23. 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. P.T. Bonoli, Dr. K.-I. Chen, Dr. R.C. Englade, Dr. V. Fuchs[25], Dr. K. Hizanidis, Dr. J.H. Irby, Dr. J.S. Levine, Dr. S.C. Luckhardt, Dr. S. Migliuolo, Dr. A.K. Ram, Dr. J.J. Ramos, Dr. R.E. Shefer, Dr. L.E. Sugiyama, Dr. D.J. Tetreault, E.W. Fitzgerald, I. Mastovsky, 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, D.A. Humphreys, K.D. Jacobs, M. Kanapathipillai, R.D. Kaplan, D.A. Kirkpatrick, B.L. LaBombard, W.P. Marable, J.J. Martinell, M.J. Mayberry, A. Pachtman, Y.-K Pu, C.M. Rappaport, R.R. Rohatgi, S.E. Rowley, D.R. Thayer, J.N.S. Villasenor

23.1 Coherent, Free-Electron Radiation Sources

National Science Foundation (Grant ECS82-13485)
University of Maryland (Subcontract A200728)
U.S. Air Force - Office of Scientific Research (Grant AFOSR-84-0026B)

The possibility of developing lasers and masers in which the active medium is a stream of free electrons has evoked much interest in recent years. The potential advantages are numerous and include continuous frequency tuning through variation of the electron energy, and very high power operation since no damage can occur to this lasing medium as can happen in solid, liquid and gas lasers.

The concept of transforming the kinetic energy of free electrons into coherent electromagnetic radiation is by no means new; as early as 1933 Kapitza and Dirac predicted the possibility of stimulated photon scattering by electrons. Indeed, the klystron, the magnetron and the traveling wave tube conceived and developed in the forties and fifties are examples of such free electron sources capable of generating coherent microwave radiation. In the decameter and centimeter wavelength ranges, these devices can be made to emit at power levels as high as tens of megawatts and with good efficiencies exceeding 80 percent. Today these systems, and variations thereof, have become indispensable instruments of modern science, technology and

---

[25] IREQ-Hydro Quebec, Montreal, Canada

communication.

The new generation free-electron radiation sources being actively pursued at many centers aim to extend the electromagnetic spectrum from the microwave to the millimeter, infrared, visible and ultraviolet regimes with previously unattainable intensities and efficiencies. Potential applications are numerous. They include; spectroscopic studies in condensed matter physics; design of novel accelerators; millimeter and submillimeter radar; heating and current drive in thermonuclear fusion plasmas; and biological and medical research.

The three most prominent free electron radiation sources actively studied during the past several years are (a) cyclotron resonance masers; (b) the free electron laser (FEL); and (c) the relativistic magnetron.

The experimental facilities available to this group include three pulsed high voltage accelerators capable of delivering up to 100 kA of current at 0.5 to 1.5 MV. Their characteristics are summarized below:

Pulserad 110 A	
Voltage	2.0 MV
Current	20 kA
Pulse Length	30 ns
Pulserad 615 MR	
Voltage	0.5 MV
Current	4 kA
Pulse Length	1 μs
Nereus	
Voltage	0.6 MV
Current	100 kA
Pulse Length	30 ns

During the past year our major efforts and successes concerned the amplification and the wave refractive measurements index in our Raman free electron laser. The collective (Raman) free electron laser (FEL) produces coherent radiation by subjecting a cold intense electron beam to a transverse, periodic "wiggler" magnetic field that induces transverse oscillations on the electron beam. The undulating electron beam interacts with an incident electromagnetic wave to produce an axially directed ponderomotive force.[1,2] This force causes axial bunching of the undulating electron beam, thereby driving the incident electromagnetic wave. The energy for the radiation comes at the expense of the beam kinetic energy.

In a previous study[3,4] we focused our attention on the frequency characteristics of the emitted radiation, and the effects of the electron dynamics on the emission properties. We demonstrated continuous FEL tuning with beam energy from 7–12 GHz, observed output powers in excess of 1 MW, and found that as much as 12% of the electron beam energy can be converted into coherent electromagnetic radiation in a single (TE_{11}) waveguide mode. Reference 4 also contains an extensive listing of experimental work in other laboratories.

During the past year we studied two other major aspects of free electron lasers. One is wave amplification (proportional to the imaginary part of the FEL dispersion characteristics) which we have studied as a function of various parameters including frequency, the strength of the wiggler magnetic field, the strength of the guide magnetic field, electron beam current, energy and temperature, and axial distance within the interaction region.

The other aspect concerns the phase shifts and wave refractive index associated with the FEL dispersion characteristic. The behavior of the real part of the dispersion relation is critical to the theoretically predicted phenomena of optical guiding,[5] in which the electromagnetic radiation energy is guided by the electron beam in a fashion similar to light being guided on an optical fiber. Optical guiding is thought to be necessary in future high frequency FELs to extend the interaction length beyond the Rayleigh range. Our measurements provide the first experimental measurement of FEL induced shifts in the real part of the dispersion relation, (albeit in a frequency range far different from that of interest to optical guiding).

References

1. N.M. Kroll and W.A. McMullin, Phys. Rev. A. 17, 300 (1978).
2. P. Sprangle, R.A. Smith, and V.L. Granastein, in K.J. Button (Ed.), Infrared and Millimeter Waves, Vol. 1, (Academic Press, New York 1979), p. 279.
3. J. Fajans, G. Bekefi, Y.Z. Yin, and B. Lax, Phys. Rev. Lett. 53, 246 (1984).
4. J. Fajans, G. Bekefi, Y.Z. Yin, and B. Lax, Phys. Fluids 26, 1995 (1985).
5. E.T. Scharleman, A.M. Sessler, and J.S. Wurtele, Phys. Rev. Lett. 54, 1925 (1985).

