ANNUAL REPORT October 1, 1976 to September 30, 1977

PLASMA PHYSICS LABORATORY PRINCETON UNIVERSITY

PPPL-Q-35

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Annual Report

Princeton University
Plasma Physics Laboratory
Princeton, New Jersey

PPPL-Q-35

Covering the Period
October 1, 1976 to
September 30, 1977

Issued January 1979

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Contents

Summary

Many factors combined to delay this report covering fiscal year 1977. In retrospect, it is clear that the work in this year laid the foundation for the rapid progress that occurred in the next. The principal ingredients were: (1) the careful study of impurity control in PLT as well as the installation of neutral beams; (2) the continued progress on fabrication of PDX and (3) the intensive and productive effort on TFTR marked, in particular, by the beginning of actual building construction.

THE PRINCETON LARGE TORUS (PLT)

Work on the Princeton Large Torus (PLT) proceeded during FY77 in two main areas, impurity control and preparation for heating experiments.

Impurtity control occupied a significant fraction of experimental time, with efforts devoted mainly to the control of low-z impurities (such as carbon and oxygen).

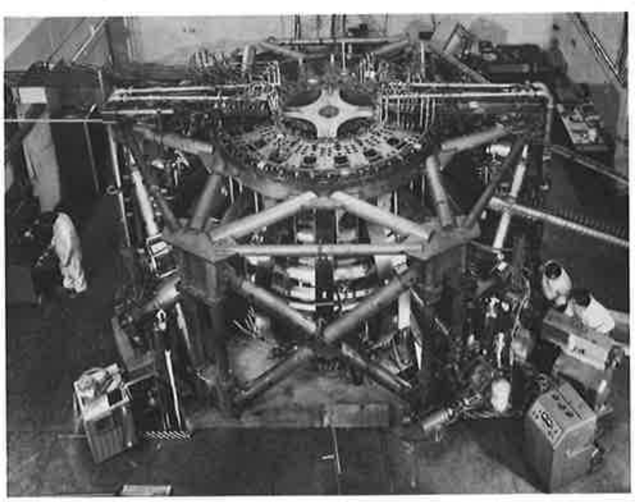


Figure A. The PLT device before installation of neutral beam heating apparatus. A few initial diagnostic systems can be seen on the platform.

In preparation for ion heating experiments to be conducted in FY78, work was carried out on two supplementary heating techniques, neutral-beam injection and ion cyclotron radio frequency (ICRF) heating. Two neutral-beam units, each capable of producing 750 kW at 40 kV of neutral power, were installed. By the end of FY77 all major high power components for ICRF were in place.

POLOIDAL DIVERTOR EXPERIMENT (PDX)

During FY77 Poloidal Divertor Experiment (PDX) project activity consisted primarily of on-site assembly tasks and power testing of the poloidal coil systems. Various problems with TF coil production, which caused a postponement of the target date, were resolved and successful production of TF coil assemblies begun.

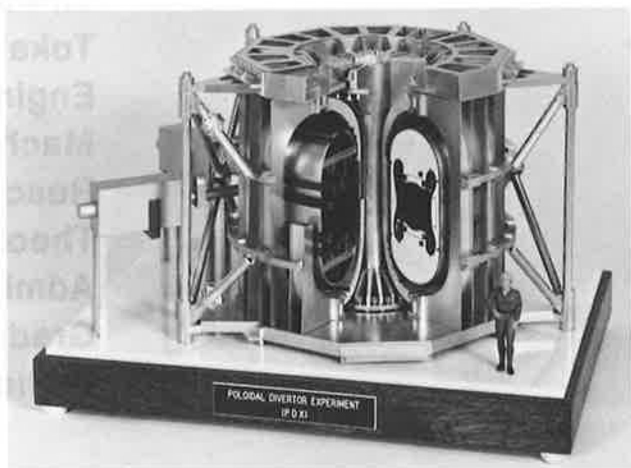


Figure B. A model of the Polodial Divertor Experiment (PDX).

In other areas, plans were designed and submitted to fit PDX with 6 MW of neutral beam heating power. Other research in FY77 included the computer-modeling of equilibrium, stability, transport and divertor operation. This work established the theoretical foundation for the experiments which will be performed during the first year of operation.

DRIVEN TOKAMAK PLASMAS

The PPPL Experimental Division has continued to explore and analyze various reactor related concepts and techniques; these investigations are intended to support the development of tokamak fusion-neutron sources and electrical power reactors.

Work in FY77 concentrated on the design of intermediary fusion devices between TFTR and EPR (Experimental Power Reactor). Proposals were developed for two technological approaches, the superconducting-coil long pulse experiment (LPX), operating in hydrogen and deuterium, and a conventional coil ignition test reactor (ITR). The combination of these two machines could provide the plasma physical and technological basis from which to develop a successful EPR.

PPPL also provided, in conjunction with MIT, the conceptual design for a high-field compact tokamak power reactor (HFCTR).

LINEAR DEVICES

During FY77 PPPL continued to utilize various smaller linear devices to supplement its experimental research into large tokamak operational characteristics.

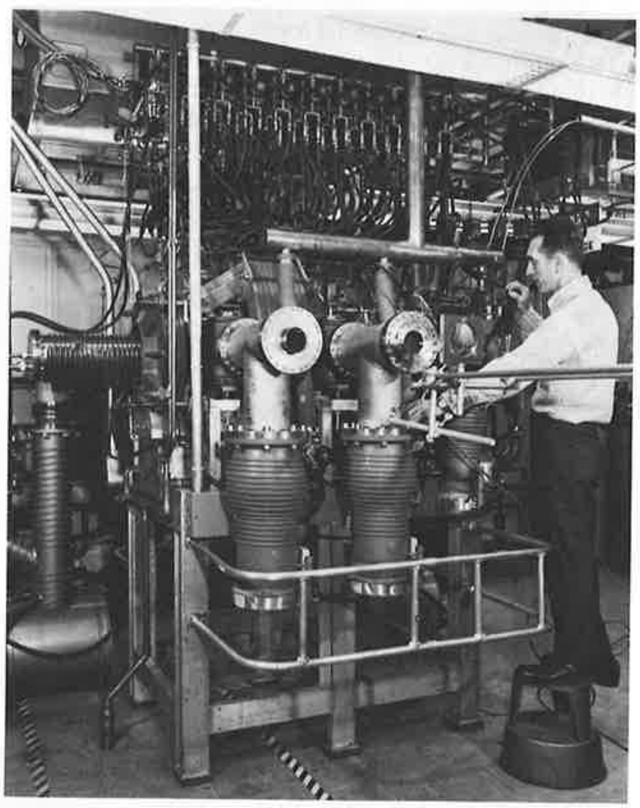


Figure C. Apparatus for the QED-1 plasma gettering experiment.

Detailed work involving plasma waves and their instabilities was performed with the L-3/L-4 and Q-1 machines. The QED-1 device was used to study sticking coefficients and cooling rates of high energy plasma flux. In the COOL experiment, the reduction of axial energy loss in a linear device was demonstrated by means of end stoppering with gaseous and solid plugs, resulting in improvement in plasma energy confinement time up to a factor of five.

THE TOKAMAK FUSION TEST REACTOR (TFTR)

Activity during the report period was marked by procurement progress, start-up of site-construction, finalization of subcontract agreements with Ebasco Services, Inc. and Grumman Aerospace Corporation and development of a management information system.

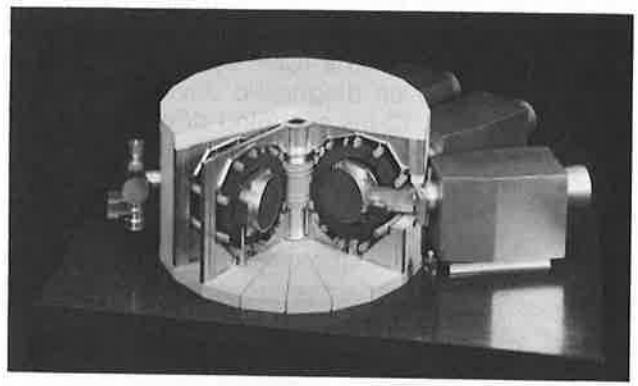


Figure D. Model of Tokamak Fusion Test Reactor (TFTR).

Site design and construction was begun early in the year. Reports and drawings for the Experimental Complex and Motor Generator Building were issued and approved in September. Construction contracts were awarded to PJR Construction Corporation, Santaniello, Inc., and Or-di Construction Corporation.

Two full-scale TFTR mockups were designed and assembled by Ebasco and Grumman in FY77, one modeling a cutaway portion of the tokamak, the other a lower portion and the basement of the TFTR system. Grumman also offered conceptual designs for teleoperator and remote handling operations.

ENGINEERING

Extensive progress was made in the Engineering Division in all its sections during FY77.

In the Electronics Section, an analog data safety link was developed as well as a PLT neutral beam fault detector. Other Electronics Section accomplishments included a PLT neutral injection gas valve driver, a PLT neutral beam flux monitor and a Thomson scattering system for PDX.

The Power Electronics Section pursued the construction of the PLT ICRF system. Also during FY77, this section upgraded the ATC lower hybrid system after which it was loaned to General Atomic for use on Doublet II. An in-depth study of RF power sources and handling techniques for future large machines was also made.

Major work in the Instrumentation Section during FY77 revolved around interferometers; an 8-channel 2-mm microwave system for measuring electron density was completed for PLT. An HCN laser interferometer (⅓ mm) was installed on PLT.

The Mechanical Engineering Section worked in conjunction with the Power Electronics Section towards the manufacture and installation of two half-ton load coils for PLT's ICRF system. In addition, work proceeded on diagnostic devices, including completion of a 10-ms scanning drive for a visible spectrum monochrometer. Extensive modifications were made to the laboratory's main deionized water-cooling system to supply all PLT neutral beam injectors and the test stand.

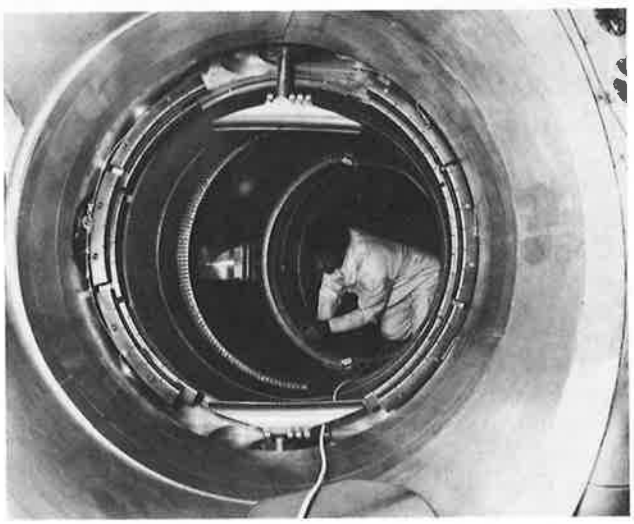


Figure E. ICRF ½-turn coil installation on PLT.

The Power Engineering Section's major accomplishments for FY77 included the completion of the four power supplies, controls and instrumentation for the PLT neutral beam injection system and the fabrication and testing of specialized poloidal field coil power systems for PDX. The availability of the existing basic OH (ohmic heating) power supply was improved and the system was tested at full design capacity as well as at special low current levels required for PDX.

The Data Acquisition Section of the Engineering Division added a considerable amount of new computer hardware and software in support of the increasing requirements for the PLT/PDX data acquisition system.

MACHINE DESIGN AND FABRICATION

During FY77 the various sections of the PPPL MD&F Division were heavily involved in PDX assembly, PLT neutral beam injection work, and engineering support work for the TFTR project.

All poloidal field coils for PDX were installed on the machine and ready for testing by September 1977. The PDX toroidal field coil fabrication at Kaman Aerospace was monitored and supported throughout the year, with the first coil delivered to Princeton in June, 1977.

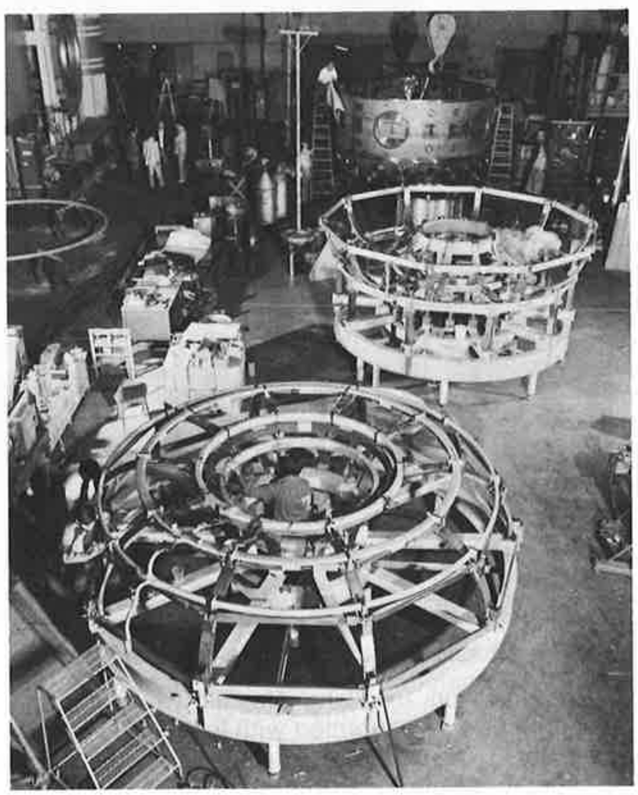


Figure F. Top and bottom PF coil arrays for the PDX machine.

Other major PDX work included the assembly of the substructure and lower shelf; pre-assembly of seven TF coil cases, the torque frame and the upper shelf; assembly of internal elements within the vacuum vessel; and permanent assembly of all PF Coils and the vacuum vessel.

Figure G. Preassembly of PDX outer structure and TF coil cases.

On the PLT machine, MD&F Division staff tested and adapted large turbomolecular vacuum pumps capable of pumping 1,500 liters per second. MD&F technicians fabricated structure, assembled components and connected wiring for the PLT neutral beam power supplies. Support work on the PPPL neutral beam test facility was also provided.

Engineering support was supplied to the TFTR project in the areas of TF coil case design and computer analysis of laminated structures. An eddy current investigation was initiated for TFTR in October 1976 and was still underway at the end of FY77. A magnetic poloidal field design was completed as well as a preliminary study of bundle divertors for TFTR.

REACTOR STUDIES

A two-year investigation was brought to an end in FY77 when the PPPL Reactor Design Division completed its study of tokamak-based fusion-fission hybrid reactors. The detailed report is to be published. Other work included development of a versatile systems analysis code and improvements in several engineering concepts, such as neutral particle transport technique, transport equations for toroidal geometries and improved toroidal field coil designs.

THEORY

The PPPL Theoretical Division's research effort is closely correlated with the various aspects of the experimental tokamak program. The work on MHD equilibrium and stability is also closely interwoven with the TFTR and PDX design efforts. In addition, computations have been performed for the Joint European Torus (JET) program.

After four years of effort, the Princeton Equilibrium Stability and Transport Code became operational and was published in FY77, providing an effective tool for studying the MHD spectrum and the stability properties of tokamaks.

To investigate one of the most serious threats to tokamak operation, axisymmetric instability, the Division developed a two-dimensional, time-dependent, nonlinear ideal MHD code in FY77. Other work in the MHD area included the refinement of the theory of resistive MHD instabilities in a torus and the development of a series of codes for treating ideal MHD and resistive problems in two dimensions.

One of the major efforts of FY77 was to increase the accuracy and generality of calculations of the linear growth rate and two-dimensional structure of trapped-electron and drift modes.

In the area of divertor theory, features of the divertor scrape-off were investigated. In work relating to lower-hybrid heating, the emphasis during FY77 was on prediction of the spatial disposition pattern of the rf energy, the percentage absorbed by ions and electrons and the important parameters to manipulate for optimum heating.

Figure H. Construction at C-site, Plasma Physics Laboratory. TFTR site is at upper left.

ADMINISTRATION

Fiscal year 1977 was one of continued growth for PPPL. The Laboratory's full-time staff rose by approximately 150. The rapid growth of the last few years necessitated a strengthening of lines of communication between management and staff.

In preparation for major research with TFTR, PPPL has embarked on a major program of expansion and construction. During FY77 an additional 16,420 gross sq. ft. were added to the Laboratory's facilities. Construction work was begun on TFTR facilities, including the 60,000 sq. ft. Office and Laboratory Building. The Library also reflected the heightened activity at PPPL by its increase in journals, reports, special services, and interlibrary loans.

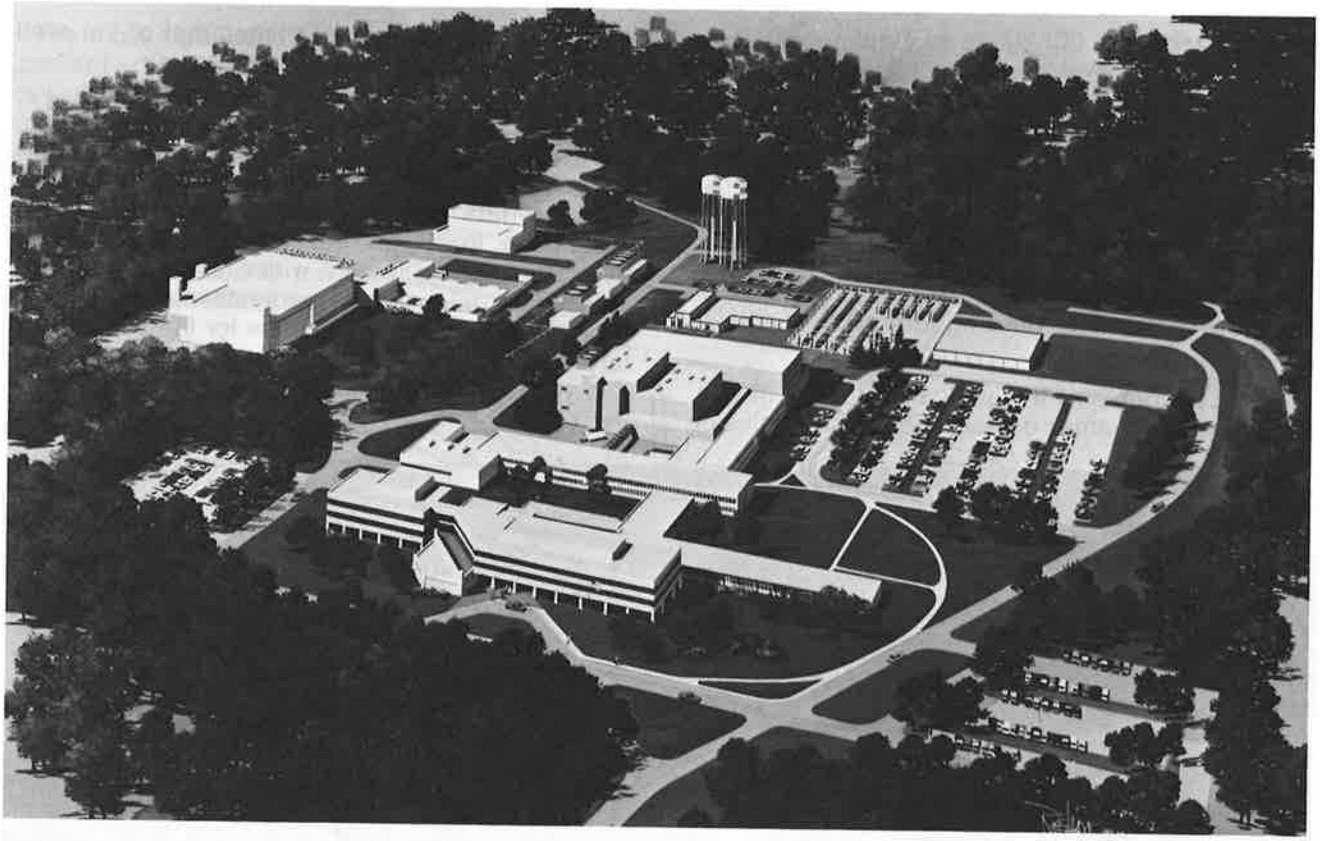


Figure I. Artist's drawing of TFTR and support facilities, Princeton Plasma Physics Laboratory.

Princeton Large Torus (PLT)

OVERVIEW

The Princeton Large Torus (PLT) is a toroidal confinement device of the tokamak type. The major objectives of PLT are to investigate:

- Plasma confinement scaling with size
- Large plasma heating, utilizing ohmic, neutral beams and radio frequency (rf) concepts and techniques
- Plasma behavior utilizing extensive diagnostics.

The PLT represents a significant increase in size over previous tokamak devices. The minor radius of the torus is more than four times that of the predecessor device, the Symmetric Tokamak.

MAJOR ACTIVITIES

The main thrust of the FY1977 program has been to investigate more systematically the role of impurities, i.e. to vary and especially to lower the effective ion charge (Z) over a wider range of densities. This effort will enhance understanding of how to produce proper target plasmas for the supplementary heating with neutral beams which was begun this year and which should yield significant results in FY78.

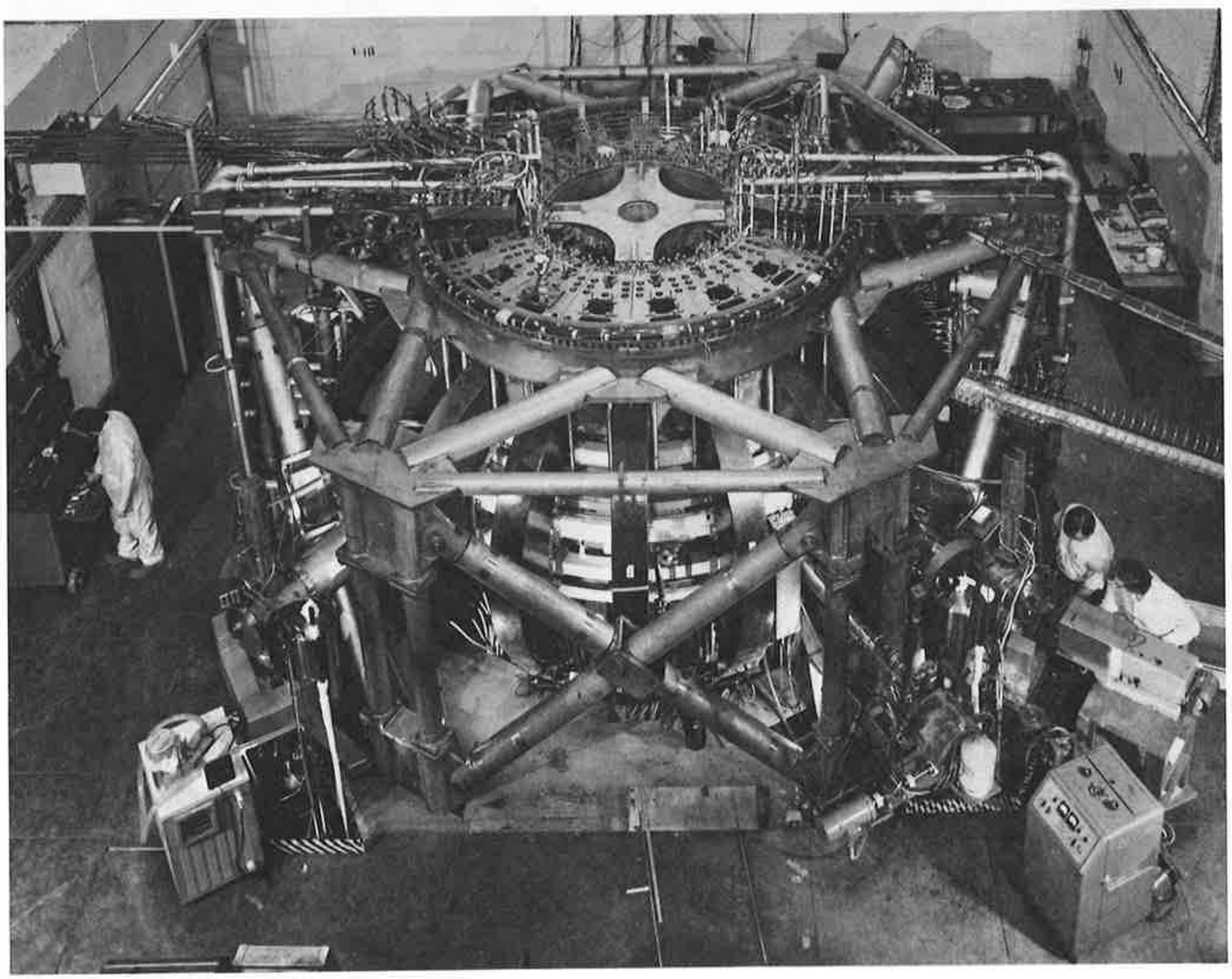


Figure 1. The PLT device before installation of neutral beam heating apparatus. A few initial diagnostic systems can be seen on the platform.

The most significant sources of low-Z impurities (primarily oxygen and some carbon) are: (1) Materials like water vapor and hydrocarbons that are rather loosely bound to the surface of the vacuum walls; (2) carbon/oxygen combinations which are embedded in the body of the wall materials; and (3) oxides of the metals in the walls.

The sources of heavy impurities (i.e. iron, chromium, nickel and tungsten) are the stainless steel walls themselves and the aperture limiters.

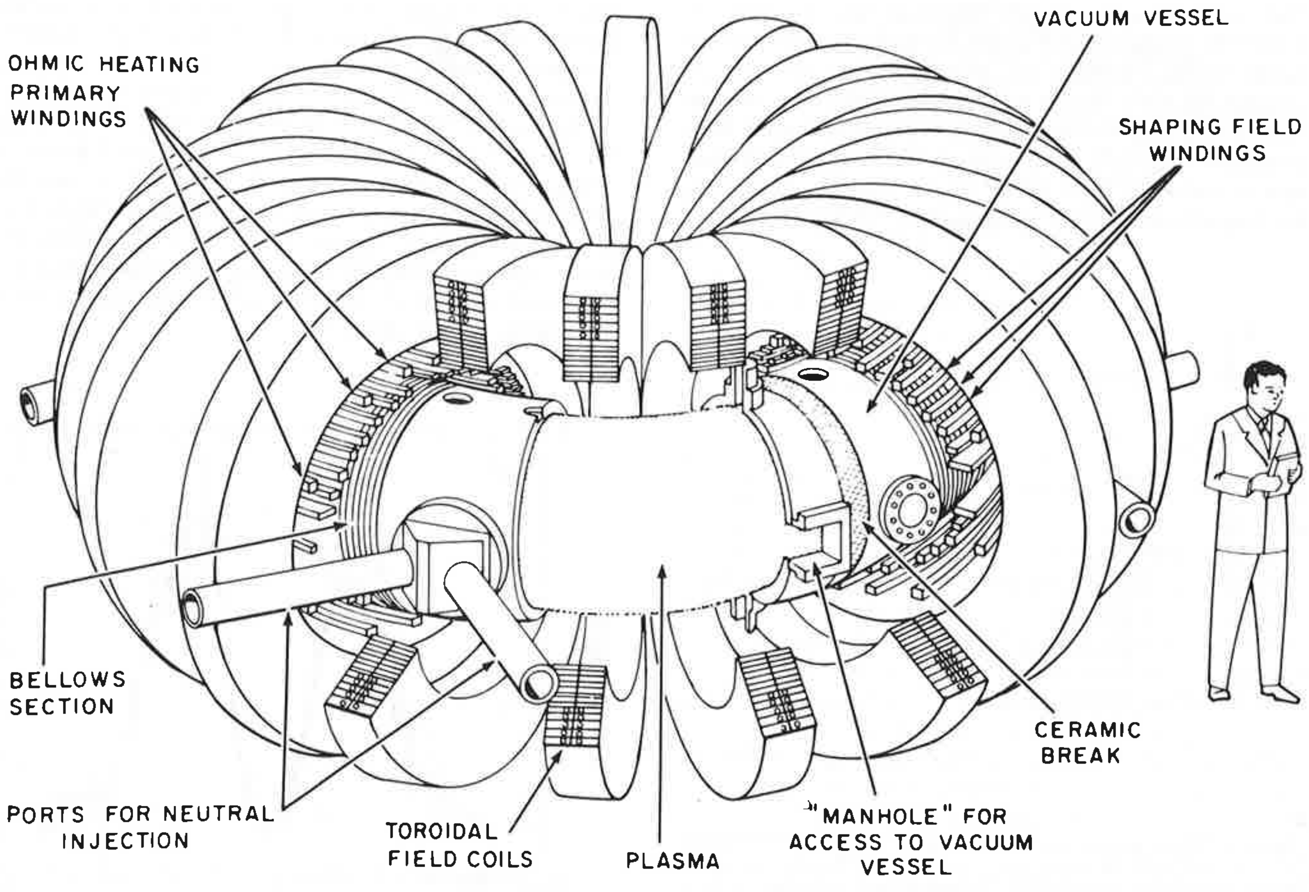


Figure 2. Schematic of the PLT.

In the discharges of late 1976, oxygen was identified as the most significant impurity affecting plasma properties (i.e. resistivity, radiated power, degradation of the electron density). Initially, light impurities were removed from the torus wall by discharge cleaning with short intermediate-current pulses. These pulses were at a current level high enough in energy to produce full impurity ionization and temperatures of about 100 eV. The molecules containing oxygen were completely dissociated with the oxygen being mostly deposited back on the walls during and after the discharge. Additionally, some of the oxygen combined with hydrogen to form water vapor which was removed down the vacuum pump lines; however, the rate of water vapor removal was rather slow. Subsequently, in 1977, the low power discharge cleaning method used by R. J. Taylor (MIT and UCLA) and R. R. Parker (MIT) was adapted for use on PLT. With this method, because of the low temperature, small fractional ionization, and fast pulse repetition rates more oxygen combines into water vapor and is subsequently pumped out. Table 1 summarizes the characteristics of the "old" and "new" methods, also called Pulse Discharge Cleaning (PDC) and Taylor Discharge Cleaning (TDC), respectively.

TABLE I

Date	Magnetic Field	Discharge Current	Repetition Time	Designation	% Impurities in High Power Discharges After Cleaning	
					Oxygen	Carbon
1976	101G	50-100kA	10 sec	PDC	7.5%	1.2%
1977	5kG	5- 10kA	1 sec	TDC	1.0%	0.7%

The difference in oxygen removal rate for the two methods is shown in Figure 3. Here the pressure of water vapor (a measure of the rate of removal of oxygen by the vacuum pumps) is plotted for various conditions. When the method is changed from TDC (interval c) to PDC (interval e), the oxygen removal rate is reduced by a factor of 15; the rate returns to the higher value when TDC is resumed (interval f).

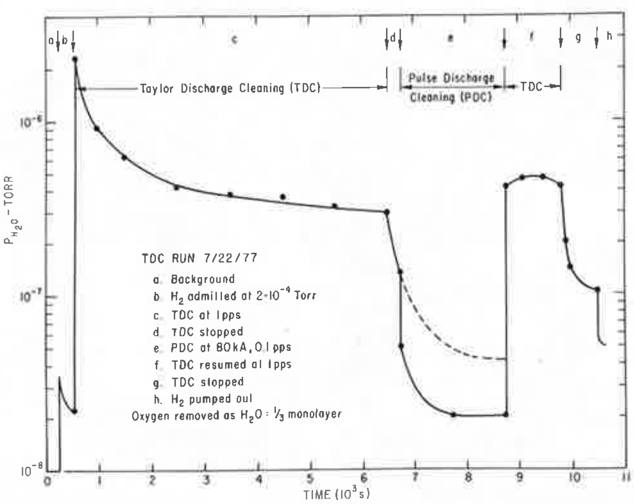


Figure 3. Partial pressure of water vapor at the vacuum pumps as a function of time for two types of discharge cleaning. Since the goal of discharge cleaning is to remove primarily oxygen from the vacuum vessel by forming and pumping out water vapor, higher pressures of H_2O are desirable. Note that TDC (Taylor Discharge Cleaning) produces water, but PDC (Pulse Discharge Cleaning) provides little more than background.

