First direct observation of whistler waves driven by relativistic electrons in a toroidally-confined laboratory plasma

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Whistlers are dispersive electromagnetic waves that can be driven unstable by energetic electrons in both space and laboratory plasmas. They are unstable in the outer radiation belts of planetary atmospheres, where they are known as chorus waves. Perpendicular scattering of energetic electrons by whistlers contributes to the aurora. The first detection (in 1894!) was generated by lightning. In the present experiment, a confined population of ~ 10 MeV “runaway” electrons drives whistlers unstable in the DIII-D tokamak (Fig. 1). The detected 100-200 MHz waves are in the band between the ion cyclotron and lower hybrid frequencies and satisfy the cold-plasma dispersion relation, with the expected dependencies on magnetic field and density. Whistler activity is correlated with the intensity of hard x-rays produced by the runaways. Fluctuations occur in discrete frequency bands, and not a continuum as would be expected from plane wave analysis, suggesting the important role of toroidicity. An MHD model including the bounded/periodic nature of the plasma identifies multiple eigenmode branches. For a toroidal mode number $n = 10$, the predicted frequencies and spacing are similar to observations. The instabilities are stabilized with increasing magnetic field, as expected from the anomalous Doppler resonance. The whistler amplitudes show intermittent time variations. Predator-prey cycles with electron cyclotron emission (ECE) signals are observed, which can be interpreted as wave-induced pitch angle scattering of moderate energy electrons. Such nonlinear dynamics are supported by quasi-linear simulations indicating that electrons are scattered both by whistlers and high frequency magnetized plasma waves. The whistler wave predominantly scatters the high energy electrons, while the magnetized plasma wave scatters the low energy electrons, abruptly enhancing the ECE signal. If whistlers that pitch-angle scatter runaways are excited in future devices, the enhanced runaway dissipation could reduce the likelihood of runaway-electron induced damage.

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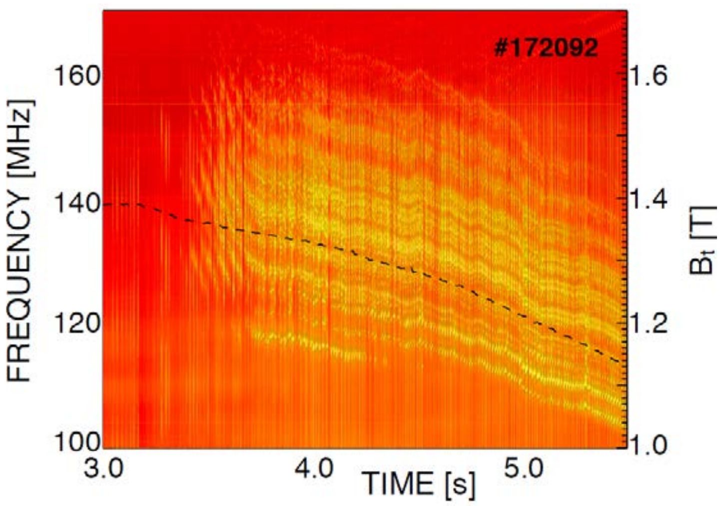

Figure 1. *Whistler waves detected by a magnetic probe. The time evolution of the dominant toroidal magnetic field is indicated by the dashed line; the density is nearly constant in this discharge. The frequency exhibits the expected linear dependence on magnetic field. The modes are more easily destabilized at lower magnetic field, probably because the electron energy is higher. The banded, discrete nature of the observed modes is evident.*