Princeton University PLASMA PHYSICS LABORATORY
JAMES FORRESTAL CAMPUS
P.O. BOX 451, PRINCETON, N.J. 08540

March 17, 1971

All those invited to attend the Meeting on Anomalous Absorption of Intense High-Frequency Waves, Thursday and Friday, March 18-19, 1971, are requested to register at the registration desk at Peyton Hall on Thursday morning. (Registration will start at 8:15 a.m.) This registration will include the cost of the banquet and will be reimbursed by the laboratory.

Enclosed is a copy of the scheduled program for your information.

P. K. Kaw
W. L. Kruer

PKK:mw
Enclosure

# PROGRAM

## MEETING ON ANOMALOUS ABSORPTION OF INTENSE HIGH-FREQUENCY WAVES

March 18-19, 1971

### THURSDAY

Morning

Chairman: C. Oberman

| | |
|---|---|
| 9:00 - 9:10 | M. B. GOTTLIEB<br>Welcoming Remarks |
| 9:15 - 10:00 | P. K. KAW<br>Review of Earlier Work |
| 10:00 - 10:20 | B. MARDER<br>High-Frequency AC Electrostatic Instabilities |
| 10:20 - 10:35 | E. VALEO<br>Relation Between Parametric and Oscillating Two-Stream Instability |
| 10:35 - 10:55 | COFFEE |
| 10:55 - 11:10 | Y-C. LEE<br>Parametric Excitation of Lower Hybrid Instabilities and Possible Anomalous Ion Heating |
| 11:10 - 11:25 | S. BODNER<br>Parametric Excitation of an Electromagnetic Instability |
| 11:25 - 11:40 | Y-C. LEE<br>Parametric Instabilities in Super-Intense High-Frequency Fields |
| 11:40 - 12:00 | F. W. PERKINS<br>Parametric Instabilities in Non-Uniform Plasmas |
| 12:00 - 12:20 | W. MANNHEIMER<br>Instabilities in a Plasma Co-existing with a Large Amplitude Wave |

## THURSDAY

Afternoon

Chairman: T. Stix

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|---|---|
| 2:30 - 2:55 | W. L. KRUER<br>Computer Simulations of Anomalous High-Frequency Resistivity |
| 2:55 - 3:20 | J. KATZ<br>Computer Simulation of Anomalous Absorption of Very Intense Laser Pulses |
| 3:20 - 3:40 | J. SHEARER<br>Plasma Density Perturbations Near the Cut-off Density |
| 3:40 - 4:15 | H. DREICER<br>Observation of Anomalous AC Plasma Resistivity for Large-Amplitude Electric Fields Near $\omega_{pe}$ |
| 4:15 - 4:35 | COFFEE |
| 4:35 - 4:55 | H. EUBANK<br>Experimental Observation of Plasma Heating by Microwaves With $\omega \approx \omega_{pe}$ |
| 4:55 - | INFORMAL DISCUSSIONS |

### BANQUET AT PROSPECT

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|---|---|
| Cocktail | 6:30 p.m. |
| Dinner | 7:30 p.m. |

## FRIDAY

### Morning

Chairman: W. Kruer

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| 9:00 - 9:40 | A. WONG<br>Recent Experimental Results on Nonlinear Interaction of EM Waves With Ionospheric and Laboratory Plasmas |
| 9:40 - 10:00 | G. MELTZ<br>Conjecture on Triggering of Spread F by Anomalous Absorption of Radio Waves |
| 10:00 - 10:35 | R. COHEN<br>Radio-Reflectivity Studies on Ionospheric Modification |
| 10:35 - 11:00 | COFFEE |
| 11:00 - 11:30 | D. DUBOIS<br>Anomalous Absorption of Radiation Near the Plasma Frequency |
| 11:30 - 12:10 | B. BEZZERIDES and J. WEINSTOCK<br>Nonlinear Saturation of Parametric Instability |
| 12:10 - 12:45 | E. VALEO<br>A Nonlinear Theory of Parametric Instabilities |

### Afternoon

Chairman: J. DAWSON

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|---|---|
| 2:30 - 3:10 | M. GOLDMAN<br>Anomalous Absorption Near Electron Plasma Frequency |
| 3:10 - 3:30 | S. BODNER<br>Saturation of Unstable Waves in Parametric Instabilities |
| 3:30 - 4:00 | D. ARNUSH<br>Parametric Instabilities and Mode Coupling for Plasma in a Magnetic Field |
| 4:00 - 4:15 | J. SANMARTIN<br>On Nonlinear High-Frequency Plasma Conductivity |
| 4:15 - 4:35 | COFFEE |

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|---|---|
| 4:35 - 4:50 | A. HASEGAWA<br>A New Interpretation of Anomalous Resistivity in Turbulent Heating |
| 4:50 - 6:00 | INFORMAL DISCUSSIONS |

## SATURDAY

Possible Working Session
dependent on interest generated.

