FINAL REPORT

"PLASMA RESEARCH"

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INTRODUCTION

EXECUTIVE SUMMARY

The research in plasma physics and controlled thermonuclear research at M.I.T. has evolved from a relatively long tradition of basic theoretical and experimental contributions, during the period covered by this contract. A major commitment to research in magnetically confined plasmas was undertaken with the Alcator program that began in 1969 and with the theoretical effort necessary to back this up. The Alcator A device was brought to successful operation and, after the identification of a sequence of plasma regimes that have been realized in it, led to attainment record values of plasma density, of the confinement parameter $n\tau$, and of the degree of plasma purity. A second more advanced device, Alcator C, has been designed and is presently under construction. A line of toroidal experiments characterized by relatively low cost and extreme simplicity has been developed in order to study basic plasma physics problems related to magnetic confinement and relevant processes of plasma decontamination. The devices that have been operated are Versator I, now discontinued, Rector, with non-circular cross section, Erasmus, with small aspect ratio and Versator II. A number of theoretical contributions concerning the interpretation of the regimes found in Alcator, runaway phenomena, new trapped particle instabilities, internal resistive modes, etc. have been given and presented in publications or appropriate meetings.

A special consideration, within the theoretical effort, has been devoted to the study of plasma regimes that are important in devising future experiments of thermonuclear interest.

BASIC RESEARCH

The experimental and theoretical plasma physics program at M.I.T. began in the mid-nineteen forties, primarily under the sponsorship of the joint services (Army Signal Corps., Office of Naval Research and the Air Force), and under the sponsorship of the National Science Foundation. Support by the Atomic Energy Commission began in 1958 immediately after the First Geneva Conference on Peaceful Uses of Atomic Energy.

Studies that began some thirty years ago and are still continuing have resulted in some 200 scientific papers and in 7 scientific books. The studies can be conveniently subdivided into four major groups.

Atomic Physics and Gaseous Electronics

Investigations in Atomic Physics and Gaseous Electronics were concerned with two aspects. First, the determination of basic atomic parameters relevant to both hot and cold plasmas, and secondly, studies addressed themselves to developing novel techniques of diagnosing plasmas. The measuring techniques in both of these areas concern themselves mainly with the interaction of electromagnetic radiation with the ionized gas. In the early days microwaves were the primary tool of the experimenters. In the late fifties and early sixties infrared radiation was employed, and in the seventies the main concern was with the use of visible light.

Summary of this work will be found in the following texts.

Basic Data of Plasma Physics by S. C. Brown, M.I.T. Press 1959.

Basic Data of Plasma Physics by S. C. Brown, M.I.T. Press 1966.

Introduction to Electrical Discharges in Gases by S. C. Brown, Wiley 1966.

Electron Ions and Waves by W. P. Allis, edited by S. C. Brown, M.I.T. Press 1967.

Principles of Laser Plasmas edited by G. Bekefi, Wiley 1976.

Radiation Processes in Plasmas

Work on the spontaneous emission of radiation by ionized gases began in 1958 under the support of the Atomic Energy Commission and the work continued until the early seventies. The primary concern in these studies was the bremsstrahlung, cyclotron radiation, and scattering of laser radiation in weakly and highly ionized plasmas. Initially these processes were investigated in essentially stable plasmas. Later work had to do with emission and scattering processes from marginally stable and unstable systems.

The aforementioned work will be found in the following texts.

Radiation Processes in Plasmas by G. Bekefi, Wiley 1966.

Radiation Processes in Plasmas by G. Bekefi, revised edition in Russian, Moscow, 1971.

Collective Emission Processes in Unmagnetized Plasmas, chapter in Plasma Physics,

Les Houches 1972 (Gordon and Breach 1975).

Waves and Instabilities

In the early sixties a very large effort, both theoretical and experimental, was mounted concerning the interaction of electromagnetic waves with magnetized plasmas. The early studies had to do with small amplitude waves in which the interactions could be fully explained by linear theories. Work in the late sixties continuing throughout the seventies was focused on nonlinear interactions and parametric coupling between waves.

The substance of this body of work will be found in the following scientific tracts.

Waves in Anisotropic Plasmas by W. P. Allis, S. J. Buchsbaum, and A. Bers, M.I.T. Press 1963.

Electron Stream Interactions with Plasmas by R. J. Briggs, M.I.T. Press 1964.

Linear Waves and Instabilities by A. Bers, chapter in Plasma Physics, Les Houches 1972 (Gordon and Breach 1975).

Physics of Hot Magnetically Confined Plasmas

The early work and the early thinking in this field will be found in the text Plasmas and Controlled Fusion by D. J. Rose and M. Clarke, M.I.T. Press 1961, 1965. Our present interest which began in the summer of 1974 concerns the tokamak discharge. In particular, we are interested in those tokamak discharges produced in relatively small, highly accessible devices. (See appendix 1 of World-wide Summary of Small Tokamaks.) In such devices novel ideas can be treated rapidly. Our first device, Versator I, was used in impurity studies, in the study of runaways, in the development of ultraviolet spectroscopy, and in devising a novel technique of measuring the energy containment of a tokamak plasma.

The small primitive Versator I was laid to rest in May 1977 and was at the time replaced by the rather sophisticated device, Versator II. This device is now operating and its primary purpose between now and about the year 1980 will be the testing of various rf heating schemes. In the fall of 1977 we shall begin a program, in conjunction with the Princeton Plasma Laboratory, of lower hybrid heating. An initially 40KW of rf power at 800 MHz will be injected into the torus. In 1978 this will be upgraded to 200 KW of rf power at the same frequency.

In addition to these lower hybrid studies, we plan to initiate in the summer of 1978 a program of electron cyclotron heating at a frequency of 36 GHz. This will be done in cooperation with the Naval Research Laboratories, who are presently developing a 200 KW gyrotron device.

MAGNETIC CONFINEMENT RESEARCH

The confinement work has focused on the development of high field toroidal plasma confinement devices based on the tokamak configuration. The first device in this category, Alcator A, has been operating successfully during the period 1972 to the present, and has produced a number of important results which have had great impact on the field of controlled thermonuclear fusion research.

Among these results we cite the production of tokamak discharges at plasma densities one order of magnitude higher than has been achieved in any other tokamak. This has allowed variation of the operating parameters over unprecedented ranges, making it possible to show clearly that the energy confinement time, τ_E , in tokamaks increases in proportion to the density n . By exploiting this result at the highest density ($n \approx 1 \times 10^{15} \text{ cm}^{-3}$) values of $n\tau_E$ product and is only a factor of three less than the minimum required for breakeven at higher temperatures.

An equally important result is the production of discharges with extremely low impurity content; the effective charge, Z_{eff} , of Alcator discharges is typically in the vicinity of 1.05 to 1.2 as shown by a number of independent techniques of measurement. It has long been realized that a relatively small concentration of impurities could inhibit ignition in fusion reactors. Thus the result of $Z_{\text{eff}} \approx 1$ and the methods employed to achieve this result have set a standard by which other tokamaks are measured, and given encouragement to the belief that impurities in reactors can likewise be controlled.

It should also be mentioned that Alcator A was the first tokamak to operate in the opaque regime, where the mean free path of a neutral atom with the energy of a thermal ion was less than the minor radius. In this case, the neutral atom density drops to levels determined by recombination. This regime simulates that expected in a reactor and demonstrates successful application of the plasma blanket concept of shielding the vacuum wall.

The major results of the Alcator A program have led to the development of a sequence of machines leading ultimately to a demonstration reactor. The next device, Alcator C, has been designed and is under construction with operation scheduled to begin early in Calendar Year 1978. The goal is to achieve $n\tau_E$ of $2 \times 10^{14} \text{ sec-cm}^{-3}$ at an ion temperature of 2 keV or more. This device is an extension of the advanced technology developed for Alcator A. The toroidal Bitter magnet has steel strengthening plates which are keyed to the magnet plates, rather than relying on a frictional bond as in the A device. This permits a design field of 140 kG. The air core transformer and vertical field systems are similar to those of the A device, but more extensive use of thyristor-controlled power supplies is planned in order to energize and control these systems. The vacuum chamber is again similar to that in A, but the plasma radius is increased from 10 cm to 17 cm. Thus, Alcator C should retain all of the features of A, and allow even higher field operation with greatly improved confinement times owing to the larger size.

Of central importance to the C machine and a beam-heated modification now under design is the procurement of a 225 MVA alternator. This machine will be installed in the parking

lot of the National Magnet Laboratory near the end of 1977, and will be capable of powering the Alcator C device to full design values by the end of 1978. Calculations indicate that a beam-heated version of Alcator C, powered by the same alternator, should be capable of approaching $Q_{eg} \approx 1$, that is in a D-T mixture, net fusion power output equal to external power input. Preliminary designs of the beam-heated version of Alcator C are underway, with a tentative target date of late 1980 being established for completion.

In summary, advances achieved in the confinement program during the last 5 years have had profound impact upon the understanding of tokamak devices. New regimes have been explored at plasma densities one order of magnitude larger than any other tokamak. These regimes and the advanced technology developed for Alcator has led to a sequence of experimental devices which are scheduled to meet major milestones on the path to fusion power generation. More detailed summaries of the last year's research are given below.

I. Energy Confinement Studies

Nearly classical behavior, from the viewpoint of energy confinement, is observed in the Alcator tokamak. Stable discharges, free of disruptions, with peak density of 10^{15} cm^{-3} have been obtained in deuterium at toroidal fields of $B_T = 6\text{--}8 \text{ T}$. Nearly complete thermal equilibration between electrons and ions obtains, with electron and ion temperatures close to 1 keV. The highest density so far achieved is $\bar{n}_e = 6 \times 10^{14} \text{ cm}^{-3}$; the corresponding $n_0 \tau_E \approx 2 \times 10^{13} \text{ cm}^{-3} \text{ s}$. The measured global energy confinement time τ_E still follows the empirical law observed for lower densities, $\tau_E \approx 1.7 q n_{14} \text{ msec}$ (Fig. 1). The central region of the plasma column, however,

Fig. 1. The global energy confinement time τ_E as a function of $\bar{n}_e$, showing a linear increase of τ_E for $\bar{n}_e > 10^{14} \text{ cm}^{-3}$.
 $B_T = 6.0 \text{ T}$, $150 \text{ kA} < I_p < 195 \text{ kA}$.

shows behavior characteristic of the neo-classical ion thermal conductivity dominated regime, the anomalous electron heat conductivity appearing at lower densities having decreased. Thus, energy confinement at the plasma center does not further improve with increasing density at fixed toroidal field and current (Fig. 2). The measured heat flux in the central core of the plasma is in agreement with the neo-classical ion heat flux. The electron heat flux remains anomalous in the outer regions of the plasma where only a small fraction of the total plasma energy resides. Values of the global energy confinement time (τ_E) and poloidal beta (β_θ) are consistent with neo-classical estimates.

Fig. 2 Central confinement time τ_{EO} as a function of peak density. $B_T = 6.0$ T, $150 \text{ kA} < I_p < 185 \text{ kA}$.

II. Fluctuation and Turbulence Measurements

A cylindrical molybdenum Langmuir probe has been used to look at floating potential fluctuations in the limiter shadow. A broad-band frequency spectrum is observed to be relatively flat from 5-300 kHz, then decreases linearly out to 10 MHz. Within 0.7 cm of the limiter edge, the fluctuation amplitude is relatively constant, dropping abruptly by 30-40 db at this point, and thereafter remaining constant out to the bellows. Simultaneous with the injection of neutral gas, a broad-band precipitous drop of ≈ 20 db in the fluctuation level has been observed. Such behavior may be associated with what appears to be a transient density inversion. No other systematic dependence of the fluctuation amplitude on average plasma density has been observed.

The modulation of microwaves reflected from the cutoff surface ($n_e = 2.4 \times 10^{14} \text{ cm}^{-3}$) has also been investigated. Again a broad-band frequency spectrum of unresolved k has been found. The modulation amplitude increases as the cutoff surface moves out away from the plasma center, and appears to peak around the rational q surface of $q = 3$; however, $m = 3$ MHD activity was observed on the pickup loops.

Heterodyne detection of small angle scattering of CO_2 laser radiation has also been employed to study electron density fluctuations. Chord averaged values for the wave vector and frequency spectra indicated a turbulent spectra from 0-1 MHz with wavelengths of 1 mm

1 cm and $k_r, k_\theta \gg k_z$. No obvious peak in the spectrum for any given k has been found. The chord-averaged value of the density fluctuations, $\tilde{n}$, is found to be such that $\tilde{n}/n$ is approximately constant as a function of $\tilde{n}$.

More recently a technique has been developed which allows us to also make spatial measurements of the fluctuation spectrum by correlating the separately detected scattering light from each of two CO_2 laser beams crossed at 3° . In Alcator the spatial resolution is ≈ 4 cm (HWHM), being limited by the correlation length of the fluctuations, which is estimated to be 1-3 mm. The density fluctuations are peaked near the limiter where $\tilde{n}/n > 0.1$. More precise measurements of the wavenumber and frequency spectra in the plasma center are presently being conducted.

III. Impurities

a. Gaseous Impurities

Routine mass spectroscopic analysis is done on the neutral gas composition in Alcator before and after tokamak operation. Gases such as H_2O , CH_4 , CO , and CO_2 are measured during discharge cleaning and before and after tokamak discharges in order to arrive at a better understanding of the sources of oxygen and carbon impurities. During the first few minutes of discharge cleaning in D_2 at 2.4×10^{-4} Torr, with warm (150°C) walls, the methane and water partial pressures rise rapidly to peak values near 0.2% of the fill pressure and then decrease steadily with time to the range of 0.11% to 0.001%. The main impurity in the working gas is N_2 , in concentrations of between 0.2% and 0.1%. The main impurity in the working gas is N_2 , in concentrations of between 0.2% and 0.01%. This is in agreement with the optical spectroscopic data from tokamak discharges. Additional impurities seem to originate from chemical reactions between the H_2 and D_2 working gas and carbon and oxygen of unknown origin.

b. Impurity Emission in the Vacuum Ultraviolet

A 0.4 m normal incidence monochromator and a 2 m grazing incidence monochromator have been used to study impurity line emission from Alcator plasmas; the total spectral range was $15 \text{ \AA} - 1600 \text{ \AA}$. Oxygen, nitrogen, carbon, molybdenum, iron and chromium impurities have been observed, and their concentrations have been determined using the measured emissions. For a typical high density deuterium discharge, the concentration of the light impurities was a few parts per thousand, while the total metal concentration was about a factor of 100 less. The Z_{eff} inferred is 1.2.

