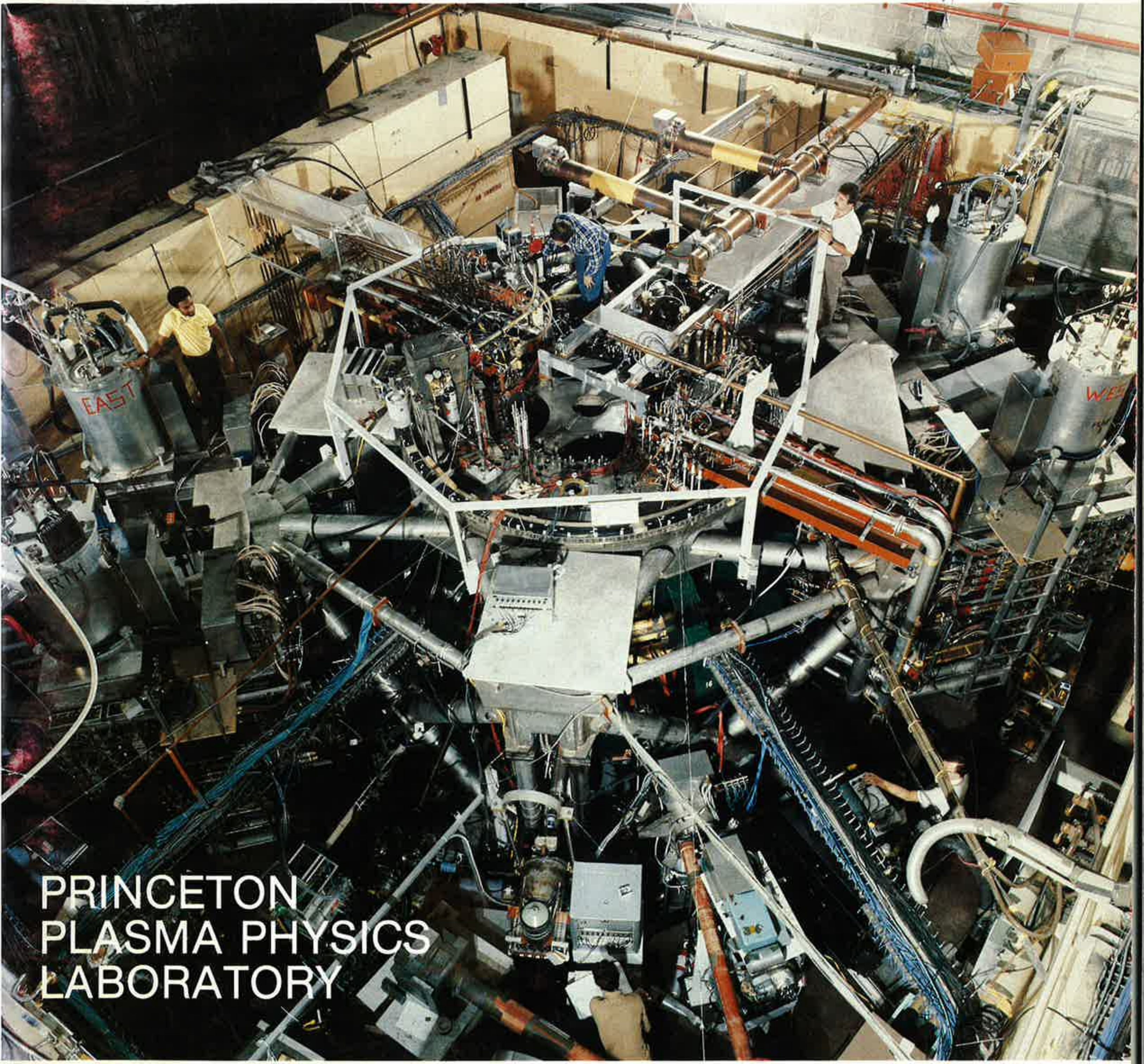
ANNUAL REPORT October 1, 1977 to September 30, 1978

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA



PRINCETON PLASMA PHYSICS LABORATORY

PPPL-Q-36

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Annual Report

Princeton University
Plasma Physics Laboratory
Princeton, New Jersey

PPPL-Q-36

Covering the Period
October 1, 1977 to
September 30, 1978

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Preface

Fiscal year 1978 began with groundbreaking ceremonies for the Tokamak Fusion Test Reactor (TFTR), attended by distinguished guests from at home and abroad. The TFTR is designed for breakeven operation with deuterium and tritium. It is scheduled for completion at the end of 1981.

The achievement of a 60-million-degree ion temperature on the Princeton Large Torus (PLT) during the summer of 1978, and of 75 million degrees in the fall, attracted widespread attention. Most importantly, these results were obtained without detriment to plasma confinement, although in a regime theoretically susceptible to high-temperature microinstabilities.

Meanwhile, fabrication of the Poloidal Divertor Experiment (PDX) was entering its final stage. This large and flexible research tokamak is designed to explore the control of impurities by the use of a magnetic divertor, and to optimize magnetic confinement by shaping of the plasma cross sections. Around-the-clock, turn-by-turn installation of PDX's 20 toroidal field coils, and placement of numerous other components proceeded on schedule in preparation for major power tests that began in September. First plasma and initiation of experimental activities were scheduled for early FY79.

Progress on the TFTR during FY78 was highlighted by the award of substantial orders through PPPL's major subcontractor, Ebasco Services, Inc. Over $35 million were committed to more than 20 domestic and foreign vendors. Final design reviews were completed on many of TFTR's major subsystems, and building construction proceeded throughout the year. The TFTR Technical Improvements Project (TIP) began in FY78 as a means of extending the parameter range available to this device and with the object of making possible operational performance above the breakeven point.

A number of programs were underway during FY78 to explore new facilities beyond TFTR. At Princeton, two complementary next-step concepts were proposed: The Superconducting Long Pulse Experiment (SLPX) and the normal-coil Princeton Ignition Test Reactor (PITR). Major objectives of the SLPX are to demonstrate quasi-steady-state hydrogen or deuterium operation at high temperature; heat removal from the plasma, first wall, and divertor plates; and the operation of superconducting magnets. Major objectives of the PITR are to demonstrate the attainment of deuterium-tritium ignition and a sustained thermonuclear burn of at least five seconds. PPPL also participated in planning towards a national Engineering Test Facility (ETF), which would combine the two objectives of ignition and long-pulse operation.

Princeton Large Torus (PLT)

OVERVIEW

The Princeton Large Torus (PLT) (Figure 1) is a tokamak device of 130-cm major radius and 45-cm minor radius. The main objectives of PLT are to investigate:

- Plasma confinement scaling with size;
- Plasma heating, using ohmic, neutral beam, and radiofrequency (RF) techniques;
- Plasma behavior and stability, using extensive diagnostics.

PLT represents a significant increase in size over previous tokamak devices, but is only half-size compared with TFTR.

The PLT device has outstanding experimental flexibility, due to the high accessibility of the large plasma column. The plasma parameters approximate reactor-relevant conditions.

MAJOR ACTIVITIES

Summary

The emphasis of the PLT program during FY78 was on producing a high-temperature regime with auxiliary heating by neutral-beam injection (Figure 2). Plasma ion temperatures as high as 6.5 keV (75 million °C) were achieved.

Improved control of plasma impurities and intensive development of new diagnostics contributed importantly to achieving this high-temperature plasma regime and evaluating it properly. In addition, investigations have been started at low power on ion-cyclotron resonance heating (ICRH).

Impurity Control

The high-Z plasma impurity content was reduced during FY78 by removing the tungsten limiters and

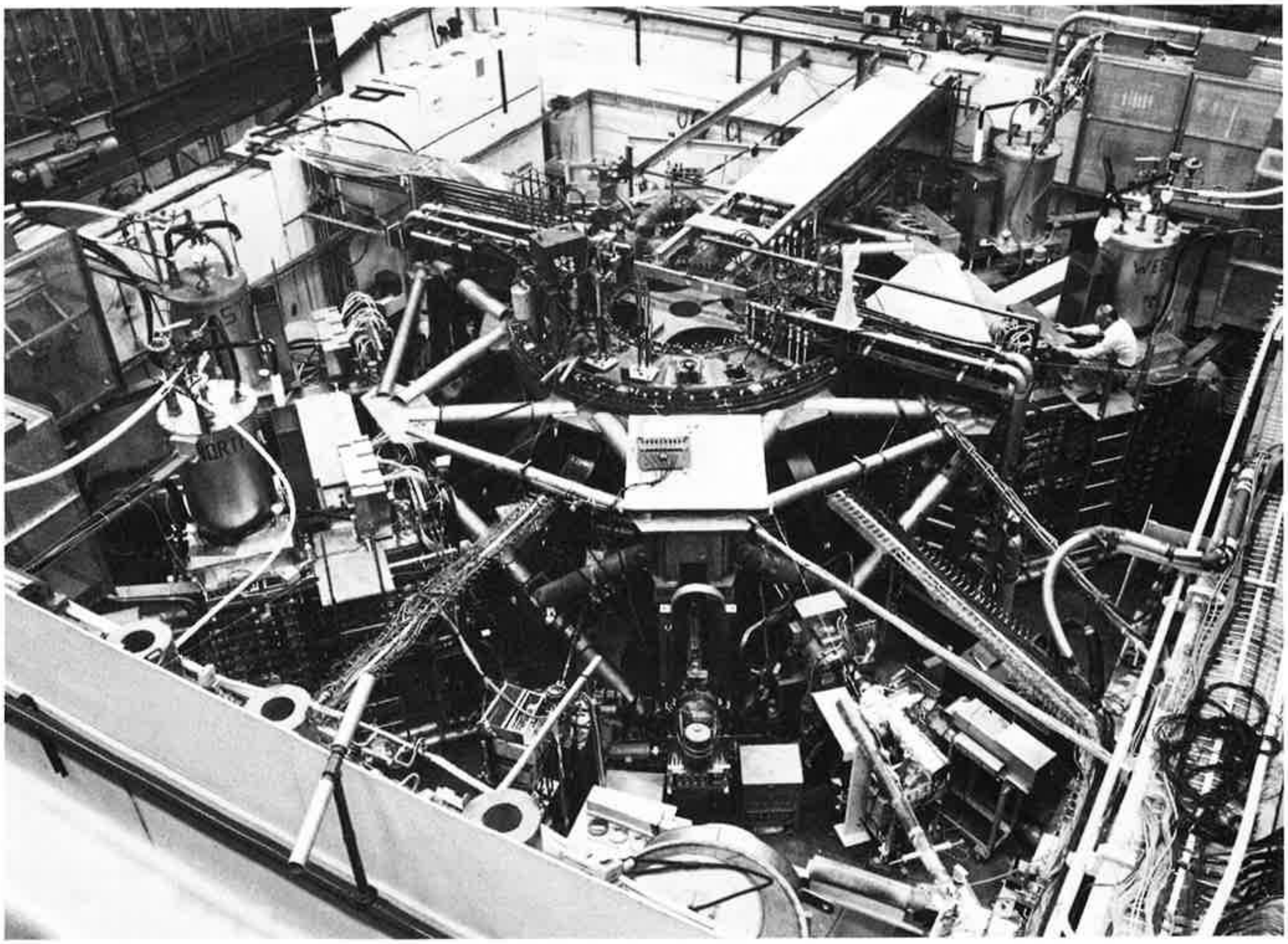

Figure 1. The PLT device after installation of neutral beam heating. Diagnostic systems can be seen on the platform.

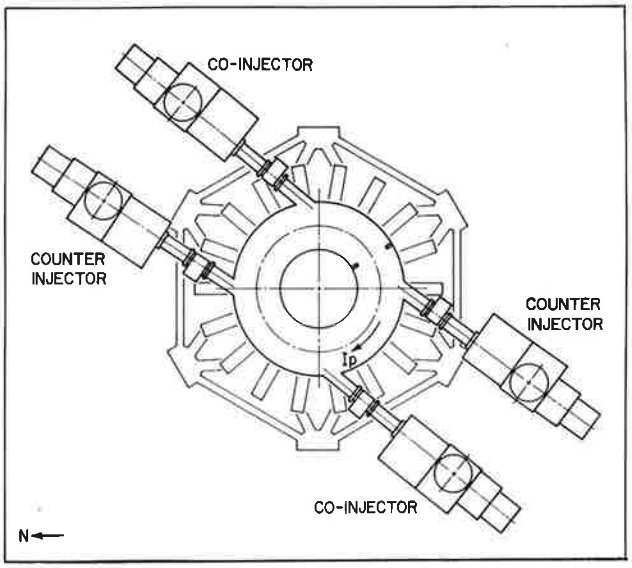

Figure 2. PLT schematic indicating the direction of the plasma current and the position of the neutral beam injectors.

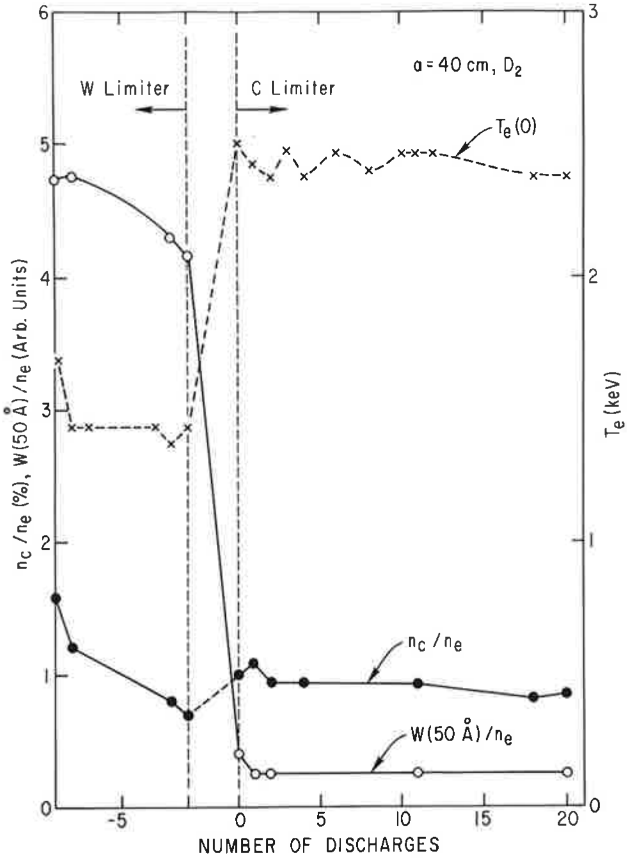

Figure 3. Changes in concentrations of tungsten and carbon when graphite limiter is substituted for tungsten limiter. Indicated tungsten level after change is spectroscopic background level. Note that there is no significant increase in the carbon concentration after introducing the graphite limiters; there is an appreciable increase in central electron temperature.

substituting limiters of lower-Z material — water-cooled graphite or stainless steel (Figure 3).

The low-Z impurity content was reduced by adding a titanium gettering technique to the pulse-cleaning techniques developed last year. In this approach, a thin film of titanium is deposited on the vacuum-vessel wall, leading to adsorption of the recycled gas (H,D) and of the impurity components (O,C) (Figure 4).

The beneficial effects of plasma-edge cooling by impurity radiation can be recovered partly by maintaining a high, neutral background of hydrogen at the plasma edge, with enhanced gas puffing made possible by the titanium gettering.

In ohmic-heating discharges, the energy flow from the plasma core is primarily ($\gtrsim 75\%$) by conduction and convection when graphite limiters are used with or without gettering. Without gettering, about 85% or more of the input power is radiated from the outer, cool part of the plasma, while about 15% goes to the limiter. With gettering, a smaller fraction, about 50%, is radiated and 30% to 50% deposited on the limiters. Figure 5 displays the balance between transport and radiation within the plasma for several different discharge conditions with graphite limiters.

The gross electron-energy confinement time, τ_{Ee} (total electron energy/total power input), is a useful characterization of the energy balance. Values of τ_{Ee} and of other plasma parameters are derived primarily from profiles of electron temperature and density obtained with a multi-channel Thomson scattering system. Figure 6-a shows that the confinement time normalized to the density is correlated with the average electron temperature, but displays little or no correlation with Z_{eff} (Figure 6-b). Gettered and ungettered plasmas of like density and temperature display the same global confinement. This phenomenon is consistent with more detailed analysis of the power balance, which generally shows that the outer plasma zone — where gettering most strongly affects the radiation level — does not contribute much to the thermal isolation of the plasma core, where most of the plasma kinetic energy is stored. A clear relation between the empirical thermal conductivity and the electron temperature has not yet emerged.

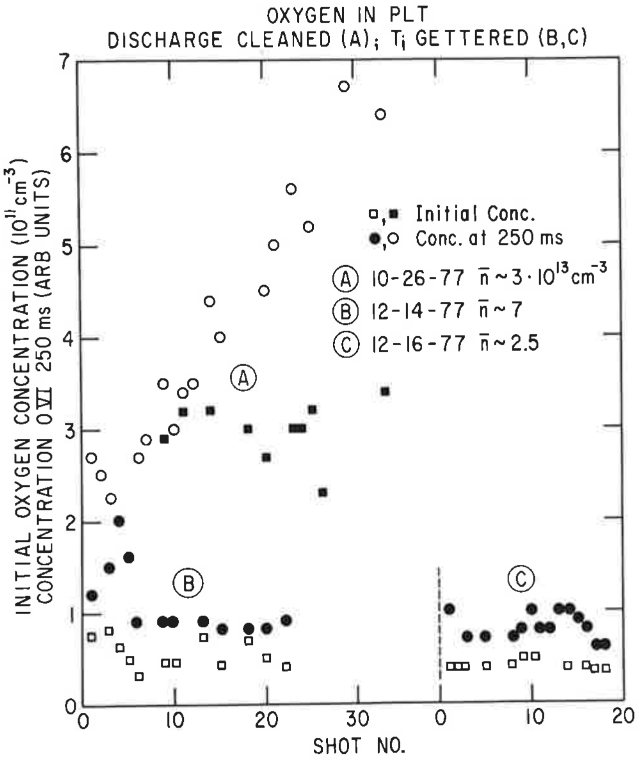

Figure 4. Oxygen levels with TDC and Ti gettering (A). After TDC, oxygen level tends to rise with successive high-power pulses (B,C). With recurrent gettering between discharges, oxygen levels remain constant, at high (7 × 10^{13} cm^{-3} and low (2.5 × 10^{13}cm^{-3}) average densities, respectively.

Neutral-Beam Heating

In the design of PLT, careful consideration was given to auxiliary heating. The four neutral-beam injection systems of PLT, consisting of 40-kV ion sources, were designed and fabricated by the Fusion Energy Division of the Oak Ridge National Laboratory. The large size and high accessibility of the PLT plasma column make it well suited for neutral-beam injection heating. The injection is tangential to the plasma column to give good beam adsorption at low density and to minimize unconfined orbits; two beams are parallel (co-injectors) and two, anti-parallel to produce toroidal momentum balance (Figure 2).

The neutral-beam power obtainable at this time per injector is 400 to 500 kW for hydrogen and 600 kW for deuterium. The power deposition distribution is shown in Figure 7. It is the result of trapping fast ions that are formed through charge exchange with plasma ions and impact ionization electrons and ions (hydrogen, and also impurities). Following capture, the beam ions transfer their energy by small-angle coulomb collisions to the background plasma, with a ratio of energy transfer to the electron and ion species which depends on the ratio of electron-to-beam energy. For the PLT experiment the beam power is transferred primarily to the plasma ions, and thus neutral-beam injection is predominantly a method of ion heating.

The improved control of neutral gas recycling by titanium gettering made it possible to operate at low plasma density during neutral-beam injection, and therefore to achieve high temperatures with the present beam-power levels. Ion temperatures up to 6.5 keV (75 million °C) have been obtained in PLT at central plasma density of 5 × 10^{13} cm^{-3} with 2.5 MW of injected beam power (Figure 8). This temperature is considerably higher than those achieved before in toroidal devices and is substantially close to the 10-keV level generally assumed to be required for reactor operation to permit reasonable extrapolations to the reactor regime.

Three methods have been used to determine the ion temperatures with an internal agreement of about 10%: mass and energy analysis of fast neutrals generated by charge exchange, which escape from the plasma column carrying the energy of the plasma ions; measurement of the Doppler line broadening of impurity radiation in the ultraviolet and X-ray regions of the spectrum; and thermonuclear neutron emission from a deuterium plasma heated by hydrogen beams (Figures 8, 9, 10).

The ion temperature increase over the value obtained by ohmic heating alone was found to be proportional to beam power and inversely proportional to plasma density (Figures 10, 11).

At low plasma density, it is possible to obtain conditions in which ion collision frequencies lie in the "collisionless" regime. This is particularly interesting because, although theory predicts enhanced energy transport for this regime, no enhancement was observed. Unfortunately, the effect that entering the "collisionless" regime has on ion-heat transport is obscured at low density by charge-exchange losses and at high density by transfer of energy from ions to electrons. In neither case is neoclassical diffusion the dominant energy-transport process.

In addition, in extreme cases much-enhanced plasma fluctuations were observed, whose nature is not fully understood, but again no enhancement of ion energy transport was observed. Much more detailed investigation of the fluctuations is needed to identify their origins and determine whether they are actually

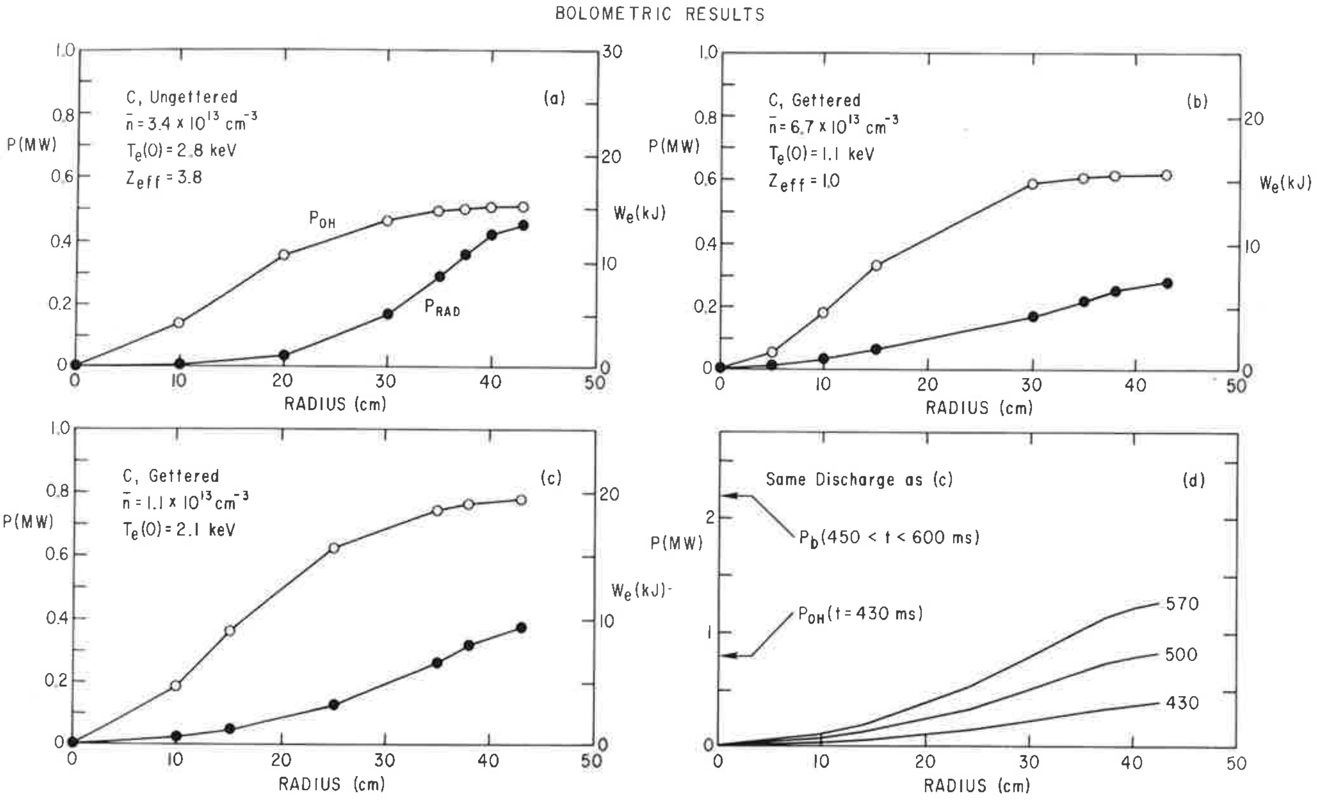

Figure 5. Comparison of ohmic input power and bolometeric measurements. Power is integrated from center to radius r. Ohmic power $P_{OH}(r)$ deduced from Thomson scattering profiles of electron temperature and density; P_{RAD} from Abel-inverted profiles obtained with narrow-angle scanning bolometer. (a) Typical for ungettered discharges with carbon or steel limiters. Limiter — carbon; $\bar{n}$ = 3.4 × 10^{13} cm^{-3}; $T_e(o)$ = 2.8 keV; Z_{eff} = 3.8. (b) Gettered; carbon limiter; $\bar{n}$ = 6.7 × 10^{13} cm^{-3}; $T_e(o)$ = 1.1 keV; Z_{eff} = 1.0. (c) Gettered; carbon limiter; $\bar{n}$ = 1.1 × 10^{13} cm^{-3}; $T_e(o)$ = 2.1 keV; Z_{eff} = 4.3. *(d) Same discharge as (c) during neutral injection with 2.2 MW, commencing at 450 ms.*

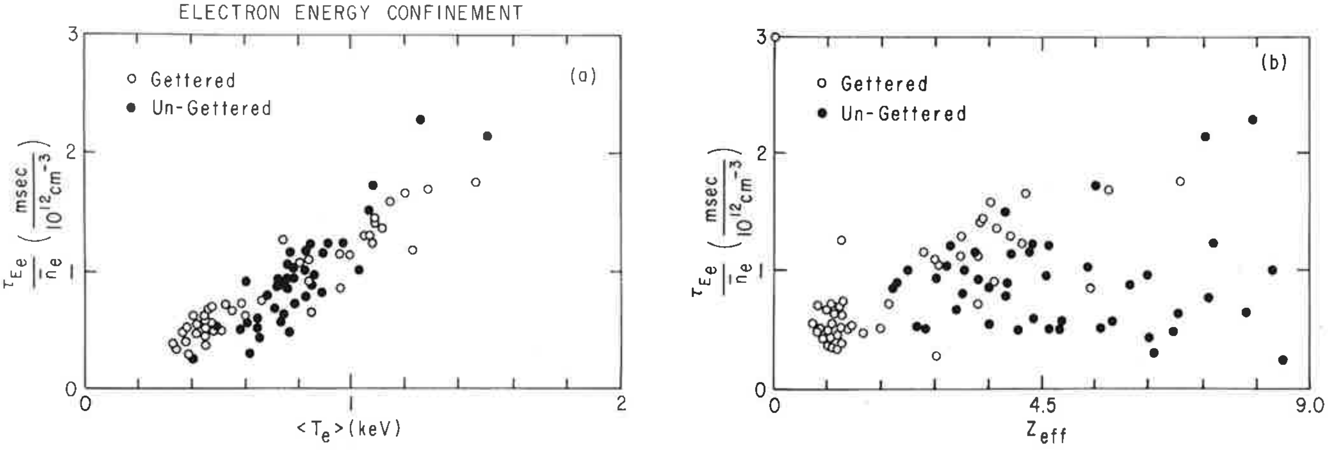

Figure 6. Correlation of $\tau_{Ee/\bar{n}}$ with $<T_e>$ *and* Z_{eff}. *Open circles (o), gettered discharges; closed circles (•), ungettered discharges.*

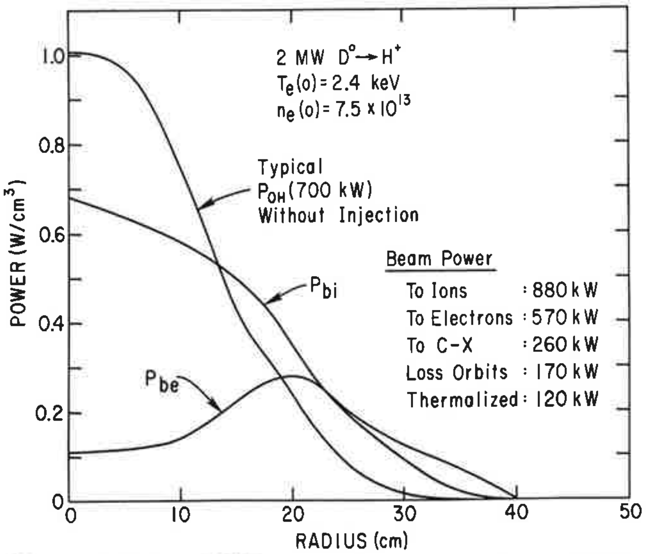

Figure 7. Beam power deposition profiles from Monte Carlo beam-orbit code.

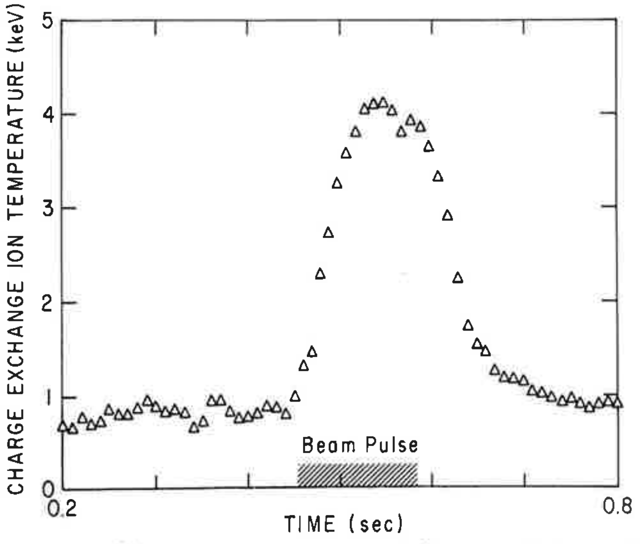

Figure 8. Charge exhange ion temperature as a function of time during the discharge. Time resolution is 10 ms. A peak ion temperature of 4 keV is attained during injection of 1.6 MW of H° into a D^+ plasma.

related to the predicted trapped-ion modes. Nevertheless, the result permits optimistic predictions for larger devices like TFTR.

The improved condition of cleanliness also made it possible to reduce radiation losses enough to observe electron heating by neutral injection. Using carbon limiters and Ti getters, electron heating up to 3.5 keV, with an accompanying ion temperature of 5.5 keV, has been obtained at low density (Figures 12, 13).

