24.0 Plasma Dynamics

Academic and Research Staff

Prof. G. Bekefi, Prof. A. Bers, Prof. B. Coppi, Prof. M. Porkolab, Prof. J.S. Wurtele, Dr. K-I. Chen, Dr. S-C. Chen, Dr. R.C. Englade, Dr. S.C. Luckhardt, Dr. S. Migliuolo, Dr. F. Porcelli, Dr. A. Ram, Dr. L. Sugiyama, I. Mastovsky

Visiting Scientists

V. Fuchs[1], R.A. Cairns, [2] P. Detragiache, Dr. C. Leibovitch, Dr. K. Xu, X.H. Lu

Graduate Students

G.A. Allen, R. Betti, C. Chow, S. Coda, J. Colborn, M. Conde, C. DeGraff, A.C. DiRienzo, R. Kirkwood, K. Kupfer, Y-K. Pu, J. Puchala, J.P. Squire, J.N.S. Villasenor

24.1 Relativistic Electron Beams

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George Bekefi, Kongyi Xu, Chaim Leibovitch, Ivan Mastovsky

24.1.1 Coherent, Free-Electron Radiation Sources

The primary objective of the group is to develop a basic experimental and theoretical understanding of coherent generation by free electrons for wavelengths in the 1 μm to 10 cm range. Particular emphasis is placed on free electron lasers, Cerenkov sources, relativistic magnetrons, and other novel radiation sources.

The experiments are carried out on four high-voltage pulsed accelerators available in our laboratory. Their characteristics are summarized on the next page.

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[1] I.R.E.Q., Quebec, Canada

[2] University of St. Andrews, North Haugh, St. Andrew, Scotland

PHYSICS INTERNATIONAL PULSERAD 110A ACCELERATOR

Voltage	1.5 MV
Current	20 kA
Pulse Length	30 nsec

NEREUS ACCELERATOR

Voltage	600 kV
Current	150 kA
Pulse Length	30 nsec

PHYSICS INTERNATIONAL 615MR PULSERAD

Voltage	500 kV
Current	4 kA
Pulse Length	1 μsec

HIGH VOLTAGE MODULATOR

Voltage	750 kV
Current	600 A
Pulse Length	1 μsec
Repetition Range	4 pps

In the area of free electron lasers (FEL's), experimental studies have been carried out on the amplification and phase coherence,[1] nonlinear saturation,[2] beam quality,[3] and optical guiding in a free electron laser.[4] These results contribute to the basic understanding of this important new type of coherent radiation source. An outstanding issue in free electron laser research is the problem of optical guiding. One of the remarkable properties of the free electron laser, apart from its wavelength tunability and high efficiency, is the large phase shift which the resonant interaction induces in the amplified electromagnetic wave. Under proper circumstances this phase shift can have a sign such that the electromagnetic wave is refracted towards the axis of the electron beam, in a manner somewhat akin to the guiding properties of an optical fiber. This theoretically predicted behavior has important implications. Optical guiding would mitigate the effects of diffraction, and thereby allow the length of FEL wigglers to exceed the Rayleigh range. Such long wigglers are needed if free electron lasers are to operate either in the vacuum ultraviolet (VUV) or at high efficiencies in the infrared wavelength regime. Using the MIT free electron laser facility, the phenomenon of optical guiding has been observed. This is the first such experimental demonstration.[4]

In addition to the above work, a new type of permanent magnet helical wiggler has been developed for free electron and gyrotron application. The system consists of an assembly of staggered samarium-cobalt magnets.[5,6] Other innovative magnetostatic wiggler configurations are being investigated, including a circular wiggler in which a rotating electron beam is surrounded by an assembly of samarium-cobalt magnets.[7]

The physics of the FEL interaction when the magnetostatic wiggler is replaced by an electromagnetic wave is being studied theoretically. A novel FEL device using a gyrotron powered electromagnetic wave wiggler has been designed.[8]

A long-pulse relativistic magnetron microwave source using a superconducting magnet has also been designed and is under construction.[9] A 35 GHz cyclotron autoresonance maser (CARM) amplifier with high efficiency has been designed, and experiments have begun.[10]

Recently, a novel technique of studying intense relativistic electron beams has been developed and tested.[11,12] It permits time resolved measurements of the beam with subnanosecond time resolution. In this method one observes the Cerenkov light through a fast electrooptic shutter and thereby obtains a two-dimensional picture of the beam on a piece of regular photographic film.

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24.2 Plasma Wave Interactions - RF Heating and Current Generation

National Science Foundation (Grant ECS 85-15032)
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Abraham Bers, Vladimir Fuchs, R. Alan Cairns, Abhay Ram, Kenneth Kupfer, Carson Chow

The work of this group is generally concerned with theoretical and computational studies on the *Electrodynamics of Plasmas.* Such studies encompass the linear and nonlinear excitation and propagation of stable and unstable waves in plasmas, and the nonlinear interactions involved in energy and momentum exchange among waves and between waves and plasma particles. Much of our work is directly related to *plasma heating and current generation* by electromagnetic fields coupled to a plasma from external power sources. This work is also relevant and coupled to ongoing experiments in toroidaly confined plasmas at MIT (Versator and Alcator) and elsewhere. Other basic studies are concerned with the *space-time evolution of instabilities*; these studies have extended to problems outside plasma dynamics and found applications in fluid dynamics and other continua. Our interest has also focused on nonlinear phenomena of *intrinsic stochasticity and chaos* in plasma electrodynamics. A more in-depth overview of our research can be obtained from the progress reports of the past few years (RLE Progress Report Nos. 124 through 129).

In the following four subsections we describe our work over the past year. In 24.2.1 we outline some initial work aimed at understanding the diffusion and transport induced by waves in a plasma. This builds upon our previous studies on intrinsic stochasticity and Fokker-Planck studies of the particle distribution function evolution in the presence waves. Subsection 24.2.2 describes our progress in achieving a much simplified (reduced) description of mode conversion at singular layers in inhomogeneous, hot plasmas. Away from such layers, ray tracing is an important tool in studying the wave energy flow and deposition in complex geometries of magnetically confined plasmas; this is described in subsection 24.2.3. Finally, in subsection 24.2.4 we describe the importance of an elecromagnetic (kinetic) mode at ion-cyclrotron harmonics and how it modifies our usual understanding of wave propagation and damping for waves at such frequencies.

