Study of the asymmetry of helicon discharges with m = 1 and m = 2 helical antenna coupling

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1. Introduction

Helicon discharges exhibit a pronounced axial asymmetry with respect to the centre of the antenna if the rf power is launched to the plasma column via helical antennas [1,2]. This asymmetry can be attributed to the different propagation behaviours of the helicon modes. Recent theoretical-numerical studies have shown that the helicon modes with negative azimuthal mode numbers *m* can strongly be damped or even be evanescent if the radial density gradient is steep enough [3]. The rf power is then predominantly transferred to the $m > 0$ helicon modes. In this case, only the modes with positive mode numbers propagate and, thus, produce and sustain the plasma. The aim of the present paper is to study the axial asymmetry of helicon discharges with helical antenna coupling in more detail.

2. Experiment

The investigations have been carried out on a pulsed large-volume helicon wave discharge in argon. The plasma is produced by *rf* power pulses ($P_{RF} < 4$ kW, $f_{RF} = 13.56$ MHz, $\tau_{pulse} = 2$ –3 ms, $f_{pulse} = 25$ Hz, typically) alternatively through m = 1 and m = 2 helical antennas surrounding the quartz tube (Fig. 1). The m = 1 antenna is a Shoji type antenna consisting of two helical current paths with opposite directions of the rf current (180° turn over the antenna length $L_a = 22$ cm) while the m = 2 antenna has 4 helical current paths with alternating rf current directions. The experimental parameters are $n_e < 2\text{x}10^{19}$ m^{-3} , $T_e = 3 – 4$ eV, $B_0 < 0.1$ T, $r_p = 7.4$ cm and $L_p = 200$ cm. Due to the radial rf power deposition profile peaking on the axis, the m = 1 discharge can be sustained in a wider pressure range, namely $p = 0.1$ - 3 Pa argon gas, while stable conditions for the m=2 discharge were achieved between $p = 2$ and 4 Pa.

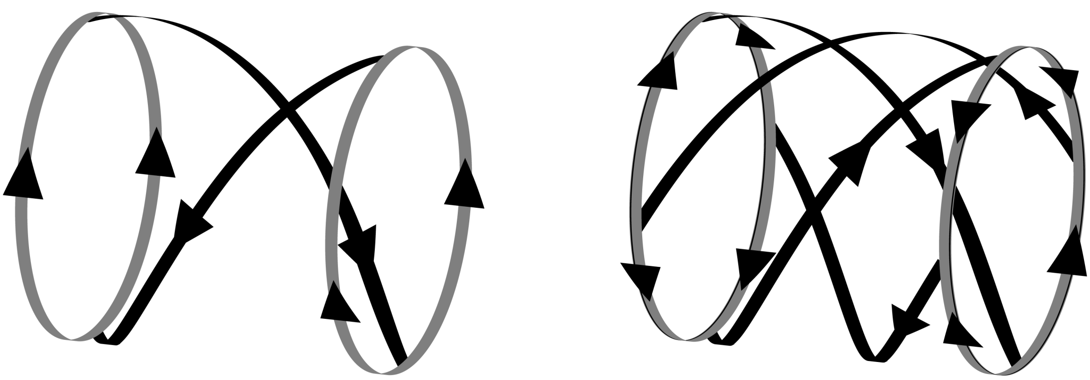

Fig. 1 : Helical m = 1 (left) and m = 2 (right) antennas

3. Helicon wave guide model

The helicon wave propagation in a radially non-uniform plasma is governed by the wave equation (EMHD approximation)

$$\frac{\partial^2}{\partial r^2} B_z + f(r) \frac{\partial}{\partial r} B_z + g(r) B_z = 0 \tag{1}$$

where $f(r) = \frac{1}{r} - \frac{2\alpha^2 \beta}{\alpha^2 - k_z^2}$, $g(r) = \alpha^2 - k_z^2 - \frac{m^2}{r^2} - \frac{m\alpha\beta\left(\alpha^2 + k_z^2\right)}{k_z r\left(\alpha^2 - k_z^2\right)}$, $\alpha = \frac{\omega}{\omega_{ce}} \frac{\omega_{pe}^2}{c^2 k_z}$, $\beta \equiv L_n^{-1} = \frac{n_e'}{n_e}$,

and the prime denotes the derivative with respect to r.

Assuming that the plasma is surrounded by a perfectly conducting tube (radius $r_w = r_p$), the radial component of the rf magnetic field vanishes due to $\nabla \cdot \mathbf{B} = 0$. This equation along with the wave equation can be solved simultaneously by standard routines [3].

In a non-uniform plasma the propagation behaviours of the helicon modes with positive and negative azimuthal mode numbers m may differ considerably. Formally, this is due to the fact that g(r) may be negative for $m < 0$ if the radial density gradient is steep enough. The $m < 0$ modes can then be strongly damped or even be evanescent. The plasma is then predominantly generated by the helicon modes with positive m so that the discharge becomes axially asymmetric. Assuming a Gaussian density profile of width w, one can deduce as an estimate for evanescent $m < 0$ modes the condition

$$q = \frac{\omega_{ce}}{\omega} \frac{c^2}{\omega_{pe}^2} \frac{2|m|}{w^2} > p = O(1) \tag{2}$$

where the parameter p depends on the ratio of the perpendicular and parallel wave number components. Fig. 2 shows the dispersion curves of the m = +1 and m = -1 modes for typical discharge parameters (n_e $(r=0) = 4.2\times10^{18}$ m^{-3}, $B_0 = 33$ mT). The cutoff of the m = -1 modes can be seen from the merging of the real and imaginary parts of the axial refractive index.