Radial scans of $\text{O VI} - 1032 \text{ \AA}$, $\text{O V} - 630 \text{ \AA}$, and $\text{N V} - 1239 \text{ \AA}$ emission have been performed with the normal incidence instrument. As expected, these ionization states occur in radial shells near the plasma edge ($r \approx 9 \text{ cm}$ for O VI).

However, at high electron densities a large up-down asymmetry in emission is observed. The degree of asymmetry has been measured as a function of electron density and plasma current. Furthermore, the sense of the asymmetry was found to reverse when the direction of the toroidal field was reversed. This change is shown in Fig. 3.

Fig. 3. $\text{O VI} - 1032 \text{ \AA}$ emission integrated along a chord is plotted versus the vertical position of that chord above or below torus mid-plane. Data points are taken on a shot-to-shot basis. Solid circles are points for emission with normal field direction. Open circles are points for emission with reversed field direction.

Plasma parameters for the scans were:

$$n_e = 2.3 \times 10^{14} \text{ cm}^{-3}, I_p = 120 \text{ kA},$$

$$B_T = 5.0 \text{ T}.$$

The experimental evidence strongly suggests that the mechanism responsible for the asymmetry is the VB drift, which causes a vertical gradient in the ionization state number density.

At high electron densities ($n_e > 10^{14}/\text{cm}^3$) impurity ions at the edge of the plasma are deep into the Pfirsch-Schlüter regime; a typical mean-free-path along field lines is about 5 cm, while the top to bottom distance along a field line (πqR) is ≈ 200 cm. Thus, the diffusion time along field lines is about 2000 collision times or 5 msec. In this time the VB drift can carry an ion about 2 cm vertically. As a result, with a "normal" (reversed) toroidal field, most incoming impurity atoms ionized at the top (bottom) of the plasma drift back out before penetrating regions where they are further ionized. However, the incoming impurity atoms ionized at the bottom (top) do drift through regions where T_e is appropriate for subsequent ionization, those highly ionized species drifting up (down) at the top (bottom) of the torus do not recombine fast enough to preserve poloidal symmetry.

c. X-Ray Measurements

A comparison of the observed continuum flux between 1 keV with that expected from a purely hydrogenic plasma yields values of Z_{eff} for deuterium plasmas of 0.9 0.5. An estimate of the central Mo density of $2 \times 10^8 \text{ cm}^{-3}$ has been obtained from the flux of the Mo-L line and reasonable assumptions for excitation and ionization rates. The Mo density shows an increase with minor radius. Electron temperature profiles have been measured out to 6 cm in minor radius, with spatial resolution of 1 cm. Departures of the electron velocity distribution function from a Maxwellian have been observed to increase with increasing plasma current at a fixed density and to decrease with increasing density at a fixed current. Hard x-ray spectra from 400 keV to 5 MeV indicate that the flux is higher as well as harder in the forward direction from the limiter than in the radial direction. A positron annihilation line at 511 keV has been seen in deuterium plasmas.

IV. Ion Temperature Measurement

a. Charge-Exchange Neutral Particle Analysis

Measurements of ion temperature in Alcator have been carried out by energy analysis of charge-exchanged neutrals emitted from the plasma. Central ion temperature has been measured at average plasma densities $\bar{n}_e$ up to $1.5 \times 10^{14} \text{ cm}^{-3}$ employing continuous flow of N_2 in the stripping cell. As the plasma density rises above this value, the outgoing fast neutral flux is severely attenuated. A decrease of order 10^2 is observed in the flux of fast effluent neutrals as the central plasma density is increased beyond $2 \times 10^{14} \text{ cm}^{-3}$, thereby reducing the neutral flux below the sensitivity of the analyzer. However, the sensitivity of the analyzer can be transiently increased by pulsing helium into the stripping cell. Such techniques have extended the range of densities (to $\bar{n} \sim 4 \times 10^{14} \text{ cm}^{-3}$) over which energetic neutral particle flux can be detected.

b. Thermonuclear Neutron Emission

A superior determination of the central ion temperature T_{i0} in the ultra-high-density regime in Alcator is now possible with the use of a calibrated BF_3 long counter system. This allows determination of the total neutron flux produced in the discharge. The thermonuclear neutron production rate, R_N , is given by

$$R_N \sim \frac{n_D^2}{T_i^{2/3}} \exp \left\{ - \frac{18.76}{T_i^{1/3}} \right\},$$

where n_D is the deuteron density and T_i is the ion temperature. The total yield is obtained by integrating over the plasma volume, assuming that the radial deuteron density and temperature profiles are similar to those measured for electrons. Central ion temperature is used as a parameter in these calculations. Comparison of the above with the measured rate yields T_{i0} . At intermediate densities, ion temperatures determined from neutron production and from analysis of neutrals are in good agreement. At very high densities, $\bar{n} > 4 \times 10^{14} \text{ cm}^{-3}$, the difference between T_{e0} and T_{i0} is in agreement with values expected from power balance considerations (Fig. 4). Using an array of long counters, the neutron flux has been found to be isotropic, thus

Fig. 4. Ion temperature determined from neutron production rate. Corresponding central electron temperature is also shown.
 $B_T = 6.0 \text{ T}$, $150 \text{ kA} < I_p < 185 \text{ kA}$.

eliminating any photonuclear neutron contribution to the total neutron flux. In addition, presence of neutrons which originate from electrodisintegration processes is excluded due to lack of correlation between the forward hard x-ray and the neutron fluxes. Energy measurements of the emerging neutrons using fast neutron spectrometers are in progress.

V. Cyclotron Emission Measurements

Observations of emission in the vicinity of the electron cyclotron frequency and its harmonics show the radiation to be polarized; the ratio of extraordinary to ordinary mode intensity is about 2:1. In the thermal spectra, the effects of cold plasma resonances upon propagation of the radiation from emission layer to observation point are evident: (i) the extraordinary mode first harmonic is always suppressed by the upper hybrid resonance layer; (ii) the ordinary mode first harmonic is suppressed when plasma frequency exceeds cyclotron frequency; (iii) for sufficiently high density the second harmonic is also affected by the hybrid cut-off. In the non-thermal spectrum, the broad-band emission is polarized at high frequency but not at lower frequencies. The feature in the vicinity of the plasma frequency at intermediate density is broader than previously observed and almost entirely above ω_{pe} . Internal saw tooth relaxations have been observed in the central temperature even up to peak densities of $7 \times 10^{14} \text{ cm}^{-3}$ (Fig. 5). Temperature profiles deduced from second harmonic cyclotron emission are consistent with Thomson scattering measurements.

Fig. 5. Cyclotron emission measurement of central electron temperature showing sawtooth oscillations. Resistive voltage, 1.8 V/div; plasma current, 55 kA/div; electron density, 10^{14} cm^{-3} /fringe; rel. electron temperature 1 keV/div. Time scale is 20 ms/div; expanded relative electron temperature of 200 eV/div.

SECTION I CONFINEMENT SYSTEMS

Final Report

Contract Number

Alcator "A" & "C" Operations

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Alcator "A" & "C" Operations

Bruno Coppi & Ronald R. Parker

Our magnetic confinement activity emphasizes experiments with high plasma currents and current densities to achieve regimes of thermonuclear interest. These goals can be reached with devices featuring large magnetic fields such as Alcator, or non-circular cross sections such as Rector, or both. We also have developed and are developing a range of advanced diagnostic systems to investigate the dynamics of the plasmas produced. In this latter task we have greatly benefited from the contributions of domestic and European scientists and of their home institutions who have participated in our effort.

With the advances achieved with the Alcator A device, we have been encouraged to consider a sequence of high-field toroidal systems having the ultimate goal of achieving ignition conditions. We have developed a design and begun the construction of Alcator C which we feel represents the next logical step. The purpose of Alcator C is to study the confinement of high-density plasmas in a device of minor radius roughly twice that of Alcator A, and with a toroidal field strength 40% larger. The cornerstone of the Alcator C device is a new 150MW toroidal-field power supply, scheduled for operation in FY'78. Extrapolating the results of Alcator A shows that it should be possible to realize $n\tau \sim 10^{14} \text{sec-cm}^{-3}$ at temperatures between 2 and 3 keV with Alcator C.

Our present and foreseen activity in the field of plasma magnetic confinement involves the use of motor generator sets and rectifiers to produce the confining magnetic field of the Alcator machine and of liquid nitrogen for its cooling. To the best of our knowledge, none of these have any direct adverse or beneficial effects on the environment nor conflict with any Federal, State, regional, or local plans or programs.

Correlation with Other Projects

The high magnetic field and compact dimensions adopted for Alcator make it unique in its class. Its performance can be most closely compared with that of the TFR at Fontenay-aux-Roses (France) and the Frascati Torus (Italy). The performance of the Frascati Torus (confinement time and value of $n\tau$) should lie between that obtained with Alcator A and that expected with Alcator C.

Rector has the purpose of investigating the equilibrium and stability properties of plasmas with non-circular cross sections, and is most closely related to the Doublet experiment carried out by General Atomic, San Diego, California and to the "Finger-Ring" experiment at the Kurchatov Institute in Moscow.

Alcator A

The focus of the Alcator A program during FY'77 has been the further study of the ultra-high-density (UHD) regimes which have so far been produced only in the Alcator device. The machine and plasma operating parameters appropriate to these regimes are given in Table I.

Machine Operating Conditions	Plasma Operating Conditions
$a = 10 \text{ cm (limiter)}$	$2 \times 10^{14} < n_o \lesssim 1.1 \times 10^{15} \text{ cm}^{-3}$
$R = 54 \text{ cm}$	$75 < I_p < 200 \text{ kA}$
$40 \text{ kG} \leq B_T \leq 84 \text{ kG}$	$500 < T_{eo} < 1200 \text{ eV}$
$p_o = 3 \times 10^{-9} \text{ T}$	$\tau_E \lesssim 20 \text{ msec}$
	$\lesssim \beta_o \lesssim$

Table I

Summary of Machine and Plasma Operating Conditions for the Ultra-High Density Regime

The technical performance of the machine has been upgraded in several areas. The liquid nitrogen cooling system has been improved and now allows 80 kG operation at 8 minute intervals with no cumulative heating. The pulsed-gas handling systems have been improved by the use of piezoelectric valves and capacity manometers, and the resultant precision in measurement and control of the gas flow allows a new method of determination of the particle confinement time. Reverse swinging of the OH transformer by a programmable power supply has increased the volt-second capability of the transformer without increase of the stress and has permitted reduction of q to 3.5 in the UHD regime. It is important to emphasize that these improvements have enabled us to show that the UHD regimes are not transient in character, but can be maintained for several energy confinement times, and that further increase in B_T also yields improved physics performance. In this connection, values of $n_o \tau_E$ of about $10^{13} \text{ sec-cm}^{-3}$ have been routinely produced, with maximum values recently obtained of $2 \times 10^{13} \text{ sec-cm}^{-3}$.

In addition to making progress on extending the parameter ranges available on Alcator, we have also improved our basic understanding of our discharges. Recently, an extensive program of UV spectroscopic measurements in collaboration with spectroscopists from Johns Hopkins University has been initiated. The results, based on the measurements of the brightness of transitions in the light impurities have confirmed the more macroscopic measurement of Z_{eff} by conductivity and bremsstrahlung techniques. Specifically, the fractional content of oxygen has been estimated to be at levels

which can account for Z_{eff} between 1.05 and 1.5, depending on discharge conditions. Molybdenum levels, as determined by K_{α} soft x-ray transitions make only an infinitesimal contribution to Z_{eff} .

In another line of research, we have studied the spectral (ω - k) content of density fluctuations using nearly-forward CO_2 -laser scattering techniques. The results obtained so far are of a preliminary nature, but reveal fluctuation levels ($\delta n/n$) of a few percent over the frequency and wave number range (≤ 300 kHz, ≤ 1 cm $^{-1}$) observed. The fluctuation level does not appear to decrease with density, nor is there any substantial dependence on density of the ω - and k - spectrum. Thus the correlation with confinement studies is not readily apparent at this time. These experiments suffer from lack of spatial resolution, and work is underway to improve it. The work is being performed by a group from Bell Telephone Laboratories in collaboration with the members of the Alcator group. In addition, this work is being complemented by fluctuation measurements using probes and 2 mm scattering, and by a novel "scintillation" experiment involving CO_2 -laser scattering.

As a third area of study, we mention extension of the charge exchange method to measure ion temperature in the UHD regime. This is difficult owing to the small neutral flux which occurs for densities above 10^{14} cm $^{-3}$, or where the neutral mean-free path is less than the radius of the machine. Using pulsed-gas in the stripping cell, and thereby operating the cell at pressures in the 10-100 micron range, sufficient signals were obtained to provide measurement of ion temperature at a central density of 5×10^{14} cm $^{-3}$. These measurements have confirmed $T_{\text{io}} = T_{\text{eo}}$ in this regime, as expected from comparison of the electron-ion energy exchange time and the electron energy replacement time. Soviet scientists, A. Kislyakov and Y. Sokolov have played an important role in these measurements.

RECTOR EXPERIMENT

The philosophy and aims of the Rector experiment are indicated in Ref. 1. Construction of this device began in January, 1974 and was completed by June, 1974. The machine was rapidly brought to operation and produced, at first, well confined Tokamak discharges with circular cross section and relatively low stability margin q_s . We recall that the major radius is 57 cm., the minor radius of the plasma chamber, that has the additional function of a continuous limiter, is 17.5 cm and the height of it (the chamber has a rectangular cross section) is 70 cm. In particular, for toroidal magnetic fields of about 4kG a current of 30kA can be routinely obtained with a pulse length of 20 msec. This corresponds to $q_s \approx 3.7$.

The main objective of the experiment is to produce toroidal plasmas with

an elongated cross section, typically 2:1, and compare their MHD equilibrium and stability properties with those of toroidal columns with circular cross section, same major radius and same toroidal field. Prior to Rector the only toroidal experiments aimed at producing elongated cross section were the "Doublet" device of General Atomic, San Diego, California and the "Finger-Ring" device of the Kurchatov Institute, Moscow, USSR. Both of these devices employed at first a properly shaped copper shell in order to generate the desired equilibrium. Rector was designed at the outset with no copper shell, the equilibrium being maintained by a programmed set of conductors surrounding the plasma chamber. In order to obtain a deformed cross section, a "stretching" transverse magnetic field has to be produced. This field alone would tend to make the plasma column unstable to rigid up-down displacements. Therefore, a feedback system based on varying the horizontal component of the equilibrium magnetic field is provided in order to compensate for the destabilizing effect of the "stretching" magnetic field coils. This idea has proven to be experimentally successful and reliable plasma equilibria with elongation 2:1 have been obtained in time for the 1974 I.A.E.A. conference in Tokyo.²

A cross section of the Rector device with its dimensions is shown in Fig. 1. We recall that the index of curvature of the vertical can be changed in discrete steps from $n = 1$ to $n = -1.4$ where $n = R_p/B_z) (dB_z/dR)$. As indicated earlier, Rector has a closed loop feedback system to maintain stable vertical plasma position for $n < 0$.

