

Schlieren Measurements of a High Density Z-Pinch

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The dense plasma phase of a dynamic z-pinch working at a high filling pressure is studied. By using the Schlieren-technique it is found that the compressed plasma column, though macroscopically stable for times less than $1\ \mu\text{s}$ develops quickly from a homogeneous state to a turbulent one with a perturbation scale length of typically some millimeters. Quantitative measurements of light deflection give electron densities of typically $10^{19}\ \text{cm}^{-3}$ at 0.25 Torr He filling.

In order to study the interaction of high power CO_2 laser radiation ($\lambda = 10,6\ \mu$) with dense plasmas a linear pinch device has been constructed since at high filling pressures it can produce plasmas with densities above $10^{19}\ \text{cm}^{-3}$ during the dynamic phase of the compression^{1–6}. This is desirable since for a strong interaction the plasma frequency should be near the laser frequency. In addition the plasma is preferably fully ionized as well as homogeneous. In the following we briefly describe the device as well as an investigation of the plasma homogeneity and density.

Design

The experiment is constructed so that the plane end electrodes of stainless steel are 50 cm apart in an 18 cm diameter discharge tube having a coaxial return conductor. Four windows in the midplane are provided. The main capacitor bank stores 32 kJ at 40 kV. Each of the nine capacitors is individually switched with a three-element spark gap. Also incorporated is a preheater circuit which stores 400 J at 25 kV.

The usefulness of the preheater is questionable in this experiment; although the ignition of the main discharge becomes more reproducible, the dynamic compression worsens. The preheated plasma acts against the imploding shock front. Generally the preheater is not used with easily ionized gas such as H_2 , but it is necessary with He. The time between firing the preheater discharge and the main discharge is selected between 5 to $10\ \mu\text{s}$.

Diagnostics

The voltage across and current through the discharge are measured respectively by a low in-

ductance voltage divider and a Rogowsky coil. These signals are used as monitors and are similar from shot to shot. The bremsstrahlung and recombination continuum radiation in the visible spectral range is recorded as an additional monitor signal. Since this continuum intensity is proportional to the product of electron and ion density, it clearly indicates the dense plasma phase.

Schlieren photographs using a Q-switched ruby laser as a light source were made in order to observe the structure and homogeneity of the dense plasma column. The Schlieren apparatus responds to density gradients in the plasma and is very sensitive to small scale perturbations caused by macroscopic plasma turbulence. A schematic drawing of the arrangement is shown in Figure 1.

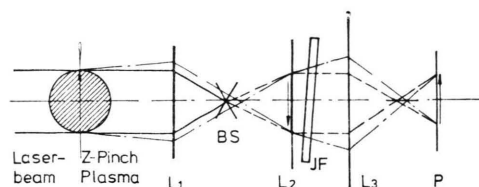


Fig. 1. Schematic arrangement of the Schlieren setup.

The parallel beam of a ruby laser having a duration of 20 ns falls on the dense plasma column and lens L_1 which focuses the undeviated portion on to a beam stop (BS) where it is absorbed. The beam stop consists of two crossed wires each 1 mm thick. Lenses L_2 and L_3 focus the deviated light through an interference filter (IF) on to a photographic film (P), such, that the image of the plasma column through lenses L_1 , L_2 and L_3 coincides with the plane of the film. Because of the unknown optical thickness of the plasma and the rapid erosion

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of the windows by the plasma, measurements of absolute intensities were difficult. These problems have led to the concept of measuring the density by measuring the refraction of the incident laser light. Figure 2 shows the arrangement of the optical apparatus used for those measurements.

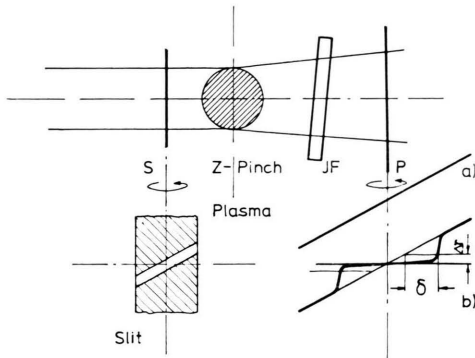


Fig. 2. Experimental setup for measuring the light deflection due to density gradients in the plasma; (a) shows the image of the slit on the film with no plasma present, (b) with plasma.

