22. Plasma Dynamics

Academic and Research Staff

Prof. G. Bekefi, Prof. A. Bers, Prof. B. Coppi, Prof. T.H. Dupree, Prof. L.M. Lidsky, Prof. J.E. McCune, Prof. M. Porkolab, Prof. L.D. Smullin, Dr. R.H. Berman, Dr. R.T. Bonoli, Dr. T. Boutros-Ghali, Dr. K.-I. Chen, Dr. R.C. Englade, Dr. V. Fuchs[26], Dr. K. Hizanidis, Dr. J.H. Irby, Dr. V.B. Krapchev, Dr. J.S. Levine, Dr. S.C. Luckhardt, Dr. A.K. Ram, Dr. J. Ramos, Dr. R.E. Shefer, Dr. L.E. Sugiyama, Dr. D.J. Tetreault, E.W. Fitzgerald, R. Li, I. Mastovsky, Y.Z. Yin, M.-L. Xue

Graduate Students

J.G. Aspinall, P.E. Cavoulacos, J. Fajans, M.E. Foord, G. Francis, R.C. Garner, T.R. Gentile, A.M. Hamza, F. Hartemann, L.P. Harten, D. Hinshelwood, D.A. Humphreys, K.D. Jacobs, M. Kanapathipillai, D.A. Kirkpatrick, B.L. LaBonbard, W.P. Marable, J.J. Martinell, M.J. Mayberry, F.S. McDermott, A. Pachtman, Y. Pu, C.M. Rappaport, R.R. Rohatgi, S.E. Rowley, D.R. Thayer

22.1 Tokamak Research: RF Heating and Current Drive

U.S. Department of Energy (Contract DE-AC02-78-ET-51013)

George Bekefi, Miklos Porkolab, Kuo-in Chen, Stanley C. Luckhardt

The main goal of the Versator II tokamak research program is to study physics issues of plasma-wave interactions in purely RF-driven or combined ohmic and RF discharges. Two RF systems at frequencies of 800 MHz and 2.45 GHz have been used to launch lower-hybrid waves through different grill structures at power levels up to ~100 kW each. This yields a unique position for us to study the dependence of current drive efficiency on RF source frequency in the same machine. In addition to the installation of the new 2.45 GHz RF system,[1] a major machine upgrade was completed during 1984, enabling us to obtain fully RF-driven plasmas with the ohmic heating system shut off. Longer plasma discharges (~60 ms) have been obtained with the new ohmic system.

Present Status

[26] IREQ-Hydro Quebec, Montreal, Canada

I. 800 MHz Lower-Hybrid Current Drive (LHCD) Experiments

The global particle confinement study during LHCD has been finished.[2,3] It has been found that significant density increases in combined ohmic and RF discharges are due to an improvement of global particle confinement (τ_p increased by ~2.3 compared to ohmic discharges). This improvement has been shown to take place when the anomalous doppler instabilities are stabilized by lower-hybrid waves. The threshold RF power to suppress these instabilities was found to be as low as ~4~6 kW. However, the value of the threshold RF power seemed to be dependent on discharge purity and equilibrium.

The current drive efficiency of launching the wave through a top port has been found to be ~50% of the current drive efficiency when the wave is launched through a side port.[4] These results seem to be consistent with the theoretical predictions of the effects of toroidal geometry.

2.45 GHz Lower-Hybrid Current Drive Experiments

The 2.45 GHz RF system used in the previous Alcator A experiments has been installed on the Versator II tokamak. RF power is launched through a new stainless steel 4-waveguide grill with the capability to change phases independently. Up to 80 kW RF power (power density ~2.3 kW/cm^2) has been coupled into the Versator plasma. The reflection coefficient is typically 5% when the grill position is optimized. With an RF power of ~80 kW, discharges with flattop plasma currents ($\dot{I}_p = 0$, $V_L = 0$) have been achieved at densities up to ~$1.0 \times 10^{13} cm^{-3}$, which is almost twice as high as the density limit obtained with the 800 MHz system. Furthermore, current increases and loop voltage decreases have been observed even at higher densities, i.e. $\bar{n}_e$~$1.7 \times 10^{13} cm^{-3}$. Thus, we conclude that the current drive density limit can be exceeded by raising the source frequency.

It should be noted that the current drive efficiency is still good even in the higher density regime even though the plasma dielectric constant, $\omega_{pe}^2/\omega_{ce}^2$, is larger than one. At lower density ($\bar{n}_e$~$7 \times 10^{12} cm^{-3}$), plasma current can be ramped up with a rate of ~(150-200) kA/sec when P_{RF}~80 kW.

2 mm Microwave Scattering Experiments

We have successfully demonstrated the detection of 800 MHz lower-hybrid waves using the 2 mm microwave scattering diagnostic.[5] Preliminary results have shown that the scattering signal is strongly dependent on phasing between waveguides. This indicates that the wave number spectrum of the lower-hybrid waves in the plasma is controlled by the spectrum launched by the antenna structure.

References

1. M.J. Mayberry, S.C. Luckhardt, M. Porkolab, K.I. Chen, D. Griffin, and R. Rohatgi, Bull. Am. Phys. Soc. 29, 1248 (1984).
2. K.I. Chen, S.C. Luckhardt. M.J. Mayberry, M. Porkolab, and R. Rohatgi, Fourth Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas, Rome, Italy, March 1984.
3. M. Porkolab *et al.*, Tenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research. London, England, September 1984.
4. S.C. Luckhardt, G. Bekefi, K.I. Chen, M.J. Mayberry, M. Porkolab, and R. Rohatgi, Bull. Am. Phys. Soc. 29, 1248 (1984).
5. R. Rohatgi, K.I. Chen, G. Bekefi, S.C. Luckhardt, M.J. Mayberry, F.S. McDermott, and M. Porkolab, Bull. Am. Phys. Soc. 29, 1248 (1984).