24.2.1 Diffusion in Velocity and Configuration Space due to Waves

As part of our studies on intrinsic stochasticity, we are turning our attention to understanding the diffusion of plasma particles that results when stochasticity is induced by finite amplitude waves. The most familiar situation is that of a homogeneous plasma where wavepackets induce diffusion in velocity space, e.g., the well-known quasilinear diffusion. In inhomogeneous plasmas velocity-space and configuration-space diffusion are, in general, coupled. We have clearly seen this in our studies of FM induced stochasticity for charged particles in a potential well,[1] as reported in previous Progress Reports. To understand this and other similar situations of diffusion in wave-particle interactions in an inhomogeneous plasma, we have been studying a Fokker-

Planck formulation which couples wave driven flows in velocity space to transport flows in configuration space. To simplify the situation further, we have initiated such a specific study for electrons in the tail of a distribution function maintained by rf fields, a situation that is very familiar to us from our past studies of current genration by rf waves in plasmas.

24.2.1.1 Transport Due to RF Generation of Energetic Tail Particles

Anisotropic distribution functions can be easily created in plasmas by having electromagnetic/electrostatic waves interact with the tail particles of the distribution function. For instance, in lower-hybrid current drive, an energetic electron tail is created by the lower hybrid waves; in ion-cyclotron heating of a two ion-species plasma an energetic minority species tail is created by the incident fast Alfvén wave coupled to an ion-Bernstein wave. These wave-particle interactions result in velocity space diffusion and the creation of a broad energetic tail to the distribution function. Since such tails are maintained by the waves and may contain a large fraction of the total plasma energy, it is important to understand their transport properties.

In general there are several mechanisms which can lead to the transport of energy from a tail. A stable tail will exhibit transport resulting from its interactions with the bulk plasma turbulence, the ripple magnetic field, and the wave fields themselves. Collisional transport is comparatively unimportant for tail particles because of their low collision frequency. An unstable tail can exhibit all of the above as well as the direct liberation of energy in the form of collective oscillations.

In the case of a stable tail, the fluctuations causing transport (including the waves themselves) are all supported by the bulk plasma. We have been studying these effects using a Fokker-Planck equation which in its most general form couples the wave driven flows in velocity space to transport flows in configuration space.[2] We have been concerned primarily with formulating this Fokker-Planck equation correctly in toroidal geometry while retaining a physical understanding of the various processes which contribute to the diffusion tensor. We have also done some numerical studies investigating the effect of a finite confinement time for fast electrons. This work is also coupled to our previous studies on lower hyrid current drive[3] and stochasticity.[4] The correct formulation of the diffusion coefficients that appear in the Fokker-Planck equation requires detailed understanding of the wave-particle interaction and the subsequent phase-space diffusion. Our stochasticity studies provide the basis for the diffusion and its correct analytical modelling; it can then be incorporated into our transport analysis. When studying phase-space diffusion in stochastic processes, it was convenient, at times, to describe diffusion in action-angle coordinates.[1] We find that similar transformations of the Fokker-Planck equation are necesary to facilitate the transport analysis. A gyro-center kinetic theory for rf transport in tokamaks with the appropriate physics has been setup in action-angle coordinates. The diffusion coefficients include the relevant toroidal dynamics of the tail particles in the spatially localized rf fields. An analysis of this equation is in progress to eventually determine the effect of rf on the transport of the tail particles.

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24.2.2 Singular Layer Reduction Theory for Wave Propagation in ICRH

The treatment of singular layers in wave propagation in inhomogeneous plasmas, where geometric optics techniques break down, is a long-standing unsolved problem for plasmas whose dynamics are described by the Vlasov equation. In regions around such singular layers, the natural waves of the plasma are coupled so that a wave incident upon such a region may be partially converted to another wave, partially reflected, and partially transmitted. What is of primary interest is the magnitude of each of these processes, i.e., determining the so-called transmission, reflection and mode-conversion coefficients of such singular layers. In the absence of kinetic (Landau-type) dissipation and for cases where the coupling of waves is only pairwise, we have shown, some time ago,[1] that the singular layer region can be described by appropriate second-order differential equations, and, thus, several important characteristic problems in propagation across a magnetic field were solved.[2]

For propagation that involves a nonzero wavenumber parallel to the magnetic field, and in particular near cyclotron and cyclotron harmonic resonances, dissipation cannot be ignored and the coupling problem is intrinsically fourth-order or higher. Up to now, the solution to such specific problems was obtained only by difficult numerical integrations of the differential equations (of fourth and sixth order). Recently, we have been successful in showing that this type of coupling problem can be reduced to a set of simpler, first and second-order, problems, some of which can be solved analytically.[3] Thus we have shown that the transmission through the singular layer can be reduced to a first-order differential equation and solved for analytically.[4] This was based upon extending well-known perturbation techniques for homogeneous plasmas[5] to inhomogeneous plasmas, and was a direct outflow of the Ph.D. dissertation work[6] we reported in last year's Progress Report. In addition, we have shown that the transmission and reflection at the singular layer can be obtained from an appropriate second-order equation whose numerical solution is very easy.[7] Both of these results have been tested against results obtained by integrating the fourth and sixth-order equations[8,9] and shown to be in excellent agreement.

Currently we are in the process of formulating an appropriate second-order equation to describe transmission or reflection and mode-conversion. Success in this endeavor will complete this reduced description of kinetic wave propagation at singular layers, since with the knowledge of the transmission, reflection, and mode conversion, the dissipation can be deduced from conservation of energy flow.

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24.3 Ray Tracing for the Mode Converted IBW in ICRH

The fast wave component of the externally launched ICRF wave undergoes mode-conversion to the ion-Bernstein wave (IBW) near the ion-ion hybrid resonance (in a two ion species plasma). In last year's progress report we described the detailed numerical analysis that was being carried out with the help of a ray trajectory code that we had developed. This code was for following rays in a hot, Maxwellian plasma in toroidal geometry with gradients in density, temperature, toroidal and poloidal magnetic fields, included in a WKB sense. One of the major conclusions of this work[1,2,3] was that the IBW can Landau damp onto the electrons by significant upshift of the $k_{\parallel}$ spectrum along the rays in a torus. The externally launched $k_{\parallel}$ spectrum was not capable of accomplishing this.

The ray tracing analysis which we have used so far relies on a basic assumption that the anti-hermitian part of the conductivity tensor describing the plasma be much greater than the hermitian part. The ray tracing equations that are derived with this assumption are then the standard geometric optics ray equations. In our analysis of the propagation of the ion-Bernstein wave in a toroidal plasma, we find that this particular assumption breaks down along the rays. A next order correction to the conventional ray trajectory equations is needed to follow the rays through such regions.[4] We are in the process of modifying our ray tracing code to include the next order correction. With that in place we will be able to complete these studies on the propagtion of ion-Bernstein waves and the electron heating by such waves as they propagate in toroidal geometry.