Parallel light from the Q-switched ruby laser illuminates a slit of 0.4 mm width inclined 45° to the plasma column axis. After passing through an interference filter to exclude the plasma radiation, the laser light is recorded on a film 45 cm distant from the plasma axis. If no plasma is present, the laser light appears as a straight bar on the film (Figure 2a). If the plasma is present, light is refracted and the exposure is similar to that sketched in Figure 2b. The angular deviation of the ray may be determined from the horizontal displacement (δ), while the vertical position (Δr) gives the corresponding radius of the incoming light.

In order to calculate the plasma density, the deflection measured is compared with that deflection that would be produced by a cylindrically symmetric medium with a refractive index of $n(r) = [1 - \omega_p^2(r)/\omega_L^2]^{1/2}$; $\omega_p(r) = [\varrho(r)e^2/m\epsilon_0]^{1/2}$ is the plasma frequency, $\varrho(r)$ is the radial density function, and ω_L is the laser angular frequency. Suitable functions for $\varrho(r)$ are chosen and the equations of motion for the light rays are integrated numerically to obtain the deflection. Two functions have been used: a Fermi function of the type

$$\varrho(r) = \varrho_0 [1 / (\exp[(R - R_1)/R_2] + 1)],$$

and a resonance function

$$\varrho(r) = \varrho_0 R_2^2 [1 / ([R - R_1]^2 + R_2^2)].$$

The constant ϱ_0 is the peak density, R_1 the radius of the plasma, and R_2 the characteristic width of the sheath. For both cases, the maximum deflection is linear in ϱ_0 ; the location of this maximum determines R_1 , and R_2 must be adjusted to bring the data and the calculations into reasonable agreement. The deflection is proportional to $n^{-1} dn/dr$; it is possible to have rays deflected toward or away from the axis depending upon the sign of the gradient. The Fermi function, peaked on axis, only bends light away from the axis. However, the gradient of the resonance function with a peak at $R = R_1$ changes sign, and thus light is bent in both directions.

Both the Schlieren and refraction methods are limited to plasmas, which are not completely optically thick. Light absorption in our experiment restricts both methods to fill pressures of less than 2.0 Torr. Another limitation poses the rapid destruction of the optical windows by the plasma with increasing plasma density.

Results

Typical results of the time dependence \dot{I} , V and the intensity of continuum radiation are shown in Fig. 3 for a filling pressure of 0.25 Torr He.

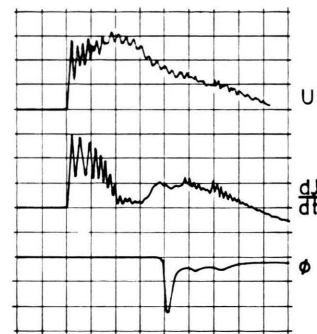


Fig. 3. Time dependence of dI/dt , voltage and intensity of continuum radiation for the z-pinch discharge at a filling pressure of 0.25 Torr He; time scale $0.2 \mu\text{s}/\text{div}$.

After an initial turn-over transient, the current increase is similar to $\dot{I} = \dot{I}_0 \cos(\omega_0 t)$ with $\omega_0 = 2\pi \cdot 10^5 \text{ s}^{-1}$ and $I_0 = 1 \text{ MA}$ while the voltage decrease is similar to $U = U_0 \cos \omega_0 t$. During this

phase the plasma is accelerated towards the axis, increasing the inductance of the Z-pinch. At the moment of maximum compression, the time derivative of the inductance changes sign. This causes a distinct dip in the course of $I(t)$ and $V(t)$. Correlated with this "dip" a maximum of the continuum radiation appears, indicating the dense plasma phase. At low filling pressures (e.g., 0.25 Torr) the lifetime of the dense plasma is $\sim 0.25 \mu\text{s}$, at a pressure of 1.0 Torr it is $\sim 0.5 \mu\text{s}$. Current derivative, voltage and continuum monitor display

very good reproducibility, the shot to shot variation of the signals being less than 10%.

The evolution of the plasma column, recorded by the Schlieren technique, is shown in Figures 4a–7a. In Figures 4b–7b, the continuum radiation signals are shown and a marker produced by the laser pulse indicates the time point of the Schlieren measurement.

