Modulation instability of Langmuir waves excited in a plasma by an electron beam

S. V. Antipov, M. V. Nezlin, E. N. Snezhkin, and A. S. Trubnikov

I. V. Kurchatov Institute of Atomic Energy

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It is demonstrated by experiment that Langmuir waves produced in a magnetized collisionless plasma by an electron beam are subject to a modulation instability that leads to soliton formation. The large-amplitude solitons have a width not larger than 25–30 electron Debye radii and a self-consistent well of density $\delta n/n \approx (5\text{–}10)\times 10^{-2}$.

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As already reported,[1] we are experimentally investigating the onset and the behavior of Lagmuir solitons in a plasma. In contrast to our first paper[1] (and also[2,3]), in the present study the Langmuir waves (from which the solitons are produced) were produced in the plasma not by an external electric RF field, but by an electron beam; this method of producing solitons seems much more natural and effective.

The experimental setup employs two beams: the first, as before,[1] produces the plasma, while the second excites the Langmuir waves in the plasma. Both beams are produced by the same gun, to which two independent accelerating-voltage pulses of separately adjustable amplitude are applied. The plasma produced by the first beam moves along the magnetic field on the axis of the apparatus (being rid at the same time of the neutral gas in a "delay line"[1]) and reaches the working volume $\sim 50\ \mu$sec after the first beam is turned off. The second beam is turned on during the entire time that the plasma is present in the working volume. The plasma density is $n \approx 3\times 10^9$ cm^{-3} (Langmuir frequency $f_p \approx 500$ MHz), electron temperature $T_e \approx 10$ eV, plasma-column parameter 3—4 cm, intensity of longitudinal magnetic field $H \approx 2000$ Oe, working gas—hydrogen, gas pressure in working volume $p \approx 3\times 10^{-6}$ mm Hg.

These experimental conditions differed substantially from the conditions used by others,[2–5] namely, in our experiments the plasma is, first, collisionless (because the neutral-gas pressure is lower by two orders of magnitude), and, second, magnetized (electron Larmor frequency $(eH/2\pi mc) \gg f_p$).

The main experimental fact with which this article deals is the following: *When the current of the second beam exceeds a certain threshold* (~ 3 mA at a beam-electron energy ~ 100 eV), the Langmuir oscillations excited in the plasma by the beam take the form of relatively infrequent but very powerful electric-field pulses (clusters) at a frequency 500 MHz. Simultaneously, a distinctly pronounced spatial modulation of the plasma density sets in: at the place where the wave clusters are localized, density "wells" appear, in which the electron density turns out to be much lower—as little as 5—10% of the density of the surrounding plasma.

This was observed in the following manner: Since the entire plasma moves

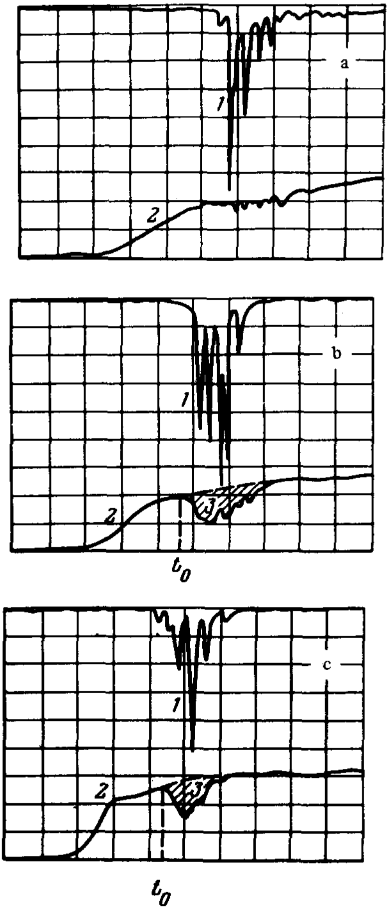

FIG. 1. 1—pulse Langmuir-wave electric-field, 2—plasma-density wells, 3—(shaded)—region of decreased density, a, b—$z = 30$ cm, c—$z = 10$ cm. The coordinate z of the measuring apparatus is reckoned from the "modulating" grid. Sweep—10 μsec/cm.

