( \Delta \varphi \approx 60^\circ \pm 10^\circ \) is determined for the conditions of figure 3. The uncertainty is determined by the temporal resolution of the PROES measurements of 2 ns. In section 3.1, all measurements are performed at this phase of \( \Delta \varphi \approx 60^\circ \). Although the coupling between the two RF sources is found to be stronger in the range of \( -60^\circ < \Delta \varphi < 60^\circ \), the PROES measurements do not allow analysis of the physical origin of this coupling, since the electron beams generated by the expansion of the top and bottom sheaths cannot be separated and, thus, no clear interpretation of the electron heating and coupling mechanisms is possible. Therefore, \( \Delta \varphi \approx 60^\circ \) is the phase of strongest coupling between both sources, i.e. the strongest effect of \( P_{\text{ICP}} \) on the E- to H-mode transition, where all excitation maxima can still be separated. In this work, \( P_{\text{ICP}} \) is systematically increased from low to high values, i.e. hysteresis effects [6–8] are not investigated.

For a fixed value of \( P_{\text{ICP}} \) the inductive power at which the E- to H-mode transition occurs can be determined based on Langmuir probe measurements of the plasma density, since a strong increase of the density is found around this value of \( P_{\text{ICP}} \) [77, 78]. Here, we propose an alternative and novel way to determine the mode transition power, \( P_{\text{tmp}} \), based on PROES. Figure 4(a) shows an example of a spatio-temporal plot of the excitation rate within one RF period of both driving sources in the phase-locked mode of operation. Three excitation maxima are observed. The plot is dominated by two strong excitation maxima between about 2.5 cm and 3.5 cm (I and III). These maxima are predominantly caused by the inductively induced electric field that causes maximum excitation twice per RF period. The first maximum at about 10 ns, however, is slightly stronger compared to the second maximum at about 45 ns. This is caused by additional excitation at the same position and time due to an energetic electron beam.
generated by the expanding sheath adjacent to the quartz surface located at 5 cm and propagating downwards towards the RF electrode. Similarly, an energetic electron beam is generated by the expanding sheath at the RF electrode located at 0 cm. This beam propagates upwards towards the ICP antenna, but crosses the inductive skin layer at a time of low induced local electric field, i.e. it overlaps with neither of the dominant excitation maxima but forms a separate maximum instead (maximum II).

It will be shown that the value of the total excitation in maximum I determined by integrating the measured excitation rate over the region of interest (ROI) in time and space marked by a rectangle in figure 4(a) can be used as a substitute for the relative change in the electron density when investigating the mode transition. This rectangle has the same width (8 ns in time and 1 cm in vertical space) for all conditions but its position is changed so that it is always centred around the time and the position of maximal excitation.

