Whistler Waves Radiation by Loop Antenna in Plasmas with Magnetic Field Irregularities

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Abstract

Whistler waves radiation by loop antennas immersed in a large laboratory magnetoplasma with magnetic field irregularities was studied. Two types of ambient magnetic field irregularities were investigated : (i) an elongated "duct-like" irregularity localized between launching and receiving antennas; (ii) inhomogeneity localized in the vicinity of launching antenna. The magnetic field irregularities created without any significant plasma density disturbances were considered. It was found that the presence of the magnetic field perturbations change the whistler waves amplitude. Plasma regions with locally enhanced magnetic field strength provide an increase of amplitude of whistlers emitted by the loop antenna; oppositely, local magnetic field minima decrease the amplitude of whistler waves. The calculations are presented which confirm the related experimental measurements. The results are of great importance for laboratory plasmas as well as for physics of magnetosphere.

1. Introduction

Whistler waves excited over a frequency range between the low hybrid frequency ω_{lh} and the electron cyclotron frequency ω_{ce} play a major role in many space and laboratory plasma processes. Whistlers emissions are observed during satellite missions and by ground-based receivers and can be successfully used for near-Earth plasma diagnostics [1,2]. In laboratory plasmas whistlers are studied extensively in connection with various applications, as the design of high-performance inductive rf plasma sources [3]. Plasma density perturbations stretched along the geomagnetic field lines (ducts) serve as effective waveguides for whistlers, and assist the magnetospheric propagation of very low frequency waves. Effects induced by the presence of plasma density crests and troughs have been studied rather well both experimentally [4-6] and theoretically [7]. However, whistler waves' propagation can be strongly affected not only by the plasma density irregularities, but also by nonuniformities of the magnetic field [8]. Here we present the studies of whistlers emitted by loop antenna in a uniform background magnetoplasma with artificial ambient magnetic field irregularities.

2. Experimental Arrangement

The experiments were performed in the "KROT" facility, which was built-up as a source of extremely large plasma for the purposes of modelling waves' propagation in the Earth ionosphere and magnetosphere. The device represents a stainless steel vacuum vessel of total volume $V = 180$ m^3, which is evacuated down to a base air pressure of $p = 5 \times 10^{-6}$ Torr. A pulsed inductive radio-frequency source ($\omega/2\pi = 5$ MHz, 2 generators with power 1 MW, pulsed time of 1.44 ms) is used to produce the argon plasma column (500 cm in length and 150 cm in diameter) under a working gas pressure of 7×10^{-4} Torr. The solenoid used for the magnetic field generation is installed inside the vacuum vessel. The electron temperature is about $T_e = 10$ eV, and the ion temperature T_i is typically smaller than T_e. The experiments are usually performed in a quiescent afterglow plasma; the plasma decay characteristic time is of the order of several milliseconds. The discharge is pulsed once per ten seconds. Plasma density nonuniformity scales along and across the magnetic field are typically much greater than the axial whistler wavelength. The vacuum vessel walls are very far from the experimental plasma area (about 500 cm along and 170 cm across $\mathbf{B}_0$), so that parasitic wave reflections from the metal surfaces are eliminated. The experiments discussed here were conducted in a plasma with typical density $n_e = 4 - 9 \times 10^{11}$ cm^{-3} and electron temperature $T_e = 0.2 - 0.5$ eV, in an ambient magnetic field of strength $B_0 = 35 - 40$ G.

An elongated "duct-like" irregularity localized between emitted and receiving antennas were created by means of a compact cylindrical six-turn solenoid (coil diameter: $d = 7.5$ cm, interval between coils: $l = 5.5$ cm, length of the solenoid: $L = 30$ cm) installed coaxially with the main solenoid used for the ambient magnetic field generation. Six-turn solenoid were fed up with rectangular current pulses of duration τ =0.2–1 ms, and the maximum dc current strength was about $I_0 = 200$ A. Since the direction of $\mathbf{B}_0$ was fixed, the type of magnetic field irregularity was determined by the polarity of coils commutation to the source of the current. For the excitation and reception of the whistler waves over the frequency range 20 MHz $< \omega/2\pi <$ 100 MHz, electrostatically shielded, single-turn loop antennas (1 cm in diameter) were used.

