Evolution of the distribution of ion density in potential wells of a velocity-modulated neutralized ion beam

V. F. Virko and G. S. Kirichenko

Institute of Nuclear Research, Academy of Sciences of the Ukrainian SSR, Kiev
(Submitted 23 January 1980)
Zh. Eksp. Teor. Fiz. 79, 143–149 (July 1980)

A discontinuity of the current and an associated potential well for ions appeared in a neutralized ion beam whose velocity was reduced abruptly by external modulation. Free oscillatory motion of the beam ions trapped in the well became disturbed during the first quarter of an oscillation period because of the space charge of the ions themselves. The dynamics of filling of the current discontinuity with ions was found to be governed by the excitation of a strongly nonlinear ion-acoustic wave process in the potential well. This produced bunches of trapped ions inside the discontinuity and the density of these bunches was comparable with the beam density.

PACS numbers: 41.80.Gg

The capture of plasma particles by the field of a finite-amplitude potential wave is an important process in many nonlinear phenomena such as nonlinear Landau damping, formation of steady-state waves etc. We shall describe an experimental study of the process of capture of ions from a monoenergetic neutralized ion beam at minima of the potential created by modulation of the beam velocity. It is pointed out that the space charge of ions trapped by a potential well alters qualitatively the pattern of their motion in the phase space compared with the case of oscillations of noninteracting particles in a well.

APPARATUS

Use was made of a beam of potassium ions traveling against the background of cold electrons which neutralized the space charge of the beam. The apparatus (Fig. 1) was in the form of a cylindrical copper chamber with a source of potassium ions, operating on the surface ionization principle, at one end. An accelerating grid 2 was grounded and the ion energy was governed by the voltage U applied to a heated tungsten disk 1 which was the ion emitter. The length of the chamber was 36 cm, its diameter was 10 cm, the diameter of the tungsten emitter was 4 cm, the energy of the ion beam was $eU\sim 100-200$ eV and the ion beam was ~1 mA (the ion density was $n_0\sim 10^8$ cm^{-3}). Under working conditions the pressure in the chamber was $\sim 10^{-5}$ Torr. The space charge of the beam was compensated by electrons emitted from heated neutralizer filaments 3. The static distribution of the potential along the axis of the system, measured with a heated probe, had the form shown schematically at the top of Fig. 1. The residual potential in the beam was 10–15 V and the termperature of the neutralizing electrons was $T_e\sim 1$ eV.

The ion velocity was modulated by subjecting the emitter not only to a static accelerating voltage U but also, at the time $t=0$, to a negative polarity pulse from a generator 4; the amplitude of this pulse ΔU was up to 60 V and its leading edge was ~0.1 μsec. This caused the beam velocity to decrease abruptly from $V_1=(2eU/M)^{1/2}$ to $V_2=(2eU-\Delta U)/M)^{1/2}$, where e and M are the ion charge and mass. Lagging of the slower part of the beam produced a density perturbation which gradually expanded, drifted together with the ion beam along the axis of the system, and at some distance from the source was recorded by a mobile electrostatic analyzer 5 and an oscilloscope 6. The energy distribution of the beam ions could be reconstructed at any moment by analyzing oscillograms of the collector current from the analyzer obtained for various analyzing-grid potentials. An alternating potential assocaited with the density perturbation was measured with an insulated probe 7.

EXPERIMENTAL RESULTS

At low modulation amplitudes corresponding to $\Delta V = V_1 - V_2 \ll C_s$ (C_s is the ion sound velocity) two ion-acoustic waves appeared in the beam and they traveled in opposite directions from the point where the velocity changed abruptly. In the case described by $\Delta V \gtrsim 2C_s$ a density perturbation became a discontinuity of the beam current. One could then expect the time dependence of the ion current density measured at a distance L from the source to be similar to that shown in Fig. 2a. Here, 1 is the current in the faster beam, 2 is the current in the slower beam, and 3 is the discontinuity region where there are no ions; $t_0=L/V_0$ is the average flight time to the analyzer and $V_0=(V_1+V_2)/2$. The width of the discontinuity δ is governed by the velocities V_1 and V_2 and by the distance from the point where the analysis is made:

$$\delta=2L\frac{V_1-V_2}{V_1+V_2}.$$

However, the experimental distribution of the ion density in the discontinuity region was much more complex.

