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Covering the Period October 1, 1981 to September 30, 1982

**Princeton University
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MASTER

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Cover: Tokamak Fusion Test Reactor vacuum vessel and toroidal-field coil assembly before installation of final sector module.

Photographed by John Peoples and Joseph DiBartolo

Preface

The construction of the Tokamak Fusion Test Reactor (TFTR) has been proceeding in a highly satisfactory manner, giving confidence that the project schedule will be met. The vacuum vessel and toroidal-field coil systems are now in place, and the entire mechanical assembly process is about to be completed. Experimental operation of TFTR will begin with ohmic-heating studies in early CY83, and will proceed to intensive neutral-beam heating in CY84.

Radio-frequency experiments on the Princeton Large Torus (PLT) have used a new 3-MW ion cyclotron heating source to demonstrate second-harmonic heating of hydrogen ions up to temperatures of 3 keV. Lower hybrid current drive has sustained plasma currents as large as 400 kA in quasi-steady state. The 7-MW neutral-beam-heating capability of the Poloidal Divertor Experiment (PDX) was utilized to investigate finite-beta stability limits. Beta values above 3% were achieved at safety factor values as low as 1.7. A physical mechanism for beta-limitation was discovered and documented: the energetic-ion-driven "fishbone mode" of MHD instability.

Construction of the S-1 spheromak is progressing on schedule, with preliminary experimental operation planned for early CY83. The stabilization of the

spheromak plasma-tilting mode has been studied successfully on the Proto S-1 devices. A number of basic new plasma-wave interaction phenomena have been found on the Advanced Concepts Torus (ACT-I).

The Soft X-Ray Laser Development Experiment is pursuing an important opportunity for a near-term spin-off from controlled-fusion technology. Experimental evidence of population inversion and directional amplification has already been achieved.

Theoretical MHD studies have not only helped to clarify the nature of the beta limit in the PDX experiment, but have pointed to a new tokamak configuration with greatly improved stability properties. Tokamaks of bean-shaped minor cross section should be able to pass into the "second stability regime," where the beta value is effectively unlimited. Studies of the heliac—the stellarator analogue of the bean-shaped tokamak—also point to favorable high-beta prospects.

Now that the basic TFTR facility is approaching completion, increasing attention is being given to options for a follow-on experiment. The possibilities range from upgrades of TFTR, such as the Tokamak Fusion Engineering Test (TFET), to plans for a separate new ignition device.

Principal Parameters of Experimental Devices

Parameters	Primary Facilities			Secondary Facilities	
	PLT	PDX	TFTR*	S-1*	ACT-I
R (m)	1.3	1.4	2.48	0.40	0.59
a (m)	0.4	0.4	0.85	0.25	0.1
I_p (MA)	0.6	0.5	2.5	0.5	—
B_T (T)	3.2	2.4	5.2	0.5	0.57
τ_{TF}	1.5 sec	1.0 sec	1.6 sec	1 msec	dc
P_{AUX} (MW)					
NB	2.5, 40 keV	8, 50 keV	27, 120 keV	—	—
ICRF	3.5, 42 MHz	—	—	—	0.002
LH	0.6, 800 MHz	—	—	—	0.02
ECRH	—	0.4*, 60 GHz	—	—	0.002
τ_{AUX} (sec)	0.3	0.3	0.5	—	dc
$\bar{n}_{max}$ (cm ⁻³)	10^{14}	10^{14}	10^{14}	3×10^{14}	2×10^{12}
T_{max}	7 keV	6 keV	20 keV	200 eV	10 eV

*Under construction.

Tokamak Fusion Test Reactor

The plan and schedule for completion of the construction phase of the Tokamak Fusion Test Reactor (TFTR) Project remains unchanged from the program developed during the latter half of FY81, despite a number of difficulties that have developed during the construction of the tokamak. There have been significant delays in the delivery of materials and vendor-fabricated components, and also design and manufacturing problems have produced mismatches and interference of some component parts during assembly. In spite of such problems, steady progress has been made this past year in the installation of the tokamak device and its supporting systems, and in initial subsystem testing. The timely completion of the work scheduled during the last quarter of FY82 has improved considerably the confidence that a December 1982 first-plasma date will be achieved within the 314 million dollar PACE budget.

An integrated systems testing program preceding first-plasma operation was begun at the end of FY82 and will continue during the first quarter of FY83. An Operational Readiness Review (ORR) will be conducted prior to initial device operation to ensure that all essential requirements in terms of design, hardware, support facilities, manpower, and safety considerations are in place and meet Laboratory and Department of Energy (DOE) standards. Following first plasma the TFTR experimental program, which remains basically unchanged from the beginning, will initially study the ohmic heating and adiabatic compression of large-size, high-current hydrogen and deuterium plasmas. High-powered neutral-beam heating experiments will begin in 1984 and are expected to reach "deuterium-tritium equivalent" break-even conditions in deuterium plasmas toward the end of 1985. The experiment will then be repeated in actual deuterium-tritium (D-T) plasmas in order to demonstrate the design level of TFTR fusion power output, i.e., an output power equal to the input power required to heat the plasma at levels near 30 MW.

FACILITY CONSTRUCTION

Figure 1 is an aerial view of the TFTR site. Two major facility construction milestones were achieved in 1982. At the end of June, with completion of the installation of the Energy Conversion System (ECS) cabling between the transformer yard and the rectifier areas inside the building, responsibility for the Field Coil Power Conversion Building was transferred from DOE to the Princeton Plasma Physics Laboratory (PPPL). The high-voltage transformers for the ECS are shown on the

Figure 1. Aerial view of the Tokamak Fusion Test Reactor (TFTR) site early in fiscal year 1982. The experimental areas are at the left. They include the main TFTR Test Cell, a Neutral Beam Test Cell and Hot Cell, and a Mock-Up Bay for equipment testing and remote handling development. The Neutral Beam and Field Coil Energy Conversion Buildings and the outdoor electrical equipment yards are in the center of the complex. The Motor Generator Building is at the right. (82A0126)

Figure 2. Field coil energy conversion system outdoor power supply equipment. Primary power transformers for the toroidal-field coil energy conversion system are shown at left and the resistor yard for the ohmic heating power supply system is to the right. (82E0515)

left in Fig. 2. On the right is the resistor yard which is part of the Ohmic Heating Electrical System that induces current in the plasma.