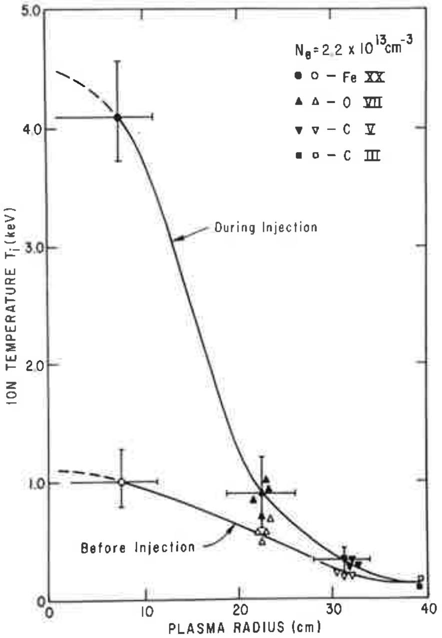

Figure 9. Radial profile of ion temperature before and during neutral beam injection, all four beams on (H° → D^+; P = 1.6 MW) from Doppler broadening of FeXX 2665Å, OVII 1623Å CV 2271Å and CIII 2237Å lines.

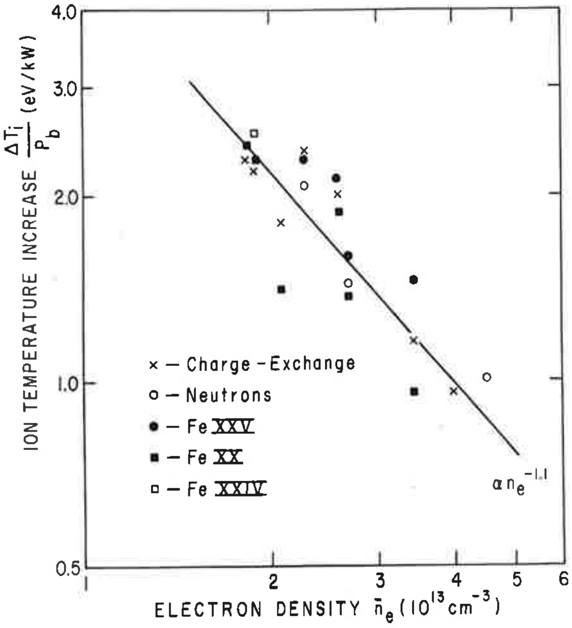

Figure 10. Scaling of ion temperature measurements vs. line average electron density P_b = 0.5 – 2.0 MW.

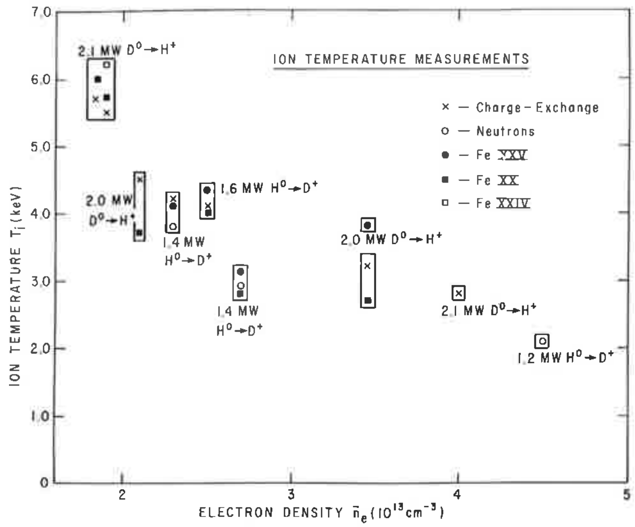

Figure 11. Ion temperature measurements vs. line average electron density for four beam operation, carbon limiters and titanium gettering.

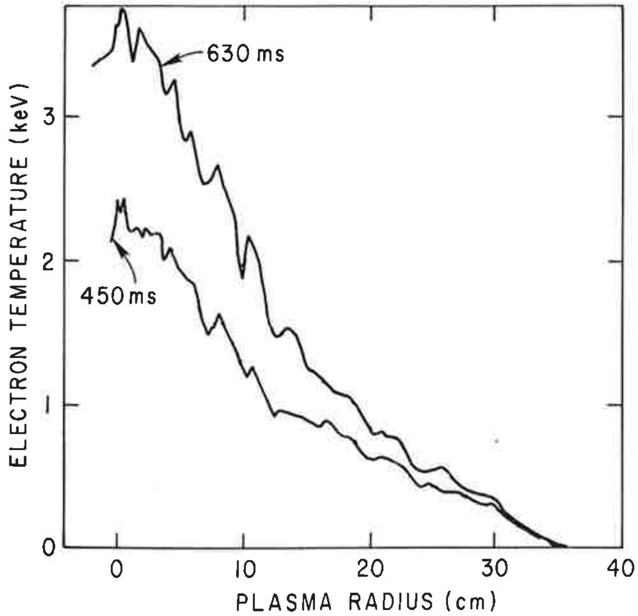

Figure 12. Electron temperature profile before and after injection of 2.1-MW deuterium neutral beams at time t = 450-600 ms into a hydrogen plasma ($\bar{n}_e$ = 1.8 × 10^{13} cm^{-3}). The electron temperature peaks 30 ms after the end of injection because the electrons are still being heated by fast ions, but there is no longer a source of cold electrons coming in with the beam ions. These profiles were obtained from the fundamental electron cyclotron emission measured by a fast-scanning heterodyne receiver.

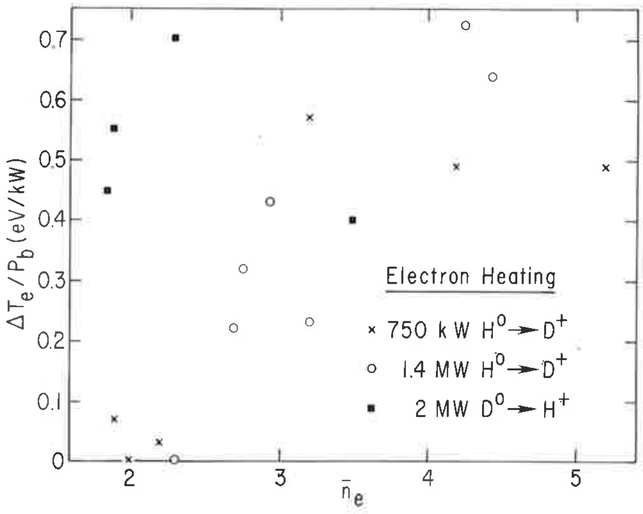

Figure 13. Compilation of the results of high power injection into gettered carbon limiter plasmas. The overall picture suggests that under the best conditions $\Delta T_e P_b$ = 0.6 eV/kW, independent of plasma density.

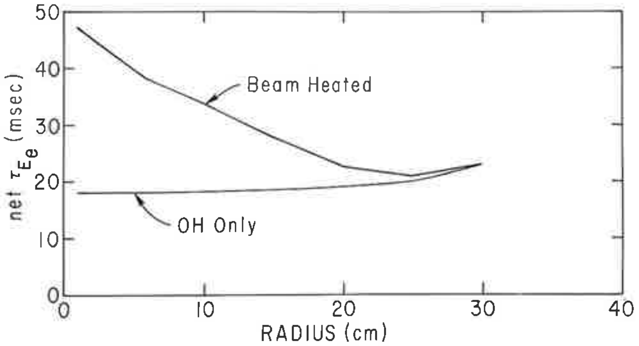

Figure 14. Radially integrated net τ_{Ee} for 2 – MW D° injection into moderate density H^+ plasma.

For the electron power balance, it was observed that the net electron energy confinement time integrated over the plasma volume does not differ noticeably from that of ohmically-heated plasmas. On the other hand, more detailed evaluation of the electron temperature profile during neutral-beam heating indicates that the electron heat transport may actually decrease near the hot plasma core while remaining unchanged at the plasma edge (Figure 14).

The development of a workable method of heating, supplementary to ohmic heating, provides an additional degree of freedom for detailed study of the parameter dependence of electron and ion transport rates.

If the injection system is used in an unbalanced way with either the co- or counter-beams operating, toroidal plasma rotation is produced, with velocities up to 10^7 cm/sec, which has no detrimental effects on the plasma confinement. The momentum-transport time constant observed for the first time in this experiment is of the same order of magnitude as the energy confinement time.

The rate of neutron production is about 10^{14} $\sec^{-1}$, or 2×10^{13} per discharge (Figure 15). About 90% of this yield is due to the reactions of energetic beam-injected ions with each other and with bulk plasma ions.

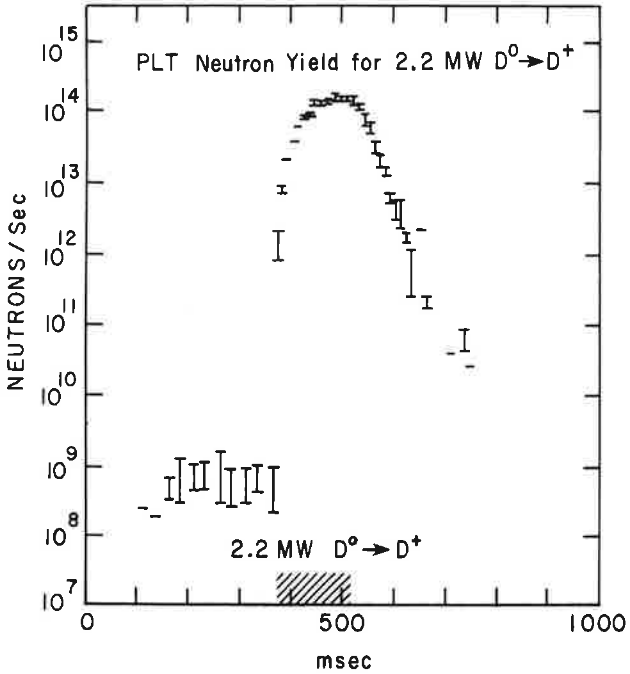

Figure 15. Neutron emission as a function of time for a 2.2-MW neutral-deuterium pulse injected into a deuterium plasma.

Ion-Cyclotron Resonance Heating (ICRH)

Most of the ICRH experimentation on PLT during FY 1978 has been directed toward evaluating the mode-generation and damping characteristics with ½-turn test antennae excited at low rf power levels. The essential features include the observations that toroidal eigenmodes tend to be suppressed in the two-ion regime (minority proton in deuterium or helium-3 discharges) and that such eigenmodes enhance the wave coupling to the antennae by a factor of ~5 in the pure second-harmonic regime. Mode-tracking systems have been developed to enhance the power transfer to the excited waves for this latter regime.

Initial heating experiments at modest RF power (~30 kW) were begun during this period (Figure 16). For the two-ion regime, energetic proton distributions were produced and these serve as a conduit for the wave energy (through direct minority damping) to the deuterons and the electrons. Deuterium temperature increases of ~80 eV were thus obtained.

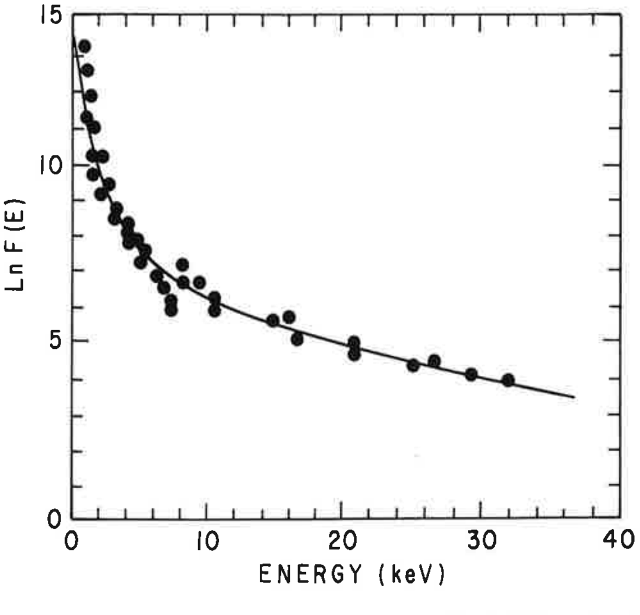

Figure 16. Hydrogen charge exchange spectrum at P of ~30 kW. The theoretical Fokker-Planck curve is shown. The energy distribution for E>5 keV exhibits an effective temperature of ~7 keV.

Poloidal Divertor Experiment (PDX)

OVERVIEW

The Poloidal Divertor Experiment (Figure 17) is a large, flexible tokamak device equipped with a poloidal divertor for impurity control and with a capability for plasma cross-section shaping. The major radius is 140 cm and the minor radius, depending on choice of configuration, is about 45 cm. Heating will be provided by a plasma current of 500 kA and by 6 MW of neutral-beam power from four injectors (Figure 18). Initial operation is scheduled for the fall of 1978, with full-scale operation with neutral beams — a collaborative project of the Oak Ridge National Laboratory (ORNL) and PPPL — about a year later. The PDX goals are:

- Achievement of reactor-like plasma parameters.
- Development and determination of effectiveness of poloidal divertors, magnetic limiters, and other techniques for controlling impurities in large, high-temperature, collisionless tokamak plasmas.
- Optimization of the plasma cross-section under conditions of relatively "flat" current distributions, i.e., the conditions produced by magnetic limiting in conjunction with effective divertor control of neutrals and impurities.
- Exploration of the MHD β-limit as a function of plasma shape and profile.
- Determination of confinement scaling parameters as a function of collisionality from present-day plasmas to reactor-like plasmas by divertor control.
- Production of substantial fusion reactions.

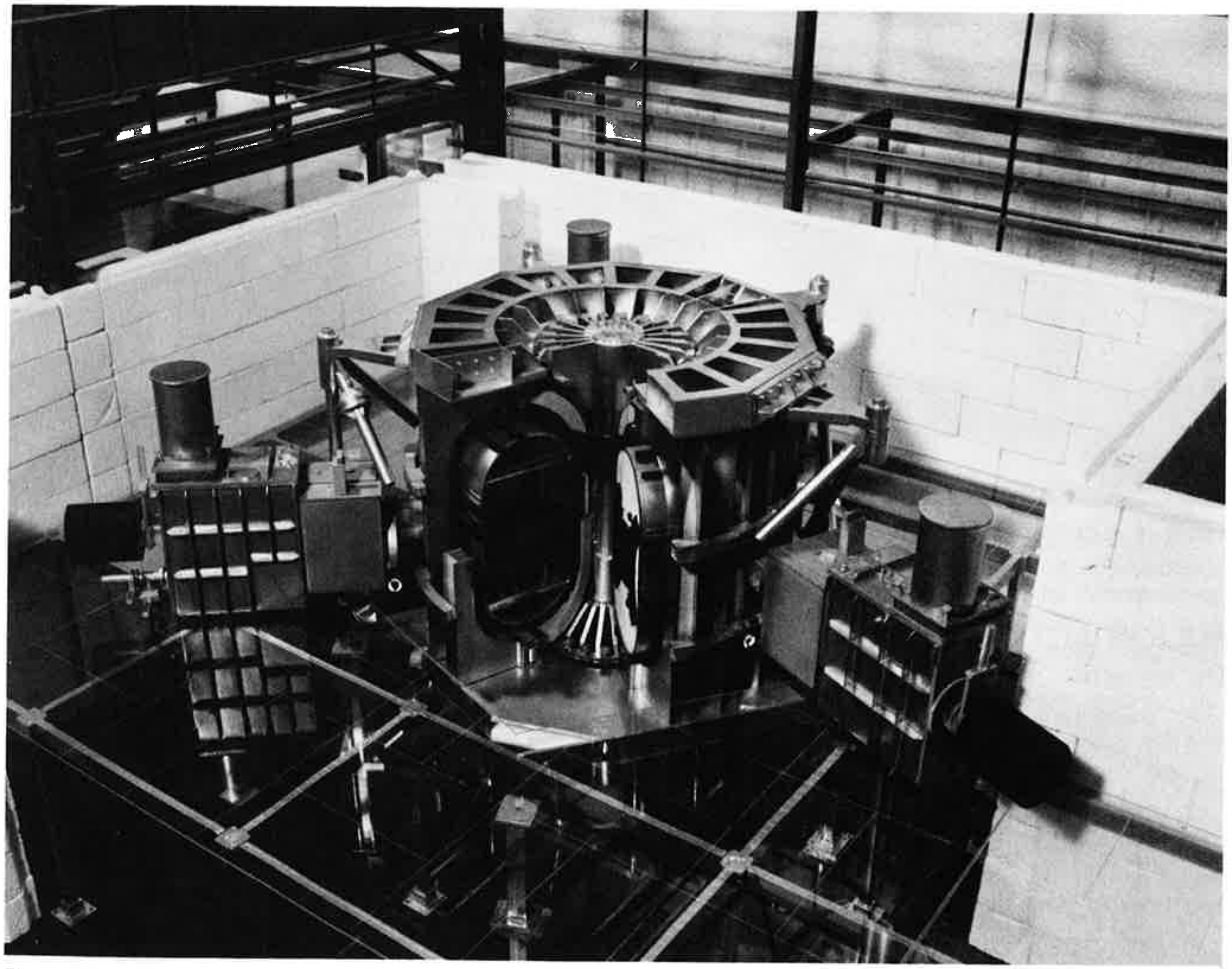

Figure 17. A model of the Poloidal Divertor Experiment (PDX).

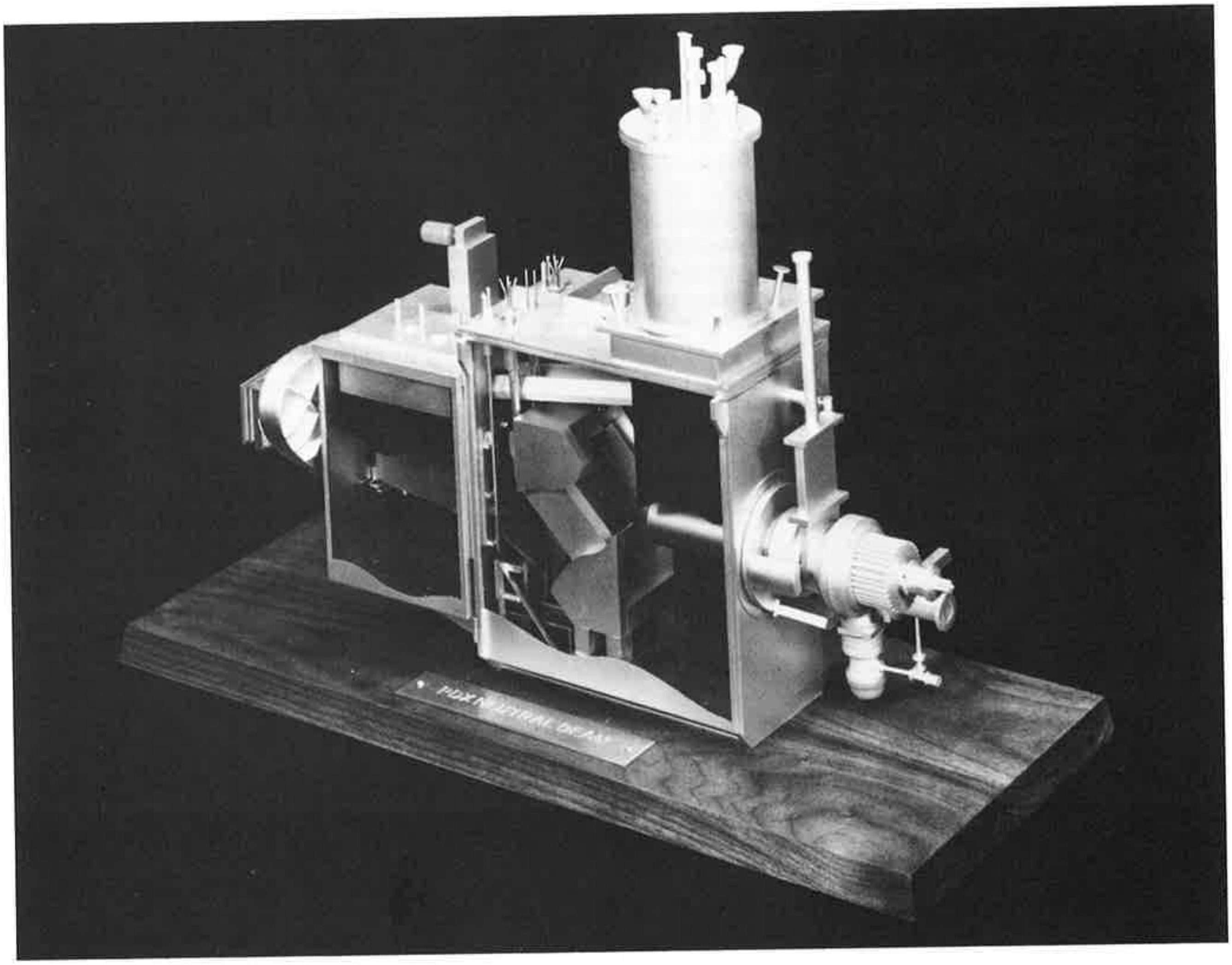

Figure 18. A model of a PDX neutral beam injector.

MAJOR ACTIVITIES

FY78 was the last full year of fabrication on the PDX. The turn-by-turn assembly of the toroidal field (TF) coils set the pace for other fabrication activities during much of the year, from November 4, 1977 through May 17, 1978 (Figures 19 and 20). The coils were manufactured in C-shaped sections, so that they could be positioned around the already-assembled vacuum vessel and poloidal field (PF) coils. The inner and outer C-sections of each coil were fastened by expanding pins, and contact pressure was provided by hydraulic clamps. Installation of vacuum pumps and manifolds, water fittings and hoses, and various controls and power supplies occurred in parallel with the assembly of the TF coils.

Following TF coil assembly, spacers and wedges were installed, and the coil cases were aligned. The center shaft was installed in the tunnel directly under the machine, so that it could be lifted to its final position at the appropriate time. The torque frame was reassembled by June 9, 1978; the upper shelf was installed on July 6, and the remaining (East) portion of the radiation shield wall was completed (Figure 21).

During the last quarter of FY78, computerized machine test checklists were prepared for Major Power Tests, which started on schedule during the last

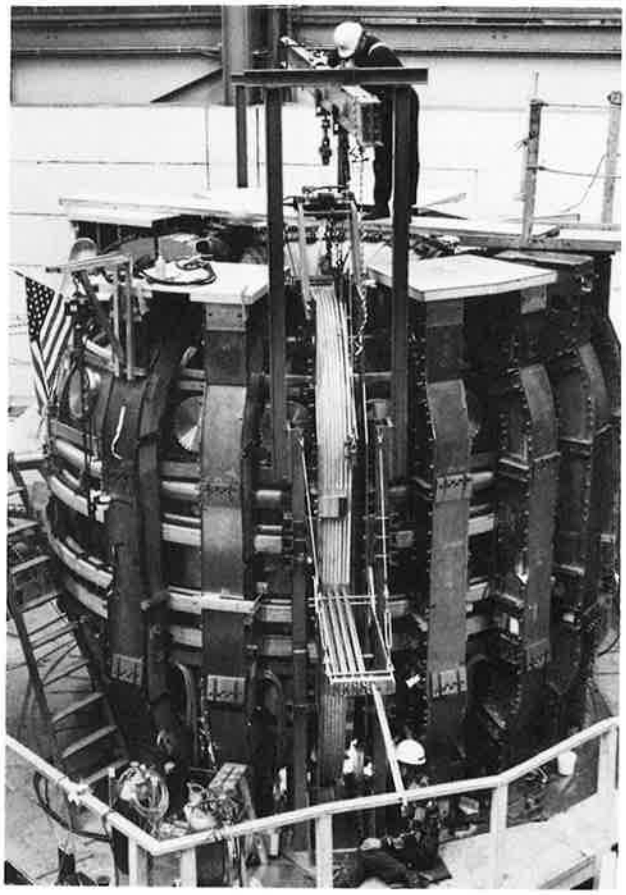

Figure 19. The Poloidal Divertor Experiment during toroidal field coil assembly.

week of September. Satisfactory progress would clear the way for first plasma and the initiation of experimental operations in November, 1978.

The formal proposal for the neutral-beam project, submitted to DOE in FY77, was funded in FY78 as a joint project of PPPL and ORNL. The program will result in a total of 6 MW of neutral beam input power from four 1.5-MW beam lines. Originally only a 4 MW maximum was planned for PDX.

The auxiliary heating is necessary to achieve reactor-like plasmas required to test the effectiveness of the poloidal divertor concept for controlling impurities in a large, reactor-like tokamak. Electron density in the beam-heated plasma will probably approach 10^{14} cm^{-3}, and ion temperature is expected to be in the range of 5 to 10 keV. Under these conditions, it will be possible to perform meaningful cross-section shaping experiments and to explore the MHD β-limit.

The injection system will use Oak Ridge duopigatron sources operated at the 50-keV level. The ion current output of the sources will be upgraded to make full use of the beamline capability. Four main beamline vacuum chambers and enclosed components will be procured from an industrial contractor. A fifth (spare) beamline and all drift tubes, sources and calorimeters will be built by ORNL. The sources will be upgrades of the 60-ampere PLT injectors to the 100-ampere level. The beam injection will be nearly perpendicular to the PDX axis.

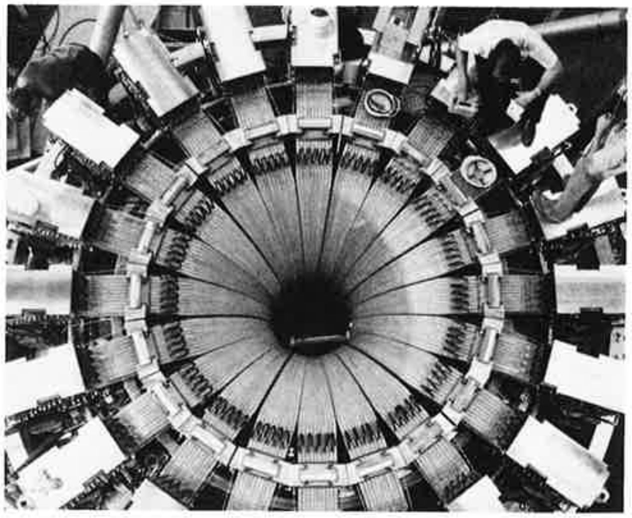

Figure 20. Top view of PDX following toroidal field coil assembly and prior to placement of the center column and upper shelf.

At the end of FY78 the PDX neutral-beam project was generally on schedule. A contract was signed with CVI Corporation on June 17 for provision of three of the beamlines. On September 22, DOE authorized procurement of the fourth beamline from CVI.

Preparation for experimental operation of PDX intensified as the date of commissioning approached. The largest effort was expended on the fabrication of plasma diagnostic systems. Essentially complete at the end of the year were: Rogowsky loop; magnetic flux loops; a 10-channel, 2-mm microwave interferometer; an 8-channel, 8-mm divertor interferometer; a 5-channel, x-ray pulse height analyzer; a hard x-ray system; a residual gas analyzer; a surface analysis station; an infrared laser interferometer; a grazing incidence monochromator; various ultraviolet spectrometers; a multichannel charge-exchange ion temperature system, as well as various divertor diagnostics. Considerable progress was also made on the PDX data aquisition system, which will use a PDP-10 shared with PLT, PDP-11's, and CAMAC equipment.

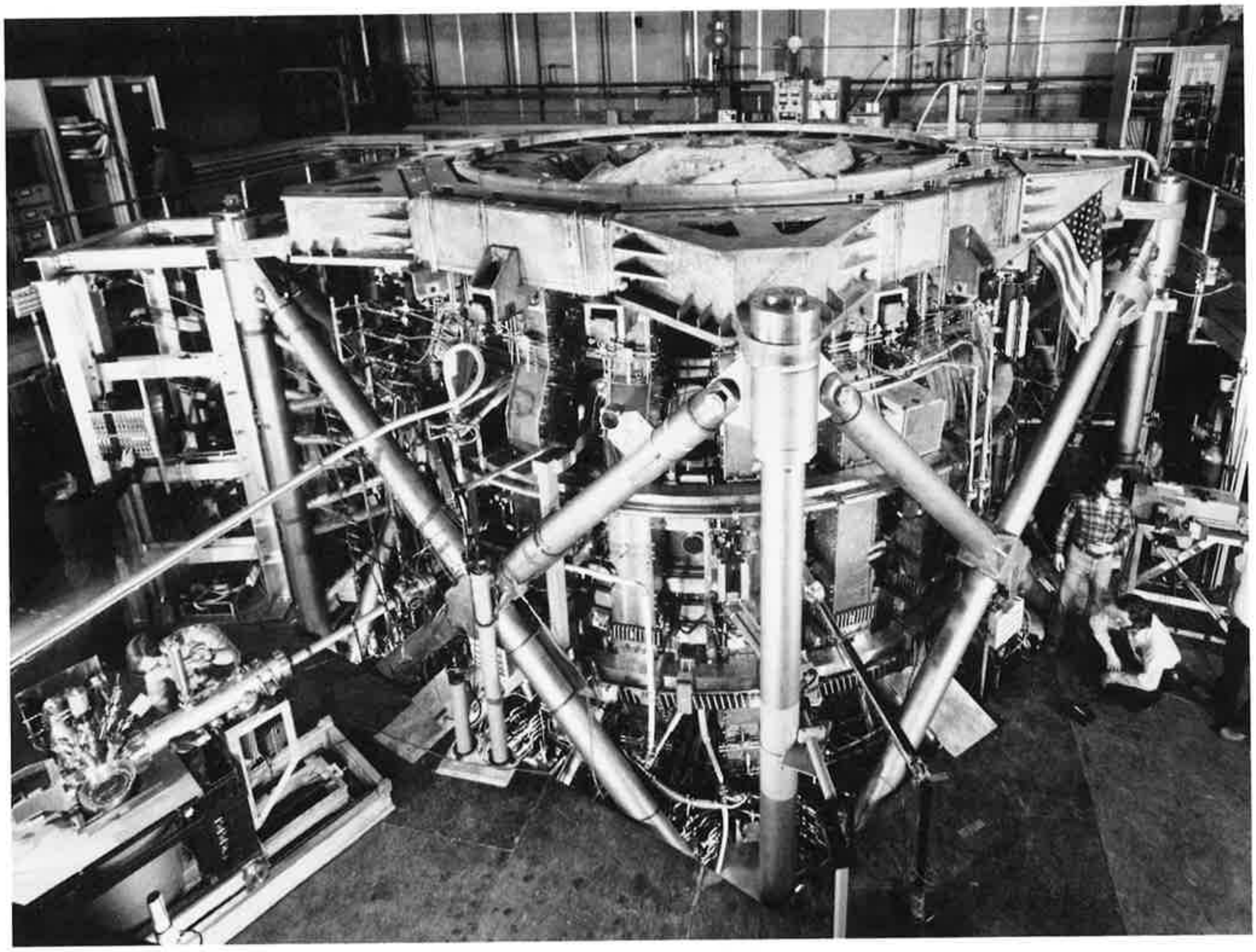

Figure 21. The Poloidal Divertor Experiment (PDX) completely assembled.

