# POWER DEPOSITION AND WAVE FIELDS
# IN A HIGH DENSITY HELICON DISCHARGE

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**Abstract**

The rf power coupling to a helicon plasma is investigated both theoretically and experimentally under high density plasma conditions. The pronounced axial asymmetry of the discharge due to the helical coupling antenna is studied numerically. By varying the shape of the density profiles it is shown that the radial gradient plays a decisive role for the rf power deposition: At sufficiently strong density gradients, the absorbed power density reveals a maximum outside the antenna.

## 1. Introduction

Important features of the helicon discharge have not yet been fully understood. This holds in particular for the rf power deposition as well as for the role of the different modes excited by the coupling antenna. An experimental finding directly related to this topic is the axial asymmetry of helicon discharges which is observed if the rf power is launched to the plasma through helical antennae [1]. The present work contains measurements of the relevant quantities in a long helicon discharge with large aspect ratio ($L_p/r_p \gg 1$), in particular the loading resistance of the antenna and the rf power deposited in the plasma, as well as the comparison with the corresponding quantities computed by applying the antenna-plasma code [2].

## 2. Experiment

The experimental investigations have been carried out on a pulsed helicon wave discharge. The plasma is produced by RF power pulses ($P_{RF} \leq 1.5kW$, $f_{RF} = 25MHz$, $T_{pulse} = 2\,ms$, $f_{pulse} = 25Hz$, typically) through a helical antenna consisting of 4 windings (two pairs of helical current paths with opposite direction of current, 180 degrees over $L_a = 11\,cm$) exciting preferentially $m = \pm 1$ helicon modes [2]. The experimental parameters are $n_e \stackrel{<}{\approx} 10^{20}m^{-3}, T_e \approx 4\mathrm{eV}$, $B_0 \leq 0.2\mathrm{T}$, $p = 1\mathrm{Pa}$ argon, $r_p = 2.8\mathrm{cm}$ and $L_p = 100\mathrm{cm}$.

Standard methods as electric probe and diamagnetic loop diagnostics as well as $4\mathrm{mm}$-interferometry are carried out to determine the plasma parameters. The spatial distribution of the electromagnetic wave fields is measured by means of magnetic probes inside and outside the plasma. The complex impedance of the antenna-plasma system $Z$ as well as the total rf power launched to the plasma are measured by means of rf current and voltage probes in the transmission line near the antenna in combination with a network analyzer.

## 3. Results

The high-density helicon discharge is characterized by narrow Gaussian-like profiles (Fig. 1). At high rf powers launched to the plasma fully ionization on the axis is achieved. A characteristic feature of the discharge is the pronounced axial asymmetry with respect to the midplane of the antenna revealing electron density and temperature maxima outside the antenna (Fig. 2). When the direction of the stationary magnetic field is reversed, the density maximum is shifted to the opposite side of the antenna.

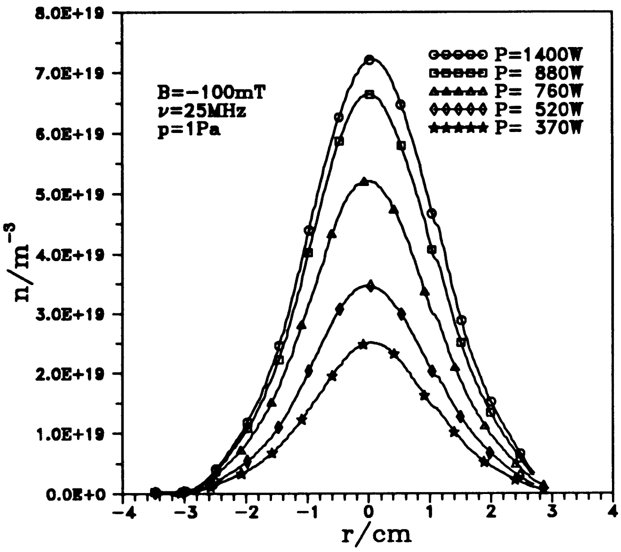


**Fig. 1.** Radial density profiles in the high-density helicon discharge

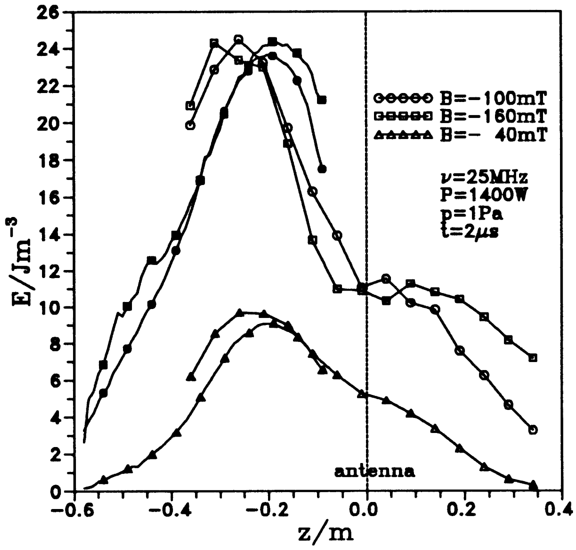


**Fig. 2.** Axial profiles of the thermal energy density integrated over the cross section from electric probe (open symbols) and dia magnetic coil (full symbols) measurements

