*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-4.068 (2004)*

Characterisation of short-scale fluctuations in helicon plasma

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1. Introduction

Parametric instabilities were recently proposed as effective mechanism for the RF absorption in helicon discharges [1]. The RF energy is transferred to short-scale electrostatic fluctuations leading to strong damping of the helicon wave as well as the electron heating [2]. In the present paper, we study these fluctuations by probe and microwave scattering cross-correlation techniques which allow determining the dispersion relations as well as the type of the parametric instability.

2. Experimental

The measurements were performed on the helicon source HE-L (r_p = 73 mm, l_p = 1.1 m, τ_{pulse} = 2 – 4 ms, f_{pulse} = 25 – 100 Hz, P_{RF} < 2 kW, f_{RF} = 13.56 MHz, m = 1 helical antenna coupling, $n_e < 2 \times 10^{19}$ m^{-3}, $T_e \approx 3$ eV, $B_0 < 0.1$ T, p = 0.2 – 0.5 Pa argon [3]). A three-probe array (distance 1 – 2 mm) was used to measure the wave vector components perpendicular to the magnetic field as well as their spectral widths. Using an additional probe movable with respect to the probe array (distance up to 150 mm) we were able to estimate also the small parallel wave number component. A statistical procedure was applied to evaluate the probe data (ensemble of 4 x M time series; typically, M = 256) [4]. As additional method, we applied cross-correlation microwave scattering at the Upper-Hybrid resonance to measure the radial wave numbers [5].

3. Results

The frequency spectra shown in Fig.1 reveal that the fluctuations are excited in the low frequency (LF) range (up to a few MHz) as well as around the helicon wave frequency f_{RF} (Fig.1a). When increasing the RF power, the fluctuation level also increases and the spectra broaden above a certain threshold [1]. In Fig.1b we show the cross-phase ϕ of two probe signals from which the wave number (here, $k_\theta = \phi$ / probe distance) can be deduced. Note that ϕ reveals jumps of 2π. Thus, wave numbers far beyond the Nyquist limit π/d_{probes} can be measured because the dispersion relation is a continuous function. It turns out that the radial and azimuthal wave numbers are nearly equal, and the wave number spectral width $\Delta k_\perp$ is roughly half the wave number. The well-defined dispersion in the LF band can be attributed to ion-sound (IS) fluctuations ($\omega / k_\perp \approx V_S = \sqrt{T_e / m_i}$) travelling obliquely to the plasma edge (Fig.2a). The upper side-band of the RF (helicon) frequency reveals a similar wave number dependence as the LF band and may thus be accounted for coupling between the helicon wave and the ion sound fluctuations. The lower side-band reveals roughly the same dispersion relation, but with opposite sign (i.e., wave propagation towards the plasma axis).

