Mode transition in a small-radius planar-coil inductively-driven discharge

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The transition from E- to H- mode in a small-radius planar-coil inductively-driven discharge in hydrogen is studied. The results show that the time variation of the spectral line intensity in the transition between the two modes correlates with the time variation of a sum of two functions which simulate the rf power deposition in the E- and H- mode of the discharge maintenance. Preliminary results for the electric field intensity display differences in the behaviour of small- and large- radius discharges.

As it is well-known, the inductively coupled plasmas can operate in two modes [1]: At low power and comparatively low plasma densities the plasma is sustained in a capacitive (E-) mode whereas at high plasma density the discharge operation is in an inductive (H-) mode. The transition between the two modes has been studied in chambers with relatively large radii (R > 10 cm), appropriate for the industrial applications of the discharge [1-4]. Recently [5] it has been shown that the small-radius (R = 2-3 cm) inductive discharges could be of interest as sources of volume-produced negative hydrogen ions. Here specific features of the transition from E- to H- mode in small-radius planar-coil inductive discharges are studied.

In the experiments, the time variation of the intensity $I(t)$ of the H_α spectral line is measured. In general, $I(t)$ of a given spectral line is determined by the time variation of the rf electric field intensity and it depends also on the heating mode (in this case, a capacitive mode or an inductive one). The normalized intensity $\eta = [I(t)/<I(t)>]-1$ is used in the presentation of the results; $<I(t)>$ is the line intensity, averaged over the rf cycle. According to the theory of the phase resolved optical emission spectroscopy [2, 6], developed for inductive driving of the discharge, the second harmonic of η is proportional to the squared velocity of the electrons and, therefore, to the squared rf electric field intensity.

The measurements have been carried out in a small-radius discharge with a planar coil (discharge radius of 2.25 cm). Hydrogen discharges at 13.56 MHz and 27 MHz are studied. The intensity of the H_α line is measured by a Princeton Instruments PI-MAX ICCD camera, using a proper optical filter. In the experiments, the applied rf power and the gas pressure have been varied, respectively, in the ranges (100 – 350) W and (6 – 270) mTorr, i.e. (0.8 – 36) Pa.

In the capacitive mode the electron heating is mainly during the expansion of the sheath, which covers a half of the period of the rf field and, thus, the shape of $I(t)$ could be roughly approximated with a half sinusoid ($f_1 = A_1 \sin \omega t$ for $\sin \omega t > 0$ and $f_1 = 0$ for $\sin \omega t < 0$). Similar shape of $I(t)$ in the E-mode is obtained in Refs. [3, 4]. In the inductive mode the electron heating is proportional to a squared sinusoid $f_2 = A_2 \sin^2(\omega t + \varphi_0)$ and, thus, $I(t)$ is a sinusoid at the doubled frequency. In the transition between the two modes the result should be a sum of these two functions: $f = f_1 + f_2$.

Figure 1 shows the obtained – with changing the gas pressure – time variation of η at a given point of the discharge cross section. At 20 mTorr the mode is a pure capacitive one. With the pressure increase the role of the inductive coupling increases and this leads to changes in the shape of the signal (the result at 55 mTorr). The best approach to an inductive coupling is obtained at 180 mTorr, but even in this case the mode is not a pure inductive one. The changes in the phase difference φ_0 between the functions f_1 and f_2 can be related to the increase the elastic electron-neutral collision frequency with the gas pressure increase. With the further increase of the pressure the effectiveness of the inductive coupling decreases and the shape of the signal at 270 mTorr resembles that at 55 mTorr, with another value of φ_0 because of the higher pressure.

It is well-known from the literature that in big-chamber discharges, higher applied power ensures discharge maintenance in an inductive mode. But in the case of a small radius tube studied here the shape of the signal does not change significantly. This has been checked by increasing the applied rf power up to 350 W, at gas pressure of 180 mTorr.

The measured spatial distribution of the second harmonic of η, i.e. of the squared rf electric field intensity (Fig. 2) shows up with a maximum at the discharge axis, whereas in large-radius discharges the field intensity has a minimum at the axis. This difference could be attributed to the existence of a radial current, in addition to the azimuthal one, due to the spiral shape of the coil, which is more pronounced when the coil is small.