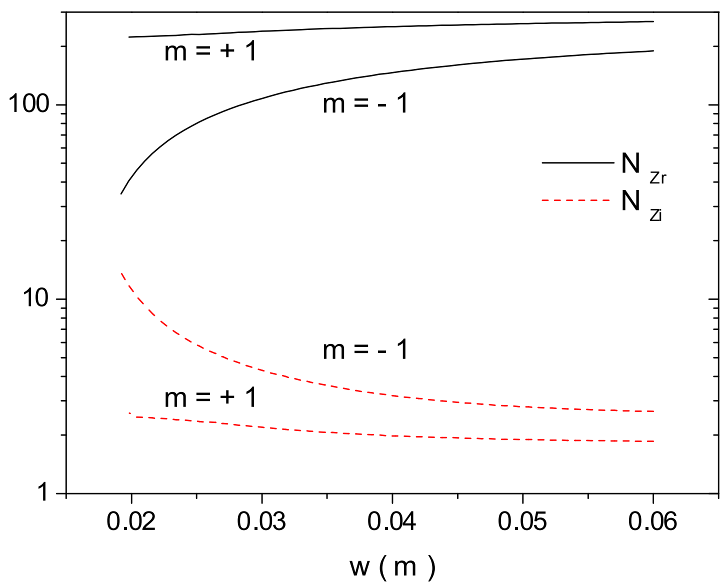

Fig.2 Dispersion relations of m=+1 and m=-1 helicon modes

4. Experimental Results

A characteristic feature of the helicon discharge is the pronounced asymmetry with respect to the centre of the antenna caused by the fact that the helical antenna excites mainly helicon modes with positive azimuthal mode numbers travelling in positive magnetic field direction. Fig. 3a shows a contour plot of the helicon wave field.

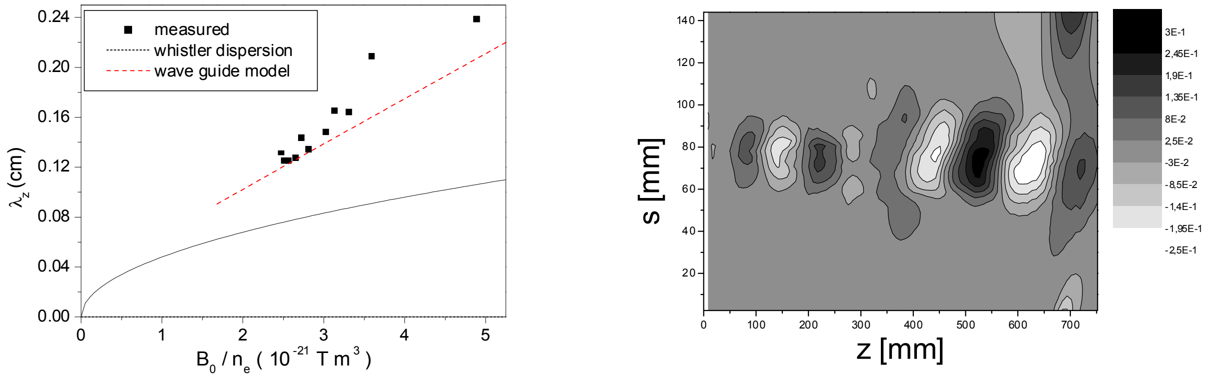

Fig. 3 : 2D-Plot of the rf magnetic field (B_θ) (left) and the axial wavelengths (right)

The 2D-pattern of the perpendicular rf magnetic field strength (essentially the azimuthal component) exhibits wave fronts moving with a small angle to the magnetic field direction into the plasma. The contour plots have been evaluated and compared with the whistler wave dispersion relation as well as with the computations from the helicon wave guide model [3]. The measured axial wavelengths are in reasonable agreement with the latter dispersion curves in a wide parameter range (Fig. 3b).

In Fig. 4 it can be seen that the m = -1 mode is also excited although with a much smaller amplitude. The time-resolved *rf* measurements reveal that the m = +1 wave field appears first while the m = -1 field originates with a significant time delay. For smaller magnetic field strengths and smaller (!) values of n_e/B_0 (n_e decreases more strongly than B_0) the m=-1 modes propagate no longer. This is consistent with the condition (2) for evanescence. The rf measurements in the afterglow of the helicon discharge performed with small *rf* power reveal the same behaviour. An explanation for the weaker excitation of the m = -1 modes may be the shorter axial wave length of the m = +1 modes (see Fig.2) providing a better matching to the antenna spectrum.