23.2 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 purpose of the Versator II tokamak research program is (a) to study the physics of wave penetration of lower-hybrid waves in a tokamak; (b) to study the physics of RF current drive and electron heating at different frequencies, and to determine the efficiency of current generation; (c) to study the physics and feasibility of RF startup in the absence of OH power; (d) to improve upon the design of technology of RF couplers so that they may be more suitable to reactor applications; (e) to carry out electron cyclotron heating (ECRH) experiments, both alone, and in combination with lower-hybrid current drive (LHCD) experiments; (f) to carry out fast wave LHCD experiments to determine the coupling and absorption of such waves.

23.2.1 2.45 GHz S-band Current Drive

We have demonstrated that the plasma current can be driven by RF at higher density ($\overline{Ne} > 1 \times 10^{13} cm^{-3}$) when the RF source frequency is raised from 800 MHz to 2.45 GHz.[1] At this higher density regime, $Wpe^2 / Wce^2 > 1$, hence, the accessibility condition for 2.45 GHz LH waves is more stringent as compared to the 800 MHz experiment. Even with more stringent accessibility conditions, current can be driven by the 2.45 GHz RF source. Thus, we have concluded that the 800 MHz density limit is not due to the inaccessibility of low $-N_{||}$ waves to the plasma core.

With the maximum available RF power of 100 RW from the 2.45 GHz system; fully RF-driven discharges can be only obtained in the low density regime $\overline{Ne} \sim (0.2 - 1.0) \times 10^{13} cm^{-3}$. The current drive efficiency, N, is found to be a constant, $N = \overline{Ne}(10^{20} m^{-3})\, I_p(kA) R(m) / P_{RF}(kW) = 0.0072$. The typical $\overline{Ne}^{-1}$ dependence of I / P_{RF} fits our data well.

We have also compared our current drive experimental results with the Fisch/Karney theory[2] which predicts the efficiency of converting RF energy into poloidal field energy with the presence of a DC electric field. With a wide range of parameters, the agreement between theory and experiment is quite good.[3]

Significant density increases (($\Delta \overline{Ne}$ ($\overline{Ne}$)max ~ 1)) have been observed during 2.45 GHz LHCD experiments when $\overline{Ne} < 2 \times 10^{13} cm^{-3}$. A particle confinement study for the 2.45 GHz experiment has been carried out, just as we did earlier for the EVO MHz experiment.[4] The particle confinement time is increased by a factor of ~ 2.2 during RF injection, which is comparable to the improvement observed in the EVO MHz experiment.

23.2.2 GOV MHz LHCD experiment

We have obtained profiles to study electron energy confinement during current drive. The electron density profile is found to be more peaked, and the central electron temperature drops by a factor of three during the RF phase of the discharge. However, the total input powers for both RF and ohmic cases are comparable (~ GO - 90 kW). Thus, the global electron energy confinement during RF decreases from the ohmic levels. One caution should be taken here, namely that on the above analysis we have assumed the confinement time of the energetic tail electrons is much longer than the energy equilibrium time between high energy electrons and bulk electrons. It is possible that that is not the case on Versator. Therefore, the present results can not be interpreted as a consequence of deterioration of the bulk confinement; rather, these results indicate the need for a careful study of the confinement of energetic tail electrons.

23.2.3 2mm Scattering

The 2 mm scattering experiment was carried out for the purpose of studying the propagation of lower hybrid waves during 800 MHz LHCD experiments. Measurements are specified by the position of the normal center of the scattering volume and parallel refractive index, $N_{||}$, of lower hybrid waves. Radial scans in the current drive density regime ($\overline{Ne} \sim 4.5 \times 10^{12} cm^{-2}$) were made with scattering volumes centered on the horizontal modplane and $N_{||}$ fixed. Power density was generally found to decrease towards the center of the plasma, with measurable power (10 dB above noise level) reaching the center. A peak in power was observed near the plasma edge for $N_{||} = 3$. This is believed to be due to the presence of a resonance cone at r/a = 0.65.

$N_{||}$ scans were made both above and below the lower hybrid current drive density limit. The fit of the measured $N_{||}$ spectrum with the computed launched spectrum[5,6] is fairly good.

Evidence of wave absorption by the plasma has been found. This was done by comparison between the +90° and -90° phasing of the 4-waveguide antenna. The two phasings launch identical wave spectra in opposite toroidal directions. Assuming that the power distribution becomes smeared out and is toroidally symmetric when it reaches the plasma center, scattered power measured there should be the same for both phasings. Differences may be attributed to absorption by the plasma and 10V violation of the above assumption. Experimentally, the -90° phasing has consistently higher measured power. This is interpreted as evidence that the absorption of lower-hybrid waves when the phasing is +90° .

23.2.4 800 MHz Fast Waves Current Drive Experiment

Recent experimental successes with slow wave current drive in the lower hybrid regime of frequencies have made non-conductive current drive an attractive approach to supplement and 10v replace ohmic currents in tokamak. However, the theoretical efficiency for slow waves in present experiments is limited to $N = N_{14} \, I_{mA} \, Rm \, / \, P_{MW} \approx 0.1$, and on reactor grade plasmas it will be limited to $N \leq 0.5$. Improved current drive efficiency near the plasma center may be possible by launching a travelling fast lower-hybrid wave. Such a wave can penetrate the plasma and resonate with nearly relativistic electrons if the index of refraction is only slightly in excess of unity. The result is a current drive scenario with efficiencies in the range $1.0 \leq N < 2.0$.

