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Observation of Fluctuations Responsible for Stochastic Ion Heating in a Turbulent Plasma

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ABSTRACT

Experiments are described in which the correlation time and fluctuation level of ion acoustic waves are measured under the condition of turbulent heating using twin capacitive probes. At the anomalously resistive time, the correlation time becomes shorter, typically several periods of ion waves, and the energy density of the waves is of the order of $10^{-2} n_e T_e$. The ion heating rate previously reported is well explained by these results to be due to stochastic mechanism.

Turbulent ion heating due to ion waves excited by a strong electric field is important as a possible means of providing supplemental heating in fusion device. However, even though turbulent heating provides an efficient and relatively simple method by which energy can be fed into a dense plasma, heating mechanisms have not necessarily be clarified because of difficulties of both experimental measurements and theoretical treatments.

In this report, we present the measurements of fluctuations in a linear turbulent heating of a plasma by means of twin capacitive probes. Correlation time, the level of density fluctuations and the direction of dominant propagation of the ion acoustic waves were measured in detail. These results are compared with the existing theories[1-6] concerned with turbulent ion heating.

In the quasi-linear approximation, the effect of nonlinearity of the oscillations is taken account, for example, by introducing the oorrelation function of the amplitudes of the electric field Fourier component $E_k(t)$, which may be qualitatively equivalent to putting

$$<E_k(t)\ E_k^*(t')> = |E_k(t)|^2 \mathrm{EXP}(-t/\tau_c)\ , \qquad (1)$$

where the angle blacket denotes ensemble average and τ_c is the correlation time. In this case the correlation time has to satisfy the condition given by

$$\tau_c \gg 2\pi/\omega \quad , \tag{2}$$

where τ_c^{-1} should be of the same order of growing (damping) rate of the characteristic wave of the frequency $\omega/2\pi$. **In the** stochastic process under the condition of eq.(2), the correlation time is approximately given by[2,5]

$$\tau_c^{-1} \simeq \omega_{pi} \langle (e\phi/T_e)^2 \rangle \quad , \tag{3}$$

where ω_{pi} is angular ion plasma frequency, T_e is electron temperature and ϕ is the wave potential. Although stochastic ion heating rate has been investigated theoretically by various authors,[2-4,6] all of their resluts may be consequently reduced to

$$\begin{aligned} dT_i/dt &\simeq (T_e/\tau_c) \langle (e\phi/T_e)^2 \rangle \\ &\simeq \omega_{pi} T_e \langle (e\phi/T_e)^2 \rangle^2 \end{aligned} \tag{4}$$

provided $T_e \gg T_i$ and $\omega\tau_c \gg 1$, which is larger than that due to nonlinear Landau damping[10] by T_e/T_i.

On the other hand, only a few experiments associated with the stochastic ion heating have been reported,[7,8,9] and to our knowledge, Hirose *et al.*[7] first presented the stochastic ion heating in terms of both the correlation time and heating rate, using the relative values of wave potential obtained from floating probes and the maximum growth rate of ion waves calculated from linear theory. Apart from their qualitative agreement with quasilinear theory, their plasma, however, seems to be beyond the flamework of the theory, because the width of the power spectrum ($\Delta\omega \simeq 2\pi\tau_c^{-1}$) is the same order of the peak frequency, i.e., $\omega\tau_c \simeq 2\pi$.

Our experiments were performed on the device of linear turbulent heating plasma (THE MACH II) of the Nagoya University, which is described in detail elsewhere.[11] The almost fully ionized helium plasma was formed and injected into the vaccum vessel by a conical theta-pinch gun. The magnetic field strength at the mirror center (the mirror ratio of 1.6) was 5 kG. Two hollow electrodes with inner diameter of 3 cm were placed in the vessel separated from each other by 57 cm. The turbulent heating pulse was produced by the simultaneous discharge of two series-connected capacitors(2.2 μF each), each charged to 15 kV. The electron density ($(1\text{-}5)\times10^{13}\,\text{cm}^{-3}$) and temperature ($(1\text{-}3)\times10^3$ eV) were determined by measurements with a microwave interferometer, and X-ray absorption[12] and the velocity of ion acoustic waves.[13]

