COO-1726-42

Measurement of Plasma Conductivity for Electric Fields Larger Than the Runaway Field*

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Abstract

The electrical conductivity parallel to a magnetic field of a hot ion hydrogen plasma with $n \approx 10^9 \mathrm{cm}^{-3}$, $T_i \approx 50$ eV and $T_e \approx 5$ eV was measured for electric fields larger than the runaway field. The conductivity was found to be proportional to the plasma density with a value much less than Spitzer's conducivitity but larger than Buneman's turbulent conductivity. When the current became comparable to the electron thermal current the conductivity was found to decrease.

For sufficiently small electric fields the electrical conductivity of a fully ionized plasma is determined by electron-ion collisions and is described by the well-known Spitzer formula[1]: σ_S 1.3 x $10^3 T_e^{3/2}$mho/m, where T_e is the electron temperature in eV. Dreicer[2] has shown that the electrons begin to "run away" for electric fields larger than a critical field $E_c = 10^{-10}\ n/T_e\ \mathrm{Vm}^{-1}$, where T_e is in eV and n is the density in cm^{-3}. The conductivity will then in general be determined by the interaction of electrons with turbulent electric fields. Although there are no general theories available for this case, one can compare results with the expression given by Buneman[3] for the conductivity of a highly turbulent plasma: $\sigma_B \approx 2\pi\epsilon_0 (M/m_e)^{1/3}\omega_{pe}$ mho/m, where M and m_e are the ion and electron masses and ω_{pe} is the electron plasma frequency. The results given in this letter describe a conductivity which had a range of values between these two expressions and which apparently was related to neither.[4]

A gun injected hydrogen plasma was contained in a toroidal octupole magnetic field with a superimposed toroidal field.[5,6] Typically the plasma density, electron and ion temperatures were $n \leq 10^9\mathrm{cm}^{-3}$, $T_e \leq 5\mathrm{eV}$ and $T_i \leq 50\mathrm{eV}$. This magnetic field consisted of a poloidal component B_p produced by the current flowing in four toroidal hoops, and a toroidal component B_θ produced by a current flowing in the vacuum box. The confinement field was pulsed with a 5 msec duration which, for early plasma injection, gave an inductive electric field $\approx$2V/m. This electric field was varied by coupling a high frequency pulse relative the main field, and in this way could be increased above the critical field by a factor $\approx$300. Measurements of the parallel current flow were made in the region of the poloidal field null (minor axis) where the magnetic field was toroidal ($B_\theta \approx 350$G). The resulting electric field and plasma current response are shown in Fig. 1.

The electric field was determined by measuring the voltage across the insulated gap in the vacuum tank and normalizing to the fraction of flux enclosed by the minor axis. The current (carried primarily by the electrons) was measured with a two electrode directional Langmuir probe.[7] The "D. C." level in Fig. 1 corresponds to the main confinement pulse. The current was essentially in phase with the electric field pulse i.e. the plasma was highly resistive. Note also that the current response tended to saturate at high (>5 V/m) electric fields. This was studied in more detail by plotting the current at the peak value of the electric field pulse versus electric field. The data are shown in Fig. 2 for two sets of plasma parameters. It was found that the saturation occurred when the directed current became comparable to the electron thermal current.

At a given value of electric field the dependence of the conductivity on the density was determined by varying the amount of plasma entering the confinement region. The density was monitored with a Langmuir probe placed near the minor axis. The data, shown in Fig. 3, indicate that the conductivity was proportional to the density and thus could not be related to either Buneman's conductivity or Spitzer's (collisional) conductivity.

A rough estimate of the electron temperature dependence of the conductivity was obtained by using the fact that the electron temperature and density decayed in time with a lifetime ≈1msec. A conductivity lifetime of ≈2 ± .5msec was found by measuring the current at a fixed time relative to the magnetic field pulse, while varying the time of plasma injection. This implied $\sigma \propto nT_e^k$ with $-.7 \leq k \leq -.3$, i.e., the conductivity had a weak inverse temperature dependence of roughly the form $1/\sqrt{T_e}$. It was also found that, to within experimental accuracy, the conductivity was independent of the strength of the magnetic field and the ion temperature.

