

# INTERACTION OF A MODULATED ELECTRON BEAM WITH A MAGNETIZED PLASMA

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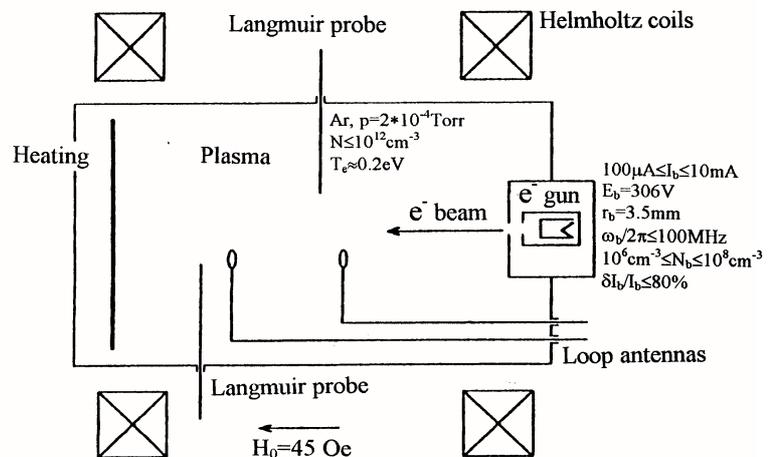
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**Abstract.** Experimental results concerning the interaction of a modulated electron beam with a magnetized plasma in the whistler frequency range are reported. It was shown experimentally that when a beam is injected into the plasma, waves can be generated by two possible mechanisms: Cherenkov emission of whistlers by the modulated beam, and transition radiation from the beam injection point. In the case of weak beam currents ( $n_b/n_p \ll 10^{-4}$ ) the Cherenkov resonance radiation is more than an order of magnitude stronger than the transition radiation, the Cherenkov emission efficiency decreases at high beam currents. The transformation of the distribution function of the beam is investigated for the case of weak beam currents. It is shown that in the case of the Cherenkov interaction with whistlers the beam is retarded and the beam distribution function becomes wider and acquires a plateau region.

The possibility of using modulated electron beams as an emitter of whistler-range waves has been discussed in recent years in application to active experiments in space. The theoretical works concerning this problem focus mainly on the analysis of the Cherenkov emission of electromagnetic waves in an infinite plasma and the first laboratory experiment demonstrated the possibility of such emission of whistlers. In the present work it was shown experimentally that besides Cherenkov radiation there exists in the entire volume a nonresonance radiation from the point where the modulated beam is injected into the plasma (transition radiation).

The experiments were performed on the apparatus shown schematically in Figure 1. The plasma source consisted of a heated oxide cathode and grid between which an accelerating voltage pulse was applied with repetition frequency 5Hz. The



**Fig. 1.** Schematic representation of the experimental set-up.

resulting accelerated-electron flux ionized the neutral gas (argon at pressure  $5 \times 10^{-4}$  Torr). As a result, a 70cm long and 50cm in diameter quasi-one-dimensional plasma column was produced in the vacuum chamber. The initial plasma density  $n_p$  was of the order of  $10^{12} \text{cm}^{-3}$  and then decreased with a characteristic time of 1ms (see Fig.3a below). The experiments were performed in the decomposing plasma regime. An electron temperature  $T_e=0,2\text{eV}$  was established at the plasma decomposition stage. Two Helmholtz coils (coil diameter 2m, coil separation - 1.5m) produced a uniform magnetic field. The magnetic field was equal to  $H_0=45-60 \text{ Oe}$ .

The electron gun used to produce a density-modulated beam consisted of a triode with a grid anode. The accelerating voltage was equal to 300V and the beam current could be varied from  $10^{-5}$  to  $10^{-2}\text{A}$ , which corresponds to density  $n_b$  from  $10^6$  to  $10^8 \text{cm}^{-3}$ . The beam diameter was equal to 7mm. The electron beam density was modulated with an rf voltage applied to the grid of the electron gun. The modulation frequency was  $f_m=50-100\text{MHz}$ , which corresponded to the whistler frequency range; the degree of modulation was of the order of 80%. The modulated beam was injected continually throughout the entire period of plasma decomposition. Only longitudinal beam injection into the plasma was used in the experiments, i.e., the pitch angle was always equal to zero.