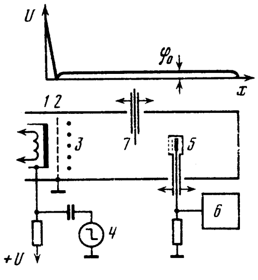

FIG. 1. Schematic diagram of the apparatus.

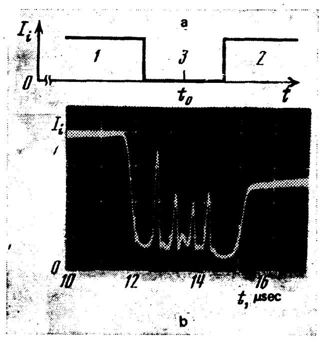

FIG. 2. Calculated time dependence of the ion current (a) and oscillogram of the ion current reaching the analyzer collector (b).

For example, an oscillogram of the ion current reaching the analyzer collector located at a distance $L = 36$ cm from the source had the form shown in Fig. 2b when the initial ion energy was 180 eV and the modulation amplitude was $\Delta U = 60$ V. The discontinuity region was filled by isolated ion bunches in which the density was comparable with the density in the unperturbed beam. The density of the ions between these bunches of peaks ($n \sim 2 \times 10^7$ cm^{-3}) did not fall to zero anywhere inside the discontinuity.

The results of our investigation of the spatial evolution of the ion density in the discontinuity region are presented in Fig. 3. Oscillograms of the ion current (upper row of traces) and of the alternating potential, measured with the insulated probe (middle row of traces), are shown for various distances L from the source. The latter oscillograms demonstrate the appearance and evolution of a potential well in the region of the ion velocity discontinuity. The lower series of graphs are the results obtained by treatment of the relevant characteristics of the electrostatic analyzer. The ordinates on the curves correspond to the analyzing grid potentials at which the derivative of the ion current with respect to the retarding potential is maximal. They show the ion energy in the laboratory coordinate system at each point of the ion current oscillogram. This series of graphs in Fig. 3 effectively gives the distributions, on the phase plane, of ions "draining" into the potential well from its walls. The abscissa gives the distances x in a coordinate system moving at the well velocity V_0. The ions at the edges of the discontinuity are accelerated toward its center, which is manifested by the acceleration of the slower beam and deceleration of the faster beam in a laboratory coordinate system. As the beam moves in the drift space, the potential drop and width of the discontinuity increase and a growing density peak appears at the center of the discontinuity. At the moment of formation of this peak the derivative $d\varepsilon/dx$ of the energy distribution reaches its maximum value, indicating bunching of ions with different velocities in the central plane of the well ($x = 0$). Subsequently, the peak splits into two components moving in opposite directions. Next, a new density peak appears at the center and it splits in the same way as the first, and so on. Under conditions in our experiments the number of peaks was five and it was clearly limited by the length of the system.

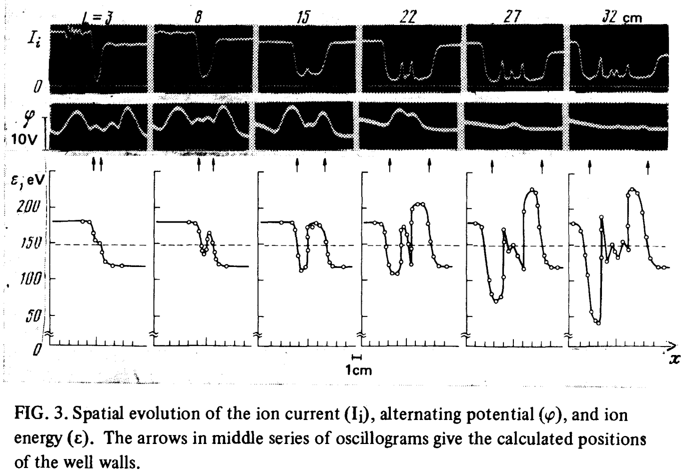

FIG. 3. Spatial evolution of the ion current (I_i), alternating potential (φ), and ion energy (ε). The arrows in middle series of oscillograms give the calculated positions of the well walls.