The experimental data are summarized by the parallel conductivity

$$\sigma \approx 4 \times 10^{-8} f(E, T_e)\, n/\sqrt{T_e} \text{ mho m}^{-1} \tag{1}$$

where n is in cm^{-3} and T_e in eV. The coefficient $f(E, T_e)$, of order unity, describes the effect of current saturation near the electron thermal current J_{th}. One such function which fits the data of Fig. 2 has the form

$$f(E, T_e) = [1 + (\sigma E/J_{th})^2]^{-\frac{1}{2}} \approx [1 + (E/2T_e)^2]^{-\frac{1}{2}},$$

with E in V/m. These results are compared in Fig. 3 with various models for plasma conductivity.

The form of this conductivity suggests an electron collision process with a constant mean free path $\lambda \approx 1$m. The saturation effect would be explained by the increase in the collision frequency as the drift speed increases. Three mechanisms have been considered to explain this result: Plasma turbulence, magnetic field effects and neutral gas.

The effects due to the neutral gas should be negligible at the operating pressure of 7×10^{-7} Torr. Moreover, it was found that a factor 30 increase in background pressure was required to produce any reduction in the measured conductivity.

The magnetic field on the minor axis, where these data were measured, was ideally a uniform toroidal field. Only a small field imperfection would take a field line into the high field region around the multipole rods where effects due to hangers (three of which supported each rod) and magnetic mirrors may have become important. Hangers alone could not explain these results since, on the average, a field line would travel a distance $\approx$200m before intercepting a hanger while the measured mean free path was $\approx$1m. Magnetic mirrors can be expected to reduce the conductivity by a factor $\approx\theta^4$, where θ is the loss cone angle, due to two effects:[8] a reduction ($\approx\theta^2$) in the number of charge carriers to those whose velocities are in the loss cone, and a reduction ($\approx\theta^2$) in the scattering time to the time for scattering out of the loss cone. These effects will also increase the value of the runaway field by a factor $\approx\theta^{-2}$. This argument as well as a recent calculation based on kinetic theory[9] predict the same functional dependence on n and T_e as Spitzer's conductivity. This is compared in Fig. 3 with the observed conductivity.

A value for the turbulent conductivity can be obtained from measurements of the correlation between density and electric field fluctuations up to the plasma frequency (300 MHz). In this experiment, however, only a cursory investigation was made of plasma fluctuations for frequencies less than 30 MHz. Fluctuation in both floating potential and ion saturation current were observed in the frequency range .5-10 MHz. As the current levels were increased the fluctuation amplitude increased and the higher frequency components became more prominent. At these drift speeds $J/J_{th} \lesssim 1$ and temperatures $T_i/T_e \approx 10$ the ion acoustic[10], ion cyclotron[11] and two stream[12] instabilities should not appear. This makes identification of these fluctuations somewhat difficult.

A similar behavior of the conductivity was reported by Demidov et al.[13, 14] They applied a parallel electric field up to 10^4V/m in a plasma with $n \approx 10^{12}\text{cm}^{-3}$ and $T_e \approx 10^3$eV. More recently Hamberger et al.[15]

reported observing a conductivity which decreased with increasing electric field until it reached the Buneman value. In all of these experiments the behavior was attributed to the development of instabilities. Demidov _et al._[13] were able to obtain a theoretical estimate by assuming that the absorption by the walls of turbulent wave energy greatly exceeded the absorption by the plasma. They obtained the result

$$\sigma = \frac{ne^2r}{2mv_{th}} = 5 \times 10^{-6} \frac{nr}{\sqrt{T_e}} \text{ mho/m}$$

where r is the distance to the wall in meters. This gave the correct magnitude for their measurements.

The above result holds provided the electron plasma frequency exceeds the electron cyclotron frequency -- a condition which is not satisfied in this experiment. Nevertheless, with $r \approx 20$ cm, their estimate is in good agreement with Eq. (1). Although this is interesting it is not clear that turbulence can explain the conductivity reported here.

FIGURE CAPTIONS

Figure 1. Oscillographs of the parallel electric field pulse and the resulting parallel electron current measured on the minor axis.

Figure 2. Parallel electron current response on the minor axis at the peak value of the electric field pulse versus electric field. The lower curve was measured at a higher background pressure to reduce the electron temperature. The scale on the right shows the ratio of the directed current to the thermal current.

