Direct observation of Langmuir turbulence in plasma by laser scattering

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It has been found experimentally that a Langmuir turbulence is excited in the interaction of an intense relativistic electron beam with a plasma. A narrow-band gas filter, which absorbs the output from a CO_2 laser on the R 14 transition, has made it possible to use the scattering method to study the turbulence.

In the experiments on the interaction of intense relativistic electron beams with plasmas which are being carried out in order to evaluate the possibilities for plasma heating through collective processes, the most important question from the physical standpoint is the nature of the waves which are excited by the beam in the plasma. In the theory of Breĭzman and Ryutov,[1] it is assumed that plasma waves (Langmuir waves) should be excited. By now we have a fair body of indirect experimental data which point to the excitation of plasma waves at the frequency ω_{pe} in the plasma.

For direct observation and study of the rf turbulence excited by a beam in a plasma, we have used the laser scattering method, detecting the scattered light at small angles from the direction of the incident light. The experiments were carried out on the GOL-M apparatus[2] with a plasma density $n_e = (0.5\text{–}2.5)\times 10^{15}$ cm^{-3}, a plasma column of length $L = 750$ cm, and a longitudinal magnetic field $H_0 = 2.5$ T. The energy of the beam electrons was $E = 0.5$ MeV, the density of relativistic electrons in the plasma was $n_b = (1\text{–}5)\times 10^{12}$ cm^{-3}, and the duration of the beam was $\tau_b \approx 100$ ns.

A single-mode CO_2 laser and a three-pass amplifier were used as the light source. The laser system provided an energy on the order of 10 J in the pulse at a pulse length of 0.07–2 μs.

Homodyne laser methods are used fairly widely to study low-frequency plasma waves.[3] Such methods are incapable of detecting electron plasma waves (the typical frequencies reach several hundred gigahertz in our case). Accordingly, a spectral instrument of the classical design with a diffraction grating was constructed for analyzing the spectrum of the laser light scattered by the rf turbulence.

The experimental layout is shown schematically in Fig. 1(a). The scattered light, resolved into a spectrum by the diffraction grating (150 lines/mm), is focused in the focal plane of the instrument, where there is a linear array of five Si:B photoresistors cooled with liquid helium. These detectors select a spectral interval on the order of 250 GHz wide. The position of this interval with respect to the laser output frequency can be varied.

The scattered light is detected at an angle $2\times10^{-3} < \alpha < 2\times10^{-2}$ rad from the propagation direction of the laser light. This angular interval corresponds to the scattering of the laser light by plasma waves with phase velocities close to the velocity of light and with wave vectors **K** making angles $\beta = 30$–$80°$ with the direction of the electron beam [Fig. 1(b)]. Other experimental layouts were also used. In those layouts it was possible to observe the scattering of the laser light by waves with wave vectors **K** at small angles ($\beta < 50°$) and also at angles $\beta \approx 100$–$150°$.

When the scattered light is detected at only a small angle from the incident light, there is the extremely serious problem of suppressing the laser light at the unshifted frequency, which penetrates through the spectral instrument and poses severe difficulties in the discrimination of small, frequency-shifted signals. This problem was solved by using as the light source a CO_2 laser operating on the R14 transition ($\lambda_0 = 10.29$ μm) and by using absorbing cells filled with ammonia to a pressure of 0.25 atm (the total length of the two cells was 40 cm). Since ammonia has a narrow absorption line, which coincides well with the R14 transition,[4] this band-stop filter suppressed the light at the output frequency by 12–13 orders of magnitude, while causing essentially no attenuation of the scattered light in the region $\lambda < \lambda_0$, where the measurements were carried out.

Figure 2 shows the spectrum of the scattered light detected simultaneously by several detectors at a plasma density $n_e \sim 2\times10^{15}$ cm^{-3}. As this plasma density is reduced, the spectral interval between the satellite and the unshifted laser frequency decreases. For waves with phase velocities $v \approx c$, the intensity of the scattered signal corresponding to wave vectors **K** making angles $\beta = 30$–$80°$ with the direction of the

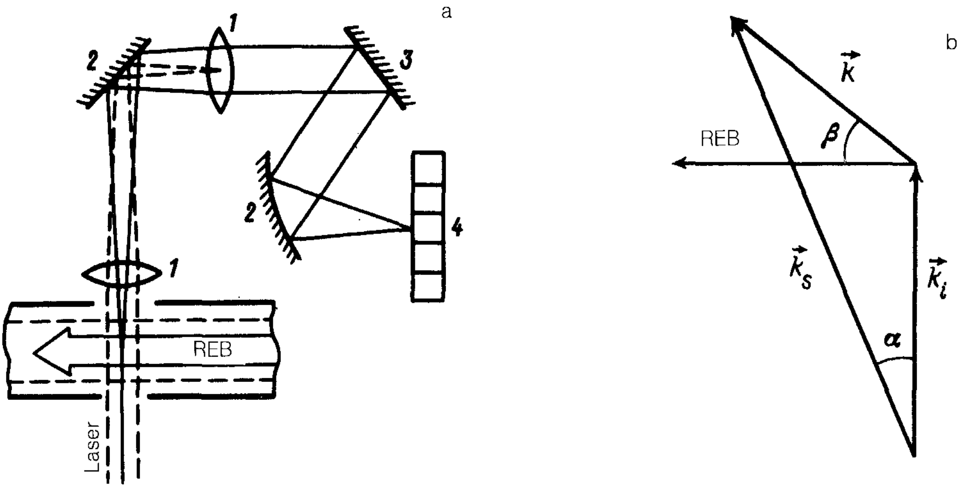

FIG. 1. a: Experimental layout. b: Geometry of wave vectors. 1—Mirrors; 2—lenses; 3—diffraction grating; 4—photoresistors. Here $\mathbf{K}_i$ and $\mathbf{K}_s$ are the wave vectors of the incident and scattered light; REB is the relativistic electron beam.

FIG. 2. Spectrum of the scattered light.

electron beam [Fig. 1(b)] is more than an order of magnitude greater than the intensity for the region $\beta = 100$–$150°$. These first experiments have thus yielded the following results.

1. It has been shown experimentally that a Langmuir turbulence is excited in the interaction of intense relativistic electron beams with plasmas.

2. In the course of the interaction, the power of the scattered light exceeds the equilibrium level by up to eight orders of magnitude. Such a substantial increase is observed only while the beam is passing through the plasma.

3. A pronounced anisotropy of the plasma waves with respect to the direction of the electron beam has been observed.

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