tions propagate obliquely to k_0; the whistler is stable to perturbations propagating parallel to itself, and hence no instability is found in one-dimensional analysis.

Sloan's rather complicated stability condition has been evaluated numerically by Macmahon[7] who finds that for a $\theta = 45°$ shock the fastest growing modes have $k_{\parallel} \approx k_{\perp} \approx (4-5)k_0$, and that these modes have their phase velocity close to the shock velocity. (Modes whose group velocity equals the shock velocity are also unstable.) The growth rate increases with increasing M_A (increasing $\tilde{B}$) and increasing θ (decreasing B_x). Thus, although the theory is derived for $\tilde{B}/B_x \ll 1$, while in the experiment this ratio is typically ~3, there is generally good agreement between the predictions of the theory and the experimental observations. The theory does not consider either binary collisions or effective collisions due to current-driven microinstabilities; inclusion of these effects might shed some light on the earlier onset of the instability in deuterium, which is otherwise unexplained.

The extremely rapid growth rate of the instability means that the single-mode whistler shock predicted by one-dimensional theory can be observed only for a brief period after the shock has been formed. Experiments in which stationary shock waves are produced by directing a stream of plasma against a magnetic dipole[8] and also Earth's bow shock[9] generally show a turbulent spectrum of whistler waves. In the present experiment we appear to be observing the initial stage of the instability, and the transition from a single-mode laminar shock structure to a turbulent one.

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Anomalous Penetration of a Magnetic Pulse into a Plasma*

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The penetration of a magnetic pulse into a cylindrical, field-free plasma has been studied under conditions where the penetration was determined by turbulent conductivity. The penetration time was found to vary as $(M_i n_e)^{1/2}/B$, where M_i is the ion mass, n_e is electron density, and B_0 is peak amplitude of the applied magnetic field. This corresponds to a mean conductivity $\sigma \propto M_i n_e/B_0^2$. These results can not be accounted for by any present theoretical model.

The development of an enhanced resistivity through the excitation of instabilities in a current-carrying plasma is a well-established phenomenon. Both experiments[1,2] and theory[3-5] have shown that an enhancement by many orders of magnitude over the classical resistivity can be obtained when large current densities are driven through a plasma by high electric fields. A consequence of this phenomenon is that when a large time-varying magnetic field is applied at the boundary of a plasma the penetration of the field will be governed by the anamolous resistivity which arises from the currents induced in the plasma. Inversely, under appropriate experimental conditions, the penetration time of the field can be used to investigate the behavior of plasma conductivity.

Consider a sinusoidal magnetic field $B=B_0 \times \sin\omega t$ applied to the boundary ($x=0$) of a semi-infinite conductor of conductivity σ. The solution[6] for the diffusion field in the conductor in steady state is

$$B(x,t)=B_0 e^{-x/\delta}\sin(\omega t - x/\delta), \quad t>0,$$

where $\delta=(2/\mu\sigma\omega)^{1/2}$. It can be seen that a field maximum propagates into the conductor with a velocity $V=x/t=(\omega/\mu\sigma)^{1/2}$. A closely similar scaling holds for the transient solution[7] provided $x/\delta<1$. If the conductor is a plasma and the penetration velocity is much greater than the Alfvén speed $B_0/(4\pi n_e M_i)^{1/2}$, it is intuitively apparent and can be rigorously demonstrated that there is negligible momentum transferred to the ions over a time $2\pi/\omega$; hence the penetration of the first cycle of the field can be regarded purely as a diffusion problem.

In this Letter we describe an experiment in which the above conditions are satisfied. Figure 1 shows a schematic diagram of the apparatus. Plasma was created in a 10-cm-diam, 50-cm-long Pyrex tube by means of an oscillatory discharge between metal end electrodes. The initial filling pressure was typically 2–3 mTorr and the ringing discharge damped away in 30 μsec. The field-free plasma diffused to the walls in about 100 μsec by which time the turbulence and fields created by the initial discharge have died out. When the desired electron density, as measured by a 4-mm interferometer, is reached, a rapidly rising magnetic field is applied to the outer boundary by means of a two-piece sectored coil driven by a double Blumlein circuit. The finite risetime of the pulse, due to switch impedance, and finite line length combine to give an approximately sinusoidal pulse. The magnetic field has a peak amplitude of 500 G and a frequency $\omega=2\times10^7$ Hz.