To determine the ICP power, $P_{\text{mtp}}$, at which the mode transition happens based on PROES measurements the following procedure is applied: first, the spatial region of high excitation is identified and is indicated by horizontal lines in figure 4(a). The spatial extension of this region is always centred around the excitation maxima I and III and is about 1 cm in width. Within this region the excitation is integrated spatially. The result of this integration is depicted in figure 4(b). This plot again shows three maxima (labelled I–III) caused by the mechanisms discussed above. Maxima I and III are not caused purely by electron heating due to the inductively induced electric field, but contain components caused by energetic electron beams generated capacitively. This is the reason for their different shapes and heights. In order to determine the mode transition power, the excitation caused by the inductively induced electric fields must be isolated and compared to the excitation caused by the capacitive coupling of both RF sources. The procedure described in the following is certainly not perfect but it allows a relatively simple way to separate the contributions of the two power coupling mechanisms and to quantify the mode transition power. A Fourier analysis of the data shown in figure 4(b) is performed to separate the excitation caused by inductive and capacitive electron heating. The results are plotted in figure 4(c). As the inductively induced electric field causes electron heating and excitation twice per RF period, the excitation observed at odd harmonics must be pure due to the capacitive coupling. However, the excitation observed at the second harmonic is a superposition of excitation caused by capacitive coupling, $h_{2,c}$, and by inductive coupling, $h_{2,i}$. In order to determine $h_{2,c}$ an exponential fit (blue line in figure 4(c)) is made to the first four odd harmonics. This fit reproduces the experimental data well and allows...
estimation of $h_{2,c}$. Then, $h_{2,i}$ is the difference between the total excitation observed at the second harmonic and $h_{2,c}$. The E- to H-mode transition criterion is then defined as $h_{2,i} < h_{2,c}$, which is fulfilled at a certain ICP power, $P_{\text{imp}}$. This procedure is applied under various discharge conditions and is found to be effective in reproducing the E- to H-mode transition characterized by intrusive Langmuir probe measurements of the plasma density. Actually, it neglects the interaction between the capacitive coupling of both power sources. This is clearly a simplification. However, the good agreement of $P_{\text{imp}}$ obtained by the Langmuir probe and inferred from our optical method justifies this approach \textit{a posteriori}. Furthermore, PROES is nonintrusive and could, therefore, be applied in commercial reactors. The mode transition criterion also allows us to define a mode transition in cases where no abrupt increase, but rather a continuous density increase is observed as a function of $P_{\text{ICP}}$.

3. Results and discussions

3.1. Effect of the capacitive RF bias power on the E- to H-mode transition

Here, we investigate the dependence of the electron heating dynamics, the electron density and the E- to H-mode transition on the RF bias power, $P_{\text{CCP}}$, with and without phase lock between the RF sources. All measurements in this section are performed in hydrogen at 3 Pa. In the phase-locked mode of operation, the relative phase between the ICP and the CCP power is set to $\Delta \varphi = 60^\circ$. At this phase difference the effect of the coupling of the ICP power and the CCP bias is close to its maximum (see also figure 8) while simultaneously the excitation by the two power sources is well separated in the PROES measurements and allows a detailed analysis.

Figure 5(a) shows the dependence of the electron density measured by a Langmuir probe on the ICP power for various RF bias powers, $P_{\text{CCP}}$, with and without phase lock. In a pure ICP, i.e. at $P_{\text{CCP}} = 0$ W, the electron density remains low when the ICP power is below about 200 W. The electron density increases abruptly at an inductive power of $P_{\text{imp},0} = (207.5 \pm 2.5)$ W. The uncertainties in the value of $P_{\text{imp}}$ are determined by the size of the steps in $P_{\text{ICP}}$. This means that the discharge undergoes a transition from the E- to the H-mode, which is associated with a much more efficient inductive power coupling and, hence, higher plasma densities. With an RF substrate bias power of $P_{\text{CCP}} = 40$ W, the electron density is higher for all values of $P_{\text{ICP}}$ as compared to the purely inductively coupled discharge. This is due to the fact that the additional capacitive power coupling enhances the electron heating and allows higher electron densities to be sustained. Furthermore, the increase of the electron density as a function of the inductive power is smoother and the E- to H-mode transition does not occur suddenly. Instead, the power coupling mode changes continuously within a wider range of $P_{\text{CCP}}$. The centre of the mode transition region is at about $P_{\text{imp},40} = (147.5 \pm 2.5)$ W. This value is 60 W lower compared to a pure ICP, although the additionally supplied capacitive power is only 40 W and this capacitive power is predominantly transferred to the ions [79], and not to the electrons. Therefore, strong coupling effects between the capacitive and inductive power sources in the plasma must be present. At $P_{\text{CCP}} = 80$ W the electron density is further increased due to the additional RF bias power and increases smoothly as a function of the ICP power. The mode transition occurs in an even wider interval of $P_{\text{ICP}}$. The centre of the mode transition region is at about $P_{\text{imp},80} = (125 \pm 5)$ W for the mode transition power.