In order to produce localized ambient magnetic field irregularities in the vicinity of launching antenna it was suggested to feed the antenna with the additional dc current along with the rf current. This loop antenna had the diameter $2b = 6.5$. To reduce the plasma influence on the shielded loop impedance, the antenna wire was covered with a thin (about 0.5 mm) dielectric (vacuum polymer adhesive) layer. The level of the rf power applied to the loop antenna was typically smaller than 10 mW; hence the thermal nonlinear effects in the antenna near fields were suppressed. In the experiments the loop antenna normal was always parallel to ambient magnetic field. A dc current with a strength up to $I_0 = 200$ A, used for the generation of the localized magnetic field disturbances, was applied to the loop in a form of a pulse with duration 0.2 - 1 ms. The type of magnetic field irregularity (magnetic enhancement or depression) was determined by the polarity of the antenna commutation to the pulsed current source.

The precise density measurements performed by a microwave resonator probe showed no significant redistribution of the plasma. Charged particles deposition on the surfaces of coils and supporting structures led to a density decrease by no more than 5 - 10%.

3. Whistler Wave Fields

Here we present the experimental results for whistlers wave radiated by loop antenna obtained in plasma with magnetic field irregularities when i) an elongated magnetic field irregularity localized between emitted and receiving antennas were created by means of a cylindrical six-turn solenoid and ii) for the whistler wave emission it was used a loop antenna with additional dc current I_{dc} perturbing the ambient magnetic field strength. Plasma density disturbances do not accompany these magnetic field perturbations.

3.1 Whistler Wave Propagation in a Plasma with a Prolonged Magnetic Field Irregularity

In our experiments with prolonged magnetic field irregularities, formed by the six-coil solenoid, whistler waves were emitted by the loop antenna installed at the axis of the system at the distance $\Delta z = 5$ cm from the extreme coil of the solenoid. The transverse structure of the whistler wave field was studied using loop antenna installed in the plane that was spaced by $\Delta z = 7$ cm from the opposite end of the solenoid. Fig. 1 shows the transverse distribution of the amplitude of the whistler wave field $B_\varphi(r)$ at frequency $\omega/2\pi = 20$ MHz. In the presence of irregularity with depressed magnetic field, the maximum whistler amplitude at a fixed cross-section was decreased, and the transverse distribution of the whistler wave amplitude was broader than in the case of an unperturbed ambient magnetic field. At the same time, the magnetic field enhancement increased the whistler wave amplitude significantly, and modified the wave field transverse distribution. Note that the structure of the wave field was changed even in case of comparatively weak magnetic field disturbances, i.e. $\Delta_0/B_0 \sim 0.1$.

3.2 Whistlers in a Plasma with a Magnetic Field Irregularity in the Vicinity of Launching Antenna

Fig. 2 shows the oscilloscopic traces of the signals (azimuthal B_φ component of the wave field) measured by the diagnostic antenna at $\omega/2\pi = 63$ MHz, when the pulsed current I_{dc} was applied to the emitting loop (6.5 cm of diameter). The results obtained at various strengths I_0 of the additional current and both polarities of the antenna commutation to the pulsed current source are presented. The direction of the current flow corresponding to the increase of the static magnetic field B_{tot} at the center of the loop antenna is marked by positive values ($\Delta B_0/B_0 > 0$); the current flowing in opposite direction is marked by negative values ($\Delta B_0/B_0 < 0$). The black rectangle (see Fig.2) represets the duration of the dc current pulse. It is seen from Fig. 2 that the generation of a localized magnetic field enhancement (magnetic "hump") provided the possibility to increase amplitude of whistlers; in the opposite case corresponding to a magnetic field depression (magnetic "well"), the amplitude of whistlers decreased.

