ANOMALOUS RESISTIVITY GIVEN BY LARGE AMPLITUDE FLUCTUATIONS
IN THE VICINITY OF LOWER HYBRID FREQUENCY
IN A HIGH-VOLTAGE LINEAR PLASMA DISCHARGE

Y. Takeda[1], H. Inuzuka[2] and K. Yamagiwa[3]

[1]*Department of Physics, College of Science and Technology*
Nihon University, Kanda Surugadai 1-8, Tokyo 101-8308, Japan

[2]*Department of Electrical and Electronic Engineering, Faculty of Engineering,*
Shizuoka University, Johoku 3-5-1, Hamamatsu 432-8561, Japan

[3]*Department of Physics, Faculty of Science, Shizuoka University*
Oya 836, Shizuoka 422-8017 Japan

Abstract

We have observed enhanced anomalous resistivity ($\approx 9\Omega$cm) mostly given by large amplitude lower hybrid fluctuations during the quasistationary current limiting phase of a high-voltage linear plasma discharge. The instantaneous power spectral density of electric field fluctuations (>10 kV/cm) calculated by *wavelet* spectral analysis shows that the peak frequency varies in accordance with dependence of the lower hybrid frequency on strength of the magnetic field and ion mass. The observed large anomalous resistivity was discussed on the basis of the quasilinear theory of lower hybrid condensation instability.

1. Introduction

Intense lower hybrid wave packets or large amplitude bursts, which have been observed by recent electric field's measurements by the sounding rockets and the space satellite FREJA near the topside ionosphere[1], attract wide interests in the discipline of nonlinear plasma physics[2]. Recently we have discovered a quasi-stationary phase of strong current limitation in a linear plasma discharge that had typical duration of several to 10 μs. Correlating with this strong current limitation, very large amplitude fluctuations in the parallel electric field whose mean amplitude was typically 10 kV/cm were picked up by a floating double probe, connected with optically isolated transmission systems. The instantaneous power spectral density, calculated by *wavelet* spectral analysis for nonstationary time series[3], clearly shows the peaking around the lower hybrid frequency $f_{lh}=(f_{ce}f_{ci})^{1/2} = 75$ MHz relevant to the parameters of the hydrogen plasma and the intensity of the magnetic field, where f_{ce} and f_{ci} denote an electron cyclotron- and ion cyclotron frequency, respectively.

We compare the anomalous resistivity $\eta = 4\pi(\omega_{lh}/\omega_{pi}^2)(W/nT_e)$ calculated by the quasilinear theory with the experimental one, where the former is given by the growth rate of lower hybrid condensation instability derived by B. I. Sturman [4], where ω_{lh}, ω_{pi}, W, n, T_e, denote lower hybrid frequency, ion plasma frequency, electrostatic wave energy density of lower hybrid waves, electron density, and electron temperature, respectively.

2. Experimental apparatus and the methods of measurement

The experimental apparatus and the axial arrangement of diagnostic tools were described in the previous paper [5]. We have drawn a high discharge current along the magnetic field with a preexisting hydrogen (or 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 1.3 kG. The discharge is ignited by applying a high voltage V_c=13-18 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 18 μs from firing the gun.

The mean electron density was monitored with a 69 GHz microwave interferometer, which was arranged at the center of the experimental apparatus and launched an ordinary-mode microwave beam perpendicular to the magnetic field. At the same time the microwave interferometer could sensitively detect electron density modulations due to the ponderomotive force caused by large amplitude lower hybrid waves or bursts.

The parallel electric fields were measured at the two axial positions, one at 10 cm in front of the cathode, and the other at the center of the apparatus (midplane), by using a pair of electric double probes and optically isolated transmission systems, where the distance of two measuring points l=20 cm. The cross correlation function of neighboring electric field fluctuations was calculated in order to obtain the propagation velocity of a prominent wave.

3. Cross-correlation of lower hybrid electric-field fluctuations and the anomalous resistivity observed in a high-voltage linear plasma discharge