LINEAR DEVICES

OVERVIEW

An active program of plasma research on several small linear devices supplements PPPL's major activity on large tokamaks. Objectives of the linear-device program are the exploration of new concepts in plasma physics together with the quantitative test of fusion-relevant plasma theory. The smaller machines offer the advantages of flexibility, specialized diagnostics, and abundant running time. In addition, they lend themselves well to in-depth plasma physics studies and to graduate student research.

Four machines were in use during this report period: the two hot-electron devices, L-3 and L-4; the venerable and still prolific Q-1 machine; and the new QED (quiet, energetic, dense) arcjet plasma apparatus. The L-3 and L-4 work concentrated on linear and nonlinear wave phenomena, with particular attention to plasma heating and steady-state current generation by radiofrequency methods. Instabilities driven by particle beams and by impurity gradients were the topics of this year's research on Q-1, while QED became the testbed for quantitative studies of whistler waves and, of particular significance, for sputtering and wall interaction studies. A direct comparison of the QED-measured sputtering yields with spectroscopic data from PLT strongly suggests that the amount of wall and limiter material found inside the PLT plasma can be correlated directly to sputtering by ions accelerated through the sheath at the edge of the PLT plasma.

MAJOR ACTIVITIES

The L-3 Program

Generation of Unidirectional Current by Lower Hybrid Waves

Toroidal current in a tokamak plasma serves two vital functions: it heats the plasma by electron-ion collisions (ohmic heating) and its poloidal magnetic field twists the field lines of the vacuum toroidal field, giving the total field topology the necessary property of rotational transform. For a *steady-state* tokamak reactor, the usual method of current drive by transformer action cannot be used, and there is high interest now in driving a unidirectional plasma current by radiofrequency waves. One promising scheme, using lower-hybrid waves, has been given a successful preliminary test in the L-3 apparatus. Unidirectional lower-hybrid travelling waves are launched by a slow-wave structure in which adjacent rings are energized 90° out of phase, and measurements show 85% of the wave energy propagating preferentially in the desired direction. The wave is Landau-damped as it propagates downstream, transferring its momentum to the plasma electrons and generating a plasma current. Figure 22 shows wave amplitude profiles at various downstream points together with current measurements by detectors of two different types. High-power experiments on this same phenomenon are planned for the new Advanced Concepts Torus-1 (ACT-1).

Nonlinear Resonance Cones

Clearly seen in Figure 22 is the radially inward propagation of the wave as it moves axially downstream away from the ring-launcher. The trajectory of the rf pulse for this wave follows the so-called "resonance cone," and this trajectory has been the subject of both theoretical and experimental research. Most recently it has been found that at high driving powers, the strong localized electric fields of the wave modify the plasma density through the ponderomotive force, and this density modification leads in turn to an alteration of the resonance cone trajectory. Careful measurements in an argon plasma of the converging resonance cone for a 50-MHz pulse from a single-ring launcher have revealed this amplitude-sensitive modification of the trajectory, and the magnitude of the trajectory alteration has been found to be in significant agreement with a self-consistent nonlinear theory.

Effect of Convective Loss on the Parametric Decay of Lower Hybrid Waves

Lower hybrid waves are under serious consideration both as a means for supplementary plasma heating and, as mentioned above, for steady-state current drive. At the high power levels necessary for these services, the waves can become subject to another nonlinear process, namely, parametric decay. Under parametric decay, the primary wave decays into two daughter waves satisfying the familiar frequency and wave-number matching conditions. However, the group velocity of the daughter waves will, in general, be different from that of the primary wave and the primary-wave decay process must be able to supply the wave-packet energy to the daughter waves. The shorter the length of the primary wave train, the more important this "convective loss"; it is possible that the threshold for lower-hybrid parametric decay may be considerably higher due to this effect than due to the usual collisional threshold for the dominant ExB coupling.

In an L-3 experiment, the length of the primary wave train was varied by energizing different numbers of rings in the wave launcher. The plasma was argon, the

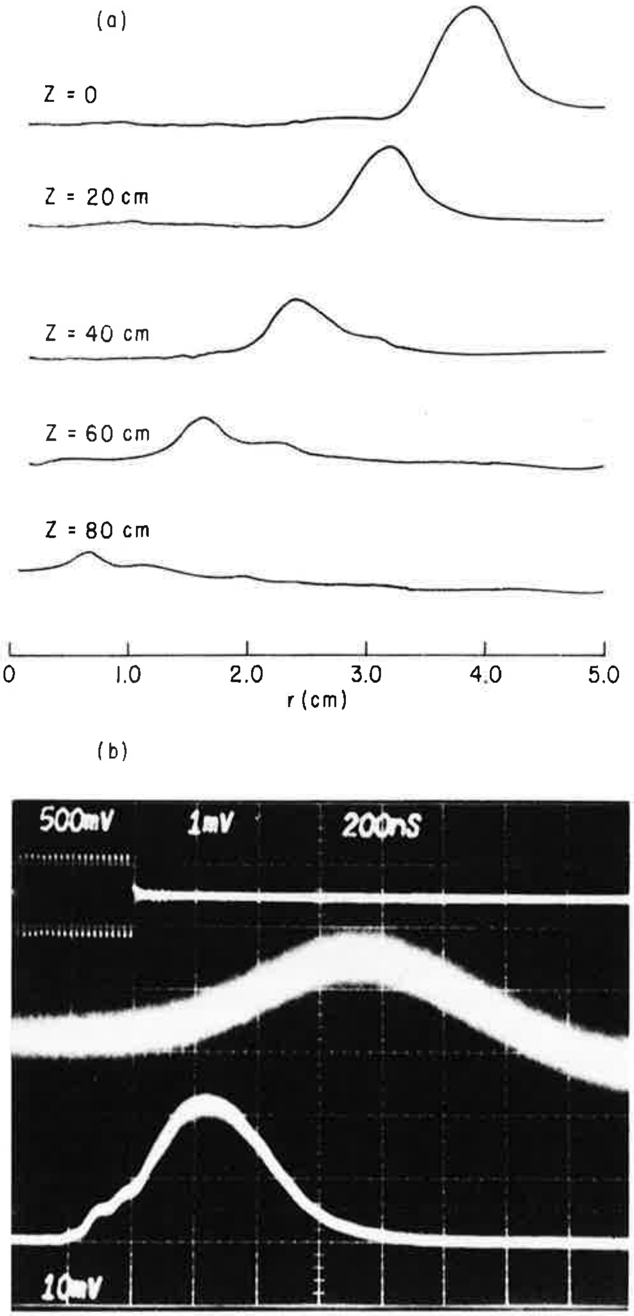

Figure 22. Profiles of the lower-hybrid wave at various axial locations show the resonance-cone trajectory (the wave peak is seen to move radially inward) and the wave damping. The uppermost oscilloscope trace shows the 400-ns rf pulse; the middle trace shows the unidirectional rf-generated current pulse measured by a Rogowski loop with a 400-ns response time; the bottom trace shows the same current as measured by a Pearson current monitor with a 20-ns response time.

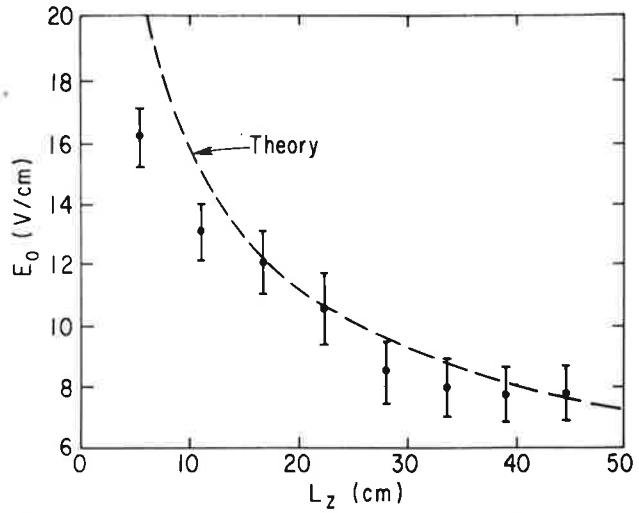

Figure 23. Variation with antenna length, L_z, of the threshold, E_0, for ExB-coupled decay of a lower hybrid wave.

pump frequency was ten-times higher than the lower hybrid frequency, and the daughter waves were identified as an ion acoustic wave and another lower hybrid wave. The effect of convective loss on increasing the threshold field (E_0) necessary for decay was confirmed quantitatively; experimental data and a theoretical curve are plotted in Figure 23.

The L-4 Program

Ion-Cyclotron Frequency Parametric Excitation of Drift Waves

Plasma heating by ion-cyclotron-range-of-frequencies (ICRF) excitation has been proven effective in a number of high-power, large tokamak experiments. Parametric decay of the primary wave is also possible in this heating scheme, and an experiment on the L-4 device has addressed this question. In particular, for two-ion-species plasmas (e.g., D and T in a fusion plasma), the *relative* ion drift velocity can become very large as the driving frequency approaches the cyclotron frequency of one of the ion species, and the phenomenon can drive a drift-wave instability with a comparatively low threshold. This decay instability was studied in L-4 over a range of pump frequencies, $\omega_0/\omega_{ci} \approx 1.3 - 1.6 << \omega_{pi}/\omega_{ci}$ and ion concentration ratios n(He):n(Ne) = 0.4 – 4. The sidebands are identified as electrostatic ion cyclotron waves. Figure 24 shows the observed drift-wave frequencies plotted against magnetic field for various ion-concentration ratios (as labeled). The curves shown are the contours for the parametric threshold for several values of pump electric field, the solid curve corresponding to value of 8 V/cm used in the experiment. In satisfying agreement with theory, parametric decay was observed only within the threshold contour.

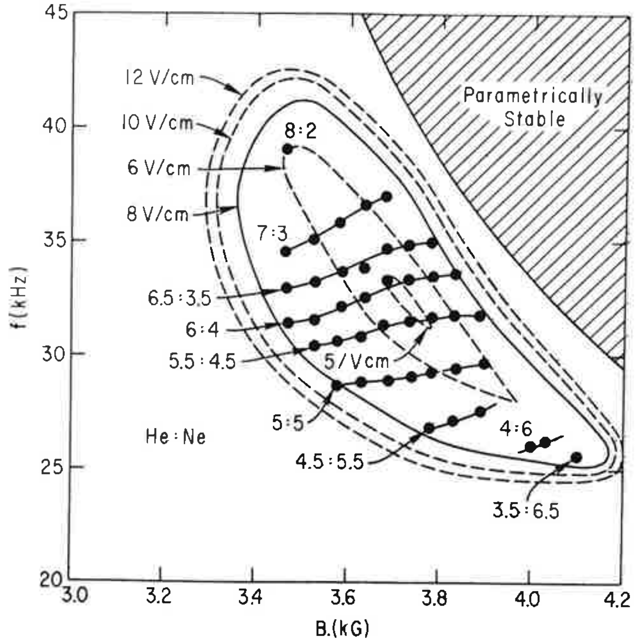

Figure 24. Observed frequencies of drift waves parametrically excited near the ion cyclotron frequency. The solid curve is the threshold contour for the 8 V/cm electric field in the experiment; parametric decay was observed only within this theoretical contour.

Cold Electrostatic Ion Cyclotron Wave

The special characteristics of the L-4 plasma — 4.2 kG axial magnetic field, low electron temperature ($T_e \simeq 0.5$ eV) and long length (~ 200 cm) — lend themselves admirably to the study, for the first time, of the electrostatic cold-electron ion-cyclotron mode ($\omega/k_{\parallel} \approx \omega_{ci}/k_{\parallel} > v_e$), which may play an important role in ICRF plasma heating in high magnetic field devices. Detailed observations on this mode have verified its electrostatic nature and resonance-cone behavior near the ion-ion hybrid frequency. Also measured was the spatial damping over a range of values of $\omega/k_{\parallel}v_e$, showing excellent quantitative agreement with electron Landau damping theory. Near the ion-ion hybrid frequency, ion-ion collisions become the dominant damping process; measured and theoretical damping rates are both displayed in Figure 25. Especially striking is the rapid increase of damping as the hybrid frequency is approached, with measured values of damping fitting well onto the theoretical curves. This process can be one of the ultimate energy absorption mechanisms in high-power ICRF heating.

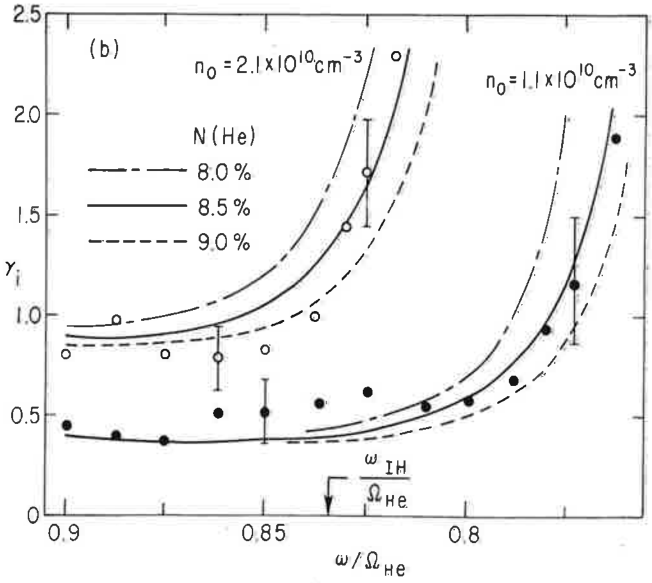

Figure 25. Damping of the cold electrostatic ion cyclotron wave near the ion-ion hybrid resonance frequency, for two densities (as labeled) in an ~8% helium plasma. Ion-ion collisions are the dominant damping mechanism.

Q-1/QED Program

Sputtering Yields for Low-Energy Plasma Ions in QED and in PLT

Using the energetic arc device, QED-1, sputtering yields of various wall/limiter materials of fusion devices have been measured extensively in the relevant plasma environment for low-energy light (H^+, D^+, He^+, Ar^+) ions ($E < 300$ eV).

In order to study the dependence of the sputtering yields on the incident energy of ions, the target samples (made of C, Ti, Mo, Ta, W, and Fe) were held at negative bias voltages up to 300 V. The sputtering yields were determined by a weight-loss method and by spectral line intensity measurements. The data obtained in the present experiment agree well with those previously obtained at the higher energies ($E \geq 200$eV) by other authors using different schemes; the present data also extend to substantially lower energies ($E \gtrsim 30$ eV) than previously considered. Figure 26 presents typical data from the measurement in which the sputtering yields of iron (SS 304) are plotted with respect to the energy of the bombarding ions, Ar^+, He^+, D^+ and H^+.

In the PLT tokamak a strong correlation has been found between high-Z impurity concentrations and the edge temperature. Tungsten line radiation (the limiter material being tungsten) becomes observable when the edge temperature is above 40 eV, and it increases quite rapidly with increasing temperature. Simultaneous measurements of electron and ion temperature at the plasma edge indicate good quantitative correlation ($T_e \simeq T_i$), supporting the notion that the incident energy of ions onto the limiter is about three times as high as the edge temperature due to sheath acceleration. Analysis shows further that the measured intensities of vacuum-ultraviolet tungsten radiation from a PLT deuterium plasma agree quantitatively with the QED sputtering yield curve, assuming that the sheath-accelerated ion energy is $E_i \simeq 3T_i \simeq 3T_e$ at the edge of the PLT plasma (Figure 27).

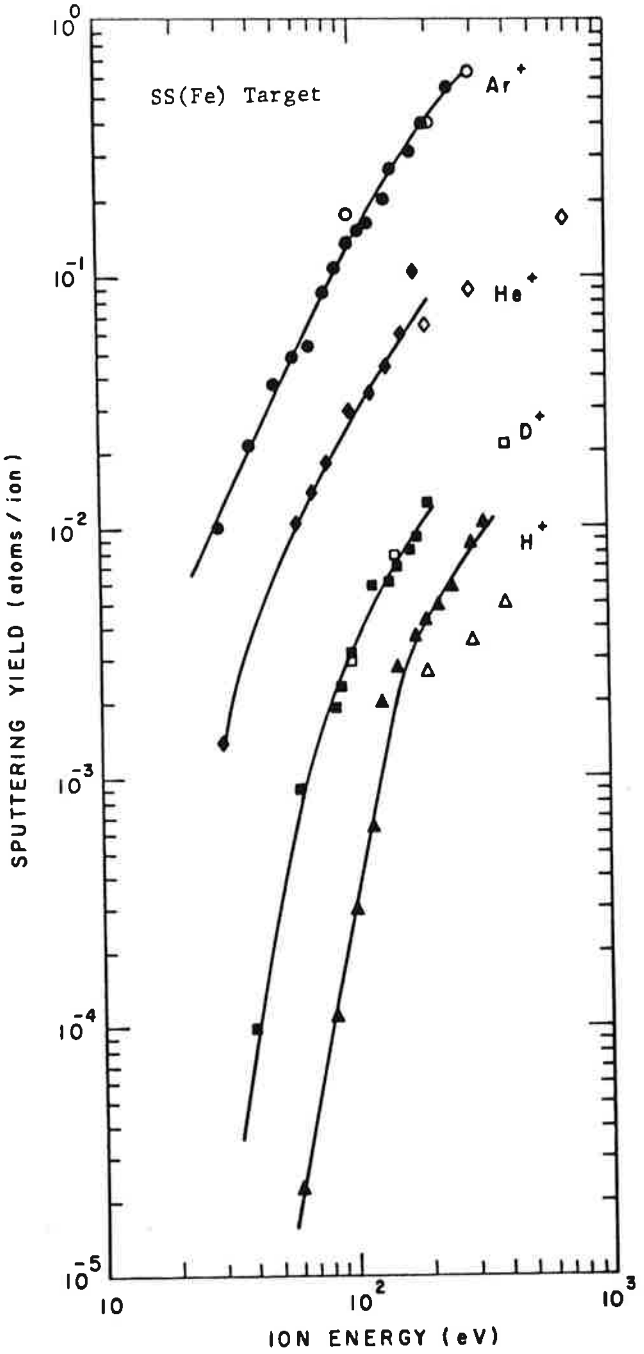

Figure 26. Sputtering yields of stainless steel SS 304 for Ar^+ (•) He^+ (♦), D^+(■) and H^+(▲) ions. Open symbols (○, ◇, □, △) were obtained by Laegreid and Wehner (Ar^+), Rosenberg and Wehner (He^+), and Bohdansky, et al. (D^+, H^+).

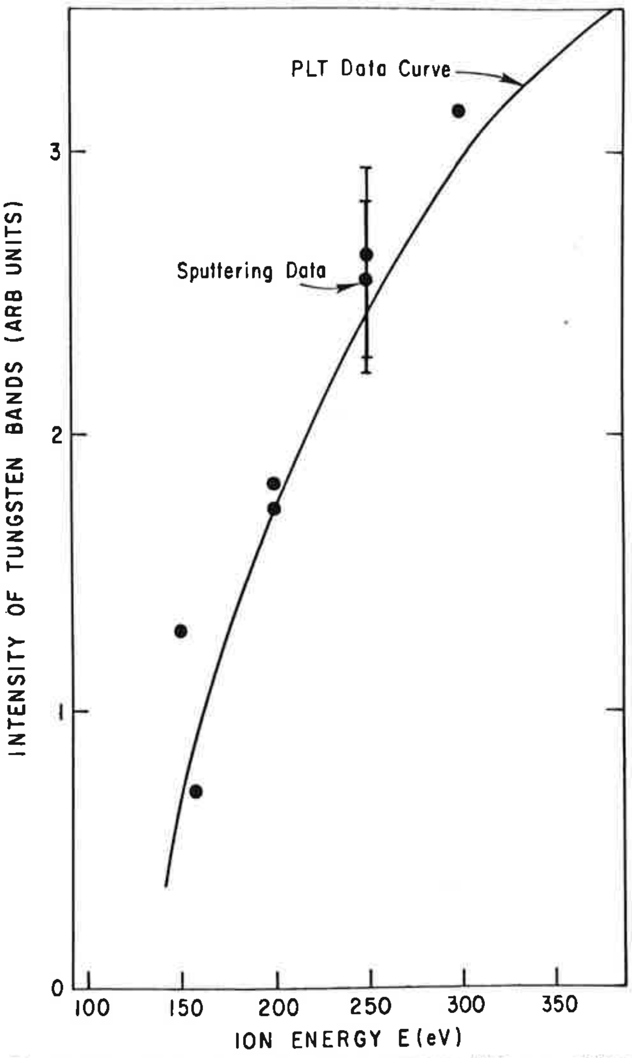

Figure 27. PLT vacuum-ultraviolet tungsten line intensities and QED sputtering data (closed circles) plotted vs. bombarding ion energy E_i (eV). PLT data curve is normalized with the assumption that $E_i \simeq 3T_e \simeq 3T_i$.

Parametric Lower-Hybrid Instability Driven by Modulated Electron Beam Injection

A modulated electron beam (diameter 6 mm), injected along the axis of a potassium plasma in the Q-1 machine, provided an oscillating radial pump field $\tilde{E}_r$ at the beam surface. When $\tilde{E}_r$ exceeded a threshold value defined by $c\tilde{E}_{ro}/Bc_s \simeq 1.5$ ($c_s^2 \equiv kT_e/m_i$), a lower hybrid wave and an ion quasi-mode (at $\omega \sim \omega_{ci}$) were parametrically generated, in accordance with the rules of frequency and wave-number matching. New results include the identification of two parametric instabilities from their dispersion curves, satisfactory comparison with the observed and computed threshold pump field as a function of pump frequency, and measurement of significant ion and electron heating when the parametric instabilities were excited. The increase in $T_{i\perp}$ is attributed to interaction with the lower-hybrid waves, while the increase in T_e appears due to electron Landau damping.

Impurity-Driven Drift Wave

An investigation of a new excitation mechanism for drift waves has been undertaken on the Q-1 machine. Impurity ions (cesium) are injected through an annular mesh-covered aperture into a potassium plasma column, creating radial profiles of ion density with a positive gradient for the impurity species (just inside the aperture) coinciding with a negative gradient for the main species. A strong ($\tilde{n}/n \lesssim 15\%$) coherent drift wave has been observed to be excited in this region when the cesium concentration is sufficiently high ($n_{Cs}/n_K \gtrsim 5\%$). Wave propagation is predominantly azimuthal with mode numbers from $m = 1$ to $m = 10$. The wave is considered to be excited by the collisional drag of cesium ions, but can be stabilized by finite-Larmor-radius effects of the background potassium ions. Measured dispersion characteristics of the mode are found to agree with a slab-model theory.

Whistler-Wave Dispersion and Damping

Preliminary measurements of whistler waves have been carried out in the QED-1 device, in which the unusually high (steady state) plasma density allows the parameter ω_{pe}/ω_{ce} to be varied over the range 10 to 100. The waves are investigated in the region of the device where typically $n \sim 5 \times 10^{12}$ cm^{-3}, $B \sim 200$ G and $T_e \sim 0.6$ eV (which is too low for Landau damping to occur). Observed dispersion and damping are compared with fluid theory in Figures 28(a) and 28(b); the curves in (b) correspond to an electron-ion collision frequency, $\nu_{ei} \sim 5 \times 10^8$ sec^{-1}, and $f_{ce} = 6 \times 10^8$ sec^{-1}.

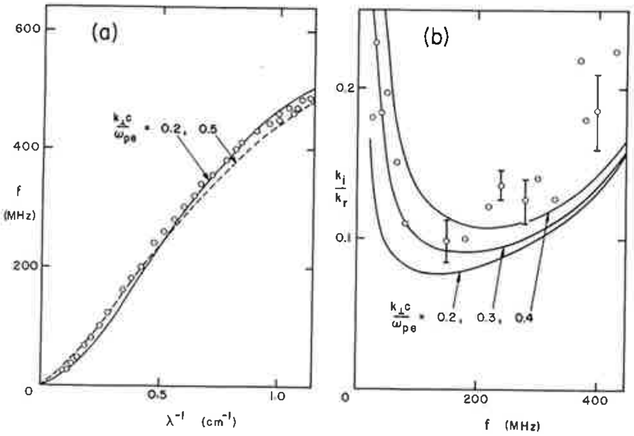

Figure 28. Dispersion and spatial damping for whistler waves in the QED plasma. λ is the parallel wavelength, $k = 2\pi/\lambda$, $f_{ce} = 600$ MHz.

The H-1 Program

As in the recent past, the linear H-1 test source has been used to study the excitation and interactions of lower hybrid waves with low-temperature, moderately dense plasma.

Steady-State Generation of Electron Current by Lower Hybrid Waves

The generation of steady-state plasma current in toroidal devices by directed lower hybrid waves is a topic of great interest. PPPL has demonstrated that directed currents can also be driven in collisional linear, afterglow plasmas by appropriate phasing (± 90°) of 8 rings on a lower hybrid wave launcher. It was found that the current drive efficiency is ~4 mA/watt, about one-half the efficiency calculated theoretically from the electron kinetic equation with a Lorentz collision operator (Figure 29). The current is observed to saturate when the electron drift velocity is close to the ion sound speed, as one would expect from imposing charge neutrality on the H-1 plasma column, which is not maintained by an electron beam.

Coaxial Plasma Source

The PPPL study of lower hybrid waves in general, and accessibility in particular, has suggested that a particularly simple source of moderate density ($<3 \times 10^{14}$cm^{-3}) plasma could be developed using an open-ended coaxial cavity driven with a few kilowatts of power at 2.45 GHz. Such a source was developed at

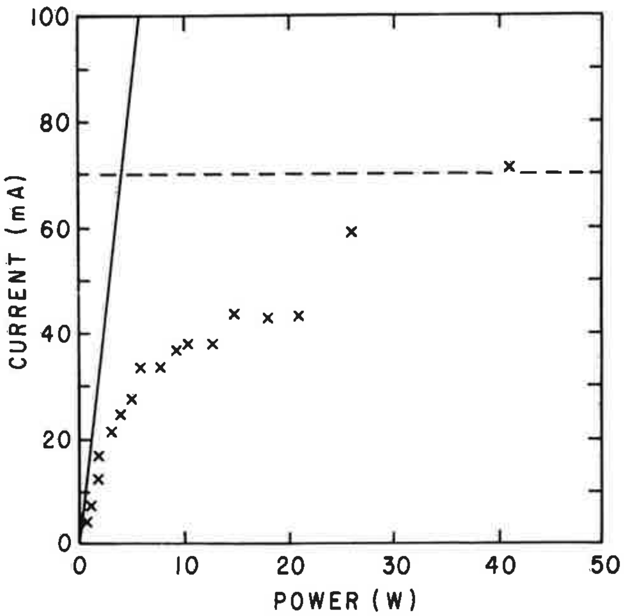

Figure 29. Current driven by 70 MHz lower hybrid waves in a collisional, linear, afterglow plasma as a function of the input power. The solid line is the theoretical prediction. The dashed line is the expected saturation level.

PPPL, and consists of an 8-cm long copper cylinder with a 4-cm long, 3-mm diameter stainless steel center electrode, terminating in a teflon insulator. Gas, injected into the cylinder near the tip, is ionized by the electric fields of the cavity and is injected along the lines of force of a magnetic guide field.

Plasma densities achieved with 2.45-GHz excitation (Figure 30) were found to be proportional to the power flux and could be driven almost to 10^{14}cm^{-3} with a limited power source (~5 kW). If the cavity were excited at much lower frequencies, the density was limited by the fundamental lower hybrid relation $n \le m_i\omega^2(1 + \omega_p^2/\omega_c^2)/4\pi e^2$.

This device may be useful either as a general purpose plasma source or as an auxiliary source for a variety of fusion applications, such as providing target plasmas for mirror machines or producing cold plasma blankets to help isolate the hot plasma core of a toroidal plasma from the vacuum vessel walls.

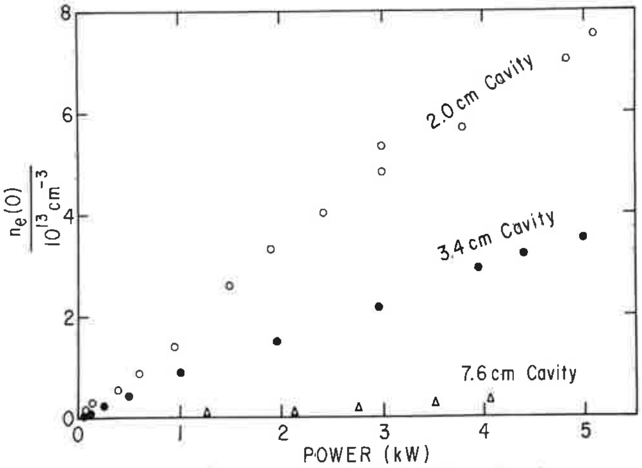

Figure 30. Plasma electron density achieved using three coaxial cavities of differing diameters, driven by 2.45 GHz microwaves.

Tokamak Fusion Test Reactor (TFTR)

OVERVIEW

The Tokamak Fusion Test Reactor (TFTR), the first magnetic confinement device capable of producing a significant quantity of fusion energy, is scheduled to begin operating in 1981. This experimental device will be the largest in the U.S. fusion program, more than twice the size of the Princeton Large Torus (PLT) and the Poloidal Divertor Experiment (PDX). Whereas PLT and other currently operating tokamaks in the U.S. and other countries were built to study plasma confinement below reactor-level conditions, TFTR is designed to attain reactor-level plasmas and to yield experimental data relevant to future fusion reactors.

The TFTR is also the first U.S. magnetic confinement device designed to demonstrate the fusion of deuterium and tritium at reactor-level power densities. It represents an essential link between the large hydrogen machines (i.e. PLT, PDX and Doublet III) and the first experimental power reactor.

The primary objectives of the TFTR are the generation and confinement of 5-10 keV reactor-grade plasmas in the tokamak magnetic-field configuration and the production of fusion energy on a pulsed basis from the reaction of deuterium (D) and tritium (T). The TFTR will be used to study the physics of burning plasmas and the engineering aspects of a D-T burning tokamak operating with reactor-level plasma conditions. The over-all TFTR program is intended to produce scientific and technical information, component hardware, and the experience necessary for the future design, construction, and operation of experimental fusion power reactors.

These objectives can be satisfied in a D-T tokamak with neutral beam injection by production of 1 to 10 MJ of thermonuclear energy (per pulse) under plasma conditions approximating those of an experimental fusion power reactor. A neutral-beam injection system capable of injecting into the plasma 20 MW of 120 keV deuterium with a pulse duration of 0.5 sec is one of the requirements for production of temperatures in the range of 5-10 keV, a maximum particle density of 10^{14} cm^{-3} and an $n\tau_e$ value in excess of 10^{13} cm^{-3} sec. The plasma handling techniques and hardware must be capable of initiating, controlling, and dissipating plasma currents of up to 2.5 MA.

