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# Chaotic Lower Hybrid Fluctuations during the Anomalous Resistivity Phase of a High-Voltage Linear Plasma Discharge

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**Abstract**

Recently we have observed self-excited very large amplitude fluctuations in the electric field (parallel to B) whose mean amplitude was typically 10kV/cm and associated with enhanced anomalous resistivity during the quasistationary current limiting phase of a high-voltage linear plasma discharge. The power spectral density of the electric field fluctuations shows the peaking around the lower hybrid frequency, and these lower hybrid fluctuations exhibit chaotic behaviors.

**Keywords:**

lower hybrid mode, anomalous resistivity, chaos, correlation dimension, Lyapunov exponent, linear machine, high voltage discharge

## 1. Introduction

Nonlinear lower hybrid waves, such as wave packets and large amplitude bursts have been observed by recent electric field's measurements by the sounding rockets and the space satellite FREJA near the topside ionosphere [1]. They attract wide interests in the discipline of space and laboratory plasma physics [2].

Recently we have observed self-excited very large amplitude fluctuations in the electric field (parallel to B) whose mean amplitude was typically 10kV/cm and associated with enhanced anomalous resistivity, typically 9 Wcm during the quasistationary current limiting phase of a high-voltage linear plasma discharge. The power spectral density of the electric field fluctuations shows the peaking around the lower hybrid frequency $f_{lh} = (f_{ce} f_{ci})^{1/2}$, where $f_{ce}$ and $f_{ci}$ denote an electron-cyclotron and ion cyclotron frequency respectively, and these fluctuations clearly exhibit chaotic behaviors.

## 2. Experimental Setup and Methods of Measurements

The plasma experiment is performed in an open system in which a high discharge current is drawn along the magnetic field for a preexisting hydrogen (or deuterium) plasma produced by a titanium washer gun. The experimental apparatus and the axial arrangement of diagnostic tools are shown in Fig. 1. 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 1.3kG. The discharge is ignited by applying a high voltage $V_c$ = 13–18kV from a capacitor with $C$ = 2.2μF between the cathode (aluminum disk 50 mm in diameter) and the cylindrical muzzle of the plasma gun after a suitable delay time, typically 18μs

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from firing the gun. The parallel electric fields were measured at the two axial positions, one in front of the cathode and the other at the center of the apparatus by using a pair of electric double probes and optically isolated transmission systems. The experimental apparatus and the diagnostic tools were described in detail in the previous paper [3].

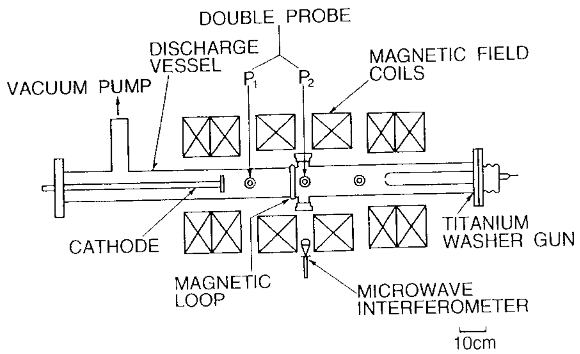


Fig. 1 Experimental apparatus and the axial arrangement of diagnostics.

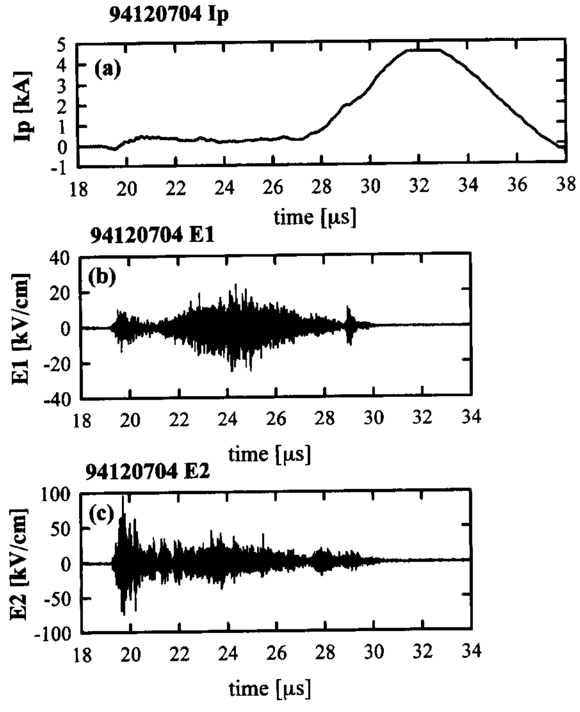


Fig. 2 Typical data sets of the high-voltage linear plasma discharge. The time trace (a) shows discharge current, (b) the parallel electric field $E_1$ measured 10cm in front of the cathode, (c) the parallel electric field $E_2$ at the center of the apparatus.

