Observations of Buneman Modes as Precursory Phenomena of a Solitary Potential Pulse

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A rapidly growing uhf (>250 MHz) wave burst, identified as the Buneman two-stream instability, was detected at the beginning of a high-current plasma discharge. It preceded by nearly 50 ns a parallel electric-field pulse with alternating polarity and amplitude of typically 2.0 kV/cm. A comparison with the nonlinear theory of the Buneman instability showed that the density evacuation mechanism in its nonlinear stage caused a solitary potential pulse within the observed delay time determined by ion dynamics.

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The Buneman-type two-stream instability, abbreviated as the Buneman instability hereafter, or the current-driven (electron-ion) two-stream instability has been of great interest since the formation of virtual cathodes and electric double layers was suggested in its nonlinear stage by analytical theories and computer simulations [1–4]. Further, it has recently attracted renewed interest in connection with the acceleration of particles in energetic phenomena of cosmic objects [5]. But, as shown by Mantei, Doveil, and Gresillon [6], the excitation of the Buneman instability imposes stringent conditions on the electron-beam or current density. This is the reason the Buneman instability has proved so difficult to observe. Hence, its further evolution into coherent nonlinear structures such as an electron hole and a double layer is an important question in the discipline of nonlinear plasma physics.

We have observed for the first time, we believe, the spatial evolution of a potential pulse generated near the cathode into a strong Buneman-type double layer (or an asymmetric electron hole) with the reverse polarity [7] in the initial phase of a high-current straight plasma discharge. The behavior of the electric fields is in accordance with a nonlinear stage of the Buneman instability [8]. However, decisive experimental verification of the above scenario has not been achieved yet.

Hence, we have tried to detect ultrahigh-frequency (uhf) fluctuations given by the Buneman instability, as a precursory phenomenon of nonlinear potential structures, such as a solitary pulse and double layer, that are generated by a plasma current along the magnetic field. This Letter presents the first observations of uhf wave bursts by a capacitively coupled probe [9] in association with the simultaneous measurement of the parallel electric field.

The experimental apparatus and the axial arrangement of diagnostic tools are shown in Fig. 1. We have drawn a high discharge current along the magnetic field with a preexisting deuterium plasma produced by a titanium washer gun. The configuration of the magnetic field is a magnetic mirror with mirror ratio 1.2, and the field intensity at the mirror point is typically 1.5 kG. The discharge is ignited by applying a high voltage, $V = 13$–18 kV, from a capacitor $C = 2.2\ \mu$F between the cathode (aluminum disk 50 mm in diameter) and the cylindrical muzzle of the plasma gun (43 mm in diameter and 34 cm long) after a suitable delay time, typically 24 μs from firing the gun. Additional details of the experimental apparatus and the plasma diagnostics, which include parallel electric-field measurement with a double probe through an optically isolated transmission system, were described in a previous paper [8].

The measurement of the electric field parallel to the magnetic field was done at almost the same axial position, i.e., nearly 10 cm in front of the cathode, as the detection of the uhf wave bursts. It should be noted that the measured value of the electric field includes an uncertain factor due to the coupling capacitance between the double

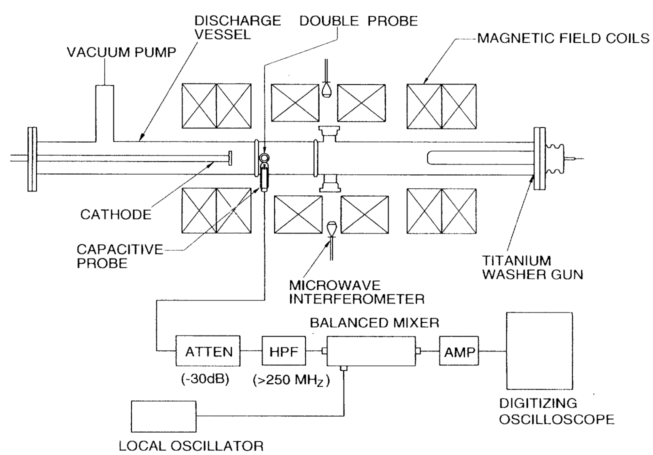

FIG. 1. The experimental apparatus and the axial arrangement of diagnostic tool. The block diagram of the detection system of the capacitive probe is also shown on the bottom.