If the phase between the ICP power and the CCP power is not locked, the effect of the RF bias power on the electron density is much less pronounced. The density measured without phase synchronization at $P_{\text{CCP}} = 80$ W resembles that in the phase-locked discharge at $P_{\text{CCP}} = 40$ W under the conditions investigated here. Thus, the overall power-coupling efficiency is enhanced by using synchronized ICP and CCP sources due to strong coupling mechanisms, as will be shown below.

The total excitation rate (figure 5(b)) obtained from the PROES measurements in the region of interest of high ICP coupling—determined as part of the procedure outlined in section 2 (rectangle around maximum 1 in
figure 4(a)—shows a qualitatively very similar dependence on the ICP and CCP powers compared to the electron density measured intrusively by the Langmuir probe. In a purely inductively coupled discharge, i.e. at $P_{\text{ICP}} = P_{0}$, a sudden increase of the total excitation occurs at about the same ICP power as before. This confirms that the discharge mode changes from the E- to the H-mode. For $P_{\text{ICP}} = 140$ W the excitation rate is higher at each value of $P_{\text{ICP}}$ due to the enhanced power dissipation compared to the pure ICP case. Again, the mode transition appears to be a continuous function of the ICP power. An increase of the RF bias power to 80 W further smoothens the mode transition region. However, no significant change in the excitation outside of this E- to H-mode transition region, i.e. for very small and very large values of $P_{\text{CP}}$, is observed. Moreover, the behaviour without a phase synchronization between the ICP power and the CCP power is again similar to that using a lower, but synchronized CCP power. The vertical dashed lines in figure 5(b) indicate the respective mode transition powers determined by the criterion introduced in section 2 ($h_{1,2} < h_{2,1}$). They agree very well with the transition powers estimated based on the Langmuir probe measurements of the electron densities. This demonstrates that nonintrusive PROES measurements can be used to characterize the heating mode based on the procedure developed in this work rather than using intrusive probe measurements.
Figure 6 shows the spatio-temporal excitation rate as well as the voltage waveforms for different values of $P_{\text{ICP}}$ and $P_{\text{CCP}}$ at 3 Pa in H$_2$. The voltage on the ICP coil (upper curves) is sinusoidal with no dc offset, as expected. The voltage on the RF electrode (lower curves) in contrast shows a large dc offset which is comparable in magnitude to the amplitude, i.e. nearly 100% self-bias. This is characteristic for completely asymmetric capacitive discharges. This is of interest for the application of these discharges, since the entire applied RF voltage contributes to the energy of the impinging ions, $E_i$. As mentioned earlier, the deviations in this case from a sinusoidal signal are due to imperfect matching.

Different mechanisms of electron heating can be identified in the excitation (middle plots). In figure 6(a), the discharge is operated as a pure ICP at low power (180 W), i.e. in the E-mode. In this mode the ICP behaves similarly to a CCP: the energetic electron beam is generated by the expansion of the sheath adjacent to the quartz in front of the ICP coil (at 5 cm). At low pressures the beam propagates through the entire plasma bulk [4, 12–24] and is partially reflected at the RF electrode (at 0 cm). This reflection of the beam electrons can be described by the quality of their confinement, defined as the ratio of the number of beam electrons injected at the expanding sheath edge to the number of beam electrons lost at the walls prior to any collision. A better confinement quality will be provided if fewer beam electrons are lost. It is difficult to quantify this parameter experimentally and here it will be used only qualitatively. Obviously the case depicted in figure 6(a) corresponds to a poor confinement quality and the excitation is strongly reduced after $t \approx 20$ ns. Furthermore, a peak in the spatio-temporal excitation can be observed at the time of sheath collapse at the quartz, i.e. at $t \approx 7$ ns and about 4.8 cm. This pattern is caused by a local reversal of the electric field accelerate electrons towards the surface in order to ensure the same RF-period-averaged fluxes of ions and electrons at the quartz. The local field reversal at sheath collapse is a well-known electron heating mechanism in hydrogen discharges [25–30].