The peak trajectories are shown in Fig. 4, where the abscissa gives the distance L from the source and the ordinate represents the distance from the center of the discontinuity in a coordinate system traveling with the ion beam. This figure includes also the experimentally observed and calculated, for a given beam velocity (dashed lines), positions of the discontinuity edges. The profile of the potential associated with the discontinuity region generally repeats the distribution of the ion density but is somewhat flatter (Fig. 3).

DISCUSSION OF RESULTS

A potential well created in an ion beam as a result of modulation of its velocity is not stationary; its width increases linearly with time. Clearly, the motion of ions to the center of the well from its walls is possible only if the depth of the well is sufficient so that

$$e\varphi > {}^1/_2 M(V_1 - V_0)^2.$$

The minimum depth of the potential well corresponding to this condition is then ~ 1.5 V. We can see from Fig. 3 that the depth of the potential well reaches $\gtrsim 10$ V sufficiently far from the source and that this depth is more than one order of magnitude greater than the thermal energy of the neutralizing electrons. This well depth is confirmed by an independent analysis of the ion energy spectrum. The observed (3) change in the energy $\Delta\varepsilon$ of ions accelerated in the region of the well walls implies the presence, in a coordinate system linked to the well, of a potential drop φ given by

$$e\varphi \sim (\Delta\varepsilon)^2/4\varepsilon_0, \quad \varepsilon_0 = MV_0^2/2.$$

Using the results of Fig. 3 ($L = 26$ cm, $\Delta\varepsilon \approx 100$ eV,

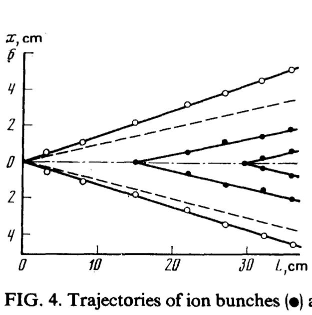

FIG. 4. Trajectories of ion bunches (●) and discontinuity boundaries (○).

$\varepsilon_0 = 150$ eV), we find that the well depth is $\varphi \approx 15$ V. On the other hand, the potential φ_m which would have been created by ions filling the discontinuity in the absence of compensation is fairly high. Since far from the source the width of the discontinuity is comparable with the diameter of the chamber, we can estimate φ_m approximately as the potential at the center of a spherical region of radius R = 5 cm containing ions of density $n \gtrsim 2 \times 10^7$ cm$^{-3} \approx 1/5\, n_0$:

$$\varphi_m = {}^2/_3 \pi R^2 en \gtrsim 150\,\mathrm{V},$$

so that there is no doubt about the presence of the neutralizing electrons in the discontinuity region.

The existence in an ion beam plasma of a potential well of depth $\varphi \gg T_e/e$ means that the neutralizing electrons have not only the thermal energy but also the energy of directional motion acquired because of the difference between the neutralizer and plasma potentials.

Growth of the potential well depth with time results in the trapping of ions arriving from its walls. It is usual to assume (see, for example, Ref. 1) that the trapped ions do not interact with one another and that their motion in the potential well can be represented schematically on the phase plane V, x (see Fig. 5; the ions moving in the positive direction of the x axis occupy the lower half-plane and the original distribution of ions is uniform along the x axis). In this case the phase velocity rotates anticlockwise at an angular frequency,

$$\omega(x) = \frac{\pi}{2}\left[\int_0^x \frac{d\xi}{\{2e[\varphi(x) - \varphi(\xi)]/M\}^{1/2}}\right]^{-1},$$

which decreases on approach to the separatrix (shown dashed). Then, at the points $dV/dx \to \infty$ the velocity bunching of ions gives rise to peaks in the density profile $n(x)$. These density peaks are created at the origin at the frequency $2\omega(0)/2\pi$ and they eventually diverge to the periphery in the same way as found experimentally (Fig. 3). However, this process should produce a multivalued velocity distribution of the ions filling the inner region between the peaks, which does not agree with the experimental results.