Formal acceptance by DOE of the TFTR Test Cell occurred in September 1981. At that time the responsibility for maintenance and operation of building

support facilities was turned over to PPPL. Prior to this, a special arrangement was in effect that allowed PPPL to maintain control over the Test Cell areas of the experimental complex so that the installation and assembly of the tokamak could proceed. In September PPPL control was extended to almost all of the other areas of the TFTR experimental complex that contained the support systems equipment for the machine.

Major construction tasks which remain to be completed include erection of high-voltage enclosures in the Neutral Beam Power Conversion Building (in preparation for installation of the neutral-beam power supply components), installation of the site boundary fencing, and completion of the exterior lighting and roadways.

TOKAMAK ASSEMBLY

All of the major components for the TFTR device have been manufactured and received at PPPL. Installation and assembly of the tokamak in the Test Cell has made great progress since November 1981 when the machine substructure was completed. The Test Cell is a heavily-shielded concrete structure with a floor area of 150 feet by 114 feet and a height of 54.5 feet. Central to the Test Cell is the machine base (shown in Fig. 3) which consists of a concrete-encased, 6-foot-thick, stainless steel I-beam structure whose upper surface is located approximately two feet above the Test Cell floor. Mounting holes for the tokamak components were drilled and tapped into the upper surface of the machine base using a portable machine tool. The machining of the underside of the machine base was accomplished with the aid of a temporary wooden platform installed under the machine in the Test Cell Basement. Figure 4 is a view of the underside of the machine base and shows some of the early machining work in progress. The large racetrack-like apertures provide access to the vacuum vessel for diagnostic apparatus, while the pair of smaller circular holes (symmetrically located around the radial girder at the outer edge of the racetrack openings) are the penetrations through which the vacuum vessel outboard supports will be connected.

Figure 3. Central support base for the tokamak machine. The upper surface of the base is approximately two feet above the Test Cell floor. (81E1297)

Figure 4. Underside of the TFTR machine base. The underside of the six-foot-thick machine base as it looked during finish machining. The large apertures for diagnostic access to the TFTR vacuum vessel are in the upper center. (Note that the wide-angle photograph distorts the machine geometry.) (82E0500)

Figure 5. Inner support structure and lower poloidal-field coils. The picture shows the status of machine assembly just prior to installation of the first sector module. (82E0572)

The first group of components to be installed included the lower poloidal-field (PF) coils, and the inner support structure (ISS). Figure 5 shows these components in position in mid-April after final alignment of the ISS and

just prior to installation of the first sector module. The tokamak proper consists of ten sector modules, each of which is composed of two toroidal-field (TF) coils, their associated shear compression panels, and a vacuum vessel segment.

Figure 6 illustrates the assembly process for a sector module. In this photograph, a vacuum vessel segment is shown installed in the Sector Module Assembly Fixture (SMAF). Two TF coils are mounted on outrigger portions of the SMAF. During assembly the outriggers were rotated inwardly in clamshell fashion to mate the TF coils with a vacuum vessel segment to form a completed sector module. Assembly was carried out in the Test Cell where the TF coils were stored upon delivery from the supplier, and where the individual vacuum vessel segments were housed after undergoing preinstallation work elsewhere at the PPPL site. The preinstallation task included assembly of access port covers, vacuum testing, and installation of thermal insulation blankets.

Figure 6. Sector module assembly fixture (SMAF). Pairs of toroidal-field coils are held on either side in an assembly fixture for mating with the vacuum vessel segment shown in the center. The TFTR is constructed from ten such units. (82E0504)

In May 1982 the first two sector modules were installed on the machine base. Figure 7 shows the first sector module being lowered into place by the 110-ton Test Cell crane. The lift fixture for handling a complete sector module is shown at the top of the photograph. It is bolted directly to the two TF coils and to an intermediate structure fastened to the vacuum vessel oval ports. Note that the large outer PF coil stack (Stack No. 9) is in its lowered position (just below the workmen's waists) to facilitate placement of the sector module. After placement of the TF coils on their respective pedestals, the sector module was optically aligned. The TF coils were then aligned to within 0.015 inch with respect to the ISS to ensure that the pulsed inward centering force (about 10⁷ pounds for each coil during operation) would be uniformly applied to the ISS, which is designed to support these high loads.

Figure 7. Sector module installation. The first sector module being positioned on the machine base. (82E0578)

A most significant step in the installation process was the preparation for the final fit-up of the tenth and last vacuum vessel segment. In order to assure perfect closure, after nine of the ten segments had been assembled in the toroidal array, an adjustable tooling fixture was fitted into the remaining gap. The adjustable parts were pinned in place, and the tooling fixture was then removed and shipped to the vacuum vessel manufacturer to serve as a template for final machining of the last segment. Installation of this tenth segment tooling fixture in the gap between vacuum vessel segments nine and one is shown in Fig. 8.

In parallel with this effort, the last two toroidal-field coils were temporarily installed to complete the toroidal array of 20 coils and their associated interconnecting shear compression panels. This fit-up, including careful measurements of the interface between the TF coils and the ISS, was completed in early September. On September 17, 1982, the tenth and last sector module was installed (Fig. 9), completing the assembly of the basic machine elements.