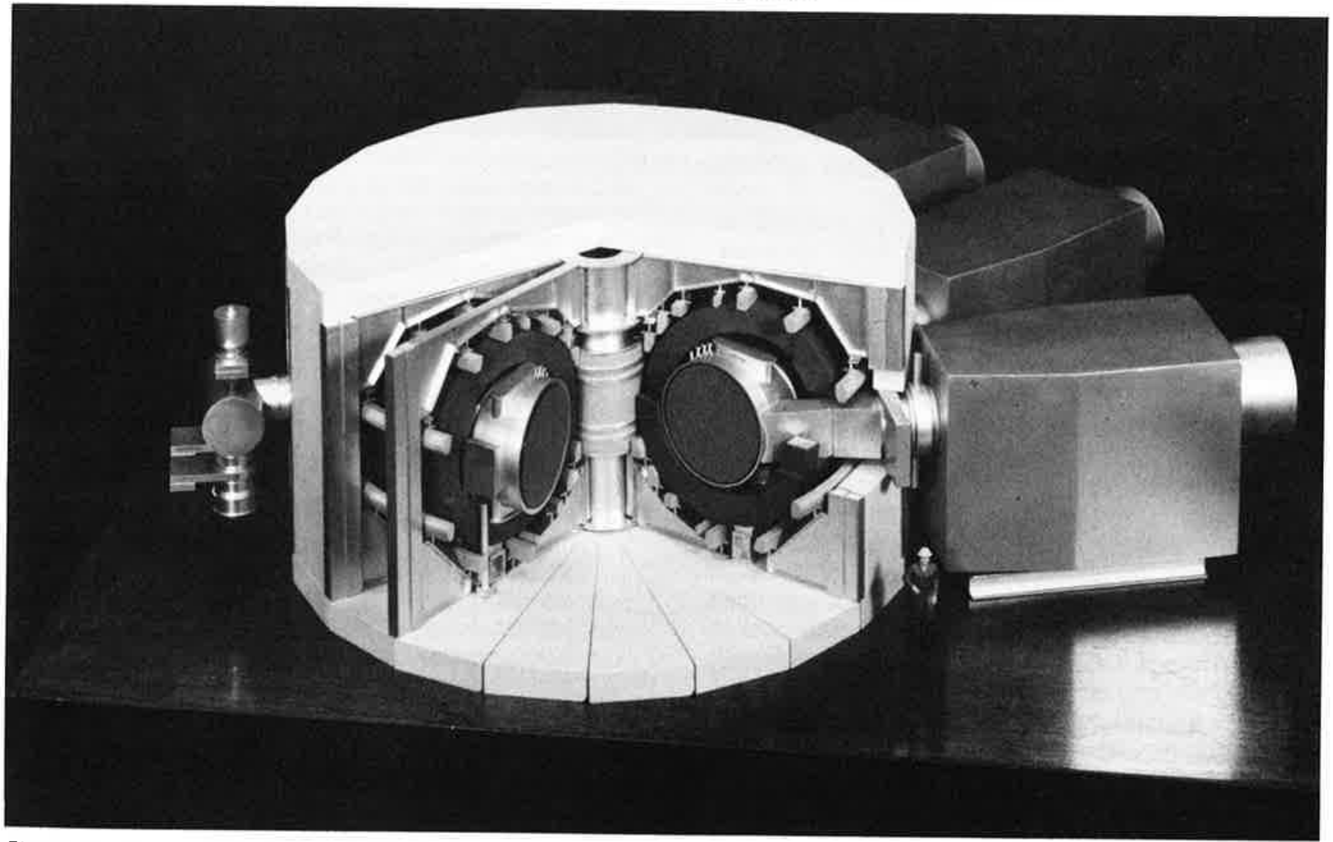

Figure 31. Model of the Tokamak Fusion Test Reactor (TFTR).

Figure 32. PPPL C-site facility, late 1978. At the right is the TFTR construction site.

MAJOR ACTIVITIES

Progress in FY78 centered around technical design activity, procurement, and continued construction of the Motor Generator Building, Office/Laboratory Complex and Experimental Complex.

Several key technical design reviews were completed during the fiscal year. Preliminary design reviews were conducted for remote handling, the central instrumentation control and data acquisition system (CICADA), neutral-beam power system, and the CVI refrigerator for the cryogenic system. Final design reviews for the vacuum vessel, vacuum-pumping system, vacuum vessel heating/cooling, water cooling system, TF coil case and inner support structure, energy supply and distribution system, PF coil and the tokamak superstructure were completed.

Major design changes to TFTR occurred during the year. PPPL engineers solved a critical stress problem in the toroidal field coil system by increasing the thickness of the outer ring, a modification which affected the design of the poloidal field coils. In addition, it was decided to reduce the number of neutral-beam injectors from four to three. The reduction in the number of beam lines will effect a cost reduction, but will not compromise TFTR operating objectives.

Remote Handling

Remote handling activities on the M1 and M2 "soft" mockups included experimental verification of remote maintenance methods and development of detailed maintenance procedures. Completed tasks include:

- Limiter blade remote installation and removal,
- Limiter actuator remote installation and removal,
- Welder/cutter remote installation, deployment, and removal,
- Horizontal port cover replacement,
- Shear compression panel installation and removal,
- Bottom obround port cover replacement,
- TF coil bottom cooling water hose connection,
- NB line duct flange disconnect mockups.

Work continued on the full-scale M-3 mockup of one-fifth of the TFTR vacuum vessel with simulated TF coils and supports. The M-3, scheduled to be completed in FY79, will be used for remote-maintenance developmental and operational tasks.

Quality Assurance

The quality assurance program for TFTR is designed to assure that specified levels of quality for the various systems are met, that work performed or hardware fabricated adheres to the drawings or specifications outlined in the contract, and that delays and costs due to rejections or failures are minimized. During the past year, strong emphasis was placed on preventative activities, such as preparing QA requirements for bid packages, reviewing and approving specifications and procurement packages, and participating in design reviews. The following documents were also issued this year: QA Policy, QA Plan, Change Control Procedures and QA Procedures. These documents represent the first formal QA program for the laboratory.

Central Instrumentation, Control and Data Acquisition (CICADA)

A contract for a computer system containing thirteen computers for the central instrumentation, control and data acquisition (CICADA) system was awarded to the Systems Engineering Laboratory. Eight of the computers and a large quantity of other CAMAC hardware were received. An operational, stand-alone CAMAC timing system was sent to the Lawrence Berkeley Laboratories to be used in neutral beam development.

Neutral Beam Development

The TFTR neutral beam system is comprised of the neutral beam power supply (NBPS) and the neutral beam line (NBL). During FY78 significant progress occurred in the NBPS. In December 1977, a preliminary design review for the NBPS was conducted and by September 1978, 50% of the final design review was completed. In March 1978, PPPL approved a contract between its vendor, Transrex, and their subcontractor, Aydin, to supply the modulator regulator, a critical element in the overall NBPS. The modulator regulator's primary function is to apply control and regulate power to the NB ion source. It utilizes the recently developed RCA high-voltage switchtube as the controlling element in this subsystem. In February 1978, developmental design for the high-voltage transmission line was started. Testing of the prototype unit began in the summer.

Physics

The TFTR physics group supported the design of the power conversion system, the vacuum-vessel system, and the area subsystems. The voltage and current characteristics of the power supplies were determined, and the time response characteristics were specified. Extensive studies were carried out on plasma initiation. The studies were a combination of computer modeling with zero and 1-D codes, and experiments on the PLT tokamak. After experimental verification, these models were used to project TFTR operation and determine TFTR system requirements. A combination of plasma discharge scenarios was developed and studied during FY78. These scenario studies included an analysis of the discharge termination characteristics.

Westinghouse was awarded a contract for fabrication of the toroidal field coils, and the decision was made to fabricate the large poloidal field coils at PPPL to avoid anticipated problems in transporting them.

Technical Improvements Project

After TFTR, the next step towards thermonuclear plasmas appears to be "hot-ion" bulk plasma operation. This requires increasing the plasma ion temperature sufficiently so that the majority of fusion reactions result from bulk plasma interactions rather than interaction of the injected ions with low-temperature plasma ions. The Department of Energy awarded the laboratory $350,000 to begin conceptual studies of the ways in which the Tokamak Fusion Test Reactor could be improved to achieve higher energy yield. These very early conceptual studies focused on defining the physics parameters and the associated engineering problems, and planning the necessary research and development tasks.

It is anticipated that in FY79 additional money will be awarded to develop a full conceptual design for the Technical Improvements Project.

Contracts Awarded

To ensure that overall cost and schedule will be met, a great deal of emphasis was placed on procurement activity during FY78. Virtually every technical area was affected. Ebasco Services, Inc., the major industrial subcontractor on the project, signed major contracts with over 20 domestic and foreign vendors, committing over thirty-five million dollars. Some of the contracts are listed below:

MATERIAL	VENDOR
Current-limiting reactors	TRENCH
13.8-kV generator main leads	GOULD, INC.
Field coil water chillers	CARRIER
Energy storage capacitor bank	WESTINGHOUSE
Structural steel superstructure	CE AIR PREHATER
TF coil case inner & outer ring forgings	JAPAN STEEL
Vacuum vessel segments	CHICAGO BRIDGE & IRON
TF coil case plate material	CARLSON
Energy conversion system thyristor rectifiers	TRANSREX
TF coil conductors	KABELMETAL
Ohmic heating interrupters	WESTINGHOUSE
Metal-enclosed dc equipment	WESTINGHOUSE
Tritium cleanup system	CVI
Inner support structure	ROCKWELL, INT.

Engineering

OVERVIEW

The Engineering Division has responsibility for providing services for design, construction, operation, maintenance, development and procurement specification of electrical, electronic diagnostic, data handling and other systems required to support the Laboratory's experimental devices and programs. During FY78, the Division added two functional groups, TFTR Diagnostics and Electro-Optics to meet increased areas of responsibility.

The TFTR diagnostics group is unique in the division; it is organized as a project, with the sole purpose of providing diagnostic devices for use with TFTR. Working closely with TFTR physicists and engineers, it is engaged in the definition and design of some forty devices, and is backed by the resources and expertise of the entire division.

The engineering group of the Princeton University Department of Astrophysical Sciences has worked with PPPL for several years, but it was not until July 1978, that the group became a formal part of the PPPL Engineering Division. The newly formed Electro-Optics Group is responsible for providing experimental machines with "state-of-the-art" sensing devices, such as XVV image sensors, bolometers, intensified CCD image sensors, and television data acquisition systems.

MAJOR ACTIVITIES

Electronics Section

During FY78, as in previous years, this section designed and constructed a large number of electronic units for machine diagnostics and appurtenance control. Speed monitoring units were designed and produced for the PDX turbomolecular vacuum pumps. Each unit utilizes an optical pickup to sense pump-shaft speed and display it on a panel meter. Logic circuitry detects a shaft-speed decrease to below a predetermined value (as would occur in event of power or motor failure) and operates a relay, actuating an alarm and an argon pump-flooding system. A battery backup supply is included to ensure monitor operation after power failure.

Solid state replacements for the electromechanical relays previously used in the speed-control system for the large MG sets were designed and installed. The units operate from the 120-V supply for the control relays, and speed values may be set by a three digit thumbwheel switch over a range of 50% to 115% of nominal full speed. This change resulted in much faster and more accurate adjustment of speed trip-out points.

Phase monitors providing analog and digital outputs proportional to the phase difference between two signals were developed for use in laser-type plasma density measurements. Two versions, one operating at 40 MHz, the other at 1 MHz, were produced, permitting ranges of either 0 to 512 cycles phase difference or 0 to 1 cycle difference. Some of the units containing digital outputs include circuitry that allows operation into the PDX CAMAC system.

Also during FY78, an electronic control device for PLT titanium sublimation pumping was designed and installed by the Electronics Section. The unit controls the position of 3 titanium balls in and out of the machine, as well as ball filament heating power. Position of the titanium balls is controlled by limit switches; signals from the limit switches are transmitted to the control unit via optical safety breaks. Heating power and position are displayed by indicator lights and meters on the unit panel.

Power Electronics Section

This section was heavily involved throughout FY78 in the installation and testing of heating and diagnostic systems for the large PPPL experimental devices.

Subsystems for the PLT 5-MW 55-MHz ion cyclotron resonance heating (ICRH) system generator were wired and tested. Some units were installed at C-Site by the end of the year (Figure 33). The first of two 2.5-MW modules was expected to become operational on PLT early in calendar year 1979. The existing 25-MHz RF system was refurbished and became operational on PLT during FY78.

The Power Electronics Section also constructed two diagnostics modulators for PDX, one for ion temperature measurement and another for the fast ion detection experiment. After testing, one unit will go to the PDX machine site, the other will be retained for neutral-beam regulator experimentation, until it is required for PDX.

Other accomplishments of the Power Electronics Section for FY78 included the reconfiguration of the aged, but operable, OH hard tube system to provide an ac output of 200-300 HZ into the OH coil of PLT for pulse cleaning. The unit provides a coil current of 200 A with a 40-ms pulse duration and a rate of one pulse per second. The Power Electronics Section also refurbished a 5-kW, 2.5-GHz magnetron source for use in H-1 experiments.

During FY78, the Power Electronics Section upgraded from 50 to 200 kW another of the four 800-MHz

Figure 33. PLT 55-MHz ICRH high-voltage power supply under construction.

lower hybrid heating power modules formerly used on ATC. The module was then loaned to MIT for operation on the Versator II machine. By the end of FY78, successful operation into a dummy load had been achieved at MIT, and plans called for debugging and final installation on Versator II during FY79. Near the end of FY78, a proposal was submitted for a PLT Lower Hybrid Program. It would utilize six 200-kW modules, requiring the return of the two modules loaned to the General Atomic Corporation during FY77 for use on the Doublet II-A experiment, and the construction of 3 additional modules. During the work at MIT a metallizing and bonding technique was developed for use on ceramic blocks used in the waveguide grill. This development will be very useful for the PLT program.

Instrumentation Section

This Section carried out several projects during FY78 in an effort to provide diagnostics hardware for PLT and PDX. A diagnostic control system for both machines was designed consisting of a PDP 11/34 computer which runs an RSX-11M operating system with Fortran, a serial telemetry system utilizing CAMAC, and closed loop digital position controllers. The system enables each diagnostic user to use an independent control program in higher level language for manual or automatic positioning of multiple parameters (motor positions, etc.) once or more per machine pulse. The major design and purchasing for this system was done in FY78 for completion and use by PDX on the first day of operation.

The Instrumentation Section also supported data acquisition by providing hardware including the following items:

- A high-voltage high-speed safety break for the CAMAC serial highway
- A touch-tone pad interface
- Improved display systems
- Programmable clocks for transient recorders
- A digital safety break for PDX
- The PDX 15-channel x-ray pulse height analyzer

In the area of microwave diagnostics, the Instrumentation Section completed the following items:

- A 4-channel, 8-mm interferometer for PDX divertor experiments (Figure 34)
- A 1-mm interferometer for PLT
- A 60 to 90-GHz swept receiver for PLT
- A 10-channel, 2-mm interferometer for PDX

The Section also performed engineering tasks on bolometry analog signal conditioning, plasma probe-drive circuitry, high-speed analog safety break transmission, and sensitive phase-locked loop receivers, all important factors in producing good machine diagnostics while maintaining personnel safety.

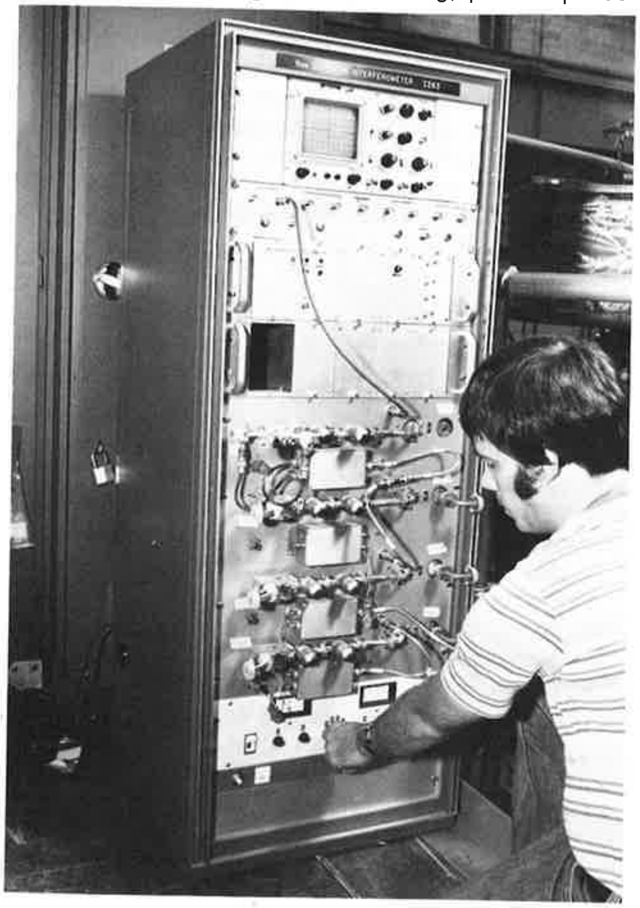

Figure 34. PDX 8-mm divertor interferometer.

Mechanical Engineering Section

One of the major activities undertaken by this Section was the design and fabrication of three carbon limiter assemblies (Figure 35) and positioning mechanisms for the ISX machine at ORNL as a part of the TFTR program to evaluate limiter blade materials. Each blade was made of Union Carbide type ATJ-S carbon and equipped with resistive heating elements and thermocouples installed in the blade rear. Experiments made with these assemblies on ISX showed that there was little or no blade contamination at blade temperatures of up to 400 °C.

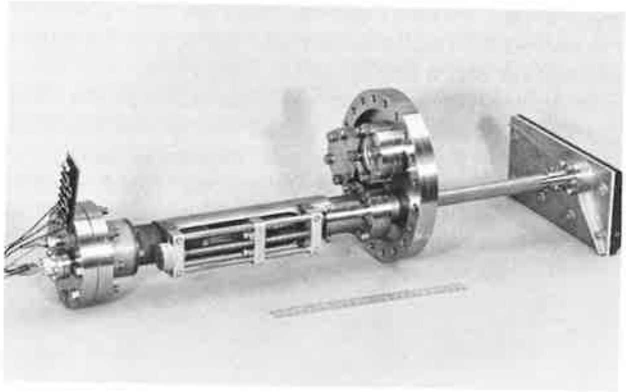

Figure 35. Carbon limiter assembly.

Another major accomplishment of the Mechanical Engineering Section was the redesign of the water-cooling piping on the PLT neutral beam lines. A recirculating system was installed for each beam line to insure a flow of water in the cooling coils when the main deionized water system was inoperative.

Other activities focused on mechanical design and construction of diagnostic devices, including neutral-injection calorimeters, hard x-ray detectors, a heavy-atom-beam midplane detector, and a nineteen-channel bolometer array and mount.

Power Engineering Section

The largest section in the Division, Power Engineering completed an expansion of the power substation, resulting in capability to supply twice the MVA previously available. A special transformer supplies the pulsed rectifier loads of PLT and PDX, and two additional transformers will supply TFTR.

One of the most significant accomplishments was the first succcessful use of voltage limiting amplifiers in the generator control system. The gain from the improvement is threefold: the routine excitation of the PLT TF to 28 kA with projected maximum of 35 kA (1.0 second flattop) using only 8 generators instead of 12 is now possible, releasing four units to serve other loads; TF excitation on PDX will be possible using 10 generators, leaving two available for the PDX divertor field; and a considerable energy savings is accomplished.

The Power Engineering Section was also responsible for the design and installation of power supply systems for PLT's four neutral beam injection systems (Figures 36 & 37). Early in FY78, all four power supply systems were ready for operation. By December 1977, two of the systems were operational, serving the two beam lines that had been installed on PLT. The third unit served the neutral beam test stand, and the fourth unit had no beam line to serve.

In April 1978, following the installation of the third and fourth beamlines on PLT, all four power systems served the PLT beam lines with improving facility for the remainder of FY78. In July the power systems were used to produce the PLT record-breaking 60,000,000°C plasma.

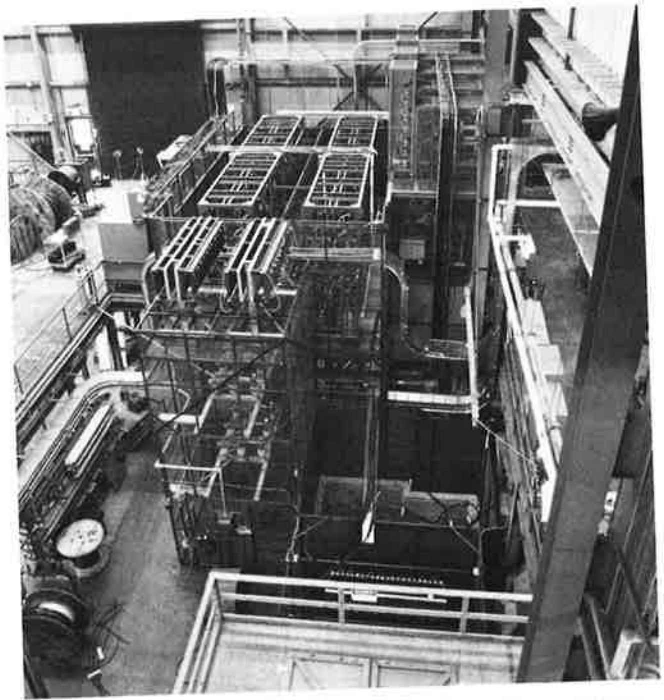

Figure 36. PLT/PDX neutral beam high-voltage power supply.

Figure 37. PLT/PDX neutral beam power supply console.

In January 1978, upon authorization from DOE, the Power Engineering Section began the design of the PDX 6-MW neutral beam power system. By the end of FY78, construction of the system had begun. The PDX beam lines will operate at 50 kV 100 A, as compared to the 40-kV 50-A PLT systems.

Data Acquisition Section

The efforts of this section were split between adding and improving diagnostic packages for PLT and developing required system enhancements to enable data acquisition from PDX during initial operations.

The following improvements were made to the PLT diagnostics package:

- The neutron temperature diagnostic was expanded to 24 channels.
- A bolometer array detector using a PDP-8 digitizer was interfaced and an analysis program developed.
- Biomations for the fast-ion diagnostic were interfaced, and a data reduction program was developed.
- The charge exchange diagnostic for ion temperature measurement was converted from a varying analog signal to a discrete counting measurement performed with a multiscaler.
- Additional memory capacity was instituted for the PDP-10 system (Figure 38), and certain software was added, enabling a few days' data to be kept on line, thus allowing orderly archival of data to magnetic tapes.

Figure 38. PLT/PDX PDP-10 data system computer.

In PDX-related activities, the Data Acquisition Section installed an RSX-11 operating system on two PDP-11's. One PDP-11 was set aside for use with the PDX TV Thomson Scattering system. This computer will control hardware through a CAMAC interface as well as provide data reduction and analysis. The second PDP-11 (connected to the PDP-10 via shared memory) was used to incorporate an RSX system into the DAS network, allowing the development of a communications link between PDP-11 tasks and PDP-10 jobs. RSX drivers were written for the PDP-11 into the CAMAC serial/parallel highway interface and for the parallel data channel built by the Instrumentation Section.

A facility enabling PDP-11 programs to write data files directly on PDP-10 disks for subsequent analysis was completed near the end of the year.

During FY78 the Engineering Division's new Electro-Optics Section was involved in the testing and associated circuit design for charge-coupled devices (CCDs) being employed on various PLT/PDX diagnostic systems.

Intensified charge-coupled devices (ICCDs) for the PDX Thomson Scattering diagnostic were delivered from Varian and tested. Submicrosecond pulsing of the units was successfully demonstrated.

By the end of FY78, components were ordered for the construction of associated electronic circuitry for the PDX soft x-ray CCD. Texas Instruments submitted a proposal for the CCD in September. Investigations were also made for the purchase of a Reticon line array with very long picture elements that can be used in the 5-keV x-ray region.

A routine maintenance program was set up for the Fairchild 100-X-100 pixel CCD camera for the PLT plasma TV. Only minor problems were encountered.

TFTR Diagnostics Project

As noted in the Overview, this project was initiated in the last quarter of the fiscal year to manage and coordinate the design, fabrication and testing of the 40 diagnostic subsytems anticipated for use on the TFTR.

By the fiscal year end, several project activities were underway. A conceptual definition of the electrical grounding network for the diagnostics was initiated to assure personnel safety and minimize noise pickup. Work was started on the definition and planning of the neutron spectrometer and charge exchange diagnostics. Several cost/benefit studies were in progress to assist the cognizant physicists in optimization of the mechanical and electrical configurations.

The laser interferometer control requirements were reviewed. An initial design of system mechanization was completed. The control system will automatically find the mutually optimum power points of the CO_2 and the two CH_3OH lasers, thereby eliminating the present manual "tweaking" approach.

Work was started with TFTR project engineers on vacuum vessel interface problems. Many of these problems are intimately related to the overall design of the diagnostics.

Machine Design and Fabrication

OVERVIEW

The Machine Design and Fabrication (MD&F) Division is one of the engineering activities serving PPPL. Its principal responsibilities are the design, fabrication, modification and maintenance of experimental devices. Associated support work includes installation, operation and maintenance of general plant facilities. In carrying out assigned tasks, resources of the MD&F Division are divided into the five technical sections discussed below. Each of these sections provides specialized capabilities developed over years of effort in support of plasma research.

Planning and management of the MD&F Division are carried out by staff within the Administration Section. A PERT-type computer system is used to generate cost and schedule data for all the Division's work, and resources-versus-time are generated in tabular and graphic form. Cost and schedule progress are monitored with these data. Time reports, and other personnel records, maintenance and trouble reports, spare parts authorization and inventory replacement approvals are organized here. The section also performs technical supervision of the Division's work.

MAJOR ACTIVITIES

Coil Design and Fabrication Section

During the year, a major portion of this Section's effort was devoted to the final component fabrication and assembly of the PDX device.

Both engineering and shop personnel followed the toroidal field (TF) coil vendor, Kaman Aerospace Corporation, as they completed their program. The final 20 of the 22 coils required were fabricated and delivered. Key steps in this fabrication process included stretch-forming of the copper conductors (Figure 39), insulation of the individual conductors and conductor assemblies, precision molding of conductor assemblies and silver plating of the lap joints.

At PPPL, receipt of the coils was followed by electrical testing and inspection (Figure 40). The turn-by-turn installation of the 20 TF Coils on the PDX machine was accomplished during the six-month period from late November 1977 to May 1978. Portions of this three-shift-a-day, six-day-week task are shown in Figures 41 and 42. Final installation of all six bus systems was accomplished and major PDX power tests began at the end of September 1978.

Other FY78 activities of the Coil Design and Fabrication Section included the fabrication of shield enclosures for the PLT neutral-beam injectors and the fabrication of coils and assembly of the deflection magnet units for the PDX neutral beam program. The first of four units was completed (Figure 43). The building of two coils and final assembly of the ripple coil sub-assembly for the Impurity Studies Experiment (ISX) at ORNL (Figure 44) was accomplished. A sample molding and electrical test program in support of the TFTR coil development program was also conducted.

Figure 39. Stretch-forming of PDX copper conductors at the Kaman Aerospace Corporation, Moosup, Connecticut.

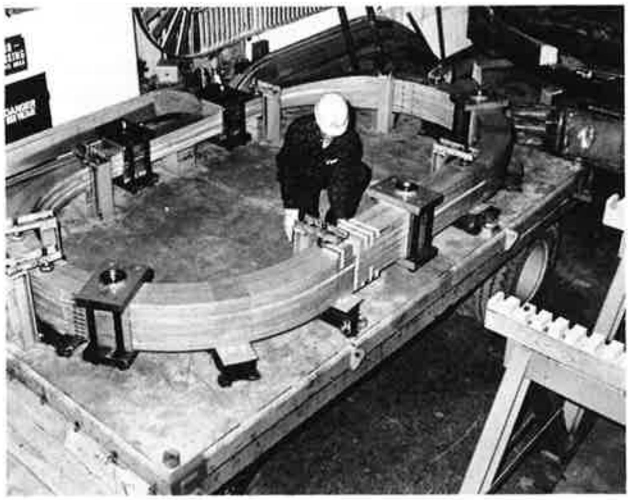

Figure 40. Inspection of PDX TF coils upon delivery to PPPL.

Field Design Section

The Field Design Section provides the personnel and expertise required for the design, simulation and

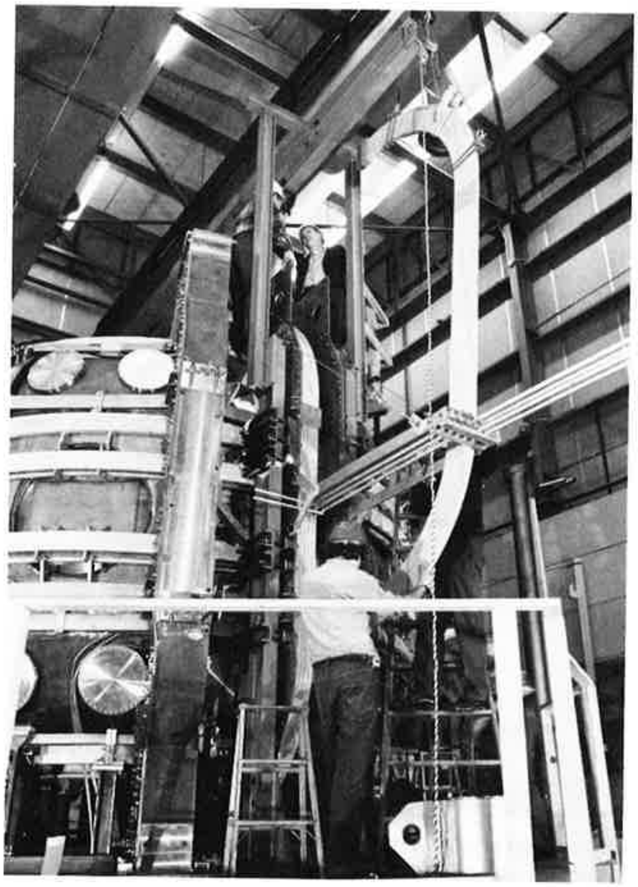

Figure 41. Positioning of the outer segment assembly of PDX TF coils.

analysis of magnetic systems as requested by the Experimental Division. Typical of the Field Design Section's work is the translation of general magnetic field parameters into specific coil requirements and associated power needs. The major activities of the Field Design Section during FY78 are listed below:

- A program to compute the eddy currents induced in the TFTR vacuum vessel wall was provided to the TFTR Diagnostic Group.
- A rigorous analysis of the forces in PDX toroidal field coils was completed. This work provided the necessary nodal point forces for the Grumman finite element structural analysis.
- A magnetic field analysis of the proposed PLT Stellarator was performed. Magnetic surface plots and data for computing the rotational transform, magnetic well and equivalent plasma current were provided.