Figure 3. A comparison of the observed conductivity with Spitzer's conductivity σ_S, Buneman's conductivity σ_B, and a mirror limited Spitzer conductivity $\sigma_m = \frac{3}{4}\,\theta^4\sigma_S$.

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*Work supported by the US Atomic Energy Commission.

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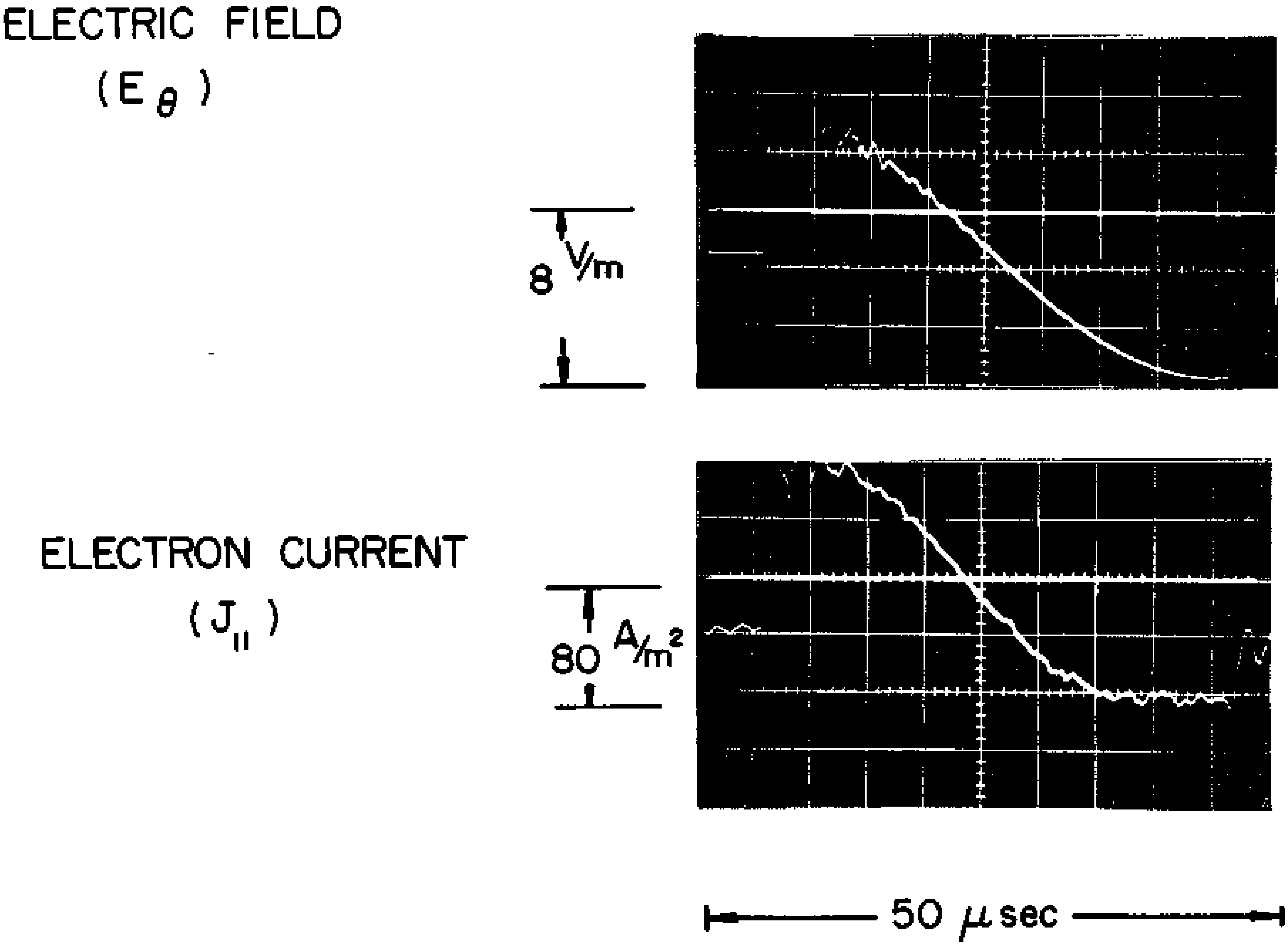
ELECTRIC FIELD
(E_θ)
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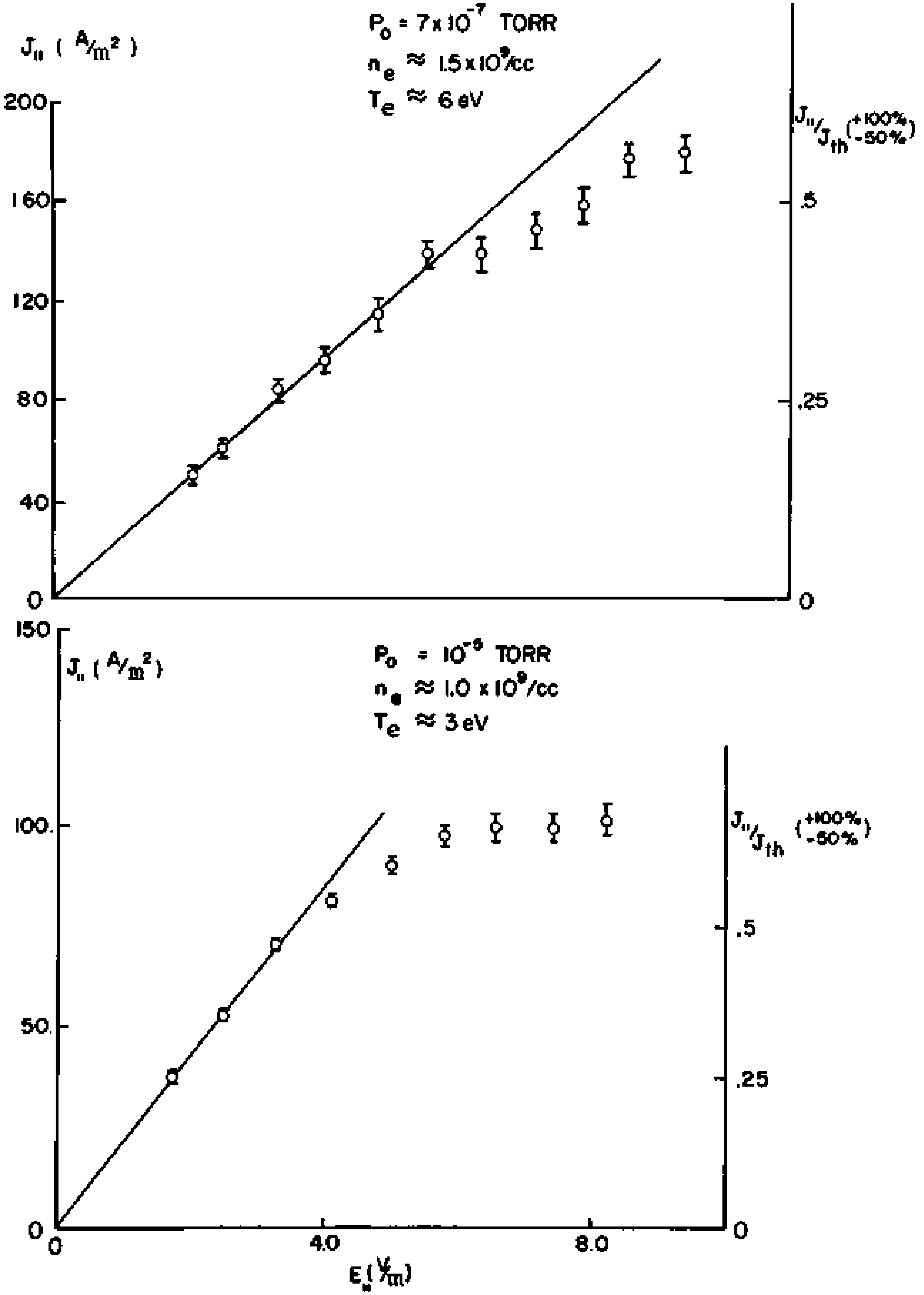
ELECTRON CURRENT
($J_\parallel$)
80 A/m^2
50 μ sec