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probe and the ambient plasma [10]. The separation of probe electrodes is nearly 1.2 mm and corresponds to roughly $60\lambda_D$ (Debye length) for typical plasma parameters of the initial plasma, which gives the spatial resolution of the double probe.

The electron density is a key plasma parameter that determines the drift velocity of electrons of excitation of the Buneman two-stream instability and sensitively affects the behavior in its nonlinear stage. Thus the electron density was monitored by a microwave interferometer, which was arranged at the center of the apparatus and operated at the frequency 69 GHz.

The electron temperature of the initial plasma produced by the titanium washer gun is also an important plasma parameter for determining the critical current density to excite the Buneman instability, and we have applied a measurement method that takes the difference of the floating potential between a hot emissive probe and a cold Langmuir probe [11]. We plan to describe the details of the measurement in a forthcoming paper.

The capacitive probe used for detection of uhf fluctuations given by the Buneman instability was made of an open-ended semirigid (50 Ω) coaxial cable. It was electrically insulated by a thin quartz tube, 4 mm in outer diameter, and inserted into a discharge vessel (Pyrex glass) at the measuring port arranged 10 cm in front of the cathode.

The block diagram of the receiving system of the capacitive probe is also shown in Fig. 1. uhf fluctuations (>250 MHz) picked up by the capacitive probe were converted to the lower IF (intermediate frequency) range by a heterodyne receiver that is composed of a fixed-frequency local oscillator (e.g., $f_1 = 400$ MHz) and a balanced mixer. The IF signal of the mixer was then amplified by a wide-band amplifier and finally recorded on a high-speed digitizing oscilloscope.

A digitized IF signal of uhf fluctuations was analyzed by taking into account the relative delay time of cable transmission 40 ns to the simultaneously measured parallel electric field.

Figure 2 shows a typical time profile of the discharge current together with temporal variation of the electron density measured at the midplane. It also shows data sets of the parallel electric field and the IF converted uhf fluctuations picked up by the capacitive probe, which were simultaneously obtained in the same discharge shot. The time sequence of the linear plasma discharge started at the instant when the titanium washer gun was fired.

The mean electron density is determined to be $4.8 \times 10^{12}/\mathrm{cm}^3$ at the onset of the discharge as seen from Fig. 2(a). Thus the real frequency of the Buneman instability, $f_B = 2^{-4/3}(m_e/m_i)^{1/3} f_{pe}$, is 520 MHz for the preexisting deuterium plasma, where m_e and m_i denote the electron and ion mass and f_{pe} is the electron plasma frequency. The highlight of the present observation is that the IF signal [see Fig. 3(b)] of the capacitive probe shows

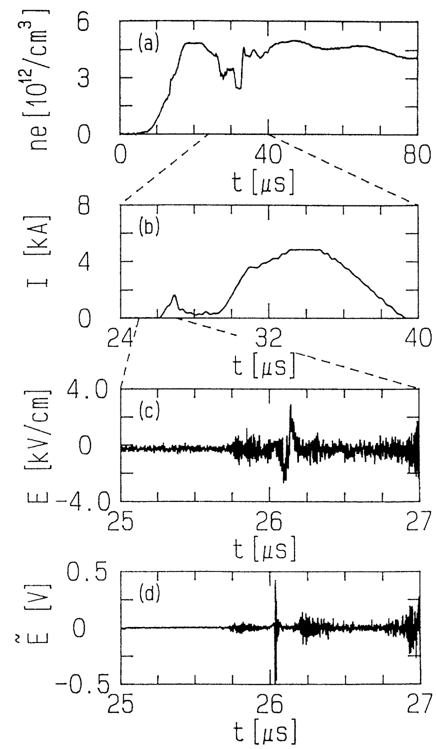

FIG. 2. Typical data sets of a high-current straight plasma discharge. (a) The electron density measured at the center of the apparatus, (b) the discharge current, (c) the electric field (parallel to the magnetic field) measured with a double probe at the axial position 10 cm in front of the cathode, and (d) the IF signal of uhf fluctuations picked up by the capacitive probe at the same position.

a rapidly growing wave burst at $t = 26.03$ μs with the peak frequency $f_{\mathrm{IF}} = 495 - 400 = 95$ MHz that corresponds to the real frequency of the Buneman instability shown above, where the peak frequency of the IF converted uhf wave burst was obtained by instantaneous fast Fourier transform spectral analysis [12] [see Fig. 3(c)].