22.2 Nonlinear Wave Interactions — RF Heating and Current Generation in Plasmas

National Science Foundation (Grant ECS82-13430)

U.S. Department of Energy (Contract DE-AC02-78-ET-51013)

U.S. Air Force - Office of Scientific Research (Contract F33615-81-K-1426)

Abraham Bers, Vladimir Fuchs[27], Kyriakos Hizanidis, Vladimir Krapchev, Abhay Ram, Gregory Francis, Leo Harten

The work and objectives of this theoretical and computational research were described in the RLE Progress Report No. 124, January 1982, pp. 112–113. A perspective of our continuing research can be obtained from RLE Progress Reports No. 125, pp. 107–112, and No. 126, pp. 110–116.

In the following five subsections we report on our accomplishments of the past year on the following problems:

A. Theoretical and computational work on current generation in a plasma by externally applied RF power — subsections 1a and 1b. This work is part of our continuing study of exploring means by which wave momentum can be transferred to electrons in a plasma. The significant application of this work is to ongoing experiments aimed at using microwave power for producing a steady-state current in a plasma for its confinement. The important, new results in 1a and 1b show:

(i) That current drive with RF induced quasilinear diffusion parallel to the main magnetic field $\vec{B}_0$ (as with lower-hybrid waves) always produces a high effective temperature perpendicular to $\vec{B}_0$.

(ii) That a two-dimensional (in momentum space) theory can properly describe the important phenomena; one dimensional models are inadequate if they do not properly account for the enhanced perpendicular temperature.

(iii) That relativistic effects in the two-dimensional description are significant in giving the details of current drive with fast electrons. This will be of importance in future experiments with plasmas at very high temperatures, near ignition.

B. Induced stochasticity in the dynamics of plasma particles by applied RF fields — subsection 2. Here we report on our finding a proper analytical description for induced stochasticity by a frequency modulated wave. As described in last year's report, such waves have a very low threshold for the onset of stochastic motion of particles trapped in a potential well. A possibly

[27] Visiting Scientist from IREQ - Hydroquebec, Montreal, Canada

important application of our results is for new means of modifying the trapped electron distribution function in tandem mirror confined plasmas where efficient generation of plug potentials or thermal barriers is needed. Another potential application is for lowering the threshold for stochastic ion-heating by lower-hybrid waves or high ion-cyclotron harmonic waves.

C. Wave propagation and mode conversion in high temperature plasmas — subsection 3. We describe a new way of treating wave propagation in an inhomogeneous, hot plasma where modified cold plasma and kinetic modes couple to each other. Such couplings are of current importance in various RF heating schemes for both laboratory and ionospheric plasmas.

D. Space-time evolution of instabilities — subsections 4 and 5. In our quest for understanding the evolution of radiating (i.e. electromagnetic) instabilities in energetic plasmas we report on the first results of the O-mode across $\vec{B}_0$. In addition we describe the highlights of our completed pulse analysis for streaming instabilities in plasmas (with finite temperatures). Radiating instabilities have been observed in intensely RF (electron-cyclotron) heated plasmas. They may also have the potential for new cyclotron-maser like devices at harmonics of the electron cyclotron frequency. In addition, they are of importance in understanding radiations from space and astrophysical plasmas.

1. Current Generation in a Plasma with RF Power

a. Lower-Hybrid Current Generation — Theoretical Model Results

The linearized, steady state, two-dimensional Fokker-Planck equation for electrons has been solved analytically in the presence of strong RF diffusion by setting $f(v_{\parallel}, v_{\perp}) = \varphi(v_{\perp}^2)\exp(\psi(v_{\parallel}, v_{\perp})/D_0)$ for the distribution function.[1] In this case the diffusion coefficient $D_0 = D_{QL}/\nu v_t^2$ is a constant for $v_1 \le v_{\parallel} \le v_2$ and zero otherwise. Here D_{QL} is the quasilinear diffusion coefficient, ν is the bulk collisional frequency, v_t the thermal velocity, and $v_1 (v_2)$ is the low (high) velocity (normalized to v_t) boundary of the resonant domain.

For the nonrelativistic case and ion charge $Z_i = 1$ it is found that there are many more current carriers in the plateau than estimated by 1-D theory[2] or previous 2-D numerical integration of the equations.[3] The ratio of the 2-D to the 1-D current and $T_{\perp}/T_B$, where $T_{\perp}$ is the perpendicular temperature of the current-carrying electrons and T_B is the bulk electron temperature, are approximately given by:

$$J_2/J_1 = v_1 v_2[\pi \ln(v_2/v_1)/(v_2^2 - v_1^2)]^{1/2} = \pi T_{\perp}/2T_B.$$

This enhancement of the current predicts (within a factor of two) our recent 2-D results obtained numerically. However, the 2-D numerical results predict a much larger (by factors of four to eight) perpendicular temperature. This latter failing of the present theory is due to the approximate treatment of the boundary conditions which was necessary in obtaining analytically tractable results. This aspect needs further attention. The figure of merit J/P_d increases by a factor of 3 compared with the 1-D theory and is given by $J/P_d = (v_2^2 - v_1^2)/[2 \ln (v_2/v_1)]$ where current density J and power dissipated P_d are in units of env_t and $m_e n v_t^2 \nu$ respectively. This aspect of the theory is very well supported by our 2-D numerical results.

b. Relativistic 2-D Fokker-Planck Equation — Computational Results

A numerical code which solves the 2--D relativistic Fokker-Planck equation[4] has been used in extensive numerical studies. The numerical results indicate a significant enhancement of the $mv_\perp^2/2$ moment (i.e., $T_\perp = \int dp_\perp p_\perp mv_\perp^2 f/2 \int dp_\perp p_\perp f$) normalized to the bulk temperature T_B. The enhancement occurs very rapidly as we enter the resonant region and is followed by a second enhancement as we exit it with $T_\perp/T_B$ subsiding eventually to 1 far from the resonant region (Fig. 22-1).