Fig. 1 shows a typical time profile of the discharge current, time series of the longitudinal electric field (abbreviated as E-field henceforth) and the electron density measured at the center of the apparatus that were simultaneously obtained in the same discharge shot. In the first place we should note that fluctuations in the electric fields E_1 and E_2 are highly enhanced during the quasi-stationary phase of current limitation, from t= 26.0μs to 36.0 μs, where E_1 and E_2 were measured on the cathode side and at the midplane of the discharge device,
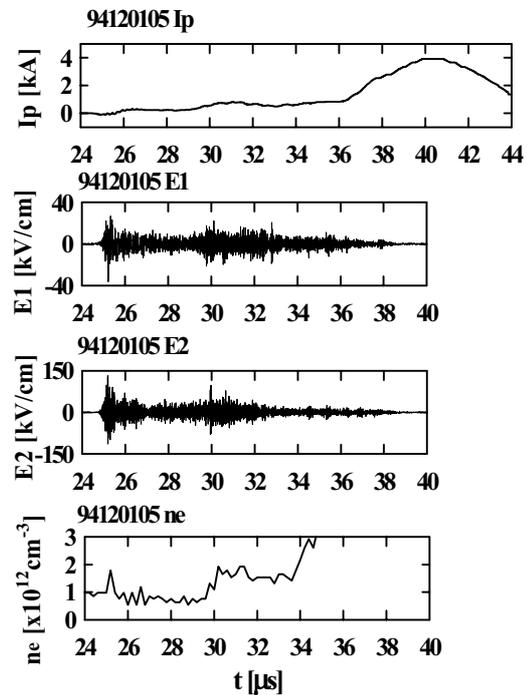

Fig. 1. Typical data sets of the high-voltage linear plasma discharge. The time trace (a) shows discharge current, (b) the parallel electric field E$_1$ measured 10 cm in front of the cathode, (c) the parallel electric field E$_2$ at the center of the apparatus, and (d) the electron density measured at the center of the device.
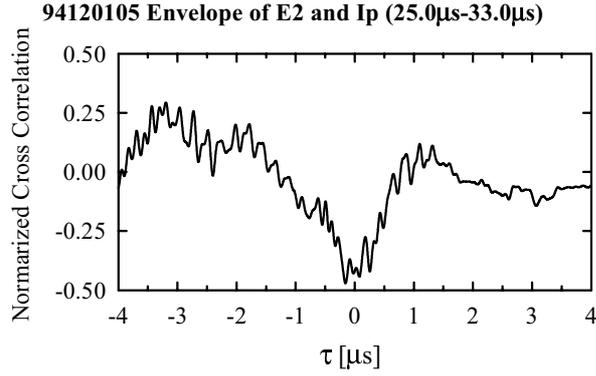
94120105 Envelope of E2 and Ip (25.0μs-33.0μs)

Fig. 2. Cross correlation function of the envelope of the E-field fluctuation E2 and the discharge current in the case of Fig. 1.

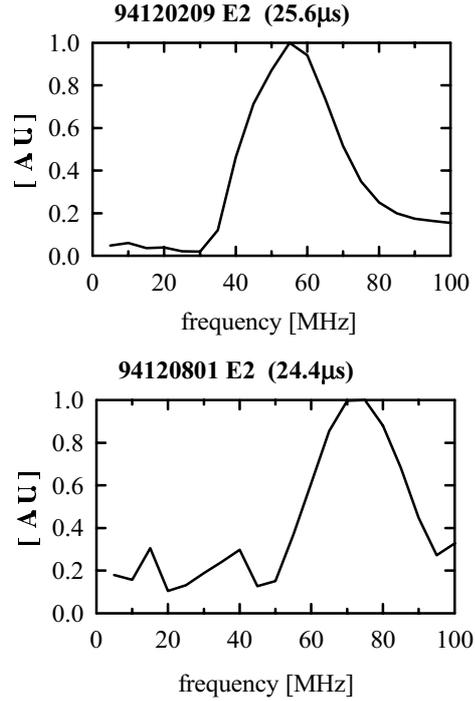**94120209 E2 (25.6μs)**

94120801 E2 (24.4μs)

Fig. 3. Instantaneous power spectral density obtained by the wavelet spectral analysis of the electric field fluctuation E_2 in the current-limiting phase of a linear plasma discharge.
(a) for a deuterium plasma at t=25.6 μs, and
(b) for a hydrogen plasma at t=24.4 μs.