The loading resistance $Z_r$, i.e. the real part of the rf impedance of the antenna-plasma system, is related to the total power deposited in the plasma through

$$P = \frac{1}{2} |\,\hat{I}|^2 \, Z_r$$

where $\hat{I}$ is the rf current amplitude. These quantities are measured as described above and calculated by applying a fully electromagnetic code that takes into account the realistic antenna geometry as well as the radial density profile [2]. The plasma column is assumed to be a uniform cylinder of finite length. In addition, the code allows the computation of the spatial distribution of the electromagnetic fields as well as the absorbed power density and the wave energy.

In Fig. 3, the measured loading resistance $Z_r$ is compared with that obtained numerically whereby the real density profiles (approximated by Gaussian profiles) have been used. As is seen, reasonable agreement is obtained between the measured and the computed values whereas the discrepancy is huge if different uniform profiles are taken (not shown here). Further computations show that the edge density affects sensitively the $Z_r$-values. Hence, it is most likely that a considerable portion of the power is coupled to the Trivelpiece-Gould mode that propagates near the plasma edge. This is also confirmed by Fig. 4 which shows the total measured rf power launched to the plasma: Estimates of the absorbed power needed for sustaining the helicon discharge yield considerably smaller values [3].

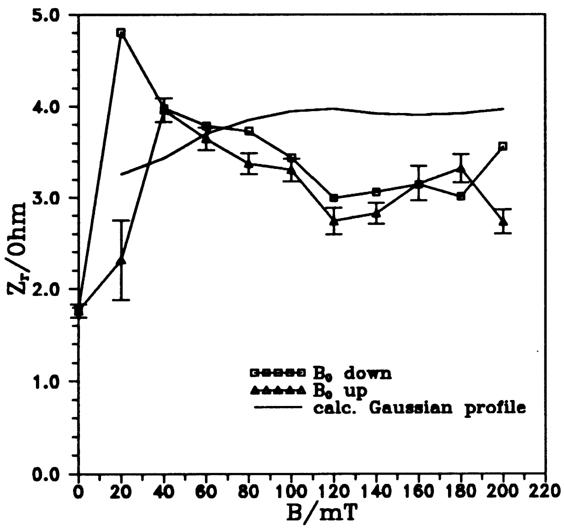


**Fig. 3.** Plasma loading resistance

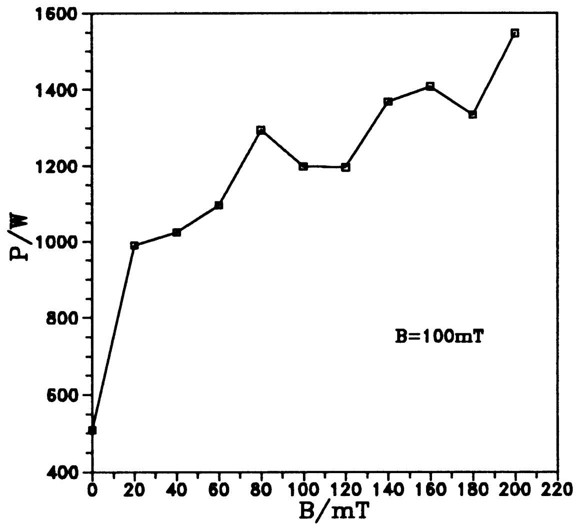


**Fig. 4.** Total absorbed rf power vs. magnetic field strength

The most interesting finding (also observed in other devices with helical antenna coupling) is the axial asymmetry of the discharge which can also be seen in the helicon wave fields (Fig. 5). Insight in this asymmetry give the computations of the field and power profiles using the antenna-plasma code. In Fig. 6, we have plotted axial profiles of the wave energy, respectively, for Gaussian density profiles of different width $r_0$ (cut at the antenna) thereby keeping the electron number over the cross section constant. It turns out that the axial profiles of the wave energy become asymmetric with narrowing of the density profile. In case of a homogeneous density (not shown here), the profiles of the field energy are nearly symmetric.