The discharge can be operated also in the H-mode at the same or even smaller values of $P_{\text{ICP}}$ (in this case 140 W) by adding a capacitive RF bias (figure 6(c)). Here, two heating maxima in the plasma bulk are observed within one RF period. They are caused by the azimuthal electric field induced in the discharge volume by the current flowing through the ICP coil [3–5, 80, 81]. These two peaks are about equal in position and excitation strength. This indicates that the capacitive coupling is weak, because the heating enhancement due to sheath expansion occurring once per period would cause different intensities of these two maxima. Accordingly, the electric field in the sheath adjacent to the quartz is strongly reduced.

At intermediate values of the RF bias power ($P_{\text{CCP}} = 40$ W) and at the same ICP power the discharge operates in a hybrid mode (figure 6(b)). A combination of the mechanisms of the E-mode and the H-mode can be observed. The sheath expansion at the quartz launches a beam of energetic electrons, which enhances the excitation at the beginning of the RF period. The excitation due to the beam overlaps with the first excitation maximum caused by the inductive coupling. The beam then hits the opposing sheath adjacent to the RF electrode at approximately the time of its expansion ($t \approx 22$ ns). Thus, it is reflected back into the bulk and can be further accelerated by bounce resonance heating (BRH) [21, 22]. Meanwhile, a second energetic electron beam is generated by sheath expansion at the RF electrode and propagates upwards into the plasma bulk. This (second) beam reaches the central region of the plasma bulk shortly before the appearance of the second maximum caused by the inductive coupling.

The expansion of both sheaths is preceded by their full collapses (at $t \approx 10$ ns for the sheath at the RF electrode and at $t \approx 70$ ns for the sheath at the quartz). The local field reversal associated with the sheath collapse causes an additional relatively weak excitation (figure 6(b)). This hybrid combination of the capacitive and inductive electron heating mechanisms, i.e. the interaction between beams of energetic electrons, high-voltage sheaths and inductive heating, ultimately leads to the continuous behaviour of the mode transition shown in figure 5. Most importantly the additional generation of energetic beam electrons and their improved confinement due to the presence of an RF substrate bias leads to a mode transition into the H-mode at lower ICP power compared to pure ICPs ($P_{\text{ICP}} = 0$ W).

### 3.2. Pressure and phase variation

The coupling between the ICP power and the RF bias, demonstrated in the previous section, was attributed to the interaction of the beams of energetic electrons with the RF sheaths and the ICP heating. To better understand this effect this section presents results for different fixed phases between the two power sources at various pressures. The phase controls the way the beams interact with the high-voltage sheaths, while the pressure influences the strength of this interaction by collisional damping of the beams.

Figures 7(a)–(d) show the spatio-temporal excitation at four different relative phases between the ICP and the RF bias power sources. The ICP power is relatively low and, accordingly, the discharge is operated in the E-mode in each case. In figure 7(a), $\Delta \phi$ is set to $-50^\circ$ ($310^\circ$) and the motion of both sheaths is out of phase by about 11 ns. Thus, the sheath at the RF electrode expands and contracts slightly earlier than the sheath adjacent to the quartz. At this phase the excitation caused by the beam electrons generated at both sheaths occurs simultaneously around $t \approx 15$ ns in the plasma bulk region. Both beams hit the opposing sheath at a time of high local sheath potential and are reflected back into the bulk. Therefore, for this phase shift most of the energetic electrons cannot reach the walls and accordingly their confinement quality is good. The relatively weak excitation maxima due to the local field reversal during sheath collapse appear around $t \approx 60$ ns close to the RF electrode and about 11 ns later close to the quartz.