PROGRESS THIS PERIOD

Low temperature discharge cleaning has reduced markedly the fractional amount of low-Z impurities in the regular high current, high temperature plasmas. Reduction of low-Z impurities tends to be accompanied, however, by an increase in high-Z metallic impurities from the walls and limiters (previously observed in the ST, ORMAK, and ATC Tokamaks). Evidence of this increased influx of high-Z atoms is shown in Figures 4, 5 and 6. Figure 4 shows the shrinking effect on the electron temperature profile: the upper profile, taken just after TDC, shows the temperature in the center being less than that at the intermediate radii, the so called "hollow" profile, first observed in ORMAK.

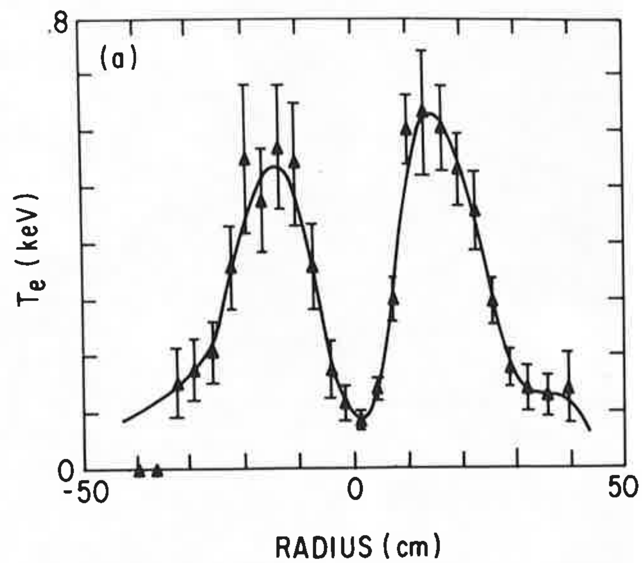
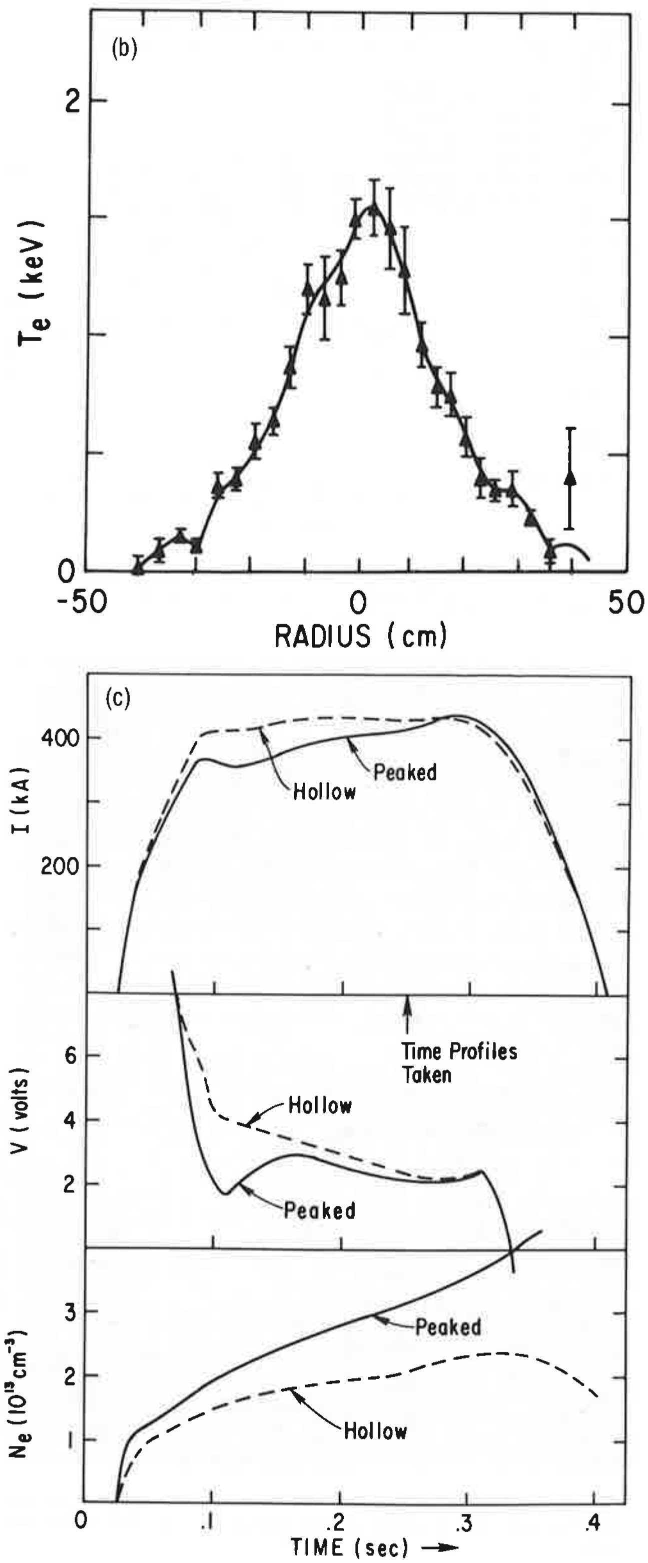


Figure 4. Two qualitatively different types of plasma discharges can be obtained in PLT, named "Hollow" and "Peaked." Plot (a) shows the hollow electron temperature profile, which is most easily obtained immediately after TDC. Plot (b) shows the normally expected peaked temperature profile. Note the large difference in plasma current, voltage and density for the two cases as shown in Plot (c).



It can be postulated that the "hollow" profiles are the result of large power losses due to radiation from partially ionized metallic ions. As shown in figure 5, there are large radiation losses; here the power radiated per unit of plasma volume is plotted as a function of radius and time.

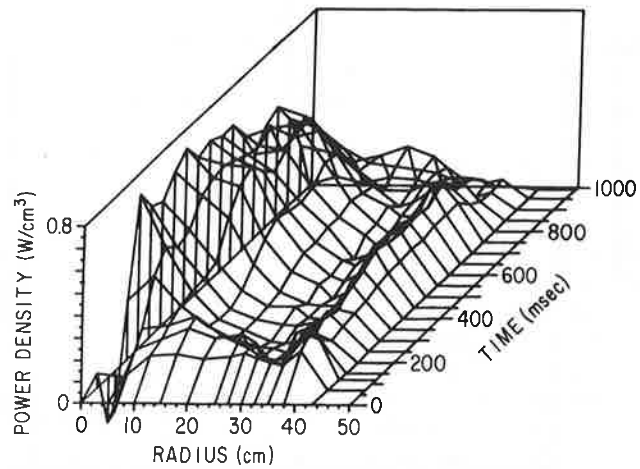


Figure 5. Bolometrically measured power radiated per unit volume in PLT as a function of radius and time for a discharge with "hollow" electron temperature profile. The large radiation from the center contributes to the collapse of T_e in the center.

The power densities are determined from bolometric measurements of energy deposited at a representative place on the vacuum wall. Extrapolated from the whole wall, the data show that almost all the input power is radiated. The radiated power density is concentrated in the center, in contrast to light-impurity dominated discharges where the radiated power is concentrated near the outer edge.

Evidence that the actual source of the radiation is tungsten, the limiter material, is shown in Figure 6, in which is plotted the spectral form of radiation in the 30Å-80Å region, measured with a grazing incidence vacuum ultraviolet spectrometer. The spectral shape corresponds closely with bands of tungsten line which have been discovered at the Naval Research Laboratory and Oak Ridge National Laboratory, and whose wavelength and approximate intensity have been calculated theoretically by Cowan, et al., at the Los Alamos Laboratory.

"Good" plasma (peaked profile, high temperature, long containment) can be produced without the presence of low-Z impurities, as illustrated in the lower profile of Figure 4; this is achieved by very careful programming of the flow of hydrogen gas

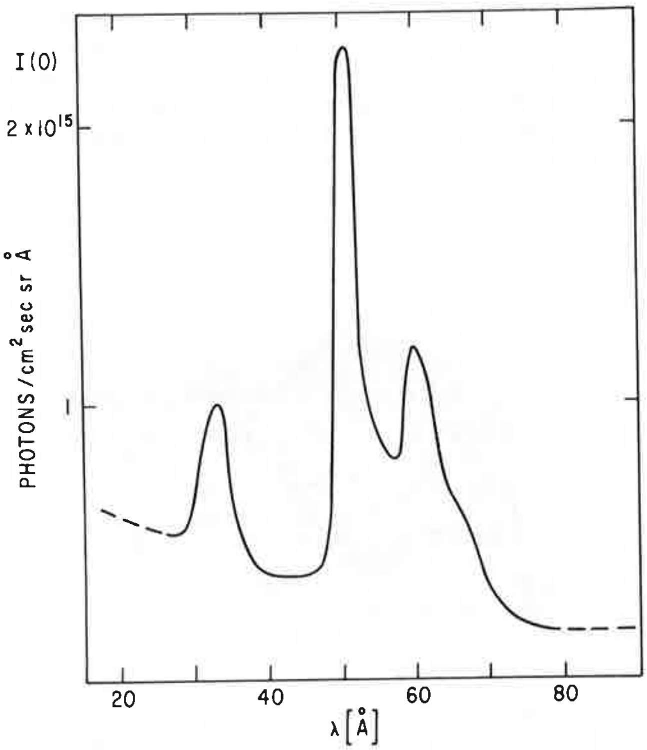


Figure 6. Spectral scan in the 30-80 Å region by the grazing incidence UV spectrometer. A large fraction of the power radiated by PLT is in these bands of unresolved lines, which have been identified as tungsten lines.

before and during the discharge. (The difference in ordinate scale between the hollow and peaked cases is evident in Figure 4.)

There is evidence that in the hollow-profile discharges the edge of the plasma is hotter than in the peaked discharges and that this leads to a greater influx of tungsten either because of increased sputtering by fast ions hitting the limiter or because of increased formation of unipolar arcs on the limiter due to higher plasma sheath potential. Low-Z impurities can cool the plasma edge region by radiation and so inhibit the influx of tungsten. In the same way a high flow of the main gas, hydrogen, deuterium, or helium, can keep the edge cool enough during the important early stages of the discharge while the current and electron temperature are building up in the central core of the plasma.

Energy confinement times obtained after TDC for peaked discharges in helium are shown plotted against linear-average density in Figure 7.

The highest values are $\tau_E \sim 70$ msec, compared with $\tau_E \sim 50$ msec observed previously (Figure 8).

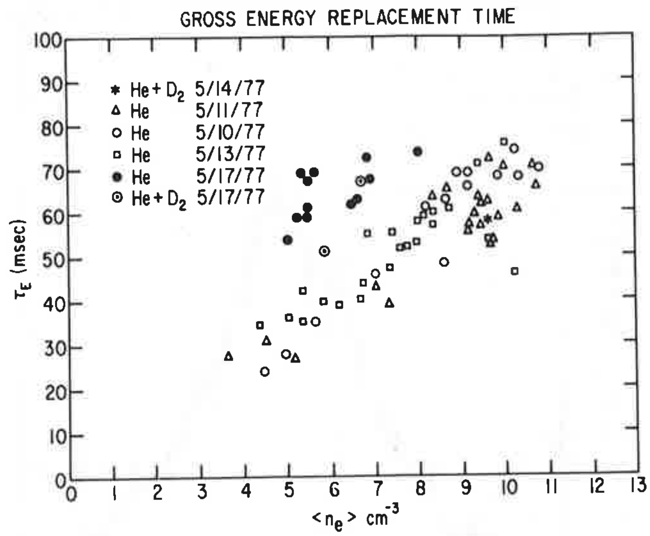


Figure 7. Total energy confinement time τ_E plotted against line averaged density for several helium discharges after TDC.

The confinement times are longer at higher electron density, but the scaling with various plasma parameters is complex and has not yet been determined. Energy transport through the electron channel is definitely faster than predicted by neoclassical theory; energy transport through the ion channel is closer to that predicted theoretically, but both theory and experiment are inaccurate enough to allow a significant anomalous loss.

The study of MHD instabilities has continued in an effort to understand the cause of the disruptions which at present limit the maximum values of current density in the plasma. No unique cause, or precur-

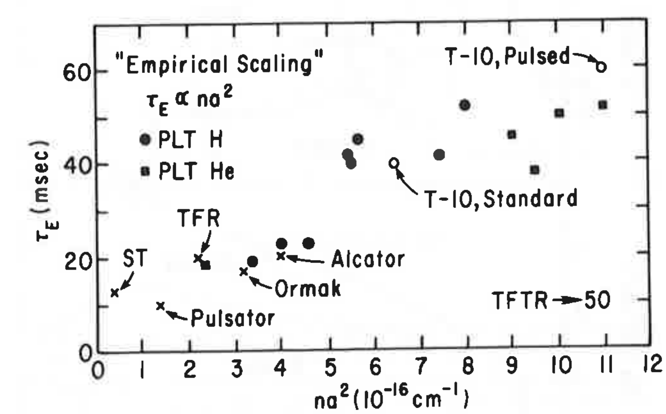


Figure 8. Energy confinement time vs $n_e a^2$, where n_e is the average density and a is the limiter radius. PLT points taken after PDC.

sor event, has been found for major disruptions. Examples have been observed having the following characteristics: (1) the q=2 surface is at large radius and m=2 MHD oscillations (and the disruption) propagate from the q=2 surface; (2) there is vertical asymmetry and an overlapping of m=1 and m=2 oscillations; and (3) there is a fast ($\sim$100 μsec) rise in power radiated from high-Z impurities. None of these, however, constitutes a necessary or sufficient condition by itself for a major disruption.

Supplementary Heating

In addition to the regular ohmic heating, work is progressing on two supplementary heating methods designed to heat ions more directly than through electron-ion collisions: neutral beam injection and ion cyclotron resonance heating.

At the end of FY77 two neutral hydrogen beam injection heating units, each capable of supplying up to 750kW at 40 kV of neutral power for heating the plasma, were installed on PLT. These injectors, made and tested at ORNL (Figure 9), will be joined by two more units in FY78, and neutral injection heating will receive an important test. Preliminary results include:

(1) At moderate density an ion temperature increase from 1 keV to 2.2 keV, but because of impurity influx and increased radiation losses, no electron heating;
(2) At higher density an increase of both ion and electron temperature of $\sim$40%;
(3) Observation of predicted slowing of injected beam particles;
(4) Predicted plasma rotation when only one direction of beam injection is used.

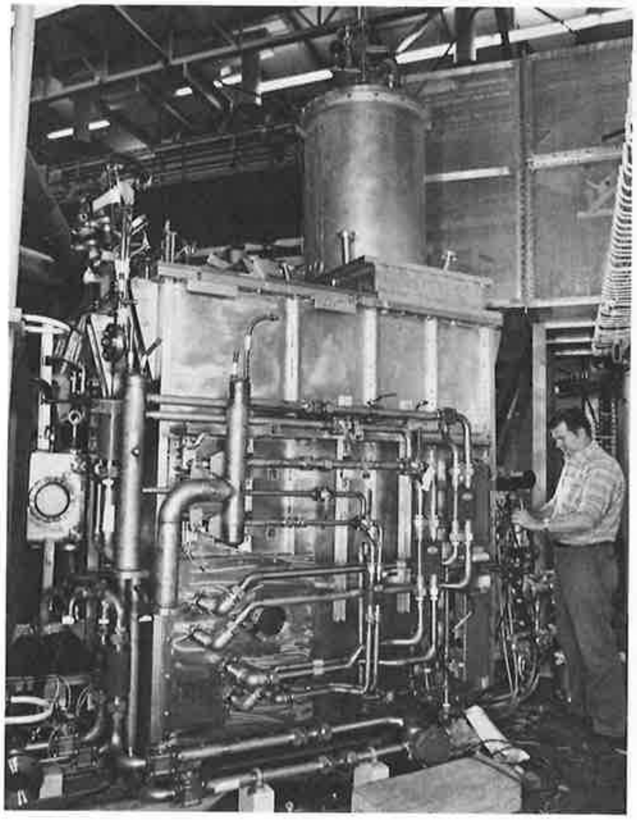


Figure 9. PLT's first neutral beam injection system being assembled on the PLT platform.

Preparations for supplementary heating by radio frequency power near the ion cyclotron frequency have proceeded rapidly during FY77. The $3.7M project to apply up to 5MW of power to PLT is scheduled for completion of the first 2.5MW system in October 1978 and the second 2.5MW system in November 1979. Figure 10 shows all major high power components in place on September 29, 1977.

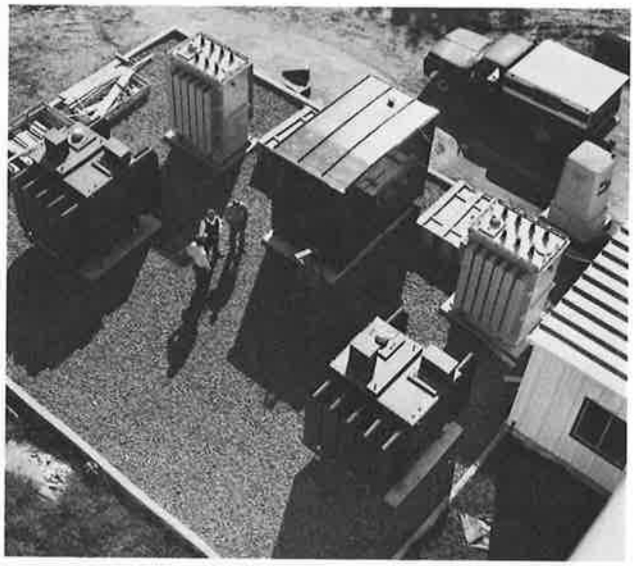


Figure 10. The major high power components for a 5-MW radio frequency heating system to be used on PLT in FY79.

Poloidal Divertor Experiment (PDX)

OVERVIEW

The Poloidal Divertor Experiment, scheduled to begin operating in the fall of 1978, is a tokamak-type device (see Figure 11) which will support development and testing of conceptual techniques expressly designed to limit and reduce the amount of plasma-transported foreign materials (impurities) within a torus. PDX will employ magnetic fields to control the size and shape of the plasma. In addition, PDX will utilize magnetic coils, called poloidal divertors, within the torus-shaped vacuum vessel to divert both escaping plasma and wall-evolved impurities to separate remote burial chambers.

PDX is a larger, more flexible device than the Princeton Large Torus (PLT) machine and has been designed to explore physics phenomena encountered or detected by PLT. The PDX goals are:

1. The achievement of reactor-like plasma parameters,
2. Development and determination of effectiveness of poloidal divertors, magnetic limiters and other techniques for controlling impurities in large, high-temperature, collisionless tokamak plasmas.
3. 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.
4. Exploration of the MHD β limit as a function of plasma shape and profile.

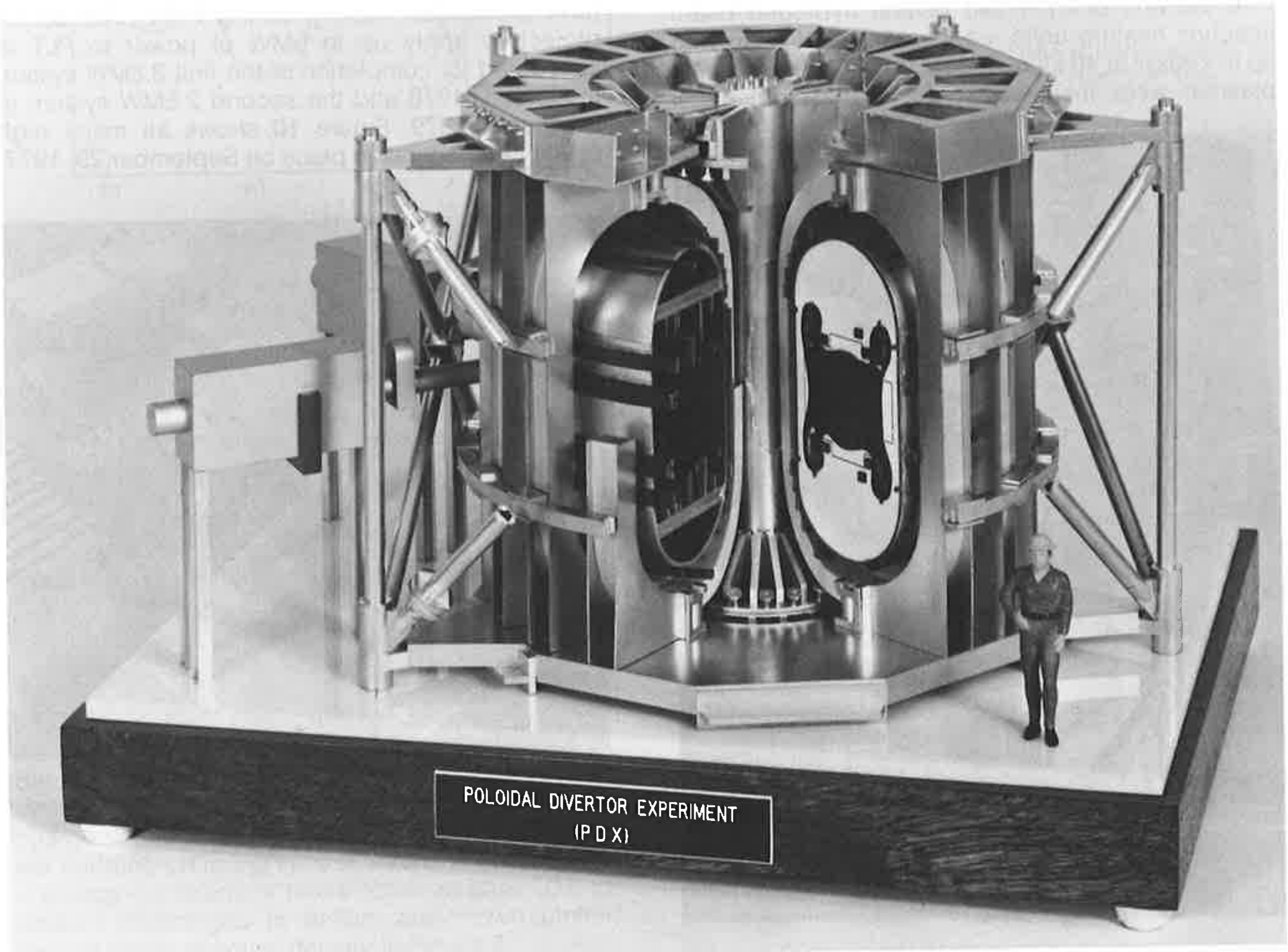


Figure 11. A model of the Polodial Divertor Experiment (PDX).

5. Determination of confinement scaling parameters as a function of collisionality from present day plasmas to reactor-like plasmas by divertor control.
6. Production of substantial fusion reactions.

PDX has a major radius of 140 centimeters, and a minor radius, depending on the choice of configuration, of approximately 45 centimeters. The maximum toroidal field is in the range of 20 to 30 kG, again depending on the configuration (see Figure 12). An OH current of 500 kA will provide the initial heating.

The PDX device, with a 6 MW neutral beam heating system, is predicted to be capable of producing plasmas with temperatures of 5-10 keV, densities in the range of 10^{14} cm^{-3}, and $n\tau$ in the range of 10^{13} to 10^{14} cm^{-3} sec. In addition the power density deposited on the walls and limiter of PDX should be typical of that in a reactor.

Economically attractive tokamak fusion reactors will need betas in the range of 5 to 10%. PDX will seek to maximize beta by optimizing the plasma shape (e.g., elongated D shapes) and plasma profiles (e.g., broad current and temperature profiles). The poloidal divertor is used to control the plasma wall interaction thereby allowing broad profiles; at the same time, the divertor fields produce the desired cross-section shaping.

When deuterium beams are injected into deuterium plasmas PDX will produce $\simeq 10^{15}$ neutrons per pulse or the equivalent of $\simeq 1$ kilowatt of thermonuclear power.

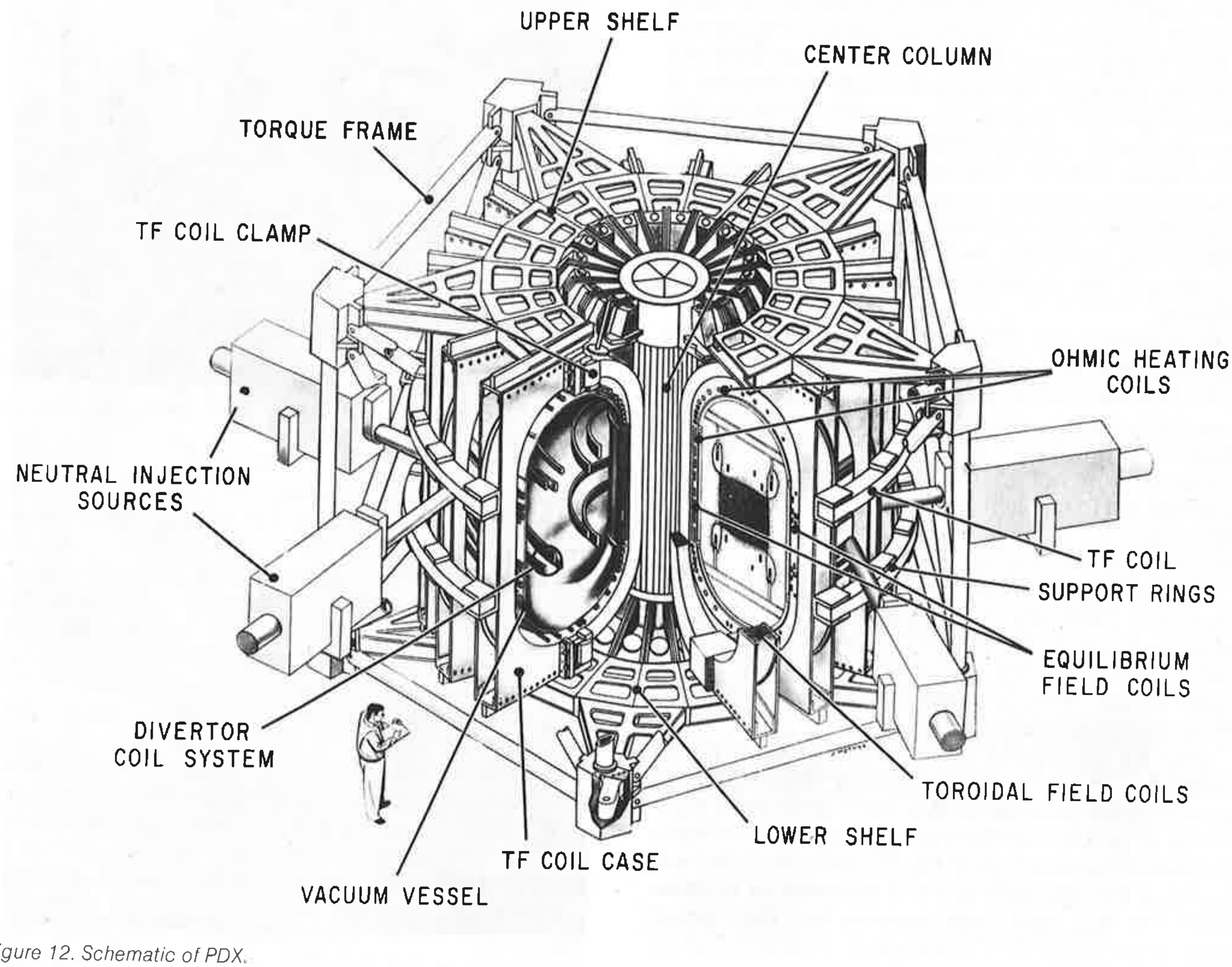


Figure 12. Schematic of PDX.

MAJOR ACTIVITIES

During FY77 PDX project activity consisted primarily of onsite assembly tasks and power testing of the poloidal coil systems. Tolerance problems experienced by the TF coil vendor have been resolved by tooling changes and modifications to the insulating scheme. The contract with the vendor was renegotiated and successful production of TF coil assemblies begun.

The problems encountered with the TF coil fabrication have resulted in program delays: the project completion date is now November 1978, compared to October 1977 in previous plans.

In preparation for PDX assembly, the ATC and FM-1 devices were dismantled and three sides of the radiation shield wall were assembled. The lower shelf was delivered by the vendor in March 1977 and erected on top of six support pylons (see Figure 13).

After alignment and leveling of the lower shelf, the external poloidal coil systems were assembled in four subgroups. These coil groups surround the vacuum vessel and are installed in stages. First the lower array and the solenoid section were assembled, then the vacuum vessel was lowered over the solenoid, then the outer and upper coil arrays were installed to complete the subassembly. This was followed by the installation of the bus and cooling systems.

Power tests of all of the poloidal coil systems were carried out at full rated current for each of the circuits. The full current tests of the individual circuits were followed by a combined test of all poloidal coil systems at one half the rated current (Figure 3), a limitation due not to the coil systems or power supplies but to the availability of primary power. The installation of a new transformer (scheduled for March 1979) will remove this limitation.

The coil and power supply systems performed as expected; thermally the coil temperature changes were very close to calculated values. The measured coil deflections were typically one-half the calculated values, reflecting some conservatism in the modeling of laminated structures.

After the successful conclusion of the PF power tests, the machine was partially disassembled (primarily for removal of bus work and water manifolds) in preparation for the installation of the toroidal field coils (see Figure 14). TF coil installation will continue through most of FY78 followed by installation of PF bus and water systems and then power tests of all systems. Commission is scheduled for November 1978.

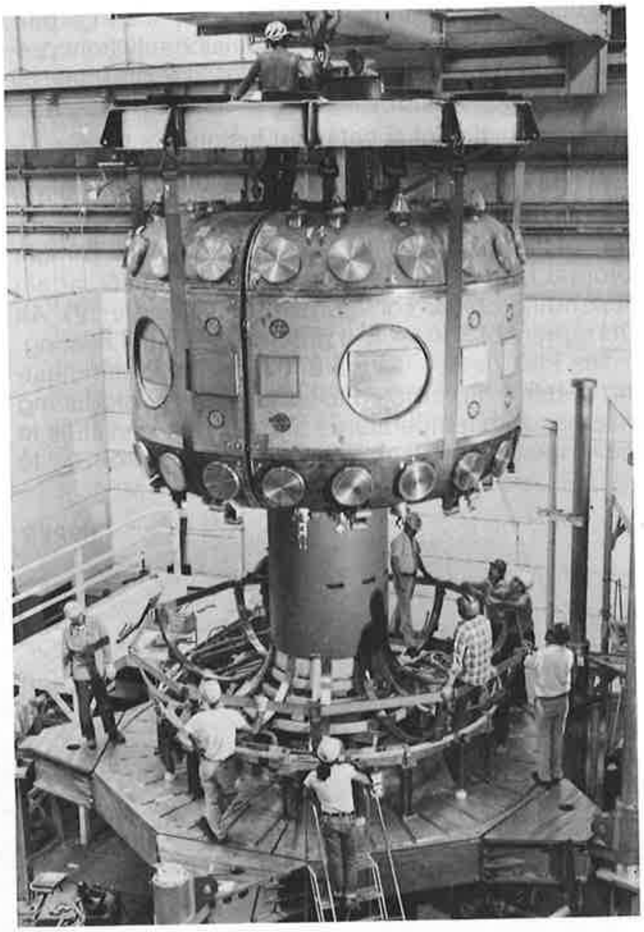


Figure 13. Placement of the 22-ton PDX vacuum vessel over the OH solenoid and lower coil array.