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24.3.1 Kinetic EM Mode Near Ion-Cyclotron Harmonics

For low β plasma ($\beta = 2\mu nkT/B^2$, where n is the density, T is the temperature and B is the magnetic field), one usually considers that there are two well-known modes that propogate perpendicular to the magnetic field near the first harmonic, $2\omega_c$, of the ion-cyclotron frequency. One of them is the electromagnetic fast-Alfvén wave which is usually shown to cross the cyclotron harmonic, and the other one is the electrostatic ion-Bernstein wave. However, at any finite value of β, we find that there is also another kinetic mode near $2\omega_c$.[1,2] The characteristic of this mode is that it is an elliptically polarized electromagnetic wave, and it remains so for all values of $k_\perp$ (the wave vector perpendicular to $\vec{B}$). Furthermore, its frequency ω, is such that $\omega/\omega_c \lesssim 2 - \beta$ through the entire range of $k_\perp$. The fast-Alfvén wave couples to this mode and this eliminates the erroneous crossing of the harmonic which is usually shown for the dispersion diagram of the fast-Alfvén wave. We have carried out detailed numerical and analytical work on this new, kinetic electromagnetic mode (see figure 24.1). For very slightly oblique propagation this mode tends to become evanescent, and rapidly enters into the complex k -plane as the obliqueness is increased. A version of this new mode exists in a two ion-species plasma as well. Here the new mode is also near the first harmonic of the cyclotron frequency and couples to the Alfvén wave branch which comes from the ion-ion hybrid cutoff (see figure 24.2).

The effect of this new mode on the transmission, mode conversion and reflection properties of the incident fast wave are presently being examined. For most β's of interest to fusion plasmas, we find that the new kinetic mode is well-defined (i.e., $k_\perp$ is essentially real) for only a very small range of $k_\parallel$'s around zero, and that it remains highly localized in the vicinity of the cutoff at $2\omega_c$. To account for this mode in the vicinity of the fast-Alfvén wave, the dispersion relation must be expanded to order $(k\perp\rho)^6 \sim \beta^3$. The damping of the fast wave is then found to be much larger than what one usually calculates from dispersion relations that are correct to order $(k\perp\rho)^2$ only (see figure 24.3).

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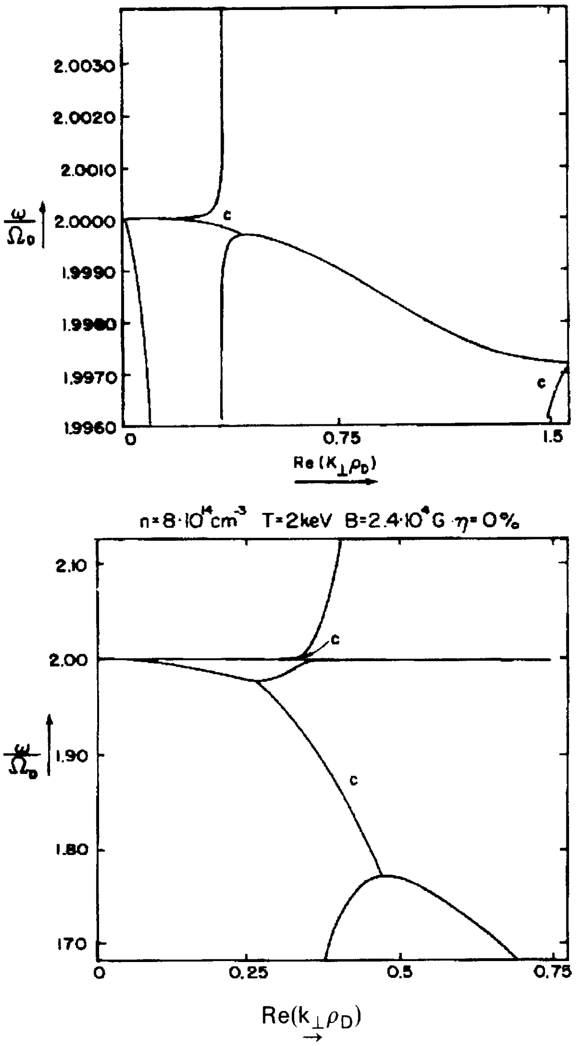

Figure 24.3.1 (a) Dispersion diagram near the first harmonic of the ion-cyclotron frequency for a single ion-species (deuterium) plasma. Branches denoted by *C* are real parts of complex $k_\perp$ -roots. (b) Detail near $\omega = 2\Omega_D$

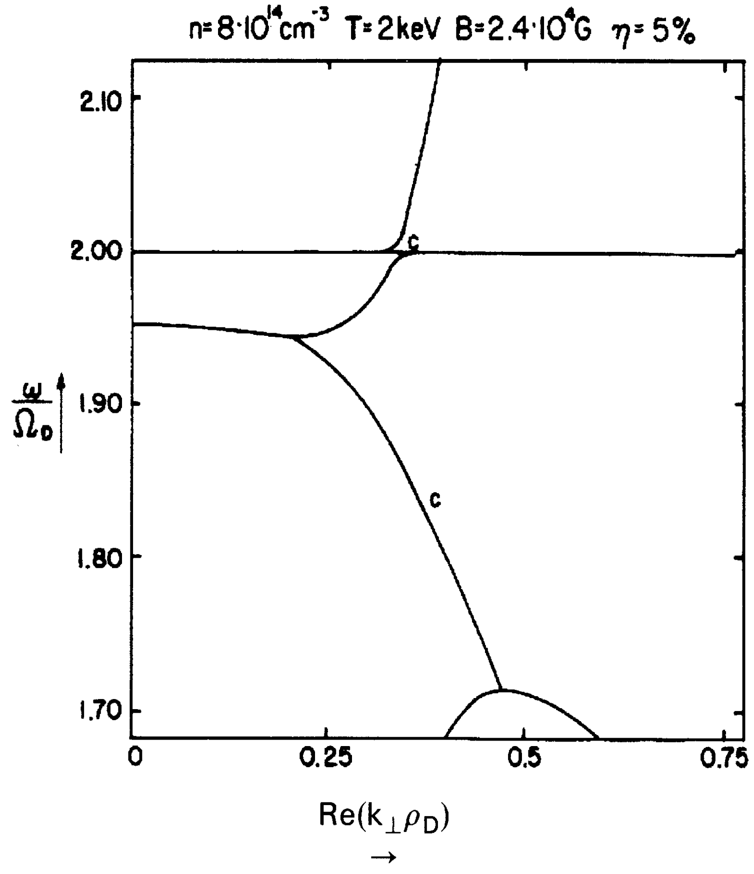

Figure 24.3.2 Dispersion diagram near the first harmonic of the deuterium cyclotron frequency for a two ion-species plasma $D(H)$. Branches denoted by C are real parts of complex $k_\perp$ -roots.

