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Anomalous Plasma Resistivity in Pre-Pulsed Flashlamp Discharges*

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Abstract

It is shown that the V-i characteristic of discharges in flashlamps operating in the pre-pulsed mode at high current densities follows the relationship $V = K_0 i^{0.85}$. This result is interpreted in terms of the Sagdeev-Galeev anomalous resistivity due to current-driven ion acoustic turbulence.

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The knowledge of the V-i characteristic of the flashlamp is important for the circuit optimization of a flashlamp pumped laser.[1] It has been found experimentally[2] that this characteristic follows the general relationship $V = K_0 i^{1/2}$, where V is the voltage applied to the lamp electrodes, i is the total current that flows through it, and K_0 is a constant for a given lamp. Assuming that the plasma in the lamp is fully ionized and radiates as blackbody, the experimental relationship given above can be obtained approximately by balancing the radiation and ohmic heating powers for the lamp.[3,4] The final result for the V-i characteristic depends critically on the form that one assumes for the plasma resistivity η in the expression for the ohmic heating power. Demenik et al.[3] and Gusinow[4] have assumed the resistivity given by the classical Spitzer expression for a fully ionized plasma.[5] This expression for the plasma resistivity is derived on the assumption that the electrons loose their momentum by classical Coulomb scattering on the ions. However, it has been verified in many experiments that the plasma resistivity is usually higher than the classical value. This anomalous resistivity is due to the scattering of the electrons by the turbulent electric field of many plasma instabilities.[6-12] Most of the experiments were done in low density magnetized plasmas. In this letter we show that anomalous resistivity may play an important role also in the high density unmagnetized plasmas[8] characteristic of flashlamps.

It is advantageous for the laser performance to operate the flashlamp in a pre-pulsed mode.[13,14] In this case it is reasonable to assume that a high level of turbulence is excited in the plasma of the flashlamp. When a pre-pulse is applied, the main pulse drives a large current in a pre-formed plasma. Under this condition, current driven ion-acoustic waves can be easily excited even in high density plasmas.[9,11] If the turbulent spectrum[11] has a sufficiently high density intensity level, one expects the value of the plasma resistivity to be higher than the classical one[15] and the V-i characteristic of the lamp to change from the 1/2-power law.

In Fig. 1 we show the V-i characteristic of a flashlamp (Xenon Corporation 850 AR; arc-length $L = 10$ cm; bore diameter $D = 5$ mm; working gas: Xenon) operating in the simmered pre-pulsed mode described by Marotta and Argüello.[14] In the same figure we plot the relationship $V = K_0 i^{1/2}$ obtained by Goncz (dashed lines) with $K_0 = 1.3\ L/D\ \Omega A^{1/2}$ (see Ref. 16). It is clear from the figure that our experimental result cannot be described by the 1/2-power law; rather, from a minimum square fit of the experimental points, we obtain the relationship $V = K_0 i^{0.85}$

with $K_o = 2.9\ (\pm.1)\ \Omega A^{0.15}$. This result suggests that the plasma resistivity is anomalous in our experiment.

We have estimated the critical runaway (Dreicer) field[17] E_r for all the experimental points shown in Fig. 1 using reasonable estimatives for the electron particle density n and temperature T_e in the lamp. We have found that the ratio between the applied and critical runaway fields is less than 1%. Thus there are almost no runaway electrons in our flashlamp discharges. On the other hand, the ratio between the electron drift u and ion-acoustic c_s velocities is always greater than one. Here $u = j/ne$ and $c_s = (kT_e/M_i)^{1/2}$, where j is the current density, e is the electron charge, k is the Boltzmann constant, and M_i is the ion mass. These two results indicate that the anomalous resistivity in our experiment is most probably due to ion-acoustic waves only.[6,7]