Preparations for experimental operation of PDX continued in parallel with the fabrication program throughout FY77, the most urgent task being that of planning for PDX auxiliary heating by neutral beams. While successful tokamak operation of PDX is expected with ohmic heating alone, auxiliary heating will be essential to achieving the primary objective of evaluating the effectiveness of poloidal divertors for controlling impurities in large reactor-like tokamaks.

Neutral beams are the only tested method of raising the electron density and the plasma temperature to the desired range. Electron densities approaching 10^{14} cm^{-3} are required for the operation of a shielding divertor (one which would reduce impurity input into the tokamak plasma by several orders of magnitude while simultaneously extracting impurities from the plasma core and refueling the plasma). Temperatures of 2 to 5 keV will be needed so that plasma-wall interactions and plasma transport into the divertor will simulate the behavior of reactor-like plasmas. Also neutral beam injection and cross-section shaping will allow PDX to explore the MHD β limit.

A neutral beam system was specified in the original PDX plan as a necessary upgrade after initial ohmic heating operation. Proposals were submitted to DOE in FY77 for a neutral beam system capable of 6 MW injection power.

Other PDX research of FY77 included the computer-modeling of equilibrium, stability, transport and divertor operation. This work, some of which is briefly described in the following paragraphs, established the theoretical foundation for the experiments which will be performed during the first year of operation.

Extensive computations of MHD equilibrium and stability were done for the initial configuration of PDX and for a hypothetical elongated plasma modification designated as PDX-M. Results indicated the importance of conductors near the plasma surface, or of conducting pressureless plasma at the hot plasma boundary. Betas of $\simeq$ 4% and 9% were the maximum values stable to ballooning modes in PDX and PDX-M, respectively. Computations are underway to determine the optimum pressure and current profiles as well as plasma shape for maximizing beta.

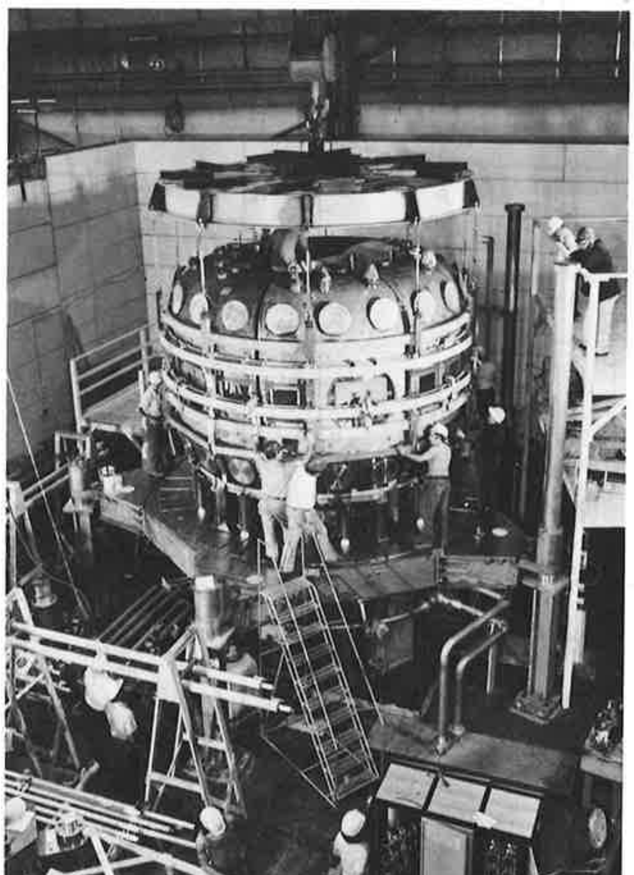


Figure 14. Positioning of the PDX PF outer coil array over the vacuum vessel.

Transport calculations of neutral beam heating in PDX indicated that 6 MW of 50 keV hydrogen beams would heat PDX plasma to a beta of $\simeq$ 4% under assumptions of empirical electron transport and of ion transport given by neoclassical scaling.

The susceptibility of PDX to axisymmetric MHD instabilities was studied by use of a dynamic nonlinear code. It was found that the standard PDX configurations are stabilized by connecting top and bottom divertor coils in parallel. This passive stabilization lasts for $\simeq$ 100 ms at which time a low frequency feedback system must take over. The specifications for this feedback system will be determined by mid FY78.

Diagnostics in preparation for the first year's operation include Rogowski coils, microwave interferometers, an x-ray pulse height analyzer, residual gas analyzer and surface analysis station, Thomson scattering, ultraviolet and visible light during start-up, TV monitor for infrared radiation from the limiter and divertor neutralizer plates, and multi-channel bolometer arrays.

The need for impurity control has been made evident by experience with stellarators and early tokamaks. In the case of PLT, initial low power operation during FY77 produced hydrogen plasmas with substantial impurity content which, however, could be controlled by gettering. Subsequent higher power ohmic heating and neutral beam experiments on PLT should quantify the magnitude of the impurity problem on large tokamaks operating at high density and high temperature. If the results continue to indicate the need for strong impurity control, then PDX will be able to contribute signficantly to an essential aspect of the design of ignition tokamak reactors of the late 1980's.

Driven Tokamak Plasmas

OVERVIEW

The PPPL experimental division has continued to explore and analyze various reactor related concepts and techniques. The subjects investigated were intended to support the development of tokamak fusion-neutron sources and electrical power reactors. These subjects included scoping studies of large machines that might follow the TFTR in the U.S. fusion program, plasma engineering studies including the conceptual design of special reactor subsystems, and the conception and design of relevant experiments for present-day tokamaks. The results of these studies are summarized briefly in the following paragraphs:

Development of Tokamak Power Reactors

An experimental power reactor (EPR) must call on many new technologies, each representing a large advance from present practice. Rather than immediately attempting the construction of an EPR, a less risky approach is the earlier implementation of a superconducting-coil long-pulse experiment (LPX) operating in hydrogen and deuterium, together with a normal-coil ignition test reactor (ITR). The combination of these two smaller machines would provide the plasma physical and technological basis from which to develop a successful EPR. The basic parameters for potential configurations of the LPX and the ITR have been determined during this report period.

One configuration of the ITR emphasizes small aspect ratio and small major radius with no central plasma current transformer (See Figure 15). Start-up of the plasma is achieved by a neutral-beam induced current together with optimized usage of the equilibrium-field flux swing. Figure 16 presents an illustrative start-up scenario.

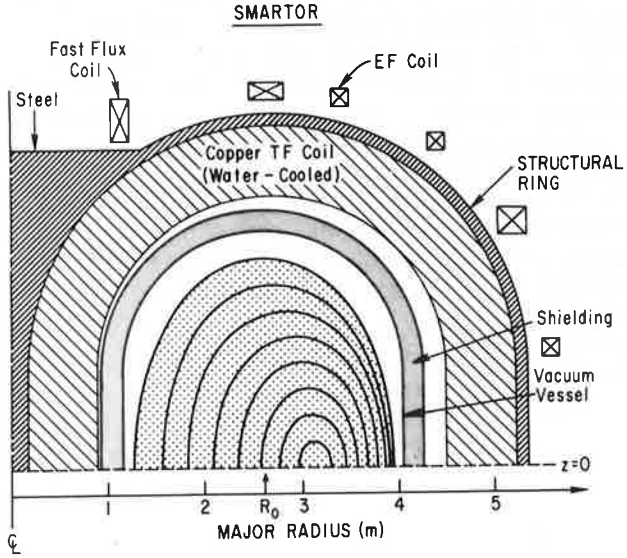


Figure 15. Ignition Test Reactor (ITR) configuration.

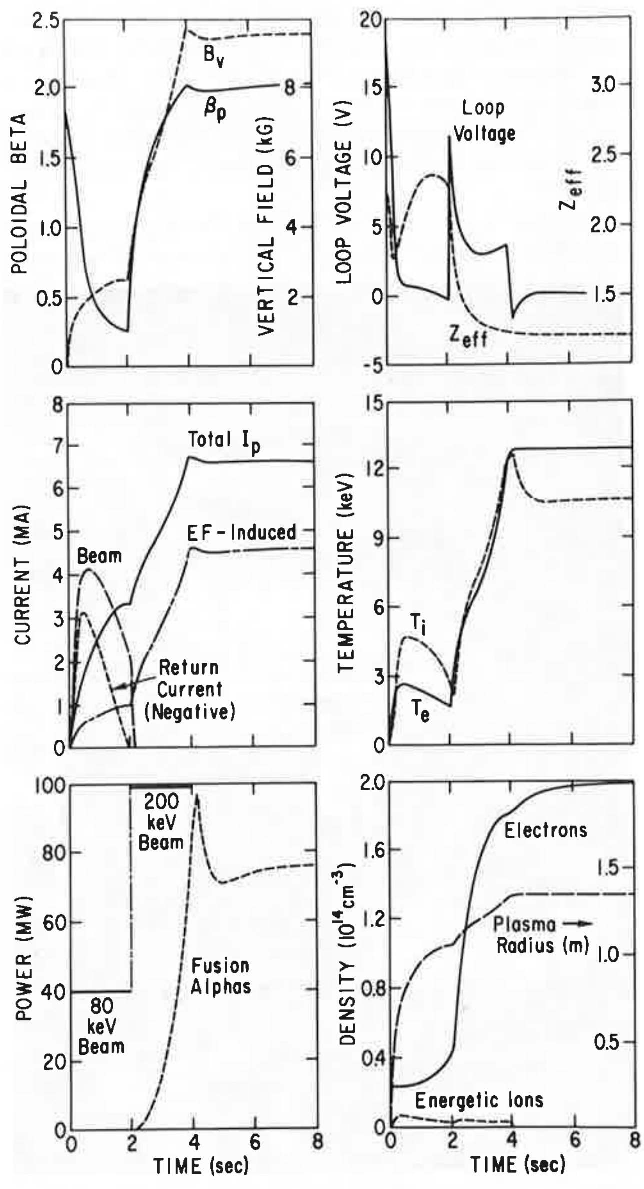


Figure 16. Ignition Test Reactor start-up scenario.

In another configuration of the Ignition Test Reactor, PPPL provided assistance to the Massachusetts Institute of Technology in the preconceptual design of a very-high-field, Bitter-magnet machine. The high field is expected to allow ignition in a low-beta circular plasma, while still at a small major radius.

These scoping studies make use of an empirical scaling for the energy confinement time, τ_E, that was derived from results obtained for tokamaks with plasma radii between 8 cm and 40 cm, as illustrated in Figure 17. This scaling of confinement time is valid only for the ohmic-heated regime, however, and is usually divided by a "safety margin" to compensate for a possible (though still only conjectured) degradation of confinement time in higher temperature plasmas maintained by neutral-beam injection or fusion alpha particles.

The conceptual design of a high-field compact tokamak power reactor (HFCTR) was also carried out with M.I.T. The HFCTR features high-field Nb_3Sn toroidal field coils (13.1 T at the windings), resulting in sufficiently high fusion power density (7 MW/m³) at moderate beta ($<\beta> = 0.042$), so that the major radius is just 6.0 m. (5).

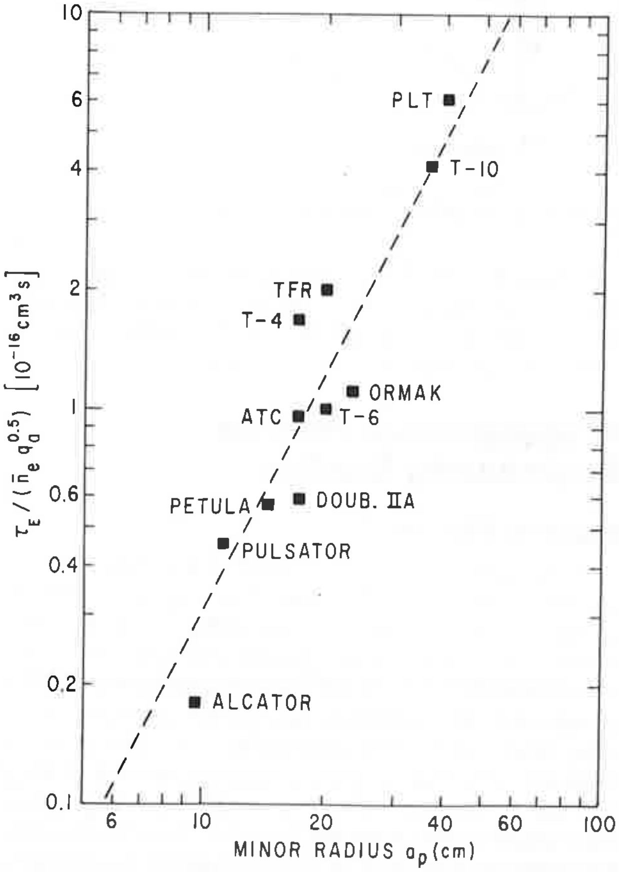


Figure 17. Energy confinement times of various tokamak configurations.

A study was also made of the possibility of obtaining ignition conditions in a tokamak plasma using "advanced fuels". It was found that specially tailored temperature and density profiles allow ignition of catalyzed-D or $D-{}^3He$ plasmas with $<\beta> \simeq 0.09$, and with a magnetic field at the TF coil windings of 15 to 16 T, giving fusion power density $\simeq$ 1 W/cm³, first-wall power loading $\simeq$ 1 MW/m², and a device major radius of about 8 m. Figure 18 shows how the $\bar{n}\tau_E$–T conditions for the catalyzed-D system depend on the plasma profiles.

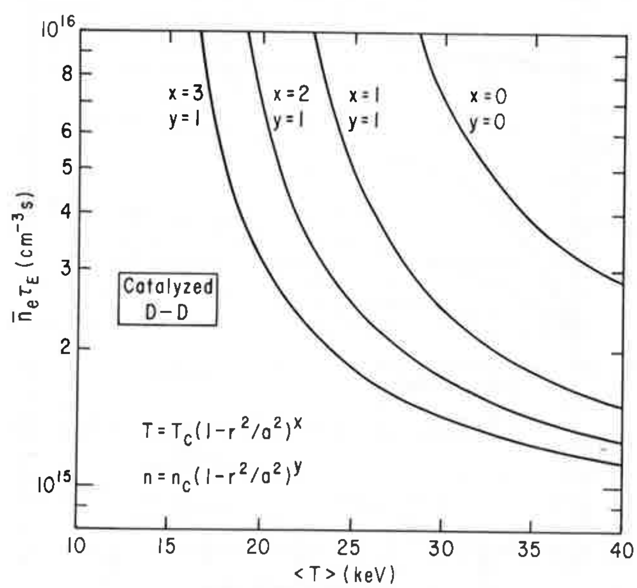


Figure 18. Plasma profile effects on catalyzed-D system conditions.

Beam-Driven Tokamak Neutron Sources

The PDX device when operating with an unload magnetic divertor and intense neutral-beam injection, will serve as a prototypical intense fusion neutron source. The optimal plasma operating conditions for maximizing fusion-neutron production in PDX plasmas have been determined with the aid of a Fokker-Planck/transport code developed by the MFE Computer Center in Livermore. For a given beam power, the largest neutron flux is obtained at lower plasma density, namely $n_e(0) \simeq 5 \times 10^{13}$ cm^{-3}, with plasma recycling minimized, and fueling performed exclusively by the neutral beams (7). Figure 19 shows the dependences of plasma parameters and neutron intensity on neutral-beam power, when the recycling coefficient is maintained at 0.2 by the poloidal divertor.

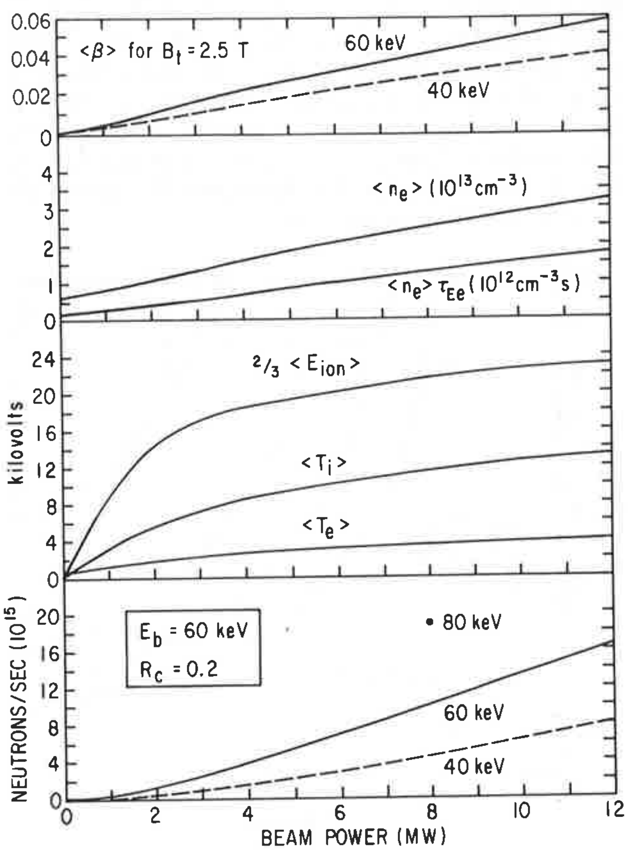


Figure 19. Neutral beam enhancement of plasma parameters.

In present tokamak experiments, gettering by titanium flashed on the wall has been found to be effective in both gas pumping and impurity control. However this method has many drawbacks for a reactor plasma. For in-torus getter pumping, a Zr-Al getter assembly was devised to serve as a high-throughput particle exhaust system for steady-state neutral-beam-driven and beam-fueled reactor plasmas. The pumped deuterium and tritium are regenerated after several hours of steady operation. Figure 20 shows one of these getter assemblies which are to be positioned at the bottom of the torus. This getter system could be used with a magnetic limiter to form a simplified unload divertor.

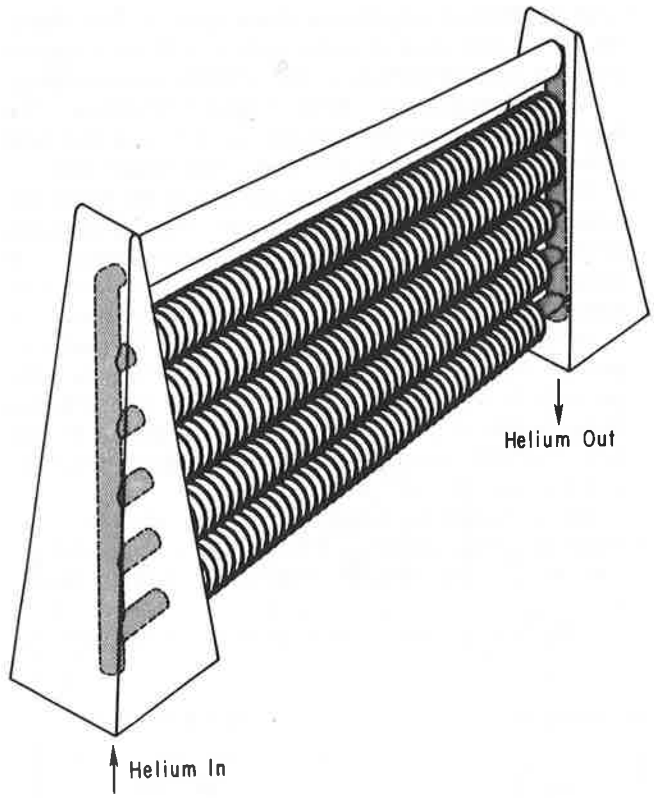


Figure 20. Zr-Al getter assembly configuration.

During FY 1977, a lengthy review paper on all aspects of neutral-beam-driven tokamak reactors, which had been completed in FY 1976A, was revised for publication in Nuclear Fusion.

Miscellaneous Plasma Engineering Studies

Impurity Effects

In conjunction with members of the PPPL Theory Division, who have developed a sophisticated impurity radiation model, a definitive analysis was made of the maximum allowed impurity concentrations for obtaining a given Q-value between 1 and ∞ (ignition) in D-T plasmas. As shown in Figure 21, it was found that the tolerable concentration of medium- and high-Z impurities for operation at $Q \lesssim 2$ can be at least one order of magnitude larger than the concentration allowed for ignition, provided that the plasma temperature is maintained by reacting ion beams. A similar impurity study was made for ignited catalyzed-D plasmas, previous studies of which had assumed only synchrotron radiation loss.

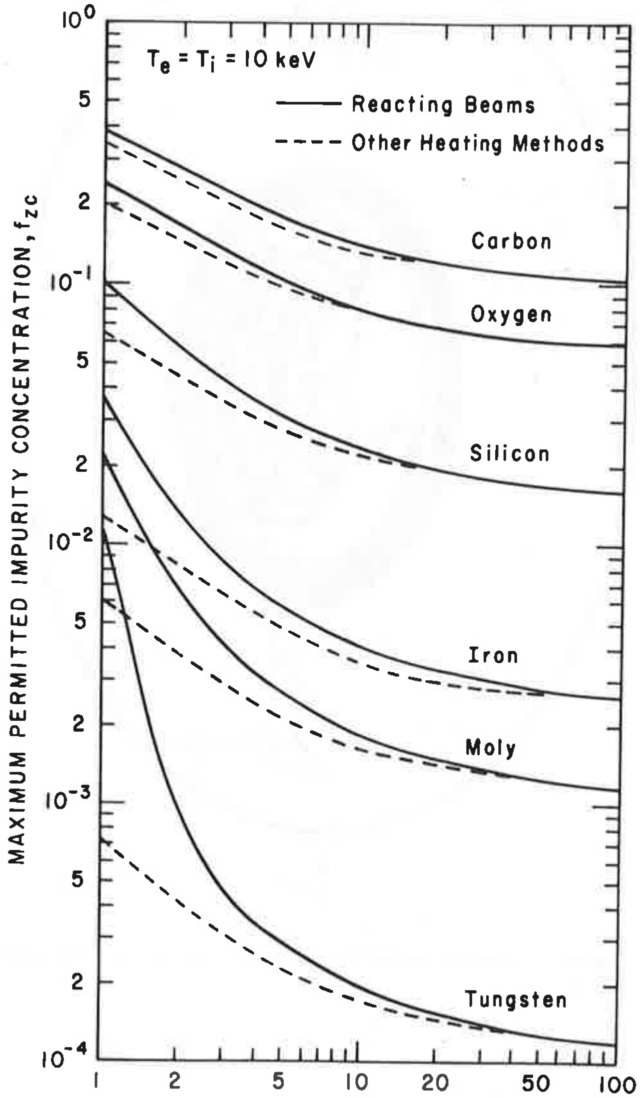


Figure 21. Impurity effects on given Q values.

Effects of Ripple on Neutron Production

In tokamak plasmas subjected to substantial toroidal-field ripple, the tail of the ion velocity distribution in the hot central region can be truncated, leading to a marked reduction in fusion reactivity (see Figure 22). This phenomenon was found to be important in beam-heated TFR plasmas and in moderate-density Alcator plasmas. In very high field tokamak devices with close-fitting TF coils, access ports must be eliminated or made extremely small if alpha particle heating of the central plasma region is to be depended on to reach high temperatures.

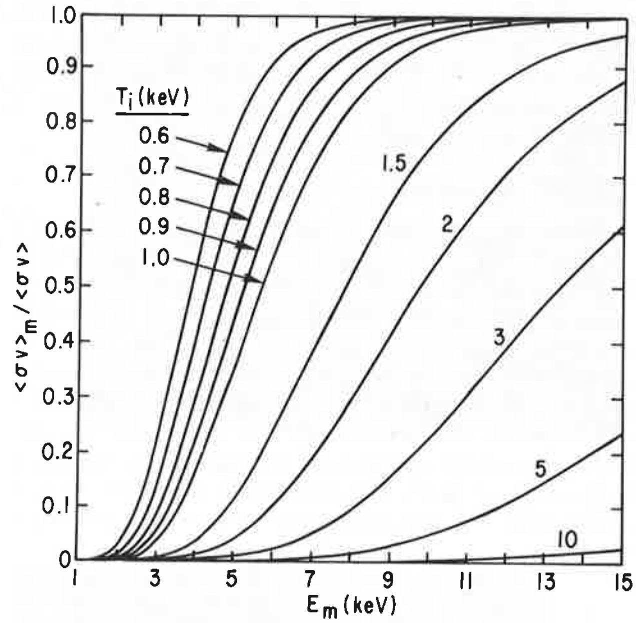


Figure 22. Effects of toroidal field ripple on fusion reactivity.

Ripple-Injection Fueling

Previous studies have shown that a potential method of *heating* the center of large dense plasmas is by injecting neutral beams vertically into a ripple magnetic well whose depth decreases to zero in the equatorial plane. Fast ions trapped in the well ∇B-drift to the center of the plasma, where they become detrapped and thermalized. The feasibility of the ripple-injection method for *fueling* was investigated in the present program. It was found to be promising for the intitial fueling and heating of dense ignited plasmas, and for the maintenance of hot-ion, warm-electron, low-Q plasmas. However, beam fueling of any type seems impractical for sustaining high-Q tokamak plasmas.

Design of Ripple-Injection Experiments

The vertically asymmetric ripple configuration required for ripple-injection heating can be established by special ripple-inducing coils. Preliminary designs were made for an experiment to be performed on PLT or on a resurrected ATC that would have tested ripple-assisted neutral-beam injection. However, the use of these machines appeared too expensive and the time scale too long. A near-term ripple-injection experiment has been designed for the ISX-B device at the Oak Ridge National Lab. This experiment (which will be performed in 1978-79) involves the design of the coils and analysis of the fast-ion orbits (see Figure 23). A ripple-injection module was also designed for the TFTR, for possible future implementation if the ISX-B experiment proves successful.

"Oven" Reactors

When high electron heat losses cannot be avoided (because of radiation loss, for example), high fusion energy gain Q can still be obtained in a reactor plasma consisting of a central thermonuclear 'reservoir'. This 'reservoir' would be insulated and fueled by a hot-ion, warm-electron blanket which is maintained by intense D° and T° beam injection at 70 to 100 keV. In principle, Q can be made arbitrarily large by increasing the radius of the reservoir (with a concomitant increase in machine size), the blanket region remaining constant in thickness.

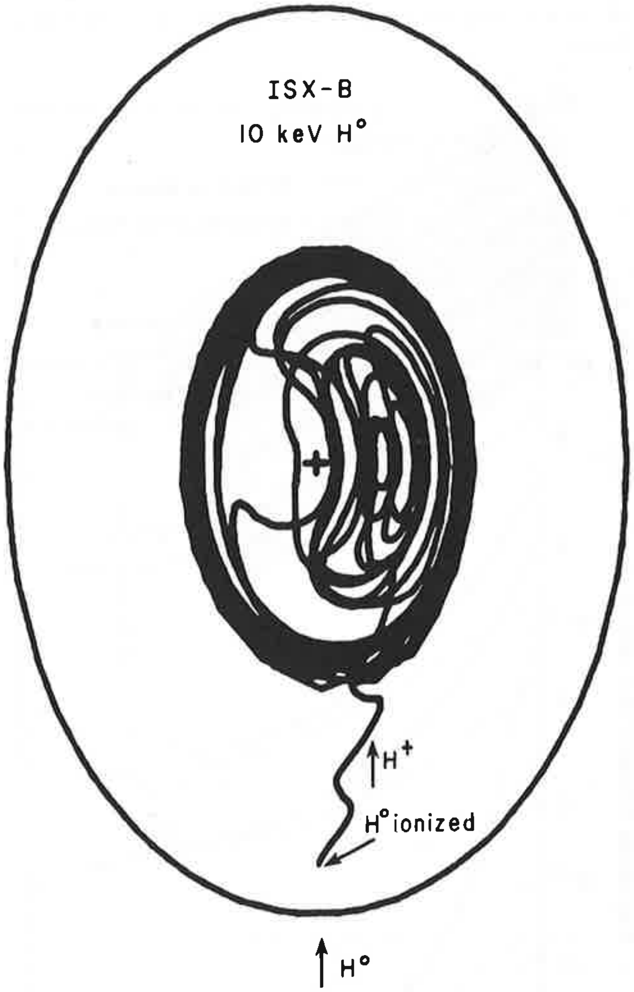


Figure 23. Ripple-assisted neutral-beam injection with fast ion orbits.

Linear Devices

OVERVIEW

Princeton Plasma Physics Laboratory is continuing to supplement its experimental research into large tokamak operational characteristics utilizing various smaller linear devices. During this report period, detailed work involving plasma waves and their instabilities has been performed with the L-3/L-4 and Q-1 machines. On L-3, the path of the lower-hybrid waves has been determined to be bent by the existence of drift waves. These drift waves have inherent density fluctuation which induces a change in the resonance cone angle. Parametric decay of the lower-hybrid waves and parametric instabilities near the ion-cyclotron frequency have also been studied using the L-3/L-4 and Q-1 devices. To date, the experimental results continue to agree with theoretical explanations.

After the linear dispersion relations of the decay waves were identified and confirmed as theorized, an additional characteristic pertaining to significant particle heating was detected and found to be due to wave-particle interaction.

In the Q-1 device, it has been found that perpendicularly-injected, high-energy, low-density ions can excite lower-hybrid waves and be slowed down much faster ($10^2 \sim 10^3$ times) than predicted by classical theory. The result will have a relevance to ripple injection proposed for heating large high-density tokamaks.

In the QED-1 device, sticking coefficients and cooling rates of high-energy density plasma flux- ($\lesssim$ 30 eV) have been studied.

In the COOL experiment, the reduction of axial energy loss in a linear device was demonstrated by means of end stoppering with gaseous and with solid plugs which reduced plasma flow. Up to a factor of five in improvement of plasma energy confinement time was observed. These results indicate that the length requirement of a linear reactor can be reduced without end-stoppering.

MAJOR ACTIVITIES

L-3 Program

During this report period the research program involving L-3 has concentrated on investigating linear and nonlinear phenomena of lower hybrid waves. The waves are launched by a multiple-ring slow wave structure which is the low frequency analog of the phased waveguide arrays used for lower hybrid wave heating of tokamak plasmas.