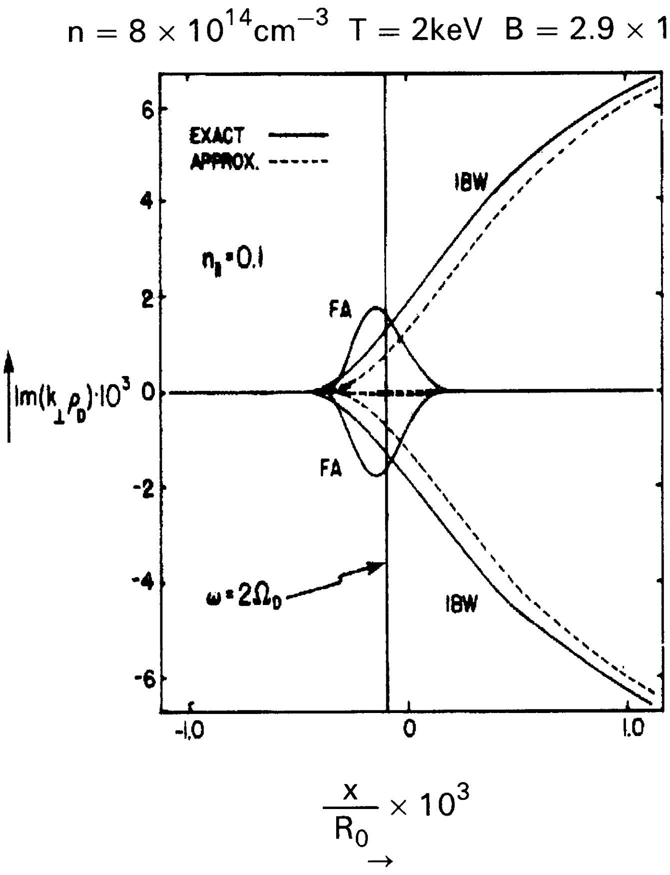

Figure 24.3.3 Damping and evanescence for finite $n_\parallel = ck_\parallel/\omega$ in the vicinity of the $2\Omega_D$ layer in a toroidal plasma. The approximate results are from dispersion relations correct to order $(k_\perp \rho)^2$.

24.4 Physics of Thermonuclear Plasmas

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

Bruno Coppi, A. Becker, Ricardo Betti, Stefano Coda, Paolo Detragiache, Ronald C. Englade, Stefano Migliuolo, Yi-Kang Pu, Linda Sugiyama

The main theme of this program is the theoretical study of magnetically confined plasmas in regimes of thermonuclear interest. A variety of physical regimes that fall in this category characterize both present-day experiments on toroidal plasmas (Alcator, TFTR, JET,...) as well as future ones that will contain ignited plasmas employing either first generation fuels, namely a deuterium-tritium mixture (Ignitor, CIT), or more advanced fuels such as deuterium-deuterium or deuterium-helium (Candor). A coordinated effort of collaboration between the design group of CIT, the U.S. compact ignition experiment, and the European Ignitor has been set up with our participation. At MIT, the Alcator C-Mod facility is under construction. This experiment combines the favorable features of elongated plasma cross-sections with those of high field compact geometries. These features have been embodied earlier in both the Ignitor and the CIT designs, as well as in a machine (proposed by us in the early 1970's) called Megator.

A recently proposed MIT program called Versator-Upgrade, has, as its main purpose, to achieve the "second stability" region for ideal MHD balooning modes. We were the first group to discover this stability region in the winter of 1977-1978, and to outline the experimental procedure by which to reach it. This consists of starting with a tight aspect ratio configuration, and raising the value of q (the inverse of the local rotational transform) on the magnetic axis above a certain level, such as 1.4, while increasing the value of the plasma pressure parameter, β_P, to those typical of the second stability region.

Our research program is now oriented along two major avenues. First, the basic physical processes of thermonuclear plasmas (equilibrium, stability, transport, ...) are being studied as they apply to existing or near-turn future systems. In this, we closely collaborate with our experimental colleagues. Second, we explore advanced regimes of thermonuclear burning, including those employing low neutron yield fuels (D-^{3}He and "catalyzed" D-D). We consider both the design of machines to contain these ultra-high temperature plasmas as well as the physics that governs their behavior.

Below, we present some salient results on topics pursued by our group this past year, as well as from current research.

24.4.1 Anomalous Ion Thermal Conductivity

Over the past few years we have undertaken a comprehensive analytic and numerical study of the anomalous ion thermal transport associated with a microinstability known variously as the ion temperature gradient mode, η_i, mode or ion mixing mode. Many of the relevant properties of this mode were outlined by our group[1] as part of the analysis of the mechanism responsible for inward particle transport in toroidal devices. Subsequently, the increased energy confinement times τ_E and record values of the confinement parameter achieved by pellet injection[2] in Alcator C have validated our previously suggested[3] "cure," for the observed inadequate energy confinement times in the plasmas produced by Alcator C, that significant anomalous ion thermal conductivity could be avoided by producing peaked density profiles.

Our recent investigations focused on the spatial profile and parameter dependence of the mixing mode in toroidal devices. Simulations[4] successfully reproduced present day regimes and have been employed in predictions regarding high field experiments in ignited regimes.

24.4.2 Profile Consistency: Global and Nonlinear Transport

It is well established experimentally that the steady-state electron temperature profile in tokamak discharges is relatively independent of the spatial deposition of auxiliary power and assumes a canonical shape that can be related to that of a macroscopically stable and relaxed current density profile outside the region of sawtooth activity. This behavior is often referred to as the "principle of profile consistency."[5] In addition, the readjustment of the profile distortion caused by pellet injection and the propagation of heat pulses associated with sawtooth crashes or transient bursts of spatially localized microwave power deposition are observed to proceed on time scales considerably faster than the steady-state electron thermal energy transport time.

These considerations have led us to conclude[6] that the relevant electron cross-field heat flux is the result of at least two different transport processes described as fast and slow. The slow process can be appropriately described by a standard diffusion term that is linear in the temperature gradient, but the fast process is strongly determined by the departure of the electron temperature from the canonical profile and has a nonlinear temperature gradient dependence in our formulation. In neither case is the magnitude of transport required to explicitly depend on the profile and strength of the source of electron thermal energy even though the solution of the energy balance equation adheres reasonably closely to the "principle of profile consistency."