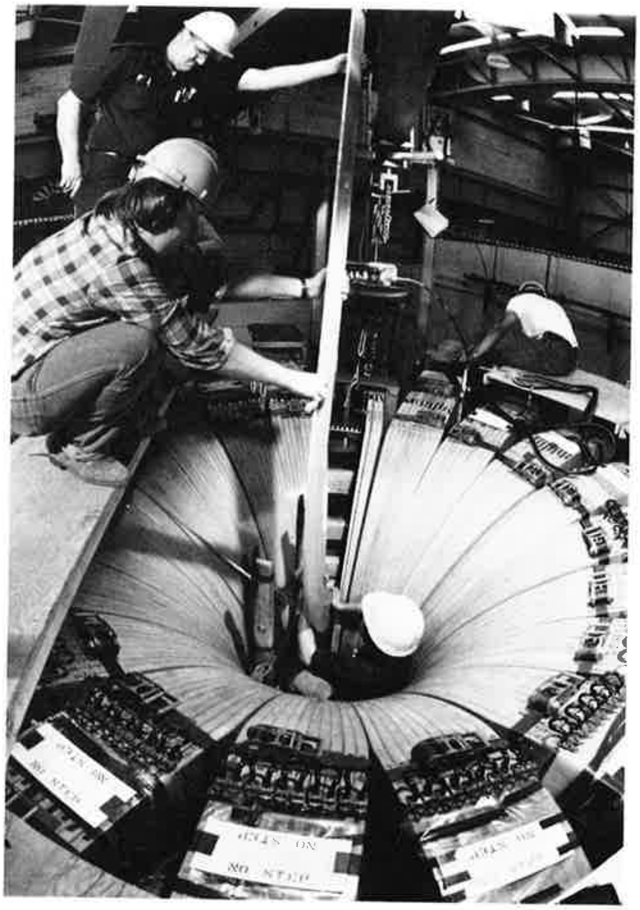

Figure 42. Inner segment assembly of the last PDX TF coil being lowered into place.

- An attempt was made to optimize the magnetic field coil systems for the proposed PDX upgrade (STRETCH). Coils were moved to provide larger plasma area. Consideration was given to modification of voltage and current profiles for the poloidal field coils.
- General magnetic field calculations were provided for TFTR.
- Studies were made of the voltages to be expected on the PDX vacuum vessel break caused by plasma disruptions and various voltage suppressions. Schemes were modeled to be applied to the machine.
- Studies were made on revised OH and SF systems for the PLT machine.
- Studies and magnetic field plots were made and are being continued for the Holomak and Spherator devices.

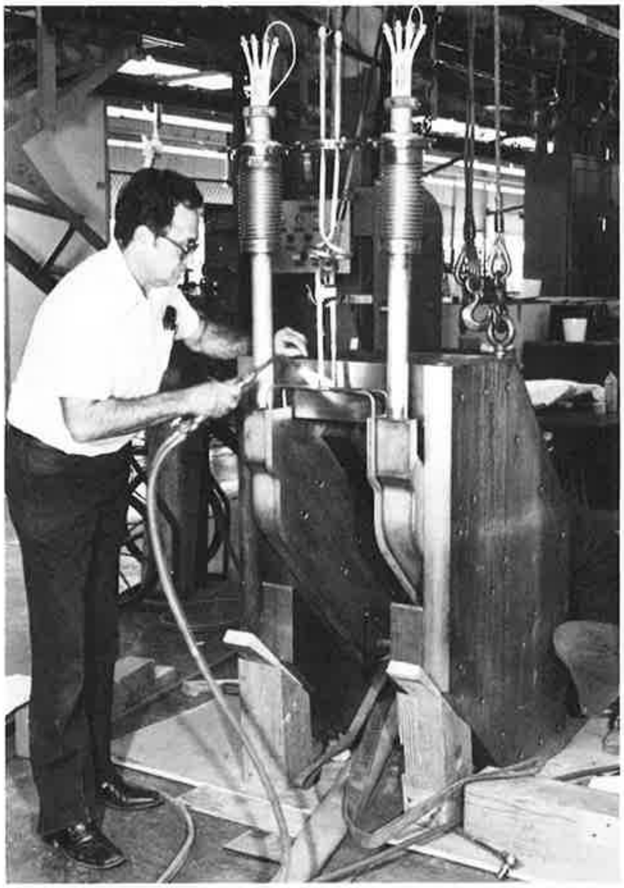

Figure 43. Final assembly of the PDX neutral beam deflection magnet.

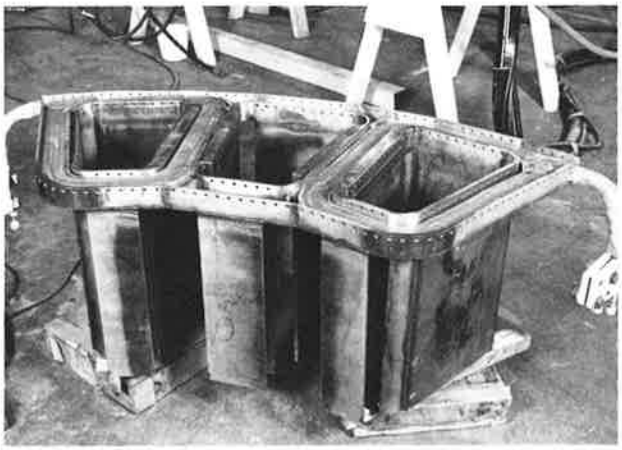

Figure 44. Ripple coil assembly for the ORNL ISX program prior to the addition of top cover and final potting.

Structures Design and Fabrication Section

PDX Assembly

Assembly of the PDX device was one of the major efforts of the section during the year. After completion of the poloidal field (PF) coil power tests in September 1977, the PDX device was partially disassembled (bus work and water manifolds removed) in preparation for the TF coil installation. Engineering personnel from the Structures Design and Fabrication Section were responsible for coordinating and supervising the TF coil installation as well as the design of the special fixtures required for assembling the coil segments. The first TF coil was completed late in November 1977. Thereafter the assembly of the coils proceeded at an accelerated pace until all 20 coils were installed by mid-May 1978.

The subsequent phase of the assembly operations included installation of the lower-thrust hub (Figure 45), the support rings, the torque frame, and the center column (Figure 46). This was followed by the upper shelf installation (Figure 47). Piers and saddles together with the hydraulic preload system and hydraulic clamp system were also installed during this phase of the assembly. Installation of the bus work and water cooling systems proceeded in parallel. The assembly of the toroidal field coil spacers and the torque tube occurred near the end of the fiscal year. The radiation shield wall was also completed during this period.

Completion of the center column assembly and final power tests were scheduled for early in FY79. A first plasma occurred in November 1978.

Design of TFTR Neutral Beam Support System

Preliminary budget estimates and scoping studies for the TFTR Neutral Beam Support System (NBSS) were completed by the Structures Design and Fabrication Section in October 1977. During the period November 1977 through March 1978 the requirements for the NBSS were made final. The conceptual design was started in March 1978. Conceptual design layouts were generated to examine interfaces with other systems and explore design features. A preliminary design review was held in July 1978. Final detail drawings incorporating the changes suggested in the design review were completed by October 1978.

Development of remote maintenance equipment and techniques for TFTR was started during FY78. A group of technicians was assembled to work on remote handling tasks. Mock-ups of the TFTR were

Figure 45. Positioning of the PDX lower thrust hub.

built, and bolt-up of the shear compression panels was made remotely. Connection and removal of the lower diagnostic tubes as well as connection of the TF coil cooling water hoses were accomplished semi-remotely from the basement area. Other remote maintenance welding procedures were conceptually designed.

Structural Design Using Finite Element Methods

Several different Finite Element Method (FEM) Models were constructed and executed to simulate the PLT-TF coil under maximum operating conditions. These models used the ANSYS Computer Code on a CDC-7600 Machine installed at the Brookhaven National Labs. There was reasonable correlation with the test results.

An FEM model of the total PDX machine was constructed defining PDX geometry, loads, temperature profiles, and boundary conditions. The work, executed by the Grumman Aerospace Corporation in close liaison with the PPPL Stress Analysis Group, was not yet completed at the end of the fiscal year.

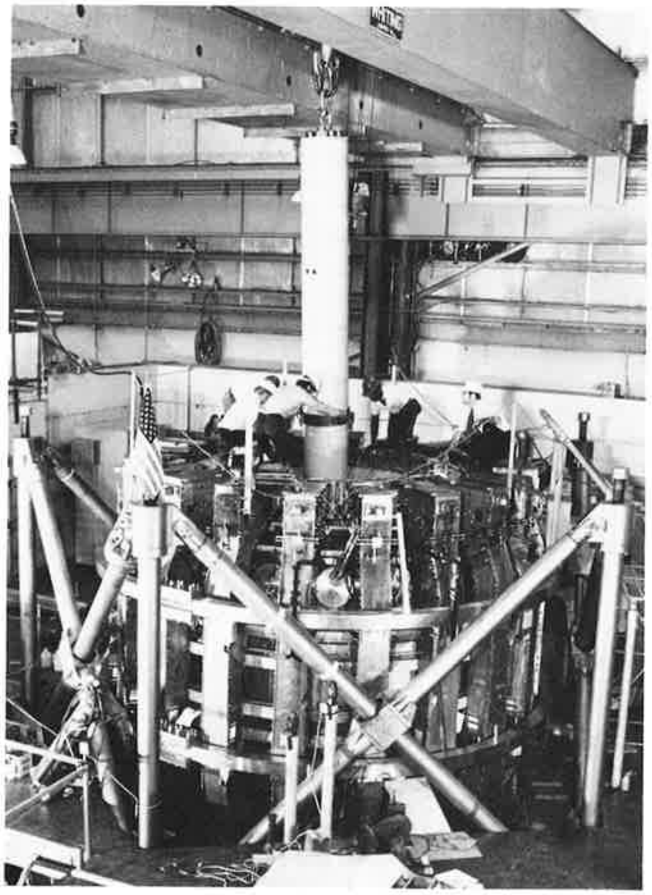

Figure 46. Lowering the PDX center column.

A review of all Ebasco/Grumman FEM work for the TFTR TF coil and the TFTR vacuum vessel was initiated. Ebasco/Grumman used the MSC/NASTRAN code. In order to continue the review, PPPL established communication with University Computing Company (UCC) at Dallas, Texas and used their computer. This work continues.

Several FEM models that simulated the superconducting TF coil were executed during the Superconducting Long Pulse Experiment (SLPX) Scoping Study. This work, reported in Chapter 4, Volume II, of the SLPX Scoping Study*, was conducted using COSMIC/MASTRAN installed in the Princeton University computers.

COSMIC/NASTRAN version 17 was installed on the PPPL CYBER-172 Computer, and a Tektronix Finite Element Modeling System known as FEM-181 was purchased. The FEM-181 system is used to construct

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*"Superconducting Long Pulse Experiment, Final Report on Scoping Study," *Princeton University Plasma Physics Laboratory Report 1501-1503*, November 1978.

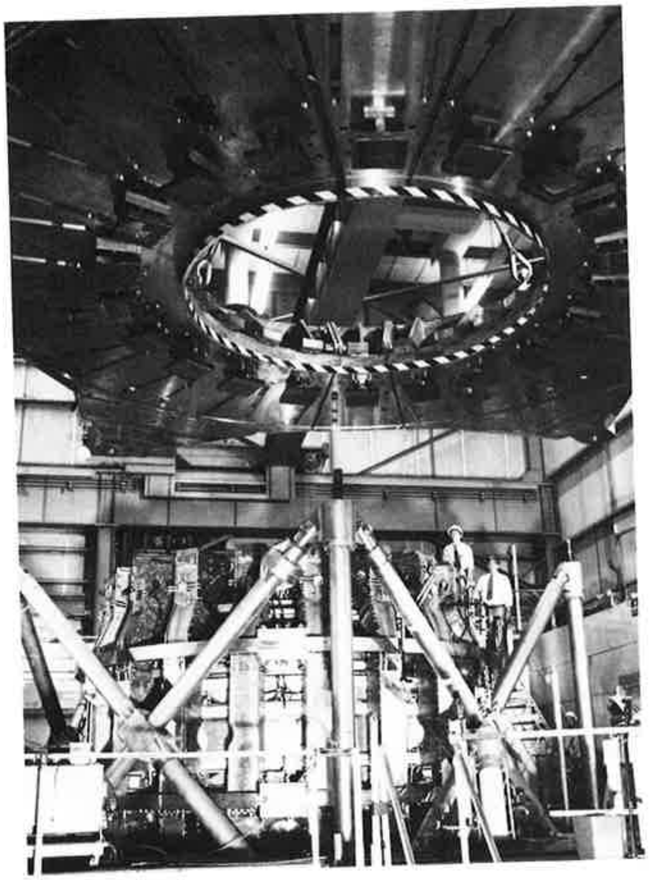

Figure 47. Positioning of the PDX upper shelf.

FEM models independently of the main frame. Interfaces with other computer codes and other computers are possible.

Materials Test Laboratory

During FY78, the work of the Materials and Testing Laboratory was primarily associated with PDX. At the beginning of the year, the poloidal field (PF) power tests were completed, and in the second half of the fiscal year preparations were made for the toroidal field (TF) and combined TF and PF power tests.

An extensive sequence of fatigue tests was performed on the TF joint assembly in a 100,000-lb. servohydraulic testing machine in order to verify design calculations. Tests were also performed on the joint pins, and some design changes were made as a result. A fixture was fabricated for tests on the rubber tires used in the TF joint clamp. Several tire design changes were made during these tests, and the reliability of the joint clamp was significantly improved.

Many routine mechanical tests (tensile, compressive, metallographic) were perfomed during the fiscal year, including tests on the PDX center band and PDX epoxy bags. These epoxy tests were performed at room and elevated temperatures and were used to select the final epoxy formulation used in the PDX assembly.

General

In conjunction with the Westinghouse Corporation, the Structures Design and Fabrication Section established designs for the mechanical structure and TF coil system for the scoping study of the SLPX. The TF coils are wound of forced-cooled Nb_3Sn conductor with stainless steel support plates (Figure 48). These are described in Chapter 4, Volume II of the SLPX Report.

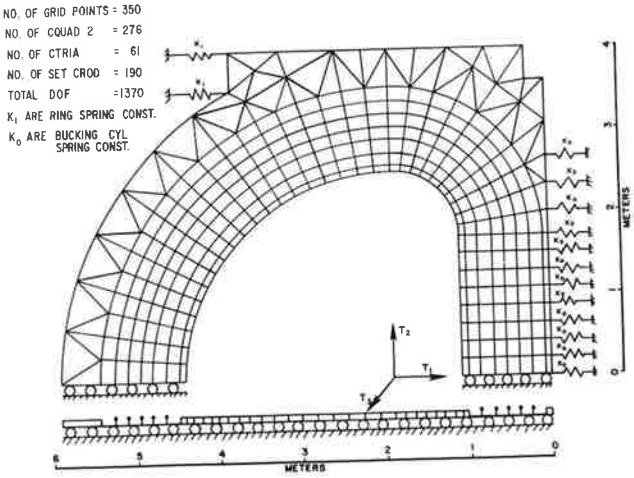

Figure 48. SLPX TF coil center plate finite element method (FEM) Model No. 1.

Vacuum Systems Design and Fabrication Section

This section is responsible for the design, fabrication, installation, maintenance and upgrade of all PPPL vacuum and cryogenic systems. Design work is performed by engineering staff, while a group of approximately 30 technicians fabricates and installs vacuum system components. A well-equipped shop is maintained.

FY78 accomplishments include the following:

- The PDX vacuum tank and pumping system were operated with a base pressure in low 10^{-6} torr range. The major vacuum problem encountered involved the dual differentially pumped elastomer "O" ring seal. A repair was performed.

- Support was provided for the installation and start-up of the third and fourth PLT neutral beam injection systems.
- Consultation was provided on the TFTR program.

Engineering Services Section

This section provides tradesmen for the various experimental activities at PPPL. In addition, operators and maintenance people are assigned to operate the large motor generator sets. Trades available include carpenters, electricians, metalsmiths, plumbers, welders, millwrights, and general technician service.

Primary emphasis during FY78 centered on assembly of the PDX machine. Installation of the TF coils, consisting of over four-hundred pieces, was performed by three crews on three shifts. Engineering Services provided one of the crews. In addition, all plumbing for the deionized water systems and hydraulic systems was installed by the Engineering Services Section. While this mechanical work proceeded, electricians were pulling cables and connecting the controls and instrumentation required in the PDX control room. This included connections to the IBM 1800, process controllers, and hard wired systems.

Motor generator operators provided their services for three shifts during most of this period. Availability of the sets remained high, and the task was accomplished with a minimum of personnel.

Design Studies For New Devices

OVERVIEW

During FY78 a number of design studies for new devices were conducted by teams of PPL staff cutting across organizational lines. Of particular importance were studies to define "the next step" beyond TFTR. During FY78 two complementary next-step machine concepts where defined. A class of tokamak experiments called by the generic term SLPX (Superconducting Long Pulse Experiment) was studied. An SLPX machine would be capable of operating at extended pulse lengths with plasma currents in the 3 to 6-MA range. In providing a firm basis of experience for a power reactor, a natural approach would be to complement an SLPX-type device with a copper-coil short-pulse ignition experiment. A design study along this line, the Princeton Ignition Test Reactor (PITR), was carried out as well.

The Advanced Concept Torus-1 (ACT-1) Program was initiated during FY78, leading to the complete design of a machine that became operational in late summer 1979. ACT-1 is a small, basic research device that will be used primarily for studies of radiofrequency heating and current generation.

MAJOR ACTIVITIES

Superconducting Long-Pulse Experiment (SLPX) Studies

The objective of the SLPX scoping studies is to provide sufficient technological and operational experience with advanced magnetics systems and long-pulse high-temperature plasmas to facilitate the successful start-up and operation of a tokamak power reactor. Since the TF (toroidal-field) system imposes no pulse limitations, it would be possible for the first time to generate tokamak discharges of >30-second duration in a machine of high thermal energy density and high thermal wall loading, so that the problems of quasi-steady fueling, impurity control, and, especially, heat removal from the plasma, first wall, and particle collection systems can be addressed in a reactor-relevant manner.

The range of sizes for the alternative SLPX design is bounded at the lower end by the SLPX-II, which has a TF-coil aperture of 2.6 m by 3.65 m, and an overall coil size appropriate for testing in the Large Coil Test Facility at the Oak Ridge National Laboratory. The upper end of the range is bounded by SLPX-III, which has a TF-coil aperture of 5.15 m by 6.8 m, and is capable of producing and sustaining ignition plasmas in D-T. However, by far the greatest attention was given to the SLPX-I which is intermediate in size (aperture equals 3.1 m by 4.8 m), and is capable of producing "ignition level" plasmas in hydrogen. Figure 49 shows a perspective view of the SLPX-I.

All the SLPX machines have the same basic design features, and differ principally in geometric dimensions and plasma current. While the SLPX-II is intended only for hydrogen operation (with a small admixture of deuterium), the SLPX-I can be equipped with sufficient shielding for full-deuterium operation. The SLPX-I can be equipped with adequate shielding and tritium handling facilities to permit 1000 D-T pulses per year of sustained ignited D-T operation. The most appropriate choice among these alternate possibilties depends on the nature of the overall fusion development program for the next 20 years.

Ignition Test Reactor Studies

In providing a firm basis of experience for a power reactor, a natural approach would be to complement an SLPX-type device with a copper-coil short-pulse ignition experiment. A design study along this line has therefore been carried out. The principal objectives of the Princeton Ignition Test Reactor (PITR) are to demonstrate the attainment of thermonuclear ignition in deuterium-tritium, and to develop optimal start-up techniques for plasma heating and current induction to determine the most favorable means of reducing the size and cost of tokamak power reactors.

The PITR geometry (Figure 50) was chosen to provide the highest MHD-stable values of beta in a D-shaped plasma, as well as to facilitate access for remote handling and neutral-beam injection. The principal design approach was to minimize dependence on a central transformer core, thus permitting a machine of small aspect ratio ($A \sim 2 - 2.5$) and small major radius ($R_0 \sim 2.8$ m), even with significant shielding inside the TF coils. Toroidal field coils of very small aspect ratio (1.45) allow:

- Significant major-radius compression to assist ignition,
- An ignited low-aspect-ratio plasma with beta approximately 0.1,
- Small magnetic field at the outside major radius, permitting implementation of a bundle divertor, if desired.

Induction of the plasma current of up to 5 MA is achieved by an optimal combination of "leaky OH" coils, equilibrium-field flux swing, a small central solenoid, and major-radius compression.

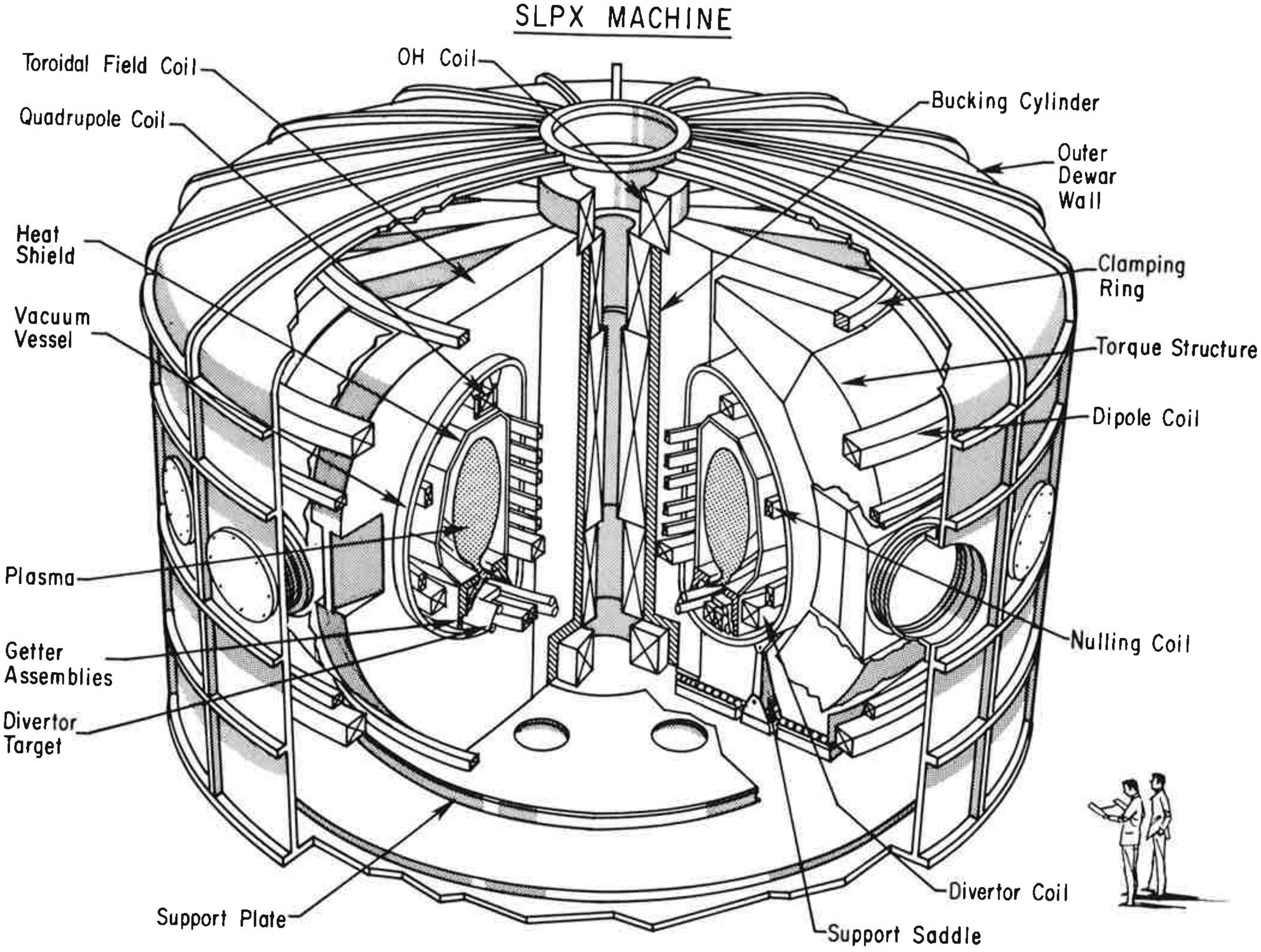

Figure 49. Perspective view of the SLPX-I.

Sixteen normal-copper TF coils of the compound constant-tension shape enable low-stress operation even at B_{max} = 12.5 T. The vacuum vessel is constructed of thin-gauge, double-wall titanium alloy, and requires no bellows or insulating break.

(ACT-1) Program

The Advanced Concepts Torus-1 (ACT-1) is a steady-state toroidal device to be used primarily for studies of radio-frequency (RF) heating and current generation. Designed during FY78, ACT-1 came into operation in late summer 1979. Figure 51 shows a schematic drawing of the device, together with a list of machine parameters.

In initial operation, ACT-1 will operate with a simple zero-transform toroidal magnetic field, with plasma equilibrium maintained by vertical plasma current flowing to the limiter to complete its electrical circuit. A warm-ion, low-neutral-pressure plasma will be produced by various techniques including electron and ion cyclotron waves, whistler waves, and tungsten filament discharge. Stronger heating will be possible with a 150-200-MHz supply, operating steady-state at 15 kW or with 10-ms pulses at 100 kW. In later operation, a ferrite core and ohmic heating are planned to give higher densities and temperature with tokamak-mode operation in ACT-1

The steady-state toroidal ACT-1 device, together with its powerful RF supply, will extend the range of studies of linear and nonlinear waves into new areas with high relevance to PPPL's tokamak program. Specifically, research will be directed toward:

- Physical phenomena near the lower-hybrid

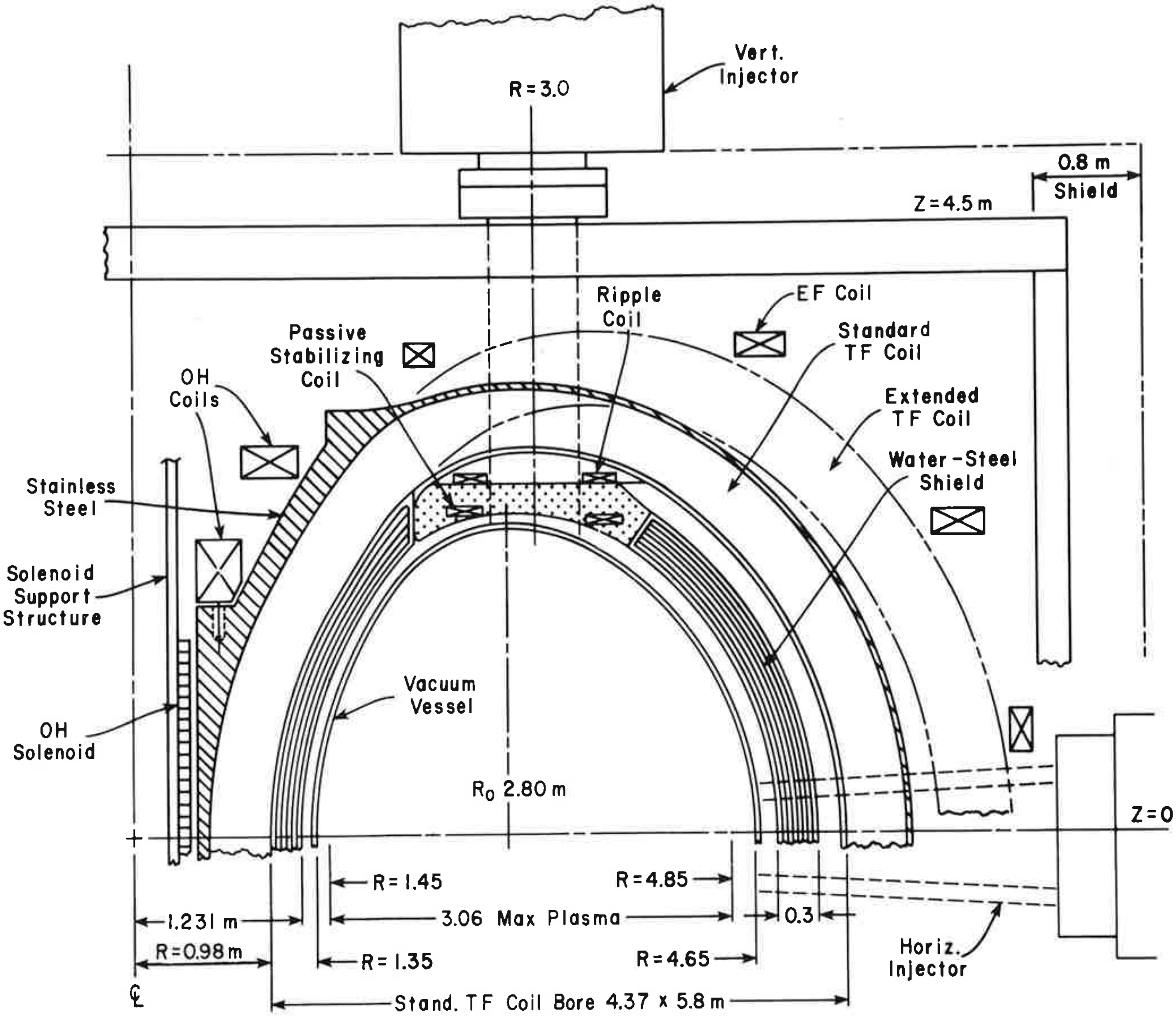

Figure 50. Elevation view of PITR. The extended TF coil is designed to accommodate a bundle divertor.

resonance layer ($\omega_0 \leq 2\omega_{th}$) where ion heating is expected to take place. CO_2 laser scattering can be used as a non-perturbing diagnostic to investigate the waves near the resonance layer.

- Steady-state RF current generation, using lower-hybrid and other plasma wave modes to impart momentum to the plasma electrodes. The absence of ohmic current makes ACT-1 and ideal test bed for these experiments, which are highly pertinent to steady-state toroidal CTR machines.
- Mode-conversion processes in ICRF heating experiments. Electrostatic waves and their role in power absorption will be studied under ICRF conditions in two-ion species plasmas.

