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C. Lan[1,2] and I. D. Kaganovich[2]

AFFILIATIONS

[1]Institute of Fluid Physics, China Academy of Engineering Physics, Mianyang 621900, People's Republic of China
[2]Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA

ABSTRACT

The excitation and propagation of electrostatic solitary waves (ESWs) are observed in two-dimensional particle-in-cell simulations of ion beam neutralization by electron injection by a filament. Electrons from the filament are attracted by positive ions and bounce inside the ion beam pulse. Bouncing back and forth electron streams start to mix, creating two-stream instability. The instability saturates with the formation of ESWs. These ESWs reach several centimeters in longitudinal size and are stable for a long time ($\gg\tau_b$, the duration of the ion beam pulse). The excitation of large-amplitude ESWs reduces the degree of neutralization of the ion beam pulse. In addition, the dissipation of ESWs causes heating of neutralizing electrons and their escape from the ion beam, leading to a further reduction of neutralization degree. The appearance of these waves can explain the results of previous experimental studies, which showed poor ion beam neutralization by electro-emitting filaments.

Ion beam neutralization has attracted much attention in the past few decades and finds applications in many fields involving astrophysics,[1] accelerator applications,[2] inertial fusion, in particular, fast ignition[3] and heavy ion fusion,[4] and ion beam based surface engineering.[5] In laboratory, these electrons can come from gas ionization caused by ion beams, hot emission of filaments, secondary electron emission caused by ion bombardment on metals, or preformed plasma in the channel of ion beam propagation. Because of the mass disparity between ions and electrons, this process can occur rapidly on the time scale of intense pulsed beams. As a typical application, the heavy ion fusion research facility like NDCX requires near-complete (99%) space charge neutralization.[6,29] Incomplete neutralization results in transverse emittance growth, even defocusing of the ion beam. In ion beam etching or nanopantography, space charge compensation is particularly important for ion beams with high current density.[5] One of the central issues of ion beam neutralization is to determine what factors would affect the ultimate degree of charge and current neutralization. In the past two decades, it has been found that these factors include a solenoidal magnetic field,[7] large-amplitude plasma wave excitation,[8,9] and the way of electron supply.[6] In this Letter, we show that a new mechanism, i.e., the excitation of nonlinear electrostatic solitary waves (ESWs), can essentially affect the capture of electrons and the degree of ion beam neutralization.

ESWs were originally discovered during simulations of the nonlinear stage of the two-stream instability[10] and have been observed in space and laboratory plasmas for many years.[11–19] See Hutchinson's paper for a recent review of ESWs.[20] But surprisingly, as far as we know, they have never been reported in ion beam neutralization experiments, and even never been mentioned or investigated in related literature studies. In those space observations, ESWs are usually positive potential structures moving along the ambient magnetic field with the typical speed on the order of 1000 km/s and duration on the order of 10 ms.[21] In phase space, in order to support a positive potential structure, trapped electrons form a localized hole. So, ESWs are also often referred to by other related terms such as electron holes.[22,23] The formation of these ESWs in current-carrying plasmas has been described in Refs. 24 and 25. But in this Letter, the ion beam motion relative to electrons is considered. For ion beam neutralization, decreased electron density results in a local maximum in charge density and hence in electric potential. The effect of solitons on the degree of ion beam neutralization and the transverse movement of ions cannot be ignored.

ESWs are essentially a type of Bernstein-Greene-Kruskal (BGK) mode[26] and do not experience any decay in one-dimensional plasma. However, the existence and stability criteria for multidimensional ESWs in unmagnetized plasmas are still under study. In Ref. 20, it was summarized that for the existence of multidimensional ESWS, "there must be a strong enough magnetic field and distribution-function anisotropy." In unmagnetized plasmas, Ng and Bhattacharjee have shown that a distribution function that depends on both energy and angular momentum is also a possible condition.[27] Although ESWs can be formed in multidimension, they unavoidably experience transverse modulation and break-up.[20,28] For the propagation and neutralization of ion beam pulses in a channel or a chamber, problems are at least two dimensional (2D). Whether ESWs can be excited and be even stable propagating in such a multidimensional system is still unknown.