A fast wave coupler is presently under development, we should commence our experiment by the end of 1986.

23.2.5 Combined Electron Cyclotron Heating (ECRH) and Lower Hybrid Drive Experiment

A 35 Ghz, 150 kw NRL gyratron will be used to launch x-mode radiation from the high field side for ECRH experiments. The purpose of this experiment is the following: (a) to start up the tokamak discharge without use of an ohmic heating transformer; (b) to increase the current drive efficiency of LHCD by raising the perpendicular temperature of the P electron tail through ECRH; (c) to drive a plasma current locally near the edge of the plasma; (d) to stabilize anistropy driven instability during steady state LHCD. Hardware construction is under way. The experiment will begin in late 1986.

References

1. M.J. Mayberry *et al.*, Phys. Rev. Lett. 55, 829 (1985).
2. N.J. Fisch and C.F.F. Karney, Phys. Rev. Lett. 54, 897 (1985).
3. M.J. Mayberry, Ph.D. Thesis, Department of Physics, M.I.T., 1986.
4. S. Luckhardt *et al.*, Phys. Rev. Lett., to be published.
5. R. Rohatgi, Ph.D. Thesis, Department of Physics, M.I.T., 1986.
6. P. Bonoli and E. Ott, Phys. Fluids 25, 359 (1982).

23.3 Plasma Wave Interactions — RF Heating and Current Generation

National Science Foundation (Grant ECS82-13430)

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

Abraham Bers, R. Alan Cairns[26], Vladimir Fuchs[27], Kyriakos Hizanidis, Abhay Ram, Gregory Francis, Leo Harten

Progress in the analytical and computational work carried out during the past year is presented in four subsections. Subsection 1 describes continuing work on intrinsic stochasticity in plasma dynamics. Studies relevant to current generation in a plasma driven by externally excited wave fields are given in subsection 2. Work on wave propagation problems in plasmas in an inhomogeneous magnetic field are summarized in subsection 3; these are particularly oriented to describing mode-conversion near ion-cyclotron absorption and heating. Finally, work on our continuing interest in basic understanding of plasma instabilities is given in subsection 4.

23.3.1 Induced Stochasticity by Coherent Waves

a. Trapped-Electron Stochasticity Induced by Frequency-Modulated Waves

A detailed analytical and numerical study has been carried out for the one-dimensional motion of electrons in a static confining well and perturbed by an electrostatic frequency modulated (fm) wave.[1,2] The normalized equation of motion is:

$$\frac{d^2 z}{dt^2} = -\sin(z) - \epsilon \sin\left(kz - \omega t - \frac{\Delta\omega}{\omega_m}\sin(\omega_m t)\right)$$

where distances have been normalized to the width of the confining well and time to the bounce frequency at the bottom of the confining well; $\Delta\omega$ is the bandwidth of the fm wave with amplitude ϵ and modulation frequency ω_m. For a fm wave with frequency close to (or slightly less than) the bounce frequency of the electrons near the bottom of the static well (in terms of the normalized quantities this implies $\omega \lesssim 1$) and its phase-velocity greater than the maximum velocity of the confined electrons (i.e., $\omega / k > 2$), 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. The second stochastic region lies inside the static well and has shown interesting and, at times, not fully understood features. The analytical work has been carried out in action-angle space (the natural coordinates

[26] Visiting Scientist, University of St. Andrews, Scotland

[27] Visiting Scientist, IREQ, Québec, Canada

for this problem) of the Hamiltonian describing the equation of motion and follows the usual approach of the Chirikov resonance overlap criterion. This has been checked against the numerical results obtained from an exact analysis of the equation of motion. The analytical calculations explain all results related to the onset of stochasticity. For instance, it can be shown that the threshold for the onset of stochasticity scales like: $\varepsilon_{TH} \propto \omega_m^{5/3}$. This is in complete agreement with the exact numerical results. The analysis shows that a significant region of phase-space for the trapped electrons can be made stochastic by fm waves with small amplitudes by an appropriate choice of the modulational frequency. The width of the stochastic region is determined by the bandwidth of the fm wave and is independent of its wavelength provided that it exceeds twice the dimensions of the static well. The analysis indicates that fm waves may be very useful for providing plugging for the central cell in a tandem mirror plasma by enhancing the electrostatic potential in the plugs.

Once there is a region of connected stochasticity, an analytical expression for the quasilinear diffusion coefficient for the electrons in that region can be derived. This can be done by using either the Vlasov theory for the electron distribution function or using the two-point correlation function for the time rate of change of the action. The two approaches give the same diffusion coefficient:

$$D^{QL} = \frac{1}{\Delta I}\frac{\pi\epsilon^2}{2k^2}\sum_{\ell,n}|n|J_\ell^2\left(\frac{\Delta\omega}{\omega_m}\right)\frac{V_n^2(k,I_{\ell n})}{|d\Omega/dI|_{\ell n}}$$

where ΔI is the width in action space (I-space) of the stochastic region and the sum is over those integers ℓ and n such that $I_{\ell n}$ is in the stochastic region; Ω is the nonlinear frequency of the electron with action $I_{\ell n}$ [i.e., $n\Omega(I_{\ell n}) = \omega - \ell\omega_m$], J_ℓ is the Bessel function of order ℓ and $V_n(k,I)$ is the Fourier coefficient of the fm wave in the action-angle representation. For amplitudes ε such that: $\varepsilon_{TH} \lesssim \varepsilon \lesssim 10^2\,\varepsilon_{TH}$($\varepsilon_{TH}$ is the threshold amplitude for onset of stochasticity) the numerically observed diffusion, D^{NUM}, is very close to D^{QL}. For higher amplitude D^{NUM} saturates and stops increasing as a function of ε – in contradiction with the behavior of D^{QL}.[2] This scaling of diffusion is not yet clearly understood.