24.4.3 Sawtooth and Fishbone Stabilization in Auxiliary Heated and Fusion Burning Plasmas

Recent experiments at JET[7] have shown that ion cyclotron resonance heating (ICRH) can stabilize "sawtooth" oscillations. Shortly after ICRM turn-off, a sawtooth crash occurs with a delay time that is a finite fraction of the slowing down time of energetic ions produced by the RF fields.[8] In collaboration with the JET theory group, we have undertaken a study of the interaction of global $n^\circ = 1$, $m^\circ \simeq 1$ internal modes (which are responsible for the sawtooth) with a high energy ion population. Standard MHD theory[9] yields an instability parameter for these internal modes, denoted λ_H. The energetic ions: 1) contribute to a reduction in this parameter $\lambda_H \rightarrow \lambda_H + \mathrm{Re}(\lambda_K) < \lambda_H$; and 2) provide a viscous-like dissipation term, $\mathrm{Im}(\lambda_K)$ that arises from a resonance between the mode and trapped energetic ions that precess around the torus due to the curvature of the equilibrium magnetic field.

In high temperature plasmas, where finite ion diamagnetic frequency has brought the ideal $m^\circ \simeq 1$ kink to marginal stability, the residual growth is provided by electrical resistivity. This growth can be negated by hot ion effects (a)-(b). This provides a qualitative understanding[10] of the mechanism that stabilizes sawtooth crashes. Detailed calculations are underway, examining plasma regimes and energetic ion distribution functions for which stabilization actually occurs.

24.4.4 Density Limit and D-T ignition Conditions

Relatively high values of the plasma density are required to insure a confinement parameter $n\tau_E$ (central electron density times energy confinement time) sufficient to reach ignition even for deuterium-tritium fuel. Collisional ion thermal conductivity and bremsstrahlung radiation, both proportional to the square of the particle density, play a strong role in the global energy value up to temperatures somewhat above T_m, the "minimum ignition temperature." Near and above T_m, the presence of anomalous ion thermal conductivity can have significant effects. Investigation of the microinstability known as the ion temperature gradient mode (also the η_i or ion mixing mode) shows that it can give rise to an ion thermal conductivity that scales as $nT_i^{3/2}$. In collaboration with W. Tang of the Princeton Plasma Physics Laboratory, we have analyzed an approximate model equation for the steady state energy balance in the central region of a tokamak plasma which includes this type of transport.[11] Multivalued solutions for the density are obtained as a function of temperature, ion thermal anomaly strength and power.

If no ion anomaly is active, the density must remain below a certain maximum value for the plasma to attain the minimum ignition temperature T_m, but any density is allowed beyond T_m. In the presence of anomalous transport, a critical heating power deposition that increases with the magnitude of the anomaly is required to open a channel between regions of allowed density for temperatures above and below T_m. Since the rate of change of the fusion cross-section decreases with temperature, the density must be progressively increased above a minimal value, to heat the plasma to steady-state temperatures considerably higher than T_m.

24.4.5 Alpha Particle Induced Fishbone Oscillations in Fusion Burning Plasmas

The "fishbone" is a burst of oscillations that occurs in some experiments in which plasmas have two components, a main plasma and an energetic ion population. The fishbone has toroidal $n^\circ \simeq 1$ and poloidal $m^\circ \simeq 1$ spatial dependence and a frequency close to the diamagnetic frequency of the core (main plasma) ions.[12] Three requirements must be met to have instability: 1) high enough temperatures are produced so that finite diamagnetic frequency brings the ideal mode to marginal stability; 2) the core plasma beta must exceed a threshold value; and 3) a viscous-like resonant interaction of the wave with trapped energetic ions, that precess due to the curvature of the magnetic field, must exist. For parameters relevant to an Ignitor device[13] alpha particles with energies near 300 keV resonate with the fishbone oscillation.

Work in progress[14] is concentrating on the stabilization of this mode (as well as that of the internal kink, see the preceding section) as a consequence of the energetic particle contribution, $\lambda_K(\omega)$, to the effective instability parameter $\lambda_H + \lambda_K(\omega)$. Here λ_H is the parameter given by standard[9] ideal MHD theory. The real part of λ_K is negative for modes with $\omega \simeq \omega_{di}$ much lower than $\omega_{D\alpha M}$ which is a measure of the precession drift frequency of alphas at their birth energy. Thus, the effective instability parameter decreases and the fishbone restabilizes at high enough α -particle pressure.

We have also found that another $m^\circ \simeq 1$ oscillation can exist, but only at very high α pressure ($\beta_{p\alpha} > 1$). This oscillation is at higher frequency ($\omega \gtrsim \omega_{D\alpha M}/3$) and can be entirely supported by trapped energetic ions which provide a destabilizing contribution: $\mathrm{Re}[\lambda_K(\omega \gtrsim \omega_{D\alpha M}/3)] > 0$.

24.4.6 Transport Simulations of Thermonuclear Ignition in Compact Experiments

The attainment of ignition in a toroidal device depends critically on the net balance between bulk heating of the plasma and energy loss due mainly to anomalous electron and ion thermal conductivity, bremsstrahlung, synchrotron radiation, and macroscopic processes such as sawtooth oscillations. Using a modified version of the BALDUR one and one-half-dimensional transport code,[15] we have investigated the impact of these processes on the time evolution of D-T plasmas in a compact, high field device of the Ignitor type with strong ohmic heating.[4]

We have used the generalization of Coppi-Mazzucato-Gruber diffusion to model electron heat transport as well as alpha particle heating contributions. For an anomalous ion heat diffusion coefficient peaked halfway out in the discharge and sawtooth repetition times down to 0.3 seconds, ohmic ignition could be achieved over a fairly wide density range. A central electron density near 8 10^{14}cm^{-3} was optimal in the sense of allowing relatively rapid approach to the state in which fusion heating dominates ohmic heating. A slightly higher density allows faster heating to fusion burning regimes. The overall magnitude of electron heat transport could be increased about a factor of two before ignition was prevented, while the magnitude of ion heat transport was not a sensitive parameter. In addition, we have studied the effects of variations in the form of electrical resistivity, plasma impurity level, and flux surface equilibrium configuration on the approach to ignition. Simulation of the CIT device illustrates the rather strong auxiliary heating requirements of that design.

24.4.7 Transport Simulations of Ohmic TFTR Discharges

We have demonstrated the validity of a one-dimensional transport model for Ohmic TFTR plasmas. Some 40 representative discharges were simulated, including current, density, and toroidal magnetic field scans from four operating periods extending from 1983 to 1986. Most of these cases were dominated by an anomalous energy transport carried by the electrons. Our work shows that a model based on the idea of "profile consistency"[5] successfully reproduces the total energy confinement times of these discharges even though the electron energy confinement model had a different form.

