Observations of the Spatial Evolution of a Potential Hump into a Strong Double Layer in a High-Voltage Straight Plasma Discharge

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(Received 11 March 1985)

The propagation and spatial evolution of a potential hump generated explosively near the cathode were observed in the current-limiting phase of a high-voltage straight discharge with a preexisting hydrogen plasma. Potential profiles along the axis numerically calculated from the real-time E field data demonstrate the evolution of a potential hump into a strong double layer (asymmetric electron hole) with an inverse potential jump ($e\phi_D/kT_e \lesssim 10^3$) as moving toward the center of the device with a mean velocity $(1.2\text{–}1.8)\times 10^8$ cm/sec.

PACS numbers: 52.35.Mw, 52.25.Nr, 52.50.Gj

Double layers are of interest in many areas of plasma physics, e.g., auroral and solar physics, intense beam production, plasma processing, and laser fusion (see recent conference reports by Schamel[1] and Takeda and Yamagiwa[2]). The formation of dynamic potential spikes or double layers as a consequence of the nonlinear evolution of the Buneman instability of a current-carrying plasma has been predicted by computer simulations performed by DeGroot *et al.*[3] and recently by Belova *et al.*[4] The roles of intrinsically nonlinear plasma states, such as an electron hole and ion hole, related to double-layer formation have been predicted and discussed by Smith[5] and Schamel.[1] Singh and Schunk[6] have investigated with one-dimensional computer simulations more details of the dynamical aspects of Buneman double layers and showed the formation of an electron hole on the high potential side of a double layer, which is especially relevant to a double layer observed in the present experiment.[2] Lutsenko *et al.*[7] previously observed very strong moving double layers in a high-current, high-voltage straight discharge with a preexisting plasma in a uniform magnetic field, but by means of external capacitive probes with a limited spatial resolution.

In this Letter, we present the first observations of the spatial evolution of an explosively generated potential hump (electron hole) into a strong double layer in the current-limiting phase of a high-voltage straight (linear) plasma discharge. These were carried out by a correlation measurement of the electric field component parallel to the magnetic field by means of floating double probes and optically isolated transmission systems,[8] henceforth called the "optoisolator." Observations of hard x rays (> 70 keV) at the measurement positions of the electric field which show the production of high-energy electrons associated with the spatial evolution of the strong double layer are also discussed.

The experimental apparatus and the axial arrangement of the diagnostic tools are shown in Fig. 1. We have carried out the high-voltage straight discharge in a magnetic mirror with a preexisting hydrogen plasma. The mirror ratio is 1.2 and the intensity of the magnetic field at the mirror point is typically 1.5 kG. An initial plasma is created by a hydrogen- or deuterium-loaded titanium washer gun and injected into a highly evacuated discharge vessel of Pyrex glass 10 cm in inner diameter and 1.5 m long. The discharge is ignited by applying the voltage $V = 23\text{–}28$ kV from a capacitor with $C = 2.2\ \mu$F between the cathode (aluminum disk 50 mm in diameter) and the cylindrical brass muzzle of the gun (43 mm in diameter × 34 cm long), which has an exit orifice with an aperture 20 mm, after a suitable delay time, typically 25 μsec from the firing of the titanium washer gun. The distance between the cathode and the muzzle of the gun is 65 cm. The cathode is fixed at the ground potential. The circuit

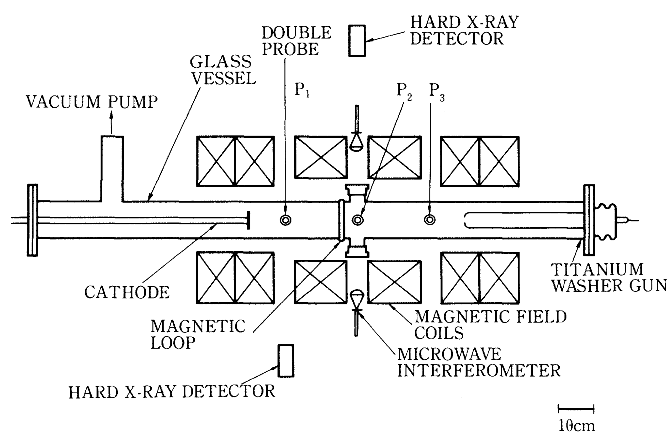

FIG. 1. Experimental apparatus and the axial arrangement of electric double probes and other diagnostics.

resistance $R_e = 0.9\ \Omega$ is inserted externally so that the discharge is in the underdamped regime. The electron density and bulk temperature $k(T_e + T_i)$ of the initial plasma measured at the center of the device were typically $3\times10^{12}\ \text{cm}^{-3}$ and 15 eV, respectively, at the beginning of the high-voltage straight discharge.