23.3.2 Lower Hybrid Current Drive

Three major studies have been completed:

a. Analytic Models for LH Current Drive Including Perpendicular Dynamics

We have achieved a relatively complete analytic model based upon nonrelativistic equations.[3] The 2-D (velocity space) Fokker-Planck equation for lower-hybrid current drive was approximated by its perpendicular moments hierarchy closed in the second moment equation.

The closure was derived on the basis of a distribution function composed of a central thermal Maxwellian plus a perpendicularly broadened distribution of fast particles that are diffused into, and pitch-angle scattered out of, the quasilinear plateau region. The resulting 2-D model reproduced the relevant features of the solutions obtained from numerically integrating the 2-D Fokker-Planck equation. An analytic estimate of the perpendicular temperature on the plateau and the plateau height as a function of spectrum width and position ($v_1 < v_{\|} < v_2$) was obtained. The plateau perpendicular temperature (normalized to the bulk temperature T_e) was found to be given by

$$T_p = \frac{v_1^{2-\alpha_i}}{2(v_2 - v_1)} \left(\frac{v_2^{\alpha_i+1} - v_1^{\alpha_i+1}}{\alpha_i + 1} + v_{\perp 0}^2 \frac{v_2^{\alpha_i+1} - v_1^{\alpha_i+1}}{\alpha_i - 1} \right) - \frac{v_1^2}{2} , \qquad (23.1)$$

where $\alpha_i = (2 + 2Z_i)/(2 + Z_i)$, velocities are normalized to $v_{Te} = (\kappa T_e / m_e)^{1/2}$, and $v_{\perp 0}^2 \approx T_p/2$ is the spread in $v_\perp$ near $v_{\|} = v_1$. The plateau height, giving the current, was then determined from the closed set of moment equations. It is given approximately by

$$F_p \simeq \frac{F_M(v_1)}{1 - \exp(-\alpha_p v_1^2/2)} , \qquad (23.2)$$

where $\alpha_p = (Z_i + 2)/(Z_i + 1)T_p + 1$. Finally, the figure of merit is given by:

$$\frac{j}{p} \approx \frac{v_2^2 - v_1^2}{\left[\frac{3}{2}(Z_i + 1) + 1\right] \ell n V_3 - \left(\frac{Z_i+1}{2}\right) \ell n V_1} \qquad (23.3)$$

where

$$V_m = \frac{v_2^2 + mT_p}{v_1^2 + mT_p} . \qquad (23.4)$$

Here $j = J/(-env_{Te})$ and $p = p_d / nm_e v_{Te}^2 \nu_0$, where $\nu_0 = 4\pi(e^2/4\pi\varepsilon_0) n \ell n \Lambda / m_e^2 v_{Te}^3$, J is the currrent density generated, p_d is the required power density dissipated, and n is bulk electron density. Table I shows a comparison of results as obtained from the Fisch 1-D theory, the present 2-D theory, and the numerically integrated 2-D Fokker-Planck equations, for six different cases of applied spectra spanning $v_1 < (\omega / k_{\|}) < v_2$ and plasma ions with charge numbers Z_i.

		1-D Theory				2-D Theory				2-D Numerical			
v_1,v_2	Z_i	T_p	F_p	j	j/p	T_p	F_p	j	j/p	T_p	F_p	j	j/p
4,8	1	1	1.3	0.3	11	10	1.9	0.6	27	9	2.4	0.7	29
4,12	1	1	1.3	0.9	20	19	2.7	1.8	45	17	3.0	2.3	53
4,16	1	1	1.3	1.6	29	29	3.7	4.4	76	26	3.5	4.8	77
4,16	4	1	1.3	1.6	15	47	6.6	8.0	58	43	5.5	7.3	55
4,16	9	1	1.3	1.6	8	60	8.5	10	38	53	7.5	9.2	34
4,20	1	1	1.3	2.6	40	38	4.5	8.5	104	33	4.5	10	108

Table 1

Note: F_p is in units of 10^4, j is in units of 10^2.

It is clear that the 1-D theory, which ignores the perpendicular dynamics, does not predict well any of the 2-D numerical results. In contrast, our 2-D theory results are very close to those obtained from numerically integrating the 2-D Fokker-Planck equations. The perpendicular dynamics, as exhibited by the large perpendicular temperature, are thus shown to give a higher current density and larger figure of merit compared to the predictions of the 1-D theory model.

Further insight into the perpendicular dynamics in LH current drive was obtained from an analysis based upon detailed balance conditions.[4]

Finally, in order to explore the possibilities of still higher efficiencies in LH current drive with the fast wave, we have initiated a relativistic analysis of such current drive. As a first step, we have obtained an analytic model for the perpendicular temperature enhancement in the relativistic regime.[5]

b. Anomalous Doppler Instability in LH Current Drive

Under current drive conditions the creation of a flat plateau in the electron distribution function can lead to destabilizing electrostatic waves and thus to undesirable enhanced transport in the plasma.

