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Electron Acceleration due to Electric Field Bursts Close to the Lower Hybrid Frequency in a High-Voltage Linear Plasma Discharge

TAKEDA Yasumasa and INUZUKA Hiroshi[1]

Department of Physics, College of Science and Technology, Nihon University, Tokyo, 101-8308, Japan

[1]Department of Electrical and Electronic Engineering, Faculty of Engineering, Shizuoka University, Hamamatsu, 432-8561, Japan

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Abstract

Lower hybrid wave bursts, which were generated in a high-voltage linear plasma discharge, give rise to intense electron acceleration evidenced by impulsive hard x-ray fluxes with energies higher than 15 keV detected in the direction perpendicular to the magnetic field and also in the direction almost parallel to the magnetic field.

The lower hybrid wave packet is more efficient to accelerate high-energy electrons than laminar electric field pulses such as double layers and localized potential structures.

Keywords:

lower hybrid wave, double layer, transit time acceleration, nonadiabatic electron heating, linear plasma discharge

1. Introduction

There have been crucial debates and discussion [1] in plasma physics and auroral physics community on the question which is more efficient in particle acceleration, laminar coherent structures such as double layers [2] or localized wave structures such as lower hybrid solitary waves [3]?

This paper presents our new findings that electric field bursts with frequency in the vicinity of lower hybrid frequency, which were generated in the initial phase of a high-voltage linear plasma discharge, give rise to intense electron acceleration.

Dependence of the angular distribution of hard x-ray fluxes on the spectral profile of an originating electric field burst is explained according to the theory of transit time interaction of a lower hybrid wave [4].

The dominant electron acceleration perpendicular to the magnetic field, which is frequently observed in association with lower hybrid wave bursts, cannot be understood according to the linear theory of lower hybrid wave. Hence the recent theory of nonadiabatic electron acceleration by a low frequency wave [5] is invoked in Sec. **4**.

Moreover contribution of laminar electric field pulses such as electrostatic double layers to the acceleration of high-energy electrons is compared with that of a fairly coherent lower hybrid wave packet.

2. Experimental apparatus and the methods of measurement

We have carried out the high voltage linear discharge along the magnetic field with a preexisting deuterium plasma produced by a titanium washer gun [6]. 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 1.2 kG. The discharge is ignited by applying a high voltage V_c = 15 – 27 kV from a capacitor with C = 2.2 μF between the cathode (aluminum disk 50 mm in diameter) and the cylindrical muzzle of the plasma gun after a suitable delay time, typically 24 μs from firing the gun.

The parallel electric fields were measured at two axial positions, one at 10 cm in front of the cathode, and the other at the centre of the apparatus (midplane), by using a pair of electric double probes and optically isolated transmission systems. The distance of two measuring points is L = 20 cm. The optically isolated transmission system of the electric field fluctuations has frequency characteristics whose upper 3 dB cut-off frequency is nearly 80 MHz.

We have detected hard x-ray fluxes in the direction perpendicular to the magnetic field line with a plastic scintillator (NE102A) and photomultiplier combinations arranged at the centre of the apparatus. The x-ray detector mounts an aluminium absorber 1-mm in thickness on the detector head. Hence the energy range of hard x-rays is roughly determined to be larger than 15 keV.

Corresponding author's e-mail: takeda@phys.cst.nihon-u.ac.jp

We also detected hard x-ray emissions in the forward (cathode side) and backward (anode side) directions almost parallel to the magnetic field in order to obtain information on the anisotropy of velocity distribution of energetic electrons produced in the localized wave structure, such as a lower hybrid wave packet.

