Dynamics of a Potential Barrier Formed on the Tail of a Moving Double Layer in a Collisionless Plasma

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A negative potential barrier on the low-potential side of a moving double layer gives rise to a current limitation in a collisionless plasma terminated by a positively biased cold collector plate in a Q machine. The double layer is produced in front of the plasma source and moves toward the collector during the limitation. When the double layer arrives at the collector, the barrier dissolves and the current increases, causing a rise in potential along the whole plasma column. The double layer then reforms at the source.

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An electron current drawn through a plasma is known to cause a number of low-frequency instabilities that may give rise to anomalous resistivity limiting the current. Recent investigations, however, have shown a different plasma response, namely, the formation of a double layer (DL).[1,2] A stationary DL is usually formed when an electron beam is injected into a plasma.[2-5] Lutsenko *et al.*[6] observed a moving DL and the simultaneous current limitation in the positive column. Because of ionization of the background gas this DL was disrupted and created randomly, inhibiting the detailed study of the evolution. Investigations of the moving DL and corresponding current oscillations were also reported by Leung *et al.*,[4] where a pulsed electron beam was injected into the plasma. The propagating DL was explained by the fact that only in the frame moving with the DL did the ion velocity satisfy the requirement needed for the formation of a stationary DL. In the results of Leung *et al.*[4] we notice a broad negative potential well on the low-potential side of the DL, which moves together with the DL. In the experiment of Sato *et al.*,[7] a stationary DL was generated by applying a potential difference between two plates on which the plasma is produced by surface ionization. The measurements showed the initial formation, the subsequent movement, and the final stationary state of the DL, together with the corresponding current limitation. This work also suggested the existence of a small negative, current-limiting, potential barrier formed on the low-potential tail of the DL.

We present new investigations of an instability mechanism in a bounded, collisionless, current-carrying plasma. The behavior of this instability is closely related to the moving DL. A current is drawn by applying a potential difference between the grounded plasma source and a positively biased cold collector plate in a Q-machine plasma. In such a system, it is known[8] that there appears an instability which shows many features of a standing ion acoustic wave. By using a newly developed method,[9] with time response better than 1 μs, we measured the time-resolved development of the plasma potential within the period of the oscillations. The instability is found to be caused by the dynamics of a negative potential barrier formed on the low-potential tail of a moving DL and an unstable sheath in front of the target.

The experiment is performed in the Risø Q machine in single-ended operation. A cesium plasma is produced by surface ionization on a 3-cm-diam hot tantalum plate and is confined radially by a magnetic field of 0.35 T. The plasma column is terminated on a 4-cm-diam cold tantalum collector plate of variable potential. The length, d, of the column can be varied from 10 to 120 cm. Plasma density is 10^7–10^9 cm^{-3}, $T_e \simeq 2T_i \simeq 0.2$ eV, and background pressure $\simeq 10^{-6}$ Torr. Collisions are entirely unimportant. The measurements are performed by an axial movable electron-emissive probe, which also may be used as a usual Langmuir probe. The probe consists of an 8-mm-long loop of 0.1-mm-diam tungsten wire. In the emissive operation the probe is heated by either a direct or a pulsed current, which is off during the measuring time. The floating potential of the emissive probe is used for determining the plasma potential. The usual method for measuring this potential is to feed the probe signal into a high resistance. This, however, works well only for very slowly varying plasma potentials, as the high resistance (e.g., 100 MΩ) combined with the system stray capacitance gives a long response time ($\gtrsim$10 ms). Therefore, we developed a method in which the zero points of the probe characteristics sampled at a given time are detected. Then an input resistance of, e.g., 1 kΩ can be used and a time response better than 1 μs is obtained. This method and the emissive probe are described in detail elsewhere.[9]

When a positive bias, V_C, is applied to the collector an electron current is drawn giving rise to a low-frequency (~1–10 kHz) instability in the plasma.[8] When V_C is a few volts, no clear peak can be found in the spectrum and the current to the collector shows a random behavior with a nonreproducible period; the relative amplitude of these spikes is rather low, $\simeq$ 5%–10%. For higher biases the irregular spikes evolve into regular coherent oscillations with a fixed period. The amplitude of these oscillations increased with bias, V_C, reaching more than 70% at V_C = 50 V.