We have studied the anomalous Doppler instability (ADI) for two-dimensional, non-relativistic velocity distributions $f(v_{\parallel}, v_{\perp})$ that are generated by an applied RF spectrum for lower-hybrid current drive. In this case, in contrast to the runaway electron problem, electrostatic waves become unstable at high plasma densities, i.e., when the ratio $\omega_{pe}^2/\omega_{ce}^2$ is sufficiently large. Increasing the maximum velocity v_2 of the rf plateau, $v_1 \leq v_{\parallel} \leq v_2$ is also a destabilizing influence.[6]

We have determined expressions for the growth rate of the electrostatic waves obeying the dispersion relation $\omega = \omega_{pe}(1 + \omega_{pe}^2/\omega_{ce}^2)^{-1/2} k_{\|}/k$ employing both analytical expressions for $f(v_{\|}, v_{\perp})$ and numerical solutions for f from the non-relativistic 2-D Fokker-Planck equation.[6] The analytical and numerical results are in close agreement. Furthermore, a relativistically correct necessary condition for instability is found; namely, $\omega_{pe}^2/\omega_{ce}^2 > \left[\gamma_2^2(v_2/v_1 - 1)^2 - 1\right]^{-1} > 0$ where $\gamma_2 = (1 - v_2^2/c^2)^{-1/2}$.

For high-temperature plasmas and current drive with the fast wave in the LH frequency regime, stability calculations based upon a relativistically correct distribution function need to be carried out.

To fully assess the effect of the ADI upon current drive we also need to develop a quasilinear theory for $f(v_{\|}, v_{\perp})$ in the presence of both the applied RF spectrum and the unstable fields.

c. LH Current Drive in the Presence of an Ohmic Electric Field

Two-dimensional Fokker-Planck studies have been carried out for the separate as well as combined effects of lower-hybrid (rf) quasilinear diffusion (D_{QL}) and of an ohmic field (E) on plasma current.[7,8,9] The principal effect is an E-dependent rf conductivity, valid when the lower bound of the rf spectrum lies below the critical velocity for electron runaway. The calculations span the region of $\varepsilon = E/E_c$ from 0.005 to 0.04, and of $D_{QL}/v_c^2\nu_0 > 1$, relevant to present day current drive experiments. The standard linearized collision operator appropriate for fast electrons was employed so that the total electron momentum was not conserved, but we compensated for this by adjusting the bulk current.

The effect of combined rf and ohmic fields can be summed up as follows. Given an rf spectrum within the range $v_1 \leq v_{\|} \leq v_2$, assume that the critical velocity for runaway $v_c = \varepsilon^{-1/2}$ is larger than v_1 (if this condition is violated, then the rf contribution is unimportant and the distribution function is dominated by runaways). We then identify the following principal effects:

i. The high perpendicular temperatures observed in the rf and runaway regimes were explained and estimated on the basis of the test electron relaxation equations. The variation of the perpendicular temperature is found to be given by[9]

$$T_{\perp}(v_{\|}) = \frac{F_M(v_{\|}) + F_p T_p}{F_M(v_{\|}) + F_p} \quad \text{for} \quad v_{\|} \lesssim v_1 \tag{23.5}$$

where F_p and T_p are the flat plateau distribution and temperature, respectively, and F_M is the (bulk) Maxwellian. This is as in the case of rf current drive in the absence of an electric field. For $v_i < v_c < v_2$ we have

$$T_\perp = T_p + \frac{\ln(v_\| \epsilon^{1/2})}{\epsilon} \quad \text{for} \quad v_\| < v_2$$

where the logarithmic dependence is characteristic of runaways. However, when $v_c \geq v_2$ we find approximately

$$t_\perp = \begin{cases} T_p & \text{for} \quad v_\| < v_c \\ T_p + \frac{\ln(v_\| \epsilon^{1/2})}{\epsilon} & \text{for} \quad v_\| < v_c \end{cases}$$

ii. There is an E–field–induced bulk effect on the rf plateau distribution represented by $F_p \sim g(\epsilon)$

$$g(\epsilon) = \exp\left[\epsilon \int_0^{v_1} \frac{x^3\, dx}{U(x)}\right] \quad , \qquad U = AT_\perp + B \tag{23.6}$$

where $A \approx 1 + Z_i$ and $B \approx 1$.

iii. There is an rf–enhanced runaway. When $v_1 < v_c < v_2$, the resonant electrons are directly fed into the runaway tail whose height therefore approximately equals F_p. Consequently, the plasma current J and the runaway rate Γ are given by

$$\frac{J}{-env_e} \simeq 7.43\epsilon + \frac{1}{2}\left(v_{\max}^2 - v_1^2\right) F_p \tag{23.7}$$

$$\frac{\Gamma}{n\nu_0} \simeq \epsilon F_p \; . \tag{23.8}$$

iv. Finally, on the basis of Eq. (23–7) we may define an rf conductivity, σ_{rf}, in terms of the Spitzer–Härm value plus an rf and runaway–supported contribution,

$$\sigma_{rf} = \sigma_{SH} + \frac{1}{2}\frac{ne^2}{m\nu_o v_e^2}\left(v_{\max}^2 - v_1^2\right) F_p^{(\epsilon=0)} \frac{dg}{d\epsilon} \; , \tag{23.9}$$

where v_{max} is the value of $v_\|$ at which the high–energy tail is cut off by some process, and g is the function (23.6).