Three electric double probes were arranged along the axis, one at the center of the device and two of them at symmetric axial positions 20 cm from the midplane. Electrodes of the double probes are platinum wires of 0.1-mm diameter and 1.4-mm exposed length. Probe tips were placed at about 2.5 cm from the axis of the discharge vessel and the electrodes were oriented parallel to the field coil axis. The separation of probe electrodes was 1.2 mm, which corresponded to roughly $40\lambda_D$ in the initial current-limiting phase of the discharge, where λ_D is the Debye length.

The fast-response ($\lesssim 5$ ns) optoisolator,[8] which has a differential input with an input impedance 1 kΩ and is designed to be used in conjunction with a floating double probe, was developed to measure directly large-amplitude electric fields associated with double layers formed in the high-voltage straight discharge.

It should be stressed that the double probe used in the present experiment does not necessarily work as a usual floating double probe which collects a small electron and ion flux (convection current), but it draws a fairly large polarization current induced by the passage of a highly polarized space-charge layer. The details and the crucial point of the present measurement of the electric field will be described in a forthcoming paper.[9]

Time traces of typical electric fields are shown in Fig. 2 together with an oscillogram of the discharge current which is transferred from the optical receivers connected to the two double probes, P_1 and P_2, mounted at 10 cm from the cathode and at the center, respectively. The positive polarity of electric signals detected by the double probe is defined such that the positive electric field points towards the cathode. The electric field measured on the cathode side shows that triple pulses with alternately opposite polarity precede the low-frequency fluctuations. The lower time trace is the electric field measured at the center and shows a corresponding negative pulse delayed by 0.17 μsec from the upper triple pulse. Hence the mean velocity of the axial propagation toward the center is 1.2×10^8 cm/sec. The amplitude of the pulse is 17 kV/cm and nearly 17 times larger than that measured on the cathode side.

The potential profiles along the axis viewed toward the upper stream (cathode side) at the probe positions are numerically calculated from the corresponding E field data, taking into account the propagation of a potential hump with a mean velocity V_s, as follows:

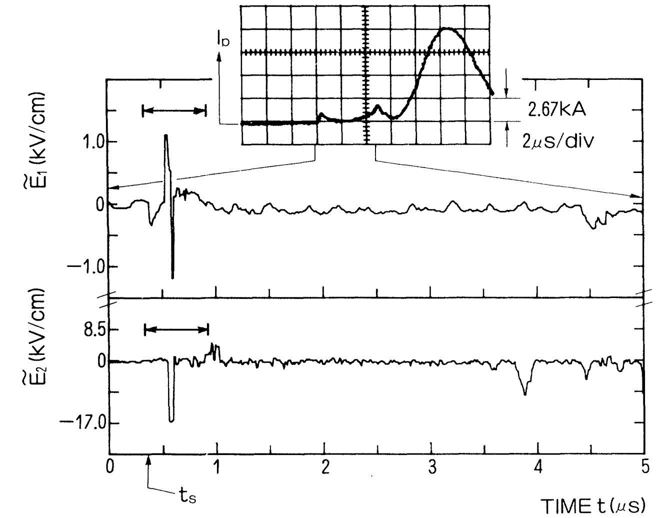

FIG. 2. Upper oscillogram: time trace of the discharge current. Middle and lower traces: electric field fluctuations measured by the double probes P_1, mounted at 10 cm from the cathode, and P_2, at the center of the device, respectively. The arrow indicated above each time trace of the E field shows the record length of sixty sampled data used in the calculation of the potential profiles along the axis.

$$\phi_j(z) = -\int_{z_j}^{z} E_j\,dz = -V_s\int_{t_s}^{t} E_j\,dt,$$

where t_s is a lower limit of the numerical integration in a time trace of the E field as indicated in Fig. 2, z_j the probe position, and j the index of the measuring position. The axial potential profiles on the cathode side and at the center obtained by the above procedure are shown in Fig. 3.

As expected, the axial potential profile on the cathode side shows a potential pulse with a dip on the foot extending toward the cathode which is held at the ground potential; it evolves into a double layer at the center with an *inverse* potential jump of about 90 kV toward the cathode. This means that the explosive buildup of an electron hole occurs in front of the cathode as a result of the mechanism presented by Belova *et al.*,[4] in which a positive potential pulse develops and reflects ions because of local rarefaction of the electron density under the condition of a stationary electron current and the reflected ions in turn give rise to a further ejection of electrons. This local rarefaction mechanism of an electron hole acts under the condition $V_d \gtrsim C_e$ and it is ascertained to be satisfied at the instant of the potential pulse formation in front of the cathode, where V_d and C_e are the drift velocity and thermal velocity of electrons, respectively.