Nearly independent of the initial parameters the dense plasma goes as follows: It starts with a shock-like, cylindrically symmetric structure of about 8–

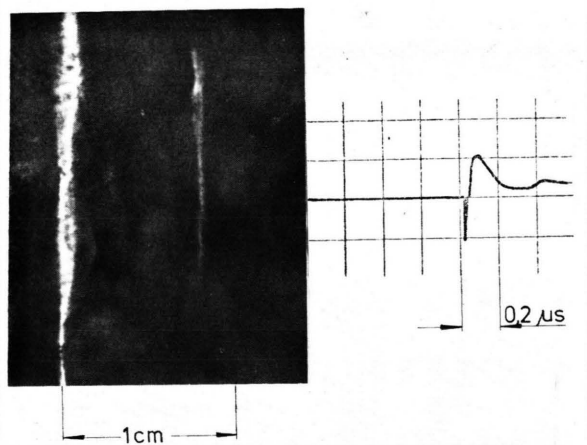


Fig. 4 a, b

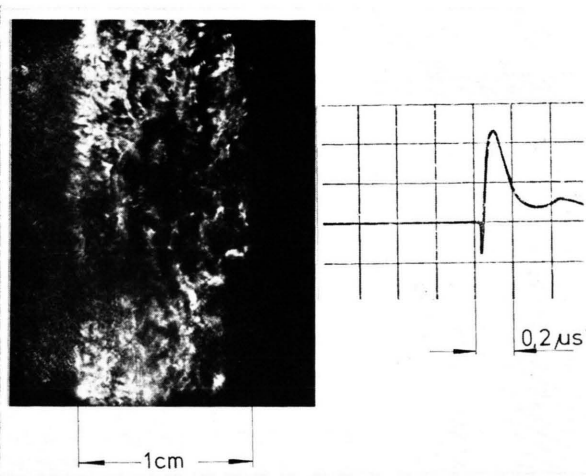


Fig. 6 a, b

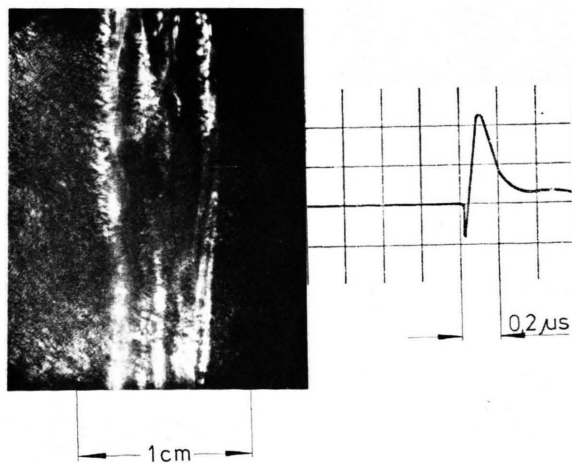


Fig. 5 a, b

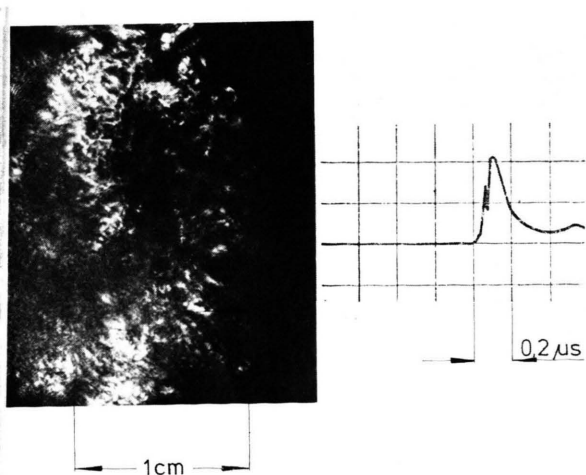


Fig. 7 a, b

Fig. 4a–7a. The formation of the dense plasma phase in a sequence of Schlieren photos. Filling pressures: Fig. 4a: 0.25 Torr H_2 ; Fig. 5a–7a: 0.25 Torr He.

Fig. 4b–7b. The corresponding signals of continuum radiation intensity. The negative spike represents the time of the laser pulse, i. e. the time of the Schlieren photograph.

10 mm diameter as shown in Fig. 4a for a filling pressure of 0.25 Torr H_2 .