In Fig. 1 we show a typical evolution of the plasma parameters when the coherent oscillations are excited (V_C = 72 V). A potential profile with

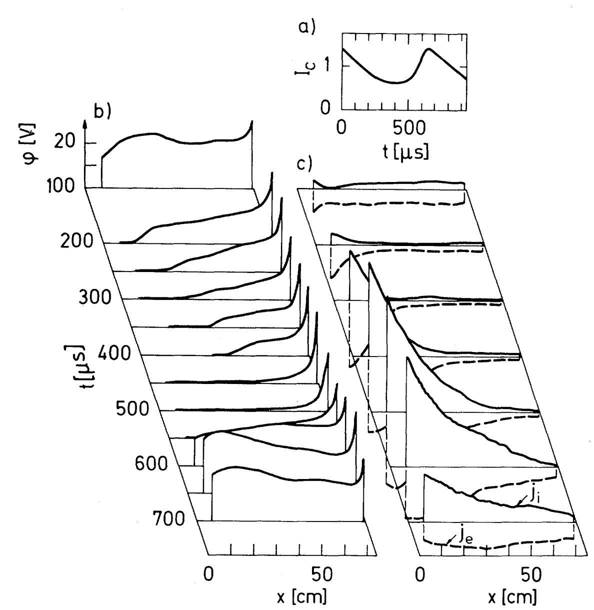

FIG. 1. Temporal evolutions of (a) target current I_C, (b) plasma potential φ, and (c) ion saturation current j_i and electron saturation current j_e. V_C = 72 V. Hot plate at X = 0 cm, collector at X = 75 cm.

DL-like form is found to exist during the phase of the current decrease and moves from the source (X =0 cm) to the collector (X =75 cm) with the speed $\simeq(2-3)C_s$ (C_s is the ion acoustic speed) [Fig. 1(b)]. Then it reaches the collector, the collector current I_C increases to its maximum in a rather short time ($\lesssim$ 100 μs), and the potential rises along the whole plasma column. Then, the DL-like shape reappears near the source and I_C begins to decrease. This cycle repeats. In Fig. 1(c) we can see that both the electron (j_e) and ion (j_i) saturation currents vary along the column during the evolution of the DL. The current fluxes decrease in the direction towards the collector and become almost zero on the high-potential side. The results on the low-potential side were also found in our previous work in a double-ended Q machine.[7]

This development is quite similar to the expansion of a dense plasma into a weak one. To check our expectation, a simple experimental simulation is performed by placing a grid in the plasma column close to the source. With application of a pulse to this grid as shown in Fig. 2(a), the plasma flow is pulsed into the region between the grid (X =50 cm) and collector (X =95 cm). The evolutions of I_C and of the plasma potential at V_C =50 V are shown in Fig. 2. In the first cycle ($t \lesssim$ 400 μs) where the plasma simply expands, we find a clear negative potential dip in front of the plasma flow, whose depth grows with propagation.[10] When this barrier approaches the collector, it dissolves.[11] Then I_C increases, the positive potential builds up in the region between the grid and collector, and the same cyclic behavior as in Fig. 1 starts. During the second cycle (400 μs$<t<$800 μs) we also observe a potential dip propagating towards the collector. The discontinuity of the electron flux through the DL shown in Fig. 1(c) is ascribed to the reflection of the electrons from the source by a similar negative potential barrier on the low-potential side of the DL. The depth of the barrier is of the order of $T_e/e \simeq 0.2$ eV. The formation of a potential barrier was also found to accompany the strong current oscillations of the thermionic converter.[12] We note that our experimental setup has some similarities with the thermionic converter. However, in this device the distance between the hot plasma source and the collector plate is in general very short (of the order of 100 Debye lengths). In Ref. 12 the mechanism of the current oscillations in the converter was investigated by a numerical simulation and the evolution of the

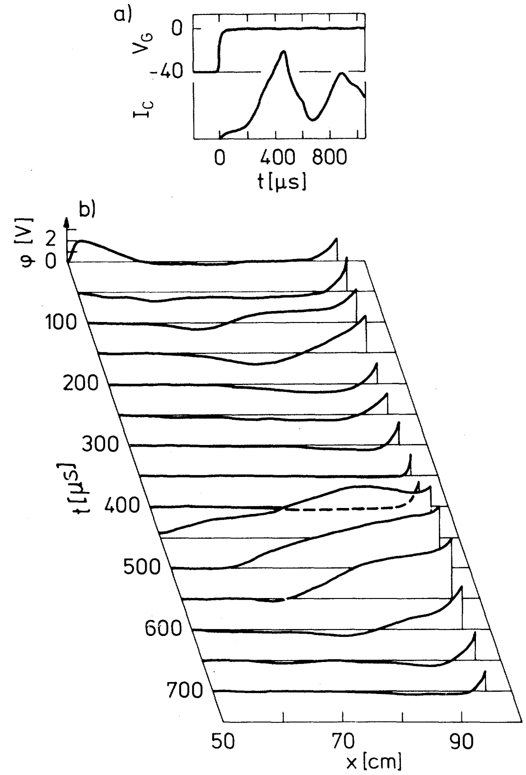

FIG. 2. Temporal evolutions of (a) target current I_C and (b) plasma potential φ in the case where the plasma flows into the region between the grid (voltage V_G) and the positively biased collector ($V_C = 50$ V). Grid at $X = 50$ cm, collector at $X = 95$ cm.

