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Whistler wave compression in nonstationary magnetized plasma

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► **To cite this version:**

Alexander V. Kostrov, Mickhail Gushchin, Sergey Korobkov, Askold Strikovsky. Whistler wave compression in nonstationary magnetized plasma. 2004. hal-00003130

HAL Id: hal-00003130

<https://hal.science/hal-00003130>

Preprint submitted on 22 Oct 2004

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1. INTRODUCTION

The investigation of whistler waves excitation and propagation in Earth magnetosphere and ionosphere is of great importance for plasma diagnostics, studying the nonlinear phenomena, dissolving the problems related with radio communications in VLF range [1]. During the signal propagation in near-earth plasma its distortion can take place, due to nonlinear processes in radiation belts and parametric whistler wave interaction with plasma density and magnetic field variations. Amplitude-frequency modulation and satellite generation is often observed in active experiments [2]. This paper is focused on parametric processes in plasma with nonstationary periodic magnetic field variation in conditions, when variation characteristic time is much larger than wave oscillation period, and geometric optic approach is applicable. In this case equation of longitudinal whistler frequency transport in nonstationary magnetic field can be written:

$$\frac{\partial \omega}{\partial t} + v_g(\omega) \frac{\partial \omega}{\partial z} = \frac{\omega}{\omega_H} \frac{d\omega_H}{dt}, \quad (1)$$

where ω - frequency of quasimonochromatic wave field, v_g - group velocity, ω_H - electron cyclotron frequency. It is clear from (1) that magnetic field modulation leads to wave frequency transformation, and dispersion of group velocity (its dependence on frequency) results in signal compression [3].

2. EXPERIMENTAL SETUP

Experimental setup is a vacuum chamber (length 10 m, diameter 3 m, Fig.1). Magnetic field of trap configuration (mirror ratio 2.4) is created with the use of solenoid placed inside the chamber, magnetic field in minimum $B_0=65$ G. Cylindrical plasma column (length 4 m, diameter 1.5 m) is formed as a result of pulsed inductively coupled RF-discharge ($\tau_p=1$ ms, $P=250$ kW, $f_{dis}=5$ MHz) in argon of pressure $p=7 \cdot 10^{-4}$ torr. The maximum plasma density is about 10^{13} cm⁻³, electron temperature $T_e=10$ eV, ion temperature $T_i \sim 0.5$ eV, plasma decays with the characteristic time ~ 10 ms. The experiments were performed in afterglow plasma, when density reached $n_e=1 \cdot 10^{11}$ cm⁻³. Periodic magnetic field disturbance was produced with the use of additional RF generator ($\tau_p=1$ ms, $P=10$ kW, $f_{dis}=1.2$ MHz), loaded on loop antenna (20 cm in diameter, “inductor”) which was installed in the center of plasma column. AC current in inductor reached $I_{max}=30$ A, and magnetic field disturbance near antenna was about $\delta B_{max}/B_0 \sim 5\%$.

High frequency probe whistler waves ($f_0=80-200$ MHz) were radiated and received by small (1-2 cm in diameter) loop antennas which were installed in different sections of chamber. Exciter loop was placed near the inductor, receiving antennas were installed on system axis, at different distances from antenna-radiator. For preventing divergence of the whistler wave the artificial density duct was formed with the use of additional RF-heating source [4]. This duct played a role of waveguide channel; effective whistler wave trapping and its propagation in transversally localized area were possible.

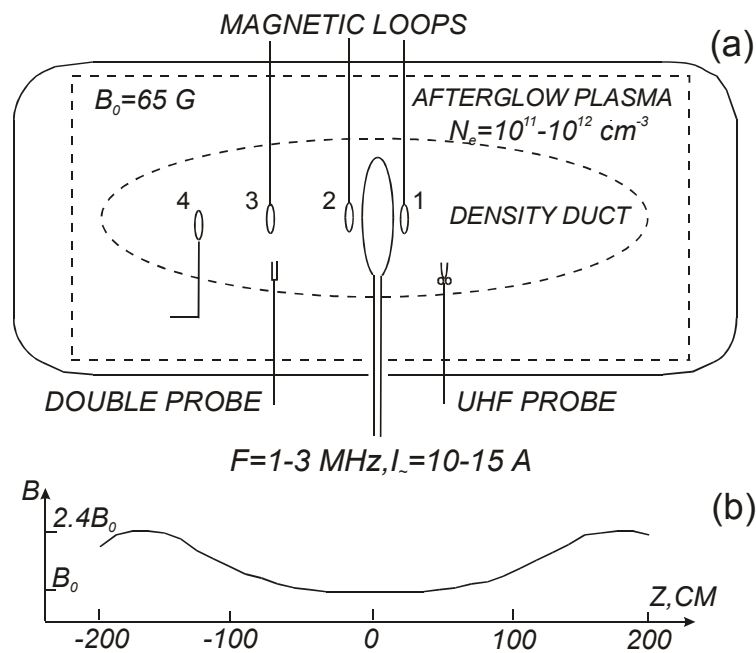


Fig.1 (a) – schematic view of setup “Krot”, (b) – longitudinal magnetic field distribution

