Experimental study of electron trapping in an ion acoustic soliton

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Résumé. — Le piégeage électronique dans un soliton acoustique-ionique est étudié expérimentalement grâce à l'analyse des caractéristiques instantanées du plasma obtenues par échantillonnage rapide du courant de sonde dont la polarisation est commandée numériquement. Les données sont traitées par un moyenneur de signal. La relation expérimentale entre les fluctuations de densité et de potentiel n'est pas une distribution de Boltzmann. Ceci peut s'interpréter par l'existence d'une population d'électrons piégés. L'importance de ce piégeage est évaluée à l'aide du modèle de Schamel.

Abstract. — Electron-trapping in ion-acoustic solitons is experimentally investigated by means of « instantaneous » probe characteristics in the soliton, obtained by fast sampling of the probe current; the probe is biased *via* a D.A.C. and the data can be processed by a signal-averager. The measured relationship between density and potential fluctuations is not the Boltzmann distribution. This may be explained by the existence of a trapped electron population. The trapping efficiency is estimated using Schamel's theory.

1. Ion acoustic solitons and electron trapping.

The ion acoustic mode is a cold ion plasma mode with no magnetic field. The phase velocity of large wavelength linear waves is the ion acoustic velocity $C_s = (KT_e/M_i)^{1/2}$ where T_e is the electron temperature and M_i is the ion mass. A weakly nonlinear wave (with a relative amplitude $\delta n/n_0 \lesssim 0.2$, with n_0 the plasma density) can evolve into an ion acoustic soliton [1-5]. Such a soliton propagates without damping at a supersonic velocity.

For plane solitons, under the assumption of weak nonlinearity, the Mach number M ($M = V/C$ where V is the propagation velocity) is given by

$$M = 1 + \frac{1}{3} \frac{\delta n}{n_0}. \tag{1}$$

A soliton is characterized by positive density and potential fluctuations δn and $\delta\phi$ such that :

$$\frac{\delta n}{n_0} = \exp\left(\frac{\delta\phi}{T_e}\right) - 1, \tag{2}$$

which, for small $\delta\phi/T_e$, may be expanded as :

$$\frac{\delta n}{n_0} = \frac{\delta\phi}{T_e} + \frac{1}{2}\left(\frac{\delta\phi}{T_e}\right)^2 .$$ (3)

When the density fluctuation becomes large enough, the interaction of the electrons with the positive potential of the soliton can no longer be neglected : electrons with small kinetic energy ($E_c < e.\delta\phi$, e the electron charge) are trapped into the soliton potential, thus modifying the relationship 2 between potential and density, as well as the soliton velocity, equation 1.

A theory of electron trapping by an ion acoustic soliton was proposed by H. Schamel [6, 7]. In this model, the « free » and « trapped » parts of the electron distribution functions are assumed to be continuous and there is a BGK [8] equilibrium. The parameter

$$\beta = T_{ef}/T_{et}$$ (4)

where T_{ef} and T_{et} are the free and trapped electron temperatures, plays a crucial rôle in the theory. The case $\beta = 1$ recovers the usual KdV assumption, with no trapping, while the case $\beta = 0$ corresponds to maximum trapping and plateau formation all over the trapping velocity range [9].

Equation 3 is strongly modified by trapping and becomes

$$\frac{\delta n}{n_0} = \delta\phi/T_e - \frac{3}{4}(1 - \beta)(\delta\phi/T_e)^{3/2} + \frac{1}{2} \cdot (\delta\phi/T_e)^2 .$$ (5)

In the following, we want to compare equation 5 with experiments on ion acoustic solitons.

2. Experimental method and results.

The experiments where carried out in a multipole D.P. device (2 m long and 60 cm in diameter) [10, 11]. The development of the Double-Plasma device allows the experimental study of plasma one-dimensional ion acoustic solitons [12].

A negatively biased grid, 50 cm in diameter, is placed in the middle plane. Solitons are excited by applying a voltage pulse between the source plasma and the target plasma. A plane shielded Langmuir probe, continuously movable along the axis of plasma machine, is located in the target plasma. The collecting surface (6 mm in diameter) is parallel to the middle plane grid. The probe detects the solitons as they travel along the discharge. Figure 1 shows the time evolution of the electron density ; the probe is 8 cm from the grid : a large amplitude soliton is followed by two smaller solitons. We used systematically the main soliton to obtain the experimental relationship between δn and $\delta\phi$ for comparison with equation 5.