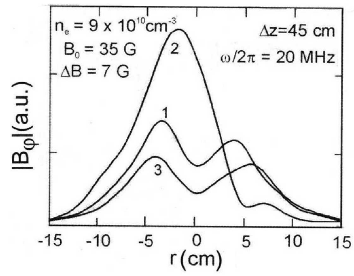

Fig. 1

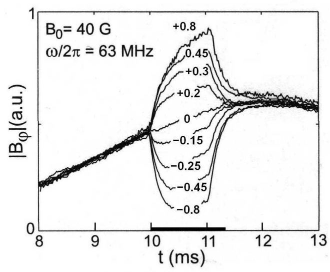

Fig. 2

3.3 Analytical Description and Numerical Results

The analytical description of whistler wave fields propagating in a plasma with ambient magnetic field irregularities have been fulfilled in the frame of a perturbation approach. A cylindrical coordinate system (r, φ, z) is considered, with the z- axis in the direction of the ambient static magnetic field $\mathbf{B}_0(r, z) = B_0(r, z)\,\mathbf{z}$. The plasma, whose density n_e is supposed to be constant, is described by the dielectric nondiagonal tensor $\hat{\varepsilon}$ [7]. We assume that the antenna current density distribution is uniform $j_\varphi(\mathbf{r}) = I_0^e \delta(r - b)\delta(z)$, where b is the radius of the loop antenna. For simplicity, we suppose that the perturbation $\Delta\mathbf{B_0}$ of the magnetic field is extended along $\mathbf{B_0}$ and can be modeled by a cylinder of radius a and a finite length L, which may be smaller or comparable with the wavelength λ_z of the whistler traveling along it. In the axisymmetric case ($\partial/\partial\varphi = 0$), the electromagnetic field excited by the source is independent of the azimuthal angle φ; its radial and axial components E_r, E_z, B_r and B_z can be expressed in terms of the azimuthal fields E_φ and B_φ which satisfy the well known system of coupled differential equations [7]. We consider here the case of small perturbations of $\mathbf{B}_0$ ($\Delta\mathbf{B}_0/\mathbf{B}_0 << 1$). In order to solve the system of coupled differential equations we use a perturbative development of the the elements of the tensor $\hat{\varepsilon}$ and the excited fields $\mathbf{E}$ and $\mathbf{B}$ inside the magnetic irregularity.

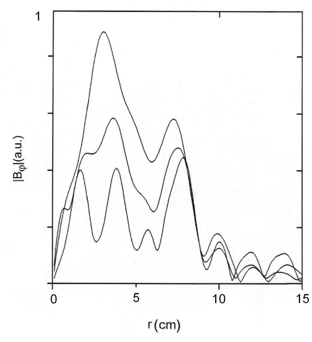

Fig. 3

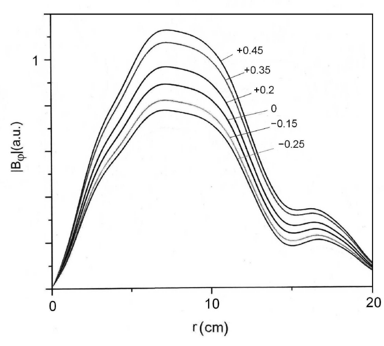

Fig. 4

Based on the this theory, we present the results of numerical calculations of the whistler wave fields performed for the plasma parameters typical of the conditions of our experiments (see Figs. 1, 2). Fig. 3 shows the distributions of $|B_\varphi(r)|$ for (i) an enhanced perturbation of $\mathbf{B}_0$ ($\Delta B_0/B_0 = 0.2$, upper curve), (ii) a depletion of $\mathbf{B}_0$ ($\Delta B_0\ B_0 = -0.2$, lower curve) and (iii) no perturbation of $\mathbf{B}_0$ ($\Delta B_0/B_0 = 0$, middle curve). It can be seen from Fig. 3 that, comparing with the case of a uniform magnetic field, $|B_\varphi(r)|$ increases (resp. decreases) in the presence of an enhanced (resp. depleted) perturbation of $\mathbf{B}_0$. Fig. 4 shows the radial distributions of the azimuthal field amplitude $|B_\varphi(r)|$ for the case of magnetic perturbation localized in the vicinity of launching antenna, here: (i) the plasma is unperturbed ($\Delta B_0/B_0 = 0$, (ii) an enhanced perturbation of $\mathbf{B}_0$ is generated ($\Delta B_0/B_0 = +0.2, +0.35, +0.45$, upper curves), and (iii) a depletion of $\mathbf{B}_0$ is generated ($\Delta B_0/B_0 = -0.15, -0.25$, lower curves). The results of computations agree satisfactory with the experimental observations (see Figs.1,2).

4. Conclusion

The experiments were performed in a large laboratory plasma device, which were revealed a significant effect of ambient magnetic field irregularities on the loop radiation characteristics in the whistler frequency band. A theoretical analysis performed for comparatively small perturbations of the ambient magnetic field in the antenna vicinity is presented. The results of the corresponding computations are in qualitative agreement with the related experimental data. It was obtained that the loop radiation efficiency increases (resp. decreases) in the presence of magnetic field enhanced (resp. depleted) perturbations nearby the antenna. Also it was shown that the plasma regions where the magnetic field is enhanced - compared to the ambient magnetic field strength - cause the focusing of whistlers, whereas the debunching of whistlers can be observed in regions where the magnetic field is depressed.

5. Acknowledgments

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6. References

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