3. EXPERIMENTAL RESULTS

The main experimental results are presented at Fig.2. It is seen that after propagation through the area with strong magnetic field disturbance the whistler wave (frequency $f_0=160$ MHz is close to local electron cyclotron frequency $f_H=180$ MHz,) is splitted into separate chirped wave packets. Dynamical spectrograms of whistlers represent the “falling tones” – frequency of initially monochromatic wave is swept in range from 165 MHz down to 155 MHz. Chirped pulse compression is observed: at distance about 1.5 m (from exciter loop) single pulse duration in periodic sequence is about $\tau_{\min} \sim 100$ ns. This minimum duration satisfies the expression $\tau_{\min} \sim 1/\Delta f$, where Δf is the full frequency deviation in modulated frequency spectrum.

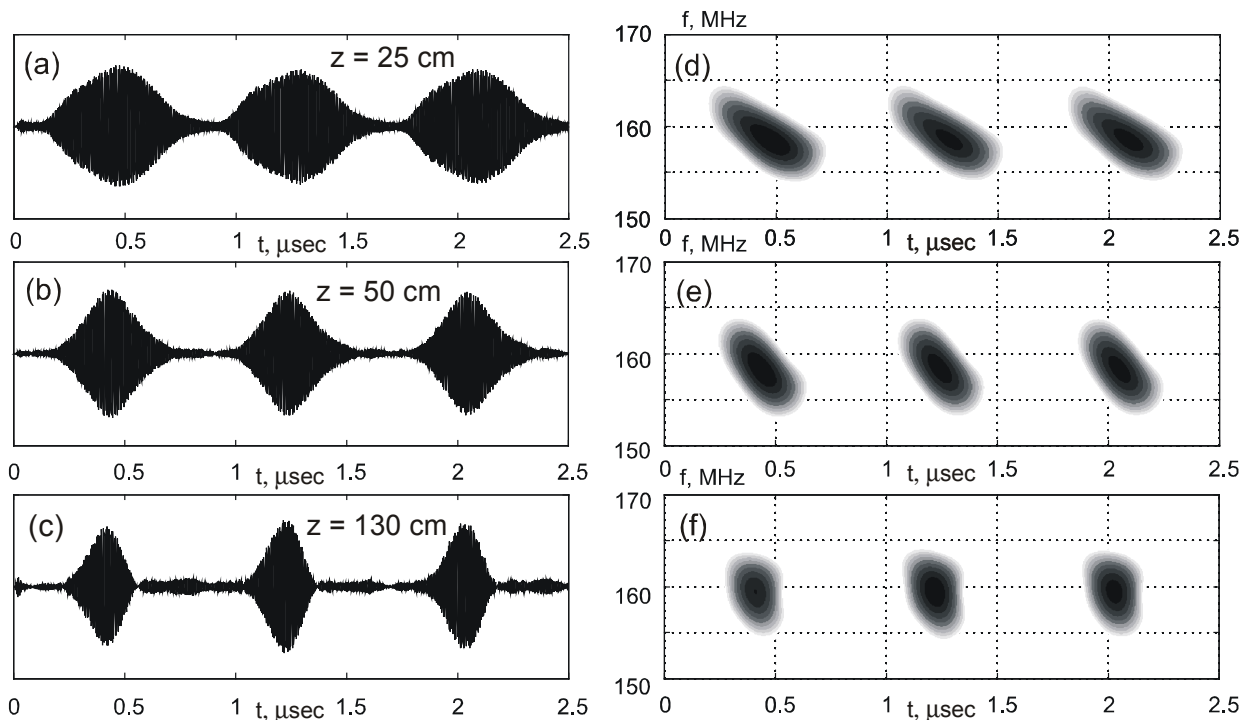


Fig.2 (a-c) – oscillograms of whistler ($f_0=160$ MHz) after transition through area with periodically modulated magnetic field, (d-f) – dynamical spectra of signals