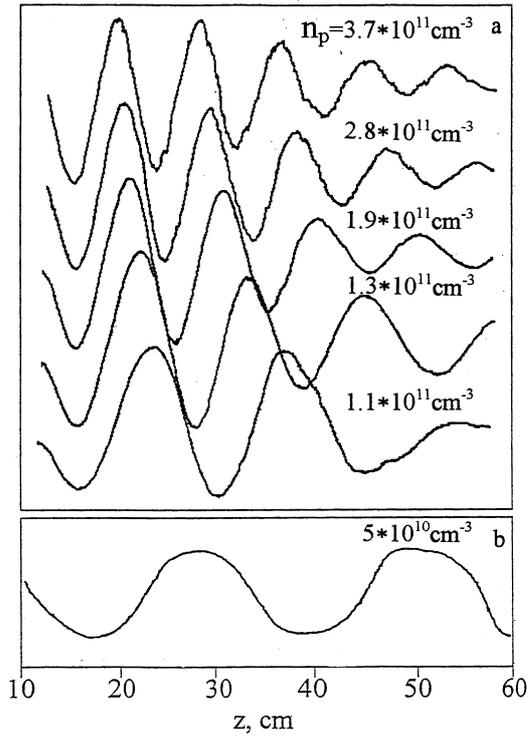
The energy distribution function of the electron beam was investigated with a multigrid analyzer. Two electrostatically shielded frame antennas, each of which could be moved in two directions — along the axis of the apparatus and in a radial direction — were used to study the structure of the fields excited in the plasma volume.

Whistlers excited through the Cherenkov resonance at the frequency of beam modulation  $f_m$  have a parallel wavelength  $\lambda_{||}^{\text{Ch}}$  equal to the spatial length  $2\pi/k_b$  of the beam modulation, i.e.,  $\lambda_{||}^{\text{Ch}}=2\pi/k_b=V_b/f_m$ . In contrast, the transition radiation, produced by a localized source near the injection point, excites at the frequency of modulation a wide angular spectrum of whistler waves and namely eigenmodes of the plasma system which propagate with different parallel wavelength  $\lambda_{||}^{\text{tr}}$  depending on the background plasma parameters.

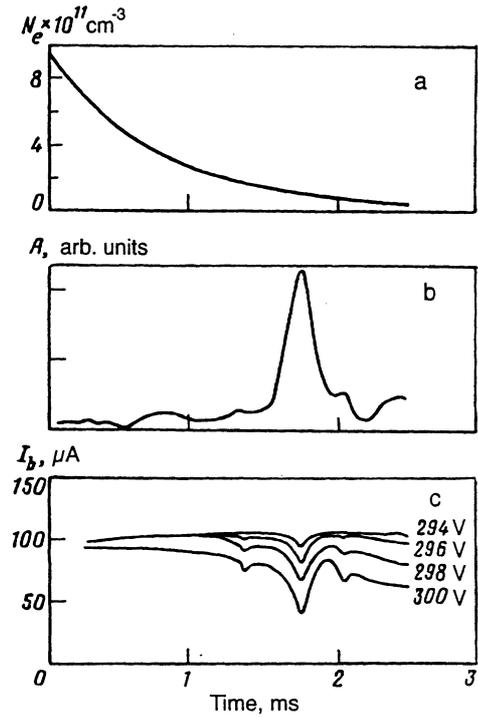
Analysis of the conditions for Cherenkov emission  $\omega=k_{||}V_b$ , shows that excitation of whistler waves with longitudinal wavelength  $\lambda_{||}^{\text{Ch}}=2\pi/k_b=V_b/f_m$  is possible if the plasma density is less than a critical value (for  $\omega_{pe} \gg \omega_{he} > \omega_o > (\omega_{he}\omega_{hi})^{1/2}$ ), determined from the condition  $\omega_{pe}^2 < \omega_{pe\text{CR}}^2 = k_{||}^2 c^2 (\omega_{he} - \omega) / \omega$ , where  $\omega_{pe}$  is the electron plasma frequency,  $\omega_{he}$  and  $\omega_{hi}$  are, respectively, the electron and ion gyrofrequencies,  $\lambda_{||}$  and  $k_{||}$  are, respectively, the wavelength and longitudinal wave number of the propagating wave, and  $c$  is the speed of light in vacuum. Outside the resonance region of the plasma this wave is a surface wave and is localized near the beam at a distance of the order of  $c/\omega_{pe}$ .

