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# Nonlinear excitation of low frequency waves in a amplitude modulated helicon plasma

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In astrophysical and space plasmas an increasing number of observations is made, which underline the importance of nonlinear wave coupling processes for the understanding of the global plasma dynamics [1]. For example, data from the Viking satellite reveal a close correlation between whistler waves and auroral Alfvén waves [2]. Although satellite measurements provide high temporal resolution along the satellite's trajectory, the lack of spatio-temporal measurements often inhibits the identification of the physical mechanisms that drive the waves. This motivates well defined laboratory experiments with tailored diagnostic capabilities. In case of low frequency Alfvén waves their long wavelengths is a challenge. This paper reports on experimental investigations of low frequency Alfvénic waves that are generated by low frequency amplitude modulation of a helicon plasma source. Because the frequencies are in the range of the ion cyclotron frequencies the ion kinetics is of special interest.

Experiments are done in the linear magnetized plasma device VINETA [3]. A schematic diagram of the experimental setup is shown in Fig. 1. The vacuum chamber is 4.5 m long and 40 cm in diameter. The magnetic field of $B_0 \leq 100\,\mathrm{mT}$ is created by a set of 36 coils. The plasma is generated by a helicon source operated at $f_{rf} = 13.56\,\mathrm{MHz}$. The helicon source provides plasma densities of $n \leq 2\cdot 10^{19}\,\mathrm{m}^{-3}$ and electron temperatures of $T_e \leq 3\,\mathrm{eV}$. The plasma is monitored by a microwave interferometer and conventional Langmuir probes, respectively. The modular design of the rf amplifier unit allows a simple way of

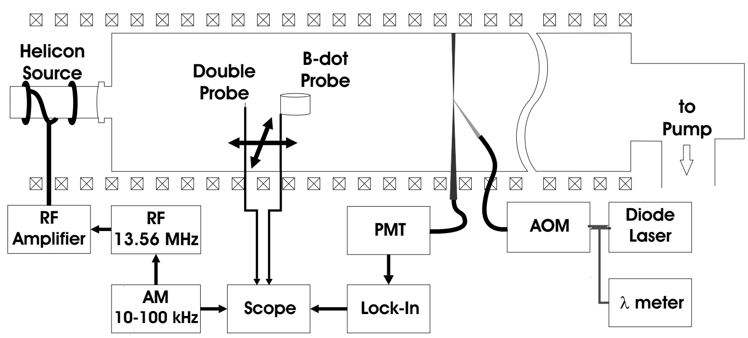


Figure 1: Schematic diagram showing the experimental setup for measurements during amplitude modulated rf discharges in VINETA. Propagating waves are detected by means of electric and magnetic fluctuation diagnostics. The ion kinetics are investigated with laser induced fluorescence.