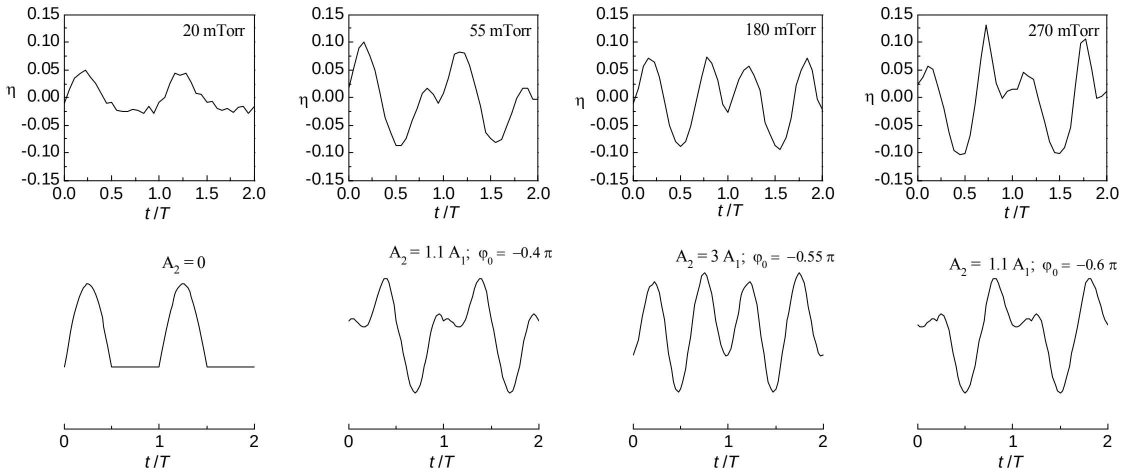

Fig. 1. First row: Time variation of the measured normalized intensity η at a given point during two rf cycles of the signal sustaining the discharge. Second row: The sum of the functions f_1 and f_2. The values of the parameters (amplitude and initial phase) chosen give the best fit to the results from the measurements. Applied power 100 W at 27 MHz.

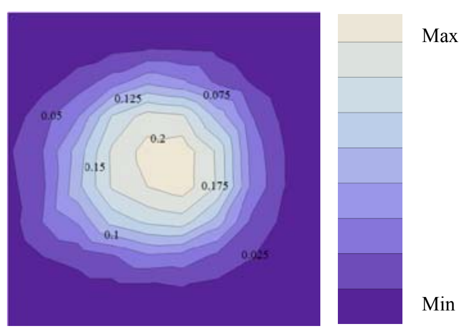

Fig. 2. Spatial distribution over the discharge cross section of the second harmonic of η and, respectively, of the squared rf electric field intensity (arbitrary units) at 100 W and 180 mTorr.

In conclusion, the results show that in the transition regime from E- to H- mode the time variation of the light emission could be presented as a sum of the time variations of the rf power deposition specifying the inductive and capacitive modes. Compared to inductively-driven discharges in large radius vessels, reaching a pure H-mode in small-radius discharges appears to be more difficult.

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References

[1] M. A. Lieberman, A. J. Lichtenberg (2005) Principles of Plasma Discharges and Materials Processing 2nd edn (Hoboken, NJ: Wiley Interscience).
[2] V. Kadetov, PhD Thesis, Ruhr University Bochum (2004).
[3] D. O'Connell, K. Niemi, M. Zaka-ul-Islam, T. Gans, *J. Phys.: Conf. Series* **162** (2009) 012011.
[4] M. Abdel-Rahman, V. Schulz-von der Gathen, T. Gans, *J. Phys. D: Appl. Phys.* **40** (2007) 1678-1683.
[5] Ts. Paunska, A. Shivarova, Kh. Tarnev, *J. Appl. Phys.* **107** (2010) 083301 (1-8).
[6] D. L. Crintea, D. Luggenhölscher, V. A. Kadetov, Ch. Isenberg, U. Czarnetzki, *J. Phys. D: Appl. Phys.* **41** (2008) 082003 (1-6).