We have found several similarities between the discharge of this 4 kG device and Alcator that has considerably higher values of the toroidal field. The most striking one is the conditioning of the walls of the vacuum chamber by discharge cleaning and the impurity influx from the wall. In particular, discharge cleaning³ in Rector is done by two methods: Pulsed and C.W. discharge cleaning. A 2 kHz oscillator is used to drive an A.C. current in a hydrogen plasma inside the chamber by energizing the Ohmic heating coils. The latter mode delivers 7 kW of continuous power to the plasma, the former about 20kW of power during a 20 msec. pulse at a rate of 2 per second.

In the past year the main objective of the experiment was to implement a 90° Thomson scattering system to measure radial distributions of T_e and n_e for the different cross sections of the plasma column that can be obtained⁴ and to use the 4-mm microwave interferometer to measure the line integrated density in the vertical direction. Profiles of electron density, temperature, and pressure ($n_e T_e$) and constant pressure contours were obtained for different values of the index of curvature. Four profiles, each at a different time into the discharge and at approximately the same pressure and under approximately the same conditions, were measured⁵ at an index of curvature of $n = -1.1$. No profiles were measured for an index of curvature of $n = -0.4$ because of the

CROSS SECTION OF
RECTOR DEVICE

PRESSURE CONTOURS IN RECTOR

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(FIG. 2)

$$n_{e0} = 1.7 \cdot 10^{13} \text{ cm}^{-3}$$

$$T_{e0} = 69 \text{ eV}$$

$$I_p = 40 \text{ kA}$$

$$\tau_E = 0.16 \text{ msec}$$

$$\beta = 0.11 \%$$

$$n = -\frac{R_p}{B_z} \frac{\partial B_z}{\partial R} = -1.1$$

low electron density at the closest off-axis port. However, stable discharges were obtained for $n=-1.5$ with feedback control of the up-down position of the plasma.

The machine operation was optimized with respect to operation parameters and instrumentation. A new Thomson-scattering ruby laser oscillator has recently been installed to improve the diagnostics.

A pressure contour map of the Rector plasma derived for an index of curvature of $n=-1.1$ of the equilibrium field is shown in Fig. 2.⁵ This was taken at 3 msec from the beginning of the discharge. We have measured a 30-50% increase in the plasma current but no significant increase in T_e and n_e in the transition from a circular plasma to a deformed cross section plasma. Further investigation is necessary in order to confirm this indication.

We have also conducted a series of discharge cleaning experiments on the conditioning of the wall of the vacuum chamber in connection with our study of deformed cross section plasma columns because the increase in Z_{eff} due to desorption of impurities from the wall can change the equilibrium configuration by increasing the number of high energy electrons. Thomson scattering profiles in Rector indicate a $Z_{eff} \approx 1$, which confirms the effectiveness of our discharge cleaning procedure.

It has been found from discharge cleaning techniques that the desorption of impurities is a strong function of the amount of hydrogen on the vacuum chamber walls. Impurity desorption is greatest when the walls are saturated with hydrogen. Also, the time needed to saturate the walls with hydrogen depends on the vacuum chamber history (condition). Pulsed discharge cleaning is found to rid the stainless steel walls of carbon, while C.W. discharge cleaning extracts oxygen (the main contaminant being water) and nitrogen. Impurity origin and stable molecule formation mechanisms have been suggested.

An investigation of the MHD modes⁷ present in the plasma as a function of the plasma cross section has been carried out to provide some contact with the existing theories on MHD instabilities in non-circular plasma columns. A study of the high frequency radiation emitted from the plasma is now being carried out with the construction and application of a RF-probe.

We have developed a set of numerical codes for the study of the relevant equilibrium configurations and of their MHD stability on the magnetic axis, while an additional code concerning the evaluation of these non-circular equilibria has been developed by S.A.I. (San Diego, California).

The present objective is to plan and implement transfer of the Rector system (minus main field capacitor banks) from the basement of Building NW14 to the first floor of the adjacent Building NW13, to provide it with more

space as needed by the diagnostic system we intend to install on it. Arrangements for the movement of the main field bank to a position directly beneath Rector's new location (basement of NW13) are being made. This would prevent any additional disruptions of machine operation when the main capacitor bank will also have to be moved in order to make space for Alcator C. The time needed to move the system and bring it back up to normal operation is estimated as two months.

Experiments involving a modulation of the vertical field in order to study processes of resonant heating at relatively low frequencies will be performed. The work necessary to prepare these experiments will be carried out while waiting for the resumption of operation of the machine.

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Alcator C

Operating funds for FY'77 were requested for the purpose of preparing diagnostic systems and instrumentation for the operation of Alcator C, scheduled to begin January, 1978. Progress has been made in the following diagnostic systems.

<u>Diagnostic</u>	<u>Purpose</u>
Multichannel Ruby Laser Scattering System	Measurement of T_e and n at several spatial positions and at several times during the discharge
Neutral Particle Spectrometer	Measurement of spatial profile T_i and neutral density as functions of time
Multichannel, Submillimeter Laser Interferometer	Measurement of spatial profile of electron density as a function of time
Rogowski Loops, $m=2,3,\dots$ Coils, Fast Pickup Coils and Voltage Loops	Measurement of plasma current, voltage and current channel deformations.

In addition to the above, we foresee use of more advanced systems such as a soft x-ray crystal spectrometer for measuring ion temperature and impurity change states, and an ion Thomson-scattering experiment using either a high-power pulsed methylfluoride laser or nearly-forward scattering of a pulsed CO_2 laser. As has been our style, we intend to continue collaboration with European laboratories and other M.I.T. and U.S. groups in the development of basic and advanced diagnostic systems.

Additional progress has been made in the instrumentation and control area. A 6-channel prototype sequencer has been designed, constructed and successfully tested on Alcator A. The complete sequencer system for Alcator C will be built during the summer of 1977. A new switch, consisting of 3 vacuum interrupters separately actuated by electronically controllable timers has also been constructed and tested to 20kA on Alcator A. This development, which represents upgraded technology based on the Alcator A device, assures reliable switching for the larger Alcator C transformer. Techniques of OH and equilibrium field control are now being developed on Alcator A and these techniques will be transferred to Alcator C. Finally, new vacuum components are being tested and evaluated for use on Alcator C. Our philosophy is that new components must outperform their counterparts on Alcator A (lower outgassing rate, cleaner mass spectra, increased reliability) in order to be adopted for the C device. We are especially interested at this time in evaluation of oil-free turbomolecular pumps, metal seal gate-valves and use of indium O-rings for sealing glass to metal. In our view, the maintenance of

conditions appropriate to producing $Z_{\text{eff}} \sim 1$ is as important as the utilization of high current densities in achieving the ultra-high density regimes.

We remark that the easy transfer of people and technology from the A-device to the C-device as well as the ability to test prototype systems on A under actual operating conditions should allow for a smooth and productive start-up phase for Alcator C.

MDF

In June, 1975 we gave a presentation at ERDA headquarters on a series of experiments that should follow along the line of Alcator A in order to try attaining ignition conditions in a device of relatively small size but capable of producing high plasma currents and current densities. Thus in August, 1975, and December, 1975, we submitted the proposals for an Alcator B device, following the lines discussed in our Form 189 for FY'76 and for a more advanced device, Alcator C, of the same size as Alcator B but with magnetic fields exceeding 140kG. Authorization to proceed with the design of the basic tokamak, common to either the B or C machine was given in March, 1976. An options document discussing various power supply alternatives for the C machine was submitted in April, 1976, and a final proposal for the most attractive option in August, 1976. Authorization to proceed with the full C machine was granted in August, 1976.

The following are the performance goals and physics parameters for the C machine.

PERFORMANCE GOALSAlcator C

Magnetic field at plasma axis	14T
Volt seconds (air core transformer system)	1.9 single swing 0.4 EF
TF flat top length (at full field)	0.5 sec
(at half field)	1.0 sec
Ripple (at plasma surface)	5%
Ripple (at plasma center)	1%
Vacuum chamber design base pressure	2×10^{-9} torr
Plasma current (max) I_p	1 MA

PHYSICS PARAMETERS

Ohmically heated plasma parameters (for $I = 1000$ kA, $n_e = 10^{15}/\text{cm}^3$)		
Electron temperature, $T_e(0)$	$\sim 2\text{keV}$	
Ion temperature $T_i(0)$		
Beta poloidal,	$\langle \beta_p \rangle \sim 1$	
Energy confinement		
time,	τ_E	~ 100 msec
Impurity change	Z_{eff}	≈ 1
Average density	$\hat{n}$	$> 10^{15} \text{ cm}^{-3}$
Density-confinement		
time product,	$n_0 \tau$	$\sim 10^{14} \text{ sec cm}^{-3}$

To meet these performance goals, the following base-line reference design characteristics have been developed.

ALCATOR C BASELINE REFERENCE DESIGN

PHYSICAL CHARACTERISTICS

PLASMA

Cross-section shape	Circular
Major radius (nominal)	64 cm
Minor radius (nominal)	17 cm
Plasma volume	130 liters

TOROIDAL FIELD SYSTEM

Number of plates	240
Plate shape	Square, wedge with central hole
Plate dimension	80 cm sq. 43 cm dia. hole
Conductor material	Copper
Coolant	Liquid nitrogen

EQUILIBRIUM FIELD SYSTEM

Number of coils	12
Coil shape	Circular with rec- tangular cross-section
Coil Dimensions (nominal largest coil)	180 cm ID; 5 cm x 10.0 cm
Conductor material	Copper
Coolant	Liquid nitrogen

OHMIC HEATING SYSTEM (Poloidal Field)

Type of system	Air-core
Number of coils	5
Number of turns	290
Coil dimensions (main coil)	46 cm OD, 80 cm length
Conductor material	Copper
Coolant	Liquid nitrogen

VACUUM CHAMBER PUMPING

Pump type	Turbo-molecular, LN ₂ trapped
Speed (each pump)	500 l/sec
Number of stations	3

PRIMARY VACUUM VESSEL

Material	304L Stainless steel
Cross-section shape	Circular
Dimensions	34 cm limiter ID
Cleaning	Bake out and plasma discharge
Vacuum access parts number	6 x 3 = 18
Size (nominal)	min 2 cm x 30 cm, max 4.5 cm x 30 cm

ELECTRICAL POWER SYSTEMS

Prime power	Cambridge Electric Sub-stations 13.8 kV, 20 MVA
Motor alternator	Used alternator GE 200 MVA Motor Driven (2000 HP)
Toroidal field	Controlled rectifier system (nominally 700 volts @ 200 kA) 140 MW
Ohmic field	Controlled rectifier system (two units, nominally 750 volts @ 25 kA each) 40 MW

SECTION II

PLASMA CONFINEMENT THEORY

Principal Investigators

Bruno Coppi and George Bekefi

SCOPEPART 1. RF Heating of Tokamak Plasmas

This research is of importance to the need for supplementary heating of tokamak plasmas. Theoretical studies are being carried out to determine the extent of the penetration of microwave power, near and above the lower hybrid frequency, into a tokamak through the density gradient. Further study is under way concerning the nonlinear processes by which the associated field energy can be imparted to the plasma particles and eventually randomized so that plasma heating actually results. The question is also being raised as to what, if any, negative effects might be caused by introducing such fields into a fusion plasma. In particular, the possible effects on the plasma properties are studied.

PART 2. Microturbulence In Tokamak Plasmas

At present, our interest here is focused on studying instabilities that have their energy source in the tail of the electron velocity distribution function. Such tails are prominent in tokamaks when the applied field is moderate, i.e., not so high that the distribution function is in the runaway regime and yet high enough so that the electron density in the tail is an appreciable fraction of the bulk density. There is considerable importance in studying such microinstabilities. First, the weak turbulence resulting from such instabilities may be useful in heating the ions. Second, such turbulence may be useful in eliminating trapped-particle effects and the deleterious instabilities and transport associated with them. Third, it should lead to a better understanding of the formation and/or inhibition of the electron distribution function tail. Finally, such microinstabilities can lead to enhanced transport and/or radiation from a plasma that may be significant for a reactor.

Relationship to Other Projects

Theoretical studies on supplementary plasma heating using lower hybrid waves are also pursued at the Princeton Plasma Physics Laboratories. The contact between the M.I.T and Princeton groups is sufficiently good so that the work is nonoverlapping and complementary in all aspects. During the past year the theory group at General Atomic has also become active in this area and we have initiated reciprocal exchanges of reports on current work. We are also in touch with several smaller efforts in this area at several universities, e.g., the University of California at Los Angeles, University of California at Berkeley, and the University of Maryland. Our theory effort at M.I.T. still remains the most comprehensive one in the sense that we are studying all of the aspects of this type of heating.

We have recently undertaken to organize at M.I.T. a three-day (March 10-12, 1977) workshop on theoretical problems associated with lower hybrid heating, at which we hope to outline the important unsolved problems and coordinate the national effort in this field.

During the past year we have initiated specific calculations relevant to lower hybrid heating in the high-density tokamaks Alcator A and C, and we are currently participating in the design of such experiments on Alcator A.

Microturbulence studies for tokamak plasmas are very widely spread. Such work is pursued at PPPL, NRL, and Maryland U. Our work is uniquely focused on understanding phenomena observed in the Alcator tokamak in both its low- and high-density regimes of operation.

Technical Progress

Several aspects related to RF heating with external power near the lower hybrid frequency have been analyzed in detail:

1) A three-dimensional WKB formulation of group velocity ray tracing for a tokamak plasma has been completed and readied for computations; this includes the effects of toroidal geometry, and plasma and magnetic field inhomogeneity.

2) Nonlinear phenomena associated with the propagation of high powers from localized sources at the wall have been studied. These include self-modulation and parametric excitations.