The case of a 60° phase shift (figure 7(b)) corresponds to the same phase investigated in the previous section. Similarly to the results shown there (see figure 6(b)), the beam, which is generated by the expansion of the sheath adjacent to the quartz, traverses the plasma bulk and hits the opposing sheath.
during its expansion phase. The fraction of the beam electrons with highest energy might be able to overcome the local sheath potential at this time and might be lost at the RF electrode. The other fraction of the electron beam is reflected and might even gain further energy via the mechanism of BRH [21, 22]. Meanwhile, another energetic electron beam is generated by the expanding sheath at the RF electrode. This beam propagates through the bulk and is reflected at the fully expanded top sheath. Based on these nonlocal kinetic electron heating dynamics, the confinement quality of energetic beam electrons is good at $\Delta \varphi = 60^\circ$.

For $\Delta \varphi = 110^\circ$ (figure 7(c)) the electron beam generated at the upper sheath reaches the bottom sheath when it is fully collapsed. Therefore, these highly energetic electrons are mostly lost at the RF electrode, i.e. their confinement quality is low. The electron beam generated by the expansion of the RF electrode sheath hits the upper sheath shortly after the time of maximum sheath extension, so that these electrons are well confined in the plasma bulk, but are slightly decelerated due to the beginning contraction of the local sheath.

At a phase shift of $\Delta \varphi = 220^\circ$ (figure 7(d)) the electron beam generated by the expansion of the RF electrode sheath hits the upper sheath at the time of its full collapse and is lost at the quartz, whereas the electron beam generated by the expansion of the sheath adjacent to the quartz is well confined, but decelerated by its interaction with the collapsing RF electrode sheath. Similarly to the situation at $\Delta \varphi = 110^\circ$ the overall confinement quality of the energetic beam electrons is low at $\Delta \varphi = 220^\circ$.

Figure 7. Spatio-temporal plots of the $H_\alpha$ excitation within one RF period for different phase shifts between RF bias power and ICP power: (a) $\Delta \varphi = -50^\circ$ (310°), (b) $\Delta \varphi = 60^\circ$, (c) $\Delta \varphi = 110^\circ$ and (d) $\Delta \varphi = 220^\circ$. The voltages at the coil and at the RF electrode are also shown. The discharge is operated in hydrogen at 3 Pa, $P_{\text{ICP}} = 100$ W and $P_{\text{CCP}} = 40$ W.
As pointed out earlier, the excitation from the energetic electrons in the beam launched from the sheath near the quartz overlaps with the excitation due to the first maximum in the ICP heating. Therefore, it is not possible to distinguish in figure 7 whether this maximum is present or not. But the presence of the second maximum is easily recognizable, since it is not obscured by any beam excitation. It is seen that even at the low power of $P_{\text{ICP}} = 100$ W this second maximum (marked by a dashed curve around 45 ns in figures 7(a) and (b))—which is a clear indication for the onset of the H-mode—is identifiable when the beam confinement is good ($\Delta \varphi = -50^\circ$ (310') and 60') and is absent when the beam confinement is bad ($\Delta \varphi = 110^\circ$ and 220'). This is clear evidence for the correlation between the E- to H-mode transition and the beam–sheath interaction. The explanation for this is that a good confinement of the beam electrons is related to lower electron losses and higher ionization and, therefore, higher plasma density. This in turn enhances the inductive power deposition mechanism.

One can now understand why, without phase synchronization, the coupling effect is not as pronounced as in the phase-locked case (figure 5). As explained earlier, when the frequencies of the two RF power sources are not phase-locked, they slowly drift relative to one other. Then each RF period corresponds to a different phase shift covering the whole range of 360°. Therefore, on average the discharge performs between the cases with bad and good quality of beam confinement. In this case the effect of interaction between the different power deposition mechanisms should obviously be less pronounced compared to the case with a fixed phase close to the optimum.

