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The enclosed talk, to be presented at the Gordon Conference on June 20, 1972, is a review of the open literature on the penetration of electromagnetic waves into plasma. A major part of this review is of our work. This is limited to work we have published and presented at other unclassified talks.

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On The Penetration of Electromagnetic Waves Into Plasma

By John De Groot

To Be Given at the Gordon Research Conference 6/20/72

I. Problem Description

Slide 1

A. A plane electromagnetic (e.m.) wave is incident from the right on a fully ionized plasma. The plasma has a density gradient in the x direction and is uniform in the y and z directions.

B. The e.m. wave travels up the density gradient, is reflected at the critical point where $\omega_o = \omega_{pe}$.

Slide 2

C. The linear solution (neglecting $\vec{V} \times \vec{B}$ forces) is given in Slide 2. The electric field increases as the wave approaches the critical density. This happens because of two things.

1. $B \rightarrow 0$ as $\omega_o \rightarrow \omega_{pe}$ and

2. $V_g \equiv \frac{d\omega_o}{dk_o} \rightarrow 0$ as $\omega_o \rightarrow \omega_{pe}$ so since energy must be conserved E must increase.

D. If we include $\vec{V} \times \vec{B}$ forces then we get a new effect - the ponderomotive force. The force density is (for normal incidence)

$$\vec{F} = - \frac{\hat{x}}{8\pi} \frac{\partial}{\partial x} (E_y^2 + H_z^2).$$

Slide 3

This is shown in Slide 3. A plus force means that the force acts into the problem. The net effect is that the plasma is pushed out.

E. Thus we expect the plasma to move and form a striated density profile.

The equilibrium condition will be:

$F = \nabla P$ or since the temperature is essentially uniform

$F = KTVN$.

II. Absorption

A. When we include electron-ion collisions some of the e.m. wave energy is dissipated and the electrons are heated.

B. The absorption coefficient is:

$$A = e^{-H/\delta_a}, \quad H \text{ is the density scale length, } \delta_a = \frac{8}{3} \frac{C}{v} \text{ for an exponential profile.}$$

and $v \sim 1/T^{3/2}$.

Therefore as the temperature increases A decreases. At high enough temperatures we will not absorb all the e.m. wave energy.

C. There are other ways to get absorption.

1) Direct coupling to electron waves. If $\vec{E}$ is along ∇n then we can directly excite plasma waves.

2) $\vec{V} \times \vec{B}$ Effects.

If $\omega_o < \omega_{pe}$ and the e.m. wave is intense enough, the $\vec{V} \times \vec{B}$ forces can directly accelerate the particles into the plasma.

3) Excitation of Instabilities.

I will discuss number 3.

D. Instabilities - Linear Theory.

1. E.M. waves in a plasma are unstable with respect to decay into plasma modes. The fastest growing of these are 3 mode couplings where

$$\left. \begin{aligned} \omega_o &= \omega_1 + \omega_2 \\ \text{e.m. plasma} \\ &\text{modes} \\ \vec{k}_o &= \vec{k}_1 + \vec{k}_2 \end{aligned} \right\}$$

Condition for decay
parametric amplification.

2. There is a threshold e.m. wave electric field.

The threshold is determined by the damping of the plasma modes.

For example:

ω_1 = Electron plasma wave

Electron Plasma -

ω_2 = Ion acoustic wave

Ion acoustic decay instability.

Threshold

$$\frac{E_T}{\sqrt{4\pi NKT_e}} = 4 \left(\frac{\nu_e}{\omega_{pe}} \right)^{1/2} \left(\frac{\nu_i}{\omega_i} \right)^{1/2}$$

where ν_e , ν_i are the electron and ion mode damping rates.

In general $E_T \ll \sqrt{4\pi NKT_e}$

3. There are many other possibilities

$$\omega_1 = \omega_e \quad \text{Stimulated Raman Scattering}$$

$$\omega_2 = \omega_t$$

$$\omega_1 = \omega_i \quad \text{Stimulated Brillouin Scattering}$$

$$\omega_2 = \omega_t$$

4. So far I have talked about linear theory. This just predicts that these linear modes will grow. Clearly the important question is what will cause saturation.