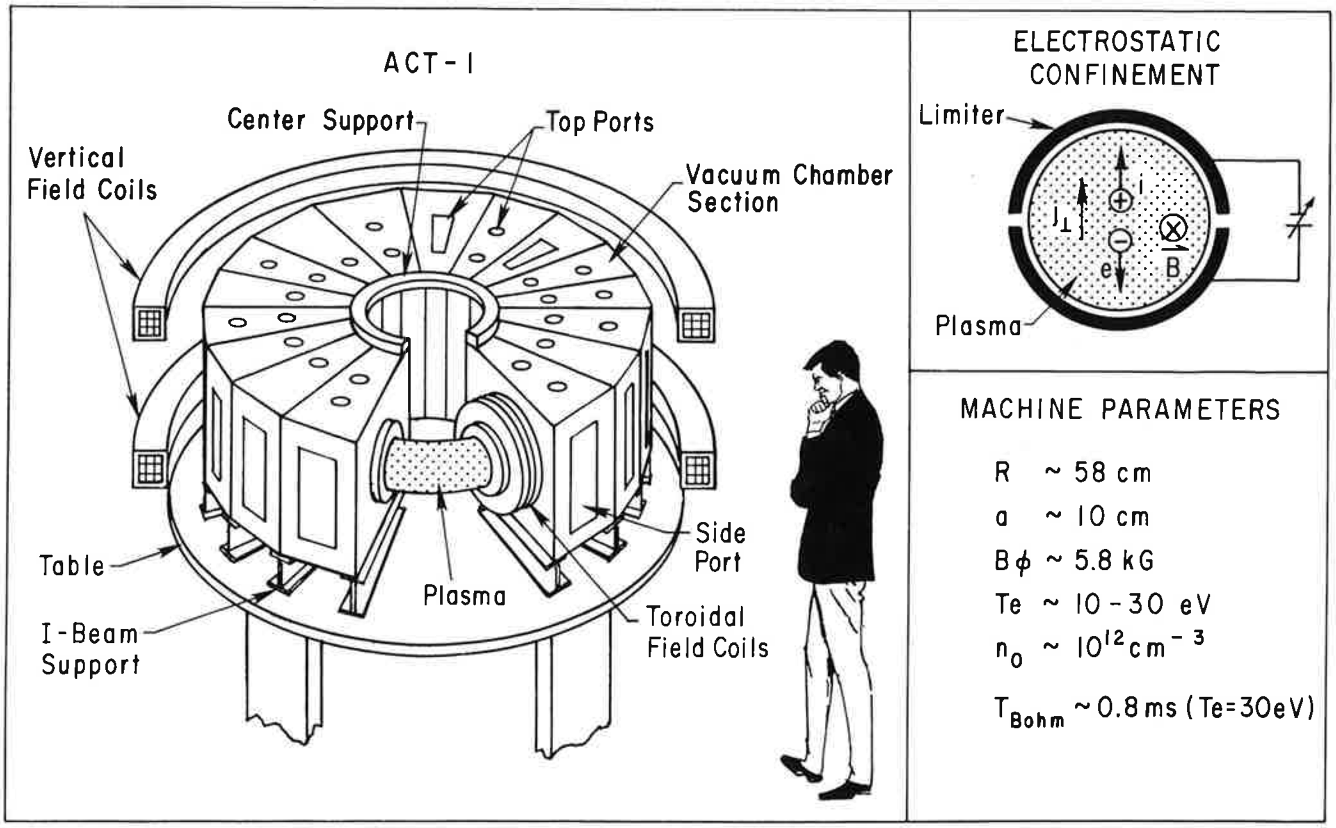

Figure 51. ACT-1 schematic indicating machine parameters.

Theory

OVERVIEW

Theoretical research has always played a key role in controlled fusion research because new devices and concepts invariably require sound predictions of their anticipated performance. Even as current tokamaks are approaching the reactor regime, the extrapolations to future devices are not small: they involve roughly factors of 3 to 10 in density, a factor of 2 in temperature, a factor of 2 in size, and a factor of 20 in auxiliary heating power. As a result, the empirical knowledge gathered from present experiments, while useful in estimating future performance, does not generate the same confidence that a first-principles (and experimentally verified) theoretical formula would engender. PPPL's progress in arriving at such formulas is discussed below.

Within the tokamak program, the TFTR device represents the most straightforward approach to experimentally demonstrate the production of a reactor-grade plasma. There are, however, many improvements to this straightforward approach that can be conceptually made. Theoretical arguments are a key ingredient in deciding which, if any, of these improvements should be tried on future devices. As examples of improvements now under consideration, one can cite divertors, feedback stabilization of tearing modes, radio frequency heating and steady-state currents driven by either radio frequency or neutral beam sources. Similar remarks can be made regarding predicting the consequences of engineering compromises,which introduce potentially deleterious properties such as toroidal field ripple.

In the alternative concepts program where experimental data are scanty, theory is even more crucial. Evidently, the first proposals for new devices are entirely theoretical in nature. The spheromak device discussed below is a case in point. Even in programs for which experiments are available, such as Tormac, theoretical results are used to summarize whatever understanding is obtained.

The following sections contain a discussion of some of the Theoretical Division's results achieved during FY78, and how it is expected they will impact controlled fusion research.

MAJOR ACTIVITIES

Confinement in Tokamaks

As tokamak plasmas become increasingly free from bulk radiative energy losses resulting from high-Z impurities such as tungsten, it is generally believed that fine scale drift and trapped-particle instabilities will govern the energy loss rate. Recently, experimental observations of these fluctuations in ATC, ALCATOR, and PLT using microwave and CO_2 laser scatterings have stimulated more in-depth theoretical investigations in this area. In particular, new and interesting advances have been made with respect to linear eigenmode analyses and nonlinear theories.

PPPL Theory Division has established that, in slab geometries with finite magnetic shear, *collisional* drift-wave eigenmodes are always damped by shear-induced convective loss. It is also clear that, if the shear-induced convection can be nullified by either sharp density gradients or toroidal effects, then unstable eigenmodes exist.

Similarly, PPPL Theory Division has employed a WKB analysis to show that, in a slab geometry model, no unstable *collisionless* drift waves exist. In the analysis, criteria for marginal stabilities are given. It is generally believed that, in parameter regimes (e.g., weak shear) where marginally stable eigenmodes exist, convective noise amplification could still be enormous. Further investigations are needed here. Preliminary results from particle stimulations and numerical eigenmode solutions indicate the possible existence of absolutely unstable eigenmodes with radial wavelengths comparable to ion Larmor radii. The conclusion here, however, is controversial. Furthermore, the questions with respect to the existence of modes at ion diamagnetic drift frequencies still need to be answered.

Toroidal geometry calculations dealing with drift and trapped electron instabilities yield quite different results. In brief, toroidal effects can overcome the stabilizing properties of magnetic shear. The results of the study on the stabilizing effect of shear in different collisionality regimes on drift and trapped-lectron modes is summarized in Figure 52 where growth rates are plotted versus the dimensionless shear parameter of q′r/q, which is typically between 0 and 2 in tokamaks. In the banana regime, for $\nu_e^* = 0.03$ and for a typical perpendicular wave-length parameter $b_{i\theta} \equiv k_\theta^2\rho_i^2/2 = 0.2$, there is a "break" in the curve at a critical value of the shear $q'r/q = 1$, below which the growth rate is independent of shear and above which the growth rate is a linearly decreasing function of shear. This "break" is a specifically toroidal effect and has been derived analytically using the techniques of J.B. Taylor. As the collisionality increases to $\nu_e^* = 10$ (plateau regime), the critical value of q′r/q decreases to 0.5, due to a decrease in toroidal coupling through the trapped-electron term; i.e., the trapped particle effects are reduced in this more collisional regime. As ν_e^* increases still further to 120 (Pfirsch-Schlüter regime), the critical value of q'r/q drops below 0.125. It should be emphasized that these results, which indicate the presence of unstable normal modes over a wide range of relevant parameters, are qualitatively different from those of the simpler sheared slab model which, as reported above, are never unstable.

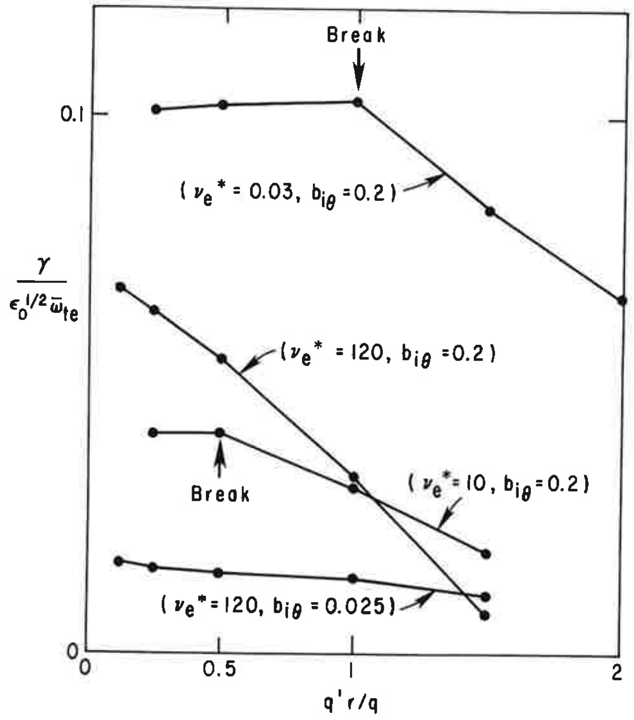

Figure 52. Variation of the linear growth rate with magnetic shear for drift and trapped-electron modes from a two-dimensional, integral formulation calculation.

From the linear instability point of view then, magnetic shear will not produce stability against microinstabilities in a tokamak. This finding is in accord with the experiments, which always detect fluctuations. The effects of shear are expected to occur in the determination of the nonlinear level of fluctuations.

At PPPL, the principal approach to nonlinear microinstability physics is via computer models. Results from both particle simulations and mode-coupling calculations indicate that, in the strong-turbulence regime, anomalous plasma transport is induced by convective cells nonlinearly excited by drift-wave instabilities. This discovery is in qualitative agreement with the observation of almost zero-frequency fluctuations, but no quantitative connection has yet been made.

Overall, the demonstration that toroidal effects are crucial and the discovery of convective cells represent two important conceptual advances in understanding confinement in tokamaks. Nevertheless, it is also clear that summary formulas representing a first-principles derivation of transport in tokamaks are not yet available and must await further research in nonlinear microinstabilities.

Alpha Particle Orbits in Tokamaks

Fusion product α-particles are expected to play several important roles in future generations of large tokamaks (TFTR, ETF., etc.). Accordingly, the Theory Division has developed an α particle transport code in a stand-alone version and as an optional package for BALDUR, a 1-D tokamak transport code. The goal is a computationally efficient code that accurately calculates the α-particle losses, heating, and ash buildup in axisymmetric tokamaks. A simulation format is used in which individual sample alphas suffer collisions with the background plasma as they follow trajectories prescribed by the guiding-center drift equations.

The striking characteristics of α-particle orbits in TFTR-size devices are the large excursions in minor radius during a single "bounce", and the long slowing down times ($\sim 10^2$ msec). Figure 53 shows the initial bounces (projected onto the upper half of the poloidal cross-section) of a number of alphas born at the point "x" in a 1 MA TFTR discharge. Each alpha has a different birth pitch-angle, and they all have the same production probability. Clearly, many of the α-particles are lost on their initial orbit.

In higher current TFTR discharges, e.g., 2.5 MA, most of the α-particles are confined, but their heating is nonlocal. The Theory Division's plans call for joining this code with the two-dimensional transport code

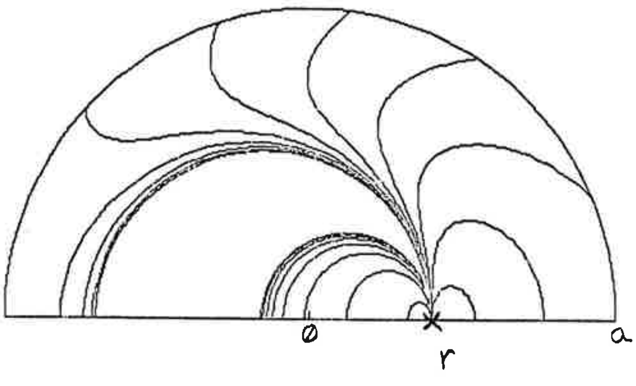

Figure 53. Poloidal projections of initial orbits of 19 alpha-particles born with different pitch angles at the point "X" in a 1 MA post-compression TFTR discharge.

described below to provide the capability of accurately describing the effects of α-particle heating on a high-β tokamak.

A Two-Dimensional Transport Code

Over the past year a self-consistent, two-dimensional description of the temporal evolution of axisymmetric tokamak equilibria on a resistive time scale has been developed, which is long compared to the Alfvén transit time. This work represents the third major part of the Princeton Equilibrium, Stability, and Transport (PEST) package of tokamak computer codes.

A reduced set of equations is obtained by expanding in the small ratio of Alfvén transit time to the classical resistive time $\tau_A/\tau_R << 1$ and in the small ratio of perpendicular to parallel mobilities and thermal conductivities. The reduced set consists of flux-averaged, one-dimensional convservation equations describing the time evolution of the differential particle number, entropy, and magnetic fluxes and a single two-dimensional generalized differential equation describing the absolute velocity of a magnetic surface enclosing a fixed toroidal flux. This equation is linear but nonstandard in that it involves flux surface averages of the unknown velocity.

The one-dimensional equations are solved using a standard vector Crank-Nicholson implicit method. New numerical methods based on Fourier analysis in a time-dependent nonorthogonal coordinate system have been developed to solve the two-dimensional equation directly (without iteration) each time step. The resulting code is efficient as well as flexible enough to include an arbitrary transport model.

There are at least four reasons for requiring a two-dimensional description of plasma transport. First, the two-dimensional (noncircular) geometry of the flux surfaces modifies the value of the plasma transport coefficients. Thus, for example, in a high β equilibria, where $|\vec{B}|$ contours tend to align with the magnetic field, the neo-classical transport coefficients, as well as anomalous coefficients driven by magnetically trapped particles, could be substantially reduced from their usual one-dimensional values.

Secondly, knowledge of the two-dimensional configuration of the plasma is necessary to apply boundary conditions and to compute the effects on the plasma of externally maintained heat and particle sources. Magnetic boundary conditions must be ultimately related to the currents in the poloidal field coils, the spatial distribution of which is inherently two-dimensional. The shape and location of pressure surfaces are important in the determination of heating profiles with neutral beam injection.

Thirdly, a self-consistent, two-dimensional transport calculation is necessary to obtain realistic pressure and magnetic field profiles to use in magnetohydrodynamic stability calculations. Once a stable initial equilibrium configuration is specified, the time-dependent transport equations determine how that equilibrium evolves in time. In particular, if the time-dependent equations lead to a steady state, this corresponds to a unique prescription for the equilibrium profiles.

Finally, a self-consistent two-dimensional calculation includes potentially important inductive contributions to the flux surface-averaged normal plasma flow. The maintenance of pressure balance can lead to deformations of the plasma magnetic surfaces with associated self-consistent inductive flows which may be comparable to the resistive diffusion during the fast transient phase of the discharge.

This transport code is expected to play a major role in the interpretation of PDX experiments and in the design of an Engineering Test Facility.

Ballooning Mode Theory

There is a growing belief that tokamaks will make economically viable reactors only if they can attain moderately high values of β, in the range of 5-10%, and that the limit on β will be determined by the onset of ballooning instabilities. These are ideal or resistive modes analogous to aneurisms that develop on a hose with weak spots. They are driven by the interaction of the plasma pressure gradient with local regions of unfavorable magnetic field curvature and are stabilized by the magnetic tension associated with localization along the field line. A new, firm theoretical basis for computing the stability of ballooning modes by means of a more accurate and complete treatment of the poloidal and radial mode structures has been established by the PPPL Theory Division. Additionally, the dynamical description has been improved by incorporating the effects of finite inertia and resistivity. The central result is that there are equilibria that are stable to ideal ballooning modes but unstable to resistive modes, so that resistivity lowers the attainable β.

The improvement in the treatment of the poloidal mode structure is accomplished by the introduction of a new representation that satisfies all of the necessary toroidal periodicity properties. The relations between this and a Fourier representation have been elucidated. The ballooning mode stability criterion is found to be at least as stringent as the Mercier criterion.

Steady-State Tokamaks

The attractiveness of a tokamak device on a reactor could be considerably enhanced if steady-state operation were possible. This, in turn, means that the current must be driven by means other than an ohmic heating transformer.

One approach to driving a steady-state current is to introduce high-phase velocity radio-frequency waves with net momentum parallel to the magnetic field. These waves lose their momentum preferentially to fast electrons which, being relatively collisionless, retain their momentum longer than the bulk electrons, effectively diminishing the plasma resistivity. The feasibility of the steady-state reactor driven by this means rests crucially on the assertion of the diminished plasma resistivity. On the basis of the intuitive assumption that velocity space dynamics perpendicular to the magnetic field play only a minor role in the determination of the effective resistance to the RF-driven current, it is possible to identify the crucial cost factor $\epsilon = P_D/P_f$ where P_D/P_f is the ratio of RF power dissipated to fusion power output. This calculation leads to $\epsilon \sim 5\%$ for typical but large circular cross-section reactors.

The recent work of the Theory Division has been to numerically solve the full Fokker-Planck equation with RF terms in order to check the conclusions of the simplified analytic treatment, in particular regarding the effective resistance to RF currents. A typical numerical run results in the steady-state distribution, and it predicts a current. By varying the location of the resonant region in velocity space, the analytic scaling law of the effective resistance was numerically verified, corrected only by a constant factor of 0.6. Thus, the numerical work points to a slightly more attractive power cost, $\epsilon \sim 3\%$.

Feedback Stabilization of Tearing Modes in Tokamaks

Tearing modes, or magnetic islands, have been experimentally observed in tokamaks, and there is strong evidence indicating that they are the principal cause not only of the internal or minor disruption, but also of the major tokamak disruption, in which a large $m = 2$ mode forms a precursor. Computational work over the last few years has led to a good understanding of nonlinear tearing mode behavior and points strongly to this $m = 2$ mode as being primarily responsible for major disruptions in present tokamaks. Since the major disruption limits the high density, low q, and large $n\tau$ operation of tokamaks, it seems reasonable to consider feedback stabilization of this precursor, especially since at high temperatures and for large machines these modes become very slow in their nonlinear stage. The stabilization of the tearing mode has been investigated using a code capable of analyzing the full nonlinear behavior of modes of a single helicity. This analysis is possible through the use of a set of reduced equations which make use of the tokamak ordering $B_z >> B_\theta$ to expand the magnetohydrodynamic resistive fluid equations to lowest order in the inverse aspect ratio.

It was demonstrated that a signal of the proper phase can effectively stabilize the mode, the proper phase being that prescribed by the linear theory, i.e., the vacuum field island should be such as to oppose the tearing mode island. The coil current necessary to stabilize an island at a width of a few percent of the minor radius is on the order of one kiloamp (for PLT), and the necessary coil response time is well within experimental capabilities.

In general, diamagnetic effects cause the mode to rotate, and the sign of the signal generalizes to the phase relation between the initial mode and the feedback signal. Stabilization has been achieved for rotating islands when the phase of the vacuum field island is such as to oppose the tearing mode island, even in the case where the rotation frequency is much larger than the growth rate. Code results, as well as analytic results using model equations derived from the full nonlinear equations, show that stabilization cannot be achieved without making use of full information regarding the phase of the mode.

Low Aspect-Ratio Limit of the Toroidal Reactor: the Spheromak

As candidate reactors, tokamaks have always been difficult from an engineering point of view because of the requirements for both toroidal and poloidal field coils. Among the alternative toroidal configurations, the Spheromak, the limiting case of low-aspect-ratio D-shaped tokamaks, stands out. Figure 54 portrays the Spheromak configuration. To avoid singularity of the coil stresses, the toroidal-field coils must be eliminated so the toroidal field vanishes outside the plasma.

The reactor advantage of the spheromak is twofold. First, the maximum field strength at the external coils is half the field at the plasma center, rather than twice, as in a tokamak. Secondly, a spherical blanket can be used, rather than a blanket that links the plasma topologically.

We begin with the force-free case ($\beta = 0$). The analysis is particularly simple for the subcase $\vec{J} = \alpha B$,

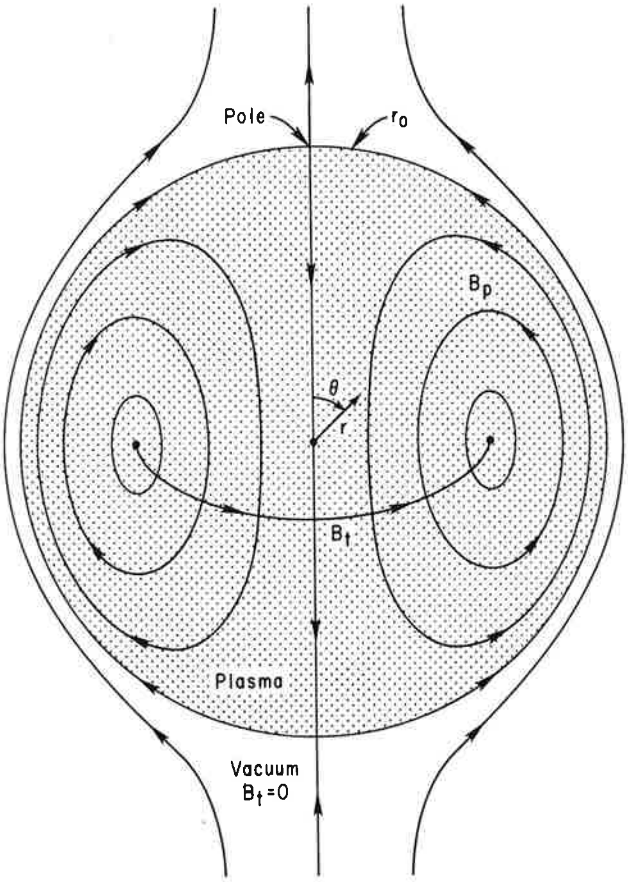

Figure 54. Idealized Spheromak configuration (b/a = 1, $\alpha = 1.0$, $\delta = 0$).

where α is independent of position. This subcase also has special significance from the point of view of stability theory. J.B. Taylor has shown that $\vec{J} = \alpha\vec{B}$ characterizes the lowest-energy state of all configurations having a given boundary and a fixed value of the quantity $K = \int \vec{A} \cdot \vec{B} d^3r$, which is conserved for both ideal MHD modes and resistive tearing modes.

The basic spheromak is the axisymmetric solution of $\vec{\nabla} \times \vec{B} = k\vec{B}$ within a sphere of radius $r_0 = 4.49/k$. The safety factor profile is very flat, varying from $q = 0.83$ at the magnetic axis to $q = 0.72$ at $r + r_0$. The plasma is bounded by a shell or a vacuum region; by modifying the boundary condition, alternative shapes may be found, such as prolate and oblate spheromaks.

Energy-minimizing perturbations of the equilibrium continue to satisfy $\vec{\nabla} \times \vec{B} = k\vec{B}$, a feature that greatly facilitates the stability analysis in this complex geometry. For fixed plasma surface (i.e., a conducting shell), a prolate spheromak (prolemak) is unstable only against tipping of the magnetic axis, while an oblate spheromak (oblimak) is stable.

When the fixed outer shell is separated from the plasma by a vacuum region, it appears likely that a low-β oblimak with a conducting shell at about 1.3-1.5r_0 will be stable against all macroscopic modes. Appropriately shaped external windings may preserve the prolemak from the $m = 1$, $n = 1$ mode; helical windings should contribute to the stabilization of the surface modes. Finite-β limits and finite-particle-orbit phenomena are also currently under study.

Administration

OVERVIEW

Fiscal year 1978, marked by the beginning of construction of TFTR, achievement of a major milestone on PLT, and near completion of PDX fabrication, was a year of continued growth for PPPL, as demonstrated in the Financial Summary (Table I). The success of the Laboratory's research efforts led to a substantial expansion of staff to meet demands for design, fabrication and operation of the three major experimental devices and other research projects. Concommitant with this growth has been an increase in the number and complexity of administrative tasks. The Laboratory initiated organizational changes, new committees and new functions to meet the needs of its expanded research program.

In January 1978, a Program Committee was established to review existing scientific programs, new program initiatives, overall program balance and priorities, and to forward conclusions and recommendations to the Director.

During FY78 an analysis of laboratory management in the light of rapid growth was performed and resulted in changes in PPPL's basic organization. A newly formed committee, the PPPL Council, replaced the Executive Committee of earlier years in its overview function. In addition to the Program Committee, other committees with particular responsibilities were established and were operating successfully by September 1978.

The effort to improve communications between management and staff gained momentum and direction with the establishment of an employee relations office within the PPPL Personnel Office. The Administrative Advisory Committee (AAC), established in July 1977, reported to the Associate Director for Administration a number of employee concerns. The report resulted in a number of policy reviews, modifications to procedures, and long-term plans for additional changes. An employee relations activity report was published in January 1978, reviewing the issues raised by employees and specific actions taken by the Laboratory administration. To communicate the various changes occurring within the Laboratory, the *PPL News*, initiated in December 1977, was expanded in format to a four to eight-page tabloid and published at six-week intervals throughout FY78.

STAFF

As of October 1977, the Laboratory's full-time staff totaled approximately 891, and by the close of FY78, this number had risen to 994, divided as follows:

Faculty	4
Physicists	101
Engineers	180
Technicians	503
Others	206
Total	994

At the close of fiscal year 1978 the total PPPL physical plant space is summarized as follows:

	Government Owned (GSF)	University Owned (GSF)
"A"-Site	29,000	135,000
"B"-Site	none	78,000
"C"-Site	328,000	none
Grand Total, Space		570,000 GSF
Total GPP-funded construction initiated		$1,270,000
Total Capital Equipment funds for space-related projects		$ 476,000

PPPL LIBRARY

The main goal of the PPPL Library for FY78 was to enlarge the engineering collection of abstract journals, monographs and reference books in an effort to keep pace with the laboratory's expansion program. This goal was realized by a continuous endeavor to obtain by purchase and transfer from the Firestone system all the material available within the budget and space constraints of this library and within the guidelines of the Library's collection development policy.

The second goal was to expand reader services, a goal attained by greatly increased use of the computer for reference and literature searches, expansion of the cataloging effort for the currently received technical reports, and by the addition of a second monthly publication.

Collection Development

Approximately ten new major reference tools and many new handbooks were purchased during FY78. Transfers of approximately 75 books were received from the defunct Forrestal and Accelerator Libraries and the Science Reading Room. These acquisitions, along with the extensive purchasing program, added about 189 monographs to the collection.

TABLE I. PPPL FINANCIAL SUMMARY ($K)

PROJECT	1974	1975	1976/76A	1977	1978
Operating (B/O)					
CLOSED CONFINEMENT:	11,885	15,037	27,634	23,073	23,883
PLT Fabrication	5,552	3,821	1,771	0	0
Operations (inc.ST)	2,880	3,540	8,060	7,304	8,082
Coil Test	0	157	615	314	0
Neut. Beam Pwr. Supp.	0	1,029	2,228	1,289	0
Test Stand	0	0	468	296	0
ICRF	0	50	72	1,035	1,022
PDX Fabrication	0	2,110	9,361	8,547	4,528
Operations	0	330	2,664	3,608	8,258
N.B.	0	0	0	0	894
ATC	2,128	2,370	1,560	0	0
FM-1	1,325	1,630	835	0	0
H-1	0	0	0	666[a]	522
Other	0	0	0	14[b]	577
DEVELOPMENT & TECHNOLOGY:	2,008	3,480	4,079	597	114
H-1	552	853	838	0[a]	
Reactor Studies	229	266	427	456	
Two Component Torus	381	2,160	2,814	0	
Advanced Tokamak Studies	0	0	0	120	114
Other	846[c]	201[d]	0	23[e]	
RESEARCH:	1,787	2,614	3,788	3,005	3,170
Theory	1,093	1,848	2,530	2,008	2,378
Basic Experiments	694	766	1,000	668	638
User Service Center	0	0	258	329	154
REACTOR PROJECTS:	0	0	1,325	10,556	13,080
TFTR R&D	0	0	1,325	9,991	11,820
Research	0	0	0	241	640
Operations	0	0	0	324	620
TOTAL	15,680	21,131	36,826	37,233	40,249
Equipment (B/A)					
Capital Equipment Not Related to Construction	610	2,066	3,277	5,190	5,140
Construction (B/A)					
TFTR	0	400[f]	20,500	75,000	71,000
General Plant Projects	212	500	950	1,455	1,350

a) H-1 moved from Development and Technology in 1977.
b) Ripple Injection Coil
c) E&D 186 PDX 414
Cryogenics 80 Vacuum 31
Computer 84 Systems 51
d) Systems
e) EPR RF Heating
f) CP&D

Reader Selections

As a consequence of the large increase in the number of reports received, a change in cataloging was required. Nearly all new reports are now indexed daily in the card catalog by a main entry card and a report number card. By eliminating the subject, agency, and secondary author entries, material can now be processed at an accelerated rate, giving PPPL staff prompt access to the literature. It became necessary to issue a second monthly publication, the Library Bulletin, in addition to the Library Acquisition List. The Bulletin lists all technical reports, new books, and selected microfiche, while the Acquisition List contains the records of fully cataloged journal articles, selected reports including PPPL reports, and reprints.

Computer Services

A portable computer terminal was acquired during FY78 making possible the increased use of computerized searching as reference service. Search activity in the library has more than doubled during FY78 proving that this rapid in-depth searching capability adds a valuable dimension to library services. A total of 168 searches were conducted, and 261 data base uses were recorded. These figures indicate an increase of 105 searches over last year.

New Library

An important project carried on since January 1978 was the design of the new library which will be located in the Administration Wing. During the winter months, five nearby business/industrial libraries were visited to obtain the latest information on library innovations. The suggestions of the PPPL Library Committee were combined with the ideas learned from the tours. The resulting designs were submitted to PPPL Facilities Department.

The growth of the PPPL Library inventory during FY78 is shown in Table II. The increase in intralibrary loan service, which the PPPL Library established in support of library user demands, is shown in Table III.

TABLE II. LIBRARY ACQUISITIONS

Category	FY77 Qty.	FY78 Qty.	% Increase
Monographs	3,046	3,225	5.9%
Bound Journals	3,493	3,777	8.1%
Reports	12,823	13,398	4.5%
Microfiche	14,701	17,066	16.0%

TABLE III. INTRALIBRARY LOAN

Library	FY77 Qty.	FY78 Qty.	% Increase
Engineering	167	211	+29.0%
Math/Physics	86	83	− 3.5%
Others	106	79	−25.5%

Graduate Education

OVERVIEW

The growth over the past quarter-century of plasma physics as a scientific discipline has been impressive. Twenty-five years ago, the research was confined to a few laboratories and to a handful of astronomers and physicists. Today, in the United States alone, plasma physics research programs are active at more than 50 colleges and universities, and the American Physical Society's Division of Plasma Physics lists approximately 2100 members, which may be compared to other Division memberships such as Condensed Matter (the largest, approximately 660 members). A measure of the scholarly output in the field of plasma physics is given by the volume of publication in major scientific periodicals, which currently exceeds 16,000 journal pages a year.

Princeton University's Graduate Education Program in Plasma Physics is jointly sponsored the Astrophysical Sciences Department and the Plasma Physics Laboratory. Since 1959, when the program began, over eighty physicists have received doctoral degrees in plasma physics from Princeton. Thus, many key positions for plasma research and technology in academic, industrial, and governmental institutions are held by Princeton/PPPL graduates.