The variation of the confinement quality of highly energetic beam electrons at different relative phases between the ICP power and the RF bias power causes a phase dependence of the time- and space-integrated plasma emission. In figure 8 this plasma emission (Balmer-$\alpha$ line) is plotted as a function of the phase for several pressures between 3 Pa and 40 Pa. All curves are normalized by their maximum values. It has been verified by PROES measurements that the discharge is operated in the E-mode under all conditions investigated here. At 3 Pa the emission exhibits a minimum around $\Delta \varphi = 180^\circ$ and a maximum around 0° and 360°, respectively. A comparison of this behaviour with the corresponding PROES measurements shown in figure 7 demonstrates that this is a direct effect of the phase-dependent confinement quality of the energetic beam electrons: the emission decreases by about 35% for the cases of poor confinement quality. The phase dependence of the $H_\alpha$ emission is reduced at higher pressures. This is due to the fact that the electron mean free path, $\lambda_{\text{mf}-e}$, becomes smaller. Thus, fewer electrons reach the opposing sheath and the role of the kinetic nonlocal effect of beam electron confinement is reduced. We estimate mean free paths of $\lambda_{\text{mf}-e}$ $\approx$ 9.2 cm, 1.8 cm and 6.9 mm at hydrogen pressures of 3 Pa, 15 Pa and 40 Pa, respectively, for electrons with 20 eV energy [82]. Therefore, the majority of these electrons dissipate their energy in collisions while moving through the plasma bulk with a typical length of about 3 cm or less at pressures above about 10 Pa.

Since above 10 Pa the electron beams hardly interact with the opposing sheaths, the RF bias on the RF electrode should no longer influence the mode transition. Indeed, this is seen in figure 9, which shows the electron impact excitation as a function of the ICP power at 15 Pa and at 40 Pa. The excitation is obtained from PROES images in the region of interest defined in section 2 (the rectangle in figure 4(a)). By comparing these two cases with each other and with the results in figure 5, it becomes clear that the effect of the RF bias power on the mode transition dynamics is reduced for increasing pressures. As explained, this is caused by the fact that at high pressure fewer energetic electrons from the beams generated by sheath expansion heating at the RF electrode and at the quartz reach the inductive skin layer, i.e. the region of high inductively induced electric fields. Thus, fewer energetic electrons are seeded into this region due to the presence of a capacitive RF substrate bias and, therefore, the effect of $P_{\text{CCP}}$ on the E- to H-mode transition is attenuated at higher pressures. At 40 Pa, the variation of the excitation with $P_{\text{ICP}}$ on the E- to H-mode transition is attenuated at higher pressures. At 40 Pa, the variation of the excitation with $P_{\text{CCP}}$ becomes virtually insensitive to the value of $P_{\text{ICP}}$. Increasing the RF bias power only slightly offsets the mode transition power but this can be understood in terms of an additional power source: having a secondary source of energy for the electrons reduces the power needed from the primary source for a mode transition.

Finally, the coupling between the ICP and CCP power sources is most pronounced at lower pressures where the addition of an RF bias significantly changes the behaviour of the ICP. This has been shown to be an effect of the interaction of the beams launched by the high-voltage sheaths with the opposing sheaths. Depending on the confinement of the beams, which can be controlled by the phase difference between the power sources, the strength of the coupling can be varied. At higher pressures where the beams cannot interact with the opposing sheath (due to the reduced mean free path) the effect disappears.

The low-pressure conditions are most relevant for applications of these plasma sources, e.g. dielectric etching [1, 2]. Therefore, the results at low pressures, where the effect of the power source coupling is the strongest, are most important.
3.3. Effect of structured electrodes on the E- to H-mode transition

The electron heating dynamics and, therefore, the electron density are known to be enhanced in capacitively coupled RF plasmas in the presence of structured electrodes [43–48]. Here, we apply the same concept to a hybrid ICP/CCP discharge. The gap between the top surface of the RF electrode and the quartz surface at the ICP coil is reduced to 3 cm, so that a pressure of 15 Pa is chosen to ensure the development of a plasma bulk in the gap between the two sheaths.