During the last quarter of FY82, preliminary preparations were completed for the installation of the remaining major components of the tokamak. In July the assembly of the umbrella structure, which supports the upper poloidal-field coils on the machine, was completed. The support columns were installed on the machine floor and a trial fit of the umbrella structure atop

Figure 8. Tenth segment tooling fixture. An adjustable tooling fixture was installed in the gap between vacuum vessel segments 9 and 1. After precise alignment with the ends of both segments, the adjustable elements were securely fastened so that the tooling fixture could be used as a template for final machining of the last segment. (82E0874)

Figure 9. Installation of the tenth and final sector module. At this stage all basic machine elements are in place. (82E0973)

the columns was made. In August the umbrella structure was lifted over the upper PF coils, which had previously been set up on temporary supports arranged in their proper spatial relationship (Fig. 10), and the attachment of the upper PF coil array to the underside of the umbrella structure was completed.

Figure 10. Assembly of upper poloidal-field coil array. The upper poloidal-field coils are shown on their temporary alignment fixture in preparation for attachment to the underside of the umbrella structure. After testing, the whole unit, weighing over 100 tons, will be lifted by the overhead crane and placed on the supporting columns that surround the tokamak. (82E0663)

Figure 11. Assembly and prefit of upper machine components on the umbrella structure. At this stage of assembly the upper poloidal-field coils were fastened to the umbrella structure while supports for the upper coil buswork and components of the vacuum vessel heating and cooling system were prefitted and then removed prior to lifting the entire assembly into place on top of the tokamak. (82E0961)

In Fig. 11, the top portion of the machine is shown during the September component prefit effort. The PF coils were clamped to the underside of the massive radial beams of the umbrella structure, and preliminary fit-up of the vacuum vessel heating and cooling manifolds and the TF and PF coil buswork supports was started. Preliminary fit-up simplified the process of locating the various components to be mounted atop the umbrella structure and avoided the necessity of performing machining operations on the assembled tokamak, thereby eliminating the potential problem of contaminating the machine with oil, grease, and metal chips. The status of machine assembly at the close of

the fiscal year is shown in Fig. 12. The vacuum vessel, TF coils, lower PF coils, and vacuum pumping ducts are in place. Lifting of the fully assembled umbrella structure into its final position is scheduled for October 1982.

Figure 12. TFTR assembly status at the end of FY82. The completed torus and support structure for the upper umbrella assembly are shown with the lower poloidal-field coils in place and the vacuum pumping ducts mounted in final position. (82E1062)

INSTALLATION OF AUXILIARY SYSTEMS

While tokamak assembly was the highest priority activity of the TFTR Project during this fiscal year, work also proceeded on all the auxiliary systems required for the plasma start-up. Eighteen of the 36 Energy Conversion System thyristor-rectifier units arrived and were installed in the Field Coil Power Conversion Building. Only seven units are required for first-plasma operation, and before the end of September five units had passed the prescribed ECS subsystem tests. Another important element of the ECS for first plasma is the array of 12 one-megajoule capacitor banks. Subsystem testing on nine of these units was also completed during FY82.

Power to drive the magnetic coil systems is fed through cables which run from the rectifiers to the cable spreading room at the entrance to the Test Cell Basement. In Fig. 13, the cables and cable trays are shown ending to the right of the cable-to-bus transition structure. From there the rigid, water-cooled, copper buswork continues overhead to the area directly under the machine where additional buswork rises vertically through penetrations in the machine floor to the coils in the Test Cell above. Solid, water-cooled bus is used near the machine because much less space is required than for air-cooled cables. Installation and checkout of all the water cooling equipment proceeded extremely well. The cooling loop for the energy conversion system hardware was completely tested, the field coil cooling system was cleaned and prepared for testing, and the chillers were started and checked out. The pump room,

Figure 13. Power cable and buswork installation in the test cell basement. Heavy cables carry the dc power from the pulsed energy conversion system rectifiers to the Test Cell Basement where they connect (right) to a water-cooled buswork array, shown overhead in the center of the photograph. The buswork then runs under the machine to connect with the vertical busses that attach to the toroidal-field and poloidal-field coil lead stems. (82E0943)

Figure 14. Pump room cooling water equipment. Shown in the foreground are an 18-inch waterline and a 3,300 gallons-per-minute centrifugal water pump for circulating deionized water to cool the TFTR coils. The 32,000-gallon stainless steel deionized-water storage tank is visible in the background. (82E0516)

which houses the major components of the cooling water systems, is shown in Fig. 14. It is part of a 30,000 square foot basement underlying the TFTR installation. Shown in the foreground are an 18-inch water supply line and the 3,300 gallons-per-minute centrifugal pump for circulating the deionized water used to cool the TFTR magnetic field coils. In the background, at the left, a 32,000 gallon stainless steel deionized-water storage tank can be seen in which the hot water from the various components is mixed with the water cooled by the chillers. The remaining work on the cooling water systems mostly involves the connection of all the flexible hoses to the coil systems and final flow testing.

During August and September 1982, set-up and installation of the two elbow and chamber duct assemblies of the Torus Vacuum Pumping System (TVPS) was essentially completed, the programmable controller was put into operation, and preoperational testing was started. The vacuum vessel is pumped by eight 3,500 liter/sec turbomolecular pumps (four mounted under each of the pumping ducts) which are backed by two Kinney Vacuum Booster Pump units. Each booster pump has a displacement of 800 cubic-feet-per-minute (cfm) with the backing pump rated at 112 cubic-feet-per-minute. Two Kinney roughing pump units are also installed and connected into the system. The all-metal sealed vacuum system will be capable of a base pressure of less than 10^{-8} Torr. Two additional vacuum booster pump units back the four turbomolecular pumps used for each of the four neutral beamline enclosures.