Figure 3(b) shows the formation of a negative potential cliff or a *virtual cathode*[6,10] around the midpoint between the electrodes due to the creation of an excess

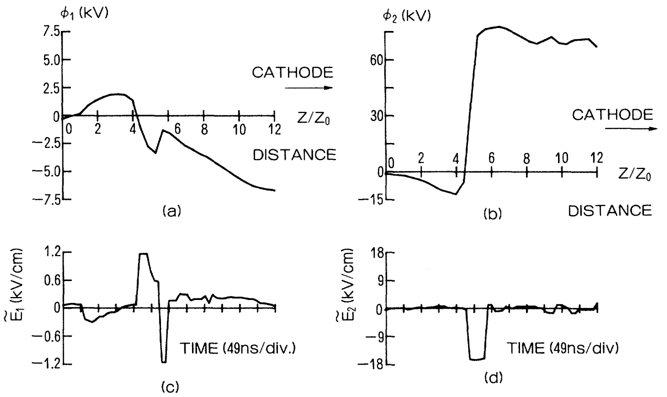

FIG. 3. Potential profiles along the axis viewed at the measuring positions (a) on the cathode side, and (b) at the center. They are numerically calculated from the corresponding E-field data shown in (c) and (d). $z_0 = 5V_s\Delta t = 5.9$ cm, where Δt is the sampling time, 9.785 ns.

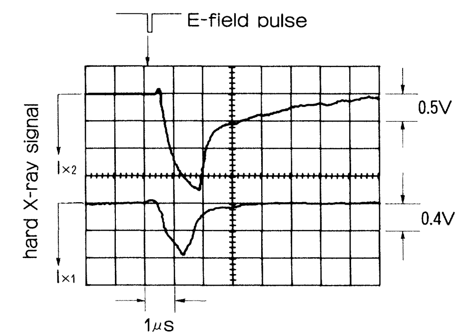

FIG. 4. Time traces showing hard x-ray signals detected (lower trace) on the cathode side with absorber (aluminum) thickness 1.5 mm and (upper trace) at the center with absorber thickness 10 mm. The amplitude and half-width of the negative E-field pulse were 7.7 kV/cm and 0.03 μs, respectively.

negative charge downstream from the crest of a potential pulse. The negative space charge is produced by current-carrying electrons incident on the potential pulse from the cathode and reflected by it. We emphasize that the buildup of the negative potential cliff in turn enhances the reflection and trapping of current-carrying electrons by a bootstrap action.

From the temporal behavior of the plasma diamagnetism and electron density measured at the center by means of a diamagnetic coil and a microwave interferometer operated at 70 GHz, the bulk T_e is roughly determined to be at most 0.1 keV in the period of the E-field measurement. Hence $e\phi_D/kT_e$ is known to be of the order of 10^3, where ϕ_D is the inverse potential jump of the double layer.

As briefly described later, hard x-ray measurements showed the presence of a hot-electron component associated with the double layer. Since the Debye length depends mostly on the cold component, the corresponding Debye length is in the range of 4×10^{-3} cm. Thus the double-layer thickness L parallel to the magnetic field is of the order of $2\times10^3\lambda_D$ and fairly larger than that given by the scaling law of a laminar double layer[11]: $L/\lambda_D \cong 10(e\phi_D/kT_e)^{1/2}$.

We have detected hard x rays at the same measurement positions of the electric field using two NaI(Tl) scintillator (1.76 in. diam × 1.4 in. long) plus photomultiplier combinations with absorber (aluminum) thickness 1.5 mm on the cathode side and 10.0 mm at the center. The energy ranges of detected hard x rays are roughly determined to be $\gtrsim 20$ keV on the cathode side and $\gtrsim 70$ keV at the center from available mass and energy absorption-coefficient data of the NaI(Tl) scintillator and the aluminium.

Typical time traces of hard x-ray signals are shown in Fig. 4 together with the timing mark of a negative E-field pulse observed at the center. We should note some differences of the temporal variation of the hard x-ray intensity between the cathode side and the center. While the hard x-ray signal shows an almost impulsive shape on the cathode side, it decays with an e-folding time of 2.2 μsec at the center, which indicates the presence of a decaying hot-electron component. Moreover, the hard x-ray emission at the center is delayed by nearly 0.2 μsec from that on the cathode side. This fact shows that the growing potential jump associated with the moving double layer gives rise to production of an energetic or hot-electron component as the origin of hard x rays. Another point which confirms the relevance of hard x rays to the double-layer evolution is that the mean energy of hard x-ray photons at the center is inferred to be much higher than that on the cathode side, from the difference of absorber thickness and of the hard x-ray signals. These hard x-ray behaviors represent a particle signature of the spatial evolution of a strong double layer.

We should point out that the double-layer structures observed in the present experiment are in the context of what would usually be thought of as a "controlled fusion" experiment, e.g., "turbulent heating[12]" by a high current along the magnetic field.

To summarize, we have observed for the first time the spatial evolution of a potential hump explosively generated near the cathode into a strong double layer (asymmetric electron hole) with an inverse potential jump ($e\phi_D/kT_e \simeq 10^3$). We have also detected intense hard x rays ($\gtrsim 70$ keV) as a particle signature of the strong double layer.

The authors would like to thank Dr. L. Lindberg and

Dr. S. Torvén of the Royal Institute of Technology, Stockholm, for valuable discussions on this work.

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