10 ns later the plasma is still nearly cylindrically symmetric but filamentous instabilities parallel to the z -axis begin to develop (Figure 5). Approximately another ten nanoseconds later, instabilities with a typical length of 1 mm have already spread out isotropically and the plasma becomes turbulent (Figure 6 and Figure 7). Nevertheless, during this time the column as a whole remains macroscopically rather stable on a scale length of cm. The macroscopic decay of the pinched plasma begins after the maximum of the monitor signal. The diameter of the column varies only slightly during the dense plasma phase, growing from ~ 8 mm at the formation of the column to 10–15 mm at the time of maximum density. The evolution of the plasma, starting with a homogeneous, cylindrically symmetric state and ending with a highly turbulent state, is typical for all parameters studied. The homogeneous state survives longer in discharges of low filling pressure, and longer for H_2 than He. The turbulence in the column grows faster and appears more distinctly with higher filling pressure.

Considering the turbulence seen in the Schlieren photographs, the reproducibility of the continuum radiation in the visible spectral region as seen by the monitor and additional spectroscopic measurements with a spatial resolution of the order of mm is surprising. This might be explained by the fact, that the integration along the line of sight averages the local inhomogeneous plasma emissivity, though the optical thickness of the plasma, which is a function of time and filling pressure is only moderate, i. e. of the order of one; the contrast properties of the photographic film restrict our measurements to plasmas with optical thickness smaller than 4. Another additional mechanism which averages the local plasma emissivity is light deflection on the turbulences so that the dense plasma column acts as some kind of "ground glass".

In most cases, the dense plasma column at the high filling pressures was found to be macroscopically rather stable for times less than $1 \mu s$. An exception is shown in Fig. 8 where a kink instability develops early. The filling pressure in this case is 0.5 Torr H_2 .

The effect caused by the windows in the sides of the discharge vessel is readily observed in Figure 9. Disturbances due to the non-uniformity of the cur-

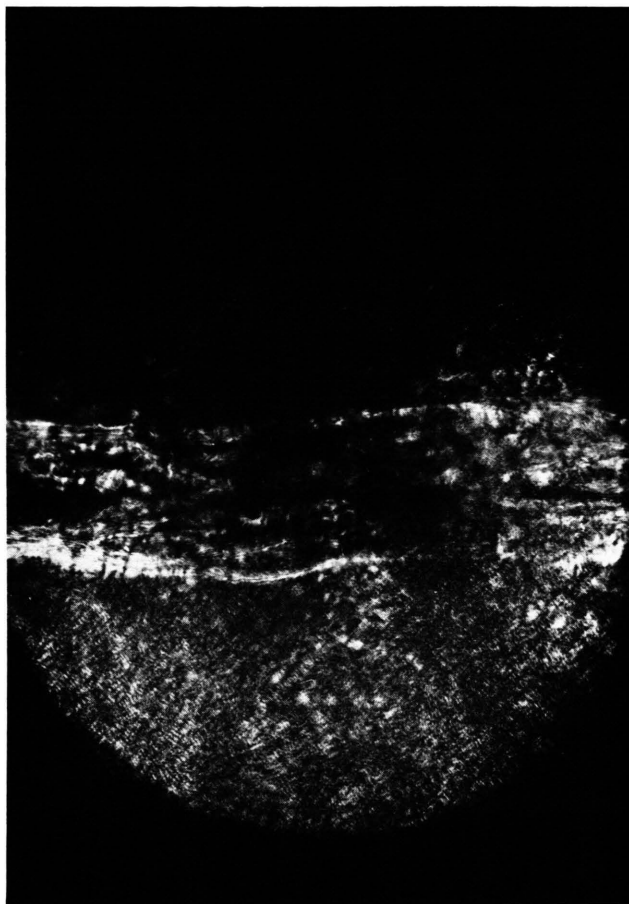


Fig. 8. Example of a kink instability at a filling pressure of 0.5 Torr H_2 .

rent return path appear when operating with high filling pressure.

In this example the filling pressure is 1 Torr H_2 , the time is 30 ns after formation of the dense phase. The density determination by the light refraction technique seems practicable only for cylindrically symmetric plasmas; therefore the low filling pressures of 0.25 Torr helium and hydrogen were chosen.