In the present Letter, we study by simulation the neutralization of a long ion beam pulse by electron injection. Previous simulations of ESWs generally assume that initial plasma is composed of two or more components of electrons with different velocity distributions,[10,21,22] which provides some default environments for the excitation of solitons. But here, these initial conditions for electrons are not necessary. The basic features of the neutralization process, for instance, ion beam propagation and electron injection, are preserved in our model. We investigate such a process using a 2D particle-in-cell (PIC) code and show the behavior of electrons in an ion beam pulse that has never been reported before.

We simulated long Gaussian-like Ar^+ ion beam pulses traveling in a metal pipe. The model is 2D in the x–y cartesian coordinate system, where x is the traveling direction of ion beams and y is the transverse direction. The size of the computational domain is 80 cm × 3 cm. The energy and the maximal density of the ion beam are $E_b = 38$ keV and $n_b = 1.75 \times 10^{14}\ \mathrm{m}^{-3}$, respectively. The parameters of ion beam pulses were chosen to be close to those of Princeton Advanced Test Stand at PPPL.[29] Because beam velocity V_b satisfies $V_b/c \ll 1$, where c is the speed of light in vacuum, for these parameters, the self-magnetic field can be neglected, and so, the computation is totally electrostatic. Ion beam pulses enter the computational domain from the left boundary and leave from the right boundary. All the outer boundaries are absorbing boundaries for particles. Electrons were injected on the axis of the ion beam. Without loss of generality, the temperature of injected electrons is set to the typical temperature (∼0.2 eV) of electrons emitted from a hot filament.[30,31] Coulomb collisions were neglected as they only weakly affect the neutralization process. The cell size of the uniform grid is $\Delta l = 0.25$ mm, and the time step of simulations is $\Delta t = 40$ ps. The temperature of neutralizing electrons can be far higher than the initial temperature of electrons emitted from the filament. Therefore, the Debye length λ_d evaluated with the ion beam density and the temperature of neutralizing electrons satisfies $\Delta l < \lambda_d$.

When electrons are attracted by a positive ion beam pulse, electrons experience a complex process in the potential well of the ion beam pulse. Figure 1 shows how electrons interact with the potential well and are captured by the ion beam pulse. For the approaching space-charge potential well, downstream injected electrons are first accelerated and then reflected by the potential well. Some of these reflected electrons then once again are reflected by the other side of the potential well. Meanwhile, the potential of the ion beam drops due to the filling of electrons into the potential well, leading to the escape of fast electrons and the capture of slow electrons. Thus, bouncing back and forth of trapped electrons naturally forms two streams in the potential well of the ion beam pulse, which will cause the occurrence of instability in phase space.

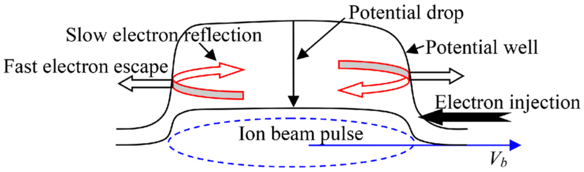

FIG. 1. Schematic of two-stream instability generation due to the potential well of the ion beam pulse. The dashed ellipse represents the ion beam pulse. Electrons are injected downstream.

Our simulations confirmed the existence of the above physical mechanism and the possibility of subsequent excitation of ESWs after two-stream instability evolving into the nonlinear stage. The results are shown in Fig. 2.

Figure 2 shows temporal evolutions of electron and ion densities on the x axis and the corresponding kinetic variation of electrons in x–v_x phase space during the neutralization. At $t = 635$ ns, the ion beam pulse has crossed the injection point where the filament is located ($x = 20$ cm). The zigzag distribution of electron density and the appearance of peaks at the edges of the ion beam pulse indicate that some injected electrons are reflected by the head and the tail of the ion beam pulse and two-stream instability is developing although most electrons still pass through the ion beam pulse and are lost on the left wall. With the ion beam pulse moving forward, at 707 ns, we see that almost all new-injected electrons are reflected by the potential well and the electron stream generates a big circle in the phase space. However, self-triggered two-stream instability leads to the mixing of electrons in the phase space and the split of this big electron hole into several smaller ones. The initial evolution stage of the two stream instability lasts until about 800 ns. In this stage, it is readily seen that some relatively small electron holes start to appear from $t = 779$. Meanwhile, as electrons are continued to be injected, the neutralization degree of the ion beam pulse keeps on increasing.