3. Relationship between electric field bursts and hard x-ray emission

Figure 1 shows a typical time profile of the discharge current flowing in a preexisting deuterium plasma, fluctuations in the longitudinal electric field, and hard x-ray emissions detected in the direction both perpendicular and parallel to the magnetic field. This data set was simultaneously obtained in the same discharge shot, where the applied voltage between the anode (the muzzle of the titanium washer gun) and the cathode V_C is nearly 27 kV and the intensity of magnetic field at the mirror point B_m is 1.3 kG. The time sequence of a linear plasma discharge started at the instant when the titanium washer gun was fired to produce and inject a deuterium plasma into the magnetic mirror. The electron density was monitored with a microwave interferometer which was arranged at the center of the apparatus and operated at the frequency 69 GHz. The mean electron density before application of the high-voltage linear plasma discharge was $2.2 \times 10^{12}/\text{cm}^3$.

As Fig. 1(b) and 1(c) show, fluctuations in the electric field are highly enhanced at t = 31.2 μs, the start-up time of the plasma discharge, and cause large anomalous resistivity [7].

The hard x-ray emission is coincident with the electric field bursts and is more intense in the direction perpendicular to the magnetic field than that in the direction almost parallel to the magnetic field (see Fig. 1(d), 1(e) and 1(f)).

For comparison, we show similar data set in Fig. 2, which was taken in another discharge shot under the operating condition V_C = 25 kV and B_m = 1.3 kG. Plasma parameters of the initial plasma were almost the same as the case of Fig. 1. It should be noted that parallel hard x-ray emissions are correlated with electric field bursts shown in Fig. 2(a) and 2(b) which broke out nearly 4 μs later than those shown in Fig. 1 as the second activity of the electric field, but hard x-ray emission was not detected in the perpendicular direction.

In order to study this remarkable difference of the angular distribution of hard x-ray emissions, we calculated power spectral density functions of the electric field bursts with FFT (Fast Fourier Transform) procedures. Sampled electric field data are taken from the relevant time interval, t = 31.0 μs to 33.048 μs for Fig. 1(b) and 1(c), and t = 38.0 μs to 40.048 μs for Fig. 2(a) and 2(b). Figure 3(a) and 3(b) show notable broadening of the spectral profile around the lower hybrid frequency f_{lh} = 55 MHz for a deuterium plasma in the case of intense hard x-ray emission

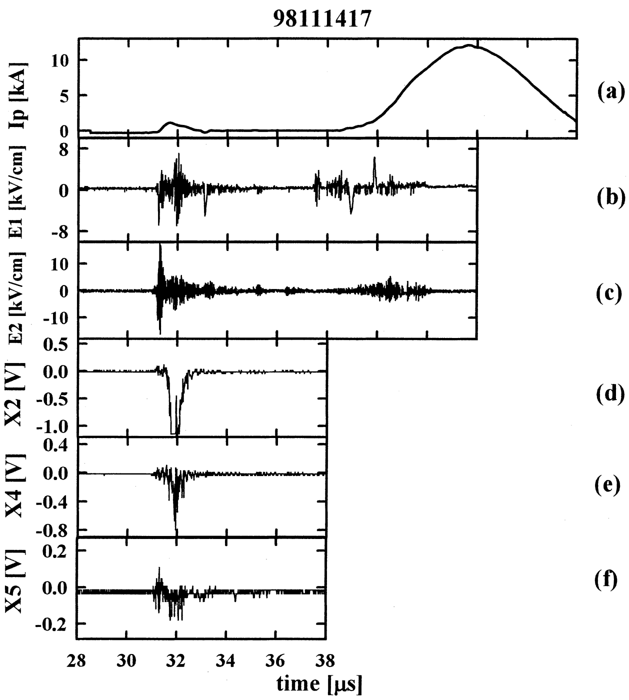

Fig. 1 Typical data sets of the high-voltage linear plasma discharge. The time trace (a) shows discharge current, (b) the parallel electric field E_1 measured 10 cm in front of the cathode, (c) the parallel electric field E_2 at the center of the apparatus, (d) x-ray emission in the direction perpendicular to the magnetic field, (e) x-ray emission almost parallel to the magnetic field detected from the cathode side, and (f) x-ray emission almost parallel to the magnetic field detected from the anode side.