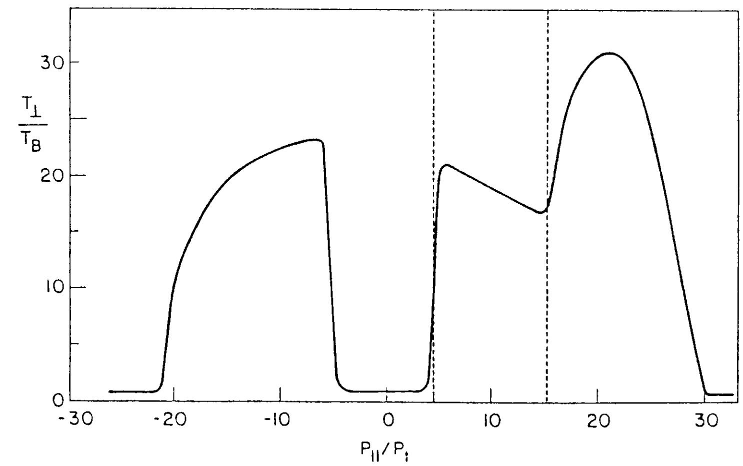

Figure 22-1: The perpendicular energy moment, normalized to the bulk temperature ($T_\perp/T_B$) as a function of the normalized momentum ($p_\parallel/p_t, p_t = mv_t$). The spectrum is located between $n_\parallel = 1.8$ and 4.5. $D_o = 20$ and $Z_i = 1$ are assumed. The interval in $p_\parallel$ between the dotted lines corresponds to the resonant region.

A similar enhancement also occurs in a region which encompasses an interval, in $-p_\parallel$, symmetric to the resonant region. This enhancement is provided by the pitch angle scattering process which connects the resonant region with its symmetric image part in $-p_\parallel$.

The current generated, power dissipated and perpendicular temperature are rather insensitive to changes of the diffusion coefficient magnitude for values of D (normalized to $\nu m^2 v_t^2$ above 10). Current and power dissipated change significantly with the location of the spectrum, especially with the location of the left (low $p_\parallel$) boundary. For wide spectra, relativity affects significantly both current generated and power dissipated. For ALCATOR-C parameters (assuming $Z_i = 1$,

$n = 10^{14}$ cm^{-3}, $R = 64$ cm, $T = 1$ kev and current-carrying cross section of radius $a/2 = 8$ cm), a spectrum located between $n_{\|} = 1.4$ and 5.5, $Z_i = 1$ and D of gaussian shape with a peak value 15, for example, we obtain an RF driven current $I = 370$ kA with a power dissipated of $P_d = 534$ kW; while for a spectrum located between $n_{\|} = 1.8$ and 5.5 we find $I = 114$ kA with $P_d = 280$ kW. These calculations, using RF spectra similar to experimental ones, reproduce the general range of currents observed in these experiments but at much lower powers than the RF powers externally applied to the plasma (by factors of 2 to 4). We conclude that lower-hybrid current drive has the potential for much better efficiencies than shown by present-day experiments. This should be particularly true for LH current drive with the fast wave as needed in hotter plasmas approaching the ignition temperature range.

A one-dimensional relativistic Fokker-Planck code has also been developed. The working equation is based on the ansatz

$$f(p_{\|}, p_{\perp}) = F_{\|}(p_{\|}) \exp\left(-\frac{p_{\perp}^2}{2T_{\perp}(p_{\|})}\right) / 2\pi T_{\perp}(p_{\|}) m^2 v_t^2$$

with p's normalized to mv_t and $T_{\perp}$ to $T_B = mv_t^2$, where $T_{\perp}$ is obtained from the perpendicular moment of the full 2-D equation. The approximation made is $\gamma = 1 + p_{\|}^2 \beta_t^2 (\beta_t = v_t/c)$. The current generated, power dissipated and the efficiency (I/P_d) obtained for various values of $T_{\perp}$ (taken as a constant $\gg 1$) are all much smaller than the ones obtained from the 2-D code. There is evidence from the form of the 1-D equation that $dT_{\perp}(p_{\|})/dp_{\|}$ (so far omitted for these one-d numerical calculations) plays a very crucial role. It has been concluded that the 1-D equation by itself is inadequate unless an equation for $T_{\perp}$ is provided.

2. Induced Stochasticity by a Frequency-Modulated Wave

The modification to the distribution function of electrons trapped in a static (electric and/or magnetic) well by a frequency modulated (fm) wave has been under study for the past year.[5-7] The onset of stochasticity obtained from the numerical integration of the (appropriately normalized) equation of motion for the electrons:

$$\frac{d^2 z}{dt^2} = -\sin z - \varepsilon \sin(kz - \omega t - \delta \sin \omega_m t)$$

correlate very well with an analytical model based on the Chirikov resonance overlap criterion. Here k and ω are respectively the wave vector and frequency of the carrier wave, and $\delta(\omega_m)$ are the fm modulational index (frequency); ε is the strength of the perturbing fm-wave. For an fm-wave with its frequency close to (or slightly less than) the bounce frequency of the electrons near the bottom of the static well and its phase velocity greater than the velocity of the confined electrons, there exist two distinct regions of phase-space where the electron motion becomes stochastic. One of the stochastic regions lies near the phase-space location of the fm-wave. This region has been studied extensively before and it will not be described here. The other stochastic region lies inside the static well and its phase-space width is proportional to the product $\delta\omega_m$ (which is the frequency band-width of the fm-wave). This is the region which we have studied thoroughly. In order to determine the conditions for the onset of stochasticity and the width of the stochastic region the equation of motion has to be transformed from the phase-space discussed above to the action-angle space corresponding to the Hamiltonian of the above equation. These turn out to be the natural coordinates for an analytical examination of the electron motion. The region of stochasticity is determined by those actions, I_ℓ (ℓ integer), that satisfy the nonlinear resonance condition $\Omega(I = I_\ell) = \omega - \ell\,\omega_m$ and

$$\left|\frac{\Delta I_\ell^{TR} + \Delta I_{\ell+1}^{TR}}{I_\ell - I_{\ell+1}}\right| > 1$$

where

$$\Delta I_\ell^{TR} = 2\left[\frac{\varepsilon}{k} J_\ell(\delta)\frac{V(k, I)}{(d\Omega / dI)}\right]^{1/2}_{I = I_\ell},$$

$$V(k, I) = 2k\,\mathrm{sech}\left\{\frac{\pi}{2}\frac{K(\sqrt{1-\kappa^2})}{K(\kappa)}\right\},$$