Fluctuation measurements were carried out by a pair of movable capacitive probes[15] (tip size: 1.7 mm x 1 mmϕ, tip sepatation: 5 mm or 10 mm) immersed in the center of mirror field. The capacitive probe may determine the absolute value of fluctuating electrostatic potential by taking accout of the capacitance between the tip and plasma (0.2 pF), and the stray capacitance (40 pF) as well as attenuation of the coaxial cable between a termination resistance and a scope. In our case, total attenuation rate for the absolute potential value is about 1.4×10^{-3} for (150-250) MHz. Fluctuations appearing at heating period were directly observed on the high speed scope (Tektronix 7844).

For the determination of the autocorrelation time and power spectrum of the wave, we analyze the raw data on the scope by virtue of digital method.[16] A block diagram for the digital analysis is shown in Fig.1. As our analysis is restricted to the stationary random process in the wide sense, which is even difficult to be checked strictly, one is allowed to take average over time instead of ensemble. Whenever one tries to estimate the power spectrum density from digital records, one should note the so called aliasing problem:[16] however, in our analysis, the interval sampling time is chosen to be 0.4 nsec or cutoff (Nyquist) frequency is 1.25 GHz, which is beyond the frequency the scope covers (400 MHz), and then the ailing problem is successfully avoided. The total number of equally spaced point along the time axis is two hundreds and the maximum number of correlation lag values is sixty: the resolution bandwidth for the power spectrum is then 41.7 MHz. Since data are desired to be stationary mentioned above and low frequency components less than 50 MHz contained in fluctuations smear the autocorrelation function corresponding to the frequency components around (200-300) MHz, the digitized original records of fluctuations are first passed through the digital high pass filter in addition to the filter for the elimination of the linear trend component. The Hanning lag window is also performed to the power spectrum density functions for the reduction of the estimation errors resulting from finite time records.

In Fig. 2 are shown typical data on fluctuations when the plasma showed high resistance. The elimination of the linear trend is already performed to all traces, and lower two traces are passed through the high pass filter of time constant 3.18 nsec. The auto power-spectrum density function and autocorrelation function of Q in Fig.2 is shown in Fig.3(a) and (b), respectively. It clearly shows that the wave of frequency about 200 MHz ($\omega_{pi}/(2\pi) \simeq (300\text{-}400)$ MHz) is not coherent but has the finite correlation time of about 24 nsec. It follows that $\omega\tau_c$ is about 30 and then the quasi-linear theory may be useful to interpret our experimental results. It is also found that the average potential of the fluctuations, which is obtained from the height of the power spectrum, is (150-250) eV:therefore $(e\phi/T_e) \simeq 10^{-1}$, or the wave energy density is of the order of $10^{-2} n_e T_e$.

From these experimental values, we obtain $\omega_{pi} < (e\phi/T_e)^2 > \sim 2.5 \times 10^7$ sec^{-1}, which compares well to $\tau_c^{-1} \sim (3\text{-}5) \times 10^7$ sec^{-1}: this good agreement confirms the relationship of eq(3). Furthermore, the ion heating rate in the stochastic process is estimated to be $(T_e/\tau_c)(e\phi/T_e)^2 \simeq (3\text{-}10) \times 10^8$ eV/sec. This value also agrees well with the heating rate of bulk energy part of bi-Maxwellian distribution of helium ion (~2 x 10^8 eV/sec), which was reported previously in the separate paper.[14] Just after the termination of rapid ion heating, fluctuations are still surviving but their correlation time is apparently getting infinite as shown in Fig.4. Consequently, the rapid ion heating in THE MACH II is mainly accompanied by the stochastic process resulting from the finite correlation time of ion waves.