Many different expressions have been proposed for the anomalous resistivity due to ion-acoustic waves.[6,7,9,15,18,19,20] We find that our experimental result is better explained by one of Sagdeev and Galeev[15], i.e.,

$$\eta \approx \frac{(m/k)^{1/2}}{\epsilon_o \omega_{pe} n e}\, j\, \frac{T_e^{1/2}}{T_i} \qquad (1)$$

where m is the electron mass, $\omega_{pe} = (ne^2/\epsilon_o m)^{1/2}$ is the plasma frequency, and T_i is the ion temperature. In the high density plasmas of flashlamps, the ions loose their energy mainly by radiation and collisions with the neutrals[21]; they are heated by the electrons directly through collisions and also via the ion-acoustic turbulence.[12,19,21] To the best of our knowledge, there is no definite expression for the ion heating rate in the ion-acoustic turbulence regime.[7,9,10,12,19,21] We have then assumed that the relationship between T_i and T_e during the anomalous heating is given by $T_i \sim \beta\, T_e^{\alpha}$; the constant α is chosen as described below and the constant β can be only roughly estimated in our experiment.

Following the procedure of Refs. 3 and 4, we equate the total blackbody radiation to the total volume ohmic heating powers, i.e.,

$$(2\pi RL)\, a\, T^4 = (\pi R^2 L)\, \eta j^2 \quad , \qquad (2)$$

where R and L are the lamp bore radius and axial length, respectively, a is the Stefan-Boltzmann constant, and T is the color temperature which is assumed equal to the electron temperature T_e. Using the relationship between T_e and j derived from (2), we can write η (1) in terms of j only. Then the V-i characteristic of the lamp can be obtained from Ohm's law $V = L\eta j$. The constant α is chosen in such a way that the V-i characteristic follows our experimental result reasonably well with the compromise that T-j characteristic follows closely the experimental data of other workers for high current densities (the experimental points given in Fig. 1 of Ref. 4). We find that these two conditions can be satisfied with $\alpha \simeq 3$. The final T-j and V-i relationships are

$$T = \left(\frac{C}{2a}\right)^{2/13} (j\,R^{1/3})^{6/13} \tag{3}$$

and

$$V = \left[\frac{C^8 (2a)^5}{\pi^{11}}\right]^{1/13} \frac{L}{R^{27/13}}\, i^{11/13} \quad , \tag{4}$$

where $C = (m/k)^{1/2} (\epsilon_0 n e \omega_{pe} \beta)^{-1}$. In Fig. 2 we show a log-log plot of experimental points given in Fig. 1 of Ref. 4 for T as a function of $(jR^{1/3})$. It is seen that the 6/13-power law of Eq. (3) is followed reasonably well at high current densities. A similar plot of T as a function of $(jR^{1/2})$ shows that the 4/11 power law derived by Gusinow[4] using the classical Spitzer resistivity does not fit the experimental points at high current densities.

The integer value for α that we have found is suggestive of some basic process of energy transfer from the electrons to the ions. However we did not succeed in our theoretical search for this process. Neither could we find any other experimental evidence for the relationship $T_i \sim \beta T_e^3$ in the literature. Finally we mention that our rough estimatives for β indicate that $T_i \lesssim 10^{-3}\, T_e$, what satisfies the $T_i < T_e$ condition for the existence of ion acoustic waves.[15]

FIGURE CAPTIONS

Fig. 1 - Voltage-current relationship obtained in a simmered pre-pulsed flashlamp discharge (solid line). The dashed line corresponds to the experimental relationship obtained earlier by Goncz.[2]

Fig. 2 - Current density dependence of the plasma temperature. The solid line corresponds to the relationship derived using the Sagdeev-Galeev anomalous resistivity (3). The experimental points were obtained from the same references listed in Fig. 1 of Ref. 4.