24.4.8 The Role of the Ubiquitous Mode in Anomalous Electron Energy Transport

Electron thermal energy transport in magnetically confined plasmas is one of the most important subjects in fusion research. Experiments indicate that such a transport process is anomalous, namely that the observed electron energy confinement time is an order of magnitude smaller than the one predicted by collisional neoclassical theory. We find that the ubiquitous mode[16] satisfies the required[6] properties for driving the anomalous transport:

1. It is driven by the electron temperature gradient;
2. It is active over a significant portion of the plasma column and is not sharply reduced in regions of considerable collisionality ($\upsilon_e/\mathrm{E}\omega_{be} \lesssim 1$);
3. Its wavelength is long enough to produce substantial energy transport over a significant portion of the plasma;
4. The energy transport is up to an order of magnitude larger than the corresponding particle transport.

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24.5 Tokamak Research: RF Heating and Current Drive

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

Mikolos Porkolab, Stanley C. Luckhardt, Kuo-in Chen, Edward W. Fitzgerald, John C. Nickerson, Stephano Coda, Jeffrey A. Colborn, Robert Kirkwood, Jared P. Squire, Jesus N.S. Villasenor

The purpose of the Versator II tokamak research program is the following: 1) to carry out a series of RF heating experiments near the lower-hybrid frequency on the Versator II tokamak, and to study toroidal current generation by RF waves using a unidirectionally injected slow (lower hybrid) wave; 2) to study the efficiency of RF current generation with combined ECRH/LHRF power injection; 3) to study RF preionization and startup with lower-hybrid waves in combination with ECRH assist; 4) to study high β_P plasmas at low toroidal currents, and the stability of the associated plasma; and 5) to study fast wave launching and coupling with a dielectric loaded waveguide phased array (grill) as well as with an extended radiating-hole structure. For the heating and current drive experiments a four-waveguide phased array (grill) is used to inject microwave power with pulse lengths up to 20msec at a frequency of 800 MHz or 40 msec at a frequency of 2.45 GHz. The 800 MHz klystron provides RF powers up to 150 kW, and the 2.45 GHz system consists of two 50 kW klystrons providing up to 100 kW of total power. For the ECRH system, a linearly polarized radiation pattern is injected from the high field side by means of a rotatable mirror.

24.5.1 Combined Electron Cyclotron Heating and Current Drive Experiments

The versator ECRH/LHCD experiment uses ECRH and LHCD to generate current and heating of the suprathermal tail component as a means to provide preionization, start-up, ramp-up and control of the steady state current driven distribution funciton. Start-up of the tokamak plasma constists of two stages: 1) the preionization stage in which the neutral fill gas is broken down and an initial low temperature plasma is formed; and 2) the current ramp-up stage in which the plasma current is increased from zero or near zero to the desired operation current and closed magnetic surfaces are produced.

In the ECRH preionization experiment, ECRH power is injected into a neutral gas filling with the cyclotron resonance layer at the center of the vacuum vessel, Bo=12.5 kG. Dense plasmas to allow effecient coupling of the lower-hybrid waves were produced easily. Time evolution of the spatial profiles of the density and the H_α emission were measured. The most surprising result of these experiments was that the ionization and peak in the density profile was shifted outward from the cyclotron resonance layer toward the location of the upper hybrid layer. This can be seen in figures 24.5.1 and 24.5.2 which show the time evolution of the density and hyrdogen emission along with the location of the upper hybrid resonance, $\omega^2 = \omega_{pe}^2 + \omega_{ce}^2$. The fact that the density and H_α light peaks between the cyclotron layer and the upper hybrid layer, is evidence that the power absorption in the preionization plasma is not due to cyclotron resonance absorption. The mechanism for the absorption may be through mode conversion to the electron Bernstein wave or as a result of a non-linear process.

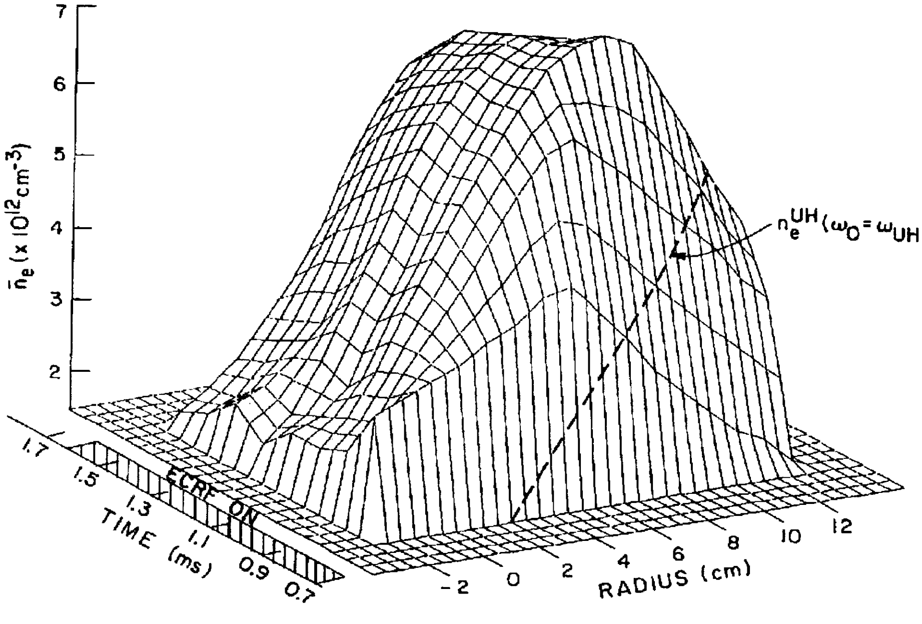

Figure 24.5.1 Temporal evolution of the density profile during 35 GHz ECRH preionization experiments (H_2 pressure = 2×10^{-4} torr, Prf = ~(40-50) kW, $B_T(0)$ = 12.5 kG).

The start-up of the plasma current with ECRH and combined ECRH and LHCD was accomplished using ECRH to preionize an initial gas fill pressure of typically 5×10^{-5} torr hydrogen. During the ECRH phase the density rises to 4×10^{12}cm^{-3} and then decays due to low recycling over a 2 msec time period. A small amount of current (< 2kA) is driven by the ECRH. When ECRH and LHCD are combined the current can be ramped up from 0 to 11 kA over a 4.5 msec period, see figure 24.5.3 Although, it was necessary to apply a small inductive voltage (less than 3 volts) to obtain this ramp up result, we believe that this voltage can be eliminated completely by improving the equilibrium control of the plasma vertical position. Note that this inductive voltage is still an order of magnitude lower than that needed for inductive start-up of the Versator plasma (typically, v_ℓ= 30-35 volts).