3) Several heating mechanisms have also been treated in some detail. These include:

- a) Electron heating by the lower hybrid fields propagating in resonance cone structures in the plasmas.
- b) Stochastic ion heating induced by either the large amplitude and shortwave length lower hybrid fields or by their parametrically excited fields.
- c) Heating by parametric decay waves coupling to electrons and/or ions, which we have emphasized in the past.

Several detailed reviews of our work have been presented this past year. Many aspects of the above work are still incomplete and continue to receive our attention. Our work has included feasibility studies for RF heating experiments on Alcator A which we are currently proposing.

We have also continued our studies of high-frequency microturbulence associated with the runaway tail in tokamak plasmas. This includes three interrelated aspects: (1) anomalous radiation associated with instabilities driven by the electron velocity distribution function tail; (2) evolution of the electron velocity distribution function in the presence of the applied E-field and the generated turbulence by the instabilities; and (3) anomalous

ion-heating which has also been observed. In the past year we have begun to tie these together. A study on the generation of unstable plasma waves by a model electron distribution function has been completed. A quasilinear analysis of the tail evolution has been initiated and is nearly completed. An important result of this work is that the power radiated by these instabilities can be an appreciable energy loss mechanism in moderate density tokamaks. In addition, it has importance for supplementary heating schemes in which the tail of the electron velocity distribution function may be modified significantly.

Scope and Relationship to Other Projects

One of the main lines of theoretical interest at M.I.T. concerns the effects of fluctuations and turbulence, as well as collisions, on the transport properties of high temperature plasmas. A considerable part of this activity has been carried out in collaboration with students and visiting scientists. Part of the relevant numerical work that was developed for this in the past was supported by European research institutions or carried out in collaboration with ERDA sponsored laboratories such as L.L.L., N.R.L. and S.A.I.

Most of the problems on which we have focused our attention have been suggested by recent experimental observations in Alcator and, in a broad sense, are directed toward providing an explanation for them.

In addition, we have taken steps to provide direct analytical and numerical support for a first hand understanding of the experimental data produced by Alcator A and to be produced by Alcator C. Some of our work is also used as guidance for future directions to be taken by our program. Then we list some of the topics on which work has been carried out or that are being undertaken for investigation.

Technical Progress

Description of Research Interests

1) "Ubiquitous" Mode

The properties of the "ubiquitous" trapped particle mode, found here about two years ago, have attracted the keen interest of a team of Soviet colleagues headed by A.B. Mikhailovski, and we have had fruitful exchanges of ideas with them. Meanwhile, we have written a comprehensive paper (Theory of Ubiquitous Mode) that has been issued as a M.I.T. report and has been submitted for publication in Nuclear Fusion.

In particular we have found that in the presence of a realistic ion temperature gradient as compared to the relative density gradient:

a) a fluid-like instability, driven by the unfavorable magnetic curvature drift of trapped electrons and of the ions "caught" by the mode drifting on the outer (unfavorable) side of the plasma cross section, can be excited with wavelengths considerably larger than the ion-gyroradius and

b) a new unstable "odd" mode can be found, in the sense that the relevant electric potential is odd around the point of minimum magnetic field on a given line of force.

We have also completed the analysis of a collisional version of the same modes while our Soviet colleagues have produced a preliminary study of the electro-magnetic versions of the same type of modes. Now we intend to proceed to investigate the connection between

these modes and the finite- β MHD ballooning modes that have been found by the numerical analysis of our Princeton colleagues. Since the ubiquitous mode can be nearly purely growing, at worst, it is a good candidate to explain the formation of convective cells which, in addition to fluctuations, may be responsible for the observed anomalous transport losses in toroidal confinement configurations. Therefore, we also intend to investigate the formation of these cells on the basis of the linear theory that we have developed for the same modes.

2) Internal Oscillations

Resistive modes driven by the current induced in a toroidal plasma column can be excited and observed in the form of internal oscillations. We have found, after providing the first analytical formulation of $m = 1$ modes, that the stability properties of all these kinds of modes are strongly improved in relatively high temperature regimes where the effects of finite ion gyroradius, electrical resistivity, electron drift wave frequency and ion-ion collisions become important at the same time. We have solved the relevant equations both analytically, in significant asymptotic limits, and numerically in order to connect all these limits. After completing this task, we intend to undertake that of analyzing the non-linear evolution of these modes with the collaboration of Prof. Lin's group in the Applied Mathematics Department of M.I.T. Part of our work has been carried out and published in collaboration with colleagues at Princeton.

We have reported the state of our work and our new favorable results at the Sherwood Meeting in Madison, Wisconsin, at the I.A.E.A. Conference in Berchtesgaden (Germany), at the Varenna Symposium and at the A.P.S. Meeting in San Francisco. In addition to the paper presented in Berchtesgaden we have written two M.I.T. reports that will be submitted to Nuclear Fusion. A new paper, that includes our work and that of colleagues from the Institute of Advanced Study and discusses interpretation of available experimental observations, is being prepared.

3) Compact Magnetic Configurations

We are investigating the MHD equilibrium stability properties of configurations with relatively low aspect ratios. Configurations of this type can, in fact, achieve finite- β equilibria without relying on magnetic flux conservation. We are developing our work as a follow-up of the studies made for the JET experiment and we intend to integrate the conclusions obtained from the existing MHD analysis with the results expected from a kinetic theory that is appropriate for the high temperature regimes at which the relevant devices are expected to operate.

4) Weakly and Strongly Ballooning Modes

A revival of interest in finite- β equilibrium configurations has finally led us to see that the main roadblock to their realization is the stability of MHD ballooning modes. The first theory for modes of this kind was produced more than 10 years ago and a more general basis for their analytical treatment in toroidal geometry has been developed in connection with the theory of trapped particle modes. By combining the available results it is possible in our opinion, to provide an analytical frame for a better understanding

of the results that are being obtained by the use of the complex MHD codes such as those developed at Oak Ridge and Princeton. An analytic description, in addition, should provide reasonably simple stability criteria and indicate the limits wherein the MHD approximation breaks down.

According to our point of view, ballooning modes can be separated into two classes:

- a) weakly ballooning, or nearly flute modes, whose spatial dependence along the magnetic field can be represented by the first two terms in the relevant Fourier series.
- b) strongly ballooning modes, whose representation requires a large number of harmonics and which are not strongly affected by magnetic shear.

In addition to trying to provide a unified formulation of the relevant theory in the MHD limit, we intend to develop a moment equation treatment that includes relevant transport coefficients and finite Larmor radius effects. We also intend to connect this theory with that of trapped particle modes and with the "ubiquitous" mode, in particular.

5) Numerical Simulation of High Density Regimes in Alcator

A transport model that appears to be appropriate for the interpretation of the results of the high density regimes realized in Alcator has been adopted as a basis for our simulation effort. The final nearly-stationary phase of the discharge has been computed numerically starting from a pre-existing transport code, developed primarily by Duchs, and modifying it in order to take into account the anomalous transport of particle and thermal energy across the magnetic field. The assumed model for this is consistent with the experimental observation of energy replacement and particle confinement times increasing with density. The introduction of a modified form of electrical resistivity anomaly factor dependent on the radial variable, is also needed in order to reproduce the peaked temperature profiles that have been observed experimentally. Impurities are assumed to be absent from most of the plasma current channel.

A report on this work has been included in the Proceedings of the 1976 Varenna Symposium and a more extensive one will be submitted to Nuclear Fusion.

6) The Ion-Mixing Mode and the Problem of Inward Particle Transport

The high density regimes produced in Alcator have been attained by injection of neutral gas during a properly staged rise phase of the current. We have analyzed a number of models based on classical collisional transport processes in order to explain the rate of plasma density rise for the considered regimes and kept in close communication with interested colleagues at Princeton, Garching, and Jutphaas. So far we have not found a satisfactory model of this kind and, therefore, we have embarked on the study of possible microinstabilities which can provide a sufficiently high inward transport of cold plasma.

Our assumption is that as a result of the vigorous Ohmic heating in Alcator, a layer of relatively cold plasma is produced by ionization of the injected gas at the edge of the plasma column. We find that a fluid-like instability can develop when the electron density gradient tends to become smaller than that of each of the ion populations at the edge of the plasma column. The effect of the instability is to produce a mixing of the two ion

populations and, at a slightly lower rate, an inward transport of both electrons and ions. We are now attempting to include an appropriate inward diffusion process in our one dimensional transport code in order to stimulate the density rise phase. We have presented a preliminary report of this work at the A.P.S. meeting in San Francisco (November, 1976).

7) Energy and Particle Confinement Scaling in Alcator

A search for possible modes that may be suitable to explain the observed relationship between the electron temperature, the plasma current and the so-called safety factor q in Alcator, has been carried out. This relationship is related to the observation that the confinement time tends to improve as the density is increased up to a limit that is consistent with that predicted by the collisional theory. The mode that appears to have most of the needed features is of the electron drift type and is driven by the deformation of the electron distribution, when a fraction of the electron population is magnetically trapped. A derivation of the relevant stability conditions and nonlinear diffusion coefficient has been given and two papers on the subject have been published.

8) Temperature Profile Control by Auxiliary Heating Systems

We have continued our study of compact experiments having the purpose to investigate the α -particle heating of toroidal plasmas in which the ion and electron temperatures are kept approximately equal by a sufficiently high electron-ion collision frequency. In this connection we have analyzed the effectiveness of auxiliary heating systems that can raise the temperature near the edge of the plasma column and tend to improve its MHD stability, given the maximum value of the magnetic field that can be produced.

9) Slide-away and Intermediate Regimes

We have continued the work illustrated in last year's proposal on the slide-away and intermediate regimes identified in Alcator, at first, and then in other toroidal confinement experiments. For this we have collaborated with NRL in developing a code that gives the electron distribution function and the electrical resistivity when a fraction of the electron population is trapped and does not carry current. The assumed model includes the effects of collisions only and, in significant asymptotic limits, it recovers the results of the Spitzer-Härm approximation, the Rosenbluth - Hinton - Hazeltine expression of the resistivity, etc. The slide-away and intermediate regimes correspond to relatively high values of the streaming parameters, such that these approximations no longer hold.

A collaboration with the University of Milan is still being maintained. Here a 3D ($V_{||}$, $V_{\perp}$, θ) code for the evaluation of the collisional distribution function has been developed. In addition, the theory for the onset of the various modes (ω_{pj} , $k \omega_{pe}/k$, etc.) that are excited in the slide-away regime and that has been first exposed in our Nuclear Fusion paper is being developed further and completed. We intend to write a joint paper that should also include results from the French TFR experiment.

10) Theoretical Support to the Rector Experiments

The Rector device has been utilized to produce toroidal equilibrium configurations with non-circular cross section. A mesh of measurements by Thomson scattering has led us to

identify the iso-density and iso-baric surfaces for the first time. We are providing the theoretical support, by our MHD equilibrium and stability numerical code, for the interpretation of the experimental results.

The code we use had been developed in collaboration with the Computing Centers of Garching (I.P.P.) and Bologna (CNEN) and produces equilibria by a conducting shell with arbitrary shape or an arbitrary distribution of current carrying conductors around the plasma column. In addition, we have incorporated into this code, the Soloviev generalized criterion for the stability of all modes that can be radially localized around any magnetic axis, as a special case and covers ballooning modes as well.

11) Neutral Transport in High Density Plasmas

Our treatment of the neutral transport problem was discussed in Form 189 for F/Y 77. The theory has since been extended to include arbitrary density and temperature profiles in the high density (opaque) plasma regime where the typical neutral mean-free path, λ , is small compared to the plasma column radius, a . The neutrals must be treated with kinetic theory since their density gradient scale length is of the order of the mean-free path, and in the opaque regime, charge-exchange many times that, so that a straightforward Born expansion is not accurate. An effective expansion is obtained by summing analytically over all orders of charge-exchange to yield a renormalized series in the small parameter λ/a . The series has been coded to numerically calculate neutral density profiles and emergent charge-exchange flux for arbitrary plasma density and temperature profiles. Three terms of this series give a more accurate result than ten terms of the previous generation method for present Alcator regimes, whereas both methods have about the same computational cost per term. For denser, $n_p \gtrsim 10^{15} \text{ cm}^{-3}$, or larger, $a > 10 \text{ cm}$, tokamaks cumulative numerical errors make the generation method unworkable.

One result of this work has been to strengthen our conclusion that an inward plasma flow is taking place in Alcator and is accounting for the rise of plasma density. This conclusion has now been established from the experimental data alone and becomes virtually undeniable in light of recent Alcator results achieving peak densities in excess of 10^{15} . The importance of this phenomenon for tokamak reactors, specifically in refueling, is clear. Accounting for it will be a primary goal of future theoretical work. There has been some progress already in the identification of an "ion mixing mode" having the general features of the observed inward plasma flux, as indicated earlier.

Meanwhile, our algorithm will be used for calculating the neutral density in the computer studies of high density discharges. In addition, since the charge-exchange measurement on Alcator has been extended to the high density regime, it is necessary to have accurate calculations of charge-exchange spectra in order to make a meaningful determination of the ion temperature.

12) Theory of the Runaway Electron Tail

A problem of considerable theoretical and practical significance is the structure of the high energy electron tail in a current carrying plasma. In the classical theory, high energy electrons cannot be restrained by collisions and runaway in the applied electric field, producing a tail extending to infinite momentum. The theory is in apparent

disagreement with experiment; observations show a smaller runaway rate. While it is clear that noncollisional processes must account for the structure in the runaway region, a theoretical description has not previously been given. At the practical level, substantial energy losses can be caused by the runaways. This is particularly relevant to the anomalous energy transport associated with the electron component of a tokamak. For example, even in thermal equilibrium the energy flux from $\omega = \omega_{pe} k / k$ plasma waves can be larger than from electron thermal conduction. The extended electron tail can destabilize these waves and thus enhance the energy loss.

We have developed a self-consistent theory of the runaway tail together with the plasma wave spectrum it generates. Specifically, we treat the case of a finite magnetized plasma column in an applied electric field. Through the diffusion and friction forces caused by the waves, the particle distribution attains a steady state. Electron runaway to infinite momentum occurs only on the plasma column axis, while at other radii, the distribution is "cut off". This channeling of the runaways may account for the observations of the runaway rate. Energy transport by the waves is larger than that by neoclassical ion thermal conduction and of the order of observed transport in intermediate density tokamaks ($n \sim 3 - 10 \times 10^{13} \text{ cm}^{-3}$). In addition, the observed anomalous feature at $\omega \approx \omega_{pe}$ in the radiation spectrum can be qualitatively explained.