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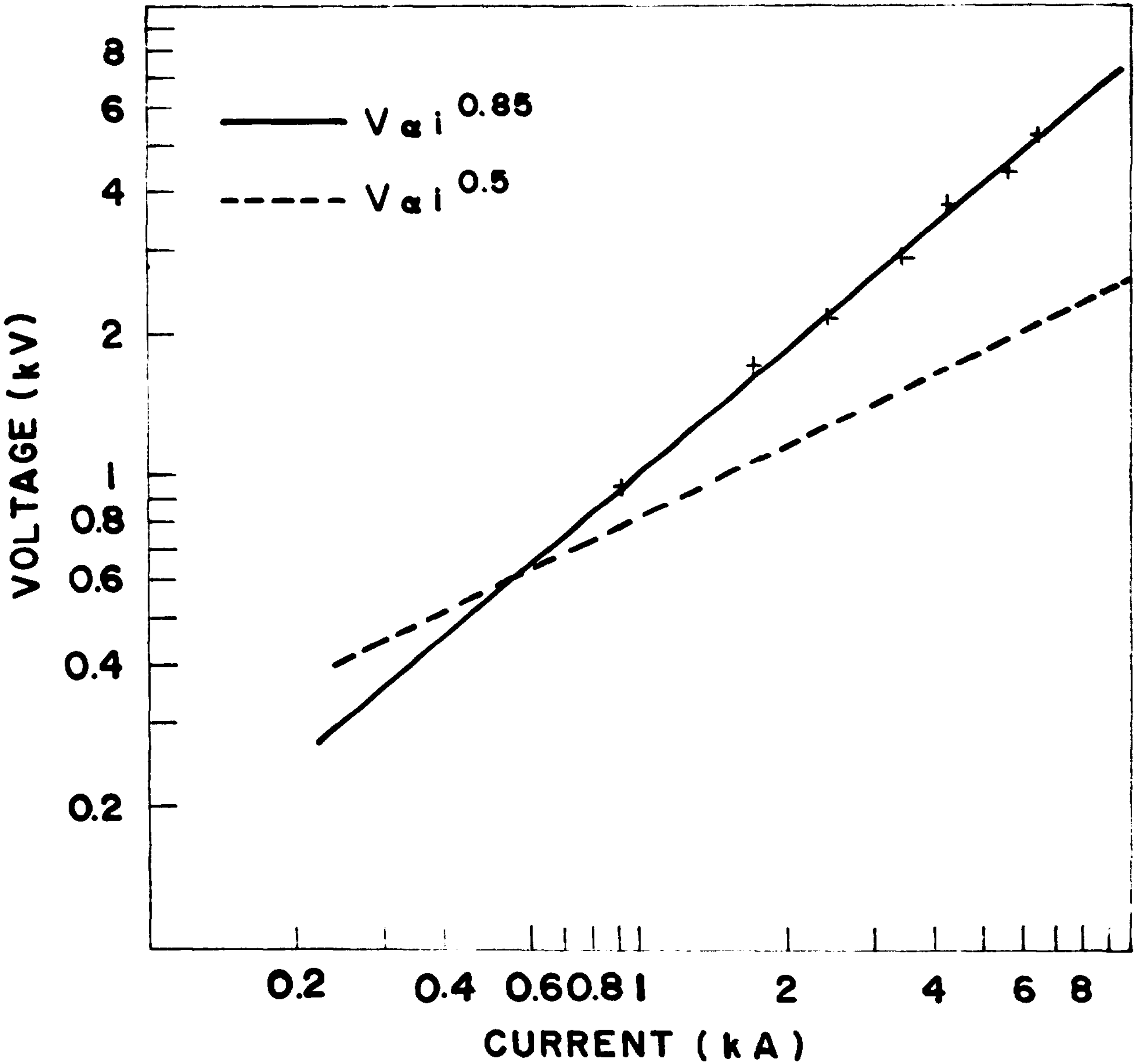
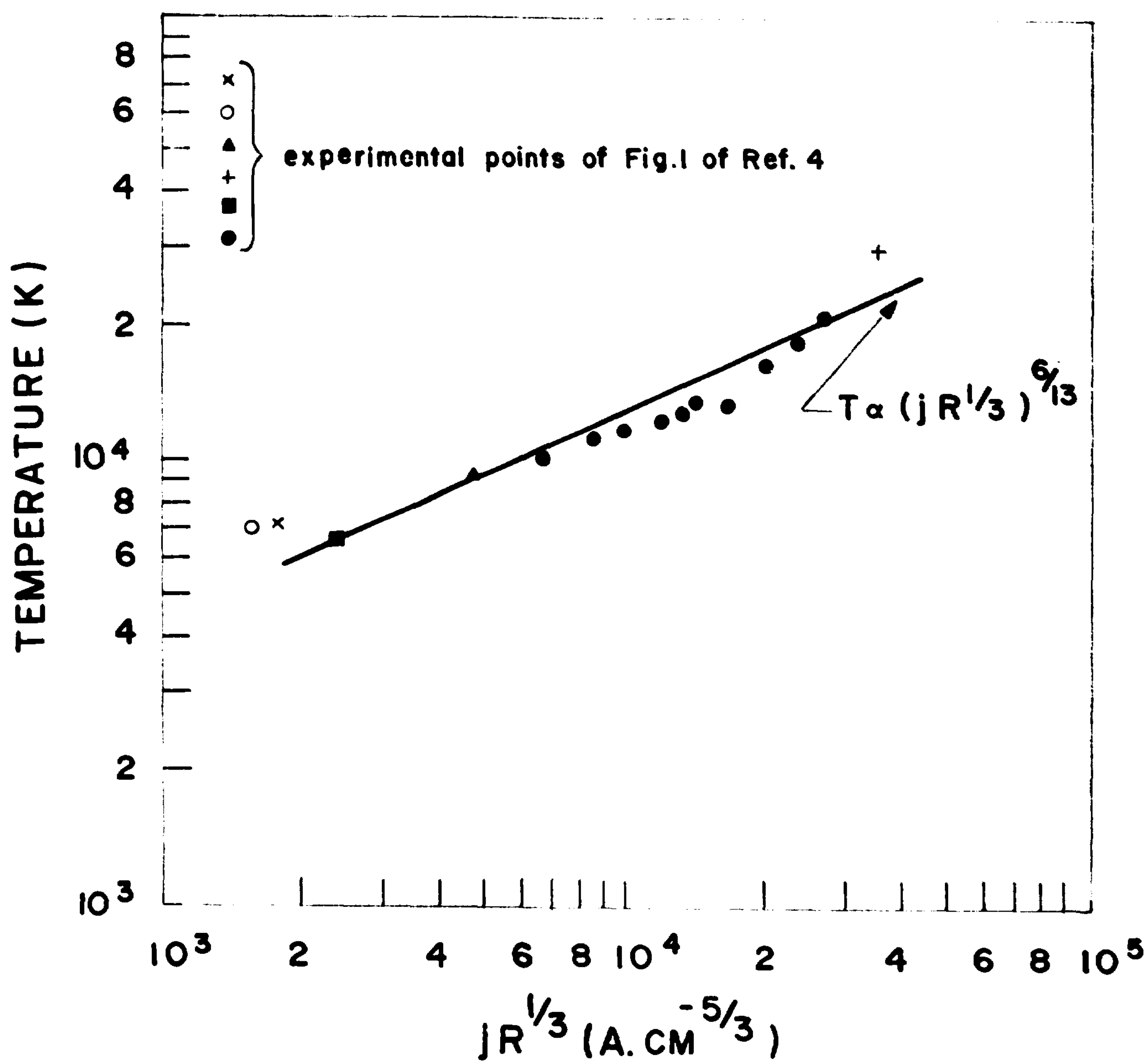


V α i 0.85
V α i 0.5
VOLTAGE (kV)
8
6
4
2
1
0.8
0.6
0.4
0.2
0.2
0.4
0.6
0.8
1
2
4
6
8
CURRENT (kA)


TEMPERATURE (K)
experimental points of Fig.I of Ref. 4
T α (j R^1/3)^6/13
j R^1/3 (A. CM^-5/3)