Oblique Langmuir solitons and their self-compression in the "free path" regime

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Slow (~motionless relative to the plasma) oblique Langmuir solitons with high-frequency (HF) population were observed experimentally for the first time in a magnetic collision-free plasma on the branch of the waves with linear Trayvelpis–Gould dispersion (1). The solitons are produced as a result of the modulation instability (self-compression) of nonliner waves and their evolution in the "free path" regime, i.e., after extinction of the electron "excitation beam."

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In this work, in contrast to Ref. 1a, first, the measurements are made *after* turning off the electron beam pumping that produces the plasma and excites the electron waves in it and, second, the diameter of the plasma pinch ($2a = 3$ cm) is less than the primary wavelength $\lambda_0 = U_0/f \approx 10$ cm ($U_0 \approx 2.5 \times 10^9$ cm sec^{-1} is the velocity of the electrons in the beam and $f \approx 2.5 \times 10^8$ sec^{-1} is the oscillation frequency), and the waves are oblique Langmuir waves. The procedure for the experiments is the same as before (Ref. 1), the plasma density is $n = (3–4) \times 10^9$ cm^{-3} (the Langmuir frequency is $f_p \approx 500$ MHz), the longitudinal magnetic field is $H \approx 2 \times 10^3$ Oe, the electron temperature is $T_e = 10–20$ eV, the residual gas pressure (hydrogen) is $p_0 \lesssim 5 \times 10^{-6}$ mm Hg, the plasma velocity is $(3–6) \times 10^6$ cm sec^{-1}, the length of the plasma pinch is ~200 cm, the plasma is collision-free,[1] the electron beam energy is $W_1 = 1–2$ keV, the current is $I = 0.5–2.5$ A, the beam density is $n_1 = (0.1–0.2)n$, and the length of the beam pulse is ~20 μsec. The major experimental results are as follows.

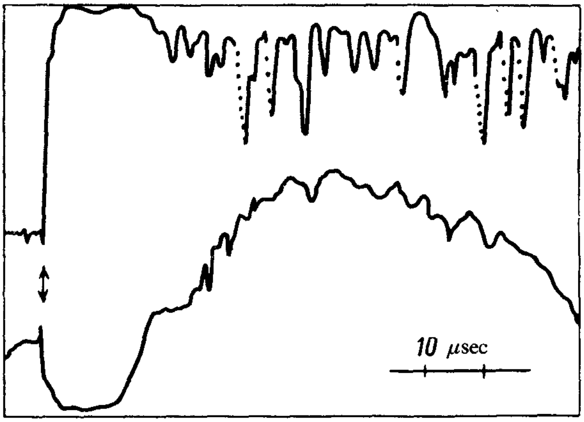

FIG. 1. Oscillograms of the plasma density indicators (the lower oscillogram denotes upward deflection of the beam) and of the amplitude envelope of the HF electric field (the upper oscillogram denotes downward deflection of the beam)[1] at a distance of 110 cm from the discharge chamber of the plasma source. The plasma velocity is $v \approx 2 \times 10^6$ cm/sec. The density holes denote downward beam deflection of the lower oscillograph.

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1. In the "afterglow" plasma, i.e., after the electron "pump beam" is turned off, clusters of oblique Langmuir waves with frequencies $f = 150\text{–}350\ \text{MHz} < f_p$ corresponding to the Trayvelpis-Gould mode are observed for a very long time (up to 100–200 μsec):

$$f = f_p \cos\theta = f_p \frac{k_{\parallel}}{(k_{\parallel}^2 + k_{\perp}^2)^{1/2}}, \qquad k_{\parallel} = 2\pi/\lambda, \qquad k_{\perp} \approx 1/a, \tag{1}$$

where λ is the longitudinal oscillation wavelength. The longitudinal dimension of the wave clusters is of the order of the diameter of the plasma pinch, and they are modulated sharply with respect to the amplitude with periods $\lambda_M = 5\text{–}6\ \text{cm} \approx \lambda_0/2$ and $\lambda_M = 10\text{–}12\ \text{cm} \approx \lambda_0$. This can be seen in Figs. 1 and 2, which show, along with the time dependence of the plasma density, oscillograms of the detected amplitude envelope of the HF waves. The spatial scales indicated are determined by multiplying the time scales by the velocity of the wave clusters; the latter is determined from the cluster transit time following the termination of the pump pulse (see Figs. 1 and 2).