23.3.3 Wave Propagation, Mode–Conversion, and Absorption

a. Minority Absorption in Ion Cyclotron Heating

We have undertaken an anlytical study of the minority cyclotron heating in an inhomogeneous plasma consisting of a deuterium majority and a hydrogen minority. Numerical studies[10] have included the effects of minority cyclotron heating in their treatment of energy absorption and mode-conversion near the ion-ion hybrid resonance layer. Previous analytical studies,[11] however, have neglected minority absorption and treated only the mode conversion process. With thermal effects included, the absorption at the minority cyclotron resonance can be understood on the basis of non-resonant coupling of the incoming fast wave to an absorption layer at the minority resonance. To calculate the absorption we generalize the coupling theory of Cairns and Lashmore-Davies[12] for the case of non-resonant coupling such that the perturbed current density in the plasma due to temperature effects is driven by the dynamically-shielded electric field. The result of the dynamic shielding is a small but important shift in the location of the absorptive layer from the position of the minority cyclotron resonance layer. The polarization of the electric field at this shifted location is then such that ion cyclotron absorption occurs for the minority species. If dynamic shielding is neglected,[12] the ion cyclotron absorption vanishes. The transmission coefficient has been calculated for the isolated minority cyclotron resonance in the limit of propagation perpendicular to the magnetic field. In the limit of a pure deuterium plasma, our transmission coefficient agrees with the Budden coefficient for second harmonic cyclotron heating.

b. Electron Heating by ICRF Waves in Tokamak Plasmas

The fast-wave component of the ICRF wave undergoes mode-conversion to the ion-Bernstein wave (IBW) at the point where the frequency of the wave is $2\omega_{ci}$ (ω_{ci} is the ion-cyclotron frequency). The perpendicular (to the magnetic field, $\vec{B}_0$) wavenumber ($k_\perp$) for this mode-converted branch increases rapidly as a function of distance away from the point of mode conversion. A ray trajectory analysis of this IBW has been carried out in toroidal geometry with sheared magnetic field[13] for a hot-plasma dispersion relation that assumes that the parallel component of the electric field is very small. As a consequence of the shear, it is found that the wavenumber of the IBW parallel to $\vec{B}_0$($k_\parallel$) increases dramatically with distance as the IBW ray propagates in the plasma. For typical Alcator-C type tokamak parameters a change in $k_\parallel$ given by $\Delta(ck_\parallel/\omega)\approx 5$ (c is the speed of light and ω is the frequency of the wave) occurs with the rays having travelled a fraction of a centimeter radially. This could help explain the strong electron heating that is observed in recent ICRF heating experiments on the JET tokamak.[14] Further investigation into this problem is in progress.

c. Propagation and Absorption Along an Inhomogeneous Magnetic Field

The slow mode of the ion-cyclotron rf (ICRF) wave in a mirror plasma propagates along a spatially inhomogeneous magnetic field. (For instance, in the central cell of the M.I.T. Tara tandem mirror machine, the wave initially propagates down a magnetic hill before reaching ion-cyclotron resonance).[15] Analytical solutions for the case of a cylindrical plasma of uniform density with an axially varying magnetic field have been formulated. In the case where the variation of the magnetic field is slow compared to the axial-wavelength of the wave, WKB techniques of solving the equations for wave propagation should apply. Such solutions have been derived which are being checked for consistency by requiring that the power flow be conserved.

There is also a study in progress looking at the case where there is a step-function change in the axial magnetic field. This would correspond to a case where the axial wavelength of the wave is much larger than the magnetic field gradient. The comparison of this case with that of the WKB situation will be made to see which one better explains the experiments on Tara.

23.3.4 Plasma Instability Studies

a. Space-Time Evolution of Two-Steam Instabilities

This work has been completed and a journal publication on it has appeared.[16]

b. Small-Amplitude Energy Dynamics in the Weibel Instability

We have studied the instantaneous small-amplitude energy conservation in the electromagnetic Weibel instability[17] driven by relativistic counter-streaming electrons in a cold, homogeneous plasma. The electromagnetic modes due to a single electron beam have positive definite small-amplitude energy density, so that we may not view the Weibel instability as the coupling of positive and negative energy waves. The usual high-frequency techniques of time-averaged energy conservation are not applicable as the Weibel instability is a zero frequency mode. The MHD techniques are not useful as the instability depends on the interaction of two electron beams. We therefore derive an equation for the conservation of instantaneous small-amplitude energy density.[18] From such a conservation equation we show that for the total counter-streaming system (i.e., both beams) the growing normal mode energy associated with the particles is indeed negative; the energy in the fields is of course positive. Thus, since the total energy is conserved, energy transfers from the particles to the fields as the mode grows.

References

1. A.K. Ram, K. Hizanidis, and A. Bers, Bull. Am. Phys. Soc. 30, 1369 (1985).
2. A.K. Ram, K. Hizanidis, and A. Bers, Phys. Rev. Lett. 56, 147 (1986).
3. V. Fuchs, R.A. Cairns, M.M. Shoucri, K. Hizanidis, and A. Bers, Phys. Fluids 28, 3619 (1985).
4. K. Hizanidis, Phys. Lett. A 109A, 325 (1985).
5. K. Hizanidis, A. Bers, V. Fuchs, and R.A. Cairns, Phys. Fluids 29, 1331 (1986).
6. S.C. Luckhardt, A. Bers, V. Fuchs, and M.M. Shoucri, Bull. Am. Phys. Soc. 30, 1634 (1985);

also M.I.T. Report PFC/JA-86-18, March 1986.