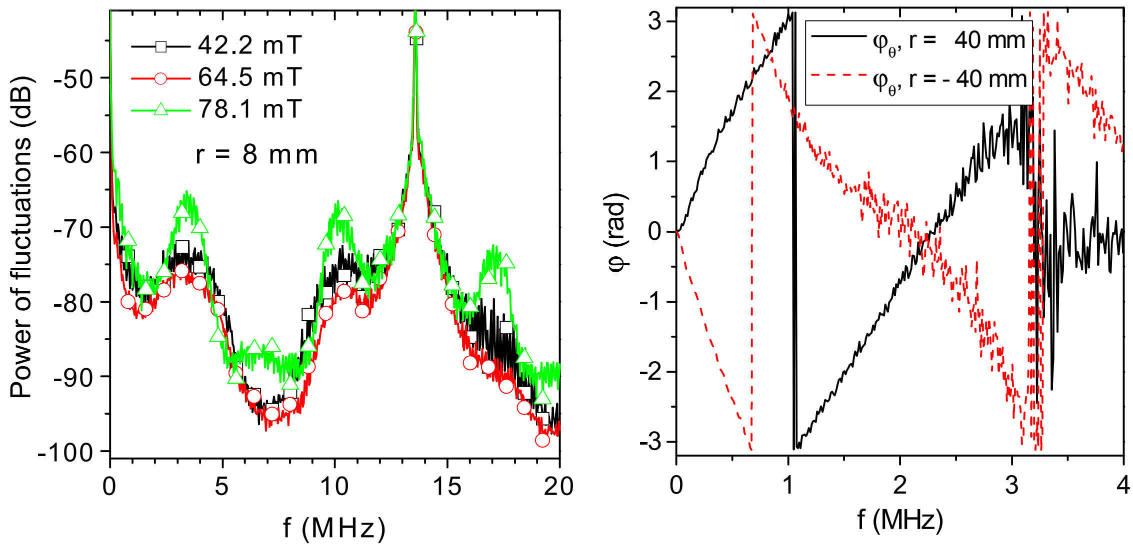

Fig.1a: Frequency spectra of fluctuations, b: Azimuthal cross-phase vs. frequency.

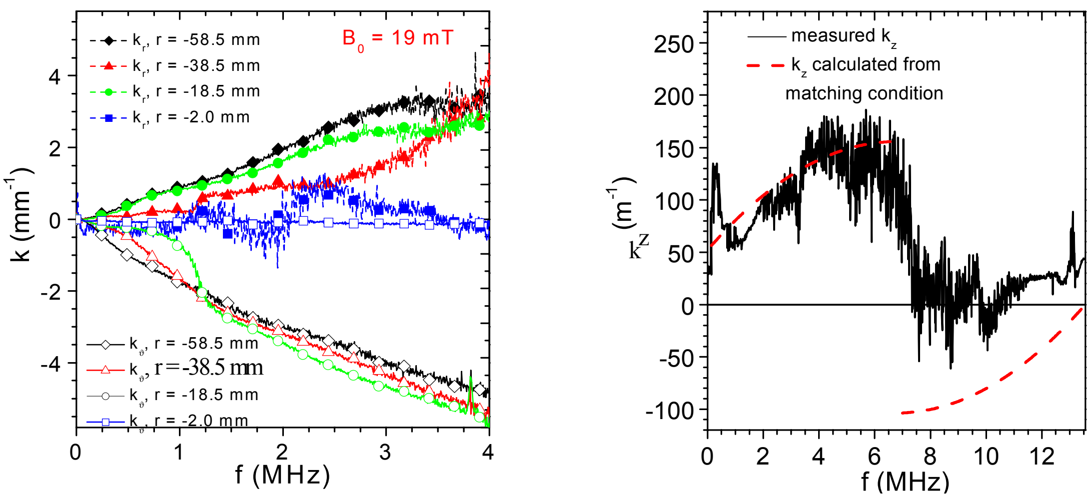

Fig.2a: Dispersion of ion-sound fluctuations from RF probe correlation analysis for different radial positions, b: Parallel wave number vs. frequency.

Thus, the LF and the lower side-band wave numbers obey reasonably the relation $\mathbf{k}_\perp(\omega_S) \cong -\mathbf{k}_\perp(\omega_0 - \omega_S)$. This suggests that the fluctuations originate from a parametric decay instability of the helicon pump ($\mathbf{k}_{0\perp} \approx \mathbf{0}$, as $k_{0\perp} << k_\perp(\omega_0 - \omega_S), k_\perp(\omega_S)$). With the further assumption that the RF side-band is formed by oblique plasma (TG) waves we have the following set of matching conditions and dispersion relations

$$\omega_0 = \omega_S + \omega_{TG}, \quad \mathbf{k}_{\perp 0} = \mathbf{k}_{\perp S} + \mathbf{k}_{\perp TG} \approx \mathbf{0}, \quad k_{z0} = k_{zS} + k_{zTG},$$
$$\omega_S = k_S V_S, \quad \omega_{TG} = (k_{zTG} / k_{\perp TG})\,\omega_{ce}. \tag{1}$$

Combining these equations we obtain the parallel wave number k_z which we compared with the measured values in Fig.2b. As expected from (1), k_z is much smaller than the perpendicular wave number. Moreover, the agreement between the experimental and theoretical dispersion curves is reasonable considering the poor accuracy of these measurements.