$$\Omega = \frac{\pi}{2K(\kappa)} = \frac{dH_o}{dI}$$

$$I = \frac{8}{\pi}\left[E(\kappa) - (1-\kappa^2)K(\kappa)\right], \text{ and}$$

$$\kappa^2 = \tfrac{1}{2}(1 + H_o)$$

K and E are elliptic integrals of the first and second kind, respectively, and J is the ordinary Bessel function. The advantage of the fm-wave is that it requires a much smaller amplitude than a single frequency wave to create an equivalent region of stochasticity. However, ω_m is crucial in determining the conditions for onset of stochasticity as well as the diffusion time-scale for the stochastic electrons.[7] For large ω_m there is no widespread connected stochasticity so that the electrons do not diffuse in action space. This can be seen from Fig. 22-2 which is the surface of section plot (I versus φ) for $\omega_m = 0.2$. There appear island structures ($n = 1$ at $I \approx 1.35$ and 2.2; $n = 2$ at $I \approx 0.7$, etc.) due to the perturbation, but the only stochasticity is near the separatrix ($I \approx 2.4$) as is expected. However, if we decrease ω_m to 0.05 (while all the other parameters remain the same as for Fig. 22-2) the region between $I = 0.1$ and $I = 1.2$ is almost completely stochastic (Fig. 22-3). At $\omega_m = 0.01$ we find that the region between $I = 0$ and $I \approx 1.3$ is completely stochastic. Here there is diffusion in action-space as shown in Fig. 22-4 which plots $< I^2 >$ versus time. ($< I^2 >$ is the ensemble average of I^2 over a large number of electrons starting with different conditions.) For very small ω_m, $< I^2 >$ oscillates with time as shown in

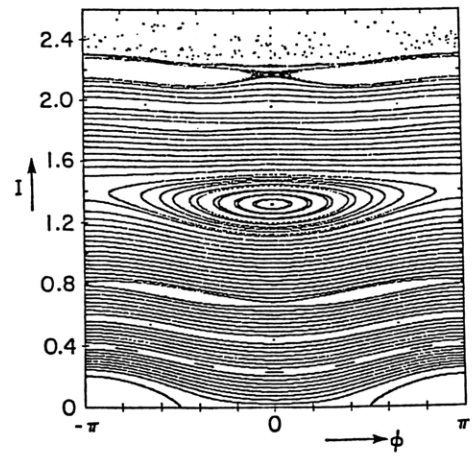

Figure 22-2: Surface of section plot for $\varepsilon = 8 \times 10^{-3}$, $k = 0.2$, $\omega = 1.0$, $\omega_m = 0.2$, $\delta\omega_m = 0.1$.

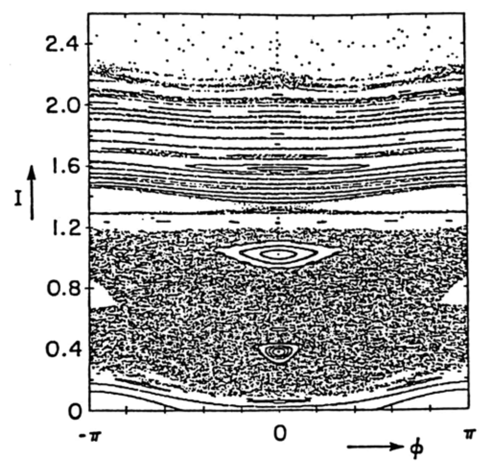

Figure 22-3: Surface of section plot for $\varepsilon = 8 \times 10^{-3}$, $k = 0.2$, $\omega = 1.0$, $\omega_m = 0.05$, $\delta\omega_m = 0.1$.

Fig. 22–5 with a characteristic frequency equal to ω_m. In this case there seems to be no diffusion. Thus, there exists a range of ω_m over which this does not happen and there is a well-defined diffusion of the electrons in action-space. The diffusion is time-dependent eventually going to zero when the electron distribution function has flattened. The application of this technique to the heating of mirror trapped electrons has also been developed.[6]

3. Mode Conversion Theory for Plasma Heating

Expanding upon our earlier work on kinetic mode-conversion theory,[8] and utilizing energy-flow conservation in lossfree coupling, we have shown that most such mode-conversion processes of interest in plasma heating can be fully described by appropriately extracted, second-order differential equations. Given a local dispersion relation $D(\omega;k,z) = 0$, describing stable waves

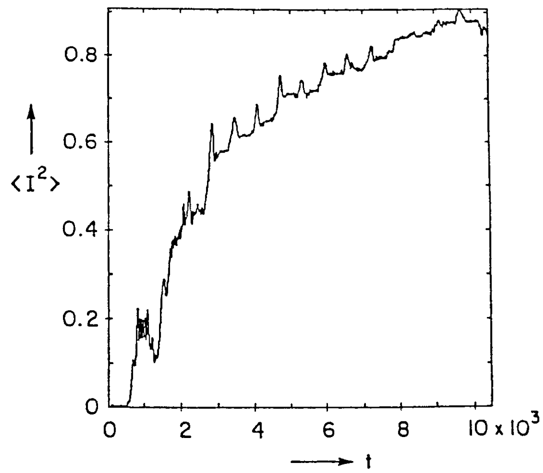

Figure 22-4: $< I^2 >$ versus time for $\varepsilon = 8 \times 10^{-3}$, $k = 0.2$, $\omega = 0.9$, $\omega_m = 10^{-2}$, $\delta\omega_m = 0.1$. $< I^2 >$ is the ensemble average of I^2 over 1200 electrons starting with different initial conditions.