7. V. Fuchs, M.M. Shoucri, A. Bers, and R.A. Cairns, Annual Controlled Fusion Theory Conference, Madison, Wisconsin, April 15-17, 1985.
8. M.M. Shoucri, V. Fuchs, A. Bers, and R.A. Cairns, Bull. Am. Phys. Soc. 30, October 1985, p. 1621.
9. V. Fuchs, M.M. Shoucri, A. Bers, and R.A. Cairns, "Lower Hybrid Current Drive in the Presence of an Ohmic Electric Field," M.I.T. Report PFC/JA-86-14, March 1986.
10. P.L. Colestock and R.J. Kashuba, Nucl. Fusion 23, 763 (1983).
11. D.G. Swanson, Phys. Rev. Lett. 36, 316 (1976).
12. R.A. Cairns and C.N. Lashmore-Davies, Culham Report CLM-P740.
13. A. Ram, K. Hizanidis, and A. Bers, Bull. Am. Phys. Soc. 30, 1634 (1985).
14. J. Jacquinot *et al.*, Proc. 12th European Conf. of the European Physical Society Plasma Physics Division, Plasma Physics and Controlled Fusion 28, No. 1A (1986).
15. R. Myer, S. Golovato, A. Ram, D.K. Smith, and A. Bers, Bull. Am. Phys. Soc. 30, 1488 (1985).
16. G. Francis, A.K. Ram, and A. Bers, "Finite Temperature Effects on the Space-Time Evolution of Two-Stream Instabilities," Phys. Fluids 29, 255 (1986).
17. A. Bers and G. Francis, Bull. Am. Phys. Soc. 30, October 1985, p. 1563.
18. A. Bers and P. Penfield, IRE Trans. on Electron Devices, ED-9, 12 (1962).

23.4 Physics of Thermonuclear Plasmas

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

The main theme of this program is the theoretical study of plasmas in thermonuclear regimes. Topics include, but are not limited to, study of basic plasma properties (stability, transport,...), simulation of present day and future experiments on magnetically confined plasmas, and design of machines for fusion burn experiments and advanced fuels. Theoretical guidance for and participation in the Alcator experiment program are an important part of our effort.

We are particularly interested in the physics of high density plasmas that has been pioneered by the Alcator program in view of its outstanding confinement as demonstrated by the record values of the parameter, $n\tau_E$, and of the degree of plasma purity $1/(Z_{eff}-1)$ achieved.

The line of compact ignition experiments that we have proposed first in 1975, as a follow up to the Alcator and the Frascati Torus programs, and developed through a series of design studies in later years, was adopted as the major next undertaking of the U.S. fusion program in 1985. In addition, following the agreements to pursue collaboration in fusion research concluded at the Geneva summit meeting, a compact ignition experiment has been considered as the first step to be undertaken in a more general frame for the development of fusion research through the end of this century. Meanwhile the Ignitor effort that was initiated in Europe about 10 years ago has been stepped up and a set of tests on the most critical machine component is being planned.

Among the general criteria that we have tried to formulate a few years ago in order to describe the "anomalous" transport characteristics (that are not explained by classical transport theories that include the effects of discrete particle collisions only) of magnetically confined plasmas is the so-called "Principle of Profile Consistency." This predicts, in particular, that no local transport coefficient could be defined that would be independent of the spatial distribution of the thermal energy source. A relatively wide variety of experiments involving different forms of injected heating and different spatial distributions of the rate of thermal energy deposition have confirmed the predictions of this principle. Therefore the interested theoretical community is engaged in an intensive effort to expand the basis of this principle and of its implications.

Another activity that we have pioneered is the investigation, by a set of appropriate transport codes, of evolution of magnetically confined plasma toward ignition conditions. This has enabled us to identify several processes that are important in order to achieve these conditions. Because of the national and international interest in compact ignition experiments, by now we have acquired a relatively large number of competitors and coworkers. However, we have continued with our activities in this field. A notable achievement has been the first numerical simulation of the series of advanced confinement experiments performed by the large TFTR machine at

Princeton.[1]

In this connection we may mention that the Princeton team has reproduced on this machine the same type of high plasma density regimes attained on Alcator C with record values of $n\tau_E$, thus confirming the validity of our line of research and interpretation. One of the consequences of these is that the near term feasibility of experiments with advanced fusion fuels (D–D and D-He^3) that we had proposed a few years ago and that require well-confined high density plasmas has acquired a stronger experimental foundation.

We have continued our analytic and numerical analysis of the ion mixing mode. This instability, due to the temperature gradient of the ions, was proposed by us as the factor responsible for the observed enhanced levels of plasma thermal conductivity and for the degraded confinement in Alcator C until the appropriate step was taken to generate the conditions (peak density profiles produced by the injection of pellets) under which the relevant mode is stable. This mode may play a role in determining the feasibility of high temperature ignition experiments. In particular, we have proposed[2] an expression for the amplitude of the saturated instability in the nonlinear regime. This amplitude has been shown, numerically, to account reasonably well for the experimental conductivity profiles. These profiles were obtained[3] with improved diagnostic techniques from collisionless, beam heated discharges. The crucial parameter is given, from linear stability theory, by $\eta_i = (d\ell n\ T_i / dr)/(d\ \ell n\ n_i / dr)$. Thus it is of importance to determine the critical values of this parameter, for instability, as precisely as possible. A study has begun with this objective, that improves past slab geometry calculations[4] and includes toroidal effects such as curvature and gradient-B drifts. The more precise values of $\eta_i)_{crit}$ will then be used within 1-D transport codes to simulate and predict experimental situations.