Rather than the analogue technique previously used by others [13-14] to obtain the « instantaneous » or « perturbed » probe characteristics, we have used a fast sampling technique of the probe current. The probe potential is increased by means of a Digital-Analog Converter. The sampling time corresponds to the peak arrival of the soliton at the probe (or any other time, according to the region of the perturbation we want to measure) : the current amplitude at that time is digitized and stored in the fast sampling unit. The D.A.C. is then triggered, and so on until the whole probe characteristic is stored. These characteristics can be processed by a signal averager. The block-diagram of the data acquisition system is given in figure 2.

Figure 3 shows two superposed instantaneous probe characteristics measured, the first in the unperturbed plasma and the other at the top of a soliton with an amplitude $\delta n/n_0 = 0.24$. The (unperturbed) plasma potential V_{po} increases to the value V_{ps} when the soliton reaches the probe (both of these values are given by the intersection of the selection region and saturation
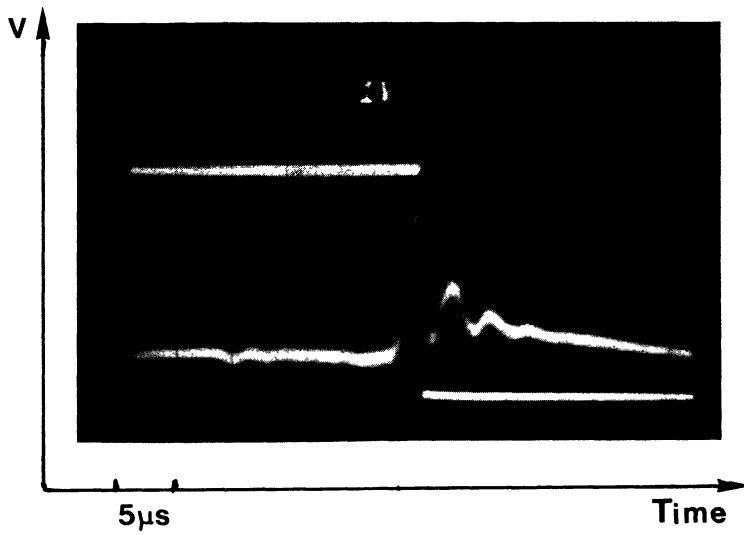
Fig. 1. — Plot of the electron density perturbation *versus* time : the nonlinear pulse evolve into a soliton train. The super imposed step signal triggers the D.A.C. by which the probe is biased.
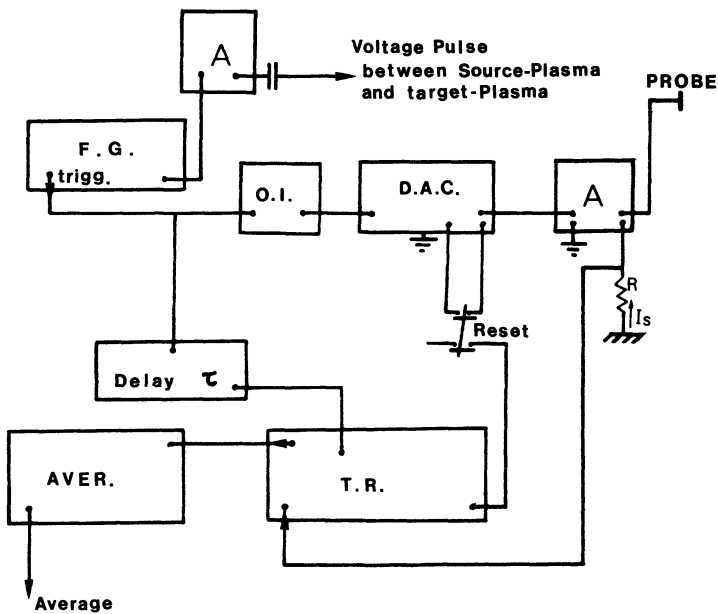