13) Fluid-Ion Cyclotron Instability

A pulsed-single frequency hybrid CO_2 laser for measuring low level long wavelength fluctuations developed by a member of the Alcator experimental group was tested on a magnetically stabilized hydrogen arc and revealed a new type of low frequency wave activity. A mode was then found theoretically: the Fluid-Ion-Cyclotron Instability which accounted, quantitatively, for all the measured data. The predictions gave the correct dispersion relation for arbitrary propagation angle including a 3 MHz modulation of the scattered signal, and the absolute level of the fluctuations.

SECTION III

EXPERIMENTAL PLASMA RESEARCH

Principal Investigators

George Bekefi and Bruno Coppi

Scope

The proposed work will have two parts: the continuation of our work on positive ion sources, and the beginning of a new study of the problem of high voltage (>500 keV) acceleration of negative ion beams.

The work on positive ion sources will focus on the completion of a 7" diameter chamber insulated by cusp magnetic field and excited by an electron beam extracted from a magnetron-type cathode. This will be a continuation of the work we have done on a 4" diameter system. This had an effective plasma area of $\sim 30 \text{ cm}^2$; the new system will have an effective area of $\sim 100 \text{ cm}^2$.

The work on high-voltage systems will study the problems of high-voltage acceleration of negative ions. The issues to be considered are: inter-electrode breakdown, beam focusing, compatibility with high-speed pumping, the reverse acceleration of positive ions, and current interception by the electrodes. The first year's work will be mainly a survey of the relevant literature and high-voltage technology with the aim of designing a paper prototype system of components capable of producing beams with 1-5 MW of power.

Relationship to Other Projects

The positive ion sources are similar to the more recent ORNL design. We are in contact with both ORNL and Lawrence Livermore Laboratory.

Technical Progress

During FY 77 we will have completed the study of the 4" diameter ion source, with detailed studies of terminal characteristics, plasma density and temperature. A Master's thesis by P. Kenyon will summarize this work. We have begun the study of the 7" system and are measuring operation with the extractor plane at various potentials between that of the chamber (ground) and of the cathodes ($-V_k$, reflex operation).

With the magnetron cathode configuration, we can achieve arc power levels of $\sim 10 \text{ kW}$ at 1000 V and 10 amperes. This represents a 10-20 times reduction in cathode demand as compared to existing sources. At these power levels, plasma density exceeds 10^{12} cm^{-3} . On the 4" system we have observed a strong temperature gradient near the extractor electrode; it appears to be due to secondary (or Photo) electron emission into the plasma, replacing escaping hot electrons.

The theory of hot-cathode, low-pressure discharges has been extended to predict the macroscopic behavior of the plasma discharges used for positive ion sources. Quantitative calculations have been made of the Berkeley multi-filament arc and good agreement has been found with published data on:

terminal volt-ampere characteristics, plasma density, and electron temperature. An extension of this model is now being developed to describe discharges such as ours, having rather complex magnetic field structures. This work will be reported this year in a Ph.D thesis by L. Bromberg.

Research Program on Versator Tokamaks

Versator I and II are research-size tokamaks specifically designed to permit rapid modifications and easy accessibility by a variety of diagnostic apparatus which accommodates the research activities of a larger number of graduate students than would be possible on a large-scale device such as Alcator. The systems support a broad program on the physics and technology of hot toroidal discharges. These include:

- (i) Studies of microwave heating and ray tracing near the lower hybrid frequency and electron cyclotron heating (with gyrators as sources presently under development).
- (ii) Impurity studies.
- (iii) $T_{||}$ and $T_{\perp}$ temperature measurements and their radial profiles.
- (iv) New measurements of energy confinement time.
- (v) Measurements of collective fluctuation by microwave scattering.

Relationship to Other Projects

This program is closely coordinated with other Tokamak research, particularly Alcator and its needs.

Technical Progress

(a) Studies on Versator I Tokamak

Under this heading we have completed three pieces of research which are being submitted for publication.

- (i) Quantitative ultraviolet spectroscopy in the range of 1000-2000 Å was used in determining the absolute magnitudes and particle flux of the various impurities in the Versator I tokamak. The details of this work are described in Appendix I.
- (ii) A novel method was used in determining the energy confinement time of the tokamak plasma. In this technique a small supplementary heating pulse was applied and the subsequent electron temperature decay was measured. The rate of decay determined the aforementioned energy confinement time. The results of these studies are described in detail in Appendix II.
- (iii) A study was made on the effect of magnetic field errors on electron runaways. This was accomplished by applying a small vertical perturbing magnetic field at some time during the discharge. The characteristics of the runaways were observed by measuring the hard x-ray emission and the synchrotron radiation from the Versator II

facility. For details see Appendix III.

(b) Construction of the Versator II Tokamak

During F/Y 1977 we are completing construction of the Versator II facility. Assembly of the machine has begun and the first discharge is expected during the Spring of 1977. At that point Versator I will be disassembled and all useful components incorporated in Versator II.

As of April 15 Versator I has been dismantled and Versator II is being assembled. The first discharge is expected early in May 1977.

Scope

The goal of this project is the development of a diagnostic for measurement of the relatively low-frequency turbulence that apparently plays the dominant role in ion transport and heat transfer in plasma confinement devices. Although the original goal of this program was the development of techniques for the analysis of spatially resolved scattering measurements at a wave length chosen for the experimental ease ($10.6\mu\text{m}$), recent developments in high-density confinement in Alcator and elsewhere indicate that the apparatus, experimental technique, and analytical methods developed in this project might be used on Alcator with minimal further development. The experiment in progress is an attempt to measure the low-frequency "ion component" of $10.6\mu\text{m}$ radiation scattered from a HCD-generated steady-state plasma ($n = 5 \times 10^{13}/\text{cm}^3$, $T_e = 10\text{ eV}$). The scattered signal is to be analyzed to deduce first the ion temperature and then, more importantly, the amplitude and spectrum of low-frequency fluctuation. We use the same basic apparatus already used successfully to detect and resolve the high-frequency "electron component" scattering from thermal level density fluctuations in the HCD plasma. These measurements allowed the computation of plasma density through direct measurement of the electron plasma frequency and the conclusion that the high-frequency turbulence level with wave number on the order of 10^5 m^{-1} was very close to the thermal equilibrium value.

Although the project is involved now in scattering experiments in the HCD plasma, both the experimental techniques and theoretical models will be applicable to high-density tokamak experiments. Present experimental parameters ($\alpha = 1.45$ at $\theta_s = 22.5^\circ$) are almost exactly duplicated in existing high-density tokamaks at the same scattering angle ($\alpha = 1.50$ for $n_o = 2 \times 10^{15}/\text{cm}^3$, $t_o = 300\text{ eV}$) and will be useful at reasonable angles even for much higher temperatures. Therefore, we are using our preliminary results and improved analytical understanding to develop the requirements for a high-density tokamak diagnostic with sufficiently high time resolution.

Relationship to Other Projects

The measurement of low-frequency fluctuation spectra in tokamaks and its correlation with observed transport properties is a problem of great importance in the tokamak program, and several candidate diagnostic techniques are under development. Although there clearly is a generic relationship between all these development efforts, especially the microwave scattering experiments, only the relatively short wavelength CO_2 scattering experiments appear to have much potential for detailed spatially resolved probing of high density tokamaks. The M.I.T. program is most closely related to those of UCSD and Bell Laboratories. However, both of those efforts utilize homodyne detection rather than

wavelength filtering for frequency resolution. Therefore, they have potentially higher resolution at very low frequencies but are unable to investigate as wide a frequency range. The homodyne experiments sacrifice spatial resolution and potentially wider bandwidth but have more stringent beam quality and background requirements. The frequency filtering experiment in progress at M.I.T. is more nearly analogous to the right-angle, small- α Thomson scattering experiments presently being carried out to measure electron velocity distributions, albeit it is much more difficult in detail. Despite the differences in experimental resolving technique, there are clearly many common problems encountered in working in this regime. Furthermore, there will be an overlapping but not identical set of measurements obtained by applying both techniques to the same or similar experiments.

Technical Progress

By the end of FY 76, we had detected and resolved scattering from thermal level density fluctuations at the frequencies characteristic of the electron component. The shape of the scattered spectrum agreed well with other measurements as well as with theoretical predictions. We have shown that with proper care in minimizing the thermal background in reducing electronic and detector noise and in stray scattering isolation that Thomson scattering in the coherent regime can be clearly detected and resolved from a plasma close to thermal with density in the range $5 \times 10^{13}/\text{cm}^3$ using a laser of relatively modest power (100 watts). Furthermore, we have shown that the scattered spectrum agrees with theoretical calculations at the electron frequency feature and that the measurements of electron temperature and plasma density derived from the measured spectrum agrees well with those quantities measured by other techniques. We extended the theory of collective scattering phenomena for the particular plasma conditions of our device ($T_e \gg T_i$) and attempted to resolve the ion feature. However, these attempts were not successful because our instrumentation lacked the required sensitivity and resolution. Our measurements were sufficient only to indicate that the level of density fluctuations in the low frequency regime was probably lower than that predicted by collisionless theory. Since the completion of that work, we have analyzed and done experimental measurements to determine the experimental features limiting the sensitivity and resolution. We have substantially rebuilt the detection portion of the apparatus, replaced most of the original optics with Gallium Arsenide, redesigned the mechanical structure of our Fabry-Perot interferometer to eliminate some rather subtle causes of drift and limited resolution, and improved the optical coupling of the interferometer to the detector. We calculate that these changes will be sufficient to make the ion feature observable and resolvable. The completed system is now being reinstalled and optically aligned.

Scope

The measurement of the ion temperature in large, high-density tokamaks is important for understanding and extrapolating the confinement properties of these devices. This work is concerned with the design and construction of a vacuum ultraviolet spectrometer capable of giving spatially and temporally resolved measurements of the ion velocity distribution in such plasmas. The system is based on measurement of the Doppler profile of the Lyman- α (1216 Å) line emitted by neutral hydrogen atoms within the tokamak discharge. The excited neutrals are produced in charge exchange collisions between plasma ions and a high-energy neutral atom beam, which also serves to define the source volume. The Lyman- α line is used because its lifetime is sufficiently short that multiple collisions can be neglected and at this wavelength the signal-to-noise ratio is expected to be large.

Relationship to Other Projects

The spectrometer is being designed specifically for use on the Alcator tokamak, but may be used on other devices with only minor modifications. In contrast to neutral particle energy analyzers presently used for ion temperature measurements, which are limited by the short mean-free path for charge exchange, this system allows measurement of the entire ion temperature profile in high-density tokamaks. Furthermore, unlike collective Thomson scattering measurements, this method gives a direct and unambiguous determination of the ion velocity distribution.

Technical Progress

A detailed optical and mechanical design for this spectrometer has been developed. The instrument proposed is self-contained, rugged, and transportable. It consists of a 12-inch reflecting telescope in a Cassegrain configuration which images the source volume on the entrance slit. The dispersing element is a 316 line/mm echelle grating in a one-meter Czerny-Turner mount. The dispersion is approximately 0.2 Å/mm at the multichannel plate detector.

Scope

The purpose is to explore the frequency range from roughly ω_{pi} to above the upper hybrid frequency for mechanisms related to plasma parameters. We have the following two specific experiments in mind.

1) Measurement of Current Density Fluctuations in a Tokamak

The transmission of a wave $\omega > \sqrt{\omega_p^2 + \omega_{ce}^2}$, through a plasma is commonly used to measure the line integral of density when $E \parallel B_0$. In a sheared magnetic field (due to plasma current in a tokamak), there will be generated a small cross polarized component at the output. The magnitude and phase of this component will depend upon the density and current distributions- $n_e(r)$ and $J_z(r)$. Our computations have shown that the measurement of the complex value and phase of the cross polarized component in a plasma where $B_p/B_0 \approx 0.1$ is technically practical. The proposal here is to study the fluctuations in the cross polarized component and to relate them to fluctuations in a magnetic island formation. Initial studies will be made on Versator II or on Rector.

2) Measurement of Electron Temperature by "Blackbody" Radiation in the Lower Hybrid Frequency Range

The linear theory of penetration of the plasma by rf signals in the lower hybrid range is well developed, and the absorption as a function of r can be calculated. The inverse problem of calculating the thermal radiation arriving at the launcher is very similar in all details. We propose to study the possibility of building a simple secondary thermometer for measuring T_e (approximately averaged over radius).

Relationship to Other Projects

The $n r$ scaling discovered in Alcator is believed to be related to magnetic island formation and fluctuations. There is no direct way of detecting these. X-ray sawtooth oscillations can detect $q = 1$ disruptions that result from island formation. Laser fluctuation measurements by the Bell Telephone Laboratory group on ATC and Alcator are probably related to the same phenomena, but the interpretations are not yet clear. The proposed technique has an output that depends directly on the distribution of the transverse field within the plasma, rather than on secondary effects, and thus it should be an important complement to our diagnostic capabilities.

A simple means for measuring T_e and rapid changes in T_e would be valuable adjunct to the more cumbersome (but absolute) Thomson scattering technique. At temperatures 500-1000 eV, the radiated noise power density should exceed that of a commercial microwave receiver by ~45 dB.

Technical Progress

These are new projects. We have made calculations of the dependence of the complex ratio of E_z / E_0 of the transmitted field on the distribution of the plasma current density $J(\bar{r})$, and these predict first-order changes that depend upon $J(\bar{r})$ for a fixed total current I .

We are studying various low-power couplers to give the desired n spectrum for matching into a plasma at $\omega \approx \omega_{LH}$.

Scope

The proposed work is an experimental study of the behavior of the ion-cyclotron loss cone instability in a minimum B mirror system. The apparatus has been built and is now in operation, with all major diagnostics except for the millimeter wave interferometer, which will be completed by May 1977. We are exploring techniques of stabilization by electron heating. The possible heating techniques are by rf and by electron-beam-plasma interaction. E beams have the advantage of being able to heat the plasma interior, whereas ω_{ce} heating of the interior of a plasma in a min-B field, with $\omega_p > \omega_{ce}$, may not be possible. The axial position of the peak energy deposition, due to E-beam induced oscillations, may be controlled by varying the axial growth rate of the convective instability, which depends on the beam admittance I_o/V_o .

Relationship to Other Projects

We are in close contact with Lawrence Livermore Laboratory, and they encouraged us to use our experience with permanent magnet cusp fields to design this experiment. We are also in contact with the group at United Technologies and have exchanged visits there.