# ANOM. ABSORP. MEETINGS

| | | | | |
|---|---|---|---|---|
| | 1971 | | I | |
| 18-Mar | 19-Mar | Princeton | | New Jersey |
| | 1972 | | II | |
| | | Boulder | | Colorado |
| | 1973 | | III | |
| | | Los Alamos | | New Mexico |
| | 1974 | | IV | |
| | | Livermore | | California |
| | 1975 | | V | |
| 22-Apr | 24-Apr | Los Angeles | | California |
| | 1976 | | VI | |
| 10-May | 12-May | Vancouver | | British Columbia |
| | 1977 | | VII | |
| 18-May | 20-May | Ann Arbor | | Michigan |
| | 1978 | | VIII | |
| 18-Apr | 21-Apr | Tucson | | Arizona |
| | 1979 | | IX | |
| 16-May | 18-May | Rochester | | New York |
| | 1980 | | X | |
| 28-May | 30-May | So. San Francisco | | California |
| | 1981 | | XI | |
| 2-Jun | 5-Jun | Montreal | | Canada |
| | 1982 | | XII | |
| 10-May | 13-May | Santa Fe | | New Mexico |
| | 1983 | | XIII | |
| 5-Jun | 10-Jun | Banff | | Alberta |
| | 1984 | | XIV | |
| 6-May | 11-May | Charlottesville | | Virginia |
| | 1985 | | XV | |
| 23-Jun | 28-Jun | Banff | | Alberta |
| | 1986 | | XVI | |
| 13-Jul | 18-Jul | Lake Luzerne | | New York |
| | 1987 | | XVII | |
| 17-May | 22-May | Lake Tahoe | | California |
| | 1988 | | XVIII | |
| 26-Jun | 1-Jul | L'Esterel | | Quebec |
| | 1989 | | XIX | |
| 19-Jun | 23-Jun | Durango | | Colorado |
| | 1990 | | XX | |
| 9-Jul | 13-Jul | Traverse City | | Michigan |
| | 1991 | | XXI | |
| 14-Apr | 19-Apr | Banff | | Alberta |
| | 1992 | | XXII | |
| 12-Jul | 17-Jul | Lake Placid | | New York |
| | 1993 | | XXIII | |
| 21-Jun | 25-Jun | Wintergreen | | Virginia |

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|---|---|---|---|---|
| | 1994 | | XXIV | |
| 6-Jun | 10-Jun | Pacific Grove | | California |

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Review of
1st Workshop
in Comments
on Plasma Physics
and Controlled Fusion

# Anomalous Absorption of Intense Electromagnetic Waves in Plasma

A conference on this subject was held in Princeton, March 1971, to discuss linear theories of excitation of instabilities by high-frequency fields, nonlinear theories of saturation of the instabilities, and experimental evidence from the laboratory, the ionosphere, and computer simulation.

The classical absorption process is due to electron–ion collisions. Let us review the anomalous process, for an electromagnetic wave whose frequency is of the order of the plasma frequency.

An incident transverse wave $(\omega_0, \mathbf{k}_0)$ may be scattered by an ion-wave fluctuation $(\omega_i, \mathbf{k}_i)$ into a longitudinal electron wave $(\omega_e, \mathbf{k}_e)$, subject to the conditions $\omega_i + \omega_e = \omega_0 \approx \omega_e$, $\mathbf{k}_i + \mathbf{k}_e = \mathbf{k}_0 \approx 0$. The latter waves then transfer energy to the particles directly by Landau damping, trapping, or collisions, or indirectly by mode coupling to other waves. Thus the incident wave is attenuated, and the plasma heats up. The theory of this process, called anomalous absorption, was developed by Dawson and Oberman.[1]

When the incident wave is sufficiently intense, the ion wave plus electron-wave pair is driven unstable. The resulting attenuation is thus greatly enhanced. The linear theory of this parametric instability has been developed by Silin,[2] DuBois and Goldman,[3] Jackson,[4] Nishikawa,[5] Kaw and Dawson,[6] Tzoar,[7] Sanmartin,[8] and others. In macroscopic terms, the ion wave is driven unstable by the low-frequency pressure gradient due to the high-frequency fields $(\sim \nabla E^2)$, the latter including both the incident and the longitudinal waves. The electron wave in turn is driven unstable by the charge-density fluctuations produced by the incident wave in the inhomogeneous plasma representing the ion wave.