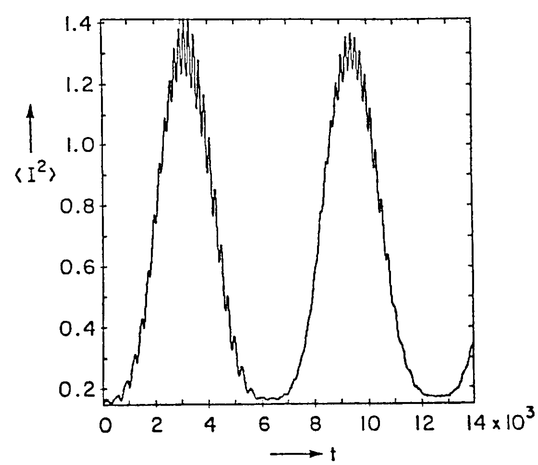

Figure 22-5: $< I^2 >$ versus time for $\varepsilon = 8 \times 10^{-3}$, $k = 0.2$, $\omega = 0.9$, $\omega_m = 10^{-3}$, $\delta\omega_m = 0.1$.

excited at an externally imposed frequency ω, a pairwise mode-coupling event embedded therein is extracted by expanding $D(k,z)$ around a contour $k = k_c(z)$ given by $\partial D/\partial k = 0$. The branch points of $D(k,z) = 0$ are the turning points of a second-order differential-equation representation. In obtaining the fraction of mode-converted energy, the connection formula and conservation of energy must be used together. Also, proper attention must be given to distinguish cases for which the coupling disappears or persists upon confluence of the branches, a property which is shown to depend on the forward ($v_g v_{ph} > 0$) or backward ($v_g v_{ph} < 0$) nature of the waves. Examples occurring in ion-cyclotron, lower-hybrid, and Alfven-ion cyclotron heating have been worked out to illustrate the use of the theory.[9]

4. Space-Time Evolution of Relativistic-Electromagnetic Instabilities

The analysis of absolute and convective instabilities has been extended to the study of relativistic[10] electromagnetic (em) instabilities propagating across a constant magnetic field ($\vec{B}_0$) in which a homogeneous plasma is immersed.[11-14] The distribution function of the electrons is assumed to be a highly anisotropic function of the perpendicular (to $\vec{B}_0$) momentum ($\bar{p}_\perp$) while it may or may not have any parallel (to $\vec{B}_0$) drifts in momentum ($\bar{p}_\|$). Such distributions exist in electron-cyclotron heated mirror plasmas and are the driving mechanism of experimentally observed instabilities. To investigate the properties of instabilities generated by anisotropic distribution functions we choose an unperturbed distribution function of the form:

$$f_0(p_\perp, p_\|) = \frac{1}{4\pi p_{0\perp}} \delta(p_\perp - p_{0\perp})[\delta(p_\| - p_{0\|}) + \delta(p_\| + p_{0\|})]$$

where $p_\perp, p$ are the magnitudes $\bar{p}_\perp, \bar{p}_\|$, respectively. The appropriate dispersion relation is derived from the relativistic Vlasov and Maxwell's equations. Such a distribution function has the property that the dispersion relation splits up into two parts. One part describes the extraordinary em-mode (X) with eliptically polarized electric fields perpendicular $\vec{B}_0$. The other part describes the ordinary mode (O) with its electric field along $\vec{B}_0$. For either case, instabilities are found to exist very near the electron-cyclotron frequency (Ω) or its harmonics. The results obtained from our analysis are summarized below.

For the X-mode we find that: for low densities the only absolute instability is at $\omega \approx \Omega$ with $k_\perp \leq \omega/c$ (ω is the frequency, $k_\perp$ is the wave-vector perpendicular to $\vec{B}_0$ and c is the speed of light); as the density is increased the instabilities at $\omega \approx \Omega(k_\perp \gtrsim \omega/c)$ and $\omega \approx 2\Omega(k_\perp \gtrsim \omega/c)$ are absolute with the latter having the greater growth rate; further increases in the density lead to the instability at $\omega \approx 2\Omega(k_\perp \gtrsim \omega/c)$ being the only one that is absolute. For very high densities, $\omega_p/\Omega > 1$ (where ω_p is the electron plasma frequency) the instabilities are in the electrostatic regime with $k_\perp \gg \omega/c$ and $\omega \approx n\Omega$ and $\omega \approx (n+1/2)\Omega(n = 1,2,...)$. These are then of much larger growth rate.

For the O-mode we find that: for $p_{0\|} = 0$ there are no instabilities; for $p_{0\perp} = 0$ the only instability is at $\omega = 0$ which is of the Weibel type; for $p_{0\|} \neq 0, p_{0\perp} \neq 0$ and $\omega_p/\Omega \leq 1$ the instabilities are at $\omega \approx n\Omega(n = 1,2,...)$; for $\omega_p/\Omega > 1$ the instabilities are at $\omega \approx n\Omega(n = 0,1,2,...)$ and $\omega \approx (n + 1/2)\Omega$. Further studies are in progress.

5. Finite Temperature Effects on the Space-Time Evolution of Two-Stream Instabilities

We have studied the effects of finite temperature on the space-time evolution of two-stream instabilities based on the kinetic (Vlasov) theory description of the dynamics. This allows us to explore their absolute versus convective nature from threshold (Penrose) conditions into the strong hydrodynamic regime. Using the pinch-point analysis,[15,16] we study the time-asymptotic pulse shapes of electrostatic (Pierce-Buneman, beam-plasma) and electromagnetic (Weibel) instabilities generated by two-stream interactions.[17,18] The dispersion relations are derived from the linearized, non-relativistic Vlasov-Maxwell equations for an infinite, homogeneous plasma without any externally applied fields.