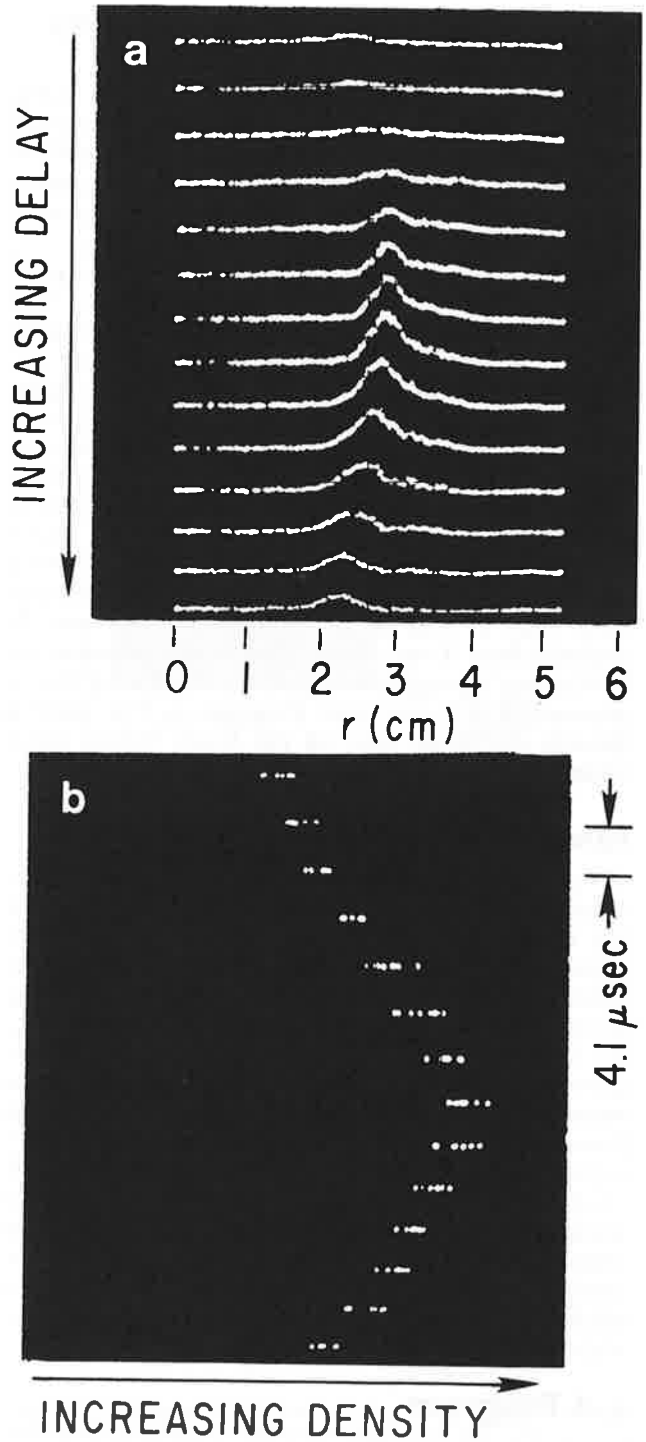


Figure 24. Typical experimental data showing resonance cone position being modulated and resonance cone amplitude changing with the density fluctuation. These data were taken with an oscilloscope as an X-Y recorder.

Interaction Between Lower Hybrid Waves and Drift Waves

Lower hybrid wave propagation is sensitive to the plasma density and is therefore expected to interact strongly with drift waves. In the L-3 experiments, it has been found that at low rf power, the drift waves have modulational and focusing effects on lower hybrid waves as shown in Figure 24.

In Figure 24a resonance cone amplitude was plotted against radius at different phases of the drift wave. In Figure 24b a horizontal deflection proportional to density at a given radius is given for the phases of the drift wave corresponding to Figure 24a. It is apparent that the radial position of the resonance cone depends on the phase of the drift waves (modulational effect) and the cone amplitude changes as well (focusing effect). This has proven to be in good agreement with wave refraction theory and has been extended to describe lower hybrid wave propagation through turbulent density fluctuations such as has been observed in tokamaks. At high rf power, it has been determined that lower hybrid waves can enhance drift waves, giving rise to anomalous diffusion and changes in the plasma density profile as well as the lower hybrid wave trajectory.

Parametric Decay of Lower Hybrid Waves

The resonant decay of lower hybrid waves was investigated in the regime $\omega_0 \simeq 10\ \omega_{lh}$ where ω_{lh} is the lower hybrid frequency. The daughter waves were identified as ion-acoustic waves and lower hybrid waves. The wave lengths in all directions were measured by interferometry as shown in Fig. 25. Conservation of momentum and energy was experimentally verified. The sideband lower hybrid wave was found to follow the resonance cone of the pump wave, and the decay threshold was much higher than the collisional threshold due to $\vec{E}_0 \times \vec{B}$ coupling. These results tend to corroborate recent theoretical predictions made for lower hybrid wave heating in tokamaks, namely, that parametric instabilities driven by $\vec{E}_0 \times \vec{B}$ coupling due to the finite extent lower hybrid wave will be effectively stabilized in the region $\omega_0 \geqslant 2\ \omega_{pi}$.

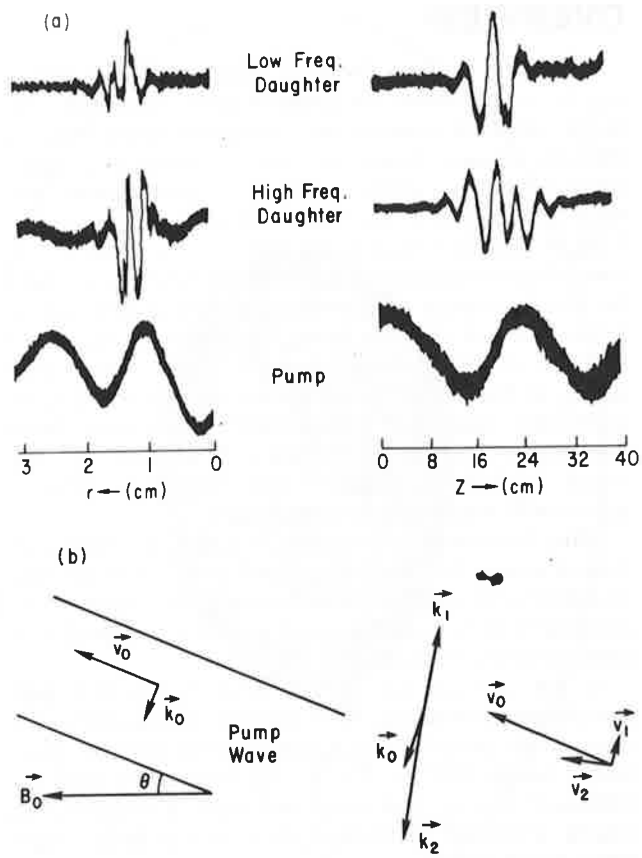


Figure 25. (a) Radial and axial interferograms of the pump and the decay waves. (b) $\vec{k}$-vector diagram and group velocities constructed from the interferogram.

L-4 Program

The L-4 program to date has directed its main effort into the investigation of parametric decay instability processes associated with an RF electric field near the ion cyclotron frequency (i.e., $\omega_0/\Omega_i = 1.25 - 7.0$ where ω_0 is the pump frequency and Ω_i is the ion cyclotron frequency). In this frequency range, the ion drift motion is no longer negligible and considerably modifies the picture of the decay process. In ongoing experiments, three types of new parametric instabilities with relatively low threshold electric fields have been observed.

Single-Ion-Species-Plasma

In a single ion species plasma, strong excitation of a non-resonant ion cyclotron quasi-mode when the plasma density was reduced such that $\omega_{pi} \simeq \omega_0 \simeq 2\ \Omega_i$ (here ω_{pi} is the ion plasma frequency) has been observed. In Figure 26a a typical decay spectrum obtained in a helium plasma and the decay frequency variation with the magnetic field is shown. Figure 26b shows the measured dispersion relation of the quasi-mode which is markedly different from the cyclotron wave dispersion.

Associated with this decay, strong ion heating was observed. This type of instability may become important in the high power ICRF experiments in the region near the induction coil where $\omega_{pi} \simeq \omega_0$.

Two-Ion-Species-Plasma

When there are two types of ions ($\Omega_1 \neq \Omega_2$) present in the plasma, the relative ion-ion drift motion can excite parametric instabilities. For $\omega_0 > \Omega_1 + \Omega_2$, the electrostatic ion cyclotron waves can be parametrically excited above each ion cyclotron frequency (i.e., $\omega_1 > \Omega_1$, $\omega_2 > \Omega_2$, and $\omega_0 = \omega_1 + \omega_2$). In Figure 27 the measured dispersion relation of such decay waves is shown. Note that the lower mode frequency approached the ion-ion hybrid frequency for large k where it exhibits a strong resonance behavior.

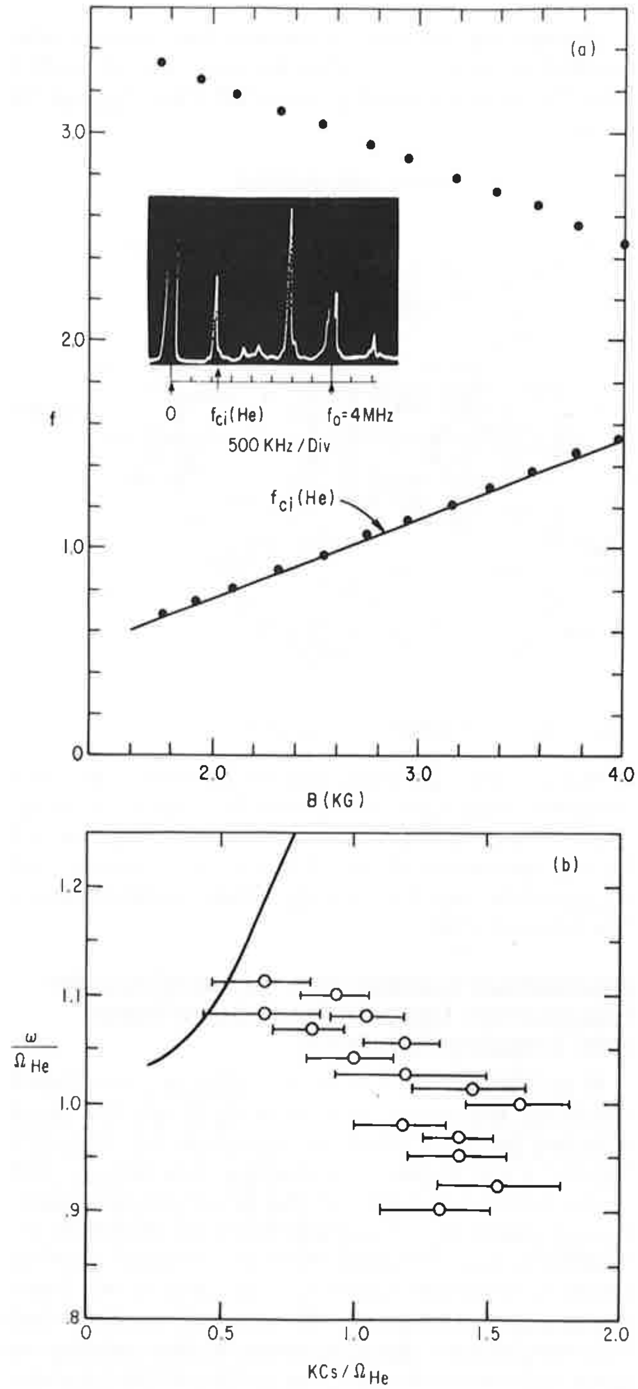


Figure 26. (a) Observed decay frequency versus magnetic field strength. $f_0 = 4$ MHz. The insert shows a typical decay spectrum in a helium plasma. $B_0 = 3.15$ kG. (b) Measured dispersion relation of the ion cyclotron quasi-mode (circles) and the theoretical dispersion relationship of the cyclotron wave (solid curve). ($f_0 = 4$ MHz, $B_0 = 3.15$ kG).

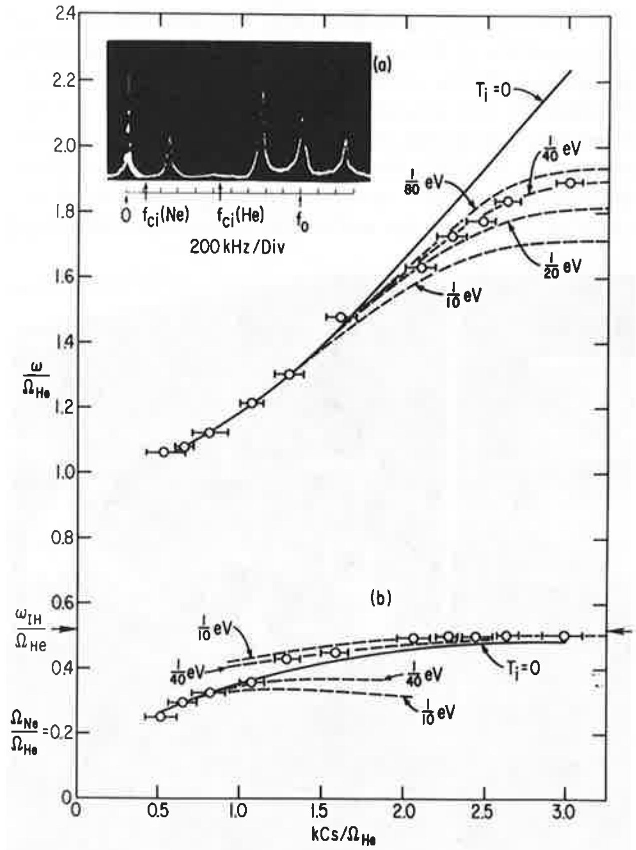


Figure 27. (a) Parametric decay spectrum. f_{ci}(He) and f_{ci}(Ne) are the helium and neon ion cyclotron frequencies ($B_0 = 2.9$ kG, $f_0 = 2$ MHz, He:Ne = 4.6). (b) Dispersion curve of the decay waves. Solid and dashed curves are theoretical values and the circles represent experimental values; ω_{IH} is the ion-ion hybrid frequency. (He:Ne = 4.6).

In a two-ion species plasma, the same excitation process, namely the relative ion motion was found to excite drift waves in the density gradient region for $\omega_0/\Omega_{He}=1.25-1.6$ and for N(He):N(Ne)=8.2−3:7. Here the sideband modes are the electrostatic ion cyclotron waves. This type of instability may become important, for example, during radio frequency heating near the ion cyclotron frequency of a deuterium-tritium fusion reactor plasma.

For all three instabilities, the frequency and the wave number matching conditions have been verified and it has been concluded that the measured threshold electric fields agree well with theory.

Q-1/QED-1 Program

Divertor Simulation Experiments

In order to estimate, and later analyze, the divertor performance in tokamaks, data for particle-gettering efficiency at the divertor chamber wall are vitally needed. In the energetic arc device QED-1, measurements are being obtained of sticking coefficients of various relevant hot gases of $0.1 \text{ eV} < T < 20 \text{ eV}$ on titanium, which is the gettering material to be used on PDX divertor walls. The gettering coefficient is derived by monitoring neutral gas density with respect to time in the divertor chamber of QED-1 after the plasma pulse is injected (See Figures 28 and 29).

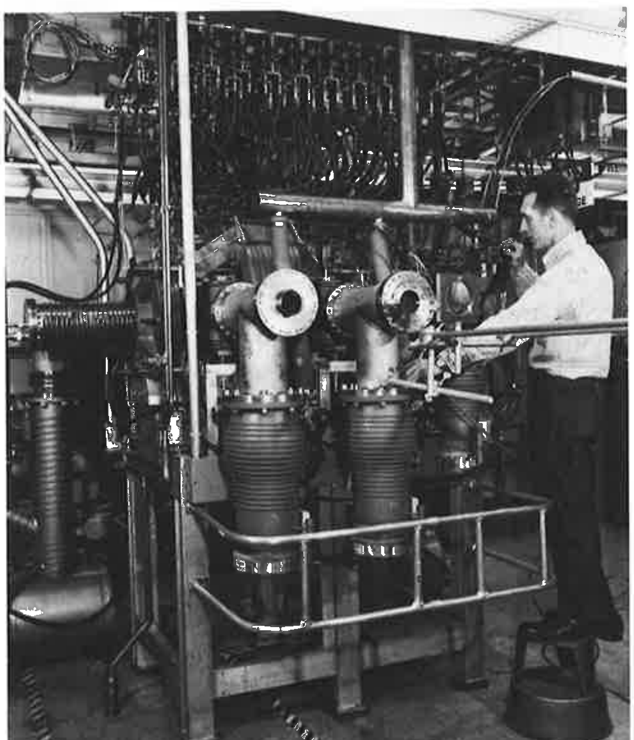


Figure 28. Apparatus for the QED-1 plasma gettering experiment.

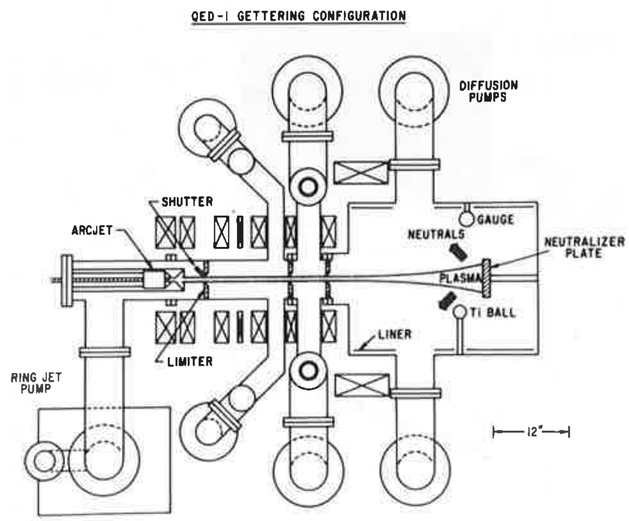


Figure 29. QED-1 gettering configuration.

Preliminary data show that the sticking coefficient of atomic hydrogen on titanium films is in the range 2-6%. The data imply that particles (< 30 eV) which hit the neutralizer plate in the divertor chamber, but do not stick, lose their energy rather rapidly (within a few bounce times).

Anomalous Slowing of a Perpendicularly-Injected Ion Beam in Both Quasilinear and Trapping Regimes

In the Q-1 device converted into a double-plasma machine, the anomalous slowing of an ion beam injected perpendicularly to the confining magnetic field of a low β plasma was experimentally verified in the nonlinear stages of the beam-excited lower-hybrid instability. In pulsed beam experiments the instability was followed from the linearly growing stage to nonlinear saturation. By varying the beam parameters, a transition of the nonlinear saturation mechanism from the quasilinear to the trapping regime was demonstrated. The enhanced perpendicular momentum loss of the beam ions was examined by using a fast-response energy analyzer and by measuring the resultant beam orbit modifications (Figure 30).

The anomalous beam slowing ($v_{eff}/v_{classical} \simeq 10^2 \sim 10^3$) observed in the present experiment has a strong

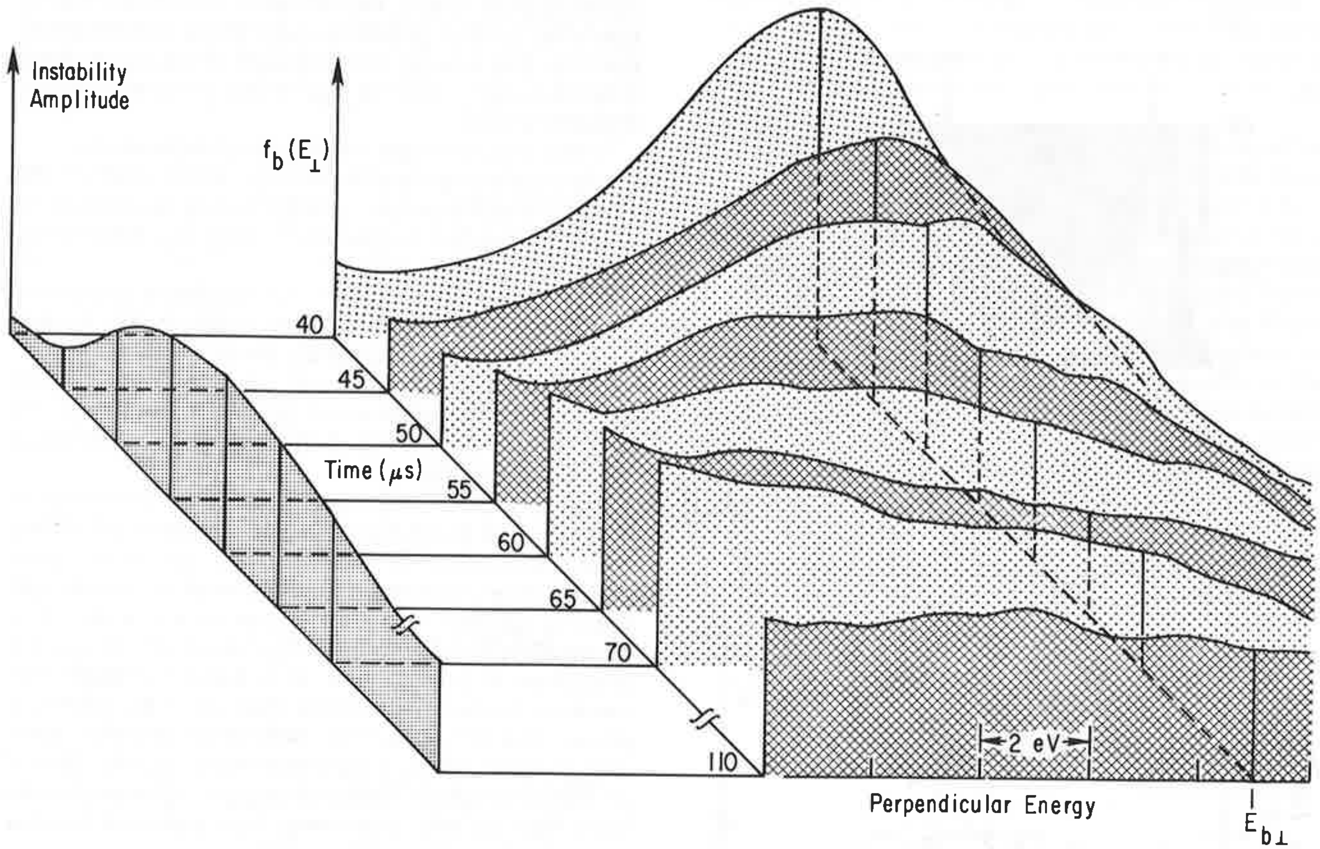


Figure 30. Beam perpendicular energy distribution and wave amplitude versus time.

impact on perpendicular neutral-beam injection in tokamak or mirror fusion devices. In the preheating stage this anomalous effect could provide rapid energy absorption. However, if a device relies on perpendicular injection and on significant beam-beam or beam-plasma fusion rather than on thermal fusion (such as the mirror or the ripple injected driven tokamak), then the rapid thermalization due to the instability could severely reduce the energy multiplication. (Because injection into PLT and TFTR is tangential, LHW are stable and these effects do not occur.)

Cross-Field-Current Driven Lower-Hybrid Instability and Stochastic Ion Heating

In the Q-1 device, a suprathermal electron beam was injected parallel to $\vec{B}$ in a low-β plasma. The sharp space-potential drop across the surface of the beam generated a strong cross-field (electric) current which, in turn, drove a modified two-stream instability at the lower hybrid frequency. Intense stochastic ion heating was observed with the onset of the instability, and the heating rate was found to be proportional to the wave energy.

Parametric Lower-Hybrid Instability Excited by a Modulated Electron Beam (Q-1)

Electrostatic lower-hybrid waves and ion-cyclotron modes have been excited via a parametric interaction with a density modulated electron beam injected parallel to a strong magnetic field in the double Q-1 device. In this experiment, a parametric decay of the pump mode into a lower-hybrid wave and either an ion cyclotron wave or an ion quasimode in an isothermal plasma ($T_e \simeq T_i$) has been identified. Detailed measurements have demonstrated frequency and wave number matching ($\omega_0 = \omega_1 + \omega_2$, $k_\perp = k_{\perp 1} + k_{\perp 2}$) of the decay process, and the dispersion relations and growth rates of the decay waves Fig. 31. Additional important features of this instability are the strong perpendicular ion heating, parallel electron heating, and its possible application to fusion plasmas.

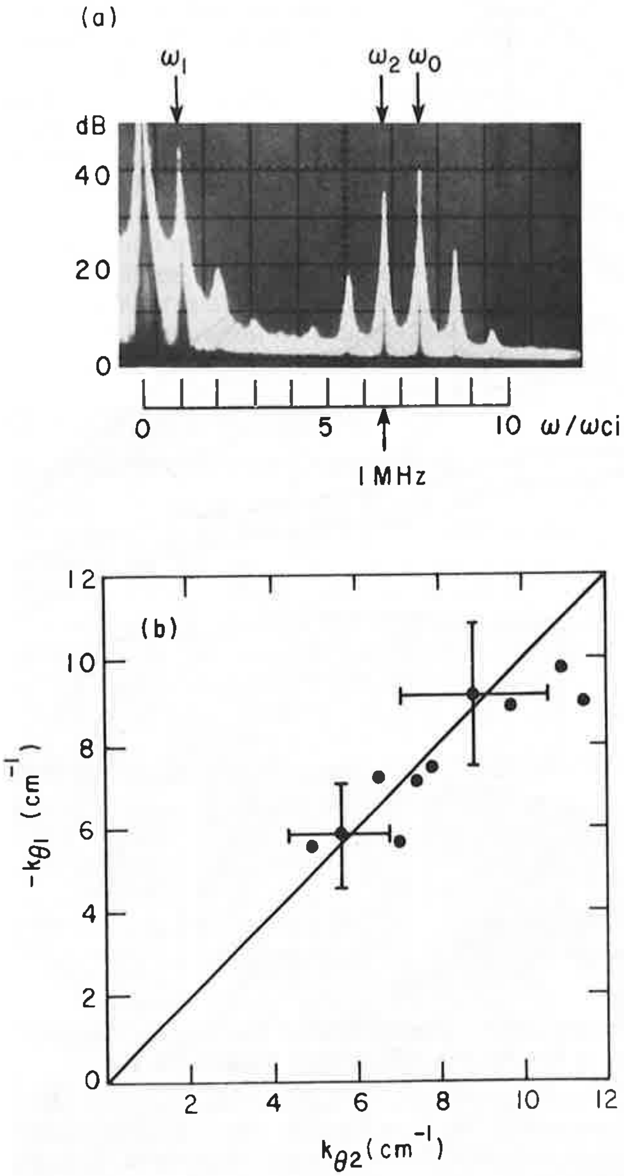


Figure 31. (a) Typical frequency spectrum of the Parametric Lower-Hybrid instability ($\omega_{ci}/2\pi = 156$ kHz, $\omega_{lh}/2\pi = 1.1$ MHz). The ω_0, ω_1, and ω_2 markers indicate the pump wave, the ion quasimode and the lower hybrid-decay wave, respectively. (b) Wave number matching for predominant propagation direction; solid line is $k\theta_1 = -k\theta_2$. Data points correspond to various ω_0 with all other parameters constant.

CO_2 Laser Program — COOL

The COOL experiment has aimed at careful experimental evaluation of various ideas, both old and new, for designing a linear fusion reactor of reasonably short length. Recent work has shown that by applying solid or gaseous plugs at the column ends, particle and energy confinement times for a linear plasma column may be significantly increased over present results.

In the previous year calculations showed that:

(1) in contemporary linear Θ-pinches in which the plasma is collisionless, energy loss is dominated by electron thermal conduction along the field lines; and

(2) in the reactor regime, the plasma is collisional ($L/\lambda_{mfp} >> 1$) and energy loss is dominated by that due to particle flow out of the ends.

Therefore, in a collisional plasma column if the plasma flow is eliminated by end stoppering, the energy loss will be reduced to the level of loss due to thermal conduction.

The reduction of plasma flow in the presence of material end plugs has been analyzed by obtaining exact solutions to the problem of ideal, one-dimensional, isentropic expansion of a finite-length plasma column into dense gas at the ends. It is shown that for both solid and gaseous end plugs, the reduction in plasma flow is achieved through momentum conservation rather than by static pressure alone. The only essential difference between solid and gaseous plugs is the initial mass density. Based on this conclusion, two end-stoppering experiments were carried out, one using high pressure neutral gas, and the other with a solid plug.

The gaseous plug experiment is carried out in a plasma produced by CO_2-laser induced gas breakdown of hydrogen at a sonic jet exhausting toward the incident laser beam. Initial plasma parameters are $n_e \approx 2 \times 10^{18}$ cm^{-3}, $T_e + T_i \approx 100$ eV, $r \approx 3$ mm, $L \approx 5$ cm, and the plasma is radially confined by a magnetic field of 100 kG. The plasma expands longitudinally along the field in both directions into neutral gas at the column ends. The density of the gas at the end facing the incident beam is $\simeq 1/30$ of the initial plasma density, while the gas density at the opposite end is several times the plasma density. The results are entirely consistent with the one-dimensional gas dynamic flow model described previously; namely, the flow velocity is inversely proportional to the square root of the mass density in the plug material. The model predicts that a factor of three improvement in energy confinement time can be achieved if the mass density of the cold gas is about thirty times that of the initial plasma column.

In the second experiment, a solid end plug (boron nitride) facing the expanding plasma in a configuration similar to that described previously, is situated 11 cm away from the jet to stop the plasma flow. (The plug is in the central, hollow region of the annular laser beam.) A reflected shock wave, having a speed less than that of the incident expanding plasma, is observed to originate from the plug following the arrival of the expanding plasma at the plug. Axially, the plasma pressure at the arrival time of the reflected shock decreases in the direction away from the plug. The radial density profile is sharply peaked on axis before the arrival of the reflected shock and gradually broadens after the arrival. The reflected shock also results in plasma reheating as shown in Fig. 32. The total plasma line density along a diameter of the plasma, measured at a location 3 cm from the plug, remains nearly constant in the time following the passing of the reflected shock. During this period, the plasma energy decreases continuously. With end-plugging, the plasma density and energy confinement times are $\simeq$ 15 and $\simeq$ 7 μsec, respectively. Without end-plugging, these times are reduced by a factor of about five. More extensive experiments will be carried out in the future.

In another experiment, the parametric decay of an incident electromagnetic radiation into two plasma waves in a plasma density layer whose density is one quarter of the critical density corresponding to the incident CO_2 laser frequency has been measured. The measurement was done by direct Thomson scattering of a ruby laser beam, and the decay process was confirmed by observation of enhanced scattering of the probing ruby laser beam at the plasma frequency as shown in Fig. 33. This experiment establishes for the first time by a direct Thomson scattering measurement the existence of the two-plasmon decay instability, long suspected to exist in laser-plasma interactions.

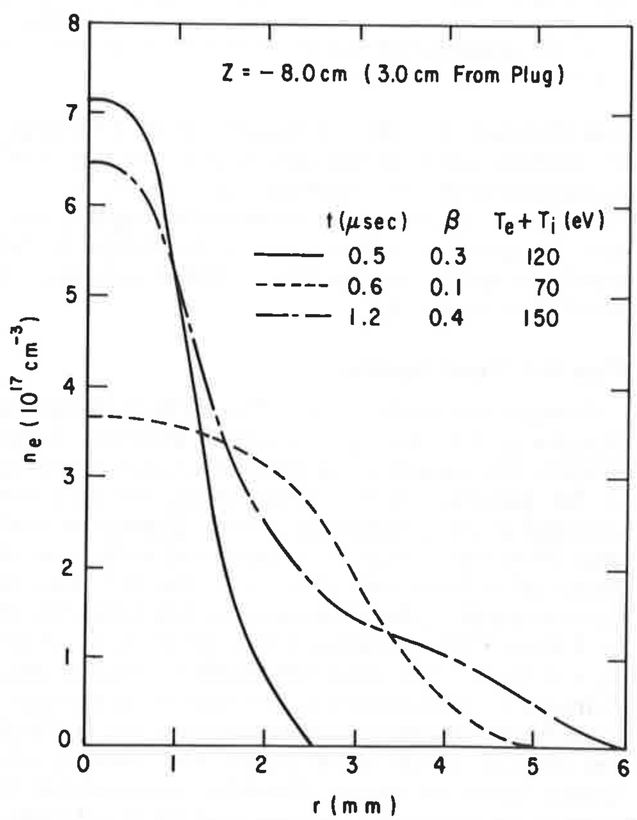


Figure 32. Plasma density profile at z = −8.0 cm (3 cm from plug) experiment at t = 0.5 and 0.6 μsec (before the reflected shock) and at t = 1.2 μsec (after the reflected shock). At t = 1.2 μsec, both plasma density and temperature increase due to reheating by the reflected shock.

