INFLUENCE OF NONLINEAR EFFECTS ON THE ELECTRODYNAMIC CHARACTERISTICS OF VLF LOOP ANTENNAS IN MAGNETOPLASMA

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Abstract. The influence of thermal and strictional nonlinear effects on the whistler emission in magnetoactive plasma is studied experimentally. It is established that a nonlocal thermal nonlinearity determines the directional pattern of the antenna, while a strictional nonlinearity, which is strongest near the antenna surface, is responsible for the matching of the emitter with the surrounding plasma.

The emission of intense electromagnetic wave fields in plasmas is often accompanied by the development of various nonlinear processes (strictional, ionization, thermal) that strongly alter the electrodynamic characteristics of the surrounding medium. The nonlinear effects are strongest near antennas, where, as a rule, the electric and magnetic field intensities reach their maximum values. They influence the radiator-plasma matching and, generally speaking, the structure of the near (quasistatic) and radiation fields.

The nonuniformities arising in a magnetoactive plasma as a result of heating of the electrons in the near fields of antennas stretch along the magnetic field and can maintain spatially localized electromagnetic modes, which are emitted into the surrounding space as the nonuniformities vanish. As a result, in the absence of a nonunifonnity the directional pattern becomes substantially narrower. In the direct proximity of an antenna, strictional processes give rise to small-scale nonuniformities (of the order of the characteristic transverse dimensions of the conductors) which determine the input impedance of the radiators. It is a very attractive idea to use this effect to match antennas and plasma. In the present work the effects listed above were studied experimentally.

The experiments were performed in a decaying argon plasma with neutral gas pressure $P_0 = 5 \times 10^{-3}$Torr. The apparatus consisted of a vacuum chamber 150cm long and 80cm in diameter. The plasma was produced by a high-frequency pulsed discharge in a uniform magnetic field $H_0 = 100$ Oe. The density reached $N_e = 10^{13}$cm^{-3} and then (after the plasma source was switched off) decayed with characteristic time $t = 2$ms. The main experiments were performed with plasma density 10^{12}cm^{-3} the electron temperature was equal to 0.5eV.

The density of the background plasma was monitored with a microwave interferometer (λ=8mm), while local density disturbances were measured with mobile double and microwave probes. The spatial distribution of the electromagnetic fields was investigated by means of a mobile frame antenna with a diameter of 0.7cm, which was electrostatically shielded and insulated from the plasma by a layer of a dielectric material.

Two signals were simultaneously introduced into the transmitting antenna section, which consisted of a frame with a diameter of 5cm, which was electrostatically shielded but not insulated from the plasma: The first signal consisted of a continuous low-power (P=0.2W) probe signal whose frequency could be varied in a band from 10 to 500MHz, covering the entire whistler range; the second signal was a pump pulse (P_0=100W, f_0=60MHz) with duration t_i = 1.25ms (hatched region in Fig.2a).

The pump signal strongly modified the parameters of the surrounding plasma and influenced the efficiency of emission of probe waves and their directional pattern. As a result of the heating of the electrons near the antenna by the pump field and further thermal diffusion processes, a low-density channel stretching strongly along the magnetic field forms in the plasma. The probe waves are trapped in the plasma waveguide formed and propagate over large distances from the radiating antenna. The plasma nonuniformities thereby arising as a result of thermal nonlinearity form the directional pattern of the radiator for both the pump and the probe waves.

The structure of the high-frequency fields of the probe waves propagating in the plasma channel is interesting. It is known that at frequencies $\omega_0 < \omega_{he}/2$ quasilongitudinal whistlers with longitudinal wave number $k_z = \omega_{pe}(\omega/\omega_{he})$, where ω_0 is the frequency of the probe wave and ω_{pe} and ω_{he} are, respectively, the plasma frequency and gyrofrequency of the electrons and c is the speed of light in vacuum, can propagate in the high-density channel, while oblique whistlers propagate (conical-refraction waves with transverse wave number $k_\perp = \omega_{pe}/c$ in channels with low plasma density.

Figure 1a shows the plasma density distribution over the transverse cross section of the channel at the moment the pump wave operates (curve 2) and 0.1 ms after it is switched off (curve 3). The central maximum in the curve 2 is due to the structure of the vortex electric field of the wave. The transverse spatial scale of the thermal conductivity $L_{T\perp} \approx \rho_{eH}/(2m/M) \approx 2$cm ($m$ and M are the electron and ion masses, respectively, R_{eH} is the gyroradius of an electron) is of the order of the frame dimensions ($2a \approx 5$cm). Under such conditions the transverse nonuniformity of the electron temperature results in a nonuniform plasma density distribution in the channel. After the pump pulse is switched off, the maximum density at the center relaxes over a time $\tau_\perp \approx L_{T\perp}/(2.6)^2 \rho_{eH}^2 \nu_{ei} \approx 10^{-5}$ s (ν_{ei} is the

electron-ion collision frequency), i.e., much more rapidly than the entire channel with a radius of 6 cm is filled up (see Fig.2a, curve 2).

One can see that when a density maximum is present at channel center the field H_z is localized only at this maximum (Fig.1b). This attests to excitation of a quasi-longitudinal whistler mode. After the pump pulse is switched off and the channel becomes quasiuniform (curve 3 in Fig.1a), whistler waves with shorter wavelengths can propagate in it (specifically, conical-refraction waves (Fig.1c)).

Therefore whistler waves with different transverse wavelengths can be efficiently separated and then emitted into the surrounding plasma, i.e., the directional pattern of a frame radiator can be controlled by varying the shape of the plasma waveguide.

