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Helicon mode formation and rf power deposition in a helicon-produced plasma

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Abstract. Time- and space-resolved B-dot probe measurements in combination with measurements of the plasma parameters were carried out to investigate the relationship between the formation and propagation of helicon modes and the rf power deposition in the core of a helicon plasma. The Poynting flux and the rf power deposition is deduced from the measured rf magnetic field distribution (amplitude and phase of all components). Special attention is devoted to the helicon absorption under linear and nonlinear conditions. The present investigations are attached to recent observations in which the nonlinear nature of the helicon wave absorption has been demonstrated by showing that the strong absorption of helicon waves is correlated with parametric excitation of electrostatic fluctuations.

1. Experimental

The investigations were carried out on the helicon source HE-L (geometry: r = 73 mm, l = 1.1 m; power input $P \leq 1.5$ kW at 13.56 MHz via $m = 1$ helical antenna coupling in pulses of 2–6 ms at 50 Hz; plasma parameters $n_e \leq 2\times10^{19}$ m^{-3}, $T_e \approx 3$ eV, p = 0.2–1.0 Pa argon gas, $B_0 \leq 0.1$ T) [1]. A *double pulse* technique (a high rf power pulse producing the helicon plasma is followed by a second pulse of variable rf power with 20 μs delay) is applied to study the helicon absorption under nearly identical conditions.

2. Results

2.1 Quasi-stationary helicon discharge

A characteristic feature of helicon discharges with helical antenna coupling is the predominant excitation of $m = +1$ helicon modes traveling in positive magnetic field direction and, thus, leading to a pronounced axial asymmetry of the rf power deposition with respect to the antenna. Guided helicon waves have a non-vanishing wavenumber $k_\perp$ perpendicular to the magnetic field $\mathbf{B}_0$ due to the transverse boundary conditions. In our experiment, the situation is somewhat different, as is seen in Fig.1, which shows a *quasi-snapshot* of the amplitude and the phase of the rf magnetic field components in the *r-z*-plane. From the large field amplitudes (Fig.1a) it is apparent that the rf energy density peaks on this axis. The helicon wave fronts travel obliquely to $\mathbf{B}_0$ from the antenna to the centre (Fig.1b). On the axis, they superimpose to form a standing wave structure travelling along $\mathbf{B}_0$. This structure becomes more complex with increasing distance from the antenna due to superposition of higher radial modes.

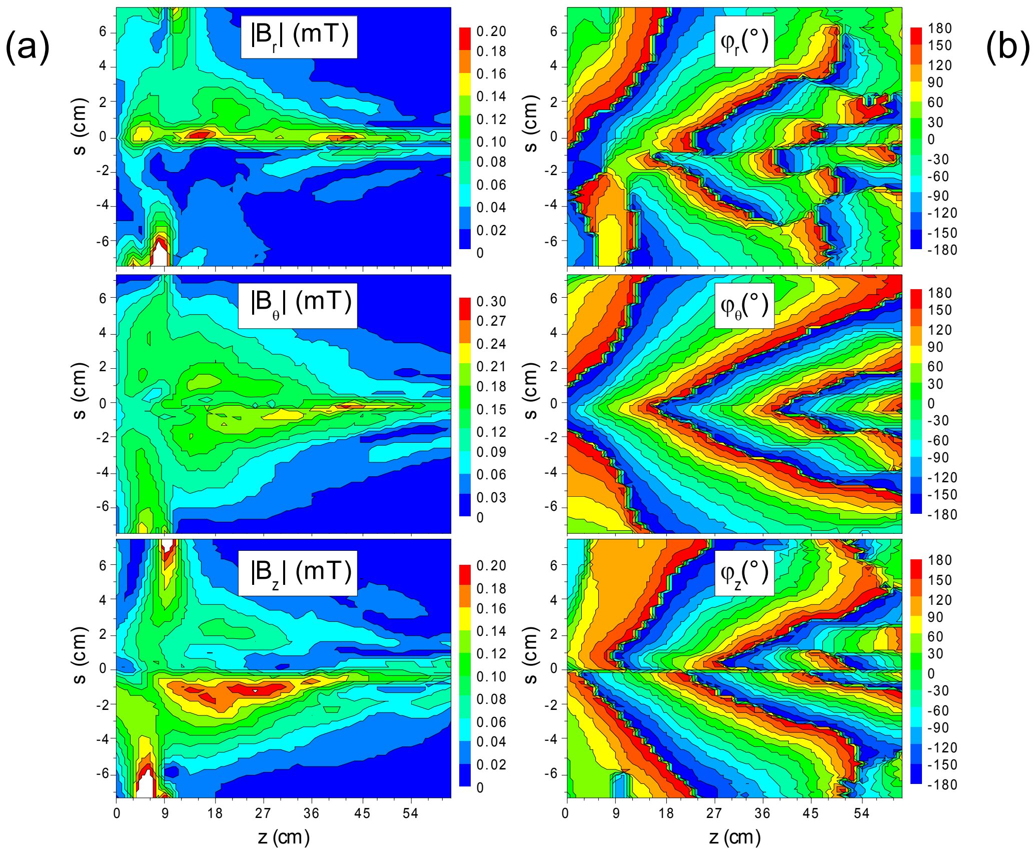

Fig.1: Amplitude (a) and phase (b) of the magnetic field components in the quasi-stationary helicon discharge of the main rf pulse; $B = 50$ mT, $p_{Ar} = 0.6$ Pa, $P = 1.5$ kW.