Technical Progress

The basic apparatus is now completed, and we have begun the study of the parametric behavior of the system. The pumping system has a 500 l/s turbo-molecular pump, to maintain the base vacuum and 4 Ti getter pumps in the main chamber, with the central mirror region isolated from the ends by a series of baffles. The plasma gun is energized from a high-voltage delay line with the pulse length controlled by an ignition crowbar. For pulses less than 500 μ sec duration, the peak pressure in the mirror is $< 5 \times 10^{-6}$ for 1 msec after the plasma pulse. Under these conditions we see a repeatable instability at about $4\omega_{ci}$.

A 6-channel data recording system using digital transient recorders has been built and is in use.

A single-channel neutral particle energy analyzer is installed on the system.

An 8 mm interferometer will be operating in May 1977.

In order to lower the ratio of peak cusp field to mirror field, we are moving a larger power supply into this laboratory that will allow us to raise the central axial field > 4 kG. This should also allow us to vary the effective plasma radius over a range $4a_i < r_p < 10 a_i$ where a_i is the ion Larmor radius.

An annular electron gun is being built, and a variable pulse width pulser is being refurbished to produce the electron beam for auxiliary heating.

By the end of FY 77 we expect to have made exploratory measurements, characterizing the confined plasma, identifying the drift cyclotron loss-cone mode, and calibrating our experiment against the results of Joffe, and of 2XII.

Scope

The central effort of this part of our program is the development of new techniques for studying the overall dynamical development of toroidal discharges in a variety of collisionality regimes. Application to tokamaks of standard, as well as to the so-called high-tokamaks, is underway. Treatment in the high collisionality (Pfirsch-Schlüter) regime has been reported earlier. Analysis for more practical operating parameters (lower collisionality) makes use of a generalized drift-kinetic approximation.

The present analysis is being used to interpret corresponding computer studies; comparison with time-resolved experimental data is also beginning. The study is expected to indicate when, or whether significant plasma rotation can be expected to develop under practical operating conditions, and what effects any such rotation might have on the eventual toroidal plasma as a fusion device.

Relationship to Other Products

Our theoretical studies are being carried forward in very close collaboration with the computational work underway at ORNL. Our analytical interpretation of numerical results obtained with the Collisional Plasma Mode (CPM) have from time to time helped to lead to improved versions of the CPM code. At the same time, information gained from the CPM results have led to the improvement of our own analytical models. An example is the development of an improved technique for the use and interpretation of the concept of quasi-neutrality in determining all components of the self-consistent electric field, as various neo-classical equilibria are approached. Comparison of our low-collisionality time-dependent theory, as it matures, with data from Alcator, ORMAK, and other devices beginning to provide time-resolved data, is in its preliminary stages, but is considered an important measure of the success of the present program.

Technical Progress

Completion of our study of the temporal behavior of toroidal discharges, including inertial and viscous effects, in the high-collisionality regime took place in FY'76.

We have now turned our attention to the analytical treatment of the analagous problem at low collisionalities. From our earlier work we are particularly cognizant of the potential presence of a variety of time scales.

The first step required for further progress has been the development of a generalized drift-kinetic equation, in which the principle new feature is the inclusion of a significantly larger self-consistent electric field than that traditionally included. (Inertial effects, when important, are described in the drift-kinetic framework, primarily in terms of the $(\underline{E} \times \underline{B})/B^2$ particle drifts).

Having developed a systematic ordering scheme involving the relative importance of various characteristic time scales or frequencies ($\omega_{\text{transit}}/\Omega_i$, $\nu_{\text{coll}}/\Omega_i$, $\dots$, $\Omega_i = \text{ion gyrofrequency}$), we have attempted to solve the generalized drift kinetic equation at various

orders in these parameters. At each step, an assessment of the relative importance of collisions is made; in many cases it is sufficient to determine the effect of collisions on the individual moment equations for each species.

The moment equations not only provide constraints on our solutions of the kinetic equations but also provide useful guidance in determining the relative importance of various physical phenomena at each phase of the time development of the discharge. This procedure is being followed both for the standard tokamak ordering and for the relatively newer concept of high-beta tokamaks.

Jay Fisher is expected to complete his Ph.D. thesis during the present fiscal year, with primary emphasis on tokamak dynamics at low collisionalities, using the conventional beta-ordering. Of particular interest in this work is the recognition of the possibility of the existence of a certain, very special class of particles. These exist when significant poloidal rotation [or $(\underline{E} \times \underline{B})/c$ drift] is present. Such particles, if they exist, attain purely circular toroidal orbits, see therefore no modulation in the $\underline{B}$ -field, and appear capable of causing enhanced radial transport of angular momentum (enhanced viscosity). Fisher's analysis should provide an indication of the relative importance of this phenomenon, not previously investigated.

Upon completion of the full time-dependent problem in the low collisionality regime, in complete analogy to the Pfirsch-Schlüter problem previously studied, all previously undetermined quantities become unknown, and a preliminary assessment of the value of such a toroidal discharge as a fusion device becomes possible.

Scope

The objective of this program is to provide theoretical support for the magnetic mirror confinement concept and build computational models useful for the analysis of such systems. The critical problem in mirror confinement at the present time is to devise effective means for achieving a more favorable energy balance and a number of concepts such as the tandem mirror, field reversal and linked mirrors, have recently been proposed. A part of our effort is directed towards analysis of the confinement properties and microstability of such a system. A second part of our effort is directed towards incorporation of theoretical results to phenomenological modeling of mirror systems in order to provide insight into synergistic effects, to test concepts and to interpret experiments.

Relationship to Other Projects

This project is intended, at least in part, to complement the much more extensive effort in the mirror program currently going forward at Livermore. As our own work matures, more and more contact with the Livermore group is anticipated. Meanwhile, we are also concentrating on enhancing collaboration between our own theoretical studies and the experimental work going forward at M.I.T. under the direction of L. Smullin. This will require not only improved modeling and systems studies, but also more accurate microinstability studies in a regime appropriate to the actual experiments.

Technical Progress

We are presently concerned with the refinement of a zero and one-dimensional model to include both atomic and plasma physics effects prevalent in current experiments. It is the intent of this program to coordinate our efforts with the major mirror research program at Livermore and elsewhere and to use a combined analytical-computational approach to provide theoretical support for these programs. Systems studies are going forward using both point, or multigroup, plasma modeling, as well as one-dimensional modeling mentioned above. The latter features spatial resolution sufficiently small to describe finite gyro radius effects.

Efforts are underway to set up a numerical study of drift orbits in various types of linked systems, such as the tandem mirror concept.

As our knowledge of the self-consistent space charge improves, our ability to study accurately various microinstabilities will be enhanced. Such improved knowledge will further increase our ability to assess the relative economic advantages of various proposed mirror systems.

A P P E N D I X I

SMALL TOKAMAKS*

(A Survey)

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Today, there exists a class of toroidal devices variously called small-scale tokamaks, research tokamaks, and on occasion - irreverently - junkamaks. Whatever their name may be, they serve as sources of hot, quasi-steady, magnetized plasmas the likes of which cannot be readily generated by other means. Their importance in present day magnetic fusion research can be compared to what the positive column and microwave discharge meant to gaseous electronics and atomic physics in the forties and fifties; and what the Q machine meant to wave-plasma studies in the sixties.

Early pioneering models such as LT-1 and VERSATOR I were rather modest devices somewhat limited by one or another of the following: diagnostic accessibility, vacuum technology, and magnetics technology. Today, while retaining the advantage of relative simplicity, some of the devices¹ (see references 2-30 and Tables 1 and 2) have attained a high degree of sophistication. They take advantage of the versatility which results from smaller magnets to provide good experimental access, and a flexible design which facilitates a wide variety of experiments.

VERSATOR II shown in Fig. 1 is typical of these newer machines. The design emphasizes accessibility: 16 radial and 6 tangential ports

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(30 cm × 5 cm) allow a variety of diagnostics and basic plasma studies to operate simultaneously. They also allow for such possibilities as testing of different rf and neutral beam injection schemes for purposes of supplemental plasma heating. This multiplicity of ports is a consequence of the magnetics system, which uses the "window frame" coils shown in Fig. 1. Since no winding gaps are needed for the ports, field error is minimized (however, this results in a periodic ripple in the toroidal field of $\leq 3\%$ at the outer edge of plasma, and $\leq 0.1\%$ at its center). Careful attention is also paid to vacuum technology. The use of a turbomolecular pump, metal gaskets (aluminum, copper, and indium); viton O-rings, and ceramic insulating breaks separating the two halves of the stainless steel vacuum chamber results in base pressures in the 10^{-8} Torr range. The chamber is regularly cleaned by both continuous and pulsed rf discharges, and a mass spectrometer monitors the impurity concentrations.

Today's "small" tokamaks can be very large (the MACROTOR plasma chamber is physically larger than in PLT or T-10). However, they differ from their "big" counterparts mainly in two respects. First, they operate at magnetic fields typically in the range 5-18 kG, whereas the big ones operate at 25-50 kG and as high as 85 kG. Secondly, small tokamaks have discharges with current pulses that last typically 5-20 msec; the big ones operate with current pulses of 100-300 msec duration. And, while these two items do not make a profound difference in the plasma properties (plasma temperatures are down by factors of 2-5, plasma density is down by factors of 1-10), they have far reaching budgetary implications: the cost of the small-scale tokamaks ($\leq \$100,000$) is two to three orders of magnitude less than that of the large devices.

As was already mentioned, the small as well as the large machines

contain similar plasmas. Both plasmas are governed by the same MHD stability criteria; both exhibit similar instabilities and both follow the same scaling laws. The latter is well illustrated in Fig. 2 which shows a plot³¹ of the energy containment time τ_E (suitably normalized), as a function of the plasma minor radius a_p . It is seen that τ_E (normalized) scales as $a_p^{2.5}$ for big and small machines alike.

Small tokamaks have been playing a visible role in the fusion program. For example, early studies^{15,32} on VERSATOR I and RECTOR discovered the importance of discharge cleaning toward the attainment of low Z_{eff} plasmas. This work has been continued on MICROTOR,³³ where it was shown that the most effective form of cleaning consists of low temperature hydrogen discharges.

Plasma stability has been a major area of research in the small tokamak. The somewhat lower plasma temperatures in some of these devices allows magnetic probes to be inserted into the ionized medium; thus, a direct determination of the poloidal magnetic field (B_θ) surfaces can be made. Using an 18 coil array inserted in the plasma, the LT-3 group³⁴⁻³⁹ has been able to derive complete B_θ , j_ϕ , and E_ϕ profiles of their plasma during the disruptive instability cycle (see Fig. 3). The elusive magnetic island was observed by a direct measurement of B_θ and B_r profiles in MINIMAK,^{16,17,40} and studies on ERASMUS⁴ have shown that a stable plasma with a very tight aspect ratio ($R/a \sim 2.5$) can be maintained.

Modifications of the basic plasma configuration can be incorporated into a small tokamak. One example is the noncircular cross section. The RECTOR²⁰ and TNT¹⁶ research groups have done extensive studies of the pressure profiles and magnetic surface structure of an elongated plasma. In particular, the effects of varying external control fields on the degree of elongation and other properties of the plasma were examined in

the TNT⁴¹ tokamak. Another example is TOSCA²⁶ which has a quadrupole field in addition to the normal tokamak configuration. The designers of JFT-2a incorporated a poloidal divertor in the vacuum chamber to study the properties^{6,42,43,44} of a divertor and its separatrix surface.

Another area of research concerns the study of runaway electrons. The Australian group investigated^{45,46,47,48} the generation of runaways and their subsequent space-time behavior. The effect of a localized magnetic field perturbation on the runaway population was examined⁴⁹ in VERSATOR I.

Small tokamaks which require minimal "downtime" for maintenance or modification (for example, VERSATOR II can be taken apart and completely reassembled in one day) lend themselves to the testing of novel diagnostic techniques. We mention three examples. An HCN laser operating at a wavelength of 337 μ m was incorporated into a Mach-Zehnder interferometer and used^{50,51} on SPAC-II for plasma density measurements.

In LT-3, the density of runaway electrons as a function of radius was determined⁴⁶ using a runaway "target" probe and a runaway "quencher" probe inserted into the plasma and monitoring the hard x-ray signals. This provides information on the magnetic surface structure and the runaway diffusion rate in the plasma.

A new method⁵² of determining the electron energy confinement time τ_E was tested in VERSATOR I which does not require knowledge of the absolute electron temperature and densities, or their spatial profiles. A short (~1 msec) supplementary ohmic heating pulse was imposed on the plasma discharge (see Fig. 4). Well after its termination, the temporal electron temperature decay was determined from electrical conductivity measurements. The e-folding time for the exponential decay (see Fig. 5) gives the energy containment time.

Many studies can be envisioned in which the small tokamak will prove its worth. These include spectroscopy^{53,54,55} of highly stripped atoms, observations of thermal and nonthermal plasma emissions (bremsstrahlung, synchrotron radiation, plasmon-photon conversion), the chemistry of plasma-wall interactions,^{33,56} etc.

Supplemental plasma heating (rf, neutral beams, and electron beams⁵⁷) may be necessary in the tokamak reactor. The research tokamak, owing to its smaller ohmic heating input power and larger port size will be used by several groups to test promising ideas.

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Captions to Figures

Fig. 1 VERSATOR II. Top: Stainless steel vacuum chamber showing both radial and tangential access ports (5 cm $\times$ 30 cm). Bottom: 16 "window frame" toroidal field windings each comprised of 5 turns.

Fig. 2 Normalized energy containment time as a function of plasma radius for small tokamaks (solid circles) and large tokamaks (open circles).

Fig. 3 The evolution of the poloidal magnetic field through a disruptive instability (After I. H. Hutchinson, reference 35).

Fig. 4 (a) Loop voltage, and (b) plasma current in VERSATOR I, for plasmas with no heating pulse and with heating pulses of different amplitudes.

Fig. 5 Electron temperature $\langle T_e \rangle$ from resistivity, for two of the plasmas of Fig. 4. In the insert the difference $\Delta \langle T_e \rangle$ between the two curves is plotted on a logarithmic scale (with the same time scale). The slope yields the electron energy containment time.