There is a strong interaction between the Plasma Physics Laboratory and the students in the Graduate Education Program in Plasma Physics. Most of these students hold Assistantships in Research at PPPL, through which they participate in both the experimental and theoretical research at the Laboratory. PPPL staff members serve as advisors to the students, allowing them to receive training at the very forefront of plasma research. On the other side of the coin, the high-calibre students attracted to Princeton for their graduate work are a direct and valuable stimulant for PPPL scientists.

MAJOR ACTIVITIES

The teaching faculty for the plasma physics program, in Princeton's Department of Astrophysical Sciences, currently numbers seventeen members who offer a variety of courses to thirty students now in residence (Tables IV and V). First-year students this past year worked with the various experimental groups at PPPL, including the PLT, PDX, Q-1, L-3, L-4, and H-1 groups, and second-year students assisted a number of members of the Theoretical Division. In addition, PPPL physicists shared their expertise each week with the students at a student-run, two-hour Tuesday afternoon seminar. The students are, of course, regular attendees at the Laboratory's own seminars and coloquia. All of this experience provides a natural transition to doctoral thesis research which, again, is carried out in collaboration with PPPL staff members. A list of thesis projects, completed and in progress during FY78 under the plasma physics program at Princeton, is given in Tables VI and VII.

TABLE IV. PLASMA PHYSICS COURSES TAUGHT AND NAMES OF TEACHERS

	Fall 1978	
AS551	General Plasma Physics I	C. Oberman and S. Yoshikawa
AS553	Plasma Waves and Instabilities	T.H. Stix
AS557	Advanced Mathematical Methods in Astrophysical Sciences	M.D. Kruskal
AS558	Seminar in Plasma Physics	S. Yoshikawa
AS559	Nonlinear Interactions in Plasma	P.K. Kaw and J. Krommes
	Spring	
AS552	General Plasma Physics II	R. Kulsrud and W. Tang
AS554	Irreversible Processes in Plasma	J. Krommes and C. Oberman
AS558	Seminar in Plasma Physics	S. Yoshikawa
AS560	Computational Methods in Plasma Physics	R.C. Grimm and H. Okuda

TABLE V. PPPL STAFF

Faculty Members	Title
Thomas H. Stix	Professor of Astrophysical Sciences and Assistant Director, PPPL, for Academic Affairs
Edward A. Frieman	Professor of Astrophysical Sciences
Harold P. Furth	Professor of Astrophysical Sciences
Melvin B. Gottlieb	Professor of Astrophysical Sciences
Raymond C. Grimm	Research Physicist and Lecturer with rank of Associate Professor of Astrophysical Sciences
Predhiman K. Kaw	Senior Research Physicist and Lecturer with rank of Professor
John A. Krommes	Research Staff and Lecturer in Astrophysical Sciences
Martin D. Kruskal	Professor of Astrophysical Sciences
Russell M. Kulsrud	Senior Research Physicist and Lecturer with rank of Professor
Carl R. Oberman	Senior Research Physicist and Lecturer with rank of Professor
Hideo Okuda	Research Physicist and Lecturer with rank of Associate Professor in Astrophysical Sciences
Francis W. Perkins, Jr.	Senior Research Physicist and Lecturer with rank of Professor
Marshall N. Rosenbluth	Visiting Lecturer with rank of Professor
Paul H. Rutherford	Senior Research Physicist and Lecturer with rank of Professor
William H. Tang	Research Physicist and Lecturer with rank of Associate Professor in Astrophysical Sciences
Schweickhard E. Von Goeler	Senior Research Physicist and Lecturer with rank of Professor (l/a 1978-79)
Shoichi Yoshikawa	Senior Research Physicist and Lecturer with rank of Professor

TABLE VI. Recipients of Ph.D. Degrees

January 1977

Jack Schuss Advisors: T.K. Chu and L. Johnson

Thesis: Thompson Scattering Measurements of Plasma Turbulence Near Quarter-Critical Density in a CO_2 Laser-Heated Gas Target Plasma.

Employment: Massachusetts Institute of Technology, Francis Bitter National Laboratory, Cambridge, Massachusetts

June 1978

Masayuki Ono Advisor: M. Porkolab

Thesis: Experimental and Theoretical Studies of Parametric Instabilities Near the Ion Cyclotron Frequency in Single and Multi-Ion Species Plasma.

Employment: Princeton Plasma Physics Laboratory

October 1978

E. Allen Adler Advisor: R. Kulsrud

Thesis: Magnetic Reconnection

Employment: University of California, Los Angeles

Adilnawaz Hassam Advisor: R. Kulsrud

Thesis: Characteristics and Lifetime of Convective Plasma Motions in Tokamaks.

Employment: University of Maryland

TABLE VII. DOCTORAL THESES IN PROGRESS

Gary Allen — Advisor: M. Yamada
Thesis: Trapped-Particle Instability Simulations in a Linear Plasma

Cris Barnes — Advisor: J. Strachan
Thesis: Runaway Electron Studies on the Poloidal Divertor Experiment

Amitava Bhattacharjee — Advisor: R.L. Dewar
Thesis: Variational Principle for MHD Equilibrium and Stability with Global Constraints

Edward Caramana* — Advisor: F.W. Perkins
Thesis: A Transport Code for the Reserved Field Pinch

Robert Chrien — Advisor: J. Strachan
Thesis: Confinement and Slowing Down of Fusion Reaction Ions in a Toroidal Plasma

David Eames — Advisor: N. Sauthoff
Thesis: The Role of Tungsten Radiation in Major Disruptions in PLT

Gerald Elder — Advisor: H. Hsuan
Thesis: Study of Wave Properties During Electron Cyclotron Heating Experiment

Robert Horton — Advisor: K-L Wong
Thesis: Generation of Plasma Current by Lower Hybrid Wave

Wen Ling Hsu — Advisor: M. Yamada
Thesis: Related Subjects of Spheromak Plasma

Robert Kleva — Advisors: J. Krommes and C. Oberman
Thesis: Transport in Braided Magnetic Fields

Richard Marchand — Advisor: W. Tang
Thesis: Two-Dimensional Eigenmode Analysis of the Trapped-Ion Instability

Roger McWilliams — Advisors: R.W. Motley & F.W. Perkins
Thesis: The Role of Quasilinear Effects in Landau Damping of Lower-Hybrid Waves

Philippe Similon — Advisor: J.A. Krommes
Thesis: Nonlinear Theory of Drift Wave Turbulence

Harold Thompson — Advisor: J.C. Hosea
Thesis: ICRF Probe Measurements

Donald Voss — Advisor: S. Cohen
Thesis: Wall Flux of Low Energy Neutrals in the PLT Tokamak

J. Randy Wilson — Advisor: K-L Wong
Thesis: Nonlinear Behavior of Lower-Hybrid Resonance Cones and Soliton Formation

*Visiting student from University of Colorado

Bibliography

PRINCETON LARGE TORUS (PLT)

Arunasalam, V., Barnes, C., Bol, K., Boyd, D., Brau, K., Bretz, N., Brusati, M., Cohen, S., Davis, S., Dimock, D., Dylla, F., Eames, D., Efthimion, P., Eubank, H., Furth, H., Goldston, R., Hawryluk, R., Hill, K., Hinnov, E., Horton, R., Hosea, J., Hsuan, H., Ignat, D., Jobes, F., Johnson, D., Mattioli, M., Mazzucato, E., Meservey, E., Moriette, P., Sauthoff, N., Schivell, J., Schmidt, G., Smith, R., Stauffer, R., Stodiek, W., Strachan, J., Suckewer, S., and von Goeler., S., "Recent Results from the PLT Tokamak," *Eighth European Conference on Controlled Fusion and Plasma Physics* (Institute of Plasma Physics, Czechoslovakia Academy of Science, Prague, 1978) *Vol. II,* pp. 17-28. *PPPL-1436* (1978).

Arunasalam, V., Cano, R., Hosea, J.C., and Mazzucato, E., "Turbulent Temperature Fluctuations in the Princeton Large Torus," *Phys. Rev. Lett. 39* (October 1977) 888-891. *PPPL-1363* (1977).

Bohr, A.H., and Christie, R.S., "Scanning Drive for Visible Spectrum Monochromator," in *Proceedings 7th Symposium on Engineering Problems of Fusion Research,* Edited by M.S. Lubell and C. Whitmore, Jr. (IEEE, New York, NY, 1977) *Vol. I,* 402-405.

Bol, K., Arunasalam, V., Bitter, M., Boyd, D., Brau, K., Bretz, N., Bussac, J., Cohen, S., Colestock, P., Davis, S., Dimock, D., Dylla, F., Eames, D., Efthimion, P., Eubank, H., Goldston, R., Hawryluk, R., Hill, K., Hinnov, E., Hosea, J., Hsuan, H., Jobes, F., Johnson, D., Mazzucato, E., Medley, S., Meservey, E., Sauthoff, N., Schmidt, G,. Stauffer, F., Stodiek, W., Strachan, J., Suckewer, S., Tait, G., Ulrickson, M., and von Goeler, S., "Radiation, Impurity Effects, Instability Characteristics, and Transport in Ohmically Heated Plasmas in the PLT Tokamak," *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 7th Int. Conf., Innsbruck, Austria, 1978) IAEA, Vienna, 1979, *Vol. I,* 11-33. *PPPL-1492* (1978).

Bretz, N., Dimock, D., Foote, V., Johnson, D., Long, D., and Tolnas, E., "Multichannel Thomson Scattering Apparatus," *Appl. Opt. 17* (January 1978) 192-202. *PPPL-1356* (1977).

Brusati, M., Davis, S.L., Hosea, J.C., Strachan, J.D., and Suckewer, S., "Ion Energy Balance in Ohmically Heated PLT Discharges," *Nuclear Fusion 18* (September, 1978) pp. 1205-1216. *PPPL-1403* (1977).

Cohen, S.A., "Tokamak Plasma Diagnosis by Surface Physics Techniques," *J. Nuclear Materials 76/77* (September/October 1978) 68-77 *(Proceedings of the Third International Conference on Plasma Surface Interactions in Controlled Fusion Devices). PPPL-1445* (1978).

Cohen, S.A., and Dylla, H.F., "OH Charge-Exchange in Cold, Dense Hydrogen Plasmas," *Nuclear Fusion 18* (January 1978) 5-8. *PPPL-1348* (1977).

Cohen, S.A., and Dylla, H.F., "Lower Limits for Parallel Impurity Fluxes in the PLT Edge Plasma," *J. Nuclear Materials 76/77* (September/October 1978) 425-430 *(Proceedings of the Third International Conference on Plasma Surface Interactions in Controlled Fusion Devices). PPPL-1440* (1978).

Cohen, S.A., Dylla, H.F., Rossnagel, S.M., Picraux, S.T., Borders, J.A., and Magee, C.W., "Long-Term Changes in the Surface Conditions of PLT," *J. Nuclear Materials 76/77* (September/October 1978) 459-471 *(Proceedings of the Third International Conference on Plasma Surface Interactions in Controlled Fusion Devices). PPPL-1448* (1978).

Colestock, P.L., Hosea, J.C., Jobes, F.C., Takahashi, H., and Thompson, H., "ICRF Heating in PLT," *Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas,* Edited by T. Consoli (Pergamon Press, Oxford, England, August 1979).

Colestock, P.L., Hosea, J.C., Paoloni, F.C., Thompson, H.R., and Takahashi, H., "Fast Wave Generation in the PLT Tokamak," *Proceedings of the Third Topical Conference on Radio Frequency Plasma Heating* (California Institute of Technology, Pasadena, CA, 1978). Paper C7-1 to C7-4.

Coppi, B., and Mazzucato, E., "Transport of Electron Thermal Energy in High Temperature Plasmas," *Massachusetts Institute of Technology Report PRR-78/40 (RLE)* (1978); to be published in *Physics Letters.*

Dylla, H.F., "Turbomolecular Pump Vacuum System for the Princeton Large Torus," *J. Vac. Science Technology 15* (March/April 1978) 734-740. *PPPL-1385* (1977).

Dylla, H.F., King, J.G., and Cardillo, M.J., "The Absorption of CO on Planar and Oxygen-Etched Silicon Surfaces," *Surface Science 74* (November 1977) 141-167.

Eubank, H.P., "Determination of Plasma Ion Temperature by Analysis of Charge-Exchange Neutrals," in *Proc. of the Course on Diagnostics for Fusion Experiments,* Edited by E. Sindoni and C. Wharton (Pergamon Press, Oxford, England, August 1979) *Vol. I.*

Eubank, H.P., "Neutron Diagnostics," in *Proc. of the*

Course on Diagnostics for Fusion Experiments, Edited by E. Sindoni and C. Wharton (Pergamon Press, Oxford, England, August 1979) *Vol. I.*

Eubank, H.P., "The Use of Particle Beam Systems in Plasma Diagnostics," in *Proc. of the Course on Diagnostics for Fusion Experiments,* Edited by E. Sindoni and C. Wharton (Pergamon Press, Oxford, England, August 1979) *Vol. I.*

Eubank, H., Goldston, R., Arunasalam, V., Bitter, M., Bol, K., Boyd, D., Bretz, N., Bussac, J.-P., Cohen, S., Colestock, P., Davis, S., Dimock, D., Dylla, H., Efthimion, P., Grisham, L., Hawryluk, R., Hill, K., Hinnov, E., Hosea, J., Hsuan, H., Johnson, D., Martin, G., Medley, S., Meservey, E., Sauthoff, N., Schilling, G., Schivell, J., Schmidt, G., Stauffer, F., Stewart, L., Stodiek, W., Stooksberry, R., Strachan, J., Suckewer, S., Takahashi, H., Tait, G., Ulrickson, M., von Goeler, S., and Yamada, M., "PLT Neutral Beam Heating Results," *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 7th Int. Conf., Innsbruck, Austria, 1978) IAEA, Vienna, 1979, *Vol. I,* 167-197. *PPPL-1491* (1978).

Foote, V.S., and Christie, R.S., "Some Mechanical Aspects of the Multichannel TV-Thomson Scattering Apparatus on the PLT Machine," in *Proceedings of the 7th Symposium on Engineering Problems of Fusion Research,* Edited by M.S. Lubell and C. Whitmore, Jr. (IEEE, New York, NY, 1977) *Vol. I,* 371-373.

Grisham, L.R., Eubank, H.P., Dylla, H.F., Goldston, R.J., Schilling, G., Stewart, L.D. Stooksberry, R.W., and Ulrickson, M., "PLT Neutral Injector Performance," in *Proceedings of the IAEA Workshop on Neutral Injectors* (Culham Laboratory, Abingdon, United Kingdom, 1978) to be published. *PPPL-1484* (1978).

Hill, K.W., von Goeler, S., Bitter, M., Campbell, L., Cowan, R.D., Fraenkel, B., Greenberger, A., Horton, R., Hovey, J., Roney, W., Sauthoff, N., Stodiek, W., "Determination of Fe Charge-State Distributions in PLT by Bragg Crystal X-ray Spectroscopy," *Phys. Rev. A 19* (April 1979) 1770-1779. *PPPL-1457* (1978).

Hinnov, E., Bol, K., Dimock, D., Hawryluk, R.J., Johnson, D., Mattioli, M., Meservey, E., and von Goeler, S., "Effects of Tungsten Radiation on the Behavior of PLT Tokamak Discharges," *Nuclear Fusion 18* (September 1978) 1305-1307.

Hinnov, E., and Mattioli, M., "Observations of Multiply Ionized Tungsten Radiation in the PLT Discharges," *Physics Letters 66A* (May 1978) 109-111. *PPPL-1375* (1977).

Hosea, J.C., "Experimental Aspects of RF Heating of Tokamak Plasmas in the Ion Cyclotron Range of Frequencies," *Proceedings of the Third Topical Conference on Radio Frequency Plasma Heating* (California Institute of Technology, Pasadena, CA, 1978). Paper C2-1 to C2-9.

Hosea, J.C, "Ion-Cyclotron Heating Technology," *Proceedings of the Plasma Heating Requirements Workshop,* December 5-7, 1977 (National Technical Information Services, Springfield, Virginia, 1978) 413-420.

Hsuan, H., Arunasalam, V., Bitter, M., Bol, K., Boyd, D., Brau, K., Bretz, N., Brusati, M., Bussac, J., Cohen, S., Colestock, P., Davis, S., Dimock, D., Dylla, F., Eames, D., Efthimion, P., Eubank, H., Goldston, R., Grisham, L., Hawryluk, R., Hill, K., Hinnov, E., Hosea, J., Jobes, R., Johnson, D., Medley, S., Meservey, E., Sauthoff, N., Schilling, G., Schmidt, G., Stauffer, F., Stewart, L., Stodiek, W., Strachan, J., Stooksberry, R., Suckewer, S., Tait, G., Ulrickson, M., and von Goeler, S., "Energy Balance of the PLT Tokamak," *Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas,* edited by T. Consoli (Pergamon Press, Oxford, England, August 1979).

Jensen, R.V., Post, D.E., Grasberger, W.H., Tarter, O.B., and Lokke, W.A., "Calculations of Impurity Radiation and Its Effects on Tokamak Experiments," *Nuclear Fusion 17* (December 1977) 1187-1196. *PPPL-1334* (1977).

Lefkowitz, E.H., "PLT OH System Operation," in *Proceedings 7th Symposium on Engineering Problems of Fusion Research,* Edited by M.S. Lubell and C. Whitmore, Jr., (IEEE, New York, NY, 1977) *Vol. II,* 1601-1604.

Mazzucato, E., "Low-Frequency Microinstabilities in the PLT Tokamak," *Physics of Fluids 21* (June 1978) 1063-1069. *PPPL-1373* (1977).

Murray, H., and Heim, W.J., "PLT Ion Temperature System Design and Operation," *Proceedings 7th Symposium on Engineering Problems of Fusion Research,* Edited by M.S. Lubell and C. Whitmore, Jr., (IEEE, New York, NY, 1977) *Vol. I,* 410-414.

Picraux, S.T., Dylla, H.F., Wampler, W.R., Cohen, S.A., Rossnagel, S.M., and Magee, C.W., "Ion Beam Analysis of Surface Modifications in Tokamaks," *IEEE Transactions on Nuclear Science NS-26* (February 1979) 1277-1280 *(Proceedings of the 5th Conference on Applications of Small Accelerators).*

Rogoff, P., "Stress and Deflection Analysis of the PLT Coil Using ANSYS Computer Code," in *Proceedings 7th Symposium on Engineering Problems of Fusion Research,* Edited by M.S. Lubell and C. Whitmore, Jr., (IEEE, New York, NY, 1977) *Vol. I,* 59-62.

Sauthoff, N.R., "The Analysis of Magnetohydrodynamic Modes in Tokamaks by X-ray Techniques," *Proceedings of the Society of Photo-Optical Instrumentation Engineers 106* (1977) 40-46.

Sauthoff, N.R., and von Goeler, S., "Techniques for the Reconstruction of Two-Dimensional Images from Projection," *PPPL-1447* (1978).

Sauthoff, N.R., von Goeler, S., and Stodiek, W., "Study of Disruptive Instabilities in the PLT Tokamak Using X-ray Techniques," *Nuclear Fusion 18* (October 1978) 1445-1458. *PPPL-1379* (1978).

Schmidt, G.L., Bretz, N.L., Hawryluk, R.J., Hosea, J.C., and Johnson, D.W., "Gas Injection in PLT — Experimental Overview," in *Proceedings of the Fusion Fueling Workshop* (National Technical Information Services, Springfield, Virginia, 1978) Conference-771129, 53-56.

Silverman, K.B., "Neutral Injection Beam Power Monitor," *PPPL-1407* (1977).

Stewart, L.D., "Neutral Beam System Reionization Losses," *PPPL-1469* (1978).

Strachan, J.D., Bhattacharjee, A., Jassby, D.L., and Towner, H.H., "Neutron Emission Profiles in the Beam-Heated Princeton Large Tokamak," *Physics Letters 66A* (May 1978) 295-298.

Strachan, J.D., Colestock, P.L., Eubank, H.P., Jassby, D.L., and Towner, H.H., "Fusion-Neutron Production in Deuterium-Beam-Heated Plasmas in the Princeton Large Torus," in *Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas,* Edited by T. Consoli (Pergamon Press, Oxford, England, August 1979).

Suckewer, S., and Hawryluk, R.J., "Plasma Edge Cooling During RF Heating," *Phys. Rev. Lett. 40* (June 1978) 1649-1651. *PPPL-1416* (1978).

Suckewer, S., and Hinnov, E., "Observation of a Forbidden Line of FeXX and Its Application for Ion Temperature Measurements in the Princeton Large Torus Tokamak," *Phys. Rev. Lett. 41* (September 1978) 756-759. *PPPL-1465* (1978).

Suckewer, S., Hinnov, E., and Schivell, J., "Rapid Scanning of Spatial Distribution of Spectral Line Intensities in PLT Tokamak," *Minutes of the Second Topical Conference on High Temperature Plasma Diagnostics* (Los Alamos Scientific Laboratory, Santa Fe, New Mexico, 1978) Abstract only. *PPPL-1430* (1978).

von Goeler, S., Sauthoff, N., Bitter, M., Brau, K., Eames, D., Fraenkel, B., Greenberger, A., Hill, K., Horton, R., Hovey, G., Hovey, J., Roney, W., Stodiek, W., "Soft X-ray Measurements on the PLT Tokamak," presented at the *Second Conference on Hot Plasma Diagnostics* (Kharkov, USSR, 1977). *PPPL-1383* (1977).

Whalton, J.H., Grisham, L.R., Tsai, C.C., and Stirling, W.L. "Effect of Preacceleration Voltage Upon Ion Beam Divergence," *J. Applied Physics 49* (June 1978) 3091-3101.

POLOIDAL DIVERTOR EXPERIMENT (PDX)

Meade, D.M., "Divertors for Impurity Control and a Review of Impurity Effects in PPPL Tokamaks," in *Proceedings of the International Symposium on Plasma Wall Interaction* (Pergamon Press, New York, 1977) 21-37.

Meade, D.M., and Sinnis, J.C., "The PDX Experiment," in *Proceedings of the International Symposium on Plasma Wall Interaction* (Pergamon Press, New York, 1977) 683-690.

LINEAR DEVICES

Allen, G.R., Owens, D.K., Seiler, S.W., Yamada, M., Ikezi, H., and Porkolab, M., "Parametric Lower-Hybrid Instability Driven by Modulated Electron Beam," *Phys. Rev. Lett. 41* (October 1978) 1045-1048. *PPPL-1460* (1978).

Bellan, P.M., and Wong, K.L., "Effect of Density Fluctuations on Lower Hybrid Resonances Cone Propagation," *Physics of Fluids 21* (April 1978) 592-599. *PPPL-1314* (1977).

Chu, T.-K., and Johnson, L.C., "Conduction Heat Loss Scaling in Open Field Line Geometries," *Physics of Fluids 20* (October 1977) 1684-1687. *PPPL-1329* (1977).

Chu, T.-K., Johnson, L.C., and Schuss, J.J., "Electron Number Density Measurement by Ruby Laser Interferometry in a CO_2 Laser-Induced Gas Breakdown Plasma," *Proceedings of the 11th International Symposium on Shock-Tubes and Waves* (University of Washington Press, Seattle, Washington, 1977).

Johnson, L.C., "Measurements of End Loss From a Linear Plasma Column with Solid or Gaseous End Plugs," *Proceedings of Workshop on End-Stoppering of Linear Magnetic Fusion Systems* (Santa Fe, New Mexico, 1977).

Motley, R.W., Bernabei, S., Hooke, W.M., McWilliams, R., and Olson, L., "Penetration of Slow Waves into an Overdense Plasma," *Plasma Physics 21* (June 1979) 567-573. *PPPL-1449* (1978).

Motley, R.W., Bernabei, S., Hooke, W.M., McWilliams, R., and Olson, L., "Demonstration of Accessibility and Inaccessibility for Slow Plasma Waves," in *Proceedings of the Third Topical Conference on Radio-Frequency Plasma Heating* (California Institute of Technology, Pasadena, California, 1978) paper A6-1 to A6-4.

Motley, R.W., Paoloni, F.J., Bernabei, S., Hooke, W.M., "Detection of Lower Hybrid Waves within a Plasma by Microwave Scattering," *Rev. Sci. Instrum. 49* (August 1978) 1143-1146. *PPPL-1414* (1978).

Ono, M., Porkolab, M., and Chang, R.P.H., "Parametric Excitation of Nonresonant Ion Cyclotron Quasi-Mode," *PPPL-1395* (1977).

Ono, M., Porkolab, M., and Chang, R.P.H., "Parametric Instabilities Near the Ion-Cyclotron Frequency in Single and Multi-Ion Species Plasma," in *Proceedings of the Third Topical Conference on Radio-Frequency Plasma Heating* (California Institute of Technology, Pasadena, California, 1978) paper D2-1 to D2-4.

Paoloni, F.J., Motley, R.W., Hooke, W.M., and Bernabei, S., "Landau Damping of Low- and High-Power Slow Electrostatic Waves," *Phys. Rev. Lett. 39* (October 1977) 1081-1084. *PPPL-1372* (1977).

Seiler, S., and Yamada, M., "Ion-Beam-Driven Lower-Hybrid Instability and Resultant Anomalous Beam Slowing," *Nuclear Fusion 19* (April 1979) 469-483. *PPPL-1412* (1978).

Wong, K.L., "Experimental Observation of Current Generation by Unidirectional Electron Plasma Waves," *Phys. Rev. Lett.* (to be published). *PPPL-1464* (1978).

Wong, K.L., and Bellan, P.M., "Enhancement of Drift Waves by Localized Lower Hybrid Waves," *Physics of Fluids 21* (May 1978) 841-845. *PPPL-1340* (1977).

Wong, K.L., Bellan, P., and Porkolab, M., "Resonant Decay of Finite-Extend Cold Electron Plasma Waves," *Phys. Rev. Lett. 40* (January 1978) 554-557. *PPPL-1402* (1978).

Wong, K.L., Wilson, J.R., and Porkolab, M., "Effect of Convective Loss on Resonant Decay of Cold Lower Hybrid Waves," in *Proceedings of the Third Topical Conference on Radio-Frequency Plasma Heating* (California Institute of Technology, Pasadena, California, 1978) paper B8-1 to B8-4.

Yamada, M., and Hendel, H.W., "Current-Driven Instabilities and Resultant Anomalous Effects in Isothermal, Inhomogeneous Plasmas," *Physics of Fluids 21* (September 1978) 1555-1568. *PPPL-1249* (1977).

Yamada, M., and Nishi, M., "A Small Low-Aspect-Ratio Tokamak," in *Proceedings of the Small Toroidal Plasma Devices Users Meeting,* Edited by M. Kristiansen and M.O. Hagler (Plasma Laboratory, Department of Electrical Engineering, Texas Tech University, Lubbock, Texas, 1978) 75-80.

TOKAMAK FUSION TEST REACTOR

Allen, H.L., Fedor, B.J., "Operations and Maintenance Plans for the TFTR" in *Technology of Controlled Nuclear Fusion,* edited by J.R. Powell and C.T. Eterno (American Nuclear Society, Santa Fe, New Mexico, 1978) CONF-780508-P2.

Ashcroft, D.L., Zuvers, H.E., "Princeton Neutral Injection Power Supply System," in *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research, Vol. II* (Institute of Electrical and Electronics Engineers, New York, New York, 1977) CONF-771029-P2.

Bonanos, P., Lontai, L., "Tokamak Fusion Test Reactor Remote Maintenance," in *Proceedings of the 25th Conference on Remote Systems Technology* edited by D.R. Wojciechowski (American Nuclear Society, La Grange Park, Illinois, 1977) CONF-771117.

Cecchi, J.L., "Tritium Permeation and Wall Loading in the TFTR Vacuum Vessel," *J. Vac. Science and Technology 16* (1979). *PPPL-1422* (1978).

Deitz, A., Murray, H., Winje, R., "TFTR Neutral Beam Power System," in *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research, Vol. II* (Institute of Electrical and Electronics Engineers, New York, New York, 1977) CONF-771029-P2.

Deitz, A., Murray, H., Winje, R., "HV Switch Tube Development Program: TFTR," in *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research, Vol. II,* (Institute of Electrical and Electronics Engineers, New York, New York, 1977) CONF-771029-P2.

Goldfarb, S., "Diagnostic Interface Problems on TFTR," *Symposium on Fusion Research Projects* (National Technical Information Services, Springfield, Virginia, 1977) CONF-771029-138.

Kaminsky, M., Das, K.S., Cecchi, J.L., "Sputtering and Surface Damage of TFTR Protective Plate Candidate Materials by Energetic D^+ Irradiation," in *Proceedings of the Symposium on Fusion Technology* (Pergamon Press, Oxford, England, October 1979).

Prichard, B.A., Jr., "Development of the TFTR Neutral Beam Injection System," in *Proceedings of the Fusion Fueling Workshop* (Princeton University, Princeton, New Jersey, 1977) CONF-771129, p. 43-47.

Prichard, B., Little, R., Post, D.E., and Schmidt, J.A., "Possible Neutron Beam Requirements for TFTR Upgrades," in *Proceedings of the Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams,"* (Brookhaven National Laboratory, Associated Universities, Inc., January 1978) 269-275.

Reardon, P.J., "Status Report on TFTR," *Highlights of Research and Development Activities for the Tokamak Fusion Test Reactor Project, PPPL-1441,* (1978) 1.1-1.8.

Readon, P.J., "Status Report on TFTR," in *Technology of Controlled Nuclear Fusion,* edited by J.R. Powell and C.T. Eterno (American Nuclear Society, Santa Fe, New Mexico, 1978) CONF-780508-P1, p. 612-619.

Winje, R.A., "HV Switch Tube Development Program Status Report: April 28, 1978," in *Highlights of Research and Development Activities for the Tokamak Fusion Test Reactor Project, PPPL-1441,* (1978) 3.27-3.31.

Wright, K.E., "Neutral Beam Fast Shutter Valve Assembly Status Report: April 28, 1978," in *Highlights of Research and Development Activities for the Tokamak Fusion Test Reactor Project, PPPL-1441,* (1978) 3.15-3.25.

Young, K.M., "Diagnostic Problems of Large Tokamaks," in *Proceedings of the Fifth International Conference on Atomic Physics* (Plenum Press, New York, New York, 1977) *Vol. 5,* 391-314. *PPPL-1365* (1977).

Young, K.M., "TFTR Final Design Report, Diagnostics Sections," *PPPL-1475* (1978).

ENGINEERING

Alekseev, Y.A., et al., "Toroidal Magnetic Machine with a 200 KG Longitudinal Field," Translated by N.M. Turitzin, *PPPL-TRANS-123* (1978).