CENTRAL INSTRUMENTATION, CONTROL, AND DATA ACQUISITION (CICADA) SYSTEM

The CICADA System CAMAC interface hardware for remote operation and monitoring of the Motor Generator (MG) System, the Water Systems, the Vacuum Systems, and the Power Conversion System was installed in the test facility and is being tested. This equipment is connected through serial data links operating at 2.5 megabits per second to the CICADA computer system located in the TFTR Main Control Room. Figure 15 is a view from the entrance to the Control Room which is located in the basement of the Laboratory Office Building (LOB). In the foreground, software engineers and computer operators are testing interactive programs at the consoles to be used by the tokamak operators. All tokamak systems will be controlled from these consoles. Along the walls are 20 terminal operating stations (TOS) from which physicists will control and monitor plasma diagnostic instruments,

Figure 15. TFTR main control room. This room and the adjacent computer room house the major components of the TFTR Central Instrumentation, Control and Data Acquisition (CICADA) system. (82E0512)

reduce the output data to the physical parameters necessary to operate the tokamak in an optimal fashion, and interpret observations made on plasma characteristics and behavior.

Six console operating stations (COS) and eight terminal operating stations have been assembled and are installed in the Main Control Room. In addition four portable console operating stations (see Fig. 16) have been set up at key locations in the TFTR test facility to aid in commissioning facility systems. These portable stations are functionally identical to those in the Control Room and they can be located adjacent to the equipment being tested.

Figure 16. CICADA system portable operating console station. One of the CICADA system's portable console operating stations is shown (right) incorporated into the test facility developed to control and monitor power testing of the Energy Conversion System rectifier units. (82E0503)

A Level-1 Application Program Generator program has been written and is in use. Level-1 programs are the basic control and monitoring programs that allow the user to interact through a console operating station with each individual interface point. Approximately one-half of the one hundred such programs required for the December first-plasma milestone are now operational.

The power conversion software program for controlling the power supply output currents that produce the TFTR magnetic fields has undergone several iterations in order to achieve the desired response time. This system is now undergoing tests with the related CAMAC hardware and an analog computer simulating the power supply systems. Initial testing indicates performance as expected.

The facility clock to control and synchronize all TFTR operations is operational. It has been used to synchronize the activities in the computer system and the programming of the power supply systems. Control of the 32 channel transient digitizers is also being tested.

In order to focus increased attention on machine start-up, the Computer Division and the TFTR CICADA Branch were merged to form the new Computer/CICADA Division. This reorganization made additional manpower immediately available for assignment to support the TFTR commissioning effort.

FACILITIES OPERATIONS

As the installation and assembly of the tokamak and auxiliary systems neared completion and the subsystem testing was being concluded, emphasis was shifted to integrated systems testing. Detailed planning for this work in terms of both the preparation of procedures and conducting of the actual tests progressed well. These plans have been coupled into the computer based TFTR management program which maintains and tracks the overall integrated activity schedule.

Motor Generator Set No. 1 is in operation undergoing acceptance tests and rotor dynamic balancing. It appears, from extensive tests and engineering analyses of the excessive vibration and bearing run-out at high speeds, that an additional bearing may have to be installed to reach full output performance at the 375 revolutions-per-minute (rpm) design value. At this time, plans allow for installation of the additional bearing in early 1983, in time for the scheduled start of high-power ohmic heating experiments in April. The unit is presently adequately balanced to permit 300 rpm operation—a level that will provide in excess of 300 megajoules-per-machine pulse, more than enough energy for start-up and initial plasma operation. Confirmation of this projection was established early in September when a successful first test of the performance of the thyristor firing circuit was conducted. By simulating planned operating conditions, where the generator speed (and corresponding frequency) drops some 25%, about 40 MVA (megavolt-amperes) of power was delivered for a full 5 seconds to one unit of the energy-conversion rectifier supplies connected into a resistive load. A set-up for testing of the energy conversion system rectifier supplies is shown in Fig. 17.

The torus vacuum pumping system is being tested. A microprocessor-based system for stand-alone testing of the system has been assembled and is in use. Installation of the transition duct to connect the pumping system to the torus is scheduled for early October, to be followed by first pumpdown of the torus.

The integrated systems test program that will be conducted early in the next fiscal year (FY83) is being designed to investigate the detailed electrical and mechanical interactions between individual subsystems, to determine the adequacy of personnel and equipment protection features, and to establish the performance characteristics of the tokamak device and its supporting subsystems as a unified system. The program will proceed through increasingly more complex tests and operations, culminating in the production of a first plasma in the machine. Prior to first-plasma operation, however, a formal Operational Readiness Review will be conducted by PPPL and a report and recommendations will be submitted to DOE for final approval to proceed. This review will cover all aspects of readiness, including safety considerations, equipment and software status, experimental buildings and facilities status, personnel support, management systems and procedures. Planning, organization of

Figure 17. Energy conversion system (ECS). One of the energy conversion system power supplies, which contains a total of 16 rectifier modules, a firing generator and a fault detector, is shown undergoing tests to verify that performance characteristics meet design specifications. (82E0659)

personnel, and review of existing documentation is being vigorously pursued in preparation for this review.

TFTR DIAGNOSTICS

During FY83, the pace of diagnostic work quickened to match the TFTR tokamak completion schedule and emphasis shifted from development and design activities toward fabrication and installation. The initial set of diagnostics required for first-plasma operation in December 1982 is nearing completion while many of the major procurements for later systems are well-advanced through specification and contractual negotiation. The diagnostic program is carefully tuned to the experimental research program plan for TFTR, which has been gradually evolving throughout the year. The major short-term effect of this program plan has been to revise the scope of the initial start-up set of diagnostics and to modify the set of diagnostics which will be installed in the spring of 1983 for use in the study of ohmic-heated plasmas. These two sets of diagnostics are given in Tables I and II.