When the two-stream instability evolves into the second stage, we see that small electron holes tend to coalesce and generate a large density hole (see $t = 995$–1283 ns). After about a few hundred nanoseconds of coalescence, this large electron density hole becomes a stably solitary structure, namely, ESW. In this period, beam neutralization basically saturates. Except for the location where the solitary wave is, other parts of the ion beam pulse reach near-complete neutralization.

The coalescence process of small electron holes results in the formation of the ESW. To our surprise, the ESW moves rapidly inside the ion beam pulse, and when the ESW reaches the axial boundaries of the ion beam pulse, it can be reflected back with almost the same amplitude. As a result, the ESW moves back and forth periodically between the head and the tail of the ion beam pulse. In the phase space, the movement of the ESW is presented in a way of clockwise rotation (just like around a running track).

Figure 3 shows variations of electron density and the potential on the axis when the ESW moves in different directions. The parameters of the ESW can be roughly estimated. In density space, the amplitude of the ESW reaches at least 2/5 of ion density and its longitudinal size reaches about 5 cm, close to 1/3 of the ion beam length. The positive potential peak caused by localized density deficit of electrons is about 20 V, that is, 2/3 of residual ion beam potential. The period of the motion of the ESW is about 300 ns, close to the duration of the ion beam pulse. The speed of the ESW (V_s) relative to the ion beam pulse ($V_b = 37.5\ \mathrm{cm}/\mu\mathrm{s}$) is about 87 cm/μs (or 870 km/s), and the relative speeds in positive and negative directions are almost the same.