We observed an electric-field pulse with alternating polarity and amplitude of nearly 2.0 kV/cm that is delayed by nearly 50 ns from the precursory uhf wave burst. The electric-field pulse characteristically changes its polarity from negative to positive, as shown in Fig. 2(c). Here the positive polarity of an electric signal detected by the double probe is defined such that the positive electric field points toward the cathode. Thus the temporal profile of the electric-field pulse is plausibly explained in the context that a solitary potential pulse moves toward the anode side in accordance with our earlier observations [8].

Our previous observations also showed that the potential pulse formed in front of the cathode moved with a mean velocity typically $V_s = 1.0 \times 10^8$ cm/s [8]. Hence the characteristic length scale of the potential structure is estimated to be $l = V_s\,\delta t = 5$ cm, where the pulse width of the electric field, i.e., $\delta t = 50$ ns, is obtained from

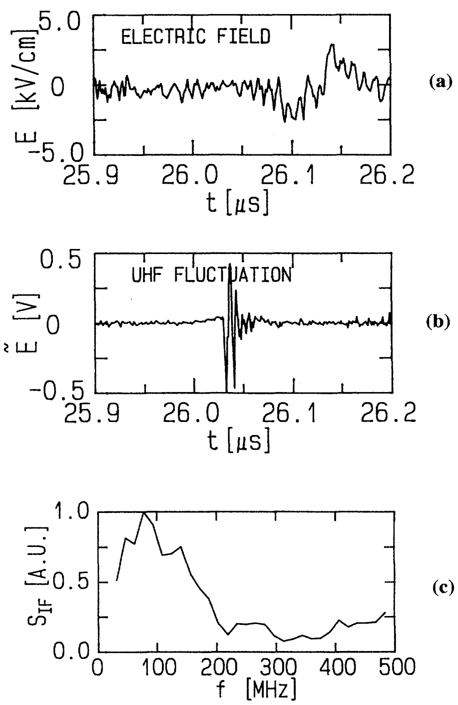

FIG. 3. Expanded time trace of (a) the electric field shown in Fig. 2(c) during 0.3 μs around the solitary potential pulse and (b) the IF converted signal of uhf fluctuations shown in Fig. 2(d). (c) Instantaneous IF power spectrum $S_{\rm IF}(f)$ of the uhf fluctuations from $t = 26.000$ to 26.064 μs.

Fig. 3(a). This length scale corresponds to $2.5 \times 10^3 \lambda_{\rm D}$, and therefore the space resolution of the double probe, $60\lambda_{\rm D}$, is sufficient to resolve the spatial potential structure.

The early temporal profile of the discharge current shows that the bursts associated with the parallel electric field and uhf fluctuations occur at the very onset of the discharge and, accordingly, the total plasma current I_p is as small as 0.1 kA. Therefore we should discuss the question of whether or not such a low plasma current can trigger the Buneman instability. The surface current density $j = I_p/2\pi r_p \delta r$ is estimated to be nearly 20 A/cm^2 on the assumption that the plasma current is carried by a thin skin current with depth δr comparable to the collisionless skin depth $c/\omega_{pe} = 0.3$ cm, where r_p is the plasma radius and ω_{pe} denotes the angular plasma frequency. Here we should note that the skin depth δr is on the order of $100\lambda_{\rm D}$ for the present plasma parameters, and the standard theory of the two-stream instability for a bulky current-carrying plasma is applicable. Mantei, Doveil, and Gresillon [6] have shown that the critical current density to excite the Buneman instability is lowered by a factor of 2 by taking into account the finite electron-to-ion temperature ratio of the ambient plasma, e.g., $j_{\rm crit} = 0.5 n_e e v_{et}$ for $T_e/T_i = 2$, where v_{et} is the electron thermal velocity. Thus the critical current density for excitation of the Buneman instability is estimated to be $j_{\rm crit} = 10$ A/cm^2, and it is clearly less than the calculated skin current density 20 A/cm^2, where a typical measured value of the electron temperature, 2 eV, is used to estimate v_{et} of the initial plasma.