$P_o = 7 \times 10^{-7}$ TORR
$n_e \approx 1.5 \times 10^9$/cc
$T_e \approx 6$ eV
$J_{\parallel}$ (A/m²)
200
160
120
80
40
0
$J_{\parallel}/J_{th}$ (+100% / -50%)
.5
.25
0
150
$J_{\parallel}$ (A/m²)
$P_o = 10^{-8}$ TORR
$n_e \approx 1.0 \times 10^9$/cc
$T_e \approx 3$ eV
100.
50.
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0
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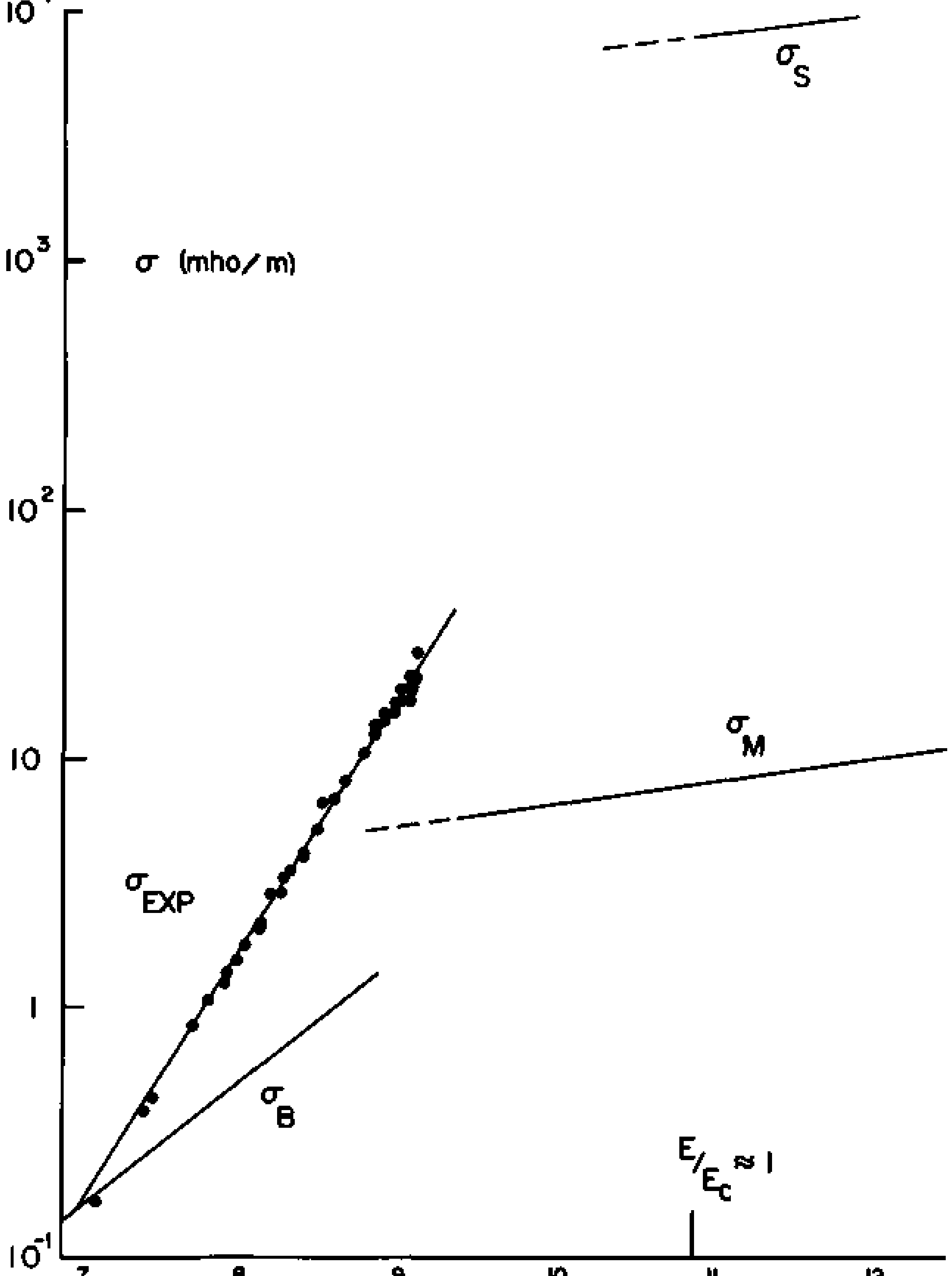
8.0
$E_{\parallel}$ (V/m)



10^4
10^3
10^2
10
1
10^{-1}
σ (mho/m)
σ_S
σ_M
σ_{EXP}
σ_B
$E/E_c \approx 1$
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
n (cm^{-3})