Table I. Diagnostics for Start-Up Plasmas.

Diagnostic	Parameter being Investigated
Rogowski Loops	Plasma Current
B_θ/B_p Loops	Plasma Position, Magnetic Perturbations
Voltage Loops	Voltage Around Torus
Saddle Coils	Plasma Position
Diamagnetic Loops (installed)	Plasma Pressure
1-mm Microwave Interferometer	Plasma Density
Hard X-Ray Monitors	Runaway Electrons
Torus Pressure Gauges	Neutral Gas Pressure
Residual Gas Analyzer	Vacuum Quality
Plasma TV	Fast TV Pictures of Plasma
Vacuum Vessel Illumination	Inspection of Vessel Interior
Glow Discharge Cleaning Probes	Cleaning of Vacuum Vessel
Electron Beam Alignment Probe	Quality of Toroidal Magnetic Field

Table II. Diagnostics for Ohmic-Heated Plasmas.

Diagnostic	Parameter being Investigated
Mirnov Loops (inside vacuum vessel)	Instability
Fast Scanning Heterodyne Radiometer	Electron Temperature
Thomson Scattering	Electron Temperature and Density
X-Ray Pulse Height Analyzer	Electron Temperature and Impurity
X-Ray Crystal Spectrometer	Ion Temperature and Impurity
X-Ray Imaging System	Plasma Instability
Charge-Exchange System	Ion Temperature
Ultraviolet Survey Spectrometer	Impurity Levels
H_α Interference Filter Array	H_α -Light, Bremsstrahlung Radiation
Wide-Angle-Bolometer	Total Radiation Levels
Bolometer Array	Spatial Distribution of Radiation
Diamagnetic Loops	Plasma Pressure
Epithermal Neutrons	Neutrons from Limiter, Ion Temperature
Infrared Temperature Monitor	Heating of Limiter Surfaces
Langmuir-Calorimeter Probe	Edge Plasma Density, Temperature

The magnetic diagnostics have been mounted on TFTR. Figure 18 is a photograph of some of the B_θ/B_p loops mounted on an external bellows cover plate during vacuum vessel segment preparation. Also shown are the slightly horn-ended tubes through which insulated wires were pulled to form sets of voltage loops. In addition, Rogowski coils, diamagnetic loops, and saddle coils were also mounted on the vacuum vessel as the tokamak was assembled. All of these were made to withstand 250°C bakeout temperatures and radiation doses in excess of 10^6 rads. The Rogowski coil was utilized in the first tests of integration with the CICADA System.

Laboratory testing of the circuitry and components for the 1-mm interferometer showed that it will have an exceptional signal-to-noise level. Full testing of the system on PLT started in early September and already shows excellent results. The hard X-ray monitors will be

Figure 18. Diagnostic B_θ/B_p loops. The loops are shown on an external bellows coverplate prior to installation of the thermal insulation on the vacuum vessel. The two horn-shaped ends of sections of the pipes through which the voltage loops will be pulled are also visible. (82E0689)

installed on the Test Cell walls after the building is cleaned up and the cabling has been installed. The vacuum diagnostics, torus pressure gauges, and residual gas analyzers have been undergoing testing, and the two sets of probes for glow discharge cleaning and electron beam alignment were delivered and are being prepared for installation. (The probe mechanisms for the Langmuir-calorimeter probes for use in the ohmic-heated plasmas were also delivered but have not yet been tipped.) The first of the plasma TV and inspection system periscopes has been fully tested and the video-recording system has been integrated with CICADA. The cameras are ordered and will be delivered soon.

A very significant part of diagnostic work in the last half-year has been the establishment of an infrastructure for the diagnostics to span the full life of the tokamak. Many man-hours have been devoted to the design of a data acquisition room to house the bulk of the diagnostic electronics and CAMAC equipment, the layout of cable trays, the single-point ground systems and ground isolation, the definition of standard cables, connectors and vacuum controllers, the provision of electrical power, air and water for the diagnostic systems, the design of flanges on port covers, and the continuing review for interferences. In the last few months this design work has begun to emerge as hardware, but a major installation effort will be required for first plasma. It is planned that design and installation of cabling and connections will be an almost continuous effort throughout the next two years. It is expected that the very large effort expended in designing the tokamak cover plate interfaces for the future diagnostics will save many man-hours in the changing of large cover plates.

Progress has been slow for the sets of diagnostics needed after first plasma. Of those required by April 1983 (Table II), many major components are still in fabrication, and, in the case of the internal Mirnov loops, the final design awaits decisions on the internal vacuum vessel hardware. The lowest frequency range of the fast-scanning heterodyne radiometer has been fully tested, but decisions on the final window design and calibration system have not yet been made. Most components of the Thomson Scattering System are on order or in final design; the lasers themselves have been delivered and have passed acceptance tests. Work assignments for the diagnostics applications programmers are under continuing review to establish priorities and determine the availability of the necessary manpower to complete the computer applications coding requirements to support the diagnostics for Spring 1983 operations.

Fabrication of the X-ray diagnostics is progressing well. The Horizontal X-Ray Crystal System requires little work since it is very similar to the PDX system and uses the same multi-wired proportional counter and electronics. The prototype of the cold-finger type of cryostat and detectors developed by the Lawrence Berkeley Laboratory (LBL) for the X-Ray Pulse Height Analysis System has been shown to meet specifications. It was designed to cut down the background noise

generated by neutrons at the detectors and, in addition to lithium doped silicon, Si(Li), detectors, includes one lithium doped germanium, Ge(Li), detector to accommodate the high electron temperatures expected in TFTR. Figure 19 is a photograph of this detector. The large number of surface barrier detectors for the channel X-ray imaging array are on hand and the amplifier boards are now being assembled.