## 3. Experimental Results

Fig. 2 shows a typical time profile of the discharge current, time series of the longitudinal electric field (abbreviated as E-field hence forth) measured by the double probes on the cathode side ($E_1$) and at the midplane of the discharge device ($E_2$) 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 = 20.0μs to 28.0μs. During this phase the discharge current is strongly limited (< 1kA) and the large anomalous resistivity appeared.

The power spectral densities of the fluctuation in $E_I$ and $E_2$ are shown in Fig. 3 (a) and (b). The spectra are calculated by conventional Fast Fourier Transform (FFT) with a Hanning window.

The power spectra at the center of the apparatus in Fig.3 (b) show the peaking around the lower hybrid frequency $f_{lh} = (f_{ce}f_{ci})^{1/2}$ = 80MHz relevant to the parameters of a hydrogen plasma and the intensity of the

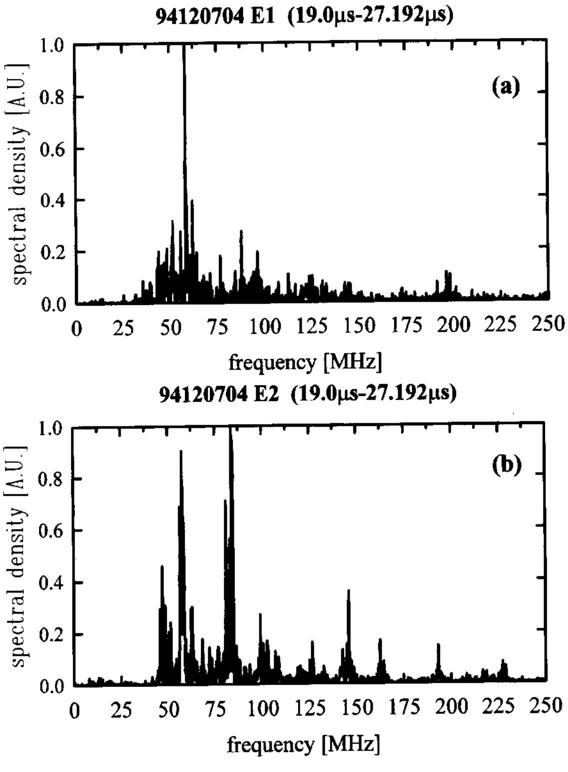


Fig. 3 The power spectral density of the E-field fluctuations (a) measured 10cm in front of the cathode and (b) the spectral density at the center of the apparatus.

magnetic field. The peak frequency of the time-resolved 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 [4].

In order to determine whether the lower hybrid fluctuations become a chaotic state or not, the correlation dimensions [5] and largest Lyapunov exponents [6] were calculated from the time series of the electric field data measured (a) 10 cm in front of the cathode and (b) at the center. The correlation dimension is defined as an exponent of the power-law dependence of the correlation integral for the strange attractors [7], and the meaningful measure of the fractal dimensions related to the system freedoms. The Lyapunov exponent is a measure of the exponentially increasing divergence of nearby orbits in the phase space [6]. When the system is chaotic, the correlation dimensions D should become a constant but non-integer value with increasing embedding dimensions and the largest Lyapunov exponents become positive. Figure 4 (b) shows that the calculated correlation dimension of the E-field at the center of the apparatus becomes constant (D = 4.1) against embedded dimensions and is not integer. The largest Lyapunov exponent shows positive value, 0.534. This is calculated from 3000 points E-field data with a sampling time 2ns. Thus the lower hybrid fluctuations clearly show chaotic behaviors in the first half period of the anomalous resisitivity phase. The difference of chaotic behavior in $E_1$ and $E_2$, as seen in Fig. 4 (a) and (b) could be interpreted as due to the difference in the power spectra of $E_1$ and $E_2$ shown in Fig. 3 (a) and (b). It should be noted that while $E_1$ has an almost singly-peaked spectrum, $E_2$ has a multiply-peaked complex spectrum having many harmonics and sub-harmonics. The correlation dimensions of $E_1$ and $E_2$ in the latter half period of the anomalous resitivity phase do not become constant with increasing embedding dimensions as shown in Fig. 5. Hence we conclude that the large amplitude lower hybrid E-field fluctuations during the current-limiting phase are highly nonlinear, and lead to a chaotic state.