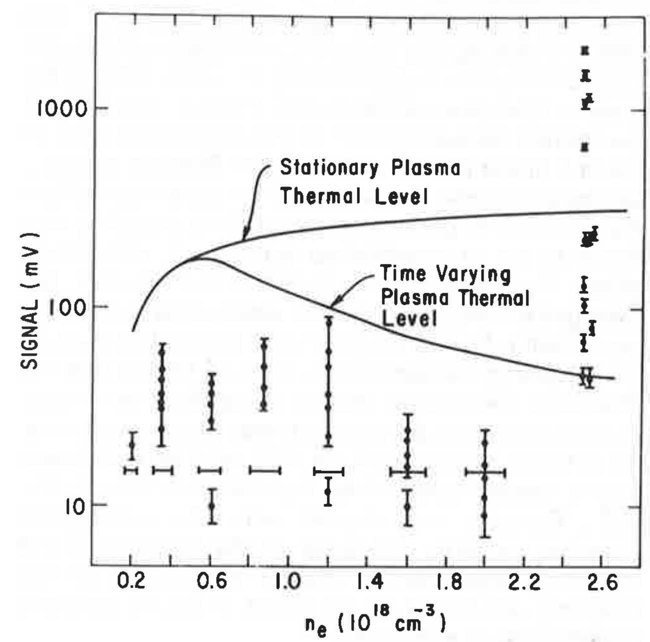


Figure 33. Scattering intensities versus n_e; the horizontal bars indicate the channel widths. The upper curve is that of a homogeneous, stationary plasma and the lower curve takes into account time and space variations in n_e; $\Delta\omega = \omega_0/2$ corresponds to $n_e = 2.5 \times 10^{18}$ cm^{-3}.

Lower Hybrid Heating

Plasma heating with rf power near the lower hybrid (LH) frequency involves extraordinarily clean engineering techniques which can be extrapolated very plausibly to reactor conditions. Uncertainties in LH heating are in the physics of the generation, penetration, and damping of the lower hybrid waves. The goal of the Princeton lower hybrid group is to learn the physics of LH heating and to develop an effective heating technique for tokamak plasmas.

Activities in 1977 centered on the following areas:

1. An ongoing analysis of the ATC tokamak experiment, terminated in 1976
2. The H-1 linear test device
3. Cooperation with the General Atomic and MIT rf heating groups

The ATC Data Analysis

One of the outstanding advantages of the LH heating approach is its use of relatively unobtrusive open-ended waveguides as couplers for the generation of the plasma waves necessary for heating; the coupler structure facing the plasma surface is merely a series of openings in the liner wall. The theory of waveguide coupling was developed by M. Brambilla from a suggestion by P. Lallia, both of the plasma laboratory at Grenoble, France. The first experimental demonstration of this technique was on the H-1 linear device at Princeton. Phased arrays of waveguides were shown to deliver more than 90% of the rf energy to plasma waves and the coupling was found to be in quantitative agreement with Brambilla's Theory. As a result of the H-1 studies, the waveguide coupling systems were used in the ATC experiment. During the past year a detailed study of the coupling measurements on ATC shows that the Brambilla theoretical model is applicable to coupling to tokamaks as well as linear plasma columns. As a result of this work on ATC and H-1 all lower hybrid experiments under construction now in the U.S., Europe, and Japan will use waveguide coupling systems. Because of the success of the coupling experiments, design confidence in the coupling structures to be used in future tokamak experiments is enhanced.

One of the most promising aspects of LH heating is the prospect of heating electrons by Landau damping of the LH waves. Theoretical analysis of the coupling structure used in the ATC experiments indicates that a small amount of power (a few 10's of kilowatts or less than 10% of the total rf power) should have been delivered to the electrons by the Landau heating mechanism. Thomson scattering measurements of the electron temperature, on first analysis, failed to show unambiguous electron heating. Recently, however, after employing a new data averaging technique, clear evidence for electron heating has emerged. Fig. 34 shows a plot of the temperature increase per unit of rf power as a function of the initial (pre rf) plasma temperature.

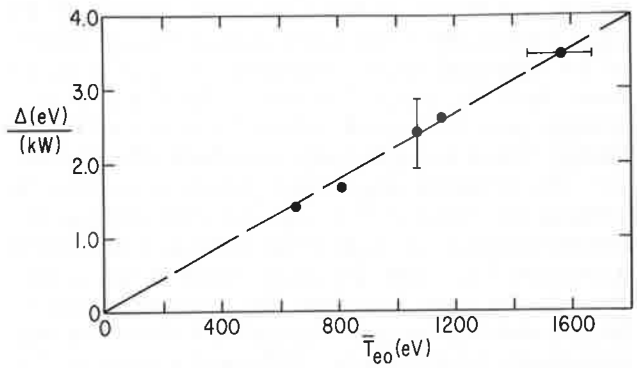


Figure 34. Increase of electron temperature per kW of coupled power, averaged over ± 3 cm from center of plasma as a function of electron temperature without RF. (Data taken on ATC with double waveguide by Thomson scattering.)

The increase in heating effectiveness as a function of temperature is in agreement with the theory of Landau heating. The important point here is that it is not difficult to construct a waveguide coupling system designed to deliver most of its energy to the electrons rather than the small fraction available in the ATC experiment.

The H-1 Test Device

Perhaps the fundamental difficulty in studying the physics of LH heating in tokamak plasmas is the inability to measure wave penetration and damping in the plasma column, which is too hot to allow insertion of wave detecting probes. During the past year PPPL has successfully scattered a microwave beam off a lower hybrid wave in the H-1 plasma column enabling the observation of the scattering of an 8.6 mm microwave beam through an angle of 30° by a 2.45 GHz, LH wave generated by waveguides. Through a measurement of the intensity of the scattered beam, the group was able to infer that ~ 2/3 of the calculated LH wave power was directly observed by this technique. Absolute measurements of plasma wave intensity are rare, and the direct measurements of a large fraction of available generator power in the desired plasma-wave mode are virtually nonexistent in rf heating studies. Thus, these measurements do more than establish a new and powerful diagnostic technique, they demonstrate directly the high waveguide coupling efficiency which, heretofore, could only be inferred from external measurements. Analysis of this technique shows that microwave scattering should be a viable and effective diagnostic for LH experiments on tokamaks.

Quasilinear Effects

As mentioned above, Landau heating is an extremely promising aspect of LH heating. However, one process that may reduce its effectiveness is quasilinear distortion of the electron energy distribution. Above a critical power level the damping of the LH wave flattens the energy distribution so that further wave damping is considerably weakened. The possibility of Landau heating of tokamaks has led to a considerable body of theoretical study of quasilinear effects in the past two years, but there has been no experimental evidence for quasilinear processes in the damping of LH waves. On H-1, during the past year, the Landau damping of LH waves was demonstrated and the dependence of this damping upon the rf power level was studied. Figure 35 shows the observed attenuation vs. power, and a rapid decrease in damping rate at high power levels is very much in evidence. A detailed study of this nonlinear phenomenon is currently underway.

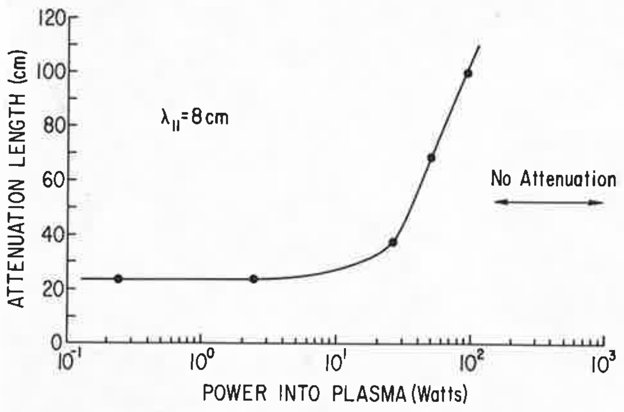


Figure 35. The damping length at 70 MHz versus input wave power. The measurements were taken when the central electron temperature was 7 eV.

Penetration of Lower Hybrid Waves

For many years it has been known that for lower hybrid waves to penetrate deep into a plasma it is necessary to generate waves with $n_z > 1$, where n_z is the index of refraction in the direction parallel to the magnetic field. However, this condition has never been demonstrated experimentally. A detailed study of wave penetration in H-1 by varying n_z, B, and n_e has verified the theory in detail.

The General Atomic and MIT Programs

During 1976 and 1977 the PPPL Power Electronics Section was able to upgrade by a factor greater than three the output power of the rf oscillators which had been used in the ATC experiment. Subsequently two of these upgraded oscillators, each delivering nearly 200 kW of rf power were constructed, transported, and installed at the General Atomic Plasma Laboratory. Similarly, a 200 kW unit was prepared in 1977 for transportation to MIT for an experiment in 1978 on the Versator II Tokamak.

These oscillators will be returned to Princeton in 1979 for a major LH experiment on PLT in 1980.

The Princeton LH group has worked in collaboration with the G.A. Doublet II-A team, and PPPL has participated in the design of the Versator LH experiment which should be underway in the second half of 1978.

Tokamak Fusion Test Reactor (TFTR)

OVERVIEW

The first magnetic confinement device capable of producing a significant quantity of fusion energy is currently being constructed by PPPL. The Tokamak Fusion Test Reactor (TFTR), the largest construction project to date in the U.S. fusion program, is scheduled to be operational at Princeton in 1981.

TFTR (see Figure 36) will be more than twice the size of PPPL's currently operating tokamak—the Princeton Large Torus (PLT). While PLT and other earlier tokamaks in the U.S. and other nations 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 will be the first U.S. magnetic confinement device planned 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.

OBJECTIVES

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 design construction and operating 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

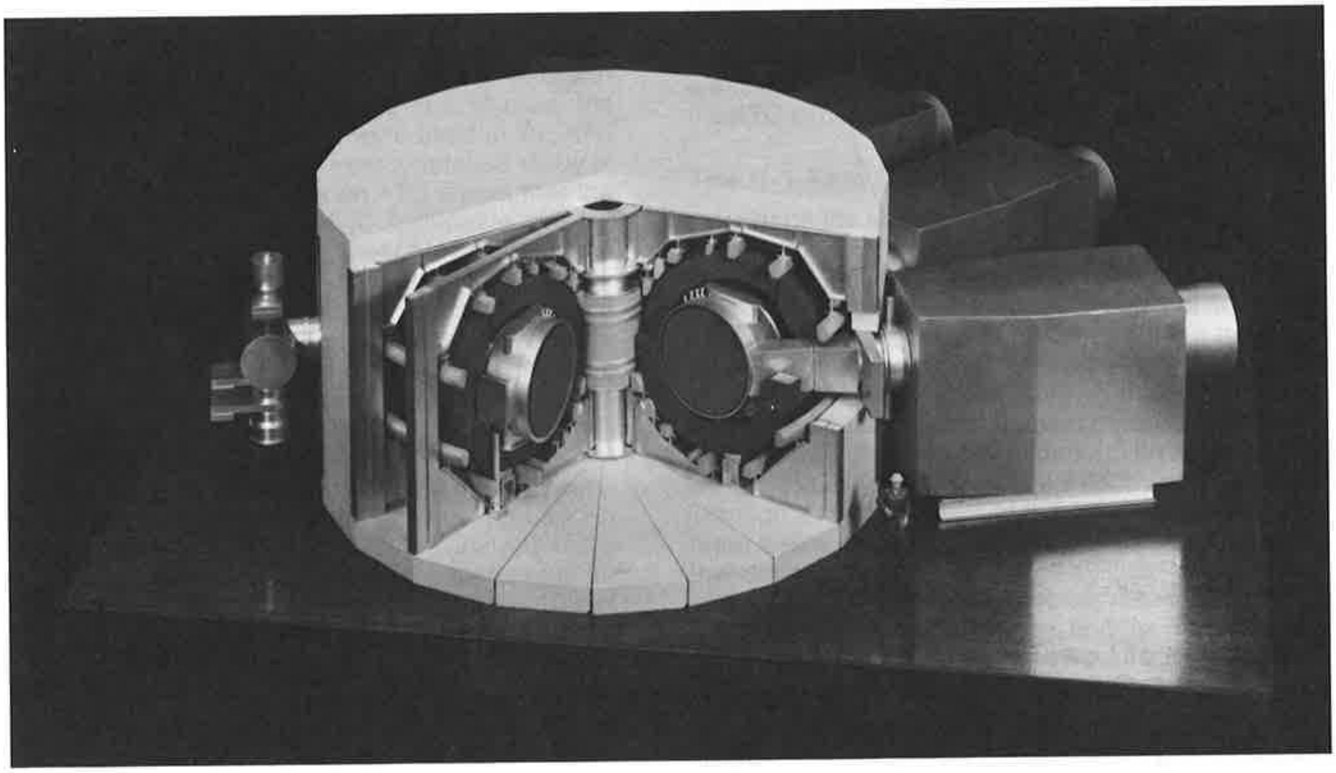


Figure 36. Model of Tokamak Fusion Test Reactor (TFTR).

one to ten megajoules 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 second is one of the requirements for production of temperatures in the range 5-10 keV, a density of approximately 100,000,000,000,000 particles per cubic centimeter (10^{14} cm^{-3}), and stable confinement with the product of density expressed in particles per cubic centimeter and confinement time ($n_e t_d$) no less than 10,000,000,000,000 per cubic centimeter second ($10^{13} cm^{-3}$sec.). The plasma handling techniques and hardware must be capable of initiating, controlling and dissipating plasma currents of up to 2.5 MA.

PROGRESS THIS PERIOD

FY77 was marked by procurement activity, start-up of site construction, finalization of subcontract agreements with Ebasco Services, Inc. and Grumman Aerospace Corporation, and development of a Management Information System. In addition, international collaboration was pursued, including exchange of personnel and information on Large Vacuum Valves, Turbomolecular Pumps and Bellows.

SITE CONSTRUCTION

Under the ERDA Chicago Operations Office (COO) and Princeton Area Office (PAO) direction, site design and construction was begun early in the year (See Figure 37). Giffels Associates, Inc., the

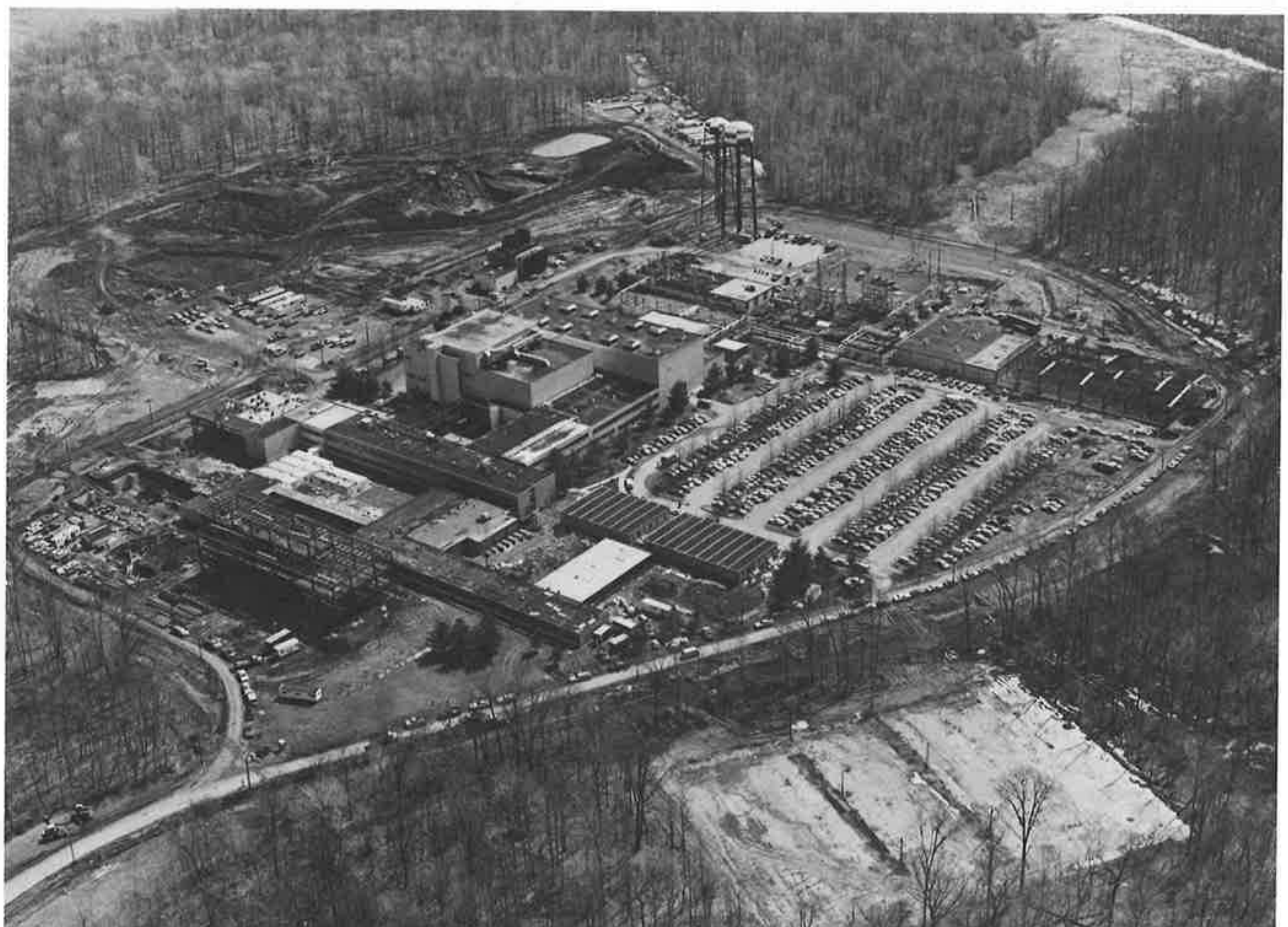


Figure 37. Current construction at C-site, Plasma Physics Laboratory. TFTR site is at upper left.

architect/engineering firm chosen in 1976, completed Title I reports and drawings for the Experimental Complex and Motor Generator Building. Title II drawings and specifications for the Experimental Complex were issued and approved in September. Construction contracts were awarded to PJR Construction Corporation of Brooklyn, New York, for the TFTR Technical Shop Addition and Site Work, Santaniello, Inc. of Newark, New Jersey, for the Switchyard-Phase II construction work and Or-di Construction Corporation for the Office/Laboratory Complex. The 3 story Office/Laboratory building will provide space for approximately 200 individuals, and contain a 270-seat auditorium, a new library and an orientation area (See Figure 38).

Negotiations for a definitized subcontract between Princeton University and Ebasco Inc. of New York were completed and the $100 million, 5-year contract was formally executed by officers of both organizations on June 17, 1977. Ebasco, together with their main subcontractor, Grumman Aerospace Corporation, accelerated manpower application and by the end of the year approximately 330 industrial employees were dedicated to the project.

M1 and M2 Mockups

Two full scale TFTR Mockups were designed and assembled by Ebasco Grumman this year. The M1 Mock-up consisting of two full vacuum vessel sectors and part of a third, five TF coils, the center column, and part of the PF coils, water system, support structure and shielding, will be used to evaluate physical design problems, remote maintenance and handling concepts, and to verify assembly and disassembly procedures. The M2 Mock-up is a representation of the lower portion of one sector of the TFTR Tokamak system and will be used to simulate machine maintenance from the basement diagnostic level.

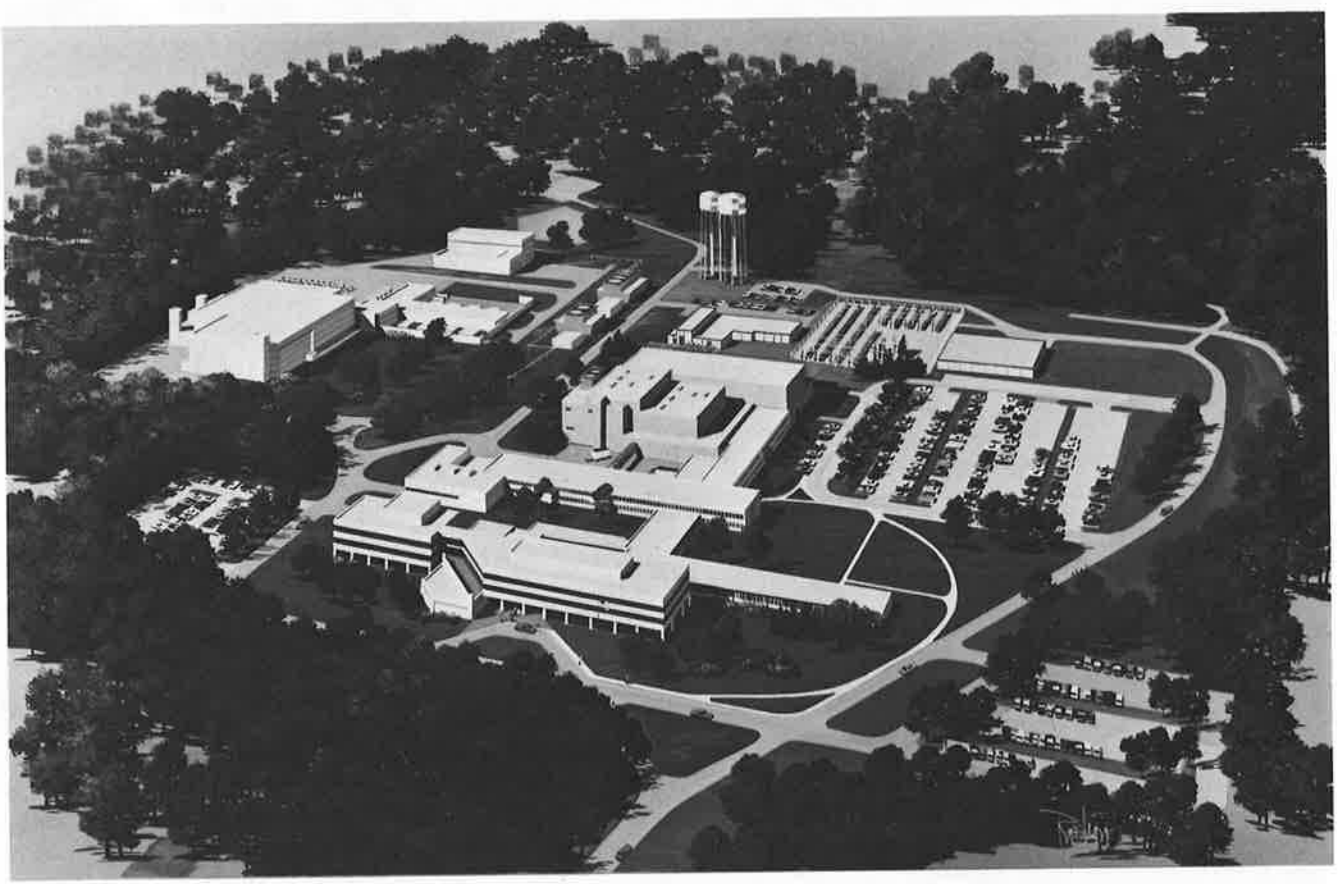


Figure 38. Artist's drawing of TFTR and support facilities, Princeton Plasma Physics Laboratory.

Remote Maintenance Considerations

In support of this consideration conceptual Teleoperator and remote handling designs were presented for evaluation by Grumman Aerospace Corporation during the year. After some period of operation, the TFTR will become sufficiently radioactive that remote handling will be necessary to execute mechanical operations within the vacuum vessel. In addition, current plans call for the design of bridge mounted manipulators which will be utilized to service the external parts of TFTR.

Contracts Awarded

Major procurements for the period included the award of contracts for two motor generator flywheels to General Electric, of Schenectady, New York; the neutral beam power supply system to Transrex of Carson, California; two 138kV substation transformers to RTE/ASEA of Waukesha, Wisconsin; one million pounds of copper ingot/extrusion from which TF, OH and EF coils will be fabricated to Phelps Dodge; vacuum vessel ring forgings to Carlton Forge Works; 13.8kV switchgear to Gould ITE; turbomolecular pumps to Leybold-Hereaus; and 41-cm high vacuum valves to VAT.

Corning Glass was placed under contract for developing techniques for bonding macor to metal. In January, 1977 the Lawrence Livermore Laboratory/Lawrence Berkeley Laboratory was chosen to design and build the first neutral beam line.

Control System

Technical proposals for the Central Instrumental Control and Data Acquisition (CICADA) System were received and bid evaluation was completed. Initial hardware requirements call for 13 computer systems which will monitor all the systems of TFTR including the tokamak, the neutral-beam injectors, the motor generator units, and the diagnostics. Attached to the CICADA Computer system will be CAMAC links. These links will interface the signals from the diagnostic to the computer.

Reports and Publications

Several reports were issued during this report period. These reports included the Preliminary Safety Analysis Report (8/77), the TFTR Reference Design Report (12/76), and a Configuration Management Plan. In addition, the Archaeological and Historical Survey Report was issued by Rutgers University during the month of August.

Major Milestones Next Period

The major TFTR milestones for FY78 are shown in Table I. These milestones are currently on schedule with preliminary efforts completed in all areas.

TABLE I

MILESTONE	DATE
Fabricate and Deliver 1st Iconel 625 Vacuum Vessel Bellows	11/77
Construction Contract for Experimental Complex to be awarded	12/77
PDR for the NB Power Conversion System	12/77
FDR for the Vacuum Vessel	1/78
PDR on the CVI Refrigerator for the Cryogenic System	1/78
Start Construction of the Experimental Complex	1/78
RFP for Torus Vacuum vessel	3/78
FDR for Vacuum Pumping System/Cryogenic System	3/78
FDR for Vacuum Vessel Heating/Cooling and Water Cooling	4/78
FDR for TF Coil, Case and Inner Support	4/78
Complete excavation for M/G Building	4/78
Complete foundation and below ground wall work for Office/Lab Complex	4/78
FDR of the Energy Supply and Distribution System	7/78
RFP for fabrication of the PF Coils	7/78
TF Case Fabrication RFP	8/78
TFTR Preliminary Safety Analysis Report	9/78
FDR of the Prototype NBSTF	9/78

Engineering

OVERVIEW

The Engineering Division provides the engineering services for design, construction, operation, maintenance, development and procurement specifying of electrical, electronic diagnostic, data handling and other systems required in support of all PPPL experimental devices and programs. Responsibility for the Forrestal Campus a.c. power distribution system is also within the Engineering Division. The Engineering Division is organized into seven functional groups. The functional responsibility of each group is as follows:

Division Administration

This group is responsible for the primary functions of management and leadership. It provides information, data and support for budgeting and monitoring, and guidelines for effective engineering procedures. It is a service group for engineers and is their liaison with other PPPL administrative offices.

Electronics

This group is responsible for the development of a wide variety of electronic circuitry including: interfaces between plasma diagnostics and data acquisition computers, multi-channel action-sequence timers used in conjunction with controlling and monitoring events of experiments. It also maintains, repairs and calibrates PPPL electronic equipment.

Power Electronics

The Power Electronics Group is responsible for the design of high-power rf generators and modulators used in the various methods (ion-cyclotron, lower-hybrid, neutral injection, etc.) of heating plasma.

Instrumentation

This group develops and produces specialized equipment and systems for plasma diagnostics including: microwave, x-ray, laser, neutron, infrared and other systems.

Mechanical Engineering

This group is responsible for all mechanical aspects of diagnostics, high-power rf equipment, laser optical mounts, probes, vacuum penetrations, access port coordination, and peripheral machine support structures. This section also has responsibility for the deionized water cooling systems.

Power Engineering

The Power Engineering Group develops high energy storage systems, including PPPL's large motor-generators, capacitive energy storage banks and power convertors that provide the power required by the various magnetic field coils and heating systems. It also has responsibility for device-related supervisory and annunciation controls, as well as the Forrestal Campus a.c. power distribution system.

Data Acquisition

This group is responsible for data acquisition systems involving on-line computer reduction of experimental physics data. This section also provides systems and scientific computer programming, in addition to the actual computers, acquisition and display hardware.

PROGRESS THIS PERIOD

Electronics Section

PLT Analog Safety Data Link

In order to protect PLT machine control room personnel and equipment from high voltage faults up to 20 kilovolts, an analog data link was developed (See Figure 39). Prior to machine use, a series of tests were conducted on the link to determine its ability to operate properly. These proved successful in over 30 tests run at 40 kv.

Along with the safety aspects, the data link has also helped eliminate interfering ground loops in the experimental system.

PLT Neutral Beam Fault Detector

The PLT machine neutral beam injection guns are high voltage, high current ion sources. They are subject to sudden internal flashovers and could completely destroy themselves, if left uncontrolled. A fault detector has been designed as part of a system to protect the ion sources during such flashovers. It limits the amount of energy delivered to the fault. Operation is expected during the next fiscal year.

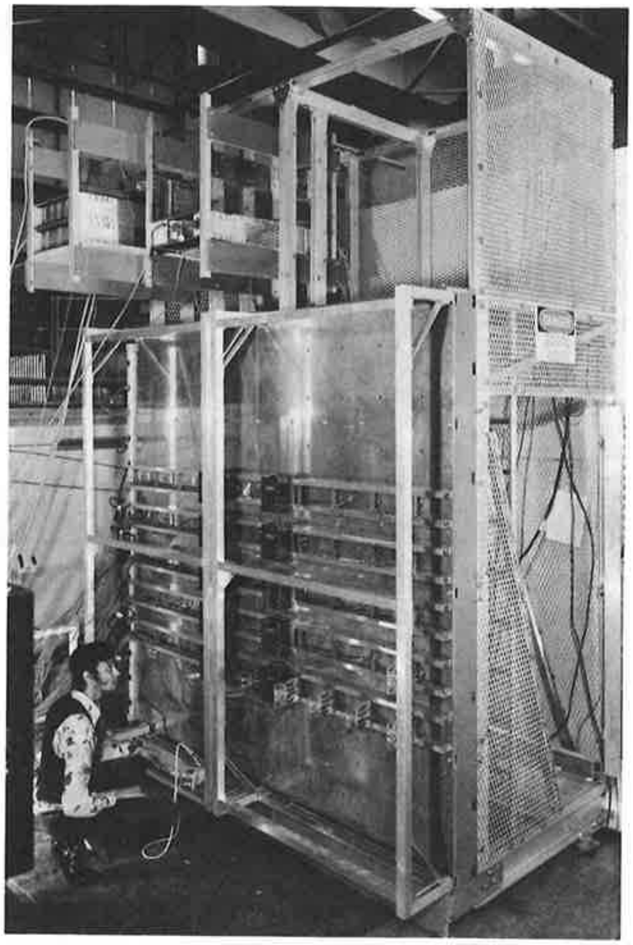


Figure 39. Safety data link rack (safe side).

PLT Neutral Injection Gas Valve Driver

A 3-channel gas valve driver was completed for the first PLT neutral injection gun. The valves are operated at high voltage with respect to control room ground. A fiber-optic cable is employed to provide isolation and carry the valve control signals.