Information about matching of the antenna with the surrounding plasma was

Fig. 1. Transverse distributions: **a** - Plasma density (1 - unperturbed, 2 - during the pump pulse, *3* - 0,1 ms after the pump pulse ends); amplitude of the H_z component of the probe wave field in the channel: **b** - during the pump pulse, **c** - 0,1ms after the pump pulse ends.

extracted by analyzing oscillograms of the reflected signal in the feeder section. Such an oscillogram for the probe wave is presented in Fig.2b. One can see from this oscillogram that the amplitude of the reflected signal changes sharply when the pump wave is switched on or off. Such a rapid change in the input parameters of the antenna (occurring over times much shorter than the characteristic thermal-diffusion redistribution times of the plasma) attests to a strictional mechanism of the action on the plasma. This action is strongest in direct proximity to the antenna surface, where the electric fields are strong. It follows from the experimental data that almost complete antenna-feeder matching is observed after the pump pulse is switched off. The thermal channel relaxes to a uniform state over times $t_{rel} = 10^{-3}$ s, much longer than the characteristic matching time $t_{mash} = 10^{-4}$ s. It should be noted that no sharp changes in the amplitude of the reflected signal of the probe waves and no matching effect after the pump pulse was switched off were observed in the case of a frame coated with a
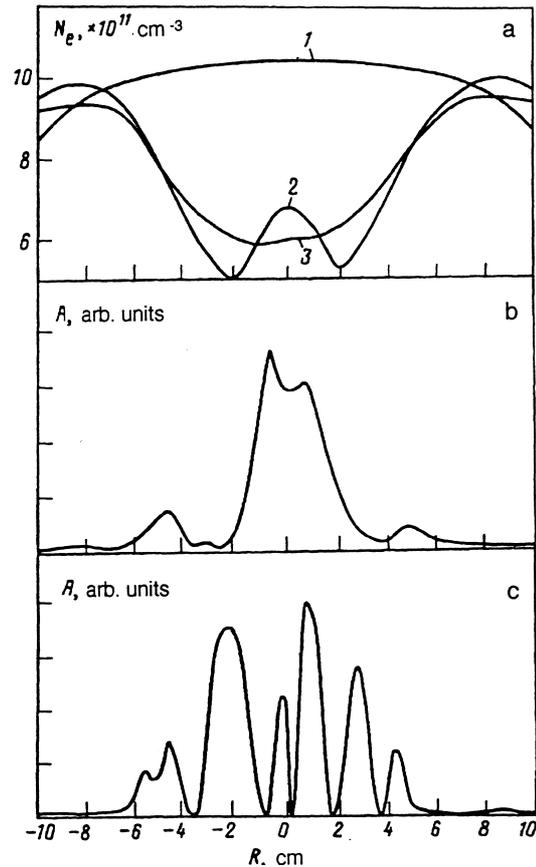
layer of insulating material much thicker than a double layer (curve 1 in Fig.2b), though a thermal channel of the same shape and characteristic size as for an antenna without an insulator did form in the plasma.

In summary, the strictional and thermal effects accompanying the whistler-range operation of a frame radiator in a magnetoactive plasma were investigated experimentally. It was shown that the feed and radiation characteristics of a frame antenna can be controlled by feeding a powerful high-frequency voltage pulse to the antenna. Strictional effects appreciably influence the input impedance of the antenna. Specifically, they can substantially improve the antenna-plasma matching, while the large-scale plasma nonuniformities formed as a result of heating change the directional pattern of the loop antenna.
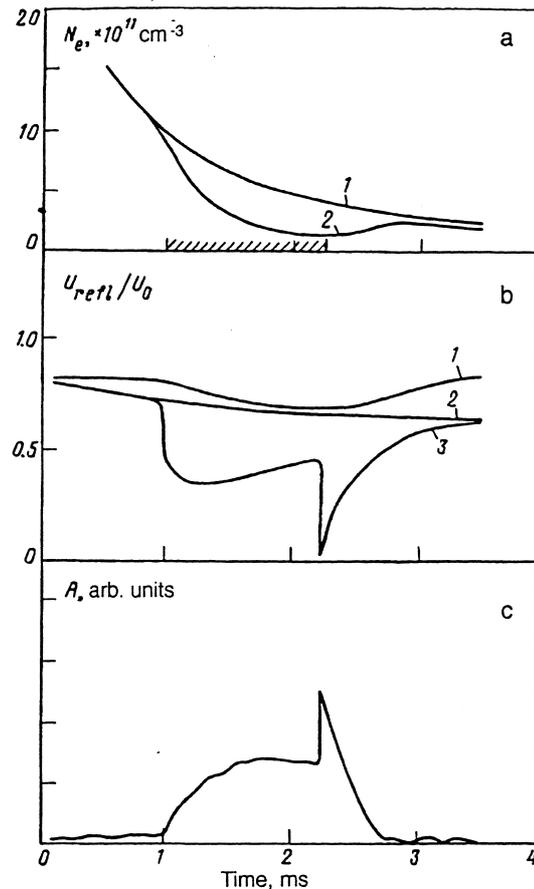
Acknowledgements

Fig. 2. a - Plasma density as a function of time: 1 - Undisturbed plasma and 2 - plasma disturbed by the pump pulse; **b** - oscillograms of the reflected wave in the feeder section at the probe frequency $f = 90$ MHz: 1 - antenna coated with a layer of insulating material in the presence of the pump pulse; 2 - uninsulated antenna without a pump wave, 3 - in the presence of a pump pulse, **c**- typical oscillogram of the H_z; component of the field of the probe wave with $f = 90$ MHz in the plasma channel at a distance z = 35 cm from the transmitting antenna.

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