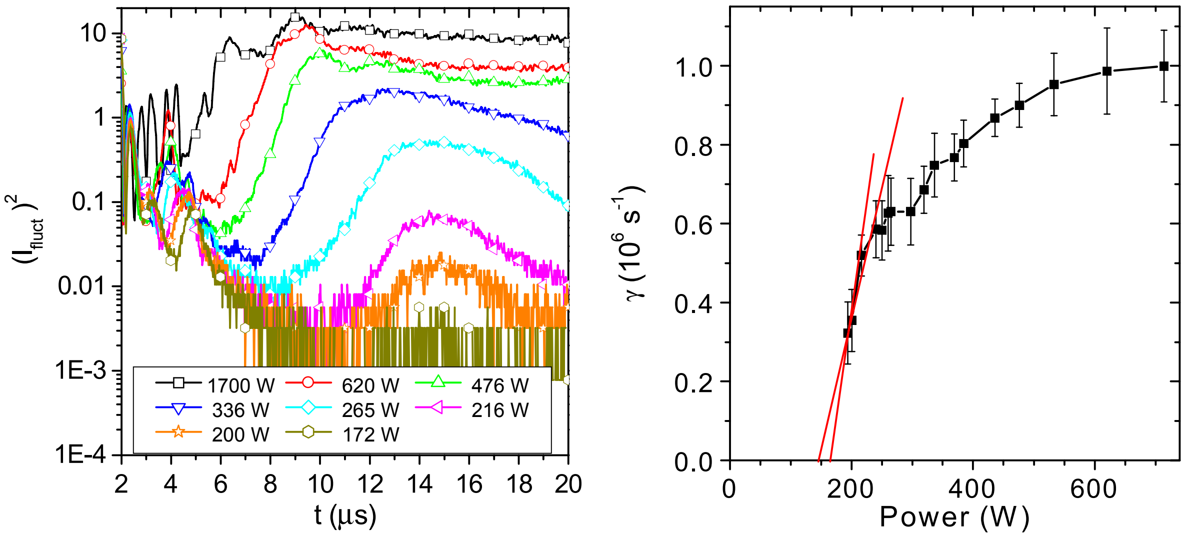

Fig.3a: Evolution of fluctuation intensity for different rf powers,
b: Growth rate vs. rf power.

Further insight into the nature of the instability is achieved by measurements of the threshold and the growth rate of the instability (Fig.3). The onset of the instability is observed at a certain rf power, and, above this threshold, the growth rate first increases nearly linearly until it saturates. The growth rate for the decay of the helicon pump wave into IS and TG waves not too far above threshold (*th*) is given by

$$\gamma=\left(\frac{V_E^2}{V_{E,th}^2}-1\right)\gamma_s,\ \text{where}\ V_E=\frac{E_{\perp 0}}{B_0},\quad V_{E,th}=\frac{4\omega_0}{\omega_{ce}}\left(\frac{4\gamma_s\tilde{\gamma}}{\omega_s\omega_0}\right)^{1/2}V_{Te},\ \ V_{Te}=\left(\frac{T_e}{m_e}\right)^{1/2}. \quad (2)$$

γ_s and $\tilde{\gamma}$ are the damping decrements of the IS and TG waves, respectively. As $E_\perp{}^2 \propto P_{rf}$ the growth rate scales linearly with power: $\gamma=\left(P_{rf}/P_{rf,th}-1\right)\gamma_s$ [6]. Knowing the plasma parameters and the propagation direction of the IS waves ($k_{\perp S}$, k_{zS}) we can relate the growth rate to the IS damping rate

$$\gamma_s(k)=-\frac{\nu_{in}}{2}-\frac{4}{5}\frac{T_i}{T_e}\nu_{ii}-\omega_s(k)\sqrt{\frac{\pi}{8}\frac{T_e^3}{T_i^3}}\cdot e^{-\frac{T_e}{2T_i}}-\omega_s(k)\sqrt{\frac{\pi}{8}\frac{m_e}{m_i}}\frac{A_0\left(k_\perp^2\rho_e^2\right)}{\left|k_z/k\right|} \qquad (3)$$

that contains the contributions of ion-neutral collisions, ion viscosity and ion and electron Landau damping; the function $A(x)=e^{-x}I_0(x)$ accounts for finite electron gyro-radius effects. Good agreement between the measured and predicted IS damping rates is achieved if we take the central density for the calculation of γ_s (Fig.4a).