Table 1. Small Tokamak Plasma Parameters (numbers in parentheses refer to maximum values).									
Device	R(cm)	2a(cm)	2a _p (cm)	B _t (kG)	I _p (kA)	τ _I (msec)	n _e (10 ¹³ cm ⁻³)	T _{eo} (eV)	τ _E (msec)
CAL TECH	46	30	26	4(5)	15(25)	10(12)	0.1-2.0		
ERASMUS	50	50 × 50	46	3.5(4)	30(50)	13(22)	0.6	300	0.7
JFT-2a	60	28 × 43*	20	10	14	30(40)	1.0	200	0.7
LT-3 (LT-1)	40	20	17	7	20	5	3.0	70	0.1
LT-4	50	28		35					
MACROTOR	100	96 × 150		10					
MICROTOR	30	20 × 25	18	10(25)	40(100)	20	0.05-20	250	3.0
MINIMAK	22.8	16.6	12	9(1.4)	4.4(5.5)	0.8(1.6)	0.7-2.0	7	0.01
PRETEXT	53	32		20					
RECTOR	57.5	35 × 70	11 × 23	3.5	30	14	0.9-1.7	80	0.2
RENTOR	45	30	26	4(6)	20	1.5	1.0	25	
SPAC-II	28	11	11	15(20)	18	1.0	2.5-10	180	0.2
TNT	40	24 × 60	20	3.7(4.4)	40	7(11)		30	
TOSCA	30	20 [†]	16	6(13)	15(25)	1(3)	0.5-5.0	300	0.15(.5)
VERSATOR I	54	28	24	5.5	30(35)	7	2.0	160	0.7
VERSATOR II	40.5	30 × 30		8					

R = major radius; 2a = chamber minor diameter or cross section; 2a_p = plasma minor diameter or cross section;
 B_t = toroidal magnetic field; I_p = plasma current; n_e = average electron density; T_{eo} = peak electron temperature;
 τ_E = energy containment time; τ_I = plasma current pulse length.

* Tear shaped cross section.

† Average diameter (cross section is not precisely circular).

Table 2. Small Tokamak Hardware Parameters

Device	Reference	Total Machine Access (cm ²)	Limiter Type	Limiter Material	Ohmic Heating Transformer Core	Preionization Method*	Plasma Position Stabilization Methods†
CAL TECH	2, 3	174	None		Iron	LC	PVF, PHF
ERASMUS	4, 5	2, 400	None		Air	LC	FVF, FHF
JFT-2a	6, 7	4, 225	Retractable Rail Segments	Au	Iron	ECRH	PVF, CS
LT-3 (LT-1)	8, 9, 10, 11	28	None		Iron	RF	PVF, CS
LT-4	11, 12	351	Diaphragm	Mo	Iron	HES	PVF, PHF
MACROTOR	13, 14, 15	18, 000	Diaphragm	Stainless Steel	Air	LC	PVF, PHF
MICROTOR	13, 14, 15	1, 800	Diaphragm	Stainless Steel	Air	LC	PVF, PHF
MINIMAK	16, 17, 18	608	Diaphragm	Stainless Steel	Iron	HES	CS
PRETEXT	19	651	Diaphragm	Stainless Steel	Iron	LC, ECRH	FVF, FHF
RECTOR	20, 21	585	None		Air	LC	PVF, FHF
RENTOR	22, 23	3, 716	None		Air	RF	PVF, FHF
SPAC-II	24, 25	45	Diaphragm	Mo	Iron	HES	PVF, AS
TNT	16, 18	762	Diaphragm	Mo	Iron	HES	CS
TOSCA	26, 27	138	Retractable Rail Segments	Mo	Air	HES	PVF, PHF
VERSATOR I	28, 29	185	None		Air	LC	PVF, PHF
VERSATOR II	29, 30	3, 351	Rail	Mo	Air	LC	PVF, PHF

* LC = ringing capacitor discharge in ohmic heating transformer. HES = hot electron source (thermionic filament or electron gun). ECRH = electron cyclotron resonance heating. RF = rf applied across opposite segments of the vacuum chamber.

† PVF = programmed vertical field. FVF = vertical field with feedback. PHF = programmed horizontal field. FHF = horizontal field with feedback. CS = toroidal conducting copper shell. AS = toroidal conducting aluminum shell.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

APPENDIX II

A Vacuum Ultraviolet Study of the Disruptive
Instability in a Tokamak

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ABSTRACT

The evolution of the oxygen impurity in the tokamak Versator I has been investigated for both stable and unstable discharges using the absolute intensity and time dependence of vacuum ultraviolet resonance line radiation from oxygen ions. The unstable discharge was characterized by a disruptive instability about one msec into the pulse. It produced a sharp increase in the line intensity from low ionization states and a decrease in line intensity from high ionization states, implying a sudden expansion of the cross-section of the current channel at the time of disruption. A one dimensional code was used to infer the rate of oxygen influx.

I. INTRODUCTION

The disruptive instability in tokamaks has been studied previously using magnetic probes [1], X-ray emission [2], and H α emission [3]. A disruptive instability cycle has also been studied in a toroidal θ - Z pinch machine using magnetic probe diagnostics and non-resonant oxygen emission [4]. We report here on a spectroscopic study of the same instability in the research tokamak Versator I [5] utilizing oxygen ion resonance lines between 450 Å and 1600 Å. Knowledge of the absolute photon flux and the use of resonance lines with well documented atomic parameters allowed us to obtain a model of the space-time development of the instability.

II. EXPERIMENTAL DETAILS

Versator I has a vacuum chamber with a major radius of 54 cm and a minor radius of 14 cm, and has no copper shell or limiter. For the series of experiments described here, the toroidal field, B_T , was ~ 5.5 kgauss on axis, the plasma current was ~ 5.5 kAmp, and the pulse lasted ~ 8 msec. Preliminary results from later spatial measurements of the light intensity, using an Abel inversion technique, show that the plasma radius is 5 - 10 cm [6]. Thus the safety factor

$q = B_T a / B_p R$ was 2 to 3 for $a = 5$ cm, the value assumed in this paper. (B_p is the poloidal magnetic field; a and R are the plasma minor and major radii.) Peak temperatures were approximately 150 eV and the average density was approximately $2 \times 10^{13} \text{ cm}^{-3}$, as estimated from the Spitzer resistivity (with $Z_{\text{eff}} = 2$), Langmuir probe and 8 mm microwave interferometric measurements. (The computer fit described in section III gave $Z_{\text{eff}} \sim 1.5$ for O and C impurities.)

Using a vacuum ultraviolet spectrometer, we monitored the following resonance lines of O II through O VI between 450 and 1600 Å (O II - 539.4 Å, O III - 703.4 Å, O IV - 554.4 Å, O V - 629.7 Å, O VI - 1033.8 Å). The spectrometer was mounted in a magnetically shielded vacuum chamber with its line of sight fixed across a diameter of the plasma cross section. The center of the plasma was ~60 cm away from the spectrometer entrance slit; for most of the measurements the instrument was stopped down to $f/100$, thus providing a 0.6 cm diameter field of view across the plasma. The spectrometer chamber was connected to the discharge chamber through a 10 cm long 3.7 cm diameter liquid nitrogen cooled tube. This cooling was both necessary and sufficient to reduce the flow of contaminants from the spectrometer electronics into the tokamak chamber to a negligibly low level. An estimate shows that ~98% of incoming impurity molecules hit the walls of the connecting tube before reaching the vacuum chamber. If the walls of the tube are

cooled to LN_2 temperatures, many types of contaminants will condense and stick to the surface. Contamination by diagnostics is a common problem and this simple but effective procedure may be applicable to many diagnostic experiments [7].

The 22.5 cm focal length normal incidence spectrometer was very similar to one designed by W. G. Fastie of the Johns Hopkins University for sounding rocket research. It used a 3600 line/mm holographic grating, digital wavelength control, and a windowless photomultiplier detector with integrated pulse counting electronics. The spectral resolutions used in this experiment were 1.5 to 3.0 $\text{\AA}$. The portability due to the small size (6 x 9 x 35 cm), light weight (~ 1 kg), and ruggedness of the instrument permitted absolute sensitivity calibration of the instrument at Johns Hopkins before, during, and after the experiments described here. No significant drifts in the sensitivity were noted.

The sensitivity calibration was achieved by sequentially illuminating first the instrument and then National Bureau of Standards calibrated diodes [8, 9] with a monochromatic beam of light. Both were located in the same vacuum chamber. The technique was similar to that described by Fastie and Kerr [10] for wavelengths above 1150 $\text{\AA}$ but utilized a new facility constructed for the windowless spectral regions

down to 300 Å. The uncertainties in the absolute sensitivity calibration are estimated to be less than $\pm 25\%$, and the uncertainties in the relative sensitivity calibration between different wavelength regions to be less than $\pm 10\%$.

Two modes of Versator operation were obtained by adjustment of the ohmic heating (O H) electric field. In one mode (Moderate O H) the time development of the emission from impurities showed a qualitative evolution similar to that found in other machines; the intensity peaks of lines of successive ionization states occurred at successively later times as the electron temperature rose. Increasing the O H increased the plasma current to an unstable value (with $q \sim 2.6$) at $t = 0.88$ msec and produced negative loop voltage spikes characteristic of the disruptive instability [11] (see Figure 1). A small positive spike was likewise seen in the current trace at this time [1, 2, 12]. Figure 1 also compares the time histories of O II and O VI emissions with and without the instability. At the time of the disruption, the higher ionization states (i. e. , O VI and O V) showed a significant drop in emission whereas emission from the lower ionization states (i. e. , O II and O III) showed a sharp increase.

III. COMPUTER MODEL

To interpret the line emissions we have modeled the oxygen ion evolution both with and without the disruptive instability. In the model we integrated a system of rate equations to solve for the concentration of the oxygen I - IX as a function of time. Terms representing ionization [13], recombination (radiative, collisional, and dielectronic), charged particle loss rate, and fresh impurity influx were included. The volume emission rates of photons were calculated with the aid of theoretical [14] electron excitation rate coefficients. For the transitions considered, population of the upper states by cascade was negligible and the branching ratios to the ground state were 1.

Computations were made for nine adjacent 1 cm thick volume elements along the line of sight passing through the plasma diameter, and then added to give the total light intensity for a given transition. Each unit volume across the plasma diameter was assumed to have the same total oxygen concentration and oxygen influx. For lack of better data from the present machine, the electron density and temperature were assumed to have parabolic profiles over the plasma cross section [15], with peak values taken from the experimental measurements. The temperature during the instability was obtained by interpolation, as the resistivity measurements are unreliable there. In order

to simplify the computations no transport of energy or matter between the elements making up the line of sight was included, and the radius of the plasma was taken to be fixed.

The particle loss rate and the cold oxygen influx as functions of time, and the initial concentration of oxygen I were the adjustable parameters, and they were varied to give the best fit to the experimental O VI time histories. The predicted emission time histories from the other oxygen ions were then fixed in absolute units by the O VI fit. Agreement between the model and experiment for the cases with and without the instability is shown in Fig. 2 for O II and O V. Intensities predicted by the model for O III and O IV (not shown) had the correct temporal behavior, but were uniformly high by a factor of 3. At present we have no explanation for this discrepancy.

We found that the O VI time histories for the stable discharges were matched with a cold oxygen influx of $\sim 2 \times 10^{13}$ particles/sec/cm³, dropping gradually to zero by the end of the pulse. We used a particle loss rate of .05% per μ sec for each species (corresponding to a confinement time of 2 msec), remaining approximately constant in time during most of the discharge. The unstable discharges were best modeled by a sharp increase in the loss rate (by a factor of 10) and a sharp increase in the flux (by a factor of 4) for $\sim 200 \mu$ sec at the time of the instability. It is important to point out that a sudden drop in the temperature alone is insufficient to account for the observed increase in O II and O III radiation intensities during the instability since characteristic recombination

times are much longer than the time intervals during which the O II and O III emissions were observed to rise.

The best physical interpretation of the instability consistent with our results and those of other workers [1, 3, 4, 16] is the following: during the instability the hot plasma suddenly expands into the colder regions surrounding the current channel. The resulting decrease in impurity density and electron density in the hot central core results in a decrease in the number of high ionization state radiators along the field of view of the spectrometer. Our computer program did not allow for change in the plasma radius directly. However, the decrease in density was modeled as a sharp increase in particle loss during the instability period. As the hot plasma column expands into regions containing colder impurities, these impurities are quickly ionized and produce the observed increase in O II and O III, represented in our model by an increase in cold flux.

Presently, the mechanism of the disruptive instability is not understood in detail [1, 16]. Because the concentration of different ionization states of an impurity peak at different plasma radii and hence magnetic surfaces, ion resonance line emissions are useful for studying the disruption. The use of

spatially resolved studies and inversion techniques now in progress [6] will be even more advantageous.

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FIGURES

Figure 1: The time development of the line emission from O VI and O II for both the stable and unstable discharge. The arrow marks the occurrence of the disruption. Transcriptions of the oscilloscope traces of the loop voltage and plasma current are also shown. The solid lines are data from the stable discharge; the dashed lines are data in the presence of the disruptive instability.

Figure 2: Comparison of the model predicted curves (dashed line) with those measured for the resonance lines of the two ionization states O II and O V (solid line). The experimental curves have been averaged from a number of shots; the error bars indicate a standard deviation from that mean.

TIME INTO PULSE (msec)

APPENDIX II

DIRECT DETERMINATION OF THE ELECTRON ENERGY CONFINEMENT

TIME OF A TOKAMAK PLASMA*

by

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Abstract

A method of determining the electron energy confinement time τ_E is presented which does not require the absolute electron temperatures and densities, or their spatial profiles. A short heating pulse is applied to the plasma; the subsequent decay of electron temperature yields τ_E .

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The electron energy confinement time τ_E is an important parameter for assessing the effectiveness of the magnetic confinement of plasmas in tokamak devices. This quantity is defined by the energy balance equation¹

$$dU_e/dt = -U_e/\tau_E + S(t) \quad (1)$$

where

$$U_e = 2\pi R \int_0^a (3/2) n_e T_e 2\pi r dr \quad (2)$$

is the total electron thermal energy contained within a torus of minor radius a and major radius R . T_e and n_e are the (spatially varying) electron temperature and density, respectively. The source function

$$S(t) = (V - L dI/dt)I \quad (3)$$

represents the Joule heating by the current I driven through the plasma. V is the loop voltage (the electric field integrated over $2\pi R$) and L is the inductance of the plasma current loop.

In conventional measurements² of τ_E it is assumed that the plasma is in near steady state with $dU_e/dt = dI/dt \approx 0$, in which case $\tau_E = U_e/VI$. This equation is the basis of all determinations of τ_E made hitherto. It may be seen that the method requires not only the values of T_e and n_e , but also a knowledge of their spatial profiles. Such numbers are not easily found, particularly in tokamaks with noncircular cross sections³ or in stellarators⁴ in which the plasma quantities have complicated distributions. Also, the assumption that $dU_e/dt \approx 0$ is often not a good one, especially in smaller tokamaks where the duration of the discharge τ_D is relatively short.