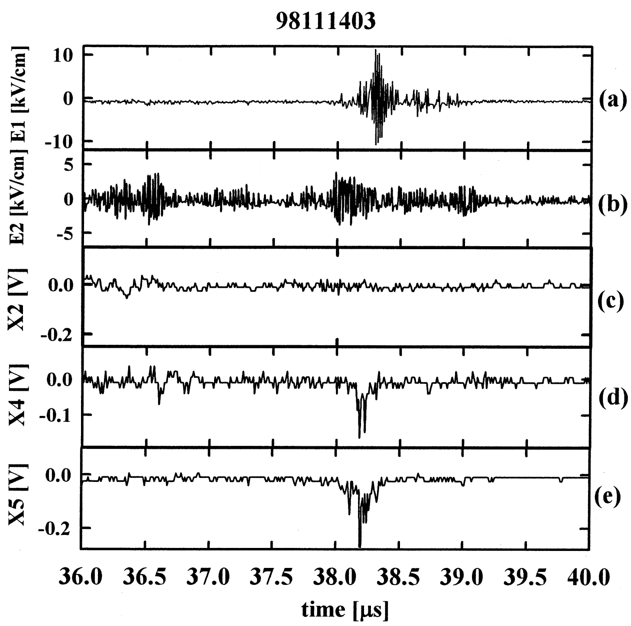

Fig. 2 Similar data sets of the high-voltage linear plasma discharge. The time trace (a) shows the parallel electric field E_1 measured 10 cm in front of the cathode, (b) the parallel electric field E_2 at the center of the apparatus, (c) x-ray emission in the direction perpendicular to the magnetic field, (d) x-ray emission almost parallel to the magnetic field detected from the cathode side, and (e) x-ray emission almost parallel to the magnetic field detected from the anode side.

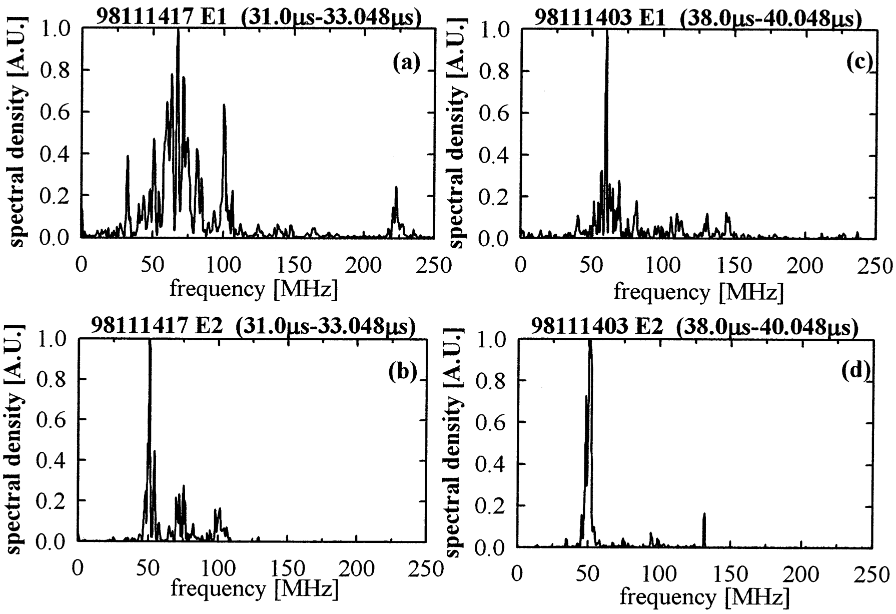

Fig. 3 Power spectral density functions of the electric field fluctuations calculated with FFT procedures. (a) and (b) show the power spectra using the electric field data shown in Fig. 1, and (c) and (d) are calculated from the electric field data shown in Fig. 2.

perpendicular to the magnetic field. On the contrary, the power spectrum of the correlated electric field burst is relatively narrow as shown in Fig. 3(c) and 3(d) in the case of impulsive hard x-ray emissions preferentially detected in the direction almost parallel to the magnetic field.