In our experiments the formation of the first ion bunch at the point $x = 0$ is accompanied by the appearance of a local potential maximum (see Fig. 3, $L = 15$ cm). This maximum prevents interpenetration of the fluxes of the ions "draining" from the well walls to the center, as deduced from the phase trajectories. The corresponding

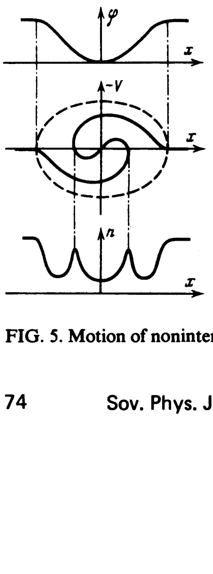

FIG. 5. Motion of noninteracting trapped ions in the phase plane.

amplitude of the potential

$$\varphi' \approx \frac{M}{2e}\left[\left(\frac{2e\varphi}{M}\right)^{1/2} - (V_1 - V_0)\right]^2 \approx 3\mathrm{V}$$

(under the conditions of Fig. 3, $L = 15$ cm) is confirmed experimentally. Clearly, the accumulation of the space charge of the ions near the $x = 0$ plane stops because of the appearance of two density waves diverging from the center ($L = 22$ cm). The potential drops associated with the fronts of these waves decelerate the ions moving from the well walls in the same way as at $x = 0$. At the same time a new density peak ($L = 27$ cm) appears in the same plane and this peak then splits into two waves ($L = 32$ cm). The value of dV/dx near $x = 0$ oscillates at a frequency close to the plasma frequency of ions in the region of the discontinuity ($n \sim 2 \times 10^7$ cm^{-3}),

$$\omega_{pi}/2\pi \approx 1{,}5 \cdot 10^5\ \mathrm{sec}^{-1}.$$

It is clear from Fig. 4 that the distance between the points of appearance of the peaks is $\Delta L \approx 15$ cm, which corresponds to a frequency $f \simeq V_0/\Delta L \sim 1.8 \cdot 10^5$ sec^{-1} close to the ion frequency.

The wave nature of the process of filling of the potential well with particles is confirmed by the fact that the distribution of the ion velocities in the phase plane is always the same. The velocities of the waves (density peaks) diverging from the center are $v = V_0 \Delta x/\Delta L \approx 2.3 \times 10^5$ cm/sec in the coordinate system of the beam (Fig. 4), which is comparable with the velocity of the fastest ions in a peak, i.e., at the wavefronts the ions are decelerated to practically zero velocity. Thus, the density peaks can be interpreted as strongly nonlinear ion waves in which the "oscillatory" particle velocity is comparable with the wave velocity. The nonlinear nature of these waves is indicated also by their shape and a clear tendency for traveling in solitary manner, as shown in Figs. 2 and 3.

Formation of nonlinear isolated waves in a system of opposite neutralized ion beams was investigated by us earlier[2] and it was found that such waves have the ion-acoustic nature. Although in the present experiments the nature of the electron distribution function governing the wave dispersion in the discontinuity region was not known, we can assume that the electron temperature does not differ greatly from T_e characterizing an unperturbed plasma. In this case the propagated waves can also be regarded as ion-acoustic and the ratio of their width to the electron Debye radius is of the order of

$$\lambda/d_e \sim 5,$$

whereas the velocity in the system linked to the well center is

$$v \sim 1{,}4 C_s$$

($C_s \sim 1.5 \times 10^5$ cm/sec is the velocity of linear long-wavelength ion-acoustic perturbations at $T_e \sim 1$ eV). We should mention also that the amplitude of the potential for internal peaks (in Fig. 3) is comparable with the maximum potential in an ion-acoustic soliton of maximum amplitude ($\varphi \sim 1.3 T_e$), whereas in the case of peripheral peaks the discontinuity of the potential is considerably greater at the leading edge.