As reported in a previous paper [13], the instantaneous peak frequency of the uhf wave burst approximately coincides with the real frequency of the Buneman instability. Thus we have further studied the dependence of the peak frequency of the uhf wave bursts on the electron density of the initial plasma by controlling the operation parameters of the titanium plasma source. The variation of the peak frequency of the uhf wave bursts as a function of the electron density is shown in Fig. 4.

Since the measurement of the electron density has been done at the center of the apparatus, the electron density at the axial position in front of the cathode should be reduced by a certain factor (0.9), although the true attenuation factor has not been determined yet. Nevertheless the straight line drawn in Fig. 4, which represents the variation of the real frequency of the Buneman instability $f_{\rm B}$ as a function of 0.9 times the electron density measured at the center, agrees well with the dependence of the observed peak frequency of the uhf wave burst on the electron density of the initial plasma. Accordingly, this is sufficient evidence to show that the uhf wave burst observed as precursor of the strong electric-field pulse can be identified as the Buneman instability.

Finally, we should discuss the delay between the uhf wave burst and the parallel electric-field pulse observed at the same axial position $z = 10$ cm (in front of the cathode). Figure 3 showed that the uhf wave burst preceded by nearly 50 ns the electric-field pulse with alternating polarity. This delay of the electric-field pulse can be interpreted by the nonlinear theory of the Buneman instability, which explains that the abrupt growth of the electric field is predominantly determined by ion dynamics [2].

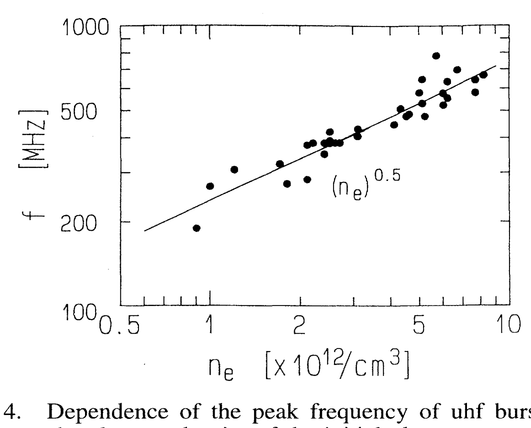

FIG. 4. Dependence of the peak frequency of uhf bursts on 0.9 times the electron density of the initial plasma measured at the center of the apparatus.

According to Galeev *et al.* [3], the characteristic growth time of the explosive potential bursts is given by $t_0 = \pi L/2(2U)^{1/2}$, where L is the characteristic length of the initial dip in the electron density distribution and $U = m_e I_e^2/2m_i n_e^2 e^2$. I_e is the electron current density necessary to grow the nonlinear Buneman instability that leads to the development of a nonreflecting potential pulse. The electron current density is assumed to be stationary on the time scale of ion dynamics, which plays a dominant role in the explosive growth of the potential pulse. Actually, we confirmed that this assumption almost remains valid up to the appearance of the electric-field pulse, even though the Buneman instability causes rapid current penetration into the whole plasma column due to the skin effect given by the anomalous resistivity [14].

Furthermore, we assume that the ponderomotive force induced by intense uhf electric fields generated in the nonlinear stage of the Buneman instability leads to a small localized dip in the electron density distribution that has a characteristic length L. Then by choosing $L = 15\lambda_D$ and using relevant experimental quantities of the current carrying plasma, i.e., $I_e = 20\ \mathrm{A/cm^2}$, $T_e = 7$ eV, and $n_e = 4.8 \times 10^{12}/\mathrm{cm}^3$, the characteristic growth time t_0 of the potential bursts agrees well with the observed delay time, typically 50 ns. This choice of the initial length scale of the dip in the electron density distribution can be well justified from the dispersion of the Buneman instability in the long-wavelength region [15], which gives the characteristic length scale of the Fourier modes representing an initial density dip as large as few tens of λ_D.

To summarize, we have observed an uhf wave burst given by the Buneman instability as a precursory phenomenon of the solitary potential pulse. The observations show that the initial excitation of the Buneman instability leads to a localized electron density dip with a characteristic length scale that represents long-wavelength Fourier modes of the instability. Then the ion dynamics under the quasineutrality condition causes the explosive growth of a solitary potential pulse and its subsequent spatial evolution into a strong electric-field spike (double layer) within the observed delay time.

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