Fig. 2a shows interferometric measurements of whistlers emitted at plasma conditions preferential to the observation of transition radiation from the beam modulated at the

frequency  $f_m$ , for  $H_0=60$  Oe,  $E_b=300$ eV and  $f_m=50$ MHz. The parallel wavelength  $\lambda_{||}^{tr}$  of the whistlers registered at  $f_m$  increase when the plasma density decreases. The parallel wavelength  $\lambda_{||}^{Ch}$  of the whistlers excited through Cherenkov resonance are shown to be always larger than those measured at observational conditions preferential for transition radiation at some frequency (i.e., in dense plasma where  $n_p > n_p^{CR}$ ). All these circumstances convinced us that above the critical density the registered whistler waves can fit to transition radiation phenomena.



**Fig. 2.** (a) Excitation through transition radiation of whistlers: interferometric measurements obtained for  $H_0=60$  Oe,  $E_b=300$ eV and  $f_m=50$ MHz at different plasma densities (Cherenkov resonance conditions are not satisfied); (b) Excitation through Cherenkov resonance for  $H_0=60$  Oe,  $E_b=300$ eV,  $f_m=50$ MHz and  $n_e=5 \cdot 10^{10}$  cm<sup>-3</sup>.



**Fig. 3.** (a) Time dependence of the plasma density; (b) amplitude of the  $H_z$  component of the rf field in the plasma (the maximum corresponds to Cherenkov resonance conditions being satisfied). The beam current equals  $100 \mu A$  ( $n_b/n_p=10^{-4}$ ); (c) signal from the beam-particle analyzer for different values of the cutoff voltage on the analyzing grid.

The Cherenkov resonance radiation of the modulated electron beam (Fig. 3b) was reliably detected at low beam currents  $I_b < 10^{-4}$  A ( $n_b/n_o < 10^{-4}$ ). In this case the amplitude of the Cherenkov radiation was more than an order of magnitude greater than the amplitude of the whistler transition radiation. As the beam current increased, the efficiency of the Cherenkov emission decreased compared with that of whistler emission from the injection and absorption points.

Analysis of the energy distribution function of the electron beam shows that efficient retardation of the beam was observed when the Cherenkov resonance conditions were satisfied. The characteristic oscillograms of the beam current at the multigrid analyzer with different cutoff voltages are displayed in Fig. 3c. One can see that a decrease of the flux of electrons reaching the analyzer collector signifies retardation of the electron beam as it interacts with the plasma. The beam distribution functions in resonance and nonresonance situations are shown in Fig. 4a and 4b, respectively. The characteristic width of the beam distribution function in the absence of resonance is of the order of 6eV. When the resonance conditions are satisfied, the beam is retarded on the average, its width increases to 12eV, and a plateau forms in the distribution function.

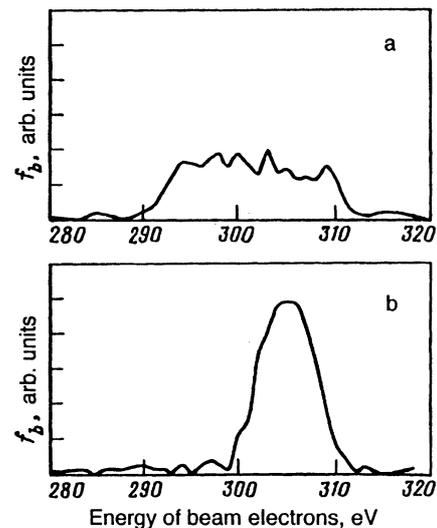
In summary, our experiments established that there exist two different mechanisms leading to whistler generation when a modulated electron beam is injected into a plasma: Cherenkov resonance radiation ( $\omega = k_{||}V_b$ ), and nonresonance transition radiation, which exists in a wide range of plasma densities. As the beam current increases ( $n_b/n_o < 10^{-4}$ ), the Cherenkov radiation efficiency decreases as a result of broadening of the beam distribution function accompanying transition radiation of electromagnetic waves at the beam injection point.

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**Fig. 4.** Distribution function of the beam (with current  $100 \mu A$  ( $n_b/n_p = 10^{-4}$ ); (a) - under Cherenkov resonance conditions (the average energy of the beam particles is approximately 300V, the width is 17V, and a plateau region is present); (b) - off the Cherenkov resonance (the average energy of the beam particles is 306V, and the width is 7V).