PLT Neutral Beam Flux Monitor

A neutral beam flux monitor was constructed for use on PLT's ion temperature experiment. A tungsten wire bolometer intercepts the beam and is heated, changing the wire's resistance. This change is a measure of the beam flux. For peripheral measurement, four secondary emission posts are symmetrically located. They are connected to charged capacitors. The change in capacitor voltage is proportional to the charge removed by secondary emission. This is a measure of the beam flux.

PDX Thomson Scattering Electronics

A Thomson scattering system, using a laser beam probe, is being developed which will be installed on the PDX machine. It will measure the electron temperature and density in the plasma cross section at any point and time during the discharge.

Power Electronics Section

PLT ICRF Heating

In conjunction with the Ion Cyclotron Resonant Frequency (ICRF) plasma heating method, a system is presently under construction for the PLT machine. It is designed to provide power of 5 megawatts at a frequency of 55 MHz. The system is being built as two 2.5 megawatt modules. This design will allow much greater power levels for larger machines (TFTR or TEPR) by adding modules. It also eliminates a need for extensive redesigning. The bandwidth of the system will be sufficient to allow frequency variation during the plasma pulse. The frequency can then be optimized to plasma conditions at all times.

During FY77, system design was completed, most major parts ordered and received, and a substantial part of equipment fabrication completed. One 2.5 megawatt module should be operating into PLT by the end of 1978. The second is expected approximately one year later.

Lower Hybrid Heating

Two of the 50 kilowatt, 80 MHz, lower hybrid modules, formerly used on ATC machine, were upgraded to provide 200 kilowatts per module. These were loaned to General Atomic in San Diego for use in experiments on the Doublet II device.

TEPR Study

At the request of the Energy Research and Development Administration (ERDA), an in-depth study was made of available and anticipated power sources and handling techniques for ICRF and lower hybrid systems on very large machines (such as TEPR).

Instrumentation section

Interferometers

The PLT 8-channel, 2mm microwave interferometer, for measuring electron density, was completed. A more sensitive heterodyne interferometer was bench tested. Work was begun on a 10-channel, 2mm interferometer, as well as one of 4 channels, 8mm. An HCN (hydrogen cyanide) laser interferometer (1/3 mm) was installed on PLT. Phase-locked loop receivers and a new synchronous digital pulse measuring circuit were developed for improving the performance of interferometers.

Additional Major Projects

An electron cyclotron microwave emission receiver was built and became operational on PLT. It operates from 60 to 90 GHz. Design began for the PDX 15-channel soft x-ray pulse height analysis system. A diagnostic control system for scanning motors and other parameter devices was designed for PLT and PDX. This system is expected to come on line before PDX. A bridge and amplifier circuit was designed for a PLT bolometer diagnostic. Design was started on a faster plasma TV instant replay camera for PDX. An x-ray optics computer program was written for the design of the curved crystal x-ray spectrograph. A power amplifier was designed for possible use in improving the controls for PPPL's large motor-generators.

Also during FY77, were: the building of an improved parallel data channel logic board; building, interfacing, installing and evaluating a number of transient recorders; doing much digital transmission and interfacing; evaluating some CAMAC data acquisition equipment.

Mechanical Engineering Section

PLT ICRF Heating

In conjunction with the Power Electronics Section and the 25MHz/CRF, two half-turn load coils were designed and fabricated (See Figure 40). These have ceramic and Faraday shields. The ceramic shield was made from machinable glass ceramic (Macor), a proprietary product of Corning Glass Co. Coaxial high voltage feed-throughs for the 25 MHz ICRF system were also designed and fabricated. These are subject to sulfur hexafluoride gas pressure up to 45 psi on one side and a vacuum on the other.

Diagnostic Devices

A 10-millisecond scanning drive for a visible spectrum monochromator, was designed and fabricated for plasma scanning of the PLT machine (See Figure 41). It has 4 to 200 millisecond scan rate and

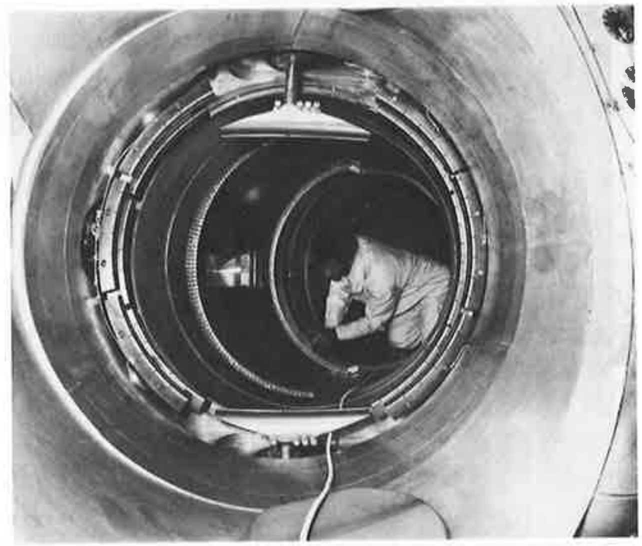


Figure 40. ICRF ½-turn coil installation on PLT.

vertical, horizontal and reversible scanning capabilities.

Other diagnostic devices completed during the year include: neutral injection calorimeters; a scanning mechanism for the PLT secondary charge exchange experiment; PLT limiter infrared scanning mirror; various probes and probing mechanisms.

Water System

Extensive modifications and additions were made to the main deionized water cooling system. A 6-inch branch line was installed to supply cooling

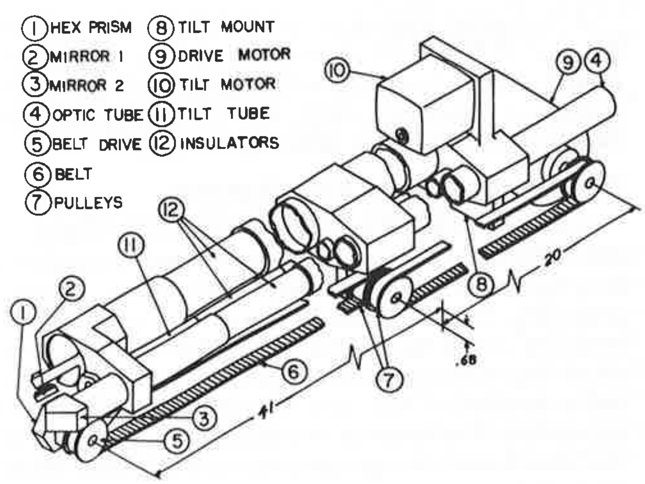


Figure 41. 10-millisecond scanning drive design.

water for the neutral beam test stand. Modifications were made for the neutral beam injectors on PLT.

A self-contained, closed-loop, deionized water system for the neutral injection rectifiers was also designed, constructed and put into operation. This system maintains a specific inlet water temperature to the ignitrons in the rectifiers. If the dew point exceeds this set point temperature, the system controls automatically adjust the inlet temperature to one degree Fahrenheit higher than the dew point. Therefore, it prevents "sweating" under high humidity conditions.

Power Engineering Section

PLT/PDX OH/SF Power Supplies

The OH (Ohmic Heating) power supply (See Figure 42) is used in conjunction with that method of plasma heating. The SF (Stabilizing Field) overcomes the tendency of the plasma, during heating, to move toward the vessel walls. During typical PLT machine operation in FY77, the OH power supply delivered 12,000 amperes at about 1,400 volts. It was available for use approximately 98% of the time. A number of steps were taken to improve availability. These included: providing more accurate and complete documentation to decrease repair or adjustment time; making replacement parts more readily available; isolating and remedying a number of chronic ailments. These measures improved availability to 99%. Others are anticipated to make this better than 99.5% in FY78.

The OH supply is designed to provide 22,000 amperes at about 1,100 volts. although this full capability was not required previously, it will be in the future. Therefore, tests were performed to 20,000 amperes, at about 1,200 volts, using PDX OH coils.

The design of the OH supply assumes that not less than 3,000 amperes will be required under normal operation. However, PDX may at times require momentary operations at much lower values. Tests were conducted and it was found possible to operate at currents of a few amperes.

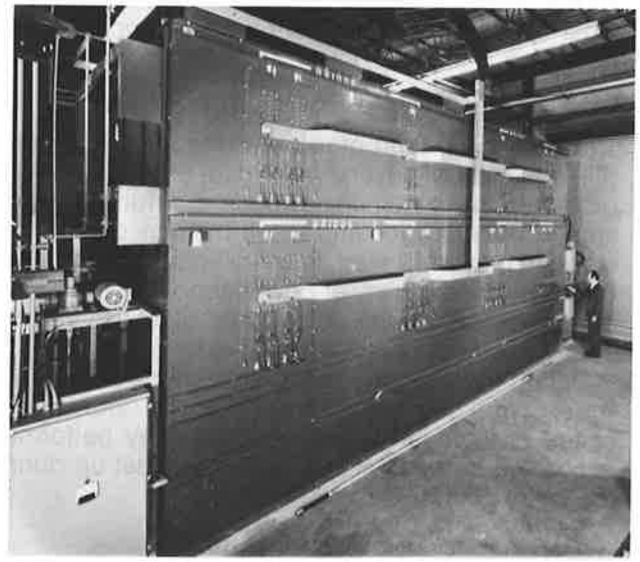


Figure 42. Ohmic heating power supply SCR rectifiers.

Neutral Beam Power System

Neutral beam injection for heating plasma requires quite complicated apparatus. The source itself is a vacuum tube of unusual design. It requires five power supplies, summarized in Table I.

In addition to the power supplies for the source, there are complex vacuum and instrumentation requirements. As a result, the controls for a single neutral injection source are as extensive and complicated as those for a tokomak, such as PLT or PDX.

Construction of the four power supplies, controls and instrumentation, for PLT neutral injection, was completed in FY77. A fifth system was constructed

TABLE I

SUPPLY	DC VOLTS	DC AMPS	REGULATION	RIPPLE
Accel	50,000	70	approx. 1%	<1%
Filament	12	2,400	5%	1%
Arc*	120 or 60	1,800 or 3,200	5%	1%
Decel*	5,000 or 2,500	8 or 16	1%	>1%
Bending Magnet	42	500	1%	1%

*These supplies can be connected in two ways; one configuration gives twice the amperes of the other, but develops only half the voltage.

for the neutral beam test stand and has operated for most of the year. All systems are expected to be operating in FY78.

PDX Poloidal Field Power Supplies

The poloidal field of the PDX machine is a complex resultant of several individual fields. These are produced by a number of coils distributed inside and outside the vacuum vessel. The time correlation, waveshapes and magnitude of currents in these coils require a variety of power supplies. They have different characteristics capable of satisfying the specific requirements of each field.

During the year, the poloidal field power supplies were completed (See Figure 43) and individually tested to their full power on PDX. They performed according to the design requirements set up during the initial planning.

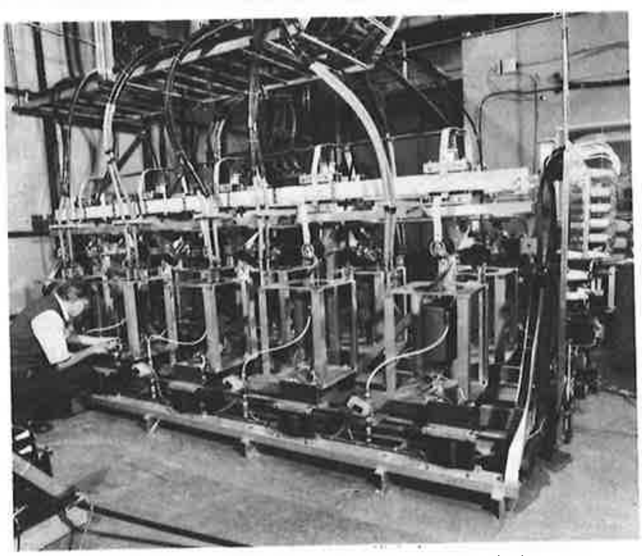


Figure 43. Poloidal field power supply ignition switch.

Substation Expansion—Transformers for Pulsed Loads

The PPPL substation expansion involved supplying power to rectifiers used for ongoing experiments. These rectifiers are configured for 4160 V AC service. In addition, transformers are required to supply power at 13.8 kV to the planned TFTR facility. The transformer configuration considerations, along with contingency plans and economics, yielded a design that involved three transformers. One is 4160 V and two are 13.8 kV. Each is rated 30/40/50 MVA (depending on the number of its cooling fans turned on). This corresponds to a 55° C temperature rise. As an "emergency" rating, 65° C was specified. The actual transformers (weighing 82.5 tons each) ran somewhat cooler. This indicates that their respective ratings might really be on the order of 35 MVA. The 4160-V transformer was specified for two million pulses for PPPL's experimental devices. A significant milestone in the TFTR construction program was achieved with the delivery of these two transformers.

Data Acquisition section

During FY77, several new diagnostics and a considerable amount of new computer hardware have been added to support the increasing requirements of the PLT/PDX data acquisition system. There was also a large amount of software work.

Diagnostics

An x-ray wave detector was added. It uses a 20-channel transient analyzer. This has a capability of digitizing at a rate up to 1 MHz it can store 4,000 samples for each of the 20 channels. Several Biomation Model 1015 waveform records have been added. These are for the Fast Ion Diagnostic and Cyclotron Emission Experiments. To record the neutrons produced from PLT as a function of time, a set of scalars have been interfaced to a PDP-11 computer. This provides a multiscaling facility (24 scalars each being read out once every 10 milliseconds). For the X-Ray crystal and neutrons from fusion experiments, two Tracor-Northern pulse height analyzers have been interfaced. These were also programmed to the system. Several Langmuir probes have been interfaced and are being recorded routinely. A study of the startup phase of plasma discharge is among the new uses for the existing slow digitized signals.

Computer Equipment

A disk drive and 128k words of memory for the PDP-10 computer was procured. Two PDP-11/34 computer systems to replace existing 11/40's and equipment to upgrade earlier 11/34's were also purchased.

Two Jorway CAMAC branch drivers that are general purpose devices were obtained. They support both the parallel and serial highways. CAMAC is a standardized packaging and interfacing specification for the design and construction of data acquisition hardware.

Software

A substantial amount of software effort has gone into the development of programs to run under the

RSX-11M operating systems, delivered with the 11/34's. The TV Thomson scattering experiment is going to be transferred to one of these 11's, with all the data analysis being performed on it. For use as drivers under RSX, a large amount of software has been developed to support the CAMAC systems and the PPPL produced parallel data channel.

Software has been written to support communications between the PDP-10 and the 11's, utilizing the existing DMA-10 interface.

Machine Design and Fabrication Division

OVERVIEW

The principal responsibilities of the Machine Design and Fabrication (MD & F) Division are the design, fabrication, modification and maintenance of experimental devices. This engineering activity also provides most associated support work required by the various experiments. This includes installation, operation and maintenance of certain general plant services and facilities in support of ongoing experimental research.

In order to control and perform economically the assigned tasks, the MD & F Division is divided into six functional groups. Each of these groups provides a specialized capability which has been developed over years of effort in support of plasma research. A brief description of each group's activities for this report period, together with details of specific accomplishments, is presented in the following paragraphs.

Division Administration

Administrative matters relative to the MD & F Division are controlled and directed by the Division Administration Section. This includes budgetary and personnel issues as well as technical supervision of the Division's work. A management system utilizing a PERT type computer program is used in the Division Office to schedule and cost projects assigned to MD & F. In this way, estimates from all of the sections are brought together to provide the initial time and cost data. Subsequently the Pert concept is used to monitor work progress. Maintenance and Trouble Reports are also compiled and made available through this office.

Field Design Section

The Field Design Section provides the personnel and techniques required for the design, simulation and/or 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 the coil's associated power needs. A number of computer codes have been developed (and continue to be modified) by the Field Design Section for the purpose of achieving the desired simulation and analysis of specified conditions.

Coil Design and Fabrication (CD & F) Section

Designs generated by the Field Design Section are converted into operating devices by this Section. Coil systems that are specified only by ampere turns at a mean dimension are carried to a full manufacturable product. This includes specification of materials, complete engineering drawings, energy balance studies and actual fabrication of the magnetic systems.

Coil Fabrication is performed both in-house and through outside contractors. Quotations are asked of capable vendors and selection is made from the responding list. The CD & F section provides vendors with materials and technical liaison. In-house resources consist of a well-equipped shop and personnel with twenty years experience in coil fabrication. This capability enables PPPL to develop unique magnetic systems that serve the experimental effort.

During the year, more than 80% of the section's effort was on PDX-related work. The coils in the interior of the vacuum vessel were completed, placed in their individual cans and welded shut (See Figure 44).

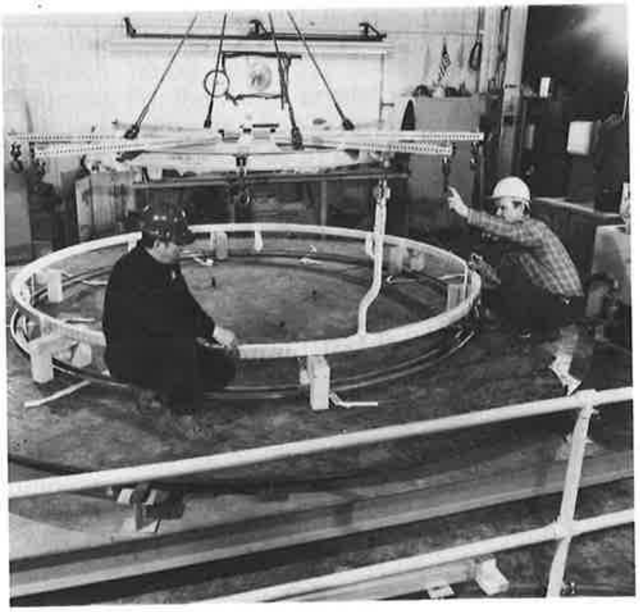


Figure 44. PDX PF coil about to be encased in stainless steel can.

At the same time the exterior coil arrays, which were up to 20 ft in diameter, were completed. An ultra sound inspection system was used to locate the copper turns in both the interior canned coils and

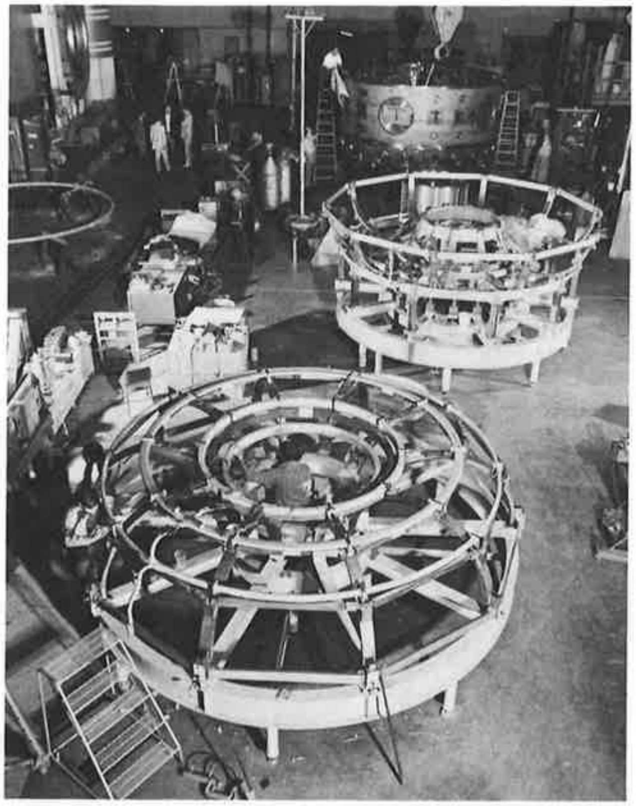


Figure 45. Top and bottom PF coil arrays for the PDX machine.

the exterior coils and coil alignment was accomplished within ± .020 inch (See Figure 45).

Other direct PDX support tasks included insulation of the center column torque tube (See Figure 46), installation of the PF bus on the machine and support of the power test program.

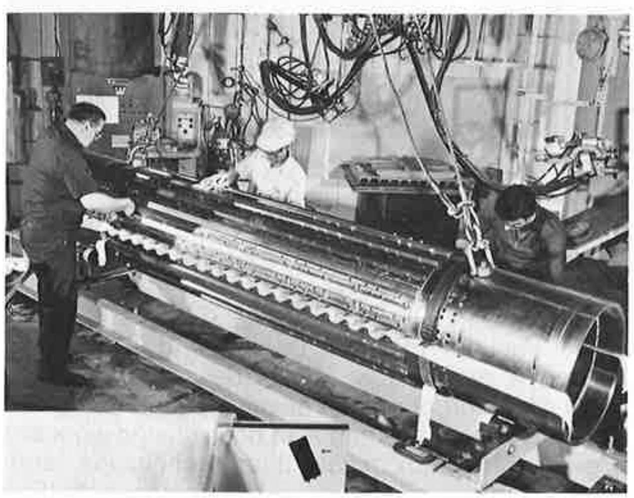


Figure 46. Insulation of PDX torque tube.

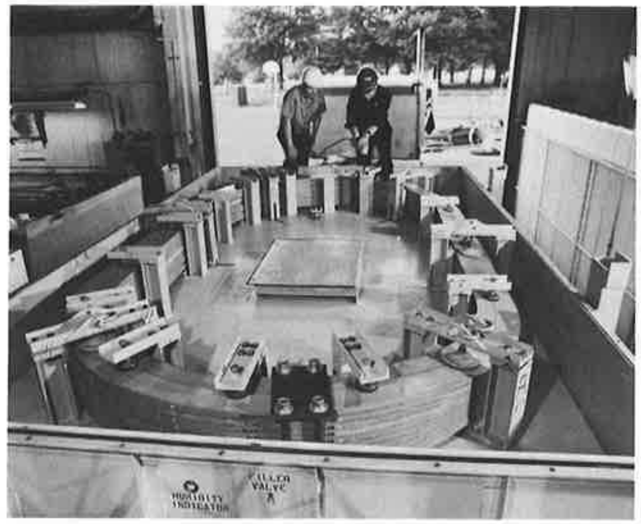


Figure 47. Arrival of first PDX TF coil – June 1977.

In addition to the shop effort, considerable engineering liaison and effort were provided in support of Kaman Aerospace Corporation. This vendor is under contract to produce the split toroidal field coils for PDX. The first two (of a total of 22) coils were delivered during the report period (See Figure 47).

Precise alignment and measurement of these coils was accomplished on a large fixture at the vendor prior to gun drilling of the pin holes (See Figure 48).

Other section activities included continued support of TFTR with insulation samples and engineering consulting.

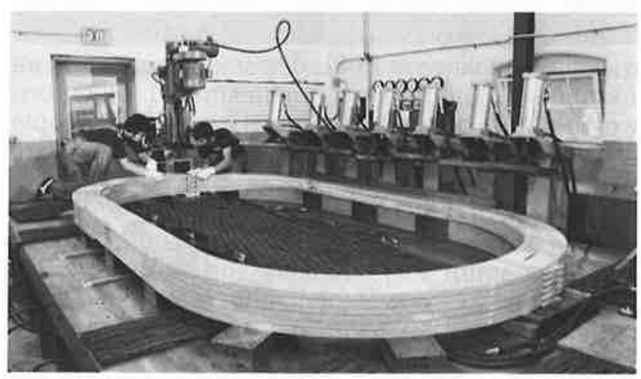


Figure 48. Alignment, measuring and drilling of PDX TF coils.

Structures Design and Fabrication (SD & F) Section

All experimental devices at PPPL have structural components that support the magnetic systems. The

SD & F Section is responsible for the design, fabrication, and assembly of these structures.

The engineering design of these structural components is the major effort of this section. Requirements generated by the Field Design and CD & F Sections are developed to provide the necessary strength and rigidity. Finite element techniques are available, using the more popular programs on several computers.

Another group within the SD & F Section provides testing capability. This includes standard materials tests at room, elevated and cryogenic temperatures. In addition, special techniques and equipment have been developed for use in high magnetic field and other conditions peculiar to plasma physics experimental machines.

With design and drawings completed, the SD & F Section purchases material and competitively contracts for fabrication of the parts. The majority of this work is performed by outside shops. As limited facilities are available in the University machine shops, as well as PPPL's own shops, these are used when quantities are small or if special attention is required in manufacture.

The final function of the SD & F Section is direction of assembly and testing of the finished product. After satisfactory completion of these tests, the device is turned over to the Experimental Division.

Engineering Services Section

This Section provides skilled tradesmen to all requesting activities at PPPL. The trades available are carpenters, electricians, metalsmiths, plumbers, welders and general utility workers. These people and their respective shop facilities support the various experimental programs.

One area of direct involvement is in operation and maintenance of the energy systems. These include motor-generator sets, rectifiers and capacitors that provide the D.C. power for magnet systems. In addition these same operators and maintenance people instlll, modify and maintain the high voltage AC lines that are PPPL's primary power source.

During FY77 the majority of effort in the Section was concentrated in PLT Neutral Injection Power Supply work and PDX assembly (See Figure 49).

Under direction of the Power Engineering Section, Engineering Services technicians fabricated structure, assembled components and did the connecting wiring required to complete the Neutral Injection power supplies. First phase work on this supply was completed during FY77 and put into operation.

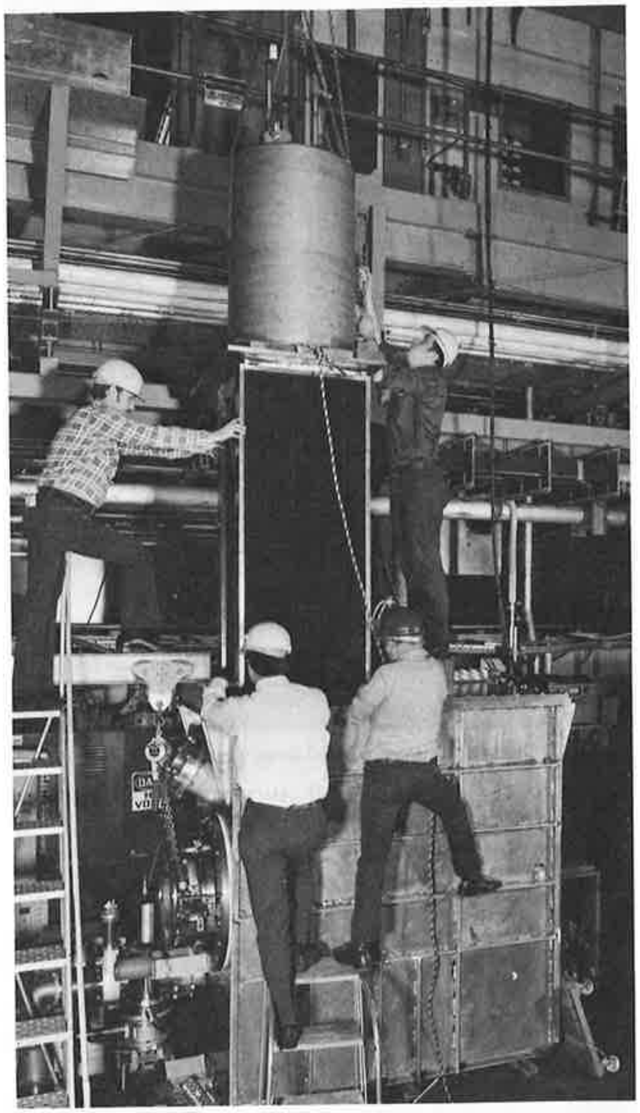


Figure 49. Neutral injection test facility cryo pump.

Vacuum Systems Design and Fabrication Section

The Vacuum Systems Design and Fabrication Section is responsible for the design, fabrication, installation and operation of vacuum and cryogenic systems. An engineering staff does design work and a group of approximately thirty technicians fabricates and installs vacuum system components (See Figure 50). A well equipped shop including facilities for machining and welding provides fabrication and maintenance capabilities.

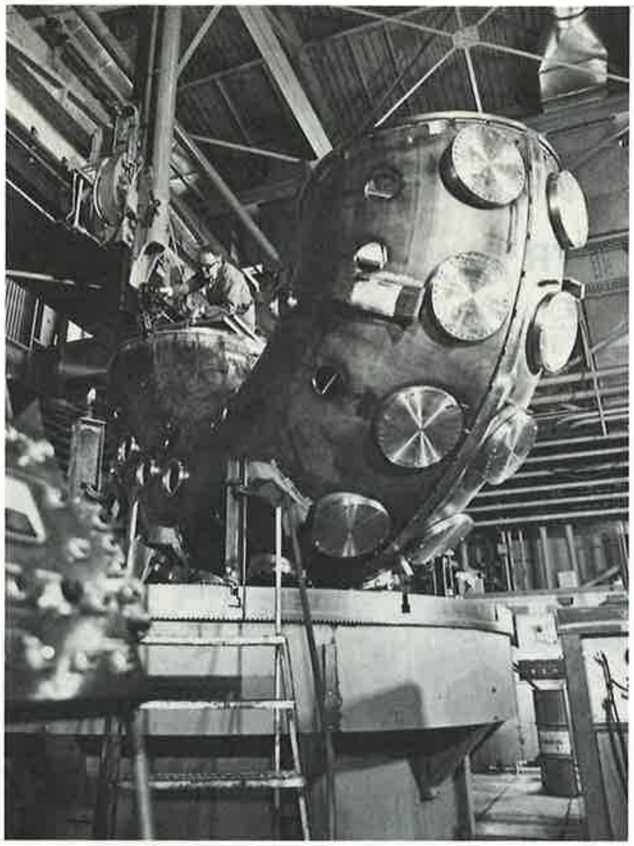


Figure 50. Machining of O-ring grooves on the PDX vacuum vessel domes.

Figure 51. Preassembly of PDX outer structure and TF coil cases.

ACCOMPLISHMENTS

The following efforts were accomplished by the Machine Design and Fabrication Division during this report period:

PDX

- The substructure was assembled in final location.
- The lower shelf was assembled and positioned on the lower base pylons.
- Pre-assembly of the upper shelf, torque frame and seven TF coil cases was completed and then dismantled to prepare for assembly of internal elements. (See Figure 51)
- The lower PF coil array and center solenoid were assembled on the lower shelf.
- The vacuum vessel was completed and leak checked (See Figure 52).
- All internal PF coils were positioned, their enclosures welded into place and the system was leak checked.
- The vacuum vessel was lowered over the solenoid onto its support system.
- The outer PF coil array was positioned around the vacuum vessel and supported on the lower array.
- The upper PF coil array was positioned over top of the vacuum vessel resting on the outer array and solenoid.
- All PF coil bus and cooling systems were installed and checked out.
- Power tests of the PF coil system were started in September, 1977.
- A detailed analysis of the TF and PF stray fields in PDX was completed.
- A fault analysis for PDX was begun and was still in progress at the end of FY77.

- A detailed numerical study of the magnetic islands in PDX was completed. The discovered linear dependence of ergodic region penetration versus perturbation strength allowed upper limits on coil tolerances to be developed.
- A program to compute ripple in arbitrary TF systems was completed. The program provides, in addition to conventional numerical output, magnetic field distribution plots on time-sharing terminals.

PLT

Large turbomolecular pumps capable of pumping 1,500 liters per second were tested and adapted to the PLT machine.

Support was provided for work on the neutral beam test facility. This test facility is used for pre-installation checking of beam lines and for the study of alternate and improved beam systems.

TFTR

- Engineering support was supplied to the TFTR group in the areas of TF coil case design and computer analysis of laminated structures.