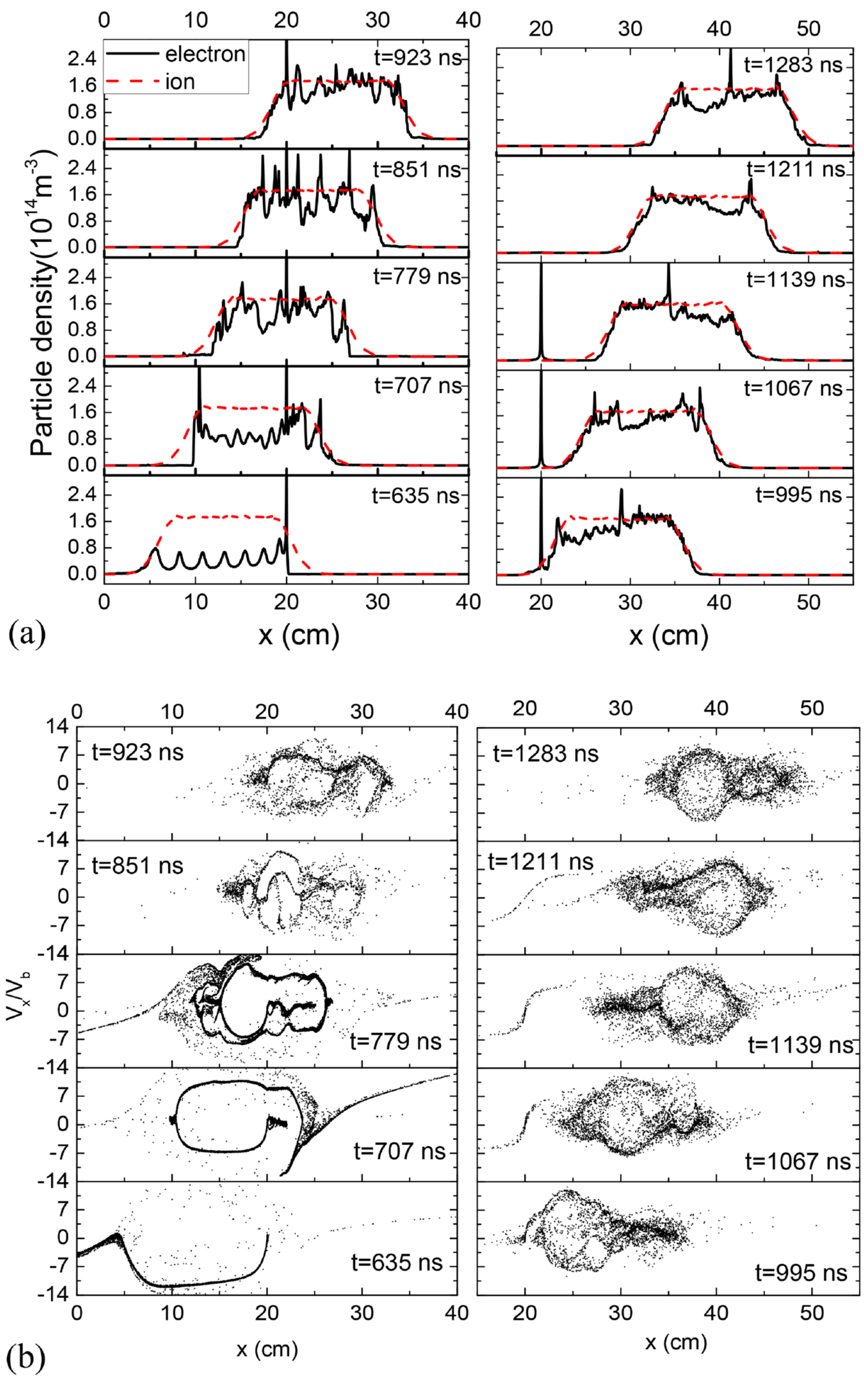

FIG. 2. Temporal evolutions of particle densities on the axis (a) and electrons in x-v_x phase space (b). The electron velocity is normalized to the ion beam velocity of $V_b = 37.5\,\mathrm{cm}/\mu\mathrm{s}$. The simulated source of the electron, which is located at $x = 20\,\mathrm{cm}$, is a line source with a length of 2 mm in the y direction. Electrons with $T_e = 0.2\,\mathrm{eV}$ are injected uniformly from 0 to 1.2 μs. The injected electron current I_e is 2/3 of ion beam current I_i. The flattop of the ion beam is 250 ns ($\sim$11 cm). At the edges, the ion beam was taken to the form $n_b\exp(-t^2/t_b^2)$, where $n_b = 1.75 \times 10^{14}\,\mathrm{m}^{-3}$ and $t_b = 60\,\mathrm{ns}$. The profile of the ion beam in the y direction was taken to the form $n_b\exp(-y^2/w_b^2)$, where $w_b = 2\,\mathrm{mm}$. Multimedia views: https://doi.org/10.1063/1.5093760.1; https://doi.org/10.1063/1.5093760.2

In order to obtain the long lifetime of the ESW in a finite computational domain, periodic boundary conditions in the x direction were applied. Then, the ion beam pulse can reenter the computational domain after it exits from the right boundary. By recording time-dependent periodic voltage fluctuations of ion beam pulses at a certain point, the lifetime of the ESWs can be evaluated. In addition, to investigate the effects of ESWs on the neutralization of the ion beam pulse, the time-dependent variation of the neutralization degree was also recorded, as shown in Fig. 4. The neutralization degree of the ion beam pulse is calculated by $\eta = Q_e/Q_i$, where Q_e and Q_i are the charges of electrons and ions in the whole computational domain, respectively.

It is readily seen from Fig. 4 that there are three periods of beam potential which have relatively intense ESW signals. After the sixth period (5 μs), the ESW cannot be visibly seen. So, the propagation of