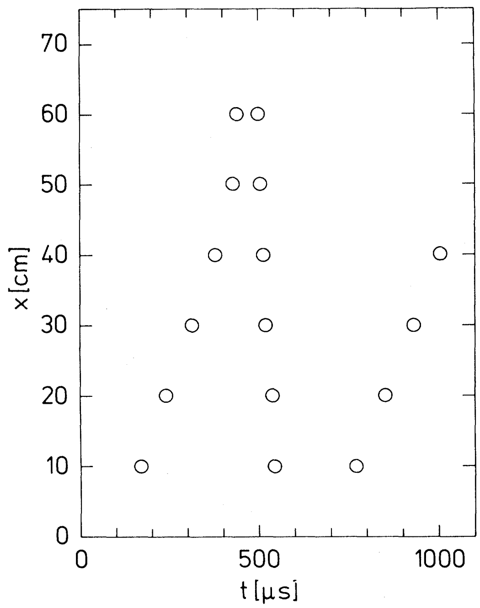

FIG. 3. Trajectory of the front of the double layer shown in Fig. 1.

current and the plasma potential was very similar to our results (e.g., Fig. 1).

As we can see from Fig. 2, the current oscillation is closely related to the growth and dissolution of the barrier on the low-potential side of the moving DL. We can explain the evolution of the instability as follows: In the phase of current suppression a DL accompanied by a negative potential barrier moves through the plasma. As the barrier grows during its propagation, the number of electrons reflected by the barrier increases with time, while the number of free electrons passing through the barrier from the source to the collector decreases with time. As we can see from Fig. 1, I_C is due mainly to the electrons which can overcome the barrier because the current flux to the probe is almost constant along the high-potential plasma. Thus, I_C decreases with time during the DL propagation. Figure 3 shows an x-t diagram of the evolution of the DL, i.e., we plot the point where the plasma potential is around zero, just in front of the DL, versus time. The speed of the DL is $(2-3)C_s \simeq 1.3\times10^5$ cm/s, which is around the plasma expansion speed in our device.[13] Reaching the collector, the DL stops and the ions may fill the potential dip. Thus, the barrier dissolves and a normal sheath forms in front of the collector, accompanied by a rapid increase in I_C. This makes the sheath unstable. The mechanism may be the following: When the normal sheath is formed at the collector, the electrons close to the collector are accelerated at first and are quickly drawn away. The resultant positive space charge gives rise to an increase in the space potential because the ions cannot respond on this time scale. The phenomena proceed toward the source, increasing the space potential along the plasma column with a speed faster than 1.5×10^6 cm/s (Fig. 3). The new state with a positive plasma potential cannot persist as the ions are returned to the source and "new" plasma expands from the source to relax the potential. Then electrons are stopped by the negative potential barrier formed again on the low-potential side of the DL, and the current decrease starts again. This evolution is similar to the ambipolar diffusion shown in the first cycle of Fig. 2, where electrons moving ahead of the ions also produce a negative potential barrier, which in turn reflects other electrons. The expansion is thus determined by the ion flow speed. Measurements at different lengths d and densities yield essentially the same results. The period of the instability is almost determined by the transit time of the moving DL. Therefore, the frequency f is inversely proportional to d, $f \simeq (2-3)C_s/d$. This agrees with the previous measurements.[8] In these experiments the instability was considered as a half standing wave without detailed investigations of its dynamics.

When the instability evolves random spiky oscillations in the current, it is not possible to perform time-resolved measurements using the procedure described above. However, simultaneous measurements with two probes at different axial positions indicate the same behavior as for coherent oscillations, that is, one "spike" corresponds to one cycle of the oscillation.

The mechanism of this instability is quite similar to the Gunn-diode oscillation where the DL propagates in a semiconductor.[14] Electrons with high and low mobilities in the Gunn diode correspond to the free beam electrons and those reflected from the barrier, respectively, in our case.

In conclusion, a strong instability in a current-carrying plasma is observed to be closely related to the moving double layer accompanied by the potential barrier and the sheath stability. In a single-ended Q machine with a positively biased target the self-consistent potential distribution[15] seems to be hardly obtainable as it is unstable. However, when the machine is operated with two plasma sources, the stationary DL is easily formed, as shown in Ref. 7. The spiky current oscillations reported there, however, are ascribed to the mechanism described in this work.

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[10]When the collector is biased negatively, no potential barrier is observed and the potential decreases monotonically towards the collector.

[11]The potential dip can exist consistently only in the moving frame with a velocity larger than or comparable to the ion flow velocity. In a stationary frame the ions will cancel the negative space charge connected with the dip. [See, e.g., M. T. C. Fang, D. A. Fraser, and J. E. Allen, Brit. J. Appl. Phys. 2, 229 (1969).]

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