4. Discussion and concluding remarks

In the present experiment, the electron cyclotron frequency f_{ce} is approximately 60 times higher than the lower hybrid frequency f_{lh} = 55 MHz. Since the longitudinal scale length of a lower hybrid caviton l is estimated to be 5.2 cm according to the theory of transit time acceleration [4], then the transit time is $t_{tr} = l/v_e$ = 2.8 ns for an electron with kinetic energy of 1 keV that comprises high-energy tail of the Maxwellian distribution. Then the necessary condition for the transit time acceleration T_{lh} = 13.3 ns $\gg t_{tr}$ is well satisfied, where v_e denotes the electron velocity and T_{lh} is the period of a lower hybrid wave.

Therefore we can assert that the preferential acceleration of energetic electrons parallel to the magnetic field in the case of fairly monochromatic spectral profile as shown in Fig. 3(c) and 3(d) could be explained according to the theory of transit time interaction of electrons with a localized lower hybrid wave packet or an elongated lower hybrid caviton.

Moreover we should mention that the recent theory of lower hybrid turbulence [8] predicts that the electron velocity distribution has enhanced fluxes of energetic electrons both parallel and antiparallel to the magnetic field due to nonlinear wave interaction near the lower hybrid frequency through modulational instability, such as the collapse of waves into soliton turbulence.

Figure 4 shows the opposite case of Fig. 2 and hard x-ray emissions correlated with the electric field burst around t = 27.4 μs are detected only in the direction perpendicular to the magnetic field. The power spectrum of the electric field burst is remarkably more broadened than that in Fig. 3(c).

The physics of preferential electron acceleration perpendicular to the magnetic field in the case of broadened power spectrum of electric field bursts is not fully understood at the present stage, and will be discussed in another paper referring to the recent theory [5] of electron heating and acceleration due to large amplitude electrostatic waves with a frequency much lower than the electron cyclotron frequency. Both nonadiabatic motions of electrons perpendicular to the magnetic field and chaos dynamics could be relevant to electron acceleration and turbulent heating perpendicular to the magnetic field.

Finally Fig. 5 shows decisive experimental results [9] that a coherent lower hybrid wave packet emerged at t = 31.5 μs is coincident with strong hard x-ray bursts and is more efficient to accelerate high-energy electrons than preceding repetitive laminar electric field pulses.

In conclusion, electric field burst with frequency near the lower hybrid frequency is more efficient in electron acceleration than laminar electric field pulses that represent coherent structures, such as double layers, if their amplitudes are comparable.

The presence of counter-streaming electrons is evidenced by hard x-ray emissions detected from both the cathode and anode sides in the direction almost parallel to the magnetic field. The simultaneous occurrence of counter-streaming electrons could not be explained by direct acceleration due to double layers. The delay time of parallel hard x-ray fluxes from the electric field pulse, typically 300 ns, also proves this interpretation.