respectively. During this phase the discharge current is strongly limited (<1kA) and the large anomalous resistivity appeared. Fig. 2 shows cross correlation function between the envelope of the electric fields E_1 and the discharge current calculated by using each sampled data sets during the period from t=25.0 μs to 29.0 μs. The cross correlation function shows the remarkable negative peaking at time lag τ=0 μs, and hence that the large anomalous resistivity, nearly 9 Ωcm is given by intense electric field fluctuations in the vicinity of the lower hybrid frequency. Fig. 3 shows a set of instantaneous power spectra of the E-field records obtained for both hydrogen and deuterium plasma by the method of *wavelet* analysis [3]. The sets of instantaneous power spectra of the E-field fluctuations are carefully selected from the point of view that they have clear similarity in the spectral shape. They clearly showed peaking at the frequency corresponding to the lower hybrid frequency, $f_{lh}=(f_{ce}f_{ci})^{1/2}$, where f_{ce} and f_{ci} denote an electron- and ion cyclotron frequency, respectively. Fig. 4 shows the dependence of the peak frequency of the instantaneous power spectra on the strength of the magnetic field in which the plasma discharge was performed. The peak frequency of the well selected temporal power spectra is proportional to the intensity of the magnetic field, as expected from the behavior of a lower hybrid wave under the condition $f_{pe}>f_{ce}$ relevant to the present plasma condition. Although a linear lower hybrid wave theory apparently could not be applicable due to the extremely large amplitude of the E-field fluctuations, the behaviors of the instantaneous power spectrum as shown in Fig. 3 and Fig. 4 is in accordance with its dependence on ion mass and intensity of the magnetic field.

Anomalous resistivity, being estimated by using the magnitude of a plasma current during the current limitation and the dimensions of the plasma, was extremely large and typically 9 Ωcm. On the other hand, anomalous resistivity $\eta = 4\pi (\omega_{lh}/\omega_{pi}^2)(W/nT_e)$, given
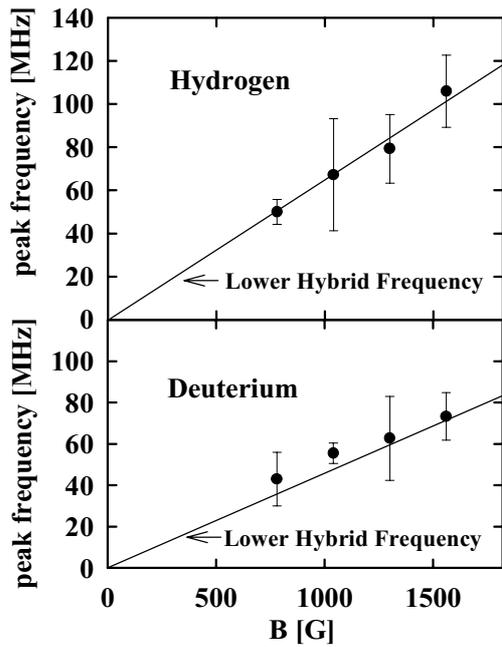
Fig. 4. Dependence of the peak frequency of the power spectra on the strength of the magnetic field.

by the growth rate of lower hybrid condensation instability [4] that was calculated on the basis of the quasilinear theory, was compared with the experimental one. But this quasilinear anomalous resistivity η could not quantitatively explain the observed anomalous resistivity, since the normalized wave energy density in the parallel direction $W_\parallel/nT_e$ could be larger than unity and hence the quasilinear condition for the total wave energy density $W_\parallel/nT_e \ll 1$ could be violated. We propose tentatively that the enhanced effective collision frequency on the order of $(M/m)^{1/2}\omega_{lh}$ can well explain the observed anomalous resistivity, where M and m denote ion and electron mass, respectively.

Here we show another evidence that the large amplitude lower hybrid fluctuations play a dominant role in generation of the anomalous resistivity. A transit time of a drifting electron which moves a distance L = 60 cm from the cathode to the anode with a drift velocity comparable to the thermal velocity 6.3×10^7 cm/s is nearly 0.96 μs and about 57 times that of the period of the lower hybrid wave, τ_{lh} = 17 ns. Thus the large amplitude lower hybrid fluctuations could collectively scatter current-carrying electrons by nonlinear wave-particle interactions and resultantly cause the large anomalous resistivity.

To summarize, we have observed the extremely large anomalous resistivity mostly given by the lower hybrid waves in the nonlinear regime. The cross-correlation function between the discharge current and the lower hybrid fluctuation demonstrates that the nonlinear lower hybrid modes possibly excited by electron beams generated in the beginning phase of a high-voltage linear plasma discharge give rise to strong current limitation and hence most of the large anomalous resistivity.

References

[1] J. Labelle, P.M. Kintner, A.W. Yau and B.A. Whalen: J. Geophys. Res. **91** A6, 7113 (1986) .

[2] S.I. Popel: J. Plasma Phys. **57**, 363 (1997) .

[3] D.E. Newland: An Introduction to Random vibrations, Spectral & Wavelet Analysis. 3rd ed., Longman Scientific & Technical, 1993.

[4] B.I. Sturman: Sov. Phys. JETP. **44**, 322 (1976).

[5] Y. Takeda and K. Yamagiwa: Phys. Fluids B **3**, 288 (1991).