Macroscopic instabilities, as well as microscopic ones like the ion mixing mode, play an important role in plasma confinement. In particular, our group has long been active in the theoretical description of $m = 1$ modes, in the ideal and resistive (i.e., reconnecting) regimes. A study of resistive internal kink ($m = 1$) modes, including the effects of finite electron drift wave frequency and finite ion Larmor radius, has recently shown[5] that moderate values of ion viscosity are sufficient to stabilize the resistive kink in high temperature regimes where $\omega_{di}/\tau_\eta^{1/3}\omega_A^{4/3} > 1$. Here, $\omega_{di}(\propto T_i)$ is the ion diamagnetic frequency, ω_A is the characteristic Alfvén frequency (computed with the poloidal component of the magnetic field) $\tau_\eta(\propto T_e^{3/2})$ is the resistive diffusion time. The ion viscosity is measured by $\hat{D} = \tau_\eta / \tau_\mu = (3/10)\ (T_e m_i / T_i m_e)^{1/2} \beta_e$, where τ_μ is the characteristic time for collisional transport of ion transverse momentum. Typically, $\hat{D} = 0.18$, in a $\beta_e = 1\%$ deuterium plasma with $T_e = T_i$. Our analysis,[5] which is analytic as well as numerical, shows that in general stabilization occurs when $\hat{D} > \tau_\eta\ \omega_A^4 / \omega_{di}^3$, a condition that can be satisfied under current tokamak regimes. This work will be extended in the coming year, to cover the linear stability of $m = 1$ modes in the tearing regimes and in regimes where the validity of the collisional fluid model (i.e., Braginskii's) is violated.

The interaction of m = 1 modes with energetic particles, such as injected beam ions, is now believed to be responsible for the so-called "fishbone oscillations." This phenomenon is likely to be the main cause of beta saturation in the PDX device[6] when neutral beam heating is employed. Loss of energetic beam particles is correlated with fishbone events, reducing the beam heating efficiency and thus limiting the achievable beta. An m = 1 mode with phase velocity equal to the core-ion diamagnetic velocity[7] can resonantly interact with trapped beam ions that precess around the torus at the magnetic curvature drift frequency. This resonant interaction is viewed as an effective collisionless viscosity that allows the release of the mode excitation energy. A hitherto strongly stable ideal MHD m = 1 mode is brought[7,8] near marginal stability by finite ω_{di}(d $\propto p_i$ / dr) where the resonant wave-particle interaction is able to destabilize it. This happens when the gradient in plasma pressure becomes significant, specifically when the plasma poloidal beta exceeds the threshold value above which unstable ideal MHD activity can be expected.[9] Of the two unstable m = 1 modes, the faster growing one manifests itself as the fishbone, superimposed on the slower growing ideal MHD m = 1 sawtooth.

In 1985, we have completed the final stages of the development of a realistic analytical and numerical model for the interaction of lower hybrid waves with suprathermal electrons in toroidal devices. This work includes the effect of the wave-particle interaction on the bulk plasma. This model has been proved quite useful in the analysis and interpretation of experiments (e.g., Versator, Alcator C, PLT) involving steady-state current generation,[10] current ramp-up,[11] and plasma heating.

We have also analyzed a class of collective modes in inhomogeneous toroidal plasmas.[12] These modes have frequencies in the ion cyclotron range and can be driven unstable by resonant interaction with populations of high energy anisotropic ions. These modes are of particular relevance to the case of a spin polarized plasma, since they can produce a fast spin depolarization rate,[13] thereby thwarting the fusion scheme.

Our collaboration with national and overseas institutions has continued, with scientists from several institutions (Scuola Normale Superiore, Kyoto University, Saha Institute of Nuclear Physics, Kharkov Physico-Technical Institute, Princeton Plasma Physics Laboratory, Columbia University, the Institute for Fusion Studies at the University of Texas, and others), several of whom have visited us. We have presented our work at major meetings, including the Sherwood Theory Meeting (Madison, Wisconsin), the sixth Topical Conference on Radiofrequency Plasma Heating (Callaway Gardens, Georgia), the Chapman Conference on Ion Acceleration (Wellesley, Massachusetts), Ignition Physics Workshops in Cambridge and San Diego, the workshop on Basic Physical Processes in Toroidal Fusion Plasmas (Varenna, Italy), the eleventh Symposium on Fusion Engineering (Austin, Texas), the meeting of the Plasma Physics Division of the American Physical Society (San Diego, California), and the Alpha Particles Effects Workshop (New York City).

References

1. J. Martinell, L. Sugiyama, and P.C. Efthimion, Bull. Am. Phys. Soc. 30, 1519 (1985).
2. R. Englade and B. Coppi, Bull. Am. Phys. Soc. 30, 1426 (1985).
3. R.J. Groebner, *et al.*, GA Technologies Report GA-17935 (1985).
4. T. Antonsen, B. Coppi, and R. Englade, Nuc. Fusion 19, 641 (1979).
5. F. Porcelli and S. Migliuolo, Phys. Fluids 29, 1741 (1986).
6. K. McGuire, *et al.*, Phys. Rev. Lett. 50, 891 (1983).
7. B. Coppi and F. Porcelli, Phys. Rev. Lett., submitted for publication.
8. F. Porcelli, B. Coppi, and S. Migliuolo, Bull. Am. Phys. Soc. 30, 1420 (1985).
9. M.N. Bussac, *et al.*, Phys. Rev. Lett. 35, 1638 (1975).
10. P.T. Bonoli and R. Englade, Phys. Fluids, submitted for publication.
11. R. Englade and P.T. Bonoli, in D.G. Swanson (Ed.) Radiofrequency Plasma Heating (AIP, New York, 1985).
12. B. Coppi, S. Cowley, P. Detragiache, R. Kulsrud, and F. Pegoraro, M.I.T., R.L.E. Report PTP-85/12.
13. B. Coppi, S. Cowley, P. Detragiache, R. Kulsrud, and F. Pegoraro, Comm. Plasma Phys. Con. Fus. 9, 49 (1985).