Figure 19. Detector array and electronics for the X-Ray Pulse Height Analysis System. The array is made up of liquid-nitrogen-cooled lithium-drifted (doped) silicon and germanium detectors. (82X2209)

The charge-exchange systems used in the measurement of the ion temperature have also advanced considerably in design. The frame and plenum of the horizontal system, which initially has one but eventually will have three analyzers, are now being built and the first analyzer has been equipped with its full complement of front-end electronics which will be tested. The diagnostic neutral beam, which is an integral part of the charge-exchange system, is required in early 1984 and is in itself a major system, producing about the same beam power as one of the PLT beamlines. This beamline is being fabricated, the ion source is on order, and the power supplies have been specified. Figure 20 shows the neutral-beam enclosure under fabrication at PPPL.

The prototype of the Ultraviolet (UV) Survey Spectrometer has been used with considerable success on PDX, and the telescope design for the H α -interference filter system is being tested. The latter system is designed to measure the neutral hydrogen light intensity, selected impurity lines, or the visible bremsstrahlung. The electronics for the total radiation measurement technique, which uses all platinum resistance bolometers, have been developed and the vacuum components are now in fabrication. The first simple total neutron flux measurement systems have been completed and calibrated in the test laboratory. Two of these U²³⁵ proportional counters, with suitable moderators, have been operated with Campbell electronic circuits to give the very wide dynamic range expected for TFTR. They need to be calibrated with a source in the tokamak before being used.

The initial development of a one-color infrared temperature system for use with the plasma TV periscope and data system has been completed after

Figure 20. Diagnostic neutral beam. The diagnostic neutral beam is shown during fabrication in the PPPL Vacuum Machine Shop. (82E0687)

detailed comparisons were made with a two-color system. The latter offered some theoretical advantages based on insensitivity to emissivity and viewing angle of the hot surfaces, but these advantages were outweighed by the practical difficulties of image superposition.

Proceeding at a relatively slower pace, work continued on the diagnostics equipment that is scheduled for later installation. In particular, contracts have been placed for long probe mechanisms for use in surface studies, the major tripod support structure for a multichannel far-infrared interferometer, and various spectrometers. The first soft X-ray spectrometer, visible spectrometer, and the infrared Michelson interferometer, as well as many other components have been delivered and are being prepared for testing. Detector development work for PPPL by the Massachusetts Institute of Technology (MIT) and the University of California at Los Angeles (UCLA) continues to show good progress.

TECHNICAL SYSTEMS

The Technical Systems Division has overall responsibility for internal components of the vacuum vessel (particularly those that provide thermal protection to the vessel wall), thermal instrumentation for those com-

ponents, remote maintenance procedures and equipment, radiation shielding, provision of specialized equipment for D-T operation and, starting in FY83, design, manufacture, installation, and testing of tritium systems. Clearly, much of the work involves planning and design in preparation for experiments that are scheduled several years after the achievement of first plasma.

Purchasing of all components for the bellows cover plates continued, but vendor financial problems seriously delayed the deliveries. As a result a stainless steel limiter was designed, fabricated, and prepared for installation into TFTR for first-plasma operations.

The movable limiter required for high-power operation after initial start-up consists of three interconnected blades which are attached independently to three screw-driven actuators. The actuators and blades will occupy Bay M of TFTR. The blades were designed and fabrication has started; fabrication of the actuators continued.

The prototype surface pumping modules were designed, and the manufacture of components for all eight units was begun. Installation procedures were developed and fabrication of the installation tooling was started. The prototype system has a hydrogen pumping speed of 104,000 liters per second as compared to the 470,000 liters per second capability of the full system.

Designs of the large-area bumper limiter for TFTR were generated. Upon further study and evaluation, however, it became apparent that due to the complexity of these initial designs the costs to implement them would be unacceptable. Several requirements were subsequently relaxed and design work was started again, employing a combined team from PPPL and GA Technologies Inc. Similar arrangements have been organized for design of the protective plates which protect the vacuum vessel against neutral-beam shine-through.

Remote handling development work was held up in FY82 due to lack of funding. Shielding walls and labyrinths were designed, fabricated, and partially installed in the Test Cell to provide protection during first-plasma and initial ohmic heating (OH) operations. The columns and lintels of TFTR were filled with a borated concrete grout using silica fine aggregate. Radiation analyses for future TFTR operational needs continued.

Improvements to the TFTR Neutral Beam System were continued during the year. Ion dumps designed to absorb longer beam pulses, improved species-mix ion sources, and components for a fourth neutral beamline were fabricated.

NEUTRAL BEAM SYSTEM

Fabrication and testing of components and assemblies for the TFTR Neutral Beam System continued during FY82. Major emphasis was placed on the completion of testing of the prototype power supply (first into a resistive load and later using a prototype ion source), the installation of equipment in the Neutral

Beam Test Cell for the three-source test, and the resolution of manufacturing and test complications associated with the production of the neutral-beam power supplies. Mechanical assembly of the beamlines continued, and two of the four beamlines to be installed on the tokamak for plasma heating are now complete.

Cryogenic systems have been designed and built to provide the high pumping speeds required to operate the neutral beamlines. Activities on these systems included the performance testing of the 1080-watt liquid helium refrigerator. During the test, all specified operating parameters were successfully achieved and, in addition, the actual cool-down of a production beamline was accomplished. Tests were performed on the small liquid helium refrigerator (200 watts) for the beamline test in the Neutral Beam Test Cell. Those tests demonstrated that the unit has sufficient cooling capacity to meet all requirements for full power operation of the three-source test facility.