In the Coulomb model, the parametric instability (with $k_0 = 0$ and $\omega_0 > \omega_p$) has two branches: (1) $k < k_c$, (2) $k > k_c$, where $k \equiv |\mathbf{k}_e| = |\mathbf{k}_i|$, $k_c$ is given by $\omega_{BG}(k_c) = \omega_0$, and $\omega_{BG}(k) \equiv [\omega_p{}^2 + k^2 v_e{}^2]^{1/2}$ is the Bohm–Gross frequency of a free electron wave.

(1) The small wavenumber branch has $\omega_{BG}(k) < \omega_0$, and thus the condition for a decay instability $[\omega_{BG}(k) + \omega_{IA}(k) = \omega_0]$ is satisfied for some $k_1 < k_c$. [Here $\omega_{IA}(k) \equiv c_s k$ is the frequency of a free ion-acoustic wave.] Here

however the instability occurs also for $k \neq k_1$; for the waves are driven, not free, and so the wave frequencies need not satisfy the free-wave dispersion equations: $\omega_e(k) \neq \omega_{BG}(k)$, $\omega_i(k) \neq \omega_{IA}(k)$. Nevertheless, this branch is called the decay instability, or the oscillatory branch (since $\omega_i \neq 0$).

(2) The large wavenumber branch, on the other hand, is called non-oscillatory, since the ion mode is purely growing ($\omega_i = 0$), with the electron mode driven at the incident frequency: $\omega_e = \omega_0 < \omega_{BG}(k)$. This branch is also called the oscillating-stream instability, as it is the generalization (to $\omega_0 \neq 0$) of the classical two-stream instability.

Contributions to the linear theory were made by the following: Marder and Freidberg[9] (Los Alamos) described a detailed numerical investigation of the instability theory using the Vlasov equation; they have mapped out the instability domains in the form of an interesting diagram. Valeo and Oberman (Princeton) presented work illustrating the relationship between the two types of parametric instabilities, and showed that a transition in the topology of the dispersion curve can occur for quite small pump field levels. Albright and Lashinsky (Maryland) discussed their instability calculation for fields with a frequency much less than the plasma frequency; as expected they get only the purely growing ion instability. Arnush, Fried, and Kennel (UCLA and TRW Systems) described a generalization of the instability theory to take account of an external magnetic field. In particular, they have introduced a susceptibility formalism which is general in its applicability. Bodner and Eddleman (Livermore) and Lee and Kaw (Princeton) discussed a relativistic generalization of the parametric instability theory. They considered oscillating electric fields so strong that the directed component of the electron velocity approaches the velocity of light. Such strong fields can be produced by some of the recently developed pico-second lasers. Furthermore, to be self-consistent, one has to use the full electromagnetic fields for the perturbations in this case. Perkins and Flick (Princeton) showed the important influence of large density gradients on the threshold for parametric instabilities. A strong density gradient confines the instability to a narrow region in space (where $\omega_0$ matches $\omega_p$), and energy convected out of the region by propagating waves is lost. If the density gradient scale-length is smaller than the collisional mean-free-path (as in many laboratory plasmas), then the density gradient determines the threshold field. Kaw and Lee (Princeton) described parametric instability and possible anomalous heating of ions by large amplitude low-frequency fields such as those around the lower-hybrid frequency and ion–cyclotron frequency; such schemes might be interesting for heating plasma ions to fusion temperatures directly.