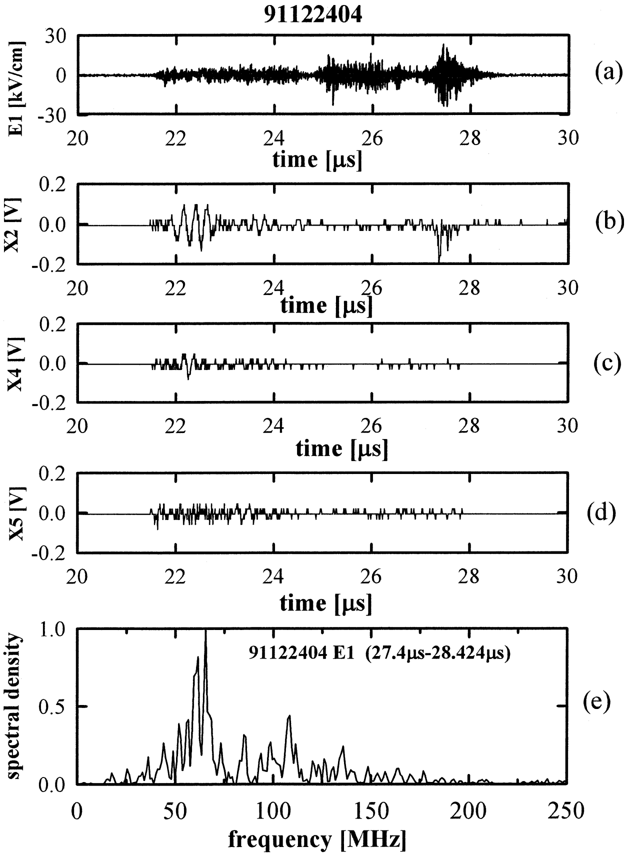

Fig. 4 The time traces show (a) the parallel electric field E_1, (b) x-ray emission in the direction perpendicular to the magnetic field, (c) x-ray emission in the direction almost parallel to the magnetic field detected from the cathode side, and (d) similar parallel x-ray emission detected from the anode side. The bottom figure (e) is the power spectral density function of the electric field E_1 during the period t = 27.4 μs – 28.424 μs.

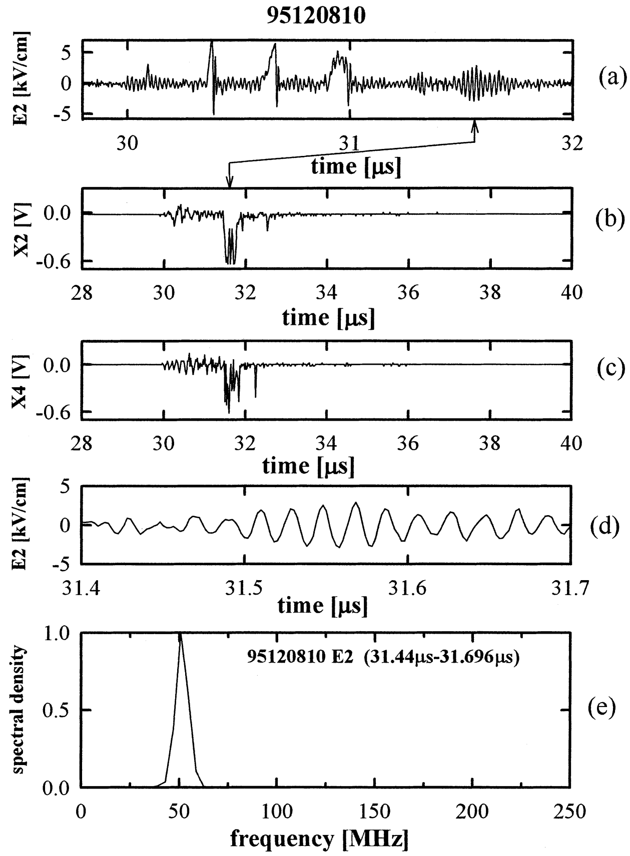

Fig. 5 An electric field burst around t = 27.4 μs is coincident with intense hard x-ray emissions. The hard x-ray emission is more intense in the direction perpendicular to the magnetic field than that in the direction parallel to the magnetic field. The time trace (a) shows the electric field E_2 measured at the center of the device, (b) a perpendicular hard x-ray emission at the center, (c) a parallel hard x-ray emission detected from the cathode side, (d) expanded time trace of the short electric field burst shown in (a) during t = 31.4 μs – 31.7 μs. The bottom figure (e) is the power spectrum of the coherent wave packet.

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