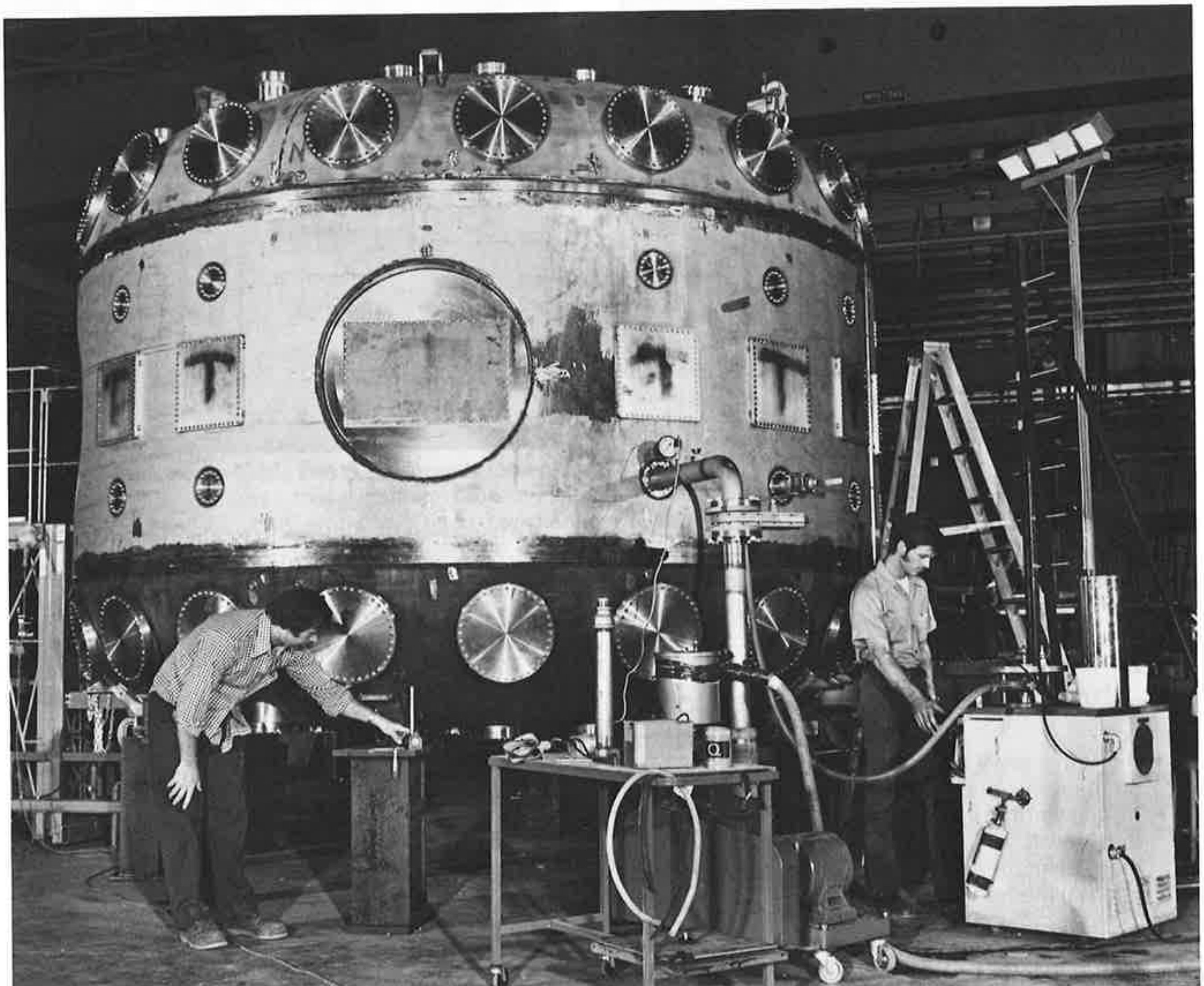


Figure 52. Leak testing of PDX vacuum vessel.

- An eddy current investigation on TFTR was begun in October, 1976, and was still in progress at the end of the fiscal year. Specific tasks were:
  a. Calculation of heating in cryogenic shields for the TFTR neutral beam.
  b. Calculation of vacuum vessel eddy currents using a resistive and inductive model.
- An analysis of the charged particle orbits in the TFTR neutral beam vacuum chamber was conducted.
- A magnetic poloidal field design for TFTR was completed.
- A preliminary study of bundle divertor currents, forces, etc., for TFTR was completed. Visits to Culham Laboratory in England and IPP and KFA Laboratories in Garsching and Julich, Germany revealed the general agreement that a divertor probably could be built for a downgraded TF field in TFTR, but that it would be a difficult task.
- Development of a program to calculate eddy currents in arbitrarily shaped conducting media was begun.

Materials Test Laboratory

Continued expansion of the SD & F Section's Materials Test Laboatory capability proved most helpful in performance of the PDX PF coil power tests. Deflection, strain and thermal measurements in magnetic fields were made without difficulty. Life tests of the TF coil joint were continued from the previous year. Acceptance testing of the TF coil joint hydraulic components was started.

Reactor Studies

OVERVIEW

The early application of fusion energy may be accelerated by using a fusion driver to breed fissile material from fertile material. Since the number of neutrons released in a high energy neutron-induced fission far exceeds the number released in a fission in any pure fission system, the combination of the two technologies (fusion-fission hybrid) leads important advantages not realizable by either single system. Hybrids may allow earlier practical application than the traditional goal of "pure fusion". They may also allow an otherwise elusive use of advanced fusion fuels.

In addition, certain categories of the hybrid fusion concept avoid many of the possibly objectionable characteristics associated with the pure fission approach (e.g., potential nuclear runaway and utilization of weapons-grade material) and the pure fusion approach requirements for large inventories of lithium and tritium. Of the various causes of concern normally associated with the deployment of nuclear power, only the problem of production of fission products will remain.

PROGRESS THIS PERIOD

During FY77, the PPPL Reactor Studies Division completed a comprehensive 2-year investigation into tokamak-based, fusion-fission hybrid reactors. This promising hybrid concept involves a characteristic of fast fission where the absorption of a 14 MeV neutron in fissionable or fertile material produces approximately 4.5 neutrons. This yield is twice the amount available in a pure fission system. The concept (i.e. accelerating the fission process utilizing fusion) reflects high potential for the realization of greatly improved energy yield by driving a subcritical fissioning system with a fusion device. The detailed report is currently being published.

Also during this period, a versatile systems analysis code was developed. This code, known as the Princeton Systems Analysis Code, is a process which compares thousands of math-modeled toroidal reactors and results in optimized toroidal design configurations. By comparing a variety of machine designs in a consistent manner, the sensitivities of reactor characteristics to design parameters have been demonstrated.

In addition, Ben-Gurion University of the Negev (under a Princeton University subcontract) completed a study of the light water hybrid reactor. (This reactor concept employs the highly successful technology of the Canadian developed heavy water reactors but with light water and the necessarily sub-critical lattice.) A formal report on this study is currently being prepared.

Also during FY77, research in Plasma Engineering resulted in the following developments: a) neutral particle transport techniques for tokamak plasma studies; b) transport equations for toroidal geometries; c) improved toroidal field coil designs.

Theory

OVERVIEW

The overall objective of the PPPL theoretical and computational efforts is the understanding of the physics of plasma confinement and heating in closed configurations.

Currently, the entire theoretical research effort is closely correlated with the various aspects of the experimental tokamak program. The work on MHD equilibrium and stability is also closely interwoven with the TFTR and PDX design efforts. In addition, computations have been performed for the Joint European Torus (JET) program.

Work on MHD stability criteria at high β is an essential component of the design of the proposed PDX high-power heating experiment, and this work has been closely coordinated with the effort at ORNL. The Princeton MHD codes are also used by the Wisconsin, Argonne, and Princeton Reactor Study Groups.

The PPPL code for obtaining tearing-mode stability boundaries has been used by the PLT experimental group to correlate the stability properties of measured current profiles with the observed magnetic oscillations. Time-dependent studies of magnetic island formation provide a good interpretation of many observed features of the internal and external disruptive instabilities.

Research on microinstabilities, and the associated anomalous transport, is forming the basis for predictions of performance characteristics of future tokamaks. Thus, the plasma transport model employed in the transport code was developed in close collaboration with the theoretical effort on low-frequency microinstabilities. Moreover, in this area, the particle-code simulation program has provided computer-experiment "data" on low-frequency turbulence in magnetically confined plasmas, for use by the PPPL microinstability group.

Ongoing computations with the transport code are performed in collaboration with the PLT group, and with the PDX and TFTR design groups. In addition, detailed comparisons are made, almost on a day-to-day basis, between transport-code predictions and experimental results from PLT. The high-grade neutral-injection codes developed by this group are proving especially useful in the design of the proposed TFTR Improvements.

RF heating theory is being coordinated with the rf experimental programs at PPPL and elsewhere. Much of the current rf theoretical work is being carried out in anticipation of the definitive ICRF experiment soon to be performed on PLT.

ACCOMPLISHMENTS/FINDINGS/ CONCLUSIONS

MHD stability limits on β in a tokamak

In 1973, PPPL commenced work on a series of computer codes expressly designed to study the MHD spectrum and, in particular, the stability properties of tokamaks. The Princeton Equilibrium Stability, and Transport (PEST) code, one result of this four-year effort, became operational in FY77, and the first results obtained with the code, (on the stability limit on β in tokamaks) were published.

The MHD group has since extended these studies, and has determined the critical β due both to surface kink modes and internal ballooning modes. Extensive parametric studies have also been made of the effects of aspect ratio, shape of the plasma cross section, and pressure profile on the critical β. In addition, similar studies on wall stabilization (by placing a conducting wall at a finite distance in the vacuum); on the influence of a pressureless plasma surrounding the main body; and of the effect of varying the safety factor q on the axis and at the plasma edge have been initiated.

The studies have indicated that $\beta \approx 5\%$ is achieved by suitable choice of parameters, in particular for aspect ration of about 3, and a D-shaped cross section with an elongation factor in the range 1.5–2.0. A survey of the effect of different q-profiles has also been completed. In general terms, it has been found that low-n (toroidal mode-number) free-boundary modes and high-n internal ballooning modes provide comparably severe stability limits on β.

A project is presently underway to extend this code to include the resistive modes.

Axisymmetric instabilities of noncircular cross section tokamaks

One of the most serious threats to the successful operation of noncircular cross section tokamaks (such as the PDX device) is the axisymmetric instability, or instability of the plasma to a change of shape of its cross section. To study this phenomenon, the Theory Division has developed a two-dimenstional, time-dependent, nonlinear ideal MHD code, based on magnetic flux coordinates.

Recently, studies performed have been extended and refined by allowing the field-shaping coils near the surface of the plasma to interact with each other and with the plasma, as determined by their mutual inductances and by the appropriate circuit equations. This simulation of the naturally occurring, passive feedback of the coils has significantly improved the realism of the model of the actual physical experiment.

Linear theory of resistive instabilities in a torus

Over the past four years, PPPL has been developing a more complete theory of resistive MHD instabilities in a torus. Past results can be summarized as follows. The current-driven tearing mode, with poloidal and toroidal mode numbers m and n, is unstable if $\Delta' > \Delta_c > 0$. Here, Δ' is a measure of the magnetic free energy available to the mode, and Δ_c is a measure of the stabilizing influence of toroidal curvature and depends on the resistivity η.

A computer code has been written which determines the stability of observed PLT discharges to these modes. The code reads averaged data files from the laser Thomson scattering experiment, evaluated Δ', Δ_c, and other relevant parameters, and calculates the eigenfunctions and growth rates for the modes. Preliminary comparison with x-ray fluctuation data has indicated that there is a good agreement, in the sense that a mode is observed if and only if the code predicts instability.

A project directed toward the development of a kinetic theory of resistive instabilities in a torus is currently in progress. The results to date indicate that the assumptions of the simple fluid theory (on which certain predictions have been based) may not be well satisfied in a tokamak. The small collision frequency implies that the resistive layer thickness may be comparable to the ion Larmor radius. The problem is being studied by means of various small-parameter expansions of the Fokker-Planck equation in toroidal geometry. Results indicate that parallel viscous and gyroviscous terms may strongly influence the mode in a torus as the collision frequency drops.

Nonlinear tearing modes and the disruptive instability

A series of codes for treating ideal MHD and resistive problems in two dimensions has been developed in the last two years. The tokamak is taken to have a circular cross section with $B_z >> B_\theta$, so that a cylindrical approximation can be used. An inverse aspect ratio expansion is also employed.

The nonlinear growth and saturation mechanisms of resistive tearing modes are of great interest in present tokamak operation. The saturation of a single helical mode has been studied and results from the code have allowed for the construction of an analytical model which describes the saturation process extremely well.

To date, two major extensions of this work, which are of immediate relevance to tokamaks, have been investigated. The first extension is the inclusion of diamagnetic corrections, which are important at present tokamak temperatures and will become increasingly so. (Linearly, these diamagnetic corrections cause the islands to rotate in the direction of the electron diamagnetic drift, as observed experimentally.)

The objective of the second extension is the study of the interaction of modes of different helicities, which has not been possible with the present two-dimensional codes. This problem is of major interest since such interaction is of undoubted importance in the major disruption observed in tokamak operation. Both numerical (partly in collaboration with B. Waddell at Oak Ridge) and analytical modes of attack on this problem are underway.

In support of the idea of the importance of different-helicity modes present at the same time, it has been recently shown (within the 2D model) that there are certain kinds of j(r)-profile that are especially unstable to $m = 2$ modes, even in the nonlinear regime, so that very large $m = 2$ islands are created. Such "square-shaped" profiles could well be created by the shrinking of earlier profiles by the action of precursor $m = 2$ modes, and the flattening of the central part of the profile by internal $m = 1$ "sawtooth" modes. Finally, a profile might be created that is strongly unstable both to $m = 2$ and $m = 1$ and, indeed, to a number of higher-order modes like $m = 3$, $n - 2$, etc. Considered alongside PLT data, this seems to provide an encouragingly successful interpretation of the major disruptive instability.

An investigation has also been completed of feedback stabilization of the $m = 2$ mode, by means of currents in a helical coil outside the plasma. Provided the phase of the impressed signal can be suitably related to the phase of the observed mode, the technique should be successful in holding the amplitude of the $m = 2$ mode to acceptable levels.

Drift, trapped-electron, and trapped-ion instabilities in tokamaks

Over the past year, a major effort has been underway to increase the accuracy and generality of calculations of the linear growth rate and two-dimensional structure of trapped-electron and drift modes. Results in the limit $k_r\rho_i << 1$, where k_r is the radial wavenumber, and ρ_i is the ion gyroradius have been generalized to arbitrary $k_r\rho_i$. The method used involves expansion of the perturbed electrostatic potential in complete sets of radial and poloidal basis functions to convert the quasineutrality integral equation into a matrix equation. Typically, it has been found that the potential is localized in θ in the region where the trapped particles are located and extends radially over several mode-rational surfaces.

Recent extensions to the two-dimensional (2-D) code have removed the restriction that ion magnetic-drift frequencies must be small compared to the mode frequency, and have improved the electron and ion collision operators to allow consideration of the plateau and Pfrisch-Schlüter regimes, in addition to the banana regime. This allows treatment of the transition in toroidal geometry from the trapped-electron mode to the well-known collisionless and collisional drift waves. In particular, a number-conserving Krook operator is used for the electrons.

Calculations of this type can eventually be used to improve the estimates of the anomalous diffusion coefficients used in transport codes.

Drift-tearing instabilities and finite-β modified drift waves

For tokamaks with $m_e/m_i << \beta << 1$ drift waves are coupled to shear Alfvén waves. Such finite-β coupling not only modifies the properties of drift modes but also provides a channel through which MHD-like tearing modes can be driven unstable by the expansion-free energy due to finite density and temperature gradients.

These two types of oscillations, drift-modified tearing modes and finite-β modified drift waves, are differentiated by their asymptotic behavior away from the mode-rational surface.

Drift-tearing modes in the trapped-electron regime have been investigated. The results indicate that the collisional detrapping of trapped electrons provides the mechanism via which the expansion free energy can be released to excite drift-tearing modes. For normal temperature gradients ($d \ln T_e/d \ln n > 0$), the modes are unstable in the collisional regime ($\nu_{eff} > \omega_{*e}$), but stable in the collisionless regime ($\nu_{eff} < \omega_{*e}$). Furthermore, for typical tokamak parameters, the unstable modes could have high poloidal mode numbers.

Driftwave turbulence

PPPL is currently in the process of developing a strong turbulence theory for drift waves. The work is primarily motivated by recent microwave/CO_2 laser scattering experiments in toroidal devices like ATC, ALCATOR, TFR, PLT, etc. These measurements indicate that turbulent drift waves often have broad spectral widths in frequency domain (i.e., $\Delta\omega \sim \omega$). This observation is consistent with the measured fluctuation level of a few percent since the dominant nonlinear mode-coupling terms in the governing equations become comparable to the linear response terms. The observations thus indicate a breakdown of conventional weak turbulence theory.

For the self-consistent nonlinear problem, the approach is twofold: viz., (i) solve the mode-coupling equations numerically and (ii) use the closure schemes of direct-interaction approximation, which have been reasonably successful in describing strong turbulence of neutral fluids. PPPL has already attempted the former for 2-D turbulence involving viscosity-driven, flute-like drift waves and viscosity-damped 2-D convective cells. Many features like isotropization of the turbulent spectrum by $\underline{E} \times \underline{B}$ nonlinearities, broadening of spectral lines, etc., have already been observed. A similar code for the 3-D problem is now under preparation.

Particle transport in braided magnetic fields

Most theories of cross-field transport in tokamaks assume the existence of magnetic flux surfaces. However, it has been determined that flux surfaces can be destroyed when small radial magnetic perturbations of incommensurate helicity are present. A crude criterion for destruction is that the stochasticity parameters $s \equiv \frac{1}{2}(\Delta\mu + \Delta\mu')\,\rho_{\mu,\mu'}$ exceed unity, where $\mu \equiv \{m, n\}$, m and n are respectively the poloidal and toroidal mode numbers, $\Delta\mu$ is the island width of resonance $\mu(m - nq = 0)$, and $\rho_{\mu,\mu'}$ is the radial separation between two adjacent islands.

In the stochastic regime, $s \gtrsim 1$, the magnetic lines wander ergodically throughout the volume. Thus, radial particle and heat transport much more rapid than neoclassical can result by flow parallel to the stochastic lines, which now link different radii. In the collisionless regime, it has been estimated that the particle radial diffusion coefficient $D \equiv <\delta r^2>/2t$ to be $D = D_M V_{\parallel}$, where D_M is the diffusion coefficient of the magnetic lines and $V_{\parallel}$ is the parallel velocity of the particle. Currently, an attempt to derive this result from kinetic theory and to extend it to the collisional regime is in progress. Of prime concern, also, is the description of the self-consistent turbulent interactions of the random stochastic currents with the modes which produce the stochasticity. It is hoped that this work will provide a quantitative theory of anomalous electron heat transport in tokamaks.

Particle code stimulation of tokamak phenomena

Over a period of several years, the particle-code group at PPPL has been applying the techniques of particle-code stimulation to the problems of toroidal devices.

Recently, a major effort has been to study the anomalous diffusion due to low frequency drift instabilities, and to develop new codes including 3-D magnetostatic codes and hybrid code in both cylindrical and toroidal geometries.

The nonlinear behavior of the collisionless drift instability, and the resultant anomalous plasma transport, have been studied by means of a cylindrical geometry as well as by analytic theory. In the simulation, the plasma initially has a Gaussian density profile, with uniform temperature. The results of simulations indicate that a strong turbulence develops through the nonlinear interaction of the drift instabilities, which results in the formation of convective cells and anomalous particle diffusion.

Tokamak transport and neutral injection calculations

A new tokamak transport code, BALDUR, has been developed over the last few years. BALDUR has been designed to be a flexible code with many features necessary for modeling current and future tokamak experiments. The code has a model for two or more impurity species, such as O, Fe, and W. The coronal equilibrium atomic data for 48 possible impurity species has been calculated and included in the code. BALDUR allows the use of two or three hydrogen species such as D and T for TFTR and other fusion experiments. The neutral gas density in BALDUR is computed with a Monte Carlo algorithm. Using a number of well-established techniques, high accuracy can be achieved for only a few particles. Extensive work has been done to construct models for neutral injection. A simplified Fokker-Planck equation with pitch-angle scattering and slowing down is solved at each radial mesh point for the beam ions. Adiabatic compression of the beam ions and background plasma is computed for fast and slow compressions. A Monte Carlo neutral beam injection algorithm has been written and tested, and has been implemented in the code. An unconventional but very rugged numerical scheme has been used in BALDUR to provide a stable, usable, and fast code. BALDUR has been written using the Olympus format and can be run on either the CDC 7600 or PDP-10. The transport coefficients may be easily chosen from a variety of standard models, which may be modified by the user.

A Monte Carlo neutral beam injection code has been written to study the orbit losses of injected fast ions from tokamaks. The main questions these calculations have tried to address are the extent of the losses due to trapping in the toroidal field ripple of TFTR for nearly perpendicularly injected ions, and the losses of tangetially injected ions due to bad conventional orbits. The first part of the code is a Monte Carlo neutral beam deposition algorithm. This algorithm takes into account all of the engineering details of the neutral beams such as focusing, divergence, arbitrary injection geometries, etc.

Recently, the code has been used to diagnose PLT data, to support the PDX 10-MW neutral injection proposal, and the TFTR Improvements proposal.

Impurity radiation for high Z ions

In collaboration with an atomic physics group at the Lawrence Livermore Laboratory, the energy loss rates due to radiation in tokamak plasmas were calculated for a variety of partially ionized impurity ions ranging from helium ($Z = 2$) to gold ($Z = 79$). For low-Z elements, the results agree very well with previous calculations, and with experimental results. The loss rates for the high-Z impurities, such as tungsten, are as much as a factor of 60 higher than previous estimates. The results imply that as little as 0.01% tungsten will prevent ignition in a 10 keV tokamak reactor.

Divertor theory

In addition to their well-known role in controlling impurities, divertors may be necessary on tokamaks due to the excessive limiter heat loads predicted for large devices. Features of the divertor scrape-off, which are determined by the magnetic configuration, were investigated. One surprising feature of the magnetic field in the scrape-off layer is that the safety factor q is not large in the bulk of the layer, although it is infinite on the separatrix. The derivative of q is quite large, however, which implies it is easy to destroy the magnetic surfaces in the scrape-off layer with magnetic perturbations. The width of this region of destroyed surfaces (called the ergodic layer) has been calculated. The ergodic layer essentially sets a lower limit on the width of the scrape-off layer due to irreducible magnetic perturbations. One could also introduce magnetic perturbations to spread the heat load on the neutralizer plate. It is important to note that the width of the ergodic layer is most sensitive to perturbations which are large on the separatrix surface away from rather than close to the x point.

Work is also being done on the width of the scrape-off layer due to classical fluid effects. These theories give scrape-off widths up to the poloidal ion gyroradius $\rho_\theta(\rho_\theta \sim 0.3$ cm in most tokamaks). The phenomenon that determines the width is the ions' carrying their momentum to the neutralizing plate as they leave.

The work on divertor and sheath problems has, until recently, been supported mainly by EPRI, under a contract for Tormac theory.

Theory of lower-hybrid heating

Lower-hybrid heating relies on launching, by waveguide arrays, an electrostatic wave that propagates in resonance cones across the field lines and heats the plasma by a variety of linear and nonlinear processes. The goal of this work is to predict the spatial deposition pattern of the rf energy, the percentage absorbed by ions and electrons, and the important parameters to manipulate for optimum heating. The main difficulty in transporting rf energy to the plasma core was identified as arising from parametric decay instabilities which occur above a threshold power per waveguide array, $P \propto B^2 T_e^{3/2} n^{-1} N^{-1}_{11}$ (where B is the magnetic field, T_e is the electron temperature, n is the local density, and N_{11} is the parallel index of refraction of the incident rf). Typically the threshold power per waveguide P $\sim$ 1 MW but, if the wave frequency equals the maximum lower-hybrid frequency, the threshold at that surface is much lower. Plasma heating, if due to nonlinear effects, should show a density threshold for a fixed frequency according to this theory, and that prediction is in reasonable agreement with experimental results on ATC and WEGA. The saturation of these parametric instabilities has been studied via mode coupling codes and particle simulation. These show that saturation occurs when the energy density in parametrically excited waves is a few times the energy density in parametrically excited waves in the incident rf. The saturation mechanism is a transfer of energy into very short wavelength modes that are strongly absorbed by ions and electrons with velocities between v_{th} and $5v_{th}$; i.e., in the tail of the distribution. Each species absorbs energy in roughly equal portions.

ICRF Heating: An interpretation of the ATC experiments

The ion-cyclotron heating experiment on the ATC produced an increase in the ion temperature from 180 eV to 300 eV. In view of these promising results, it is important to understand what physical processes govern the ion heating in the ATC experiments and how this physics extrapolates to larger tokamak experiments.

The single-species theory predicts the presence of high Q toroidal eigenmodes of the compressional Alfvén wave whenever the wave frequency is above the ion-cylcotron everywhere within the plasma. The experimental measurements show quite a different situation. These measurements pertain to nominally deuterium plasmas and show that, when the toroidal field is adjusted so that the second harmonic deuterium gyrofrequency is equal to the impressed wave frequency at the center of the plasma, the toroidal eigenmodes have a low Q value. These results suggest that the single-species theory is incorrect and that the absorption of wave energy and the ion heating is proceeding via some process other than second harmonic absorption.

An understanding of these results has been obtained by considering the role of the ion-ion hybrid resonance. The nominally deuterium plasma will contain small concentrations of protons because the deuterium heating experiments were interspersed among the hydrogen confinement experiments on a day-to-day schedule. For a plasma composed of deuterium with a minority concentration of protons, the equations governing the propagation of the compressional Alfvén wave have a resonance at the ion-ion hybrid frequency which lies close to the proton gyrofrequency for the case where protons are a minority species. Efforts have been concentrated on answering two questions. First, how large is the wave damping decrement associated with the ion-ion hybrid resonance? Second, by what process is the wave energy absorbed? It has been found that absorption by the ion-ion hybrid resonance can completely eliminate toroidal eigenmodes and that wave energy absorption proceeds via double linear-mode conversion process which depends on the presence of a finite poloidal field. For the parameters of the ATC experiment, it has been determined that *roughly* 30% of the absorbed energy goes to deuterons — in agreement with observations. The remainder is transferred to electrons.

What are the implications for future tokamak experiments? It has been learned that, to take advantage of second harmonic absorption and toroidal eigenmodes, the ion-ion hybrid resonance must be avoided. This, in turn, means that either proton concentrations of less than 1% must be achieved or that the plasma must be composed of ions for which there is not a degeneracy between the fundamental gyrofrequency of a minority species and the second harmonic gyrofrequency of the majority species. Both D-T and p-He^3 plasmas have this property. On the other hand, if a decision is made to design an experiment that does not use toroidal eigenmodes and provides strong wave absorption, then the ion-ion hybrid resonance will fill this requirement and yield mostly electron heating.

Numerical Fokker-Planck Studies

Studies of runaway production rates have been continued by employing a simplified model — Maxwellian collision coefficients and a more exact model of the Fokker-Planck equation with losses (to balance ohmic heating). The latter can only be rough since detailed loss mechanisms are unknown. For small values of $E/E_{crit}(<0.05)$, the runaway production rate is the same for both models and, therefore, probably reliable. This is consistent with the experimental results on PLT. For $E/E_{crit}>0.05$ the curves are unreliable as are any extant theories, and it is probably not possible to predict runaway rates without a knowledge of the loss mechanisms. In fact, these rates are in very poor agreement with results on runaway rates in ST.

The code has also been used to explore a number of physical problems besides those associated with runaway electrons:

1. The problem of how fast the Maxwellian tail of an isolated plasma is set up has been considered.
2. Quasilinear terms have been introduced into the Fokker-Planck equation to compute the rate of heating of a plasma by externally produced radio frequency waves. Second-harmonic ion-cyclotron wave heating, and lower-hybrid heating of electrons have also been studied.

PPPL General Purpose Computer

During FY77, a Control Data Corporation CYBER 172 was selected as PPPL's new General Purpose Computer (GPC). The dual processor CYBER 170/Model 172 represents a major addition to the computing power available to all users at PPPL. After installation and testing, the computer was scheduled to be ready for use early in 1978.

The GPC's dual processor provides both timesharing and batch processing to users. Each central processor operates independently, and may carry on computations as if it were a separate computer. A unique feature of CDC computers is the addition of peripheral processors, mini-computers with 4096 words of memory, which handle many operating system functions, such as input-output requests, and also provide for some text editing. The CYBER 172 has 14 of these peripheral processors. The GPC has 196,000 60-bit words of central memory and 262,144 words of extended core storage (ECS). ECS can be used for fast access data storage, and provides for very high speed swapping. Both memories have single error correction and double error detection (SECDED) features, for added reliability.

Attached directly to the GPC is a high speed printer, capable of printing more than 1000 lines-per-minute, a 1200 card-per-minute reader and a 250 card-per-minute punch. An electrostatic printer-plotter makes high quality graphic output available. Five magnetic disks each hold 237 million characters. Redundant access is provided for three of the disks, so that failure of a disk access path will remove only one disk from the system. The rate of transferring data from disk to memory is maximally over 900,000 characters-per-second. For comparison purposes, the disks each offer storage capacity approximately double IBM 3330 disks on the 360/91.

Four magnetic tape drivers are included with the computer system. The tapes are 1600 bit-per-inch, 9 track.

Two remote job entry terminals extend the accessibility of the computer to major groups of users within the laboratory. Each remote terminal has line printing and card reading capabilities. Users may also access the computer from keyboard terminals using the laboratory telephone system. The system is configured to handle up to 80 such timesharing terminal users.

An extensive array of software is available. Programming languages will include: FORTRAN, PL/1, COBOL, APL, BASIC, SNOBOL 4, ALGOL 60, SIMULA, LISP, and PASCAL.

Maintenance of large files of data may be accomplished by use of Data Management System-170 and the Sort/Merge and UPDATE packages, all supplied as part of the systems software.

Several text editors and various utility routines enable the user to perform routine tasks on the computer. The IMSL library of scientific subroutines is supplied as part of the software.

Administration

Fiscal year 1977 was one of continued growth for PPPL spurred by preparations for the operation of a new tokamak, the $26 million PDX in 1978, and the fabrication and operation of the $239 million TFTR in 1981. PPPL's growth is demonstrated by the financial summary presented in Table I.

STAFF

As of October 1976, the Laboratory's full-time staff totaled approximately 750 and by the close of FY77, in September 1977, this number had risen to nearly 900. The employee breakdown as of September 1977 was:

Faculty	4
Physicists	72
Engineers	168
Technicians	482
Others	165
Full time Total	891

During FY77 emphasis was placed on the improvement of communications between employees and supervisors. Regularly scheduled information and discussion meetings were conducted with various classification groups. Management meetings were established to inform supervisors on Laboratory operations and procedures; and new employee orientation programs were conducted quarterly.

In addition, the Personnel staff started a "walk around" plan, putting Personnel representatives in the work area so employees could conveniently seek advice and assistance.

The Laboratory also established an Administrative Advisory Committee (AAC), comprised of elected representatives from all classifications. The group, which meets twice each month, reviews employee concerns and suggestions and directs recommendations for change to the Associate Director for Administration.

FACILITIES

As of October 1, 1976, the Plasma Physics Laboratory occupied a total of approximately 437,000 gross square feet of building space in Government owned and University owned buildings at "A", "B", and "C"-Sites on the Forrestal Campus of Princeton University.