Using magnetic probes of 1–3 mm diam and frequency response $\approx 10^8$ Hz mounted on a radial support, we measured the diffusive penetration of the first half-cycle of dB/dt into the plasma. The penetration time τ is defined as the time taken by the first peak of the dB/dt signal to travel from the outer edge of the plasma to the detection point inside the plasma. The penetration time varied with experimental conditions while the frequency of the applied field, determined by the length of the transmission line, remained constant. In Fig. 2, we show oscilloscope traces of dB/dt under two different operating conditions. In the first case (high density) the pulse is delayed and somewhat steepened while in the second case (lower density) the pulse is less delayed and steepened. Pulse steepening occurs only for high-

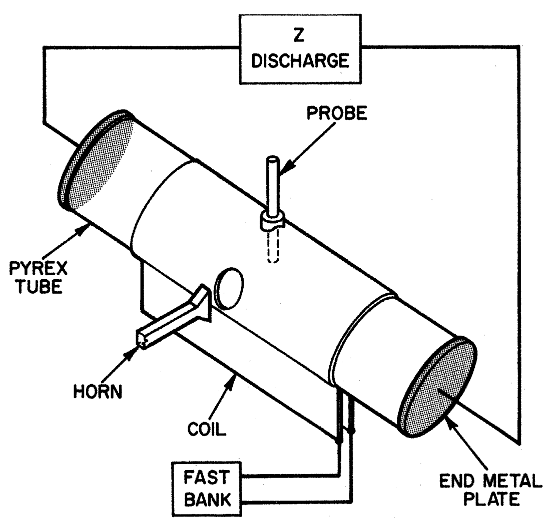

FIG. 1. Schematic of experimental apparatus.

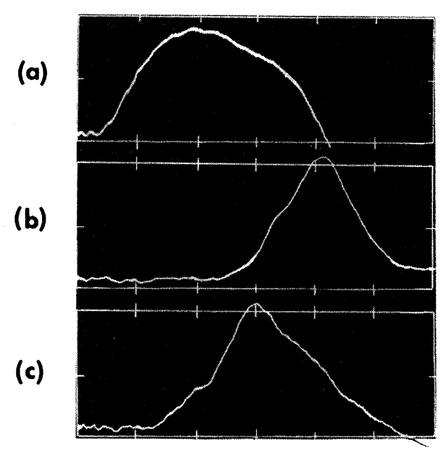

FIG. 2. Typical experimental data. (a) Oscilloscope trace showing dB/dt outside the cylindrical plasma column (3.0 G/nsec div; 50 nsec/div). (b) Oscilloscope trace showing dB/dt at the center of the cylindrical plasma column. The density of the hydrogen plasma is 1.2×10^{13} cm^{-3}. Gains are same as for trace (a). (c) Oscilloscope trace showing dB/dt at the center of the cylindrical plasma column. The density of the hydrogen plasma is 4×10^{12} cm^{-3}.

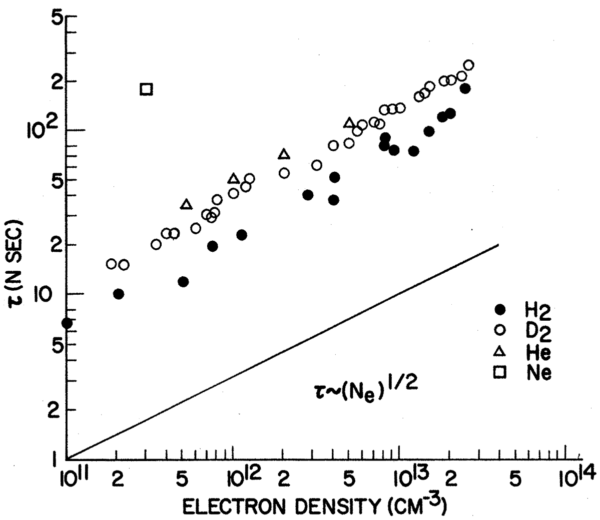

FIG. 3. Experimentally measured time delay (τ) between the peak of the dB/dt signal at boundary and at center of plasma column as a function of electron density. The solid line corresponds to $\tau \sim (n_e)^{1/2}$ and is drawn for comparison with experimental data. The amplitude of the penetrating field (500 G) was the same for all density conditions.

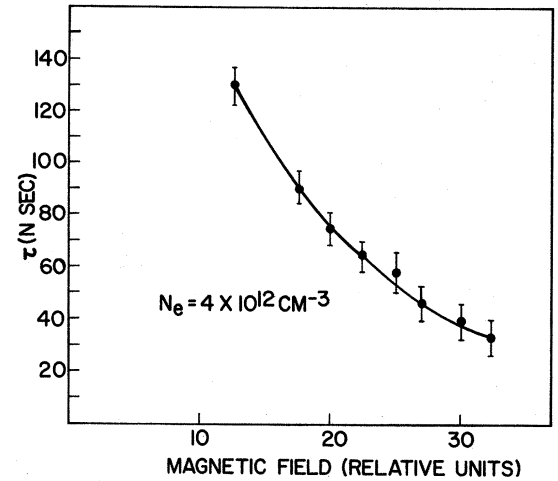

FIG. 4. Experimentally measured time delay (τ) between the peak of the dB/dt signal at the boundary and at the center of the plasma column as a function of the amplitude of the applied magnetic field. The density of the hydrogen plasma was 4×10^{12} cm^{-3}.

er magnetic fields.