Finally, we compared the predicted threshold electric fields with the measured fields. The latter was deduced from B-dot probe measurements ($B_{z,\mathrm{helicon}}$) carried out in the centre of the helicon discharge. For $p = 0.3$ Pa, $B_0 = 37.8$ mT and $P_{rf} = 2$ kW we obtained $E_{\perp,helicon} = 454$ V/m from the EMHD equations and the helicon dispersion relation. Assuming that the helicon dispersion does not alter with variation of the RF power in the second (afterglow) pulse, i.e. $E^2_{\perp,helicon}(P_{RF}) \propto P_{RF}$, we can calculate the other field values. Fig.4b shows the good agreement between experimental and theoretical threshold values predicted by eq.(2).

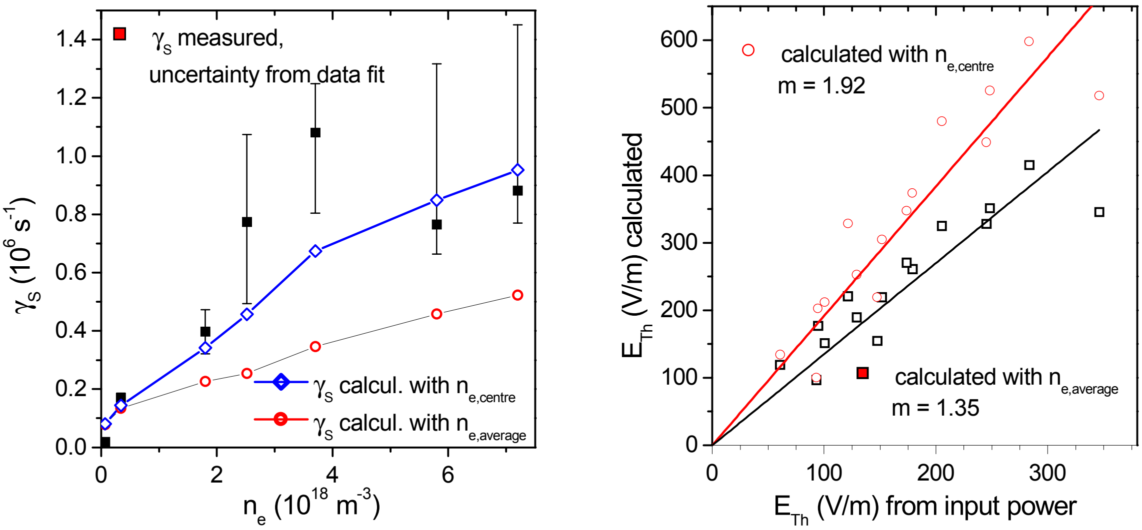

Fig.4a: Ion-sound damping rates, b: Threshold of parametric decay instability.

In conclusion, the low-frequency fluctuations excited in our helicon discharge were identified as ion-sound fluctuations travelling obliquely from the centre to the plasma edge, while the high-frequency fluctuations (lower side-band of the helicon pump) propagate inwards and obey the dispersion relation of Trivelpiece-Gould waves (oblique plasma waves); both LF and RF fluctuations propagate nearly perpendicular to the magnetic field. Their dispersion and temporal evolution suggest that they originate from the parametric decay instability: The frequency and wave number selection rules are reasonably fulfilled, and the growth rates and the thresholds are in agreement with theoretical predictions for the parametric decay of the helicon pump wave into ion-sound and Trivelpiece-Gould waves.

Acknowledgements: This work was supported by the *Deutsche Forschungsgemeinschaft* through the SFB 591 and the Russian-German Contract 436 RUS 113/590.

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