The phase velocity of the waves is also measured by use of cross power-spectrum density function calculated from the transient Fourier transform of cross correlation function. In Fig.3(c) and (d), are shown the absolute magnitude of the cross power-spectrum density function and its phase delay calculated from the two records Q and R in Fig.2, where the twin probes made an angle of $\theta=45^\circ$ with the magnetic lines of force. Changing the angle between the twin probes and the magnetic field, we find the waves propagate with ion acoustic velocity $C_s=(T_e/M)^{1/2}$ almost perpendicularly to the magnetic field, since the phase velocity obtained in the range (0.5-3) x 10^8 cm/sec has a tendency to decreasing with increase of the angle $\theta(0^\circ\text{~}90^\circ)$ and the lowest value of the phase velocity corresponds well to C_s. This is reasonable as the drift velocity of the electron current is several times as large as C_s. For the reason of almost perpendicular propagation, the ion wave (ion Bernstein mode) has also been confirmed by the measurements with 90° microwave scattering.[13]

In summary, we observe that current driven ion acoustic waves play an importnant role in turbulent ion heating, and its heating rate and correlation time agree with the stochastic heating theory which is qualitative in character.

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FIGURE CAPTIONS

FIG.1 A block diagram for numerical analysis of fluctuations.

FIG.2 Typical fluctuations obtained by twin capacitive probes: U and V are original ones after the elimination of linear trend, and Q and R are ones after high pass filter. (10 nsec/div).

FIG.3 (a) Auto power-spectrum density function of Q in Fig.2.

(b) Autocorrelation function of Q.

(c) Absolute value (arbitrary unit) of cross power-spectrum density function for Q and R.

(d) Phase delay in radian between Q and R.

FIG.4 Auto power-spectrum density function and autocorrelation function of fluctuation after termination of rapid ion heating.

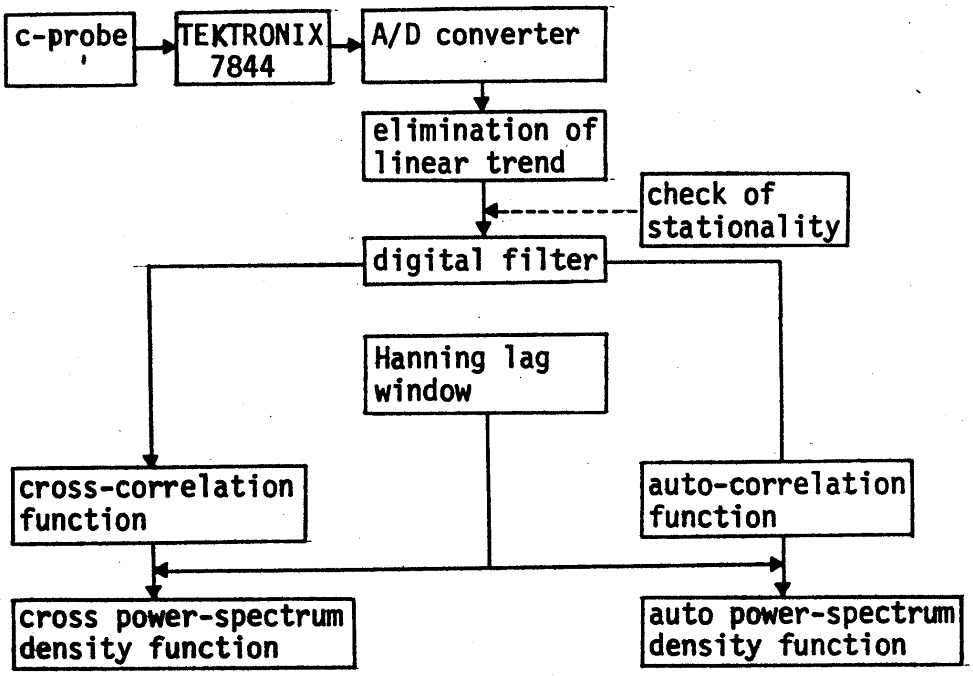
c-probe
TEKTRONIX 7844
A/D converter
elimination of linear trend
check of stationality
digital filter
Hanning lag window
cross-correlation function
auto-correlation function
cross power-spectrum density function
auto power-spectrum density function