The buildings accommodate a variety of functions and spaces including offices, laboratories, research, shops, high bay experimental areas, warehousing and storage, fabrication and assembly, maintenance activities, library and cafeteria food service. On-site support facilities include parking, electric switchyards, cooling towers, outdoor power supply equipment, utility services and distribution systems.

During the 12 month period comprising fiscal year 1977, from October 1, 1976 through September 30, 1977, a number of facility addition and improvement projects were undertaken by the laboratory.

These include the following:

- Theoretical Wing Office Addition
  5200 GSF $368,000 FY1977 GPP
  Sched. Compl. 4/78
- Computer Center Addition
  5700 GSF $433,000 FY1977 GPP
  Sched. Compl. 4/78
- Office/Laboratory Addition
  5100 GSF $340,000 FY1977 GPP
  Sched. Compl. 5/78
- M/G-C/S Passageway and Support Space
  2300 GSF $120,000 FY1976A and FY1977 GPP
  Sched. Compl. 3/78
- "C"-Site Parking Area Expansion
  250 cars $168,000 FY1976A and FY1977 GPP
  Sched. Compl. 5/78
- ICRF Power Equipment Yard
  $ 15,000 FY1977 GPP
  Sched. Compl. 3/78
- Office Addition to Buildings 1-O and 1-P
  8000 sq. ft. $250,000 TFTR
  Sched. Compl. 1/78

Construction work was begun on TFTR facilities at "C"-Site, including the 60,000 sq. ft. $6,500,000 Office and Laboratory Building, a 6,000 sq. ft. $550,000 addition to the Tech Shop, and overall site preparation and underground utility distribution work.

During FY77, approximately 7,000 square feet of space in Building 1-E at "A"-Site was modified to provide offices for Ebasco/Grumman, the TFTR in-

TABLE I
FINANCIAL SUMMARY

$K

PROJECT	**1974**	**1975**	**1976**	**1976A**	**1977**
*OPERATING					
Closed Confinement:	11,885	15,037	20,665	6,969	23,073
PLT Fabrication	5,552	3,821	1,770	1	0
Operations (inc.ST)	2,880	3,540	5,725	2,335	7,304
Coil Test	0	157	600	15	314
Neut. Beam Pwr. Supp.	0	1,029	1,960	268	1,289
Test Stand	0	0	90	378	296
ICRF	0	50	0	72	1,035
PDX Fabrication	0	2,110	6,495	2,866	8,547
Operations	0	330	1,665	999	3,608
ATC	2,128	2,370	1,545	15	0
FM-1	1,325	1,630	815	20	0
H-1	0	0	0	0	666††
Other	0	0	0	0	14†
DEVELOPMENT & TECHNOLOGY:	2,008	3,480	3,820	259	597
H-1	552	853	630	208	
Reactor Studies	229	266	355	72	456
Two Component Torus	381	2,160	2,835	(21)	0
Advanced Tokamak Studies	0	0	0	0	120
Other	846*	201**	0	0	23***
RESEARCH:	1,787	2,614	2,945	843	3,005
Theory	1,093	1,848	1,985	545	2,008
Basic Experiments	694	766	760	240	668
User Service Center	0	0	200	58	329
REACTOR PROJECTS:	0	0	340	985	10,556
TFTR R&D	0	0	340	985	9,991
Research	0	0	0	0	241
Operations	0	0	0	0	324
TOTAL	15,680	21,131	27,770	9,056	37,233
***EQUIPMENT**					
Not related to Construction	610	2,066	2,630	647	5,190
CONSTRUCTION					
TFTR	0	400#	15,000	5,500	75,000
General Plant Projects	212	500	700	250	1,455

*E&D 186, Cyrogenics 80, Computer 84, PDX 414, Vacuum 31, Systems 51; **Systems ***EPR RF Heating
†Ripple Injection Coil ††Moved from Development and Technology in 1977 # CP&D

dustrial subcontractor. In addition, 8,000 square feet of space in Building 1-A was modified to provide offices for PPPL and Ebasco/Grumman.

At "B"-Site, Building 8-A was modified to make office space for the PPPL Purchasing Department.

At the close of FY77, the total PPPL physical plant space is summarized as follows:

	Government Owned	University Owned
"A"-Site	31,300	77,000
"B"-Site	—	100,020
"C"-Site	245,100	—
	276,400	177,020
Grand Total, space		453,420 GSF

THE PPPL LIBRARY

Overview

The Plasma Physics Laboratory Library functions as the depository and control center of all published reference literature pertaining to the fusion program. This library, a branch of the Princeton Firestone Library, is located within the Forrestal complex and is fully equipped and staffed to support its intended functions.

The library is an autonomous entity and is devoted solely to supporting the reference and research activities of PPPL personnel with technical interests related to nuclear engineering and computer sciences.

The capabilities and resources of the PPPL library are upgraded and enchanced on a continuous basis with sophisticated inplace features such as the computerized literature search system experiencing constant expansion.

Progress This Period

The growth in inventory of data and documents located within the PPPL library for this report period is shown in Table II.

TABLE II

CATEGORY	FY76 QTY.	FY77 QTY.	% INCREASE
Monographs	2,890	3,046	5.4%
Bound Journals	3,012	3,493	16 %
Reports	11,239	12,943	14 %
Microfiche	12,835	14,701	14.5%

Interlibrary Loan Activity

The increase in "Interlibrary" Document Loan service which the PPPL library has established in support of library user demands is shown in Table III.

TABLE III

CATEGORY	FY76 QTY.	FY77 QTY.	% INCREASE
Engineering	126	167	32.5%
Math/Physics	83	86	3.5%
Other	18	90	400%

Special Services

- *New Journals:* Ten new journals that focus on nuclear engineering and computer sciences have been added.

- *Abstracting Journals:* New journals have been added, these include *Engineering Index*, *Atomindex*, and *U.S. Government Reports* and *Announcements*, thereby providing an in-depth searching capability in areas previously not of major concern to the laboratory.

- *Reference Books: World of Learning, Encyclopedia of Associations, National Faculty Directory, Nuclear Energy Index* were added, providing an expanded area of information sources to meet increased reader demand.

- *Daily Indexing:* Daily indexing of incoming reports was undertaken thereby providing immediate access to all current material on fusion ongoing programs.

- *Computerized Literature Searching:* Use of the Texas Instrument Silent 700 to perform on-line literature searches within the library office, on demand. This service is of significant technological benefit since more information is available in greater depth and more rapidly than heretofore.

Graduate Education

OVERVIEW

Graduate education in plasma physics at Princeton is organized under the auspices of the Astrophysical Sciences Department and concentrates on the education of a small number of selected students. These students are educated and trained both by formal course work and by intensive personal research supervision from Laboratory staff members. This enables the students to realize their full potential as research scientists. Success in this endeavor is evident by the large fraction of Princeton graduates actively engaged in plasma physics and fusion research in national laboratories, private industry, and universities (see Table I).

Plasma physics research was initiated at Prince-

TABLE I

Present Employment for Princeton Plasma Physics PhD Recipients

Academic	Government Research in Plasma Physics	Industrial Research in Plasma Physics
Bellan, P.—Cal Tech	Bateman, G.—ORNL	Bayless, J.—Hughes Research, Calif.
Cohen, I.—U. of Pa.	Berk, H.—LLL	Ghang, R.P.H.—Bell Labs, N.J.
Davidson, R.—U. of Md.	Birmingham, T.—NASA/GSFC	Chu, Cheng—General Atomic, Calif.
Dewar, R.—Aust. Natl. U.	Blanken, R.—ERDA	Grek, Boris—Canada
Ellis, R.—Dartmouth	Bodnar, S.—LLL	Sperling, J.—Jaycor, Calif.
Jablon, C.—France	Book, D.—NRL	True, M.—U. of Rochester/EXXON
Kennel, C.—UCLA	Boris, J.—NRL	
Johnston, R.—Columbia U.	Fante, R.—RADC	
Krommes, J.—PPPL Princeton Lecturer	Forslund, D.—LASL	
Montgomery, D.—Wm. & Mary	Goldston, R.—PPPL	
Orszag, S.—MIT	Hsuan, H.—PPPL	
Politzer, P.—MIT	Jardin, S.—PPPL	
Spight, C.—MIT	Jassby, D.—PPPL	
Su, C.H.—Brown U.	Kruer, W.—LLL	
Tappert, F.—NYU/Courant	Langdon, A.—LLL	
Wong, A.—UCLA	Lindl, J.—LLL	**Other**
	Marmar, E.—MIT/NML	Flick, J.
	Max, C.—LLL	Marsh, Jr.
	Mosher, D.—NRL	Mjolness, R.
	Newberger, B.—LASL	Ramanathan, G.
	Orens, J.—NRL	Robinson, B.
	Pacher, G.—CEN, Grenoble	Smith, C.
	Pacher, H.—CEN, Grenoble	Uman, M.
	Rogister, H.,—Italy	
	Rosen, M.—LLL	
	Sauthoff, N.—PPPL	
	Schlitt, L.—LLL	
	Seiler, S.—PPPL	
	Shanny, R.—NRL	
	Tsai, S.T.—Inst. Phys., Peking	
	Tsang, K.T.—ORNL	
	Valeo, E.—PPPL	
	Winsor, N.—NRL	
	Young, K.—PPPL	

ton University in 1951 by Professor Lyman Spitzer, Jr., and immediately attracted a group of outstanding scientists. The body of scientific knowledge in this area grew rapidly, and in a few years the need for specific education became obvious. The formation of the Department of Astrophysical Sciences in 1962 led to the existing academic structure under which nine courses specifically in plasma physics (see Table II) are offered on a regular basis, and in which more than 80 Ph.D. degrees have been awarded.

The usual program for graduate education in plasma physics is as follows: First-year students concentrate on basic theoretical physics and introductory plasma physics while working as assistants in research and experimental work on the PLT, H-1, and Q-1 devices. Second-year students take demanding courses in plasma physics and applied mathematics. Also, they carry out a theoretical research project under the supervision of a member of the laboratory's Theoretical Division. The third and fourth years are devoted to research for their doctoral dissertation carried out in collaboration with PPPL staff members (see Table III).

A list of thesis projects, both underway and recently completed, is presented in Table IV. During the third and fourth years, students may take one of four advanced plasma physics courses. Generally, a student's research will lead to two or three refereed research publications as well as oral or poster presentations at national plasma physics meetings. Graduate students thus make original and valuable contributions to Laboratory research programs both as Assistants in Research and during the doctoral dissertation research.

PPPL physicists share their expertise each week with the students at a student-run two-hour Tuesday afternoon seminar, and the students are, of course, regular attendees at the Laboratory seminars and colloquia.

The Plasma Physics Laboratory being a major international center for plasma research affords students an unparalleled opportunity for exposure to front-line 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. Taken together, the teaching and research environment here provides an important source for filling the continuous demand for highly qualified scientists trained in the area of plasma physics.

TABLE II

Plasma Physics Courses Taught and Names of Teachers

AS 551	General Plasma Physics I	Fall '76	S. von Goeler and P. H. Rutherford
		Fall '77	S. von Goeler and P. Kaw
AS 552	General Plasma Physics II	Spring '77	R. Kulsrud and W. Tang
AS 553	Plasma Waves	Fall '76 Fall '77	T. H. Stix F. W. Perkins
AS 554	Irreversible Processes in Plasma	Spring '77	C. R. Oberman
AS 557	Advanced Mathematical Methods in Astrophysical Sciences	Fall '76 Fall '77	M. Kruskal
AS 558	Seminar in Plasma Physics	Fall '77	S. Yoshikawa
AS 559	Nonlinear Interactions in Plasma	Fall '76	P. K. Kaw and M. Porkolab
AS 560	Computational Methods in Plasma Physics	Spring '77	R. C. Grimm and H. Okuda
AS 561	Special Topics in Magnetic Confinement	Fall '77	H. P. Furth and P. H. Rutherford

PPPL STAFF
TABLE III

FACULTY MEMBERS	TITLE
Francis W. Perkins	Senior Research Physicist and Lecturer with rank of Professor
Edward A. Frieman	Professor of Astrophysical Sciences
Harold P. Furth	Professor of Astrophysical Sciences
Melvin B. Gottlieb	Professor of Astrophysical Sciences
Raymond C. Grimm	Lecturer with rank of Associate Professor in Astrophysical Sciences
Predhiman K. Kaw	Senior Research Physicist, Lecturer with rank of Professor
John A. Krommes	Research Staff, Lecturer
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	Lecturer with rank of Associate Professor in Astrophysical Sciences
Marshall N. Rosenbluth	Visiting Lecturer with rank of Professor
Paul H. Rutherford	Senior Research Physicist and Lecturer with rank of Professor in Astrophysical Sciences
Thomas H. Stix	Professor of Astrophysical Sciences
William M. 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
Shoichi Yoshikawa	Senior Research Physicist and Lecturer with rank of Professor

TABLE IV

Recipients of Ph.D. Degrees

Oct. 1976:

Stephen C. Jardin Advisor: J. L. Johnson

Thesis: Time Integration of the Ideal MHD Equations in 2D Tokamak Geometry

Employment: Princeton Plasma Physics Laboratory; fusion research

Mordecai D. Rosen Advisor: J. M. Greene

Thesis: Radial Boundary Layers in Diffusing Toroidal Equilibria

Employment: Lawrence Livermore Laboratory; laser fusion research

Nov. 1976:

Earl S. Marmar (Physics) Advisor: S. Cohen

Thesis: Transport of Injected Impurities in the ATC Tokamak

Employment: Alcator Tokamak Project, MIT: fusion research

Apr. 1977:

Robert Goldston Advisors: H.P. Furth/H.P. Eubank

Thesis: Fast-Ion Diagnostic Experiment on ATC: Radially Resolved Measurements of q, Z_{eff}, $T_{i\parallel}$ and $T_{i\perp}$

Employment: Princeton Plasma Physics Laboratory; fusion research

May 1977:

Stephen Seiler (Physics) Advisor: M. Yamada

Thesis: Linear and Nonlinear Development of a Lower-Hybrid Wave Driven by a Perpendicular Ion Beam

Employment: Princeton Plasma Physics Laboratory; fusion research

June 1977:

Jang-Yu Hsu Advisor: P. K. Kaw

Thesis: A Study of Drift, Alfvén and Tearing Modes in a Nonuniform Plasma with Sheared Magnetic Fields

Employment: General Atomic Co.; fusion research

July 1977:

Michael True Advisors: F. W. Perkins/H. Okuda

Thesis: Drift Waves in Inhomogeneous Plasmas with Shear and Temperature Gradients

Employment: Exxon Nuclear Co.; laser fusion research

Doctoral Theses in Progress

E. Allen Adler (Physics) Advisor: R. M. Kulsrud

Thesis: Nonlinear Theory of the Tearing Mode

Gary Allen Advisor: M. Yamada

Thesis: Trapped-Particle Instability Simulations in a Linear Plasma

***Edward Caramana** Advisor: F. W. Perkins

Thesis: A Transport Code for the Reversed Field Pinch

David Eames Advisors: S. von Goeler/N. Sauthoff

Thesis: The Role of Tungsten Radiation in Major Disruptions in PLT.

Adil Hassam Advisor: R. M. Kulsrud

Thesis: Theory of Mass Motions in Toroidal Plasmas

Robert Kleva Advisors: C. R. Oberman/J. Krommes

Thesis: Transport in Braided Magnetic Fields

Richard Marchand Advisor: W. M. Tang

Thesis: Two-Dimensional Structure 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

Masayuki Ono Advisors: M. Porkolab/R.P.H. Chang

Thesis: Parametric Instabilities Near the Ion Cyclotron Frequencies in Multi-Ion Species Plasmas

C. Gören Schultz Advisor: P. Kaw

Thesis: The Effect of Braided Fields on High Colisionality Transport

****Jack J. Schuss** Advisors: T.K. Chu/L.C. Johnson

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

Harold Thompson Advisor: J. C. Hosea

Thesis: ICRF Probe Measurements

Donald Voss Advisors: S. Cohen

Thesis: Wall Flux of Low Energy Neutrals in the PLT Tokamak

James R. Wilson Advisor: K. L. Wong

Thesis: Nonlinear Behavior of Lower-Hybrid Resonance Cones and Soliton Formation

*Visiting Student from University of Colorado
**Has received degree since September 1977.

Bibliography

DRIVEN TOKAMAK PLASMAS

Bromberg, L., Jassby, D.L., "In-Torus Zirconium-Aluminum Getter Pumping for Beam-Driven Tokamaks," *in Proc. Seventh Symp. on Engin. Problems of Fusion Research,* 971-975, (Knoxville, TN, 1977).

Cohn, D.R., et. al., Mass. Inst. of Technology, Jassby, D.L., Okabayashi, M., "A High-Field, High-Density Tokamak Power Reactor," *PPPL-1347* (1977), published in *Proc. Second IAEA Meeting and Workshop on Fusion Reactor Design* (Madison, WI, 1977) .

Cohn, D.R., et. al., Mass. Inst. of Technology, and Jassby, D.L., Okabayashi, M., "Compact High-Field Ignition Test Reactor (HFITR) Using Bitter Magnets," *Trans. Am. Nucl. Soc. 27* (1977).

Goldston, R.J., Jassby, D.L., Towner, H.H., Fowler, R.H., Lyon, J.F., Rome, J.A., Brown, T., "Magnetics Design for Ripple-Assisted Beam Injection into the ISX-B and TFTR Tokamaks," in *Proc. Seventh Symp. on Engin. Problems of Fusion Research,* 1333-1338, (Knoxville, TN, 1977).

Jassby, D.L., "Fueling of Toroidal Plasmas by Ripple-Assisted Injection of Energetic Particles," *Trans. Am. Nucl. Soc. 26,* 13-14 (1977).

Jassby, D.L. Furth, H.P., Reardon, P.J., Cohn, D.R., (MIT), Williams, J.E.C., (MIT), "High-Density Tokamak Design Studies for TFTR-II," published in *Proc. Second IAEA Meeting and Workshop on Fusion Reactor Design* (Madison, WI, 1977).

Jassby, D.L., "Neutral-Beam-Driven Tokamak Fusion Reactors," *Nucl. Fusion 17,* 309-365 (1977).

Jassby, D.L., Towner, H.H., "Optimization of Plasma Profiles for Ignited Low-Beta Toroidal Plasmas Utilizing Advanced Fuels," in Proc. *EPRI Review Meeting on Advanced Fuel Fusion,* 275-284, (Chicago, 1977).

Jassby, D.L., Towner, H.H., Goldston, R.J., "Reduced Fusion-Neutron Production in NonAxisymmetric Tokamak Devices," *Nucl. Fusion 18,* 85-833, (1978).

Jassby, D.L., Cohn, D.R., Parker, R.R., "Reply to Comments on the Paper Characteristics of High-Density Tokamak Ignition Reactors," *Nucl. Fusion 16,* 1045-1046, (1976).

Jassby, D.L., "Smartor—A Small-Aspect-Ratio Torus for Demonstrating Thermonuclear Ignition," Princeton Plasma Physics Lab. Report *PPPL-1371* (1977); also Jassby, D.L., "Small Aspect Ratio, Small Major Radius Tokamak Reactors," in *Comments on Plasma Physics and Controlled Fusion III,* 151-159, (1978).

Jassby, D.L., "Tokamak Oven Reactors: Beam-Insulated Thermonuclear Reservoirs," *Bull. Am. Phys. Soc. 21,* 1161 (1976); also *Nucl. Fusion 17,* 382 (Section 2.6.2) (1977).

Jensen, R.V., Jassby, D.L., Post, D.E.,"Critical Impurity Concentrations for Ignition of Catalyzed-Deuterium Fusion Plasmas," *Nucl. Sci. and Engin. 65,* 144-146 (1978).

Jensen, R.V., Post, D.E., Jassby, D.L., "Critical Impurity Concentrations for Power Multiplication in Beam-Heated Toroidal Fusion Reactors," *Nucl. Sci. and Engin. 65,* 282-289 (1978).

Mirin, A.A., et. al., "Fokker-Planck/Transport Analyses of Fusion Plasmas in Contemporary Beam-Driven Tokamaks," *Princeton Plasma Physics Lab. Report PPPL-1437* (1978).

LINEAR DEVICES

Bellan, P.M., Wong, K.L., "The Effect of Density Fluctuations on Lower Hybrid Resonance Cone Propagation," *PPPL-1314* (April 1977), to be published in *Phys. Fluids.*

Ono, M., Porkolab, M., Chang, R.P.H., "Parametric Excitation of Drift Waves with the Pump near the Ion Cyclotron Frequency in a Two-Ion Species Plasma," *PPPL-1434* (1978).

Ono, M., Chang, R.P.H., Porkolab, M., "Parametric Excitation of Electrostatic Ion Cyclotron Waves in a Multi-ion Species Plasma," *Phys. Rev. Left. 38* (1977) 962.

Ono, M., Porkolab, M., Chang, R.P.H., "Parametric Excitation of Non-Resonant Ion Cyclotron Quasi-mode," *PPPL-1395* (1977).

Seiler, S., Yamada, M., "Ion-Beam-Driven Lower Hybrid-Instability and Resultant Anomalous Beam Slowing." Submitted to *Phys. Fluids* (1977); *PPPL-1412.*

Wong, K.L., Bellan, P.M., "Excitation of Drift Waves by Lower Hybrid Waves," *PPPL-1340* (March 1977), to be published in *Phys. Fluids.*

Wong, K.L., Bellan, P.M., Porkolab, M., "Resonant Decay of Finite Extent Cold Electron Plasma Waves," *Phys. Rev. Lett. 40* (1978) 554-558.

Yamada, M., Seiler, S., "Anomalous Slowing of a Perpendicularly Injected Ion Beam in Both Quasilinear and Trapping Regimes." *Phys. Rev. Lett. 39* (1977) 808.

Yamada, M., Owens, D.K., "Cross-Field-Current Driven Lower-Hybrid Instability and Stochastic Ion Heating." *Phys. Rev. Lett. 38* (1977) 1529; *PPPL-1327.*

Yamada, M., Hendel, H.W., "Current-Driven Instabilities and Resultant Anomalous Effects in Isothermal, Inhomogeneous Plasmas." To be published in *Phys. Fluids 21; PPPL-1249* (May 1977).

Yamada, M., Seiler, S., Hendel, H.W., Ikezi, H., "Electrostatic Ion Cyclotron Instabilities Driven by Parallel Ion Beam Injection." *Phys. Fluids 20* (1977) 450-458; *PPPL-1254.*

REACTOR STUDIES

Bathke, C.G., "An Algorithm for Locating the Extremum of a Multi-Dimensional Constrained Function and its Application to the PPPL Hybrid Study," *Princeton Plasma Physics Laboratory Report PPPL-1424,* in press.

Bathke, C.G., Bohlke, W.H., Buchanan, C.H., Gralnick, S.L., Johnson, E.F., Mills, R.G., Price, W.G., Jr., Tenney, F.H., Todd, A.M.M., "A Systems Study of Tokamak Fusion/Fission Reactors," *Princeton Plasma Physics Laboratory Report PPPL-1450,* in preparation.

Bathke, C.G., "The Optimization Process in the PPL Hybrid Study," *Transactions of the American Nuclear Society 1977 Annual Meeting* (American Nuclear Society, Hinsdale, Illinois, 1977) Vol. 26, p. 52.

Buchanan, C.H., "Energy Storage for Tokamak Cycles," *PPPL-1511* (1979).

Gilligan, J.G., Gralnick, S.L., Price, W.G., Jr., and Kammash, T., "Low Energy Neutral Transport in Tokamak Plasmas," *Nuclear Fusion, 63.*

Gilligan, J.G., Gralnick, S.L., Price, W.G., Jr., and Kammash, T., "Multigroup Calculations of Low Energy Neutral Transport in Tokamak Plasmas," *Princeton Plasma Physics Laboratory Report PPPL-1384* (1977).

Greenspan, E., "On the Feasibility of Beam Driven Semi-Catalyzed Deuterium Fusion Neutron Sources for Hybrid Reactor Applications," *Princeton Plasma Physics Laboratory Report PPPL-1399* (1977).

Greenspan, E., "Power Generation Versus Fuel Production in Light Water Hybrid Reactors," *Princeton Plasma Physics Laboratory Report PPPL-1319* (1977).

Imamura, Y., "A Feasibility Study of LiF-BeF_2 and Chloride Salts as Blanket Coolants for Fusion Power Reactors," *Princeton Plasma Physics Laboratory Report PPPL-1380* (1977).

Johnson, E.F., "The Chemical Engineering Side of Nuclear Fusion Power," *AIChE Journal 23,* 617 (1977).

Ku, Long-poe, and Price, W.G., Jr., "Neutronic Calculation and Cross-Section Sensitivity Analysis of the Livermore Mirror Fusion/Fission Hybrid Reactor Blanket," *Princeton Plasma Physics Laboratory Report PPPL-1370* (1977).

Mills, R.G., "Tokamak Reactors," The American Society of Mechanical Engineers, New York (1977) *Paper No. 77 WA/NE-3.*

Moreau, D.C., "Potentiality of the Proton-Boron Fuel for Controlled Thermonuclear Fusion," *Nuclear Fusion 17,* 13 (1977).

Price, W.G., Jr., "The Cost of Tritium Bred in a Critical Fusion Reactor," *Transactions of the American Nuclear Society 1977 Winter Meeting* (American Nuclear Society, Hinsdale, Illinois, 1977) Vol. 27, p. 78.

ENGINEERING

Ashcroft, D.L., Zuvers, H.E., "The Princeton Neutral Injection Power Supply." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research* (Knoxville, TN, 1977).

Bohr, A.H., Kloiber, F.W., Silverman, K.B., "Design of a 125 Kilogauss One Meter Magnetic Coil." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research (Knoxville, TN, 1977).*

Bohr, A.H., Christie, R.S., "Scanning Drive for Visible Spectrum Monochromator." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research* (Knoxville, Tn, 1977).

Bowen, O.N., Lawson, J.Q., "Enhancing the Power Output of the VA-655 UHF-TV Klystron." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research* (Knoxville, TN, 1977).

Christie, R.S., "A Low-Noise Control Value-II." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research* (Knoxville, TN, 1977).

Farley, R.D., Huttar, D.E., "Selection of Power Transformers for Pulsed Loads." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research* (Knoxville, TN, 1977).

Foote, V.S., Christie, R.S., "Some Mechanical Aspects of the Multi-Channel TV Thomson Scattering Apparatus on the PLT Machine." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research* (Knoxville, TN, 1977).

Lawson, J.E., "An Analog Safety Data Link." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research* (Knoxville, TN, 1977).

Lawson, J.Q., Newman, W.G.,. Sivo, A.J., "Megawatt Power Output for Ion Cyclotron Heating." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research* (Knoxville, TN, 1977).

Lefkowitz, E.H., "PLT OH System Operation." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research* (Knoxville, TN, 1977)

Murray, H.A., Heim, W.J., "PLT Ion Temperature System Design and Operation." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research* (Knoxville, TN, 1977).

Reed, B.W., Bowen, O.N., Hill, H.M., "Preliminary Report on the Development of RF Auxiliary Heating for TEPR-1," *PPPL-1410* (1977).

Silverman, K.B., "Neutral Injection Beam Power Monitor." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research* (Knoxville, TN, 1977).

Turitzin, N.M., Oliaro, G.E., "Poloidal Field Power Supplies and Their Performance on the PDX Machine." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research* (Knoxville, TN, 1977).

MACHINE DESIGN & FABRICATION

Bialek, J., Rogoff, P., and Brown, G.M., "Multilayer Coil Structures Analyzed by Laminated Beam Theory." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pg. 854. New York: Institute of Electrical and Electronics Engineers, Inc. (1977)

Bialek, J., Weissenburger, D.W., and Christensen, U.R., 'The Pure Tension Shape of a Thick Torus." *PPPL-1353.* Princeton, N.J.: Princeton University Plasma Physics Laboratory. (1977).

Brown, D.I., and Meade, D.M., "The PDX Island Study". *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 1347-1351. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Brown, G.M., and File, J., "Some Results from the PLT 3 Coil Test." *Proceedings of the Seventh Symposium of Engineering Problems of Fusion Research,* pg. 422. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Brown, G.M., "Improved Techniques for Mechanical Measurements in Time-Varying Magnetic Fields." *Proceedings of the Seventh Symposium of Engineering Problems of Fusion Research,* pp. 423-424. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Brown, G.M., and Heitzenroeder, Jr., P.J., "PDX PF Power Tests". *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 814-816. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Brown, G.M., Bialek, J., and Rogoff, P., "Multilayer Coil Structures Analyzed by Laminated Beam Theory." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 854. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Cavalluzzo, S., Knutson, D., Davenport, J., Kaminsky, E., Perry, E., and Willard, J., "PDX, Mechanical Design Update and Assembly." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 33-37. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Christensen, U.R., Bialek, J., and Weissenburger, D.W., "The Pure Tension Shape of a Thick Torus." *PPPL-1353.* (1977).

Dahlgren, F., "A Selection of Coil Design Codes." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 1358-1361. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Davenport, J., Cavalluzzo, S., Knutson, D., Kaminsky, E., Perry, E., and Willard, J., "PDX, Mechanical Design Update and Assembly." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 33-37. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Dreskin, S.A., "Magnetic Forces in the PDX Toroidal Field Coils." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 797-801. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

File, J., and Brown, G.M., "Some Results from the PLT 3 Coil Test." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pg. 422. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Haviland, T.S., and Heitzenroeder, Jr., P.J., "Design, Fabrication, and Magnetic Alignment of the PDX Canned Poloidal Coils." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pg. 817. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Heitzenroder, Jr., P.J., and Brown, G.M., "PDX PF Power Tests." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pg. 814-816. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Heitzenroeder, Jr., P.J., and Haviland, T.S., "Design, Fabrication, and Magnetic Alignment of the PDX Canned Poloidal Coils." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pg. 817. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Joyce, J.B., "PDX Overview and Status Report." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 634-637. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Kaminsky, E., Cavalluzzo, S., Knutson, D., Davenport, J., Perry, E., and Willard, J., "PDX, Mechanical Design Update and Assembly." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp.33-37. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Knutson, D., Kaminsky, E., Cavalluzzo, S., Davenport, J., Perry, E., and Willard, J., "PDX, Mechanical Design Update and Assembly." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 33-37. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Kungl, D.J., "PDX Management Techniques and Procedures." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 167-168. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Marino, R.E., "PLT Toroidal Field Coils—Operational Deflection Measurements." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 1237-1240. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Perry, E., Kaminsky, E., Cavalluzzo, S., Knutson, D., Davenport, J., and Willard, J., "PDX, Mechanical Design Update and Assembly." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 33-37. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Rogoff, P., "Stress and Deflection Analysis of the PLT-Coil Using ANSYS Computer Code." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 59-62. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Rogoff, P., Bialek, J., and Brown, G.M., "Multilayer Coil Structures Analyzed by Laminated Beam Theory." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 854. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Weissenburger, D.W., Bialek, J., and Christensen, U.R., "The Pure Tension Shape of a Thick Torus." *PPPL-1353.* (1977).

Willard, J., Cavalluzzo, S., Knutson, D., Davenport, J., Kaminsky, E., and Perry, E., "PDX, Mechanical Design Update and Assembly." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 33-37. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

Young, K.S., and Puzio, E.T., "Development of the PDX TF Coil Insulation System." *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research,* pp. 1518-1520. New York: Institute of Electrical and Electronics Engineers, Inc. (1977).

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