## 4. Conclusions

To summarize, we have observed the large amplitude E-field fluctuations with a frequency near the lower hybrid frequency. The current limitation and anomalous resistivity are highly correlated in the fluctuation level. The correlation dimensions and Lyapunov exponents derived from the E-field data

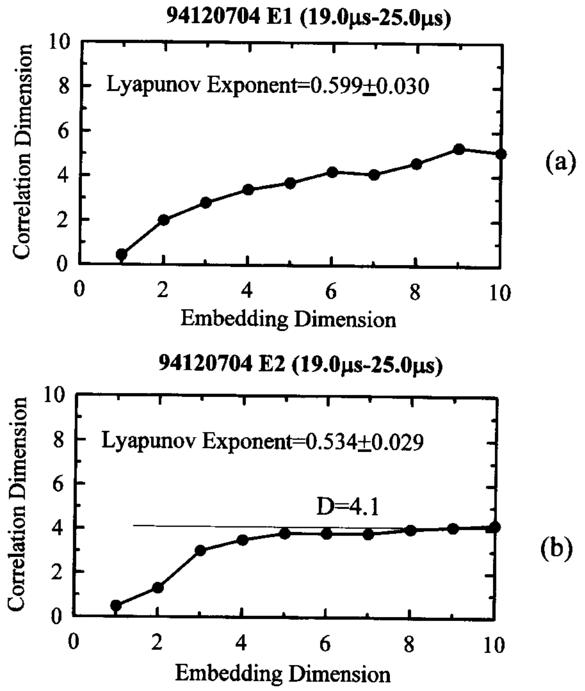


Fig. 4 Correlation dimensions of the data of the electric field measured (a) 10cm in front of the cathode and (b) at the center during t = 19.0μs–25.0μs.

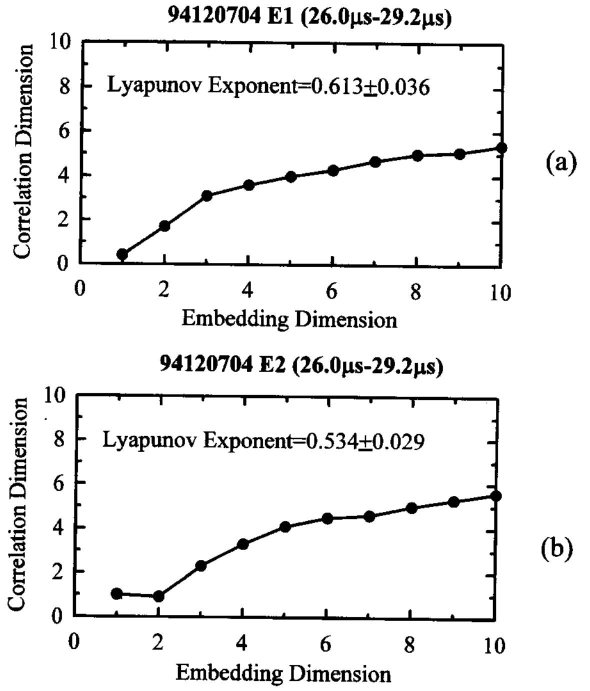


Fig. 5 Correlation dimensions of the data of the electric field measured (a) 10cm in front of the cathode and (b) at the center during t = 26.0μs–29.2μs.

indicate that the lower hybrid wave fluctuations are sufficiently chaotic in the first period of the discharge.

## 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 and J. Plasma Phys. **57**, 363 (1997).

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

[4] Y. Takeda, H. Inuzuka and K. Yamagiwa, Proc. 1998 Int'l Conf. on Plasma Physics, Prague, (1998).

[5] P. Grassberger and I. Procaccia, Physica **D9**, 189 (1983).

[6] A. Wolf, J.B. Swift, H.L. Swinney and J.A. Vastano, Physica **D16**, 285 (1985).

[7] P. Grassberger and I. Procaccia, Phys. Rev. Lett. **50**, 346 (1983).