It is known that in a system of interpenetrating opposite ion beams moving at a velocity $V \lesssim C_s$, one can expect an aperiodic $\mathrm{Re}\,\omega = 0$ ion-acoustic instability. In our case this condition is violated already during the formation of a well when its depth becomes $\varphi \gtrsim T_e/e$. Moreover, interpenetration of the opposite beams is not observed experimentally in the $x = 0$ plane, i.e., the waves are not excited by the two-stream instability but by the initial bunching of ions whose flight time to the plane is approximately the same because of the approximately parabolic nature of the potential near the bottom of the well.

As shown above, the nature of the motion of ions trapped in a potential well of an ion beam is largely governed by the space charge of the ions. The phase trajectories of the ions then differ qualitatively from the case of motion of noninteracting trapped particles. In particular, the ion space charge prevents the appearance of multivelocity motion typical of the case of free oscillations of charges in the well field. The phase picture of these motions is disturbed already after the first quarter of the period ω when the trapped ions first collect near the bottom of the well. The rapid accumulation of this space charge results in generation of nonlinear ion waves diverging to the walls at a supersonic velocity. The process of wave creation is characterized by a frequency close to the ion plasma value, which corresponds to the density near the bottom of the potential well. The resultant bunches of the ion density resemble the formation of a sequence of ion-acoustic solitons as a result of decay of a low-frequency large-amplitude perturbation in a plasma.[3]

It follows that the dynamics of filling of a current discontinuity in an ion beam is associated with the excitation of a strongly nonlinear wave process caused by the interaction of the trapped ions.

[1]B.B. Kadomtsev, Kollektivnye yavleniya v plazme (Collective Phenomena in Plasma), Nauka, *M.*, 1976.
[2]V.F. Virko and G.S. Kirichenko, Zh. Eksp. Teor. Fiz. **77**, 1943 (1979) [Sov. Phys. JETP **50**, 923 (1979)].
[3]Yu.A. Berezin and V.I. Karpman, Zh. Eksp. Teor. Fiz. **51**, 1557 (1966) [Sov. Phys. JETP **24** 1049 (1967)].

Translated by A. Tybulewicz

Pair production by photons in a dense pinch

B. É. Meĭerovich

Institute of Physics Problems, USSR Academy of Sciences
(Submitted 7 February 1980)
Zh. Eksp. Teor. Fiz. **79**, 150–161 (July 1980)

The production of electron-positron pairs by photons in the electromagnetic field of a strongly compressed discharge current channel is investigated. The dependence of the cross section on the pinch radius is connected mainly with the need of transfering the momentum to the electromagnetic field. With increasing channel radius, the cross section decreases rapidly because of the impossibility of momentum transfer. For high-energy gamma quanta, the main contribution is made by the region of distances far from the axis. In this case the cross section is determined by the logarithmic asymptotic expression for the field of a current regarded as a charged current carrying filament, and is independent of the radius. It is shown that with the aid of the pair-production process it is possible in principle to resolve the spatial structure of the pinch in the angstrom range, and consequently to determine experimentally whether the strong compression to the linear-atom state, predicted by the theory of equilibrium and radiation of a strong-current plasma, can be realized in pinches.

PACS numbers: 52.55.Ez

1. INTRODUCTION

An analysis of the phenomena that accompany the pinch effect in a high-current diode,[1-5] based on the theory of equilibrium[6] and collisionless radiation[7,8] of a dense high-current plasma, leads to the conclusion that the compression of the current channel can proceed up to degeneracy of the electrons, i.e., up to the density of the condensed state at high temperatures. The presence of such an unusual state of matter, the so-called linear atom,[9] makes it possible to explain consistently an aggregate of phenomena that accompany the pinch efect. Nonetheless, to prove experimentally the presence of linear atoms in the pinches, direct measurements must be made of the channel radius in the angstrom band during the nanosecond durations of the supercompressions.

The traditional methods of plasma study by means of its own radiation do not permit direct measurement of the radius of the current channel in the angstron band. The difficulty of measuring the radius of a pinch compressed to the state of electron degeneracy are similar to those encountered, for example, when attempts are made to determine the radius of the hydrogen atom from its emission. If the high-current compression reaches the state of electron degeneracy, i.e., atomic dimensions, then the electrons in the field of the current become likewise subject to the laws of quantum electrody-

 0038-5646/80/070075-07$02.40