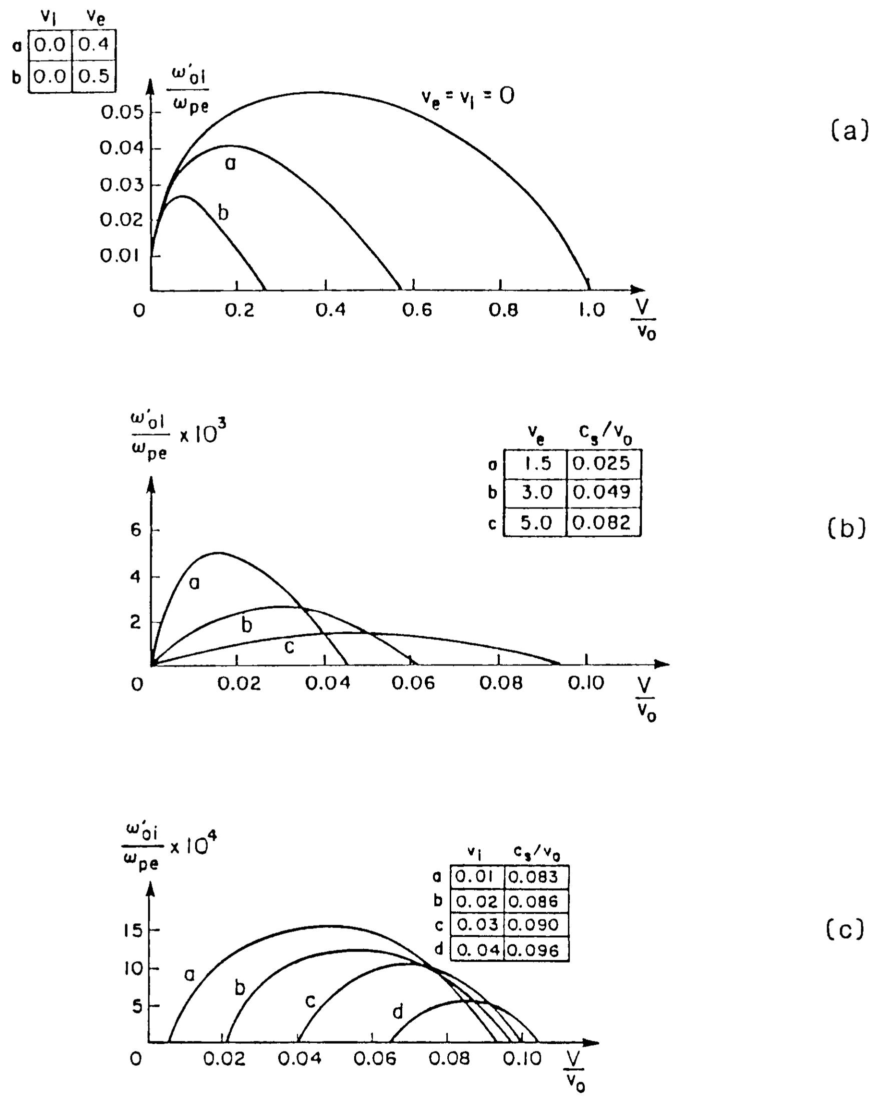

Figure 22-6: Effect of increasing $v_e = v_{the}/v_0$, while keeping the ions cold, on the time-asymptotic pulse shape in the Pierce-Buneman regime (a), and in the ion-acoustic regime (b). Figure (c) shows evolution of ion-acoustic pulse shape with increasing $v_i = v_{thi}/v_0$ for a fixed value of electron temperature ($v_e = 5.0$).

The Pierce-Buneman instability is absolute in the cold-plasma limit. It changes to a convective instability and moves away from the origin of the initial perturbation when the ion distribution has a thermal spread; the low-velocity portion of the unstable pulse being ion-Landau-damped away.

If the ion distribution is cold and we increase the temperature of the drifting electrons, the instability remains absolute. The velocity of the leading edge of the pulse decreases with increasing electron temperature due to Landau-damping until it is approximately equal to the (increasing) ion-sound velocity, $c_s = (T_e/m_i)^{1/2}$ (see Fig. 22-6a). Further increase in the electron temperature changes the instability into a new mode — the ion-acoustic instability. The waves which were previously Landau-damped now have phase velocities such that they anti-Landau-damp on the electron distribution. The leading edge of the pulse speeds up and remains slightly ahead of the ion-sound velocity (see Fig. 22-6b). In this ion-acoustic regime, an increase in ion temperature not only changes the instability into a convective one by ion-Landau-damping the lower-velocity portion of the pulse, but it also speeds up the leading edge slightly because of the ion thermal corrections to the ion-sound velocity (see Fig. 22-6c). Thus, the ion-acoustic instability is convective at threshold.

The evolution of the beam-plasma instability is found to be similar to that of the Pierce-Buneman. It is also absolute in the cold plasma-cold beam limit. As the temperature of the streaming species (the beam) is increased, the pulse slows down, yet remains absolute. If the stationary species (the plasma) is heated, the instability becomes convective.

We have also studied the evolution of the electromagnetic Weibel instability. It is an absolute instability. The growth rate of the unstable pulse and its edge velocities increase with increasing drift velocity and/or thermal spread of the electrons in the direction of the wave electric field. The pulse is stabilized by increasing the temperature of the electrons along the direction of wave propagation.

We are currently preparing a journal article that describes our results in detail.

References

1. V.B. Krapchev, D.W. Hewett, and A. Bers, Phys. Fluids 28, 522 (1985).
2. N.J. Fisch, Phys. Rev. Lett. 41, 873 (1978).
3. C. Karney and N. Fisch, Phys. Fluids 22, 1817 (1979).
4. D.W. Hewett, V.B. Krapchev, K. Hizanidis, and A. Bers, "Aggressive Time Step Selection for the Time Asymptotic Velocity Diffusion Problem," M.I.T. Report PFC/RR-84-18, December 1984.
5. A. Ram, M. Mauel and A. Bers, "Stochastic Motion of Mirror-Confined Electrons by a Frequency-Modulated Wave," Annual Controlled Fusion Theory Conference, Incline Village, Nevada, April 11-13, 1984.
6. R.S. Post, et al., "TARA and Constance-B Mirror Confinement Experiments and Theory," Proceedings of the Tenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, London, England, Sept. 12-19, 1984, IAEA Vienna (in press).
7. A.K. Ram, K. Hizanidis and A. Bers, "Induced Stochasticity of Electrons Confined in a Static Well by a Frequency-Modulated Wave," Bull. Am. Phys. Soc. 29, 1181, October 1984.
8. V. Fuchs, K. Ko, and A. Bers, Phys. Fluids 24, 1261 (1981).
9. V. Fuchs, A. Bers, and L. Harten, Phys. Fluids, 28, 177 (1985).