The principal unresolved physics question in the current start-up experiment is the large spectral gap existing between the phase velocity of the lower-hybrid waves and the initial low temperature plasma produced by ECRH. Non-linear effects have been invoked to provide waves with a range of phase velocities needed to bridge the gap to low electron energies. On Versator II initial experiments have been carried out with RF probes to detect the non-linearly produced waves. RF probes at the plasma edge during the ECRH/LHCD start-up experiment have detected evidence of low frequency wave generation in the plasma near the ion plasma frequency during both the ECRH phase and LH phase of the plasma start-up. Production of the energetic electron tail has been verified with electron energies in the range of 2-40 keV.

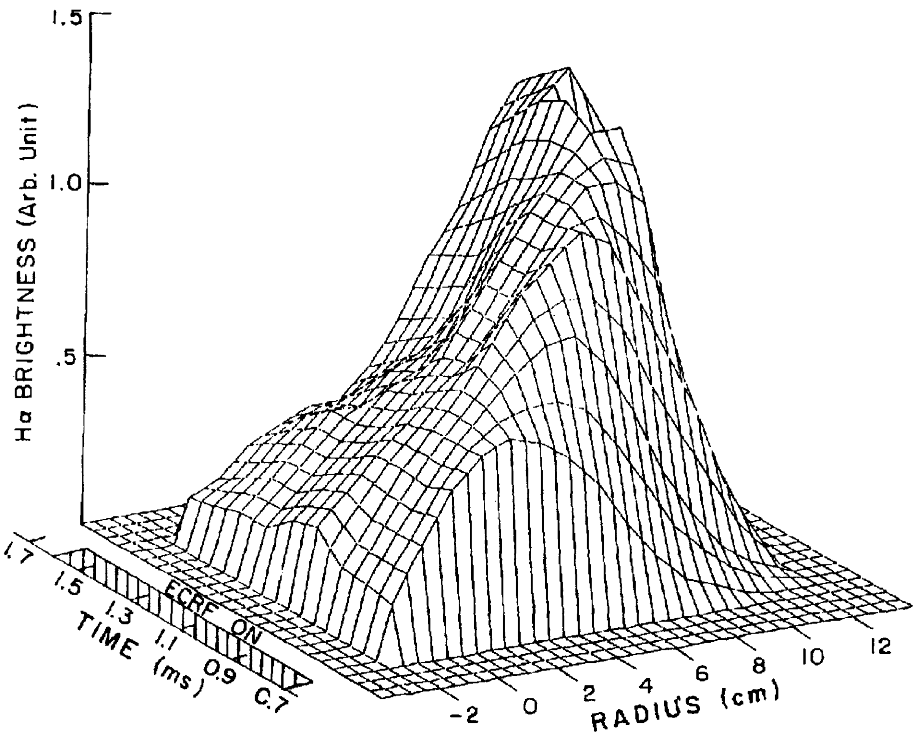

Figure 24.5.2 The temporal evolution of the H_α emission during 35 GHz ECRF preionization experiments (same conditions as in figure 24.5.1).

24.5.2 High β_P Plasma Equilibria by LHCD and ECRH Heating

The production of tokamak plasma equilibria with high values of $\epsilon \beta_P$ (>1) is important for determining the tokamak plasma β limits and for reaching the second stability regime of tokamk operation. On Versator II we have recently been successful in producing equilibria with values of β_P up to 3.8 and $\epsilon \beta_P$ up to 1.3 by means of RF current drive. In these experiments, plasma is fully sustained by RF drive with the inductive drive shut off, and the kinetic pressure from the RF driven energetic electron component provides the high plasma pressure needed to raise β_P. While the ultimate aim of high β tokamak operation is to increase the β_P of the bulk thermal plasma, the MHD equilibria, stability thresholds for ballooning modes, and other physics issues can be studied in these plasmas where the plasma pressure is produced by the energetic tail electrons.

The fact that the current is carried by energetic electrons in these plasmas allows us to obtain information about the current profile from our extensive set of x-ray diagnostics. This information is usually not available for inductively driven plasmas because of the the difficulty of current profile measurements in ohmic plasmas. The spatial distribution of the RF driven current was determined by measurement of the spatial width and profile of the hard x-ray bremmstrahlung spatial profile. The x-ray profile was found to be shifted outward also a result of high β_P. The internal inductance of the rf driven current profile, ℓi, was obtained from the width of the x-ray profile, and this allowed us to use the equilibrium measurement of $\beta_P + \ell i/2$ to determine β_P itself.

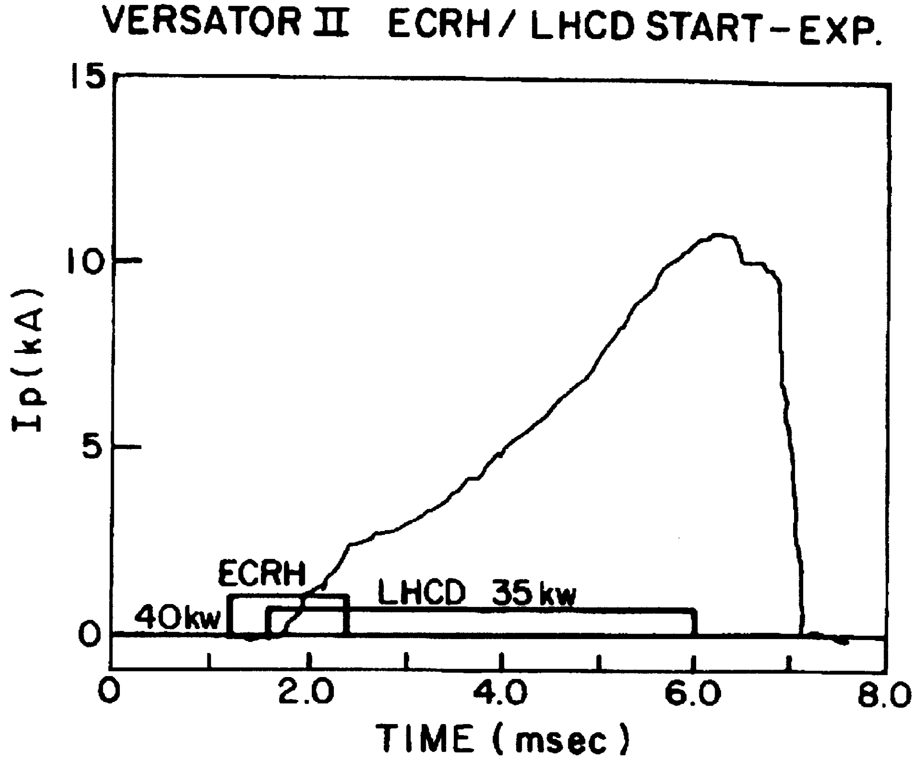

Figure 24.5.3 Plasma start-up by combined ECRH and LHCD.