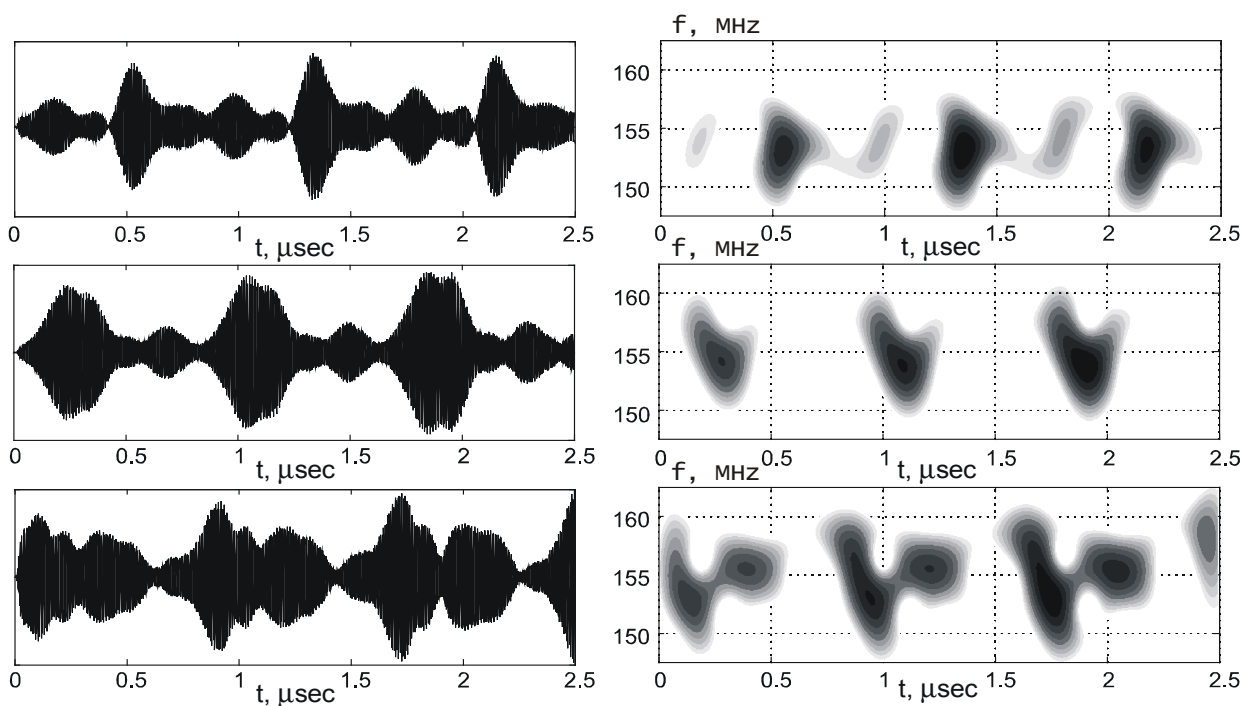


Fig.3 Oscillograms and spectrograms of whistler ($f_0=150$ MHz) after transition through area with periodically modulated magnetic field; receiving antenna installed at $r=5-10$ cm from axis of the duct

When receiving antenna is installed far from exciter loop ($L > 100$ cm) and located at distance $\Delta r = 5-10$ cm from the axis of plasma (axis of density duct), “exotic” oscillograms and spectrograms can be obtained (Fig.3). Their complicated forms can be connected with excitation and propagation of several whistler modes of plasma channel with modulated frequency and different group velocities. High frequency field detected by antenna is a result of mode interference [3].

4. DISCUSSION

The results can be explained with the involvement of two effects: (i) parametric whistler frequency modulation in area with intense magnetic field oscillations and (ii) compression of frequency-modulated wave due to strong dispersion of group velocity. The group velocity of whistlers can be written in the following form:

$$v_g = 2c \frac{\omega^{1/2} \omega_H^{1/2}}{\omega_p} (\omega_H - \omega)^{3/2}, \quad (2)$$

where c - speed of light, ω_p - electron plasma frequency. It is seen from (2) that in frequency-modulated whistler with $\omega \leq \omega_H$ intervals with higher frequency have lower group velocity and vice versa, therefore compression of wave packets with decreasing frequency takes place. As for frequency modulation in nonstationary magnetic field, maximum modulation index can reach $\delta\omega/\omega_0 \sim \delta B/B_0$ [3]. In our experiment modulation index $\delta\omega/\omega_0 \sim 1-3\%$ is in good agreement with theoretical estimations. Estimation of compression distance using formula

$$z_c \sim \frac{v_g^2}{\left| \frac{\partial v_g}{\partial \omega} \right| \left| \frac{\partial \omega}{\partial t} \right|_{\max}} \quad (3)$$

gives $z_c \sim 100$ cm, therefore estimation conforms to experimental data.

5. CONCLUSIONS

The experiment demonstrates the complex of parametric phenomena and dispersion effects, observed at frequencies close to electron cyclotron frequency. The results can be used for explanation of processes responsible for generation of quasimonochromatic frequency-modulated emissions in electron and ion whistler ranges. For example, in some cases generation of magnetic pulsations of type Pc-1,2 (“pearls”, [5]) can be explained as modulation of initially monochromatic emission by magnetic

pulsation of type Pc-3,4. Some application concerning distortion of man-made signals by magnetic field variation can also be discussed.

The work was supported by RFBR (grant 04-02-17188)

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