10. A. Bers, A.K. Ram, and G. Francis, "Relativistic Analysis of Absolute and Convective Instability Evolutions in Three Dimensions," Phys. Rev. Lett. 53, 1457 (1984).
11. A. Bers, A. Ram, and G. Francis, "Relativistic Theory of Absolute and Convective Instability Evolutions in Three Dimensions," Proceedings of the 1984 International Conference on Plasma Physics, Lausanne, Switzerland, June 27-July 3, 1984, Vol. I, p. 81.
12. A.K. Ram, G. Francis, and A. Bers, "Relativistic Electromagnetic Instabilities Near Electron Cyclotron Frequency and Harmonics," Proceedings of the EC-4 Fourth International Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Rome, Italy, March 28-30, 1984, pp. 161-166.
13. A. Ram and A. Bers, "Space-Time Evolution of Relativistic Electromagnetic Instabilities," 1984 IEEE International Conference on Plasma Science, St. Louis, Missouri, May 14-16, 1984.
14. A. Bers, A.K. Ram, and G. Francis, "Absolute and Convective Evolutions for Relativistic-Electromagnetic Instabilities," Bull. Am. Phys. Soc. 29, 1196, October 1984.
15. R.J. Briggs, Electron Stream Interaction with Plasmas, (MIT Press 1964).
16. A. Bers, "Space-Time Evolution of Plasma Instabilities — Absolute and Convective" in M.W. Rosenbluth and R.Z. Sagdeev (Gen. Eds.) Handbook of Plasma Physics; A.A. Galeev and R.N. Sudan (Vol. Eds.), Vol. 1, Basic Plasma Physics, Chapter 3.2, (North Holland Publishing Co. 1983).
17. G. Francis, A.K. Ram, and A. Bers, "Space-Time Evolution of Two-Stream Instabilities," Bull. Am. Phys. Soc. 29, 1196, October 1984.
18. G. Francis, A. Ram and A. Bers, "Finite Temperature Effects on the Space-Time Evolution of Two-Stream Instabilities," Proceedings of the 1984 International Conference on Plasma Physics, Lausanne, Switzerland, June 27—July 3, 1984, Vol. 1, p. 80.

22.3 Physics of Thermonuclear Plasmas

U.S. Department of Energy (Contract DE-AC02-78ET-51013)
Bruno Coppi

The general objective of this program is the theoretical study of plasmas in thermonuclear regimes and it extends from the design of "burning core" experiments for both D-T and advanced fuel reactors to the basic study of plasma transport and stability questions. Continuous collaboration and theoretical guidance are provided for the Alcator and Versator experimental programs that involve high density, well confined plasma regimes, as well as low and intermediate density regimes where current drive and radio frequency heating can be produced.

One of the rewards of our efforts is the record confinement parameter $n\tau_E$ and the increase in confinement time obtained by the recent series of Alcator experiments. In fact, these have confirmed the validity of our suggestion that, in order to avoid a significant anomalous ion thermal conductivity, the particle density profile has to be made more peaked than that "spontaneously" produced by neutral gas injection (i.e., "gas puffing"). This goal was the conclusion of an analysis that we had presented to the Department of Energy about four years ago and has led to the well known series of heavy pellet injection experiments in Alcator C. In fact, our analysis indicated that the smaller than expected confinement times observed in Alcator C, when compared to those of Alcator A and of its sister machine the Frascati Torus, should be attributed not to a degradation of electron energy confinement, but to an increase of the ion thermal conductivity. The circumstantial evidence of this was that the density profiles that were naturally formed in Alcator C (as a result of neutral gas injection) were flatter than those in other experiments. In particular, the parameter:

$$\eta_i = (d\ell n T_i/dr)/(d\ell n n_i/dr)$$

had values, even in the central part of the plasma column, that were above the threshold for the onset of "ion mixing" modes that can produce a strong effective ion thermal conductivity. Therefore, it was natural to suggest that the "cure" could be found by producing density profiles that were peaked to the extent that η_i would be close to unity and the relevant experiments appear to have confirmed our expectations. The concomitant prediction that the impurity transport had to be influenced by the change in η_i has also been verified by the observations. These circumstances and the need to have a firmer basis, than presently available, on which to base future predictions of ion thermal energy losses in ignition experiments have led us to intensify our interest and that of our colleagues at the Princeton Plasma Physics Laboratory on further development of the linear[1-3] and nonlinear[4] theory of ion mixing modes. Our analysis indicates that ion mixing modes are likely to persist under finite-β regimes and that long wavelength modes will most strongly affect ion energy transport. Work is under way to develop a description of the spatial structure of these modes, by solving the nonlocal linear dispersion relation via analytic and numerical (shooting code) methods.

The Alcator pellet injection experiments have also confirmed the validity of the key assumption on which we based our derivation of the diffusion coefficient of the electron thermal energy. This is that the current density profile and, in the case where the resistivity is classical, the electron temperature profile tend to remain close to a Gaussian.[5,6] Accordingly, observation made by electron cyclotron emission have shown that within a time of the order of 200 μ sec after the central electron temperature has dropped (as a result of the pellet penetration) the electron temperature profile recovers its typical Gaussian shape. This time scale is shorter by about two orders of magnitude than the electron energy transport time scale. Consequently, the observed profiles are not only the results of the microscopic processes (microinstabilities) that control the rate of energy transport, but also of stronger macroscopic constraints that operate on considerably shorter times as implied by the principle of "profile consistency" that we have put forward. We have been strongly encouraged by these experimental observations to continue our effort to construct a set of transport coefficients that, when included in the appropriate transport codes, reproduce the results of present day experiments and offer a basis to predict those of proposed future experiments.

We are involved in a collaborative effort on this problem with both the Princeton and JET (Joint European Torus) teams. In particular, we have undertaken the detailed numerical simulation of the series of TFTR and JET discharges that have been obtained by ohmic heating alone, with the intent to provide an interpretation for the results to be obtained with auxiliary heating.

The experimental discovery of lower hybrid current drive in the Versator II device at first and then, at record high densities, in Alcator C has stimulated a considerable effort on the part of our group directed at building on the expertise gained in identifying and providing a theoretical explanation for the "slide-away"[7] low density regime originally found in Alcator A. We have developed a set of analytical and numerical models and have performed a comprehensive analysis and simulation[6,8] of the available experimental results. Simplified versions of these models have also proven valuable in the interpretation of high power lower hybrid heating experiments on Alcator C.