Full power testing of a TFTR beamline with a full complement of three ion sources will be carried out in the Neutral Beam Test Cell/Hot Cell independently of tokamak operation. In order to reproduce planned operating modes the sources must be tested using both hydrogen and deuterium gas. In the latter mode there will be substantial neutron production necessitating operation inside a shielded enclosure. Figure 21 shows one side of the shielding array that has been constructed for the three-source tests. Installation of the shielding was completed in August 1982. Characteristic properties of the accelerated beams will be measured using diagnostic devices installed in a target tank designed to simulate the torus vacuum vessel in the region of an injection port. In this way, it will be possible to measure beam power profiles and predict the manner in which power will be deposited in the plasma. Construction of this tank has been completed and it is being readied for installation in the Neutral Beam Test Cell, as shown in Fig. 22.

Figure 21. Neutral Beam Test Cell shielded beamline enclosure. One side of the concrete block enclosure constructed in the Neutral Beam Test Cell is shown. This radiation shielding will allow a TFTR neutral beamline, outfitted with a full complement of three ion sources, to be tested at full power using deuterium. (82E0941)

Figure 22. Neutral Beam Test Cell target tank. The neutral-beam target tank, used to simulate the TFTR vacuum vessel, will contain detectors and other diagnostic apparatus for measuring the characteristics of the beams produced during the three-source testing program (82E1187)

Testing of the neutral-beam high-voltage power supply prototype was conducted in the Experimental Test Building. The Aydin-Transrex power supply reached 120-kilovolts working into a dummy load. In the foreground of Fig. 23 is a large tank which contains sulfur hexafluoride under pressure. This tank houses the arc and filament power supplies for one neutral-beam ion source. During operation, these supplies are electrically floating at 120 kilovolts above ground.

In order to maintain continuity in the program for development of TFTR neutral beams, while at the same time incorporating the experience and expertise gained through the PLT and PDX neutral-beam activities, all neutral-beam R&D activity efforts were reorganized as a single Laboratory-wide project.

LITHIUM BLANKET MODULE

The final design of the Lithium Blanket Module (LBM) was continued by General Atomic Technologies Inc. (GA) under contract to PPPL and with the sponsorship of the Electric Power Research Institute (EPRI). Fabrication of the LBM and the Engineering Test Station (ETS) is scheduled to begin in FY83 and the LBM will be

Figure 23. Neutral-beam power supply high-voltage enclosure. The large tank shown in the foreground of the photograph houses the arc and filament power supplies for one neutral-beam ion source. The tank contains sulfur hexafluoride gas under pressure as an electrical insulation medium, since the power supplies operate at high voltage (120 kV direct current). (82E0450)

installed on the TFTR in mid-1985. Measurements of spatially integrated neutronics and tritium production throughout the LBM during both D-D and D-T operation will be compared with the computational predictions of Monte Carlo neutronics codes. As indicated in Table III, the geometric and physical characteristics of the breeder, structure, and coolant arrangement for the LBM were selected to be applicable to the blanket modules of a power reactor.

Procedures for mass-producing 25,000 lithium oxide pellets with the required properties (2.5-cm diameter, 2.5-cm length, 78% theoretical maximum density) were developed by GA. Neutronics analyses were extended to include coupled Monte Carlo techniques and cell calculations. In the coupled calculations, a long initial run of the entire TFTR/LBM System is made to determine the neutron fields incident on the LBM surfaces. This run is followed by shorter runs treating only the LBM and using the surface neutron field as the source to obtain details of neutron fluxes, tritium production rates, and activation foil responses within the LBM.

The 20-cm diameter central zone of the LBM contains the primary test elements and can incorporate up to 13 fully instrumented rods and 25 wire bundles. This instrumentation is readily removable through the rear of the LBM.

Dosimetry feasibility experiments were performed at the Idaho National Engineering Laboratory (INEL) to qualify the activation foil dosimetry for neutron measurements under expected TFTR operating conditions. Tritium assays will be performed by the thermal extraction method, whereby the lithium oxide pellets will be heated to about 950°C in a purge flow stream of hydrogen.

Table III. Materials and Design Selections for the Lithium Blanket Module.

Blanket Component	Material	Applicable in Power Reactor
Breeding Material	Li_2O (with natural isotopic content)	yes
Coolant (15% void)	Air (corresponding to helium)	yes
Structural Material	Stainless Steel 316	yes
Breeder Element	Sintered Li_2O pellet, 2.5-cm diameter 2.5-cm length, and 78% theoretical density	yes
Cladding	Stainless Steel 316, 0.3-mm thick	yes
Breeder Lattice	923 close-packed radially oriented rods, 60-cm breeder section	yes
Sample Retrieval	1) Thirteen removable breeder rods in central region 2) Selected buffer-zone rods removable	
Neutron Dosimetry	1) Wires between rods 2) Foils in rod pockets	yes
Neutron Multiplier	Provision for 500-kg slab at front face	
Neutron Reflector	Stainless Steel 316, 20-cm deep	yes

SAFETY AND ENVIRONMENTAL MONITORING

Personnel safety and environmental impacts have continued to be an important consideration in the planning, testing, and operational activities on the TFTR Project. A program of analysis to determine the concentrations of radioactive pollutants in surface waters was initiated this year in order to establish a reference environmental baseline for these substances prior to tokamak operation. This information will augment the database for nonradioactive pollutants which is being developed. One real-time monitoring system was put into operation to carry out studies of prompt gamma and neutron production, air activation and particulate matter (alpha, beta, gamma) concentrations. As part of a phased approach to a total

environmental radiation monitoring system, four real-time prompt gamma monitors were installed at the exclusion zone boundary (EZB) and eight others were placed in close proximity to the Test Cell and prepared for operation. The TFTR Health and Safety program received support from a new system of Health and Safety Directives (HSD's), including a new Health and Safety Manual which was issued to the entire Laboratory in January 1982. The TFTR Project produced and disseminated a complete set of Safety Requirements (SR's) which covered all subsystems involved in first-plasma operations and is currently preparing a set of associated Operational Safety Requirements (OSR's). All comments by DOE to the Final Safety Analysis Report (FSAR) were resolved and incorporated into the document; the final version of the FSAR is scheduled for publication soon.