Arunasalam, V., Schivell, J.F., Barnes, C.W., Bol, K., Boyd, D., Brau, K., Bretz, N., Brusati, M., Cohen, S.A., Davis, S.L. Dimock, D.L., Dylla, H.F., Eames, D., Efthimion, P., Eubank, H.P., Furth, H.P., Goldston, R.J., Hawryluk, R.J., Hill, K., Hinnov, E., Horton, R., Hosea, J.C., Hsuan, H.C.S., Ignat, D., Jobes, F.C., Johnson, D.W., Mattioli, M., Mazzucato, E., Meservey, E.B., Moriette, P., Sauthoff, N.R., Schmidt, G.L., Smith, R.R., Stauffer, F., Stodiek, W., Strachan, J.D., Suckewer, S., von Goeler, S. "Recent Results from the PLT Tokamak." *PPPL-1436* (1978).

Bazaeva, A.V., Bikov, V.E., Georgieski, A.V., Golovin, I.N., Kaminski, A.O., Mikhailovskaya, L.V., Peletiminskaya, V.G., Pyatov, V.N. "Plasma Stability in Tokamak with Poloidal Divertor." Translated by N.M. Turitzin. *PPPL-Trans-124* (1978).

Bretz, N., Dimock, D.L., Foote, V.S.J., Johnson, D.W., Long, D., Tolnas, E.L. "A multichannel Thomson Scattering Apparatus." *Applied Optics 17:*192-202. See *PPPL-1356* (1978).

Eubank, H.P., Goldston, R.J., Arunasalam, V., Bitter, M., Bol, K., Boyd, D., Bretz, N., Bussac, J.P., Cohen, S., Colestock, P.L., Davis, S.L., Dimock, D.L., Dylla, H.F., Efthimion, P., Grisham, L.R., Hawryluk, R.J., Hill, K., Hinnov, E., Hosea, J., Hsuan, H., Johnson, D., Martin, G., Medley, S., Meservey, E., Sauthoff, N., Schilling, G., Schivell, J., Schmidt, G., Stauffer, F., Stewart, L., Stodiek, W., Stooksberry, R., Strachan, J., Suckewer, S., Takahashi, H., Tait, G., Ulrickson, M., von Goeler, S., Yamada, M. "PLT Neutral Beam Heating Results." *PPPL-1491* (1978).

Foote, V.S., Jr., "Axial Flow Valves Help Control Plasma Physics Laboratory Cooling System." *Heating/Piping/Air Conditioning 50* pp. 53-56 (December 1977).

Greenberger, A.J. "Digital Multiradian Phase Display Circuit." *PPPL-1466* (1978).

Hill, K.W., von Goeler, S., Bitter, M., Campbell, L., Cowan, R.D., Fraenkel, B., Horton, R., Hovey, J., Roney, W., Sauthoff, N.R., Stodiek, W., "Determination of Fe Charge-State Distributions in PLT by Bragg Crystal X-Ray Spectroscopy." *PPPL-1457* (1978).

Oliaro, G.E., Turitzin, N.M. "Poloidal Field Power Supplies and Their Performance on the PDX Machine." *PPPL-1406* (1978).

Reed, B.W., Bowen, O.N., Hill, H.M.J., Lawson, J.Q., Newman, W.G., Sivo, A.J., *Preliminary Report on the Development of RF Auxiliary Heating Systems for TEPR-1. PPPL-1410* (1978).

Silverman, K.B. "Neutral Injection Beam Power Monitor." *PPPL-1407* (1978).

Suckewer, S., Schivell, J., Hinnov, E. "Rapid Scanning of Spatial Distribution of Spectral Line Intensities in PLT Tokamak." *PPPL-1430* (1978).

von Goeler, S., Sauthoff, N., Bitter, M., Brau, K., Eames, D., Fraenkel, B., Greenburger, A., Hill, K., Horton, R., Hovey, G., Hovey, J., Roney, W., Stodiek, W. "Soft X-Ray Measurements on the PLT Tokamak." *PPPL-1383* (1977).

MACHINE DESIGN AND FABRICATION

File, J., Jassby, D.L., Bronner, G., Clarke, J.R., Johnson, H.G., Martin, G.D., Murray, J.G., Price, W.G., Rogoff, P., Singer, C.E., Stewart, L.D., Bundy, J.J., Gralnick, S.L., Luzzi, T., Sedgley, D. Eckels, P., Gaberson, P., Murphy, J., Hay, R.D., Lind, K.E., Paulson, C., Fuller, G.M., Gaines, A.L., "SLPX-Superconducting Long-Pulse Experiment," *PPPL-1500,* Volume II, Part I & II (1978).

Jassby, D.L., File, J., Reardon, P.J., "SLPX-Superconducting Long-Pulse Experiment," *PPPL-1481* (1978).

Jassby, D.L., File, J., Gralnick, S.L., Price, W.G., Stewart, L., Hay, R.D., Eckels, P., Gaberson, P., Gromada, R., Murphy, J., *SLPX-Superconducting Long-Pulse Experiment. PPPL-TM-315* (1978).

Jassby, D.L., File, J., Bronner, G., Clarke, J.R., Johnson, H.G., Martin, G.D., Murray, J.G., Okabayashi, M., Price, W.G., Rogoff, P., Singer, C.E., Stewart, L.D., Bundy, J.J., Gralnick, S.L., Luzzi, T., Marino, J.D., Sedgeley, D., Eckels, P., Gaberson, P., Murphy, J., Hay, R.D., Lind, K.E., Paulson, C., Fuller, G.M., Gaines, A.L., "SLPX-Superconducting Long-Pulse Tokamak Experiment," *PPPL-1488* (1978).

Jassby, D.L., File, J., Bronner, G., Clarke, J., Davenport, J., Martin, G., Murray, J., Okabayashi, M., Rogoff, P., Bundy, J., Gralnick, S., Luzzi, T., Eckels, P., Gaberson, P., Murphy, J., Hay, R.D., "SLPX-Superconducting Long-Pulse Experiment, Volume III." *PPPL-1501* (1978).

DESIGN STUDIES FOR NEW DEVICES

Bauer, W., Wilson, K.L., Bisson, C.L., Haggmark, L.G., and Goldston, R.J., "Helium Induced Blistering During Simultaneous Sputtering," *Nuclear Materials 76/77* (September/October 1978) 396-401. *(Proceedings of the Third International Conference on Plasma Surface Interactions in Controlled Fusion Devices). PPPL-1448* (1978).

Bolton, R.A., Bromberg, L., Brown, D.I., Christensen, U.R., Jassby, D.L., Okabayashi, M., and Singer, C.E., "New Techniques for Inducing Plasma Current in Large Tokamak Devices," in *Proceedings of the Third American Nuclear Society Topical Meeting on the Technology of Controlled Nuclear Fusion* (National Technical Information Services, Springfield, Virginia, 1979) CONF-780508, 824-832. *PPPL-1451* (1978).

Book, D., Chu, T.-K., Grossman, W., and Steinhauer, L., "Linear Magnetic Fusion: Summary of 1977 Seattle Workshop," (US Department of Energy, Division of Magnetic Fusion Energy, Washington, DC, 1977) CONF-770386.

Bromberg, L., and Jassby, D.L., "In-Torus Zirconium-Aluminum Getter Pumping for Beam-Driven Tokamak," in *Proceedings Seventh Symposium on Engineering Problems of Fusion Research,* Edited by M.S. Lubell and C. Whitmore, Jr., (IEEE, New York, New York, October 1977) *Vol. II,* 971-975. *PPPL-1396* (1977).

Bussac, M.N., Furth, H.P., Okabayashi, M., Rosenbluth, M.N., and Todd, A.M.M., "Low-Aspect-Ratio Limit of the Toroidal Reactor: The Spheromak," in *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 7th Int. Conf., Innsbruck, Austria, 1978) IAEA, Vienna, 1979, *Vol. III* (to be published). *PPPL-1472* (1978).

Cohn, D.R., Cook, D.L., Hay, R.D., Kaplan, D., Kreischer, K., Lidsky, L.M., Stephany, W., Williams, J.E.C., Jassby, D.L., and Okabayashi, M., "A High-Field, High-Density Tokamak Power Reactor," in *Proceedings of the Conference on Fusion Reactor Design Concepts* (IAEA, Vienna, 1978) 219-235. *PPPL-1347* (1977).

Cohn, D.R., Jassby, D.L., and Kreischer, K., "Neutral-Beam Requirements for Compression-Boosted Ignited Tokamak Plasmas," *Nuclear Fusion 18* (September 1978) 1255-1262. *PPPL-1405* (1977).

Goldston, R.J., Jassby, D.L., Towner, H.H., Fowler, R.H., Lyon, J.F., Rome, J.A., and Brown, T., "Magnetic Design for Ripple-Assisted Beam Injection into the ISX-B and TFTR Tokamaks," in *Proceedings Seventh Symposium on Engineering Problems of Fusion Research,* Edited by M.S. Lubell and C. Whitmore, Jr. (IEEE, New York, New York, October 1977) *Vol. II,* 1333-1338. *PPPL-1398* (1977).

Gralnick, S.L., "A Blister Divertor for Tokamaks," *Nuclear Fusion 18* (June 1978) 876-880. *PPPL-1388* (1978).

Jassby, D.L., Bolton, R.A., Brown, D.I., Dahlgren, F., Gralnick, S.L., Okabayashi, M., Price, W.G., Singer, C.E., Stewart, L.D., Towner, H.H., Bundy, J.J., Luzzi, T., and Marino, J.D., "PITR — A Small-Aspect-Ratio, Small-Radius Ignition Test Reactor," *Proceedings of the Third American Nuclear Society Topical Meeting on the Technology of Controlled Nuclear Fusion* (National Technical Information Services, Springfield, Virginia, 1979) CONF-780508, 1109-1118. *PPPL-1453* (1978).

Jassby, D.L., File, J., and Reardon, P.J., "SLPX — Super-conducting Long-Pulse Experiment," Presented at the *IAEA Technical Committee Meeting on the Engineering of Large Tokamak Experiments,* (Paris, France, September 1978). *PPPL-1481* (1978).

Jassby, D.L., Furth, H.P., Reardon, P.J., Cohn, D.R., and Williams, J.E.C., "High-Density Tokamak Design Studies for TFTR-II," in *Proceedings of the Conference on Fusion Reactor Design Concepts* (IAEA, Vienna, 1978) 67-75.

Jassby, D.L., "SMARTOR — A Small-Aspect-Ratio Torus for Demonstrating Thermonuclear Ignition," *PPPL-1371* (1977).

Jassby, D.L., "A Small-Aspect-Ratio Torus for Demonstrating Thermonuclear Ignition," in *Proceedings of the Conference on Fusion Reactor Design Concepts* (IAEA, Vienna, 1978) 119-129.

Jassby, D.L., "Small-Aspect-Ratio, Small-Major-Radius Tokamak Reactors," *Comments on Plasma Physics and Controlled Fusion 3* (1978) 151-158.

Jassby, D.L., "Potential Methods for Reducing Plasma Heating Requirements," Presented at the *Plasma Heating Requirements Workshop* (Department of Energy, Washington, DC, 1978) CONF-771241, 444-459.

Jassby, D.L., Towner, H.H., "Optimization of Plasma Profiles for Ignited Low-Beta Toroidal Plasmas Utilizing 'Advanced Fuels'," in *Proceedings of EPRI Review Meeting on Advanced Fuel Fission,* (Electric Power Research Institute, September 1977) EPRI-ER-536-SR, 275-284. *PPPL-1360* (1977).

Jassby, D.L., Towner, H.H., and Goldston, R.J., "Reduced Fusion-Neutron Production in Nonaxisymmetric Tokamak Devices," *Nuclear Fusion 18* (June 1978) 825-833. *PPPL-1300* (1977).

Jassby, D.L., Towner, H.H., Greenspan, E., Schneider, A., Misolovin, A., and Gilai, D., "The Energetics of Semi-Catalyzed-Deuterium, Light-Water-Moderated, Fusion-Fission Toroidal Reactors," in *Proceedings of the Third American Nuclear Society Topical Meeting on the Technology of Controlled Nuclear Fusion"* (National Technical Information Services, Springfield, Virginia, 1979) CONF-780508, 170-179. *PPPL-1456* (1978).

Jensen, R.V., Jassby, D.L., Post, D.E., "Critical Impurity Concentrations for Ignition of Catalyzed-Deuterium Fusion Plasmas," *Nuclear Science and Engineering 66* (April 1978) 144-146. *PPPL-1368* (1977).

Jensen, R.V., Post, D.E., and Jassby, D.L., "Critical Impurity Concentrations for Power Multiplication in Beam-Heated Toroidal Fusion Reactors," *Nuclear Science and Engineering 65* (February 1979) 282-289. *PPPL-1350* (1977).

Price, W.G., "Overview of the Preliminary Conceptual Design of the Princeton Ignition Test Reactor," Presented at the *Soviet-American Workshop on Conceptual Design of Blanket and Test Components for Demonstration Reactors* (Leningrad, USSR, December 1977).

Stewart, L.D., "Comparison of Methods for the Production of Neutral Beams," in *Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams* (Upton, New York, September 1977). *PPPL-1391* (1977).

Williams, J.E.C., Hay, R., and Okabayashi, M., "Magnet Conceptual Design for a High Field Tokamak Reactor," in *Proceedings 7th Symposium on Engineering Problems of Fusion Research,* Edited by M.S. Lubell and C. Whitmore, Jr., (IEEE, New York, New York, 1977) *Vol. I,* 625-629.

THEORY

Boozer, A.H., "Magnetic Surfaces in the Reversed Field Geometry," *Nuclear Fusion 18,* 1663 (1978). *PPPL-1415.*

Boozer, A.H., "Plasma Response to Symmetry Breaking Perturbations in the Reversed Field Geometry," *Nuclear Fusion 18,* 1663 (1978). *PPPL-1419.*

Boozer, A.H., "Reduction of Electron Parallel Thermal Conductivity Using Waves," *Comments on Plasma Phys. and Therm. Fusion. Vol. IV,* 31 (1978).

Chance, M.S., Greene, J.M., Grimm, R.C., Johnson, J.L., Manickam, J., Kerner, W., Berger, D., Bernard, L.C., Gruber, R., Troyon, F., "Comparative Numerical Studies of Ideal Magnetohydrodynamic Instabilities," *J., Comp. Physics 28,* 1 (1978). *PPPL-1349.*

Chen, Liu, Hsu, J., Kaw, P.K., Rutherford, P.H., "Stability and Magnetic Tearing of Finite-β Modified Drift Waves," *Nucl. Fusion 18,* 1371 (1978). *PPPL-1376.*

Chen, Liu, Guzdar, P.N., White, R.B., Kaw, P.K., Oberman, C., "Theory of Universal Eigenmodes in a Sheared Magnetic Field," *Phys. Rev. Letters 41,* 649 (1978). *PPPL-1446.*

Cheng, C.Z., Okuda, H., "Theory and Numerical Simulations on Collisionless Drift Instabilities in Three Dimensions," *Nucl. Fusion 18,* 587 (1978). *PPPL-1397.*

Cheng, C.Z., Okuda, H., "Numerical Simulation of Trapped Electron Instabilities in Toroidal Geometry," *Phys. Rev. Letters 41,* 1116 (1978). *PPPL-1454.*

Cohen, B.I., Tang, W.M., "Nonlinear Saturation of the Trappped Ion Mode by Mode Coupling in Two Dimensions," *Nucl. Fusion 18,* 1389 (1978). *PPPL-1369.*

Dewar, R.L., "Random Phase Wave: A Soluble Non-Markovian System," *J. Math. Phys. 19,* 1946 (1978). *PPPL-1401.*

Dewar, R.L., "Hamilton's Principle for a Hydromagnetic Fluid with a Free Boundary," *Nuclear Fusion 18,* 1541 (1978). *PPPL-1421.*

Dewar, R.L., "Exact Canonical Transformations," *J. Phys. A11,* 9 (1978).

Drake, J.F., Lee, Y.B., Liu Chen, Rutherford, P.H., Kaw, P.K., Hsu, J.Y., Liu, C.S., "The Internal m = 1 Resistive Mode in High-Temperature Plasma," *Nuclear Fusion Letters 18,* 1583 (1978).

Guzdar, P.N., Sen, A., "Nonresonant Pump Field Modification of the Sidescatter Threshold," *Nucl. Fusion 18,* 970 (1978).

Guzdar, P.N., Chen, Liu, Kaw, P.K., Oberman, C., "Effect of Magnetic Shear on Dissipative Drift Instabilities," *Phys. Rev. Letters 40,* 1566 (1978). *PPPL-1426.*

Hasam, A.B., Kulsrud, R.M., "Time Evolution of Mass Flow in a Collisional Tokamak," *Phys. Fluids 21,* 2271 (1978). *PPPL-1427.*

Hirshman, S.P., "Moment Equation Approach to Neoclassical Transport," *Phys. Fluids 21,* 224 (1978). *PPPL-1378.*

Jardin, S.C., Johnson, J.L., Greene, J.M., Grimm, R.C., "Dynamical Grid Method for Time Dependent Simulations of Axisymmetric Instabilities in Tokamaks," *J. Comp. Phy. 29,* 101 (1978). *PPPL-1359.*

Jardin, S.C., "Stabilization of the Axisymmetric Instability of the PDX Tokamak," *Phys. Fluids 21,* 1851 (1978). *PPPL-1400.*

Jensen, R.V., Post, D.E., Jassby, D.L., "Critical Impurity Concentration for Power Multiplication in Beam-Heated Toroidal Fusion Reactors," *Nucl. Sci. and Eng. 66,* 144 (1978). *PPPL-1350.*

Karney, C.F.F., "Stochastic Ion Heating by a Lower Hybrid Wave," *Phys. Fluids 21,* 1584 (1978). *PPPL-1429.*

Koch, R.A., Tang, W.M., "Doppler Model for Adiabatic Toroidal Compressor Driftwave Frequency Profiles," *Phys. Fluids 21,* 1236 (1978). *PPPL-1381.*

Kritz, A.H., Mahajan, S.M., Berger, R.L., Goldston, R.J., Motley, R.W., Hooke, W.M., Bernabei, S., "Wave Heating of an Ion Beam in a Tokamak Plasma," *Nucl. Fusion 18,* 835 (1978). *PPPL-1390.*

Krommes, J.A., "Plasma Transport in Stochastic Magnetic Fields: Principles and Problems of Test Electron Transport," *Supplement Progrss. Theor. Phys. 64,* 137 (1978). *PPPL-1462.*

Lin, A.T., Dawson, J.M., Okuda, H., "Thermal Magnetic Fluctuations Anomalous Electron Diffusion," *Phys. Rev. Letters 41,* 753 (1978).

Marchand, R., "Effect of Circulating Ion Resonances and Impurities on the Dissipative Trapped-Ion Instability," *Nuclear Fusion 18,* 1183 (1978). *PPPL-1367.*

Okuda, H., Cheng, C.Z., "Higher Order Multipoles and Splines in Plasma Simulations," *Comp. Phys. Communications 14,* 169 (1978). *PPPL-1404.*

Rechester, A.B., Rosenbluth, M.N., "Electron Heat Transport in a Tokamak with Destroyed Magnetic Surfaces," *Phys. Rev. Letters 40,* 38 (1978). *PPPL-1386.*

Rewoldt, G., Tang, W.M., Frieman, E.A., "Integral Formulation for the Two-Dimensional Spatial Structure of Drift and Trapped-Electron Modes," *Phys. Fluids 21,* 1513 (1978). *PPPL-1387.*

Tang, W.M., "Microinstability Theory in Tokamaks — A Review," *Nucl. Fusion 18,* 1089 (1978). *PPPL-1354.*

MISCELLANEOUS

Ascoli-Bartoli, U., Bardotti, G., Bartiromo, R., Battaglia, G., Brusati, M., Buratti, P., Cima, G., DeAngelis, A., DeMarco, F., LePretis, M., Enriques, L., Ferro, C., Grolli, M., Haegi, M., Marconero, R., Martone, M., Mazzitelli, G., Mazzucato, E., Pieroni, L., Righetti, G.B., Samuelli, M., Segre, S.E., Strangio, C., and Tuccillo, A., "Preliminary Results of Ohmic Heating in FT," *Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas,* Edited by T. Consoli (Pergamon Press, Oxford, England, August 1979).

Ascoli-Bartoli, U., Bardotti, G., Bartiromo, R., Battaglia, G., Brusati, M., Buratti, P., Cima, G., DeAngelis, A., DeMarco, F., Enriques, L., Gasparotto, M., Grolli, M., Haegi, M., Marconero, R., Martone, M., Mazzitelli, G., Mazzucato, E., Pieroni, L., Righetti, G.B., Samuelli, M., Segre, S.E., Strangio, C., and Tuccillo, A., "Preliminary Results on the TF Tokamak," in *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 7th Int. Conf., Innsbruck, Austria, 1978) IAEA, Vienna, 1979, *Vol. I*, 149-156.

Bernabei, S., "Lower Hybrid Heating Experiments in USA," in *Proceedings of the US-USSR Workshop on High-Frequency Heating* (Sukhumi, USSR, June 1978) to be published.

Bernabei, S, Heald, M.A., Hooke, W.M., Motley, R.W., Paoloni, F.J., Brambilla, M., and Getty, W.D., "Plasma-Wave Coupling and Propagation Using Phased Waveguide Arrays," *Nuclear Fusion 17* (October 1977) 929-943. *PPPL-1288* (1976).

Bitter, M., and Paris, P.J., "Current Driven Weak Ion Acoustic Turbulence in a Magnetized Plasma," *Physics of Fluids 21* (April 1978) 609-616.

Cecchi, J.L., "Fusion-Power to the People," in *Environmental Problems: Principles, Readings, and Comments,* Edited by W.H. Mason and G.W. Folkerts (W.C. Brown, 1978).

Chance, M.S., Dewar, R.L., Frieman, E.A., Glasser, A.H., Greene, J.M., Grimm, R.C., Jardin, S.C., Johnson, J.L., Manickam, J., Okabayashi, M., and Todd, A.M.M., "MHD Stability Limits on High-β Tokamaks," in *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 7th Int. Conf., Innsbruck, Austria, 1978) IAEA, Vienna, 1979, *Vol. I,* 677-686. *PPPL-1468* (1978).

Colestock, P.L., "Asympotic Solution of Lower-Hybrid Wave Propagation in Two-Dimensional Inhomogenous Plasma," *Nuclear Fusion 18* (May 1978) 740-743.

Daughney, C.C., "On Tokamak Confinement," *PPPL-1442* (1978).

Gilligan, J.G., Gralnick, S.L., Price, W.G., Jr., Kammash, T., "Multigroup Calculations of Low Energy Neutral Transport in Tokamak Plasmas," *Nuclear Fusion 18* (January 1978) 63-85. *PPPL-1384* (1977).

Goldston, R.J., "Charge-Exchange Measurements of Parallel and Anti-Parallel Ion Temperature Profiles on ATC," *Nuclear Fusion 18* (December 1978) 1611-1617. *PPPL-1431* (1978).

Goldston, R.J., "Radially Resolved Measurements of "q" on the ATC Tokamak," *Physics of Fluids 21* (December 1978) 2346-2353. *PPPL-1432* (1978).

Goldston, R.J., "A Simple Neutron Density Profile Calculation for Tokamaks with $\lambda_{mfp} << a$," *Plasma Physics 20* (November 1978) 1199-1203. *PPPL-1443* (1978).

Gralnick, S.L., and Dalhed, H.E., Jr., "Ray Tracing in Axisymmetry Toroidal Coordinates," *Nuclear Science and Engineering 64* (October 1977) 373-378. *PPPL-1324* (1977).

Grisham, L.R., Bol, K., and Hogan, J.T., "Free Expansion Experiment on ATC," *Nuclear Fusion 18* (March 1978) 315-326. *PPPL-1330* (1977)

Hinnov, E., "Iron Radiation in Tokamak Discharges," in *Proc. of the Course on Diagnostics for Fusion Experiments,* Edited by E. Sindoni and C. Wharton (Pergamon Press, Oxford, England, August 1979).

Hooke, W.M., "A Survey of the Status of Lower Hybrid Heating Experiments in Toroidal Devices," in *Proceedings of the Third Topical Conference on Radio-Frequency Plasma Heating* (California Institute of Technology, Pasadena, California, 1978) paper A2-1 to A2-16.

Hooke, W.M., "The US Lower Hybrid Experimental Program," in *Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas,* Edited by T. Consoli (Pergamon Press, Oxford, England, August 1979) *Vol. II.*

Hsuan, H., Hawryluk, R., Suckewer, S., Takahashi, H., "Energy Loss and Edge Density Measurements During ICRF Experiments on ATC," in *Proceedings of the Third Topical Conference on Radio-Frequency*

Plasma Heating (California Institute of Technology, Pasadena, California, January 1978) paper C8-1 to C8-4.

Inoue, S., Itoh, K., and Yoshikawa, S., "Sheer Stabilization of Collisional Drift Instability," *Journal of the Physical Society of Japan 44* (May 1978) 1707-1710. *IPPJ-303* (August 1977).

Inoue, S., Itoh, K., and Yoshikawa, S., "Non-Local Drift Instability of Current-Carrying Plasma with Temperature Inhomogeneities," *Nuclear Fusion 18* (June 1978) 755-759.

Johnson, B.M., Jones, K.W., Cecchi, J.L., Hinnov, E., and Kruse, T.H., "Comparison of Tungsten and Gold Radiation from Beam-Foil Excitation and Tokamak-Produced Plasmas," *Physical Review Letters 70A* (March 1979) 320-322. *PPPL-1479* (1978).

Johnson, B.M., Dalhed, H.E., Greene, J.M., Grimm, R.C., Hsieh, Y.Y., Jardin, S.C., Manickam, J., Okabayashi, M., Storer, R.G., Todd, A.M.M., Voss, D.E., and Weimer, K.E., "Numerical Determination of Axisymmetric Toroidal Magnetohydrodynamic Equilibria," *Journal of Computational Physics* (1979) to be published. *PPPL-1463* (1978).

Kritz, A.H., Mahajan, S.M., Berger, R.L., Goldston, R.J., Motley, R.W., Hooke, W.M., Bernabei, S., "Wave Heating of an Ion Beam in a Tokamak Plasma," *Nuclear Fusion 18* (June 1978) 835-841. *PPPL-1390* (1977).

Lonngren, K.E., and Hsuan, H.C.S., "A Consequence of the Invariance of Biot's Variational Principle in Thermal Conduction," *Journal of Mathematical Physics 19* (1978) 357.

Medley, S.S., "Energetic Ion Mass Analysis Using a Radio-Frequency Quadrupole Filter," *Review of Scientific Instruments 49* (June 1978) 698-706.

Mirin, A.A., McCoy, M.G., Killeen, J., Rensink, M.E., Shumaker, D.E., Jassby, D.L., Post, D.E., "Fokker-Planck/Transport Analyses of Fusion Plasmas in Contemporary Beam-Driven Tokamaks," in *Joint Varenna-Grenoble International Syposium on Heating in Toroidal Plasmas,* Edited by T. Consoli (Pergamon Press, Oxford, England, August 1979) *Vol. I. PPPL-1437* (1978).

Motley, R.W., "Lower Hybrid Heating Technology," in Proceedings of the Plasma Heating Requirements Workshop (National Technical Information Services, Springfield, Virginia, 1978) CONF-771241, 429-435.

Pegg, D.J., Griffin, P.M., Johnson, B.M., Jones, K.W., Cecchi, J.L., Kruse, T.H., "Radiative Lifetimes of the Low-Lying Levels of Na-like Copper," *Phys. Rev. A 16* (1977) 2008.

Porkolab, M., Bekefi, G., Parker, R., Bernabei, S., Motley, R.W., and Hooke, W.M., "Lower Hybrid Heating of the MIT Versator II and Alcator Tokamaks," in *Proceedings of the Third Topical Conference on Radio-Frequency Plasma Heating* (California Institute of Technology, Pasadena, California, 1978) paper B10-1 to B10-4.

Post, D.E., Goldston, R.J., Grimm, R.C., Hawryluk, R.J., Hirshman, S.P., Hsieh, Y.Y., Hulse, R.A., Jassby, D.L., Jensen, R.V., McKenney, A., Meade, D.M., Mikkelsen, D.R., Ogden, J.M., Okabayashi, M., Rutherford, P.H., Schmidt, J.A., Seidl, F.G.P., Suckewer, S., Tenney, F., Mirin, A.A., McCoy, M.G., Killeen, J., Resink, M.E., Shumaker, D.E., and Tarter, C.B., "Computational Studies of Impurity Effects, Impurity Control, and Neutral Beam Injection in Large Tokamaks," in *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 7th Int. Conf., Innsbruck, Austria, 1978) IAEA, Vienna, 1979, *Vol. I,* 471-484. *PPPL-1476* (1978).

Rechester, A.B., and Rosenbluth, M.N., "Electron Heat Transport in a Tokamak With Destroyed Magnetic Surfaces," *Physical Review Letters 40* (January 1978) 38-41. *PPPL-1386* (1977).

Schilling, G., "Summary of Fueling by Cluster Beams," in *Proceedings of the Fusion Fueling Workshop* (National Technical Information Services, Springfield, Virginia, 1978) CONF-771129, 21.

Schuss, J.J., Chu, T.-K., and Johnson, L.C., "Measurements of the Parametric Decay of CO_2 Laser Radiation into Plasma Waves at Quarter Critical Density Using Ruby Laser Thomson Scattering," *Physical Review Letters 40* (January 1978) 27-30. *PPPL-1394* (1977).

Singer, C.E., Bromberg, L., Hovey, J., and Jassby, D.L., "Evolution of Neutral-Beam-Driven Current in Tokamak Plasmas," in *Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas,* Edited by T. Consoli (Pergamon Press, Oxford, England, August 1979) *Vol. I. PPPL-1438* (1978).

Stoenescu, M., "The Effect of Neutral Particles on Anomalous Skin Current in Tokamaks," *PPPL-1439* (1978).

Suckewer, S., and Hinnov, E., "Spectroscopic Measurements of Ion Temperatures in ATC with rf and Neutral Beam Heating," *Nuclear Fusion 17* (October 1977) 945-953. *PPPL-1323* (1977).

Takahashi, H., "ICRF Heating in Tokamaks," *J. de Physique 38* (December 1977) C6-171 to C6-190. (Third International Congress on Waves and Instabilities in Plasmas, June 1977). *PPPL-1374* (1977).

Takahashi, H., "ICRF Heating Research in USA," presented at the *US-USSR Workshop on High-Frequency Heating* (Sukhumi, USSR, June 1978) to be published.

Tenney, F.H., and Mills, R.G., "Reactor Studies of Tokamak Hybrids," in *Proceedings of the Second Fusion-Fission Energy Systems Review Meeting,* Edited by S. Locke-Bogart (National Technical Information Services, Springfield, Virginia, 1978) CONF-771155, *Vol. II,* 523-538.

Todd, A.M.M., Manickam, J., Okabayashi, M., Chance, M.S., Grimm, R.C., and Greene, J.M., "Dependence on Ideal MHD Kink and Ballooning Modes on Plasma Shape and Profiles in Tokamaks," submitted to *Nuclear Fusion. PPPL-1470* (1978).