In regard to outside experimental programs, we are happy to see that the experimental ability to produce stable and well confined plasmas with low values of the safety parameter q_a has continued to be exhibited by the recent operation of large scale devices such as JET. This has confirmed earlier predictions we had made on the basis of the systematic analysis that we have carried out on modes that produce magnetic reconnection in regimes with low collisionality. Another confirmation of our theoretical indications is the observation of partial reconnection in the high temperature regimes attained by TFTR. Therefore, we are undertaking a close collaboration with our Princeton colleagues in order to produce an interpretation of these observations. The problem of magnetic reconnection in plasmas close to ignition has received much attention by our group. In particular, we have undertaken an in depth analysis[9] of the interaction of $m^0 = 1$ modes with energetic particles, such as injected beam ions or fusion products. This has led to a theoretical interpretation of the so-called "fishbone oscillations" which are believed to be the main cause of beta saturation in the nearly perpendicular neutral beam injection in the PDX device. Attention has been devoted also to the effects of ion viscosity on $m^0 = 1$ modes and to magnetic reconnection processes in collisionless regimes.

The appearance of a second stability region, that we first reported in January 1978 when submitting an abstract at the IAEA (Innsbruck) Conference, has been confirmed by numerous subsequent investigations. In addition, our own analytical work has indicated that internal $m^0 = 1$ modes also tend to become stable in the second stability region ($\beta = 8\pi\, nT/B^2$ larger than some critical value that depends on other physical parameters, e.g., shear...). Thus, we have been able to indicate a heating path toward finite-β regimes that preserves the macroscopic stability of the plasma column.[10] The PBX experiment that has been realized at Princeton in fact follows a path very similar to that indicated by our work and therefore is of considerable interest to us. The combination of these results with the pioneering investigations of D-T burning plasmas in compact, high density, experiments, makes it increasingly evident that experiments on the fusion burning conditions of advanced fuels (such as D-He^3 and D-D catalyzed) are no longer to be considered a distant dream, but can be undertaken on the basis of present day technologies. By now, a large community has become aware of the new possibilities in terms of future reactors that these results and ideas have introduced. Therefore, EPRI (Electric Power Research Institute) has commissioned us to write a review paper that is being completed in collaboration with colleagues from Columbia University and Grumman Corporation.

The widespread consensus that has been gathered around the idea of designing and constructing an ignition experiment has given new impetus to the work that we have carried out in this area. In particular, following the favorable conclusions of the Ad hoc Review Panel on Ignitor, set up by the Commission of the European Communities (C.E.C.) and the constructive interaction which we have with the Panel, we have continued the study and the physics simulation of a 10 MA compact device called $(BCX)^2$. It maintains the outer dimensions, the same technologies, and the design solutions adopted for the original Ignitor concept, but has a vertically elongated plasma cross-section with a very low aspect ratio.

The work that we have started on the collective modes that can be excited in spin polarized and fusion burning plasmas has blossomed into a fruitful collaboration with colleagues at Princeton's PPL and at European institutions. In fact, the work performed has been reported in a series of three papers[1,11,12] and includes results that extend beyond its original motivations and are relevant to the problems of ion cyclotron heating and of the anomalous slowing down of fusion reaction products.

As is traditional with our mode of operation, during 1984 we have maintained an effective system of close collaboration with national and overseas institutions, for both our theoretical and experimental programs. Our contributions have been presented at major national and international meetings, including the Tenth International Conference on Plasma Physics and Controlled Nuclear Fusion (London, U.K., 12–19 September 1984), the Sherwood Theory Meeting (Incline Village, NV, 11–13 April 1984), the APS/DPP Annual Meeting (Boston, MA, 29 October–2 November 1984), and the 1984 International Conference of Plasma Physics (Lausanne, Switzerland, 24 June–3 July 1984).

References

1. B. Coppi, S. Cowley, P. Detragiache, R. Kulsrud, F. Pegoraro, and W. Tang, Tenth International Conference on Plasma Physics and Controlled Nuclear Fusion (IAEA-CN-44/E-II-4), to be published by the International Atomic Energy Agency (Vienna, 1985).
2. B. Coppi, R. Englade, and S. Migliuolo, Bull. Am. Phys. Soc. 29, 1409 (1985).
3. Y-K. Pu and S. Migliuolo, Phys. Fluids 28, 1722 (1985).
4. S. Migliuolo, Phys. Fluids 28, in press (1985).
5. B. Coppi, Fiz. Plasmy 11, 83 (1985).
6. W.M. Tang, C.Z. Cheng, J.A. Krommes, W.W. Lee, C.R. Oberman, F.W. Perkins, G. Rewoldt, R. Smith, P. Bonoli, B. Coppi, R. Englade, J. Martinell, and L. Sugiyama, Tenth International Conference on Plasma Physics and Controlled Nuclear Fusion (IAEA-CN-44/E-III-8), to be published by the International Atomic Energy Agency (Vienna, 1985).
7. B. Coppi, F. Pegoraro, R. Pozzoli, and G. Rewoldt, Nuc. Fusion 16, 309 (1976).
8. R. Englade and P.T. Bonoli, Bull. Am. Phys. Soc. 29 1307 (1984).
9. M. Velli, F. Porcelli, and B. Coppi, Bull. Am. Phys. Soc. 29, 1386 (1984).
10. B. Coppi, G.B. Crew, and J.J. Ramos, Comments Plasma Phys. 8, 11 (1983).
11. F. Pegoraro, B. Coppi, S. Cowley, P. Detragiache, R. Kulsrud, and J.J. Ramos, Proceedings of the 1984 International Conference on Plasma Physics, Lausanne, Switzerland, M.Q. Tran and M.L. Sawley (Eds.); published by the Ecole Polytechnique Federale de Lausanne, Vol. 1, p. 68 (1984).
12. B. Coppi, S. Cowley, P. Detragiache, R. Kulsrud, and F. Pegoraro, Comments Plasma Phys. 9, 49 (1985).