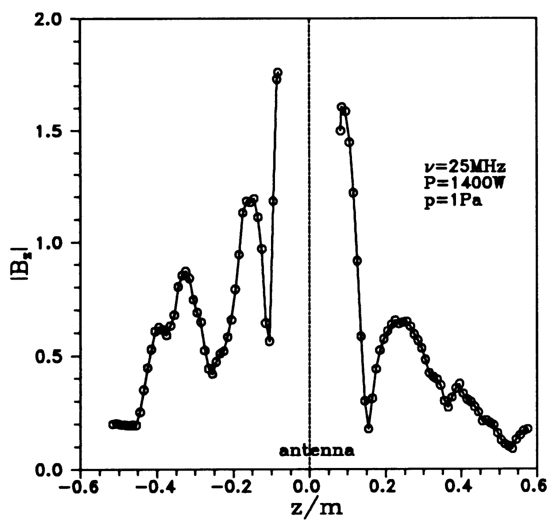


**Fig. 5.** Measured axial wave fields

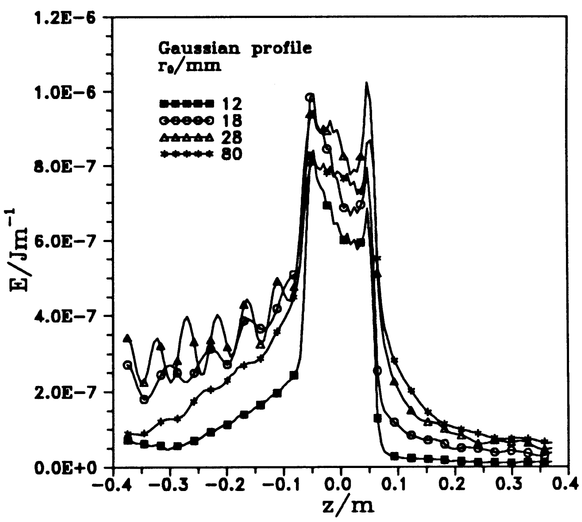


**Fig. 6.** Electromagnetic energy density (integrated over the plasma cross section)

The most important quantity is the rf power deposited in the plasma (Fig. 7). Because of the better coupling of the antenna to the plasma, it is largest when the density profiles are broad, i.e. nearly uniform. The rf power is then mainly absorbed under the antenna. A pronounced asymmetry of the absorbed power however arises if the density profiles become sufficiently narrow: The axial absorption profile exhibits a maximum outside the antenna, i.e. on that side where the $m = +1$ helicon mode propagates.

Finally, in Fig. 8, the axial absorbed power profiles are plotted for different magnetic field strengths. The field was here assumed to be proportional to the electron density roughly in accordance with the measurements. Again, the pronounced asymmetry can be seen in this diagram.

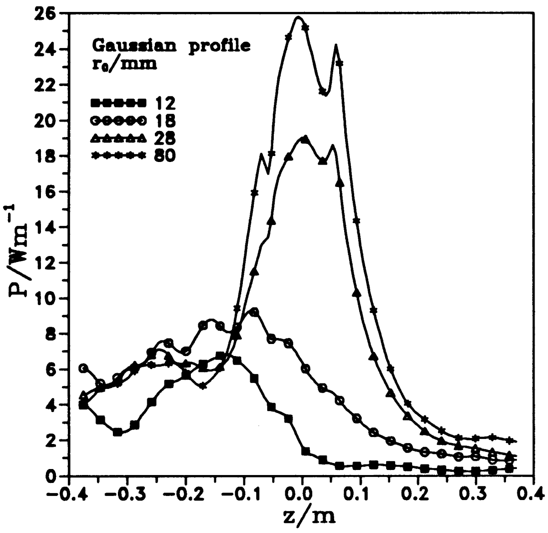


**Fig. 7.** Axial profiles of the absorbed power per length computed for density profiles of different width

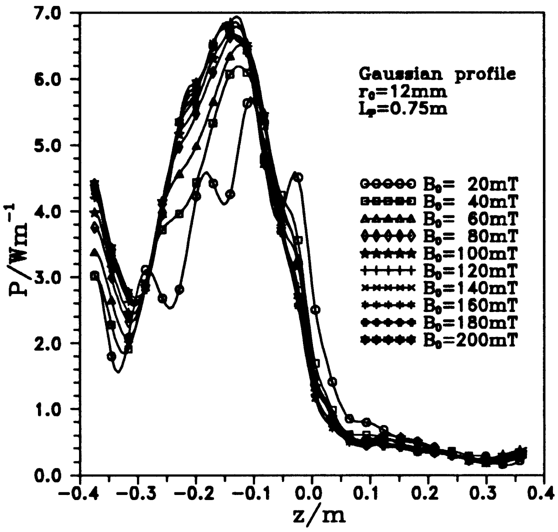


**Fig. 8.** Axial absorbed power density profiles

The numerical results are in accordance with the observation that the electron density and temperature profiles and thus the thermal energy density reveal asymmetric profiles (Fig. 2). The reason for the asymmetric power deposition is most likely the different propagation behaviour of the $m = +1$ and $m = -1$ helicon modes, in particular the strong damping of the $m = -1$ mode occurring at sufficiently steep density gradients [4].

In conclusion, we note that the rf power deposition, particularly the axial asymmetry of the helicon discharge produced by a helical antenna, can be understood already when the rf coupling to the plasma is described by a model based on the linear wave theory.

## References

[1] Chen F.F. et al.: Plasma Sources Sci. Technol. 5, 173 (1996)

[2] Fischer B., Krämer M. and Enk Th.: Plasma Phys. Control. Fusion **37**, 2003 (1995)

[3] Krämer M. and Enk Th.: *Proc. XXIII. EPS Conference on Plasma Physics and Controlled Fusion*, Kiev, Vol.III, 1391 (1996)

[4] Krämer M.: *this Conference*