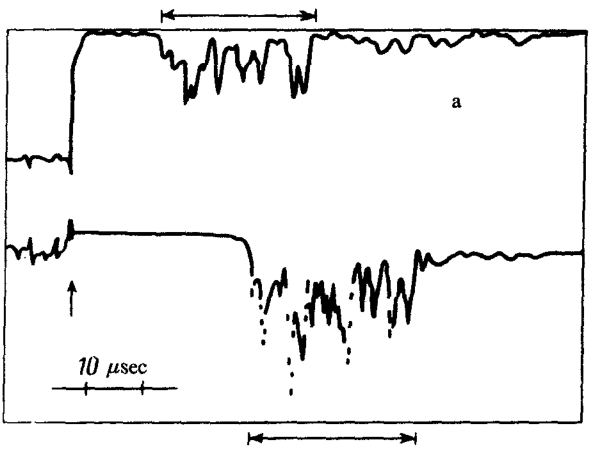
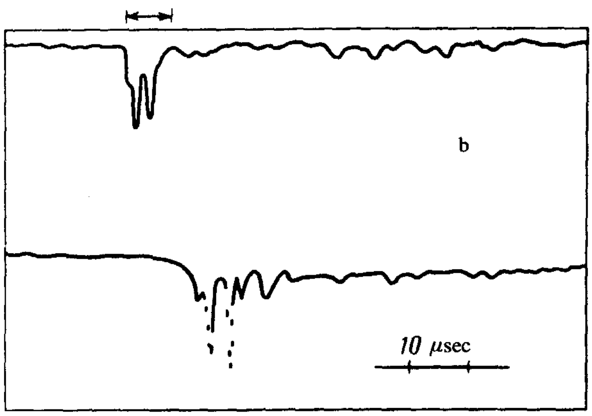


FIG. 2. The scanning rate is 10 μsec/division.



2. The modulation of the afterglow plasma density has the shape of holes and concentrations which correlate approximately with the wave clusters of the electric field—Fig. 1. Therefore, on the basis of the results of an earlier work,[1-3] the observed wave formations can be regarded as oblique Langmuir solitons with HF population (the period of the variation of the envelope is ~three orders of magnitude larger than that of the HF field).

3. The wave clusters, which propagate along the magnetic field without spreading out, move along with the plasma with a velocity close to that of the ion sound in atomic hydrogen, $C_s = (3\text{–}6)\times 10^6$ cm sec^{-1}. These conclusions were obtained by comparing the velocity of the wave clusters with that of the plasma. Figures 2a and 2b show the time shift in the oscillograms for two identical HF recording probes responding to the longitudinal plasma waves[1] placed 94 cm (a) and 80 cm (b) from one another and tuned to a frequency $f = 250$ MHz. (The oscillograms in Fig. 2 were obtained in a single "shot" of a beam using two identical detectors.) Clearly, the wave clusters travel a distance 80–94 cm without spreading out during the transit time of ~ 15 μsec, and move with the plasma at a velocity (on the average) of $\sim 6\times 10^6$ cm sec^{-1}.

4. The observed nonspreading wave clusters undergo a time evolution illustrated in Fig. 2. Thus, while the upper oscillogram (Fig. 2a) shows only the field peak "nuclei" in several places, the lower oscillogram 18–20 μsec clearly shows at the same positions but 18–20 μsec later (the plasma pinch has moved 94 cm along the magnetic field) the clusters produced in the electric field. Figure 2a is an example of the modulation instability (self-compression) of the investigated waves; for the indicated conditions its increment is $\gamma \gtrsim 10^5$ sec$^{-1} \approx (m/M) f_p$, where m and M are the electron and proton masses, respectively. Self-compression of the waves as a function of their motion (together with the plasma) along the device can also be seen in Fig. 2b; it can be seen that the field clusters become much narrower with time and are defined much more clearly.

5. The "lifetime" τ of the observed oblique Langmuir solitons in the "free path" mode is evidently greater than 20–30 μsec ($\sim 10^4$ periods).

Thus, in contrast to the linear wave packets which, first, for the dispersion (1) propagate rapidly in the plasma (with a velocity of $\sim 10^3$ C_s) and, second, rapidly spread out[1b]; the observed nonlinear wave clusters are oblique Langmuir solitons that are localized in the plasma (i.e., if in general they move relative to the plasma, C_s is slower, i.e., three orders of magnitude slower than the linear waves) and do not spread out, i.e., they undergo nonlinear self-compression.[2,1b] The mechanism for the self-compression apparently depends on the so-called OTSI—a type of modulation instability observed in Refs. 1a and 3, and is apparently unrelated to the Lighthill criterion.[2,1b]

6. The frequency spectrum of the observed solitons has a band of (40–50) MHz. Between the appearance of the oscillation clusters, a distinct time shift is observed in different regions of the frequency spectrum: the lower frequency oscillations appear much later at the far HF probe. Thus, 150-MHz waves arrive at the probe located ~ 100 cm from the plasma source $\sim 10\text{–}12$ μsec later than the 200-MHz waves, and approximately 20 μsec later than the 250 MHz waves, etc. This suggests a cascade

buildup of waves in the plasma, as a result of the collective processes of scattering and decay.[2]

Thus, slow oblique Langmuir solitons produced by the modulation instability of the Trayvelpis-Gould branch waves [Eq. 1)] were observed for the first time in this work. To avoid a misunderstanding, it should be noted that the same wave branch also contains other fast solitons observed in a number of experiments,[4] which have the following properties. First, in contrast to the slow solitons observed in this work, they are not HF-populated and do not occur as a result of the development of the modulation instability but due to the Korteweg-de Vries mechanism: as solitons in shallow water[2] or ion-acoustic solitons.[2,4] Second, they move at a velocity of the order of the velocity of the Trayvelpis-Gould linear waves (1), i.e., at least three orders of magnitude faster than the slow solitons observed in this work.

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