2.2 Radial distribution of the density and the helicon field

In Fig. 2 we plotted the radial profiles of the electron density and the helicon wave field for high and low launched rf power. The density profiles (top) are nearly identical except that there is a small sharp peak located slightly off-axis for high power. The helicon field profiles (middle) have each a broad-structured pedestal with a peak at or close to the centre. From these profiles we obtain the rf magnetic energy ($|\mathbf{B}|^2$) profiles (bottom) which are much narrower for high rf power than for low power. Estimating the radial wavenumber from the width of the profile near the axis we achieve reasonable agreement with the dispersion relation for uniform plasma in case of low rf power. However, for high rf power, k_z remains nearly unchanged although the narrow $|\mathbf{B}|^2$ profiles indicates a larger $k_\perp$ and, thus, a smaller k_z.

To clarify this finding we calculated the helicon wave fields with the aid of a helicon waveguide code. We assumed a Lorentzian density profile (plus offset) with and without superposition of a narrow Gaussian of small magnitude. The computations shown in Fig.3 reveal that the small central density peak leads to peaked profiles of the perpendicular field components. As a result, the rf energy and the absorbed power density profiles become narrow as well whereas they are much wider in the 'smooth' case of a single Lorentzian. However, in accordance with the observations, the axial wavenumber remains nearly the same, which is in contrast to the helicon theory for uniform plasma where $k_z \propto k_\perp^{-1}$ scales with the width of the $|B(r)|^2$ profile. This can be attributed to the gradient terms in the helicon wave equation.

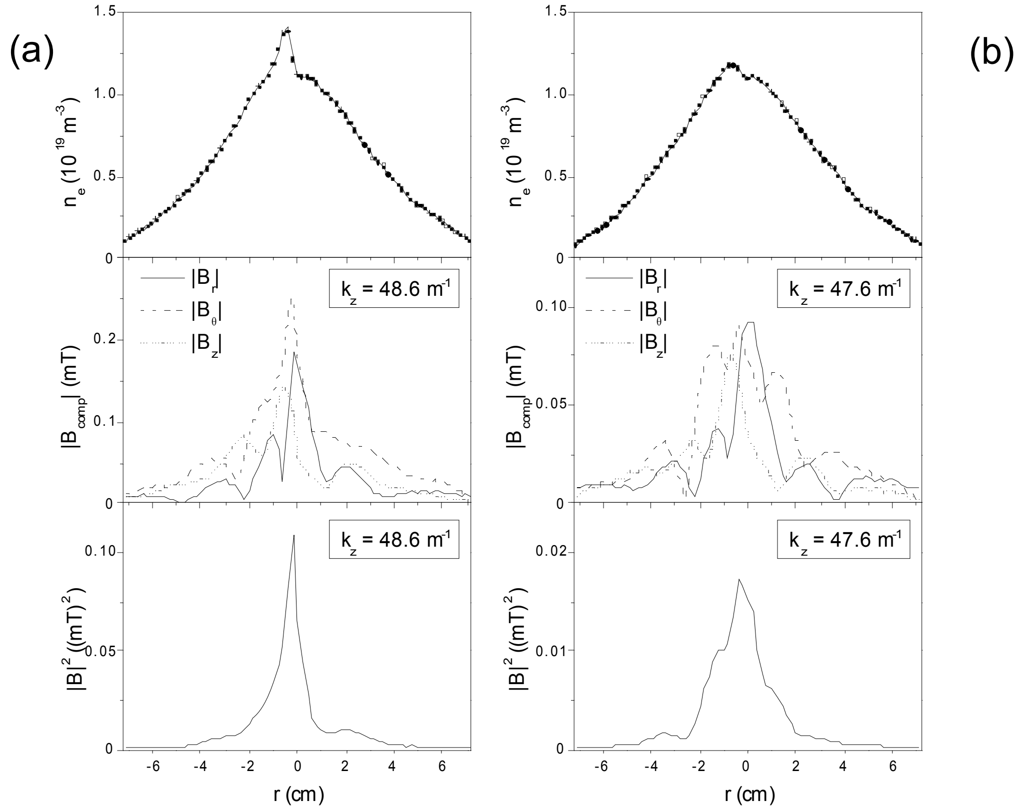

Fig.2: Radial profiles of the electron density, the magnetic field amplitudes and the rf energy density for high (a) and low (b) rf powers, P = 1.5 kW and *100* W.- *Measuring position: 40.5* cm *away from centre of antenna; B = 50* mT, p_{Ar} *= 0.6* Pa.