The penetration time τ was investigated over the density range $n_e = 10^{11}$ to 3×10^{13} cm^{-3} in hydrogen, deuterium, and helium. Results are shown in Fig. 3. Over the entire density range, it was found that τ is proportional to $(n_e M_i)^{1/2}$. In Fig. 4 we show τ as a function of B_0 for a constant electron density ($n_e = 4\times10^{12}$ cm^{-3}). The penetration time appears to be inversely proportional to B_0 over most of the range, except that at the highest values of B_0 a discontinuous transition was observed to a region of faster penetration. This may indicate the onset of a different instability mechanism.

We have therefore over most of the range a scaling $\tau \propto (n_e M_i)^{1/2}/B_0$. At first sight this seems to be the scaling one would expect for a snowplow model. However, the speed of penetration is found to be a factor of 10 greater than the Alfvén speed corresponding to the maximum applied field B_0. Furthermore measurements with a double probe showed [for the conditions of Fig. 2(c)] that a radial electric field of about 80 V/cm occurs during the penetration of the field. An ion would move only about 5 mm in the radial direction during the experimental penetration time. We conclude that there is little momentum transport to the ions. These observations are in agreement with the "leaky piston" situation found in low-density θ pinches.[8]

As can be noted in Fig. 3, the data for neon do not fit the above scaling. Probably this is a consequence of the Alfvén velocity in neon being less than the drift velocity. The penetration time in neon is nearly that of a pulse penetrating into a medium of Spitzer conductivity.

In most turbulent heating experiments the electric field is applied parallel to a strong magnetic field, and the turbulent conductivity depends primarily on the electric field. In our case, the magnetic field is not large and the electric field is developed only with dB/dt. To investigate the significance of the magnetic field, a series of experiments were conducted with a static parallel magnetic field of about the same amplitude as the pulsed magnetic field. In these experiments we found the penetration was faster by the amount $1/(B_s + B_0)$, where B_s is the amplitude of static applied field. This is in agreement with our observation that τ scales as $1/B_0$ and with pulse steepening at high B.

The local conductivity was obtained by integrating the measured $dB(r, t)/dt$ signals over radius and time. At any point, initially the conductivity is high ($\sigma > 1000$ mho/m) but drops to a lower value [$\sigma \approx 100$ mho/m for the conditions of Fig. 2(c)] within 20 nsec. At the end of the pulse, the conductivity increases to its original value. The penetration velocity of the dB/dt peak as a function of radius is consistent with penetration into a constant-conductivity region except for a region near the walls. The local values of conductivity are nearly the same as the average conductivity measured by penetration time.

According to the experimental results the conductivity varies as $\sigma \propto M_i n_e / B_0^2$ or the effective collision frequency varies as $\nu_{\rm eff} \sim B_0^2/M_i$. For our typical [Fig. 2(c)] conditions $\nu \simeq 3\times 10^9$ sec^{-1}, i.e., near the ω_{ce} at the peak of the magnetic field and roughly 2 orders of magnitude higher than either the electron-ion or electron-neutral collision frequency.

During the last few years, several theories have been developed concerning instabilities that can be excited in a plasma when an electric current flows perpendicular to the magnetic field. Based on the quasilinear equation, these theories give approximate expressions for the effective collision frequency. However, the work[5] apparently most relevant to this experiment does not give the scaling we observe. The fact that the conductivity is somewhat independent of r and τ probably means that saturation of the instability has occurred and therefore comparison with predictions from quasilinear theory is not valid. No existing theory describes this situation of considerable practical importance in the magnetic compression of a field-free plasma.

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Electron Fluctuations and Transport in Toroidal Plasmas

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Negative-energy modes driven by a normal gradient of the electron temperature are found in two-dimensional equilibrium configurations such as the toroidal diffuse pinch. These modes tend to grow by transferring (positive) energy to the resonating electrons; they have properties that make them suitable to alter considerably the orbits of the deeply trapped electrons by proper resonant interactions, and make them lead to electron thermal energy transport across the magnetic field without corresponding particle transport.

To understand the macroscopic transport properties of two-dimensional confined plasmas, a detailed knowledge of the modes which can be excited in them[1] is necessary. In particular, an important question is whether the orbit of deeply trapped electrons in a toroidal confinement configuration can be significantly altered by the collective modes[2] to which the plasma is subject. An analysis of the needed characteristics of such modes leads to requiring that (i) they exist for frequencies $\omega \sim \hat{\omega}_{be}$, where $\hat{\omega}_{be}$ is the average bounce frequency of trapped electrons; (ii) the profile of the resulting electric field fluctuations is correlated with the periodic variation of the magnetic field and is nonzero and even around the point of minimum magnetic field; (iii) they should not be damped by the process of resonant interaction with trapped electrons. This last requirement can be met, for instance, if the relevant modes are of negative energy,[3] in the sense