Nonlinear theory is needed to determine the level at which the unstable waves saturate. Bezzerides and Weinstock (Colorado) reported on their calculation of particle-orbit modification by the unstable waves, resulting in a strong saturation mechanism. They applied their theory to the problem of incoherent scatter from the ionosphere, and found a narrow spectrum. DuBois (Hughes Labs.) and Goldman (Colorado) described a general scheme for computing the enhanced wave spectrum and conductivity, under steady state conditions, when the external driver is below a threshold field which assumes an increased value due to enhanced plasma wave damping by nonlinear wave–wave and wave–particle interactions. General expressions for these enhanced damping rates and the related spontaneous emission rates were given, and a tentative calculation based on Bezzerides and Weinstock's orbit modification theory was shown to lead to low values of the nonlinear conductivity in the ionosphere. Valeo and Oberman (Princeton) showed that when particle trapping is not important, the principal mechanisms leading to saturation are the scattering of unstable electron waves by ion density fluctuations into stable electron waves and the decay of electron waves into ion waves. Using fluid equations, Bodner (Livermore) presented a calculation of saturation of the purely growing instability, in the special case that nonlinear effects do not introduce a finite frequency; however, he pointed out that computer simulations seem to be giving evidence contrary to such an assumption. Sanmartin (MIT) presented an analytical attempt at calculation of the enhanced resistivity near the plasma frequency in the interesting domain when the driving field approaches the instability threshold; however, the range of validity of his treatment was rather restricted and the modification of resitivity small.

About half of the meeting was devoted to experimental results, including the results of computer simulations. Simulations presented by Kruer[10] (Princeton) and by Katz and DeGroot (Livermore) illustrated the basic effects in a nutshell—the exponentiation of plasma waves due to the large pump field oscillating near $\omega_p$, and efficient heating of the plasma when these waves become large. The simulations confirmed the linear theories and showed that a substantial anomalous heating can be obtained. In addition to illustrating the nature of the heating (creation of very energetic tails on the electron distribution), the simulations showed two theoretical regimes for the nonlinear theory, depending on the importance of strong electron trapping at time of saturation. Values for the wave saturation levels and the anomalous heating rate as a function of the pump power were presented. Other simulations demonstrated that a large amplitude electric field oscillating near the ion plasma frequency also efficiently heats a plasma. These results were in good agreement with a simple nonlinear theory. The waves driven unstable by the slowly oscillating drift between the electrons and ions grow until they heat the electrons (via particle trapping) by an amount sufficient to quench the instability. This predicts that the effective electron thermal velocity becomes equal to the maximum value of the slowly oscillating electron drift.

A number of experiments, both in the laboratory and in the ionosphere, were presented. Eubank (Princeton) and Dreicer *et al.* (Los Alamos) presented results on anomalous absorption of intense microwaves in low-density plasmas. Eubank used a plasma produced by a helical transmission line slow-wave structure ($n_e \sim 10^{12}\ \mathrm{cm}^{-3}$, $T_e \sim 7\ \mathrm{eV}$, 10% ionization) and propagated microwaves in the ordinary mode transverse to the plasma column and a static magnetic field. He observed excitation of ion fluctuations and enhanced plasma heating when the microwave power exceeded a threshold value. The observed value was in good agreement with that predicted by the Perkins-Flick theory of nonuniform plasmas. Dreicer *et al.*[11] made their measurements on the highly ionized plasma column of a single-ended $Q$-machine. Their experiment consisted in measuring the $Q$ of a resonant cavity (from the width of its resonance curve) filled with the $Q$-machine plasma, as a function of the microwave power in the cavity. When a critical power was exceeded, the $Q$ suddenly started decreasing, which can be interpreted as an enhanced dissipation in the plasma. Shearer (Livermore) described experiments on the interaction of intense lasers with plasma. He found an anomalous production of very energetic particles which might be interpreted as arising due to energetic tails produced by the anomalous absorption effect. Cohen[12] (NOAA, Boulder) presented results of wave propagation experiments in the ionosphere. A powerful wave (the "modifier") with a frequency close to the electron plasma frequency of the F-layer was transmitted into the ionosphere. The region of strong interaction ($\omega \approx \omega_p$) was then probed by weaker exploring signals sent at oblique incidence. The enhanced extinction of the exploring signal in the presence of the modifier could be interpreted as evidence for anomalous resistivity due to excitation of instabilities in the ionosphere. At the same time it could also be attributed to enhanced scattering into regions away from the receiver. There was thus an understandable controversy on whether the anomalous absorption effect had been observed in Cohen's experiments. The presence of very energetic particles shown by airglow measurements was, however, an additional piece of evidence in support of anomalous absorption processes. Wong and Taylor[13] (UCLA and TRW Systems) described experiments in the ionosphere and the laboratory aimed at investigating parametric instability effects. In the ionospheric experiments, carried out at Arecibo with the cooperation of Carlson, Gordon, and Showen, the F-layer was irradiated with a powerful radio wave from the ground. The instabilities excited in the ionosphere were then diagnosed by incoherent scattering using a ground-based radar system. The returned radar signals showed sideband components shifted from the main radar frequency by the modifier frequency. The asymmetrical distribution of the returned sideband signal around the sideband frequency is in qualitative agreement with theoretical predictions of the instability analysis. In the laboratory experiments, Stenzel and Wong reported observations of similar asymmetry in the sideband spectrum and found that the threshold increases linearly with the ion damping. They are presently trying to make detailed probe measurements on the wavelength of the excited modes, especially when the driving field is close to the threshold of instability. Both these experiments offer good possibilities of comparison with theory. Meltz and Tomljanovich (MITRE Corp., Mass.) presented a conjecture for explaining the pronounced spread-F observed in the Boulder ionospheric heating experiments. They pointed out that the presence of anomalous resistivity in a thin region (where $\omega \approx \omega_p$) leads to large temperature gradients in the ionosphere which could lead to a temperature-gradient driven drift instability and thus account for the observed spread-F. Stern[14] (Bell Labs.) pointed out that if one of the modes excited by the external driver field meets a natural resonance somewhere in the plasma, then there might exist strong reradiation of energy which would prevent efficient heating of the plasma.