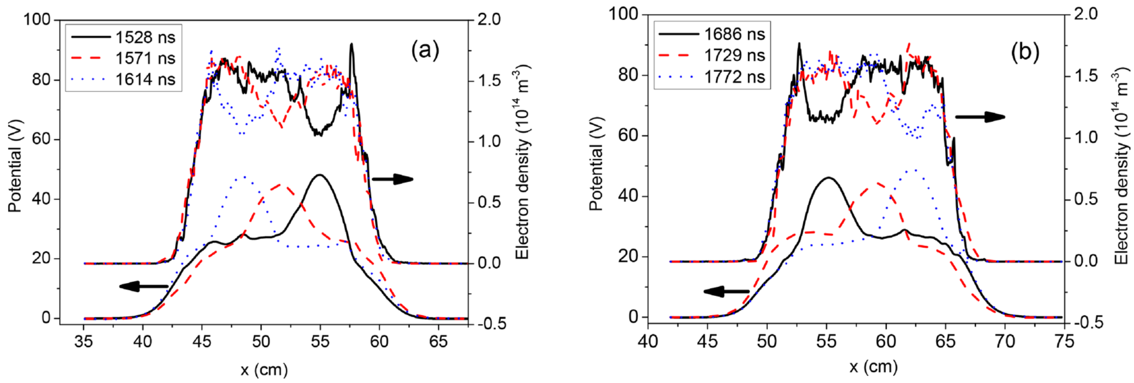

FIG. 3. Distributions of the electron densities and the potentials on the axis at different moments. The moving ion beam pulse is taken as a frame of reference. Two figures correspond to the propagation of the solitary wave to the left (a) and right (b).

the ESW lasts until 4–5 μs, and its lifetime is about 3.5 μs, which is much longer than the duration of the ion beam pulse.

The ESW would eventually decay to zero. The reason for the decay may be associated with the multidimension feature of the ESW. According to the existence and stability criteria for ESWs presented in Ref. 20, this 2D ESW generated in nonmagnetized plasma is inherently unstable. But its long life still surprised us. Besides, the negative mass instability of trapped electrons in nonlinear plasma waves is another possible reason for the decay of the ESW.[32,33]

On the other hand, we see that because of the excitation of the ESWs, the maximal value of η only reaches 0.75 (solid line, $I_e/I_i = 2/3$). Then, it decays to a stable value ($\sim$0.64) with the attenuation of the ESW. The correlation between them indicates that the attenuation of the ESW could lead to a gradual reduction of η. The reason for reduction is the heating of neutralizing electrons caused by the dissipation of the ESW. Once the energies of these thermalized electrons exceed the residual beam potential, they escape from the ion beam pulse. Therefore, it is concluded that *besides the excitation of the ESW, the attenuation of the ESW is another mechanism that causes the reduction of* η.

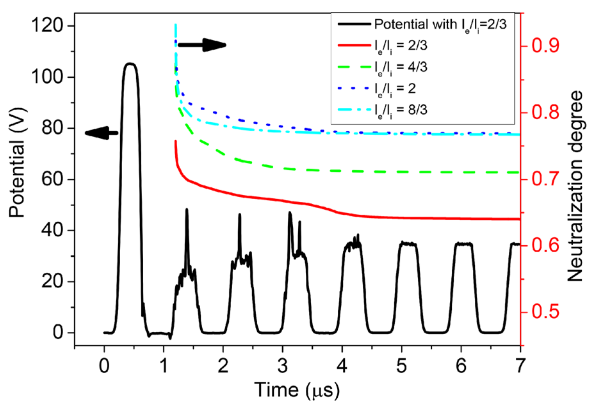

FIG. 4. Temporal evolutions of the potential recorded at $x = 5$ cm on the axis and the neutralization degrees of the ion beam pulse for different injected electron currents. The size of the computational domain is 40 cm $\times$ 3 cm.

Figure 4 also shows the influence of injected current I_e on η. When I_e is increased to three times the original value, the neutralization of the ion beam pulse tends to saturate. However, from the attenuation of the neutralization degree, it is conjectured that the excitation of ESWs still occurs. So, simply increasing the injected electron current cannot completely eliminates the excitation of ESWs.