A typical example of light deflection as a function of the radius at the beginning of the dense phase is shown in Fig. 10a for a filling pressure of 0.25 Torr He. The light deflection has a sharp maximum at a radius of 3.0 mm and a minimum with a negative value of the deflection angle; the plasma density has a positive slope in the inner region and a negative one in the outer part. In other words, the density distribution is maximum

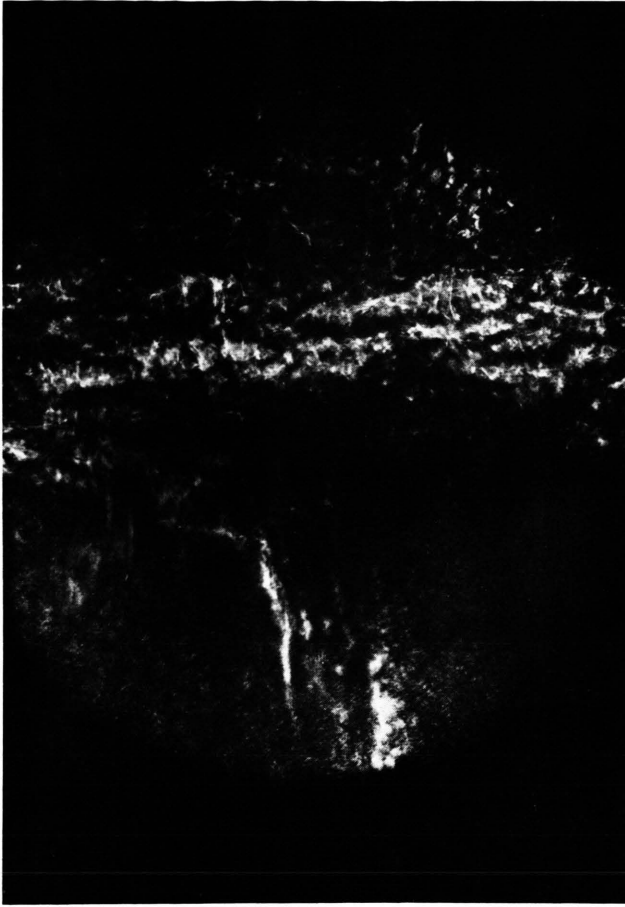


Fig. 9. Influence of the nozzles at high filling pressures (1 Torr H_2 here).

at a radius of 2.6 mm. The dashed line in Fig. 10 a is the calculated deflection corresponding to the density distribution of Figure 10 b. In the beginning of the dense phase, the plasma is similar to a hollow, cylindrical sheath with a wall of a few millimeters thickness. At this early time the maximum electron density in the case of 0.25 Torr He is already $1 \cdot 10^{19} \text{ cm}^{-3}$. If 0.25 Torr H_2 is used as a filling gas, the light deflection is much smaller. The peak density in the early homogeneous state is about five times smaller than in the first case.

The maximum error is estimated to 50%, because even at the early time of plasma formation deviations from cylindrical symmetry are observed which render the analysis of radial density distribution difficult. At later times the local fluctuations cause light deflections which are of the same order of magnitude as the deflection by the plasma column

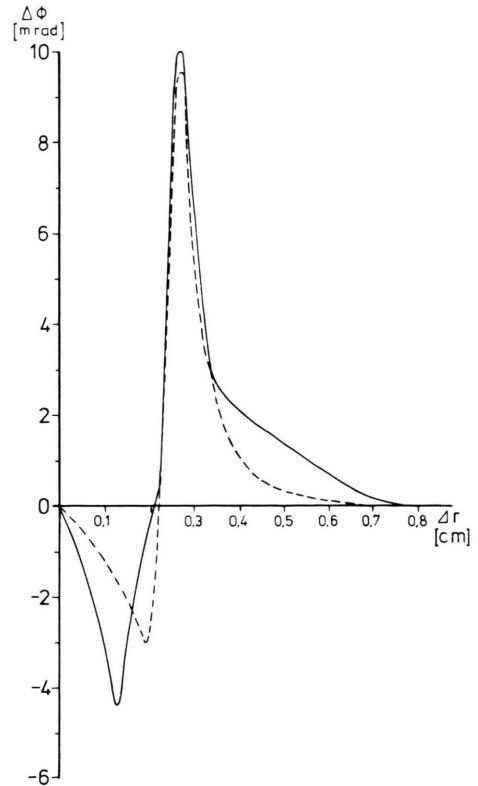


Fig. 10 a. The full raw curve shows the measured light deflection as a function of radius at the beginning of the dense phase. The filling pressure is 0.25 Torr He. The dashed line represents the best fitted deflection curve calculated from the "resonance" function.