Fig. 2. — Circuit diagram for the instantaneous characteristics measurement. A : Amplifier, D.A.C. : Digital-Analogue Converter, O.I. : Optical Insulator, AVER. : Correlator-Averager (Honeywell SAI 48), T.R. : Transient-Recorder (Biomation 8100).
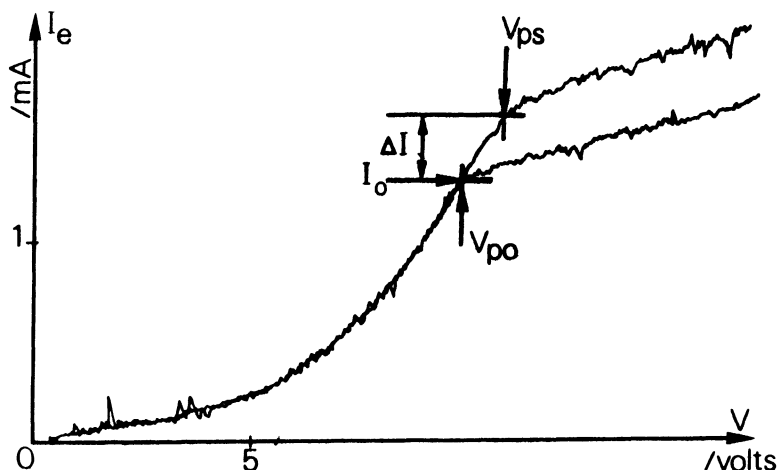
Fig. 3. — Plot of two averaged « instantaneous » probe characteristics in the unperturbed plasma (plasma potential V_{po}) and at the top of a soliton (plasma potential V_{ps}).

level). The potential fluctuation is given by :

$$\delta\phi = V_{ps} - V_{po}. \qquad (6)$$

The electron temperature T_e is derived as usual from the semi-log plots of the probe characteristics. The relative density fluctuation is related to the relative electron current fluctuation (taking account of the plasma potential shift) by :

$$\frac{\delta n}{n_0} = \frac{\Delta I}{I_0}. \qquad (7)$$

By varying the soliton amplitude, we finally obtain $\delta n/n_0$ as a function of $\delta\phi/T_e$ (Fig. 4). Three different theoretical curves ($\beta = 0$, 0.5 and 1) are displayed for comparison.

3. Discussion.

First, we shall show that the bounce frequency ν_b for trapped electrons is much greater than the various collision frequencies (that spread out electron velocities) and than the effective collision frequency for the electron-wall interaction (which can cause the transverse loss of trapped electrons). That is :

$$\nu_b \gg \nu_c, \ \nu_{ee}, \ \nu_{en}$$

where ν_c is the electron-wall effective collision frequency, ν_{ee} and ν_{en} are the electron-electron and electron-neutral collision frequencies.

We use the usual relations for ν_{ee} and ν_{en} [15] and we define :

$$\nu_b = (2 \, e\phi/m)^{1/2}/\lambda$$
$$\nu_b/\nu_c = (\delta\phi)^{1/2} \, L/\lambda$$

(where L is the plasma radius and λ is the soliton width). With the experimental parameters

$$T_e = 3\text{-}5 \text{ eV}, \quad n_0 = 5 \times 10^9 \text{ - } 5 \times 10^{10} \text{ cm}^{-3}, \quad p = 8 \times 10^{-5} \text{ - } 5 \times 10^{-4} \text{ torr},$$
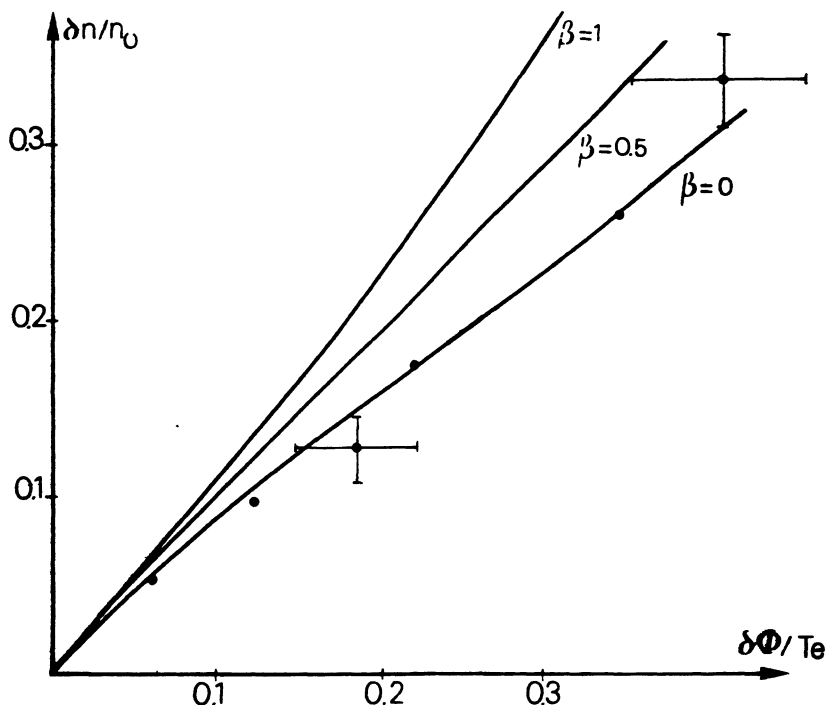$$L \simeq 30 \text{ cm} \quad \text{and} \quad \lambda = 1 \text{ cm}.$$