Figure 10 shows the excitation within the region of interest defined in section 2 (the rectangle in figure 4(a)) obtained from PROES measurements for different CCP powers, $P_{\text{CCP}}$, as a function of the ICP power at (a) 15 Pa and (b) 40 Pa. The phase is $\Delta \phi = 60^\circ$.

4. Conclusions

A hybrid ICP/CCP discharge with a planar ICP coil driven at 13.56 MHz and an RF substrate biased at the same frequency has been investigated experimentally. The discharge was operated in a modified GEC reference cell in hydrogen at low pressures. The RF substrate bias was operated both in the usual way without phase synchronization with the ICP power source and in a phase-locked mode. The latter allowed the dynamics of energetic electrons within the RF period to be studied by phase-resolved optical emission spectroscopy (PROES). These PROES measurements were complemented with Langmuir probe measurements of the plasma density. A novel method for the investigation of the mode transition has been proposed. It is based on the excitation rate in a certain spatial and temporal region of the spatio-temporal excitation dynamics obtained by the PROES method. The results from the proposed noninvasive method were compared with the ones from the invasive Langmuir probe and good agreement has been found.

Strong coupling mechanisms between the inductive and capacitive power sources were observed using both diagnostics. They have a significant influence on the electron heating dynamics and affect the plasma density as well as the E- to H-mode transition. The coupling mechanisms can be controlled by tuning the phase shift between the power sources and by using structured electrodes as a substrate.

In the pure ICP mode of operation (substrate bias power $P_{\text{CCP}} = 0$ W) the usual E- to H-mode transition was observed when increasing the ICP power, $P_{\text{ICP}}$. The
mode transition is observed as a jump in the electron density accompanied by an equivalent jump in the excitation of the Balmer-\( \alpha \) line. The addition of an RF substrate bias changes the behaviour of the mode transition: the ICP power at which the transition occurs is significantly reduced and the transition loses its step-like character, becoming smoother. The effect is more pronounced at lower pressures, at higher values of \( P_{\text{CCP}} \) and at certain phases in the phase-locked mode.

The explanation of these observations is the interaction of the high-voltage sheaths and the inductive heating with the beams of highly energetic electrons, which are launched by the expanding sheaths adjacent to the RF electrode and the ICP coil. Depending on the distance between the sheaths and the beam velocity, certain phase differences between the ICP and CCP power sources ensure a better quality of confinement of these beams than others. This leads to an enhancement of the excitation and ionization processes and, correspondingly, to an increase in the plasma density which ultimately leads to an E- to H-mode transition at a significantly reduced power level. Naturally, the influence of \( P_{\text{CCP}} \) is larger when the ICP runs in the E-mode and the electron density and the excitation are more significantly increased than in the H-mode. This explains the observed smoothing in the mode transition curves.

The asynchronous operation of the two power sources shows a phase average of this effect, which is, naturally, less pronounced than for a phase-locked operation at a phase difference close to the optimum. When the pressure is increased, the mean free path of the beam electrons is reduced. This eliminates the interaction between the beams and the opposing sheaths and the effect of coupling between the CCP and the ICP diminishes. Using structured electrodes with trenches as an RF electrode leads to enhancement of the electron beams. With the trenches positioned underneath the toroidal region of ICP heating the strength of the coupling between the two power sources increases.

These results demonstrate that there are strong coupling mechanisms between the CCP and ICP power sources in such hybrid RF plasma sources at low pressures typically used in technological applications and that a detailed fundamental understanding of the electron heating dynamics is essential to enhance process control. In particular, in the nonlocal regime at low pressures the interaction of both RF sources via the electron dynamics plays a crucial role for the entire discharge operation and the plasma density. This will be most important for the control and optimization of surface processes, because the flux-energy distribution functions of ions and electrons at the substrate can be expected to be strongly affected. By synchronising the RF power supplies and adjusting the relative phase between the ICP coil power and the RF substrate bias power, these coupling mechanisms could be used to tailor the process conditions in applications such as dielectric etching.

References