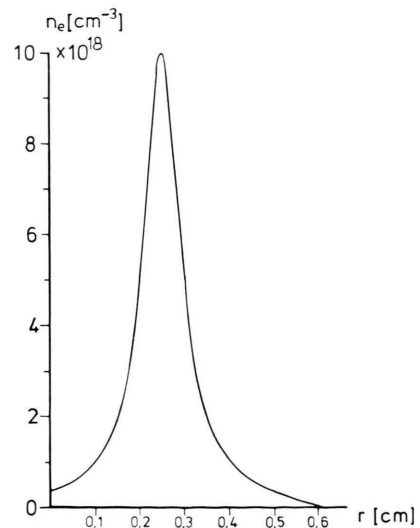


Fig. 10 b. Radial density distribution belonging to the dashed curve in Figure 10 a.

itself. Therefore a calculation of the electron density then becomes impossible. On the other hand just these results reveal, that the density fluctuations are of the same order as the mean density in the column. One has to conclude therefore, that the MHD turbulence is excited at a very high level.

From these measurements it can be concluded that at the beginning of the dense plasma phase a cylindrical sheath having a density of at least 10^{19} cm^{-3} is produced already with filling pressures of 0.25 Torr He. This represents then a suitable dense target plasma to couple strongly to the radiation of a CO_2 laser.

Discussion

The measurements show, that during the discharge three successive phases of the plasma can be distinguished: In the beginning we observe a cylindrically symmetric plasma surrounded by a nearly standing shock front; then instabilities grow in azimuthal direction with m -numbers of $4 \leq m \leq 6$; finally this filamentous structure parallel to the z -axis breaks up.

A standing cylindrical shock front is possible, for example, when the density grows exponentially with respect to time at the shock front, while velocity and temperature of the converging plasma stream remain constant. Using the conservation equations one can show, that within the shock front, the temperature stays constant while also the density grows exponentially. This model describes in a satisfying manner the observed nearly standing shock front before the maximum density is reached.

The explanation of the azimuthal instability is more difficult. Kink instabilities should grow predominantly with m -numbers of one while high m -numbers should be stable. In principle a comparison with all theories lacks from the fact that no

plasma equilibrium has been reached before the onset of the instabilities. We think that the shock front becomes unstable from asymmetries of the converging plasma stream, which probably originate at very early times of the discharge.

If the filamentous structure of the plasma is connected with filaments of the current, we prefer to explain the second type of instability as a sausage instability of the current filaments having growth rates of 10^9 s^{-1} . On the other hand other instabilities cannot be excluded. For example, the mean drift velocity of the electrons as calculated from total z -current is of the order of $1.6 \cdot 10^6 \text{ cm/sec}$ at the phase of maximum compression. The mean value is only a factor of two smaller than the thermal ion velocity.

Therefore it is plausible that locally the threshold condition for electrostatic instabilities like the modified two stream instability is fulfilled⁷.

If it is accepted that the turbulent wave density flattens over the whole spectrum as it is shown by mode coupling calculations⁸ and by computer simulations⁹, the plasma state may be regarded by a model of strong turbulence. The growth rate for the long wavelength modes is of the order of $\gamma \sim k \cdot v_s \sim 2 \cdot 10^8 \text{ s}^{-1}$. This value is comparable with the observed growth rate.

Once the turbulence is established it seems of secondary interest which instability ever may have initiated it. Nonlinear effects will become so strong, that the plasma can only be described by a MHD-turbulence theory. Therefore the high density z -pinch plasma even may become a good tool to test these theories.

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¹ W. Frie, H. Maecker, A. Michel, H. Motschmann, and H. Schindler, *Z. Naturforsch.* **16 a**, 121 [1961].

² H. Zwicker, *Z. Physik* **178**, 189 [1964].

³ H. Zwicker and U. Schumacher, *Z. Physik* **183**, 453 [1965].

⁴ A. Böhnlein, *Z. Naturforsch.* **21 a**, 1660 [1966].

⁵ M. Kaufmann, *Z. Physik* **225**, 216 [1969].

⁶ D. E. Roberts, *Phys. Fluids* **15**, 192 [1970].

⁷ N. A. Krall and P. C. Liever, University of Maryland, Techn. Rep. 71-106, 1971.

⁸ R. C. Davidson, *Methods in Nonlinear Plasma Theory*, Academic Press, New York 1972.

⁹ J. J. Katz, J. S. De Groot, and R. J. Faehl, *Phys. Fluids* **18**, 1173 [1975].