In this Letter we describe a different method of determining τ_E which does not require knowledge of the absolute values of T_e and n_e and which is also quite insensitive to the spatial profiles of these quantities. A perturbing heating pulse of short duration ($\ll \tau_D$) is applied to the plasma, thus causing a small increase ΔU_e in the kinetic energy of the electrons.

After the heating pulse one observes the temporal decay of the energy increment $\Delta U_e(t)$. Similar concepts have been used for many years in thermal conductivity measurements,^{5,6} but have not yet been applied to tokamak discharges.

This method, like the conventional one, is based on Eq. (1). One compares the equation for two plasma discharges, one with and one without the supplemental heating pulse, and by subtracting one from the other, obtains an equation for the increment ΔU_e . Note that this comparison is made after termination of the pulse. Moreover, since the pulse is taken to be too weak to change the transport properties of the plasma significantly, it follows that n_e , τ_E and the Joule heating term S are unaffected by the presence or absence of the pulse. Hence, ΔU_e is proportional to $\Delta \langle T_e \rangle$ (spatially averaged temperature) and

$$\frac{d}{dt} \Delta U_e = - \frac{\Delta U_e}{\tau_E}, \quad (4)$$

which, for τ_E independent of t , yields the exponential behavior, $\Delta U_e = \Delta U_{e0} \exp(-t/\tau_E)$. This, then, is the basis of our method of finding τ_E on the Versator I tokamak. It is seen to be independent of the values of T_e and n_e or their spatial variation, as long as the heating pulse does not alter the shape of the discharge or its transport characteristics.

Versator I is a research tokamak⁷ of minor radius 14 cm and major radius 54 cm, operating in a toroidal magnetic field of ~5kG, and generating plasma currents of ~5kA. Power is supplied by capacitor banks. The solid lines of Fig. 1 illustrate typical time histories of the loop voltage $V(t)$ and plasma current $I(t)$. The spatially averaged electron temperature $\langle T_e \rangle$ is approximately 150 eV, a value it reaches about 4 ms after initiation of the discharge. The spatially averaged electron density $\langle n_e \rangle \approx 2 \times 10^{13} \text{ cm}^{-3}$. The minor radius of the hot plasma column is ~5 cm.

The plasma is hydrogen with $T_1 \approx 50$ eV; the effective Z lies between 2 and 3.

The heating pulse of about 1 ms duration is applied to the plasma by discharging a supplementary capacitor bank into the ohmic heating transformer. In Fig. 1 the curves labelled 400, 500, and 600V show the effects of pulses of different amplitudes on the voltage and current characteristics of the discharge. For a perturbation analysis, it is desirable to study the smallest possible pulse which produces a measurable change. Because of our present crude temperature measurements (described below), temperature changes $\Delta T_e/T_e$ of about 10% are needed. The 500V pulse is the smallest pulse which causes changes of this magnitude, and consequently it is used in the analysis presented below.

The derivation of Eq. (4) required that the ohmic dissipation term $S(t)$ be unaffected by the pulsed heating perturbation. To verify this fact, we used Eq. (3) and the data of Fig. 1 to compute⁸ $S_0(t)$ for the case without the heating pulse, and $S_1(t)$ for the case with the pulse. Because the heating pulse increases the current, and because the finite width of the pulse extends the duration of the plasma, a relative time shift t' (0.75 ms) is necessary before these two quantities can be compared. We find that to within $\pm 2\%$, $S_0(t)$ and $S_1(t + t')$ are identical in the range $3 \lesssim t \lesssim 5.5$ ms. For $t \lesssim 3$ ms transient phenomena such as skin current penetration into the plasma bulk (see below) are still incomplete; for $t \gtrsim 5.5$ ms (near the end of the discharge) the rapid and irregular decay of the discharge makes our measurements unreliable. But, we believe that in the range $3 \lesssim t \lesssim 5.5$, Eq. (4) can be safely used in the determination of τ_E .

To obtain the electron temperature $\langle T_e \rangle$ we used Spitzer's resistivity formula,⁹ from which it follows that $\langle T_e \rangle \sim [I/(V-LdI/dt)]^{2/3}$. Neoclassical corrections of the formula are small for our discharge.⁹ The results⁸ with and without the heating pulse are shown in Fig. 2. (The time shift t' described above has been incorporated in plotting the graph for the pulse-heated data.) The difference $\Delta \langle T_e \rangle$ between the two curves is proportional to ΔU_e . The slope of the curve of $\log \Delta \langle T_e \rangle$ versus t shown in the insert of Fig. 2 gives an energy confinement time of $\tau_E = 1.1$ ms. This is to be compared to the value of $\tau_E \approx 0.9$ ms obtained from the conventional method based on the equation $\tau_E = U_e / VI$ applicable under steady state conditions.¹⁰ Such quasi-steady state conditions exist in our own discharge at $t \approx 4$ ms.

In conclusion, we have successfully tested a direct and relatively simple pulse-perturbation technique for determining the electron energy confinement time τ_E of a tokamak discharge. The main error arises in our way of obtaining $\langle T_e \rangle$ from the plasma resistivity inferred from the current-voltage characteristics of the discharge. More refined measurements are planned in which the electron temperature decay $T_e(t)$ will be determined from Thomson scattering of laser radiation. A second drawback of the present investigation is the phenomenon of skin current penetration into the plasma bulk. In our discharge, calculations show that the time of penetration τ_s is ≈ 1 ms and one must therefore wait at least this length of time before the temperature decay curve $T_e(t)$ can be interpreted in accordance with Eq. (4). Since for tokamaks it is typical^{1,11} that $\tau_s \geq \tau_E$ and τ_E can be tens of milliseconds, particularly for larger tokamaks, the waiting time becomes unreasonably long. We point out, however, that the perturbing heating pulse can be generated in one of several alternate ways that do not require this long skin penetration time; for

example the plasma can be irradiated by a burst of microwave or laser radiation.

Thomson scattering measurements of T_e are typically performed with an accuracy of 10%. The same method should yield $\langle \Delta T_e \rangle$ with a similar accuracy of 10-15%. This is the major source of error in a pulse perturbation measurement of τ_E . It is unlikely that similar accuracy can be achieved in the conventional technique, since this requires the determination of two parameters, n_e and T_e , plus their spatial profiles.

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The neoclassical corrections [see Ref. 2] to the Spitzer formula due to electrons trapped in banana orbits are small in our discharge ($\leq 5\%$). Also, as long as Z_{eff} remains constant during the measurement, the determination of τ_E is insensitive to the correction factor $\gamma(Z_{\text{eff}})$ of Ref. 2.

10. To calculate U_e from Eq. (2) we assumed parabolic profiles for T_e and n_e . Since these profiles have not been confirmed in our tokamak, the value of $\tau_E = 0.9$ ms must be treated as a crude estimate.
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Figure Captions

Fig. 1 (a) Loop voltage, and (b) plasma current for plasmas with no heating pulse and with heating pulses of different amplitudes.

Fig. 2. Electron temperature $\langle T_e \rangle$ from resistivity, for two of the plasmas of Fig. 1. In the insert the difference $\Delta \langle T_e \rangle$ between the two curves is plotted on a logarithmic scale (with the same time scale). The absolute value of $\langle T_e \rangle$ should be treated as an estimate that may be in error by as much as 20%; however, this does not affect the determination of τ_E .

Fig. 1
Fisher and Bekefi

Fig. 2
Fisher and Bekefi

A P P E N D I X I I I

MAGNETIC EXTRACTION OF RUNAWAY ELECTRONS FROM

A TOKAMAK PLASMA*

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Abstract

A short ($\sim 1/2$ msec) localized vertical field ($\sim 200\text{G}$) is used to extract runaway electrons from a tokamak plasma without affecting the thermal component of the plasma.

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As tokamaks have increased in size toward reactor dimensions, runaway electrons (and their associated hard x-radiation and vacuum shell damage) have become an increasingly important problem. Experimental work¹ has recently been done on the T-6 device on plasma discharges in which the bulk of the current was carried by runaway electrons. By applying a 2-3% inhomogeneity to the toroidal field, the T-6 workers saw the plasma resistivity increase by a factor of 5-6, an increase in the plasma density, and an inward shift of the plasma column, indicating a decrease in the runaway population.

The data presented in this Note add to the previous results by using more sensitive diagnostic equipment to show that a local vertical magnetic field perturbation can be used to suppress a runaway population more typical of fusion plasmas, that is, plasmas in which the runaway population carries only a small fraction of the total current. Further, we show that this extraction occurs without affecting the thermal component of the plasma.

The experiment was performed on Versator I, a small research tokamak. Versator I operating parameters are: major radius $R = 54$ cm, minor radius $a = 14$ cm, toroidal field $B_T = 5$ kG, plasma column radius $a_p = 5$ cm, safety factor $q(a_p) = 2-3$, plasma current $I_p = 5-6$ kA, electron density $n = 2 \times 10^{13} \text{ cm}^{-3}$, electron temperature $T_e = 150$ eV, ion temperature $T_i = 40$ eV, shot duration = 7 msec. The machine has no limiter, but impurity influx pinches the hot current channel to about 5 cm. This effect has been documented by Langmuir probe, microwave interferometer,² and vacuum ultraviolet measurements. The small plasma column radius and low toroidal field limit the plasma current to 5-6 kA through the Kruskal-Shafranov criterion.

In one mode of operation of Versator I we find the generation of a runaway electron population of about one part in 10^4 - 10^6 . We arrive at this estimate by measuring the integrated hard x-ray flux over all solid angles around the torus with a NaI(Tl) crystal scintillator and an ion-pair chamber integrating dosimeter. By placing metal foils in front of the detector, we have determined that the energy of hard x-rays emitted is centered at 50 keV early in the shot and rises monotonically to about 300 keV near the end of the discharge.

Raw data for a typical shot are shown in Fig. 1a. The Ka band (35 GHz within a 10 MHz bandwidth) emission is coupled into a waveguide heterodyne detector by a low gain (~15 dB) horn. This suprathermal emission was first investigated by Vlasenkov and his co-workers³ using this detection technique on the TM-3 tokamak. The detector signal, which is proportional to the microwave power coupled into the horn antenna, peaks gradually late in the discharge. [We will not concern ourselves in this Note with the copious microwave emission from poorly confined runaways which are lost to the walls during the startup phase of the discharge.] The microwave signal is proportional to the instantaneous size (n_{runaway}) of the runaway population. The hard x-ray signal indicates the instantaneous depletion rate (dn_{runaway}/dt) of that population as the runaway particles collide with the vacuum chamber walls.

Next we applied a short localized vertical field perturbation of 150-200 G to the plasma. The field is supplied by a pair of Helmholtz coils as shown in Fig. 2. The perturbation field amplitude, pulse length, and timing within the 7 msec discharge were all varied. The raw data for a typical shot with the perturbation field applied is shown in Fig. 1b. The pulse length of the perturbation was .5 msec. During the

pulse there are no spikes in the loop voltage and the plasma current remains unchanged (within a few per cent). Thus the perturbation field causes no disruption of the thermal component of the plasma.

Within .2 to .4 msec from the beginning of the perturbation field pulse,⁴ the microwave signal starts to decrease. The microwave emission then undergoes a steady decline lasting .1 to .3 msec until it falls close to zero. At this point the hard x-ray signal is cut off sharply (often accompanied by a short .1 msec hard x-ray burst). The steady decline in microwave emission implies that the runaway population is decreasing at a steady rate. The x-ray data show that runaways simultaneously collide with the vacuum wall at a steady rate until the runaway population is depleted and the x-ray signal is cut off. Thus the applied magnetic field perturbation drives the runaway population into the vacuum wall in about .1 to .3 msec, with a phenomenological runaway diffusion coefficient of $D_{\perp} \approx 10^5 \text{ cm}^2/\text{sec}$.

We found that the perturbation field amplitude must lie above a critical value of 150-200G as shown in Fig. 3. The field must be directed anti-parallel to the vertical compensation field. When the perturbation is applied parallel to the compensation field, field strengths up to one and one-half times the critical field have no effect on the runaways. This does not imply that the observed diffusion of the runaways is caused by local cancellation of the vertical compensation field. On the contrary, there is no evidence of disruption of the thermal portion of the plasma.

To attempt to explain our results, we have devised a simple computer model, which traces out the paths of single particles in toroidal geometry with energies varying between 200 eV and 300 KeV. We include the toroidal, poloidal, and perturbation fields and constrain the particles

to move along field lines with the exception of the $\vec{B} \times \nabla B$ drift. We find from the results that in following the magnetic field lines, the particles are shifted in the vertical direction due to the perturbation field. For runaway particles this produces two effects: first, a diffusion arising from untwisting of the field lines at larger minor radius which scales as $D_{\perp 1} \sim ([V_d/V_{||}][R \partial q/\partial r][B_{\text{pert}}/B_T]L)^2 V_{||}/2\pi R$,⁵ and, second, a diffusion due to the fact that the radial excursion from a flux surface due to a vertical perturbation field is proportional to the sine of the poloidal angle which changes by $\sim L/Rq$ while the particle is in the perturbation field region. This leads to a diffusion which scales as $D_{\perp 2} \sim ([B_{\text{pert}}/B_T] L^2/Rq)^2 V_{||}/2\pi R$. For thermal particles $D_{\perp 1}$ (which is proportional to $\gamma^2 v^3$) is too small to be significant, and the term $D_{\perp 2}$ dominates their diffusion. As $D_{\perp 2}$ is proportional to $V_{||}$, the runaway diffusion must be larger than the thermal particle diffusion by at least a factor of $(V_{||\text{runaway}}/V_{||\text{thermal}})$.

We hope that the results presented here will find the following applications in future work. First, we have described a simple technique for studying runaway electron generation and confinement. Furthermore, this technique shows promise as a means of suppressing runaway populations in long pulse length tokamaks in order to avoid the damage which runaway electrons can cause in colliding with the vacuum wall.

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5. Where $V_d = \gamma(V_{||}^2 + 1/2 V_{\perp}^2)(\vec{B} \times \nabla B^2) / (\omega_{be} R B^3)$, $V_{||}$ and $V_{\perp}$ are the particle velocities parallel and perpendicular to the total magnetic field $\vec{B}$, γ is equal to $(1 - v^2/c^2)^{-1/2}$, R is the major radius, r is the minor radius, B_{pert} is the peak vertical perturbation field amplitude, and L is the scale length of the perturbation field gradient.

Fig. 1

Fig. 2