The value of $\ell i/2$, the internal inductance of the RF current, was obtained by measuring the width of the current carrying energetic electron population with a hard x-ray PHA spectroscopy diagnostic. The width of the x-ray profile, figure 24.5.4, may be taken as the width, w, needed to calculate the internal inductance, $\ell i = .5 + 2 \times \ln(a/w)$ giving $\ell i/2 = 1.2$, where a is the minor radius of the discharge.

Another information about the shift of the magnetic axis as a result of reaching high β_P has been obtained from measurement of the density profile as a function of major radius. The outward shift of the density profile is an indication of the magnitude of the Shafranov shift of the magnetic axis. The spatial profile of the density was measured and was indeed found to shift outward at high β_P, see figure 24.5.5. The flux surface shift was inferred from the density profile shift. The time evolution of the density as a function of major radius shows an outward shift of the peark density as β_P increases. When the steady state RF driven flattop phase is reached the outward shift of the density profile is 6 cm (see figure 25.5.5 (d)), and the shift normalized to the minor radius is .46.

24.5.3 800 MHz Fast Wave Current Drive Experiments

The fast wave branch of the cold plasma dispersion in the lower hybrid range of frequencies promises to have a better current drive efficiency in reactor grade plasmas than the well established slow wave branch. The fast wave has a lower damping coefficient than the slow wave and has no resonance layer where it can be thermally absorbed. Therefore, the fast wave should penetrate into the plasma interior at high

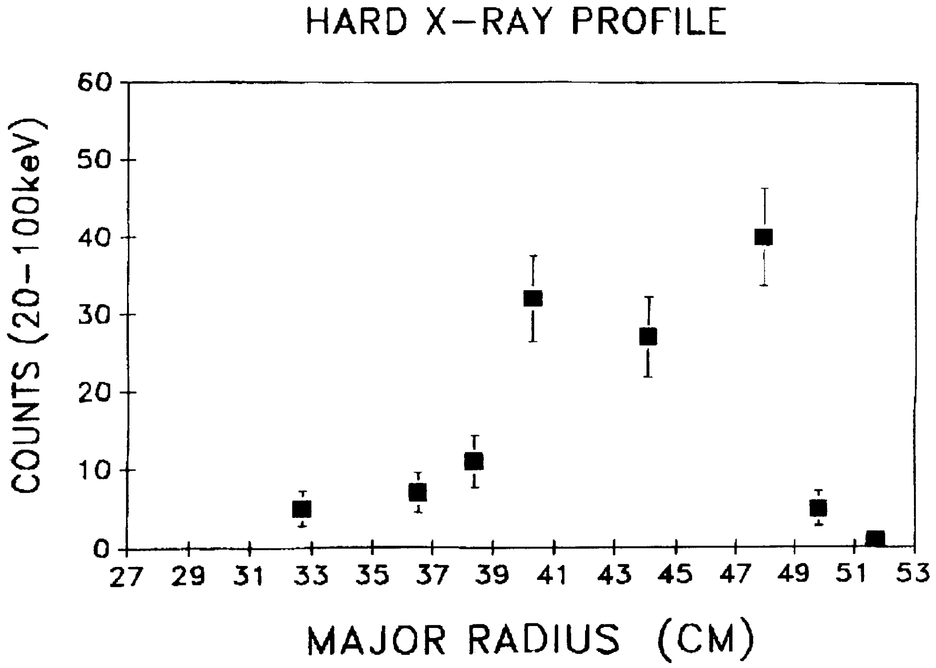

Figure 24.5.4 The hard x-ray profile of fully RF driven dicharge with high β_P . The major raidus of the vacuum chamber is 40 cm.

densities. This allows lower frequencies to be used, which also lowers the minimum $N_{\parallel}$ needed for the lower hybrid waves accessibility to the center. Low $N_{\parallel}$ waves excite higher velocity electrons, which are more efficient for current drive. Thus, assuming that non-linear effects do not dominate near the plasma surface, fast waves may be more efficient for current drive than slow waves.

The experiment is also strongly motivated by our earlier discovery of the current drive density limit which degrades slow wave current drive at high densities ($\bar{n}_e = 6x10^{12}cm^{-3}$ for Versator II at 800 MHz). The physical processes which causes the density limit is not understood as yet although we believe that parametric decay processes are the prime candidate. Comparison of the results of fast wave current drive with the previous slow wave results done at 800 MHz in Versator should help gain insight into the problem.

The fast wave antenna system has been completed and is now being installed on the Versator II tokamak. The antenna is an array of four dielectric loaded waveguides (material: TiO, dielectric loaded constant ϵ =80, loss tangent < .0005) suitably fanned to correspond to the major radius of the tokamak. The dominant $N_{\parallel}$ is 3.5 for 90 degree phasing. The fast wave experiment will commence in mid-1988.

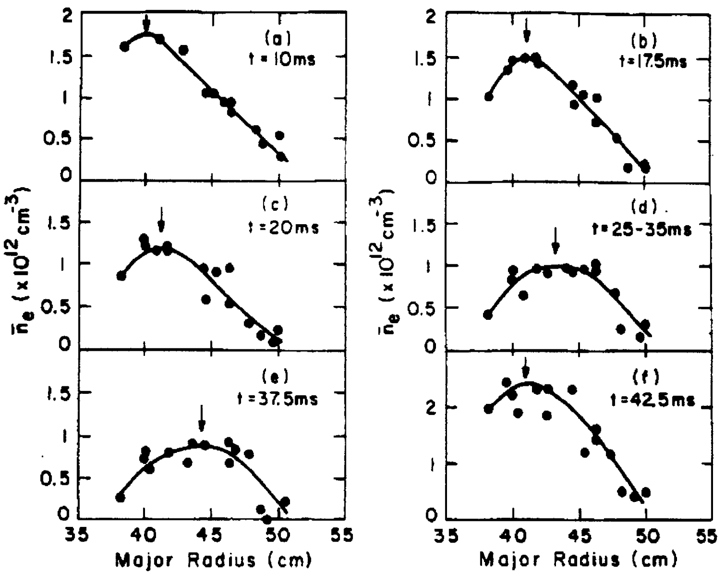

Figure 24.5.5 The outward shift of the density profile when β_P increases. Note that the RF was on from 20.5 ms to 41 ms.