Whistler Spheromaks

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Abstract—A highly nonlinear whistler wave packet has been generated in a large laboratory plasma. The wave field exceeds the ambient field, locally reverses its direction and exhibits a topology of a spheromak. It propagates along the ambient magnetic field at a speed that decreases with amplitude. Electrons are strongly energized in the spheromak. Anisotropies create whistler instabilities. The whistler spheromak becomes a propagating source for secondary whistlers, a new phenomenon in magnetic turbulence.

Index Terms—Antenna radiation patterns, electromagnetic propagation in plasma media, nonlinear wave propagation, plasma instabilities.

Whistler waves are electromagnetic waves in dense plasmas below the electron cyclotron frequency. They are important in space plasmas due to wave-particle interactions and in laboratory plasmas as helicons for efficient plasma production. In spite of an extensive knowledge about the linear wave properties, little is known about whistler modes whose wave fields exceed the ambient field. Theoretically, the wave equation becomes nonlinear, Fourier analysis is not applicable, and there exists no simple dispersion relation.

Experimentally, we have shown [1] that such nonlinear wave packets do exist and described their basic properties. The experiments are performed in a large (1 m × 2 m) discharge plasma of relatively high density (10^{12} cm^{-3}) and low magnetic field (B_0 = 7 G). Using loop antennas (15 cm diameter) with large oscillating currents (200 kHz, 500 A-turns), strong electron currents are induced in the plasma. When the axisymmetric antenna field is opposite to the ambient field, a field-reversed configuration is generated. It induces two image wave packets, which detach from the antenna and propagate along and opposite to the ambient magnetic field. The wave field reverses the ambient magnetic field and produces two magnetic null points. In addition to the dipolar or poloidal magnetic field (B_z, B_r), the wave develops self-consistently a toroidal field component B_θ such that the net field lines are helical, as shown in Fig. 1.

We call this magnetic vortex a “whistler spheromak” since it has the topology of an MHD spheromak but propagates in the whistler mode. The twist of the field lines is right handed for the spheromak propagating along B_0 and left handed for propagation opposite to B_0. The magnetic helicity, describing the field line twist, is a conserved quantity in ideal fluids. Thus, the net helicity is zero, since a loop antenna does not inject helicity. On the other hand, we have designed antennas that inject helicity and excite waves unidirectionally [2]. We have also propagated two counterhelicity spheromaks against each other. In such case, the fields merge and form a stationary field-reversed configuration with zero helicity. In contrast, linear whistlers simply propagate through each other.

During its propagation, the whistler spheromak loses its magnetic energy to the electrons. Most of the energy conversion occurs in the toroidal current layer where electrons can be freely accelerated by a toroidal electric field. Transit time effects appear to be the dominant dissipation mechanism since the spheromak propagates below the electron thermal velocity. Probe measurements show both bulk heating and formation of energetic tails (> 30 eV). Electron heating in a nonuniform magnetic field apparently also leads to anisotropies in the electron distribution function, which give rise to an observed whistler instability.

Before discussing the instabilities, it should be mentioned that on every other half cycle a large amplitude whistler mode with wave magnetic field parallel to B_0 is excited. It produces a traveling mirror magnetic field topology. These “whistler mirrors” propagate faster than linear whistlers and speed up with increasing amplitude. Since the field is produced by Hall currents, there is negligible electron heating and no whistler instabilities. Thus, a sinusoidal current drive excites nonlinear whistler modes with different properties on alternate half cycles.

As shown in Fig. 2, the propagating spheromak emits high frequency (f = 1...10 MHz) whistler waves in both directions along B_0. These are small amplitude, circularly polarized electromagnetic waves, which propagate faster than the spheromak, hence escape from it. Unstable waves also propagate and grow in amplitude against the spheromak, i.e., opposite to the energetic electron flow, consistent with an anisotropy instability produced by Doppler-shifted cyclotron resonance \( \omega - k \cdot v_e = \omega_c \).

When a test whistler wave in the unstable frequency band is propagated into the region of the instability, we observe that the instability is enhanced instead of amplifying the test wave. Also, the peak oscillation is frequency upshifted from the test wave. Thus, we speculate that the test wave has scattered the electrons, hence modified the distribution function. Such triggered whistler emissions have also been observed in the magnetosphere and are important for electron scattering in mirror magnetic field. In conclusion, we have experimentally investigated a highly nonlinear regime of whistler modes, which are relevant to certain space and lab plasmas.

REFERENCES


Fig. 1. Magnetic field lines of a whistler spheromak. It has the topology of a spheromak but propagates as a highly nonlinear whistler wave packet. Its magnetic helicity depends on direction of propagation relative to $B_0$. The field lines are constructed from probe measurements in a laboratory plasma resolved in 3-D space and time.

Fig. 2. Axial time-of-flight diagrams of the current helicity of (a) nonlinear whistler modes and (b) whistler instabilities. A 250-kHz oscillating antenna current excites whistler spheromaks at 1.5 and 3.9 $\mu$s which produce copious high-frequency oscillations. All whistlers propagating along $B_0$ have positive helicity (yellow), negative helicity (blue) for opposite propagation direction. Spheromaks emit whistlers in both directions. High-frequency whistlers propagate faster than low-frequency whistlers. The propagation speed of nonlinear whistlers in (a) varies with amplitude and polarity.