FIG. 1

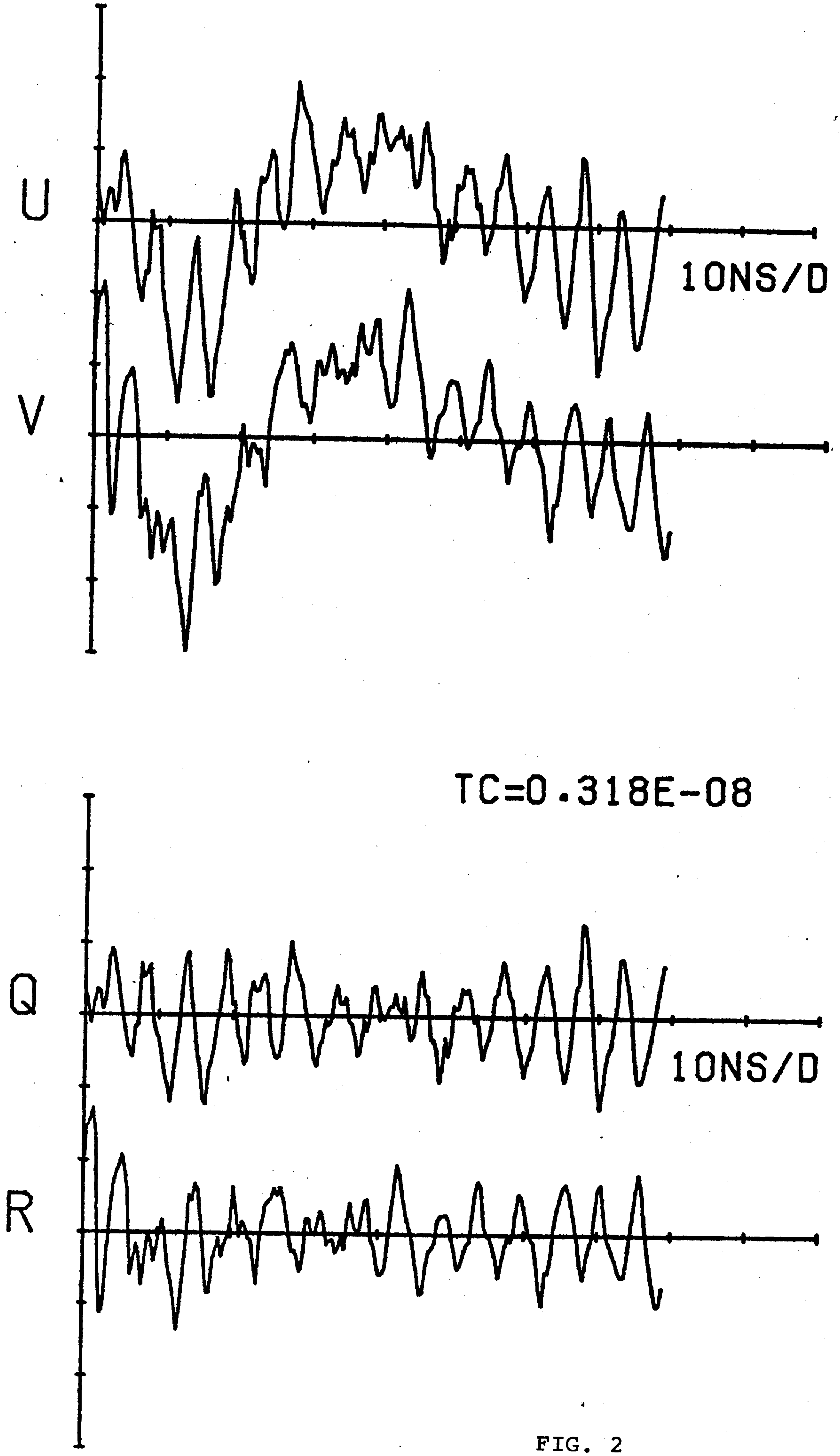

FIG. 2

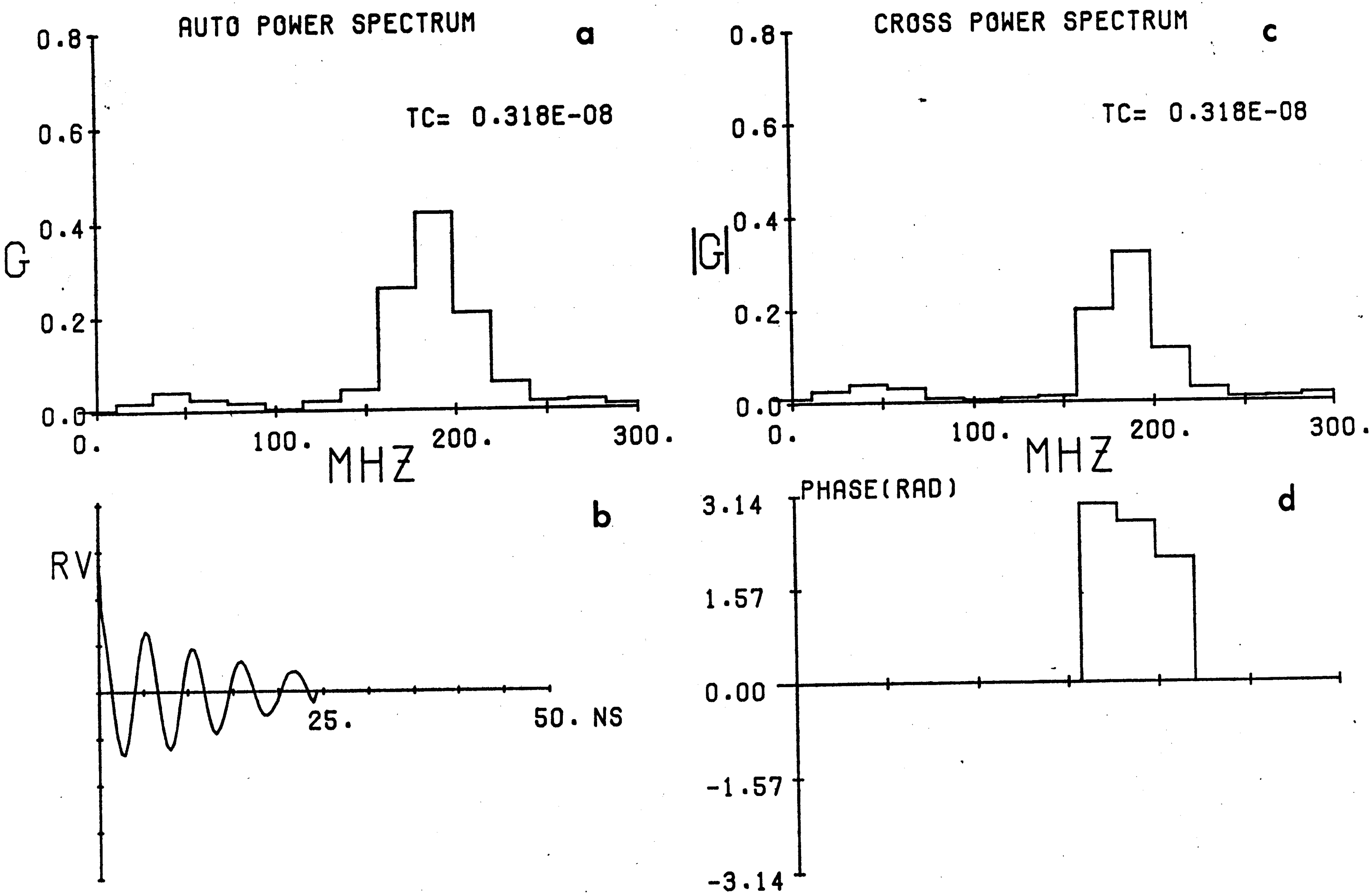
AUTO POWER SPECTRUM
a
TC= 0.318E-08
G
0.8
0.6
0.4
0.2
0.0
0.
100.
200.
300.
MHZ
CROSS POWER SPECTRUM
c
TC= 0.318E-08
|G|
0.8
0.6
0.4
0.2
0.0
0.
100.
200.
300.
MHZ
b
RV
25.
50. NS
PHASE(RAD)
d
3.14
1.57
0.00
-1.57
-3.14