Work by Mannheimer (NRL), on instabilities associated with trapped particles in large amplitude electrostatic waves, and by Hasegawa (Bell Labs.), on an interpretation of d.c. anomalous resistivity (observed in computer simulation of constant-current type) in terms of high-frequency anomalous resistivity, were interesting sidelights of the meeting.

At the end of the meeting it was clear that whereas the linear theory of instability excitation was in good shape, there was considerable controversy over the dominant nonlinear mechanisms responsible for their saturation. Clearly, more work needs to be done in this direction. From the experimental side it appeared that there was much qualitative evidence, from diverse sources, supporting the existence of anomalous absorption. However, as yet there were no definitive experiments identifying the excited instabilities or giving accurate quantitative estimates of the enhanced resistivity. Quantitative experiments designed to verify the linear theory of instability excitation and to select one of the many competing nonlinear theories are required. Computer simulation experiments with their versatile diagnostic facilities will also undoubtedly continue to play an important role in isolating the dominant nonlinear effects.

A. N. Kaufman
P. K. Kaw
W. L. Kruer

**References**

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# Microinstabilities in Mirror Plasmas

Over the last five years a considerable amount of theoretical work has been done on the subject of microinstabilities in mirror plasmas and a significant increase in understanding has been achieved. Agreement between the theoretical and experimental results has been good for some modes of instability in certain regions of parameter space. In particular the agreement between theory and experiment are very good at low densities ($n \sim 10^{10}$) but at the present time there is very little correlation between the predictions of the theory and the experimental results in the high density regime ($n \sim 10^{13}$). In this article I will summarize the main results obtained so far and then briefly mention the problems that remain to be solved.

In a mirror machine the ions are contained in the direction along the field lines by the $\mu\nabla_{\|}B$ force, however ions in the "loss-cone" region of velocity space that is particles for which $V_{\perp} < V/R^{1/2}$ ($R$ is the mirror-ratio) can escape freely from the machine. This means that the ion distribution is non-Maxwellian and always has a source of "free energy" which can drive instabilities. A typical ion distribution is illustrated in Fig. 1 and for comparison a Maxwellian is also shown (dotted line).

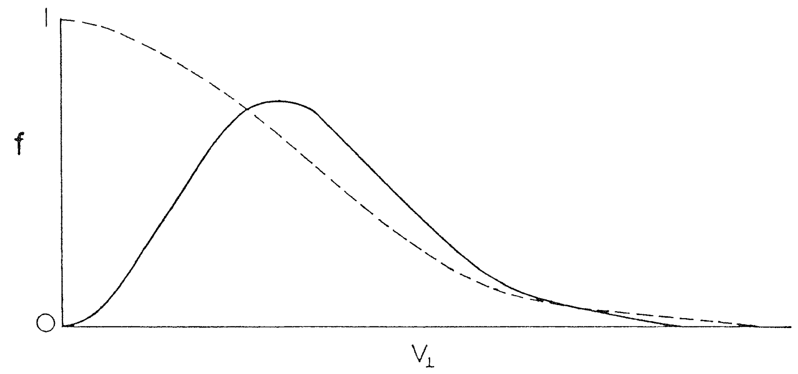

FIG. 1. The continuous line is a typical mirror loss-cone distribution and the dotted line is a Maxwellian.