Ducted Alfvén Waves in Helicon Plasmas

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Abstract / Motivation

Recent data from 1306, the new high resolution solar imaging mission [SCIENCE, 362, 877 (2018)], have been interpreted as direct evidence of Alfvén waves in solar corona and coronal loops. The new observations show mass ejections with Alfvén speed. The absorption of Alfvén waves in the corona is often suggested as the reasonable mechanism for volumetric degree temperature increase of the sun’s outer coronal layer over the solar surface. With appropriately long and close spaced magnetospheric phasers, relatively long wavelength Alfvén waves fit in laboratory devices. The high plasma densities and steep density gradients of helicon plasma make such sources good candidates for Alfvén waves investigations in laboratory; the steep density gradients introduce important effects into wave propagation. Here we report external launching of waves into a high density and steep density gradient helicon plasma source. The wave amplitude profile and wave dispersion are compared with a model that includes neutral collision and density gradient effects.

Theory I: Dispersion Relation

Here we consider perturbations of the form $e^{i (\mathbf{k} \cdot \mathbf{x} - \omega t)}$, following Müller ([ Plasma Phys. 18, 813 (1972)], the magnetic field vector differential equation can be written as

$$\omega^2 B = v_v B + \nabla \cdot j_v - i \omega \left[ \nabla \times B - \omega B \times \frac{1}{c^2} v_v \nabla \times \left( B - \frac{1}{c^2} v_v \nabla \cdot B \right) \right] - \frac{1}{i \omega} \left[ \nabla \times B - \omega B \times \frac{1}{c^2} v_v \nabla \times \left( B - \frac{1}{c^2} v_v \nabla \cdot B \right) \right] = 0,$$

where $v_v = B \int (\mathbf{v} \cdot d \mathbf{v})$ is the mean flow velocity and the phase speed of the Alfvén wave. \[ CE \sim \omega_0/\omega, \quad \eta_0 \sim \omega_0/\omega \]

is the ratio of the wave frequency to the effective ion cyclotron frequency.

$\eta_0$ is a neutral density relaxation time.

$\omega_0$ is the neutral collision frequency.

The vector differential equation above, can be written in $\mathbf{r}$, $\mathbf{v}$, and $\mathbf{c}$ directions as below.

For the case of constant density profile and axisymmetric waves, the vector differential equation is solved for magnetic field components given by $\mathbf{v}_v = x_\mathbf{v} \mathbf{v}_v$, $x_\mathbf{v} = \mathbf{v} / \rho_0$, $\rho_0 = \rho_0 + i \omega / \omega_0$, where $\rho_0$ in the $I$-rest of the force in the fluid density divided by the thermal energy, and the $A$ coefficients are the eigenvector components of the eigenvalue problem (dispersion relation):

$$\begin{array}{c}
\left[ \begin{array}{ccc}
\omega^2 - \lambda & -\nu & -\nu \\
-n^2 & \omega^2 - \lambda & -\nu \\
-n^2 & -\nu & \omega^2 - \lambda
\end{array} \right] \left[ \begin{array}{c}
A_0 \\
A_1 \\
A_2
\end{array} \right] = 0
\end{array}$$

If the waves are non-axisymmetric, the dispersion relation is given by the general case of Woods ([ J. Fluid Mech. 115 (1982)]).

Measurements I: Dispersion Relation

To verify the axial symmetry of the waves, two $\mathbf{R}$ coils were positioned at a radius of $r = 2$ cm, at $\theta = 105$ cm downstream of the RF antenna, separated by 90° azimuthal angle. The phase difference between two coils $\delta \phi$ was used to calculate the mode number through $m = \partial \phi / \partial \theta$. The figure below shows the mode number measurements for two different cases.

After defining the mode number, two $\mathbf{R}$ coils were position axially with 30 cm separation, and their phase difference was measured. The resulting parallel wave vector, and expected theoretical values are shown below.

Theory II: Magnetic Field Profiles

The vector differential equation above, can be written in $\mathbf{r}$, $\mathbf{v}$, and $\mathbf{c}$ directions as below.

Field Diagnostics

The measurements were carried out in the HELPL (Helicon Plasma Laboratory) (Plasma Science Sci. Technol. H, 284 (2000)). The 19 cm helicon antenna is driven with 0.5-1 kW RF at 9.5 MHz for argon plasmas. The antenna is amplitude modulated with a 1% modulation depth. Magnetic fluctuations were recorded with 16-bit, 100 MHz digitizer.

Plasma Diagnostics

Langmuir Probe Measurements: An RF compensated Langmuir probe was used to measure electron density and temperature. The density wave fit into a Gaussian profile:

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