Fig. 4. — Density fluctuation $\delta n/n_0$ versus potential fluctuation. Solid lines are equation 5 for various $\beta = T_{el}/T_{ep}$, circles (●) are experimental results with error bars.

We find that the above inequalities are indeed valid. In particular, one has $v_b/v_c \simeq 30$. In previous works [14], this ratio was more critical ($v_b/v_c = 6$).

Hence, we conclude that electrons can be trapped by the soliton. A comparison of the experimental results with the theoretical curves (Fig. 4) sets an upper limit on β (in the framework of the theory of ref. 6) :

$$0 < \beta < 0.5 .$$

Obviously, β should decrease when the amplitude increases, since trapping becomes more effective, but this effect can not be observed because of the experimental accuracy. The derivatives of the probe characteristics obtained for the largest solitons (Fig. 5) indicate clearly a perturbation of the electron velocity distribution in the trapping region. Again the accuracy is too poor to assert that β is strictly zero which would correspond to plateau formation.

We note that most of the experiments have been carried out in the multi-soliton regime. This is not accounted for in Schamel's theory. Since trapping effects occur mainly for the highest soliton we expect that the experimental situation may be described by Schamel's theory.
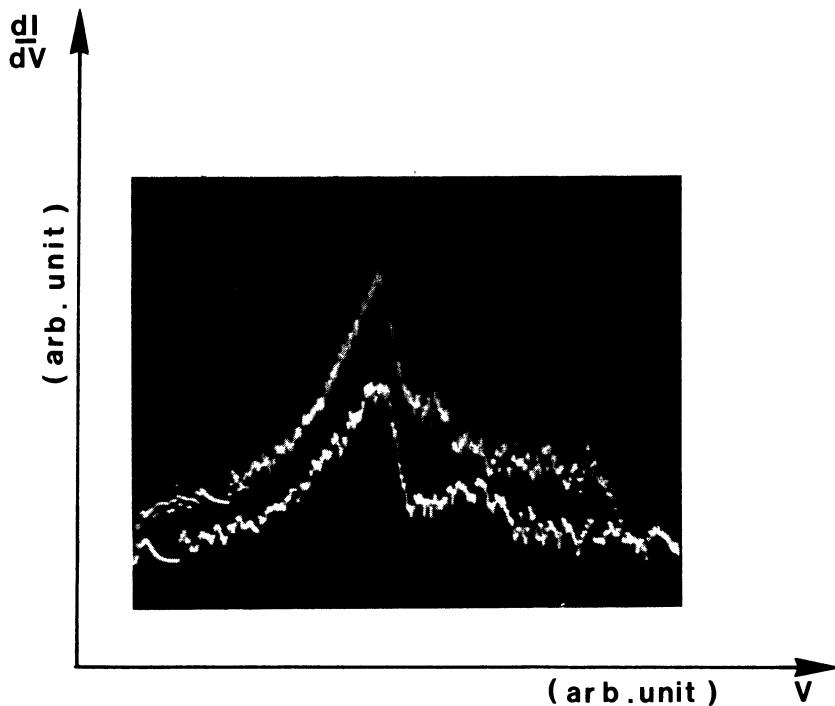
Fig. 5. — Derived probe characteristic. In the unperturbed plasma (upper trace). At the top of a soliton (lower trace).

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