2.3 RF power deposition

From the energy flux balance we determined the rf power deposition The total absorbed power $P_{abs,h}$ = 313 W for high rf power and $P_{abs,l}$ = 40 W for low rf power are quite reasonable although these values are much smaller than the rf power launched to the plasma, i.e., 1500 W and 100 W, respectively. Obviously, the major portion is absorbed in the outer regions of the plasma, probably close to the antenna. However, the ratio $R_{abs} = P_{abs,h}/P_{abs,l} \approx 8$ nearly corresponds to the ratio of the measured maximal rf field energies of about 7.

As a second approach, we deduced the absorbed power from the rf field distribution for a collisional plasma. As is seen from Fig.2, the rf power deposition as well as the measured rf field energy density for high power are more concentrated on the axis as predicted by the model. The quantitative evaluation yields the absorbed powers $P_{ca,h}$ = 27 W for high rf power and $P_{ca,l}$ = 10 W for low power yielding $P_{ca,h}/P_{ca,l}$ = 2.7. In particular, $P_{ca,h}$ is by far too low compared to $P_{abs,h}$ = 313 W thus indicating a nonlinear (anomalous) absorption mechanism. The above results are consistent with previous investigations, where we observed that the helicon wave damping under nonlinear conditions (i.e., high power) is significantly stronger than collisional damping [2].

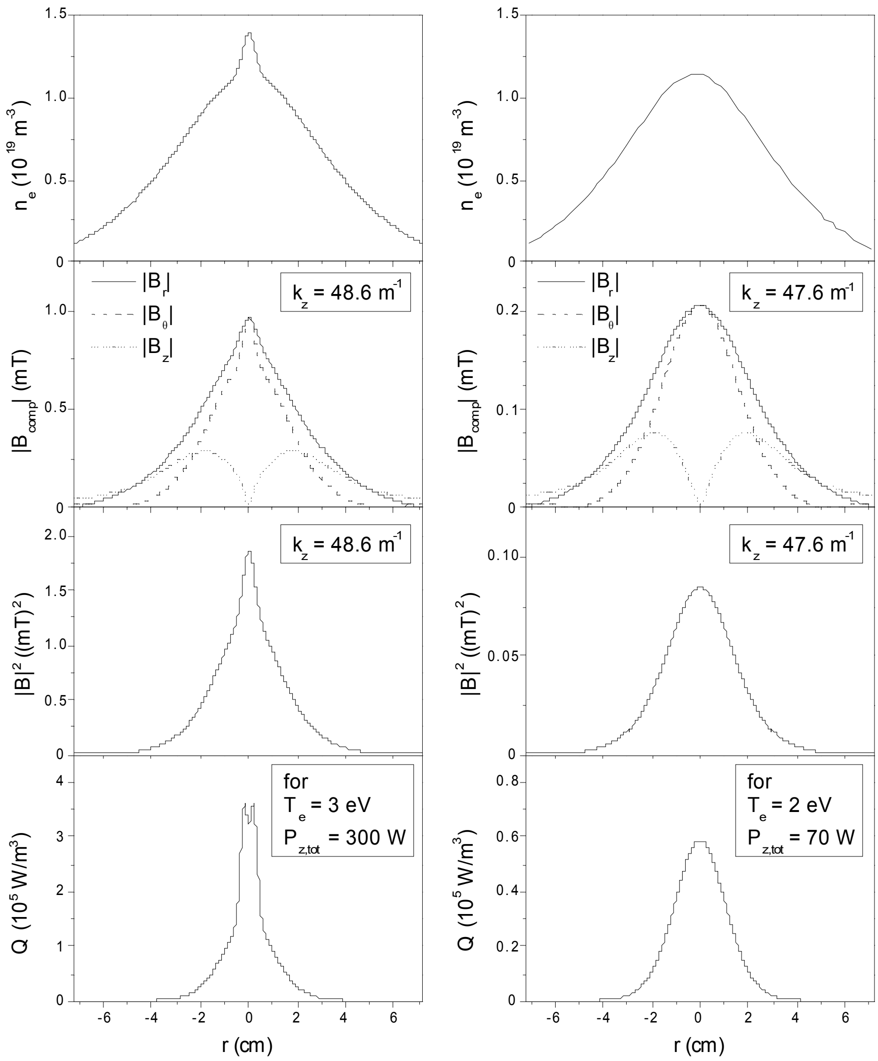

Fig.3: Computation of the radial field distribution and the absorbed power density for different model (adapted to the measured) density profiles.

3. Conclusions

From the above findings we conclude that collisional absorption is by far not sufficient to account for the absorption of helicon modes, particularly for high rf power. Most likely, nonlinear processes, possibly associated with parametric excitation of electrostatic fluctuations, are involved. In addition, effects connected with the steep gradient in the centre (e.g. mode conversion) may play a role.

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[1] M. Krämer, B. Lorenz, B. Clarenbach, Plasma Sources Sci. Technol. **11A** (2002) 120.
[2] B. Lorenz, M. Krämer, V. Selenin, Yu. Aliev, Plasma Sources Sci. Technol.**14** (2005) 623