relative to the diagnostic apparatus (with velocity $(1-2)\times10^6$ cm/sec), we observe a space-time scan of the oscillations and of the plasma density. This is shown in Fig. 1, where the upper oscillogram is the envelope of the electric field of the Langmuir oscillations at the frequency $f = 500$ MHz $\approx f_p$ (measured in relative units with an RF grid probe), and the lower oscillogram shows the time dependence of the plasma density (measured with a diagnostic resonator).[1] It is seen that the field clusters of the Langmuir waves are localized in the plasma density wells, the depth of which δn reaches quite large values, $\delta n/n \approx 0.05-0.1$. The width of the wave clusters (at half-amplitude level) is smaller the large their intensity (or the larger the well depth). At $\delta n/n \approx 0.1$, this width certainly does not exceed 1 cm, i.e., 25—30 electron Debye radii r_D, and this estimate includes the resolution time (1 μsec) of the RF receiver (P5-20), and is therefore an upper bound. The plasma-density modulation is much stronger if a region of decreased density is produced in the plasma artificially (by applying a short voltage pulse on a pair of "modulating" grids near the entrance to working volume[1]) (Fig. 1). This region possibly acts like a resonator in which the ion-sound waves that form the plasma-density wells

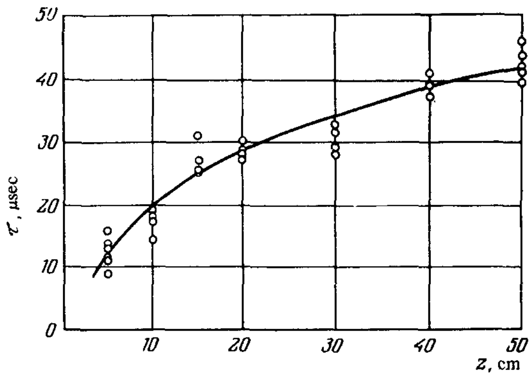

FIG. 2.

build up to a larger amplitude than in the absence of this region. It is also the "marker" used to measure the plasma velocity.

When the diagnostic apparatus is moved along the working volume, the observed picture of the Langmuir clusters and the associated density wells is significantly altered. Whereas at relatively large distances (z) from the "modulating" grids one observes an advanced modulation of the plasma density with clearly pronounced ion-sound waves and relatively larger numbers of Langmuir clusters (Figs. 1a, 1b, $z = 30$ cm), at short distances the ion-sound density modulation is not yet advanced enough, and only individual Langmuir clusters (one or two) are observed—Fig. 1c. This means that the characteristic length of the evolution of the wave clusters is of the order of 10—20 cm, i.e., the characteristic time is $\sim 10^{-5}$ sec (several thousand Langmuir periods).

The measurements have shown that the wave clusters localized in the plasma-density wells move together with the plasma, at the same velocity, i.e., they are immobile relative to the plasma. This fact follows already from a comparison of Figs. 1b and 1c, and is also illustrated by Fig. 2, which shows the delay τ between the arrival of the signals at the RF probe and at the diagonostic resonator as a function of the displacement of these devices along the working volume. It is seen that the wave clusters negotiate freely in the apparatus a distance not less than 50 cm, in a time 25—40 μsec; in other words, the lifetime of the clusters is at least 2×10^4 periods of the electron plasma oscillations. The clusters observed at larger distances from the entrance to the working volume usually turn out to be larger in magnitude and narrower. All their attributes and properties identify these Langmuir-wave electric-field clusters "trapped" in the plasma-density wells that they produce as Langmuir solitons.[6] Under the conditions of our experiments, the solitons are in first approximation immobile relative to the plasma.

Thus, we have observed for the first time a modulation instability of electron-beam-driven Langmuir waves in a collisionless magnetized plasma. The instability leads to a spatial redistribution of the oscillation energy. The resultant wave clusters produce density "wells" in which they are localized and form Langmuir solitons, which are approximately immobile relative to the plasma. The solitons with larger amplitude are narrower in width. The ratio of the relative depth of the density well (5—10%) to the soliton widths (not exceeding $(25\text{—}30)r_D$) is close to the theoretical value.[6] The soliton lifetime is not less than 30—40 μsec, i.e., it is at least several dozen thousands of Langmuir-oscillation periods.

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