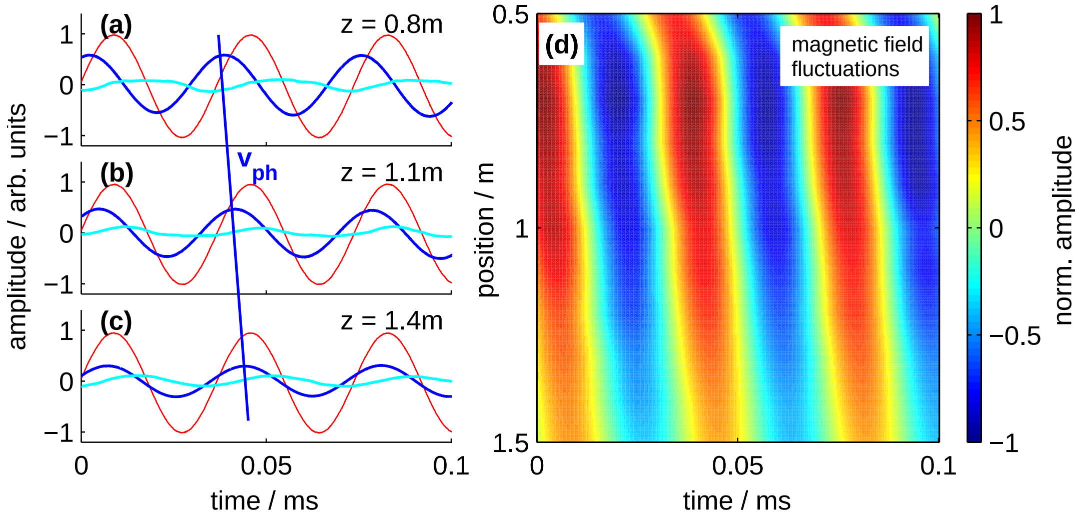


Figure 2: Time traces of magnetic (blue) and electric (cyan) fluctuations recorded by $\dot{B}$- and double Langmuir probes at different axial positions (a)-(c). Included is the modulation signal (red) as a phase reference. (d) Color-coded spatiotemporal diagram of the magnetic fluctuations.

modulating the rf amplitude by using a arbitrary waveform generator. Both the modulation depth $A_m$ and the modulation frequency $f_m$ can be varied. The modulation depth was chosen between $A_m = 10\ldots100\%$ and the modulation frequency was varied from $f_m = 10\ldots100\,$kHz. This corresponds to $\omega_m = 0.2\omega_{ci}\ldots3\omega_{ci}$ with $\omega_{ci}$ being the ion cyclotron frequency. Propagating waves are measured with electric and magnetic probes [4]. A floating double probe is used to measure the perturbed radial electric field. A negatively biased Langmuir probe is used to measure the ion saturation current. For measurements of the polarization of the wave electric field a six tip Langmuir probe (spacing 1.5 cm) records the electric field in radial axial and azimuthal direction simultaneously. Magnetic field fluctuations are measured with a $\dot{B}$-probe, which consist of a coil with 2 cm diameter and 1600 windings embedded in a copper heat shield and a boron nitride body. The $\dot{B}$-probe is oriented to measure oscillations perpendicular to the ambient magnetic field. The probes are mounted on a motor-driven positioning system that allows for radial and axial movement of the probes with high spatial precision.

The ion velocity distribution function (IVDF) is measured with laser induced fluorescence (LIF) [5]. Here, a 60 mW cw diode laser, tunable over 20 pm, is used to pump the Argon II $3d\ ^4F_{7/2} - 4p\ ^4D_{5/2}$ transition at 668.614 nm. The fluorescence radiation of the $4p\ ^4D_{5/2} - 4s\ ^4P_{3/2}$ transition at 442.72 nm is observed with a photomultiplier tube (PMT) after passing a 1 nm bandwidth interference filter. Spontaneous emission is discriminated from laser induced emission by chopping the laser light and using a lock-in technique. An acousto-optical modulator (AOM) used as laser light chopper provides frequencies of several MHz at high trans-

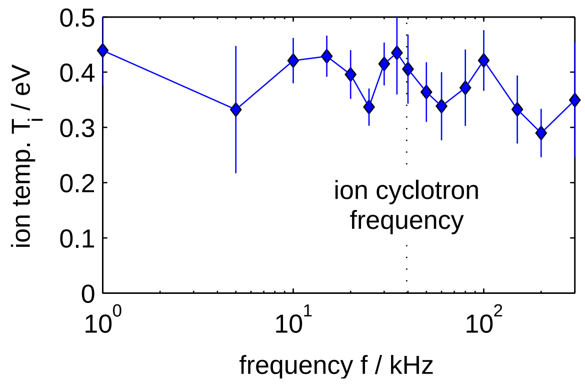


Figure 3: Ion temperature measurements at different modulation frequencies. The ion cyclotron frequency is given as a reference point (dotted line).