To achieve near complete neutralization of the ion beam pulse, any excitation of ESWs and electron heating due to ESW-plasma interactions have to be minimized. One proposed method is to use a longitudinally extended electron source instead of a thin emitter. To prove the effectiveness of this method, we made electrons uniformly inject into an area ($\Delta x \times \Delta y = 10$ cm $\times$ 2 mm); meanwhile, injected current was increased to 4/3 of ion beam current. Figure 5 shows the simulation results. It is evident that the generation of electron holes is suppressed by injection of new electrons from downstream, and no any ESWs with the amplitude comparable to that shown in Fig. 2 are created. The neutralization degree of the ion beam pulse finally reaches about 0.95, much higher than previous cases. However, more carefully observing the potential waveform, it can be found that ESWs still exist, and even, the number of solitary waves is more than 2. But their relative amplitudes are very small. Therefore, the effect of these solitary waves on the neutralization degree is not significant. In previous experimental studies, it has been concluded that electrons produced through thermionic emission cannot neutralize the ion beam well enough, and volumetric plasma can provide better charge neutralization for the ion beam.[5,31] It is reasonable to believe that the excitation of ESWs possibly is the main reason for that.

To summarize, we have presented 2D PIC simulation studies of the excitation and propagation of the ESWs during ion beam neutralization. We find that the capture process of electrons by the ion beam pulse can cause the occurrence of the two-stream instability of electrons, and more importantly, this instability quickly evolves into stable moving nonlinear ESWs. The ESWs with the longitudinal size reaching several centimeters can reflect back and forth between the two ends of the ion beam pulse and last far longer than the duration of the ion beam pulse. The excitation of the ESWs reduces the neutralization degree of the ion beam pulse. During the dissipation of ESWs, neutralizing electrons get energy from the ESWs and escape from the ion beam, leading to a further reduction of the degree of neutralization. Simulations also show that simply increasing the injected electron

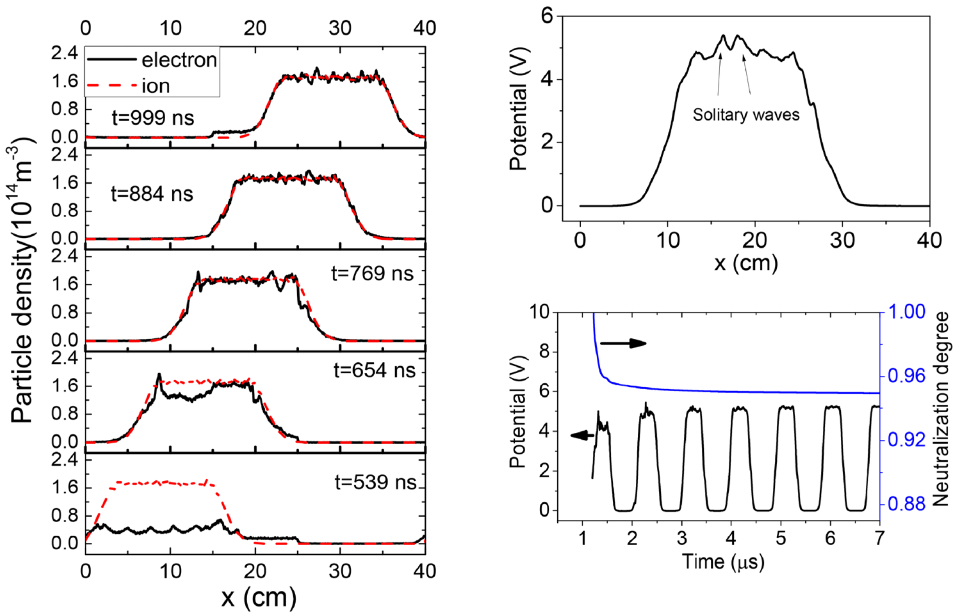

FIG. 5. Left: Temporal evolutions of ion and electron densities on the axis. Upper right: Beam potential on the axis at 2.04 μs. Right bottom: Temporal evolutions of the neutralization degree of the ion beam pulse and the potential recorded at $x = 5$ cm on the axis. Electrons were injected uniformly from $x = 15$ to 25 cm.

current cannot inhibit the excitation of the ESWs. But using a longitudinally extended electron source instead of a thin emitter can effectively minimize the excitation of the ESWs. These results provide new insight into the physics of ion beam neutralization. In addition, our 2D model should help to study and understand the mechanisms of excitation and instability of BGK mode multi-dimensional solitons.

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