FIG. 3

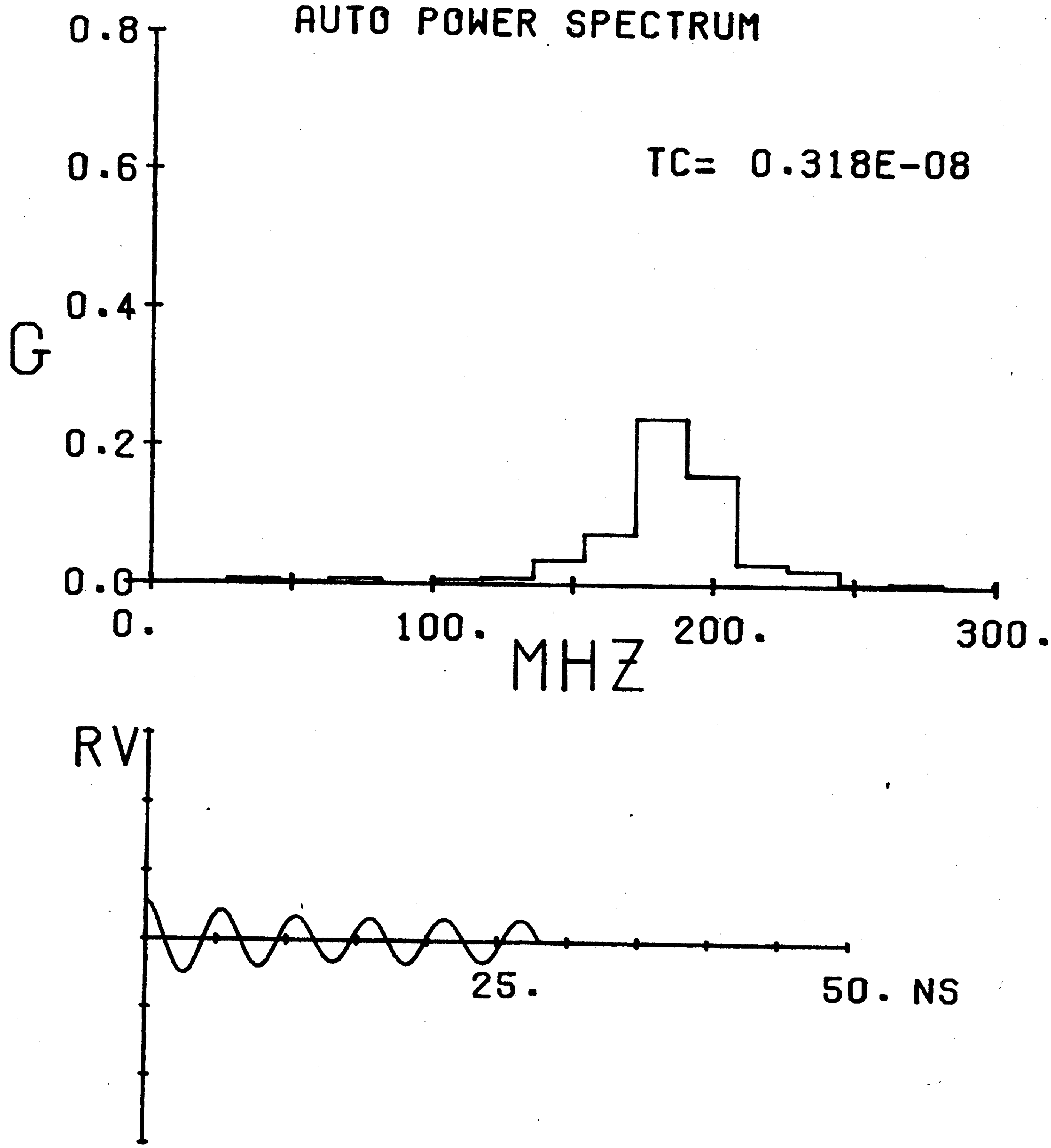
AUTO POWER SPECTRUM
TC= 0.318E-08
G
0.8
0.6
0.4
0.2
0.0
0.
100.
200.
300.
MHZ
RV
25.
50. NS

FIG. 4