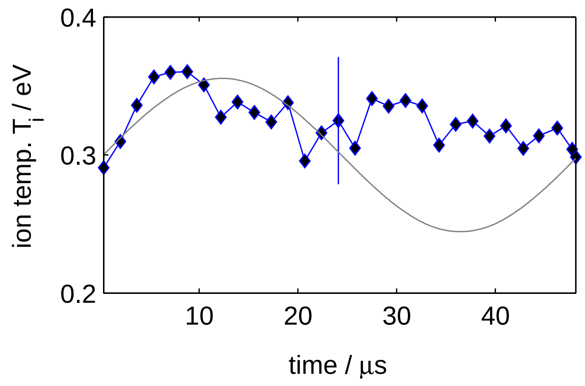


Figure 4: Evolution of the ion temperature during one complete cycle of the sinusoidal modulation drive (black line).

mission rates and high contrast ratios. All active diagnostic parts together, the AOM, the PMT with amplifier and the lock-in amplifier, permit via phase-locked averaging of the LIF signal time-resolved LIF measurements up to $10\,\mu$s time resolution.

In VINETA, non-linear wave coupling is observed if the rf helicon source is amplitude modulated, which results in sidebands around the rf frequency. Fig. 2(a)-(c) shows time traces of electric and magnetic fluctuation probe signals at different axial positions with respect to the helicon antenna. In both signals, oscillations are observed at the modulation frequency, equal to the difference of rf frequency and the modulation sideband frequency, i.e. $f = f_{rf} - f_{sb}$. In the magnetic signal a monotonous increase of the phase shift with increasing distance to the helicon antenna is found (cf. Fig. 2(d)). The wave vector is typically found to be $k \leq 2\,\mathrm{m}^{-1}$ and the phase velocity agrees well with the Alfvén velocity $v_A = 1 \cdot 10^5\,\mathrm{m/s}$. Conversely, the electric component does not support the picture of propagating wave, but reveals a more complicated spatio-temporal pattern [6]. Effort was made to identify the waves via variation of the modulation frequency and to study the dispersion of the waves. With increasing magnetic field, it is found in the waves' magnetic component that the dispersion changes from normal to anomalous dispersion and the waves' electric component exhibits the signature of a superposition of presumably two waves with different wave vector [6]. However, on small spatial scales a propagation at the Alfvén speed is also seen and measurements of the electric field polarization revealed that the waves are left-hand circular polarized, as it is the case for Alfvén waves.

The Alfvénic character and the non-linear excitation scheme makes the above described waves interesting especially with regard to the ion dynamics. Thus IVDF's were obtained for different frequencies of the modulation drive. The results are given in Fig. 3. The measured

IVDF's almost perfect Gaussians and the ion temperature is the characteristic quantity. It is found, that the ion temperature is varying between 0.3 to 0.45 eV. Except the data point at 5 kHz the uncertainty is typically in the range of 0.05 to 0.1 eV. Remarkable is the small dip in the ion temperature around the ion cyclotron frequency. Similar results were previously found in VINETA for linearly excited Alfvén waves [7]. An increase of the ion temperature is expected if Alfvén waves are excited at or close to the ion cyclotron frequency. This is due to direct resonant heating of the ions in the waves' electric fields. Surprisingly, here also dips at frequencies higher and lower than the ion cyclotron frequency occur. It is further found that the dips are located roughly at the sub-harmonic and higher harmonic frequencies of the ion cyclotron frequency. This is presumably due to the non-linear character of the waves. It was reported previously that large amplitude Alfvén waves are very efficient in ion heating at lower and higher harmonics of the ion cyclotron frequency [8]. Consistent with these findings are (almost) constant ion temperatures during a modulation drive period. An exemplary measurement with $f_m = 20\,\mathrm{kHz}$ is shown in Fig. 4.

To summarize, low frequency electromagnetic waves were generated in the linear magnetized device VINETA by amplitude modulation of helicon waves. Measurements with electric and magnetic probes revealed an Alfvénic character of the waves: The phase velocity agrees very well with the Alfvén velocity for the given parameters and the waves are left hand polarized. Measurements of the IVDF show an increase of the ion temperature close to the ion cyclotron frequency as well as at sub-harmonic and higher harmonic frequencies. This indicates that ions undergo a resonant heating. This conclusion is supported by a almost constant ion temperature over the full cycle of the modulation drive.

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