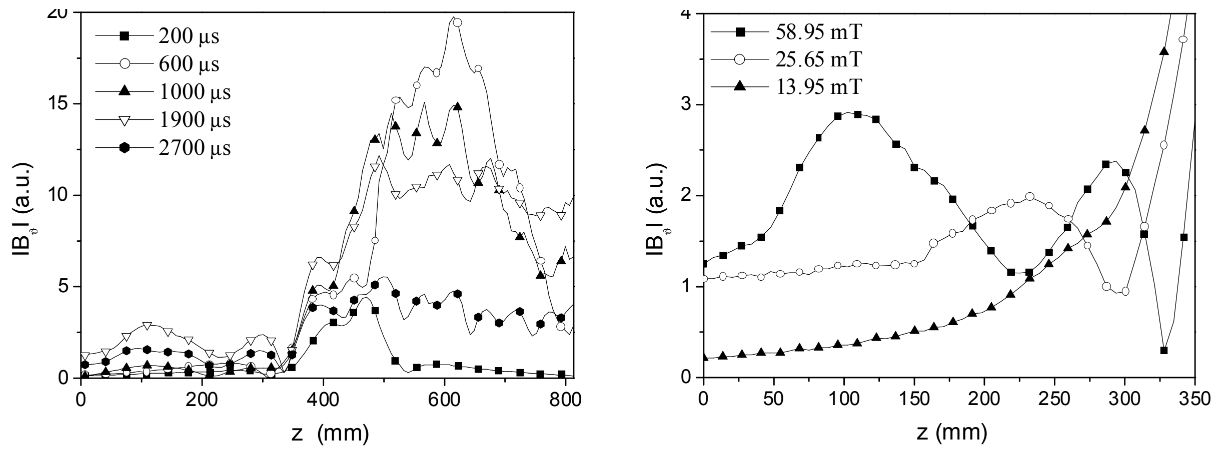

Fig.4 Axial profiles of the rf amplitude (B_ϑ)

It is obvious that nearly all the rf power is transferred to the m > 0 helicon modes which produce the plasma. In case of the m=+1 discharge the density profile is strongly peaked on the axis whereas the m=+2 discharge reveals a relatively broad radial profile [2]. The degree of asymmetry increases with growing magnetic field. This finding can be explained by the intimate relation between the rf power deposition and the density profile. Assuming that the total rf power is only transferred to damped helicon modes with positive mode numbers, one would expect that the absorbed power scales as $\exp(-2k_{zi}z)$ where k_{zi} is the axial damping decrement. If one further assumes that the density has the same dependence, the distance Δz of the centre of mass of the axial density distribution and the middle of the antenna is approximately $1/(2k_{zi})$. For thin plasma columns ($k_{perp}=\chi/r_p >> k_{zr}$) we obtain $1/(2k_{zi})= r_p\omega_{ce}/(2\chi\nu_{coll})$, $\chi = O(\pi)$. In Fig. 5, we plotted the dependence of Δz on the power decay length $1/(2k_{zi})$ for the m = 2 helicon discharge. In fact, there is a significant dependence of the asymmetry on this parameter. For the above assumptions one would expect $\Delta z = 1/(2k_{zi})$. The threshold at low magnetic fields is probably due to the fact that the formation of the helicon discharge needs a minimum magnetic field. The smaller slope of the curve at higher values of $1/(2k_{zi})$ can eventually be accounted for collisionless mechanisms (e.g., due to wave-particle interaction) which become predominant at lower pressures. Of course, this has to be confirmed in future investigations.

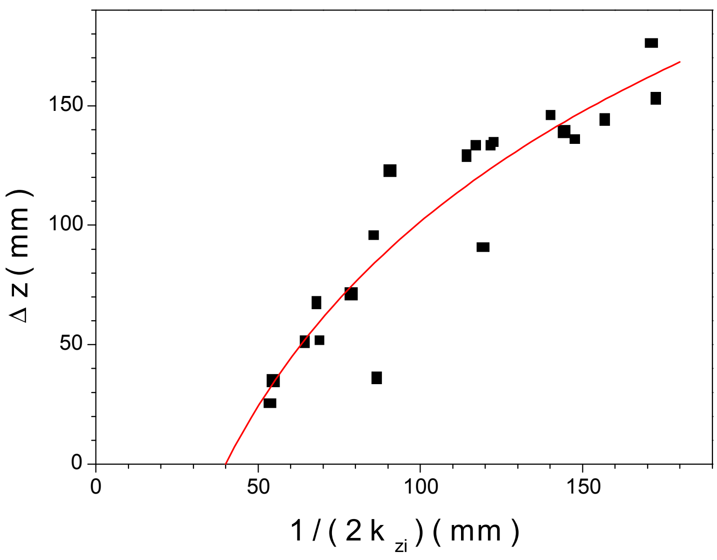

Fig.5 : Discharge asymmetry

5. Conclusions

It was found that the degree of axial asymmetry of the discharge dependings on the plasma parameters n_e and B_0. It can partly be explained by the helicon mode propagation in non-uniform plasmas. It is however obvious that the physics of the discharge asymmetry is much more complicated (see second contribution on this conference).

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