E. Instabilities - Non Linear Theory

1. Results for a strong e.m. wave.

$$E_0 = 7\sqrt{4\pi NKT_e}, \quad \omega_0 = 1.05 \omega_{pe}$$

Slide 4 and
Movie

The movie shows the time evolution of electron space and the mode amplitudes. The units of V are $\sqrt{2KT_e/M}$.

2. Movie Results

- a. The electron waves trap the particles and accelerate them to high velocities $V \sim \omega/k$.
- b. Very rapid heating when the wave crashes.
- c. Heating continues after the crash at longer wavelengths.
- d. Electron temperature increases to $\sim 100 T_{e0}$ and higher.
- e. Ion are heated, but most of the energy goes to the electrons.
- f. The saturated spectrum $|E_k| \sim 1/k$.

Slide 5

3. The electric field energy grows at essentially the linear rate. Then it saturates and decays before growing again at longer wave lengths.

The wave crashing has produced a high temperature and thus

a new quasi-equilibrium. The instability then grows at longer wavelengths because the Debye length is larger. The instability growth rate is proportional to $k \frac{eE_0}{m\omega^2}$ so that the longer wave length waves grow slower. The trapping and crashing process repeats and the instability grows at longer wavelength. Finally the k is so long that the grow rate is drastically reduced and the heating process switches to the weak mechanism.

The electron heating continues to the end of the run. The ion heating is much less than the ion heating.

4. Results for a weak e.m. wave.

Movie of Mode
Amplitudes

$$E_0 = .6\sqrt{4\pi NKT_e}, \quad \omega_0 = 1.05 \omega_{pe}$$

The movie shows that in this case trapping is not the dominant process.

Movie of Energy
Structure

The point here is that the heating results in long tails on the electron distribution.

5. 2D Electrostatic Calculations

In the strong cases, i.e. $E_0 \gg \sqrt{4\pi NKT_e}$ we see essentially the same heating.

Slide 6
($f(v_x), f(v_y)$)

The heating is different in the x and y directions. More heating occurs along the e.m. field.

6. Electromagnetic wave absorption distance

A rough extrapolation of these electrostatic results gives $\delta_a \sim 10 \lambda_v$.

7. 2D Electromagnetic Calculations

These are full e.m. calculations with a density gradient.

Slide 7

The system is $5 \lambda_v$ by $5 \lambda_v$.

The e.m. wave is incident normally on the plasma.

$$E_0 = 2\sqrt{4\pi NKT_e}$$

The movie results are:

E.M. Movie

- a. The e.m. wave penetrates the plasma, reflects at the critical density and sets up a standing wave. The electric field increases as the e.m. wave approaches the critical density.
- b. The ponderomotive force cause striations in the plasma density. There is no charge separation in the density perturbations. The pressure gradient balances the ponderomotive force.
- c. The instabilities finally grow up and strong heating begins. The heating rate is close to the estimate made with the electrostatic codes.

Slide 1

n , plasma density

Slide 1

Slide 2

Slide 3

PHASE SPACE POINTS AT TIME STEP 698 TIME- 10.906

Slide 4

MODE AMPLITUDES AT STEP 639

Slide 5

DeGroot - Fig. 2

DeGroot - Fig. 3

MINO 6 128X128 256X256 ETA=.6 140000 PART.

CA118

Slide 6

VELOCITY DISTRIBUTION OF ELECTRONS BETWEEN $X = 0$. AND $X = \pi$.

VELOCITY DISTRIBUTION OF ELECTRONS BETWEEN $x=0$. AND $x=x$.

CH-12

Slide 6

2

VELOCITY DISTRIBUTION OF ELECTRONS BETWEEN $x = 0$ AND $x = *$.

Y-NO. OF ELECTRONS WITH $v > v_0$

759.20

MOVIE TEST OF RELB

1.0

Slide 7 and Frame
from 4th Movie

VY

-1.0

X

32.

0.

VY

-1.0

0.

X

32.

T= 0.30

2

Frame from Movie #1 and Movie #2

PHASE SPACE POINTS AT TIME STEP 597 TIME- 10.891

2

MODE AMPLITUDES AT STEP 639

Frame from Movie # 3

PHASE SPACE POINTS AT TIME STEP 697 TIME- 10.891

RATIO CALCULATED/MAXWELLIAN GROUP ENERGY AT STEP 697