Princeton Large Torus

The research program conducted on the Princeton Large Torus (PLT) tokamak in FY82 emphasized studies of high-power radio-frequency (rf) heating and current drive in several regimes of interest for next generation and reactor devices. Ion-cyclotron-range-of-frequency (ICRF) minority and second-harmonic heating were both shown to be efficient processes, $\eta = 3\text{--}5 \times 10^{13} \text{ eV cm}^{-3} \text{ kW}^{-1}$, at powers up the 3-MW level. Ion-cyclotron-range-of-frequency and neutral-beam (NB) heating were combined at powers approaching 5 MW to increase the central ion temperature above 3 keV at $n_e \sim 6 \times 10^{13} \text{ cm}^{-3}$. These results support extrapolations to TFTR which gave $Q \sim 2$ (nuclear energy yield/rf energy absorbed) at $\approx 30 \text{ MW}$ of absorbed rf power.

Lower hybrid (LH) current drive was shown to sustain, in the absence of an inductive loop voltage, the plasma current over extended discharge times; currents of 165 kA for 3.5 sec were achieved at densities of $3 \times 10^{12} \text{ cm}^{-3}$ with 70 kW of LH power. Currents up to 420 kA were sustained for shorter periods (0.3 sec) at higher power. The physics of the density limit ($n_e \approx 10^{13} \text{ cm}^{-3}$) to LH current drive encountered at 800 MHz was investigated using a large assortment of diagnostics. The results suggested that higher frequency operation would permit efficient LH current drive at densities in the mid- 10^{13} cm^{-3} range. Consequently, Department of Energy (DOE) approval was obtained to begin construction of a 1.5-MW, 2.45 GHz LH source.

Investigations of confinement physics, impurity transport, and MHD stability were continued in support of the rf experiments on PLT. Initial investigations of energy confinement in high-power ICRF-heated discharges showed little degradation in the transport confinement time, $\tau \approx 40 \text{ msec}$. However, the potential importance of energetic-ion losses in the H-minority heating case was demonstrated. Energy confinement for LH current driven discharges was shown to be sufficient to sustain the discharges at relatively high temperatures [$T_d(0) \sim 400 \text{ eV}$, $T_e(0) \sim 800 \text{ eV}$] for times exceeding 0.5 sec. The effect of neutral-beam injection on impurity transport was studied to gain insight into the roles of plasma rotation, bulk transport, and surface source behavior in determining impurity accumulation.

The objectives of the PLT program in the coming years will be to optimize rf methods for reaching plasma temperatures of $\geq 5 \text{ keV}$ and for reducing the volt second requirements of long-pulse tokamaks. To achieve these goals will require techniques of impurity control and of energy removal for handling the power flux associated with intense rf heating and long-pulse current drive.

MAJOR ACTIVITIES

Summary

Two days of ICRF, two days of LH, and one day of support experiments were scheduled for each "run" week. This resulted in 54% of PLT discharges being devoted to ICRF heating, 35% to LH current drive, and 7% to neutral-beam heating. Neutral-beam injection (NBI) was also used in conjunction with ICRF to study their synergistic effects. Experiments on plasma confinement, transport, stability, and radiation were performed during about 50% of the experimental run time, in discharges devoted primarily to the heating experiments.

Technological improvements in FY82 have resulted in a five-fold increase in LH power to 600 kW, an eight-fold increase in ICRF power at 42 MHz, and a 40% increase in neutral-beam power (Fig. 24). Spectroscopic diagnostics in the μ -wave, ultraviolet, and X-ray ranges of wavelengths have been developed for the anticipated TFTR regimes to allow measurements of T_e and T_i to 10 keV as well as other important plasma parameters.

In FY82 the PLT experimental run day was reduced by four hours due to budget restrictions and to manpower requirements for TFTR. However, improved machine performance and fewer vacuum openings resulted in a 15% increase over FY81 in the number of high-power discharges (to 14,500); and a steady stream of visiting scientists from foreign and American laboratories provided able assistance, compensating, in part, for physicists transferred to TFTR.

AUXILIARY HEATING RESULTS ON PLT

At the end of FY81, as the mission of PLT was redirected towards the applications of radio-frequency waves for plasma heating and current drive, the emphasis in the auxiliary-heating program was placed on high-power ICRF and combined ICRF plus neutral beam-heating experiments. The PLT auxiliary heating system consisted of six half-turn loop ICRF antennae and three tangential neutral-beam lines. One ICRF antenna radiating 0.5 MW into a PLT plasma is shown in Fig. 25. With improved feedthroughs,¹ up to 1.6 MW at 25 (now 30) MHz has been coupled into PLT via two antennae and up to 3 MW at 42 MHz via six antennae. The lower frequency was used for the

Figure 24. Auxiliary power on PLT. Prior to FY82 there were four neutral beams on PLT with a total power capability of 3 MW. (83X0476)

Figure 25. Photograph of one ion-cyclotron half-turn antenna radiating 0.5 MW into PLT. There are six such antennae around the vessel. (83X2122)

^3He - and H-minority-heating regimes at $B_0 \sim 25$ kG and 17 kG, respectively, while the higher frequency provided heating in the H-minority and H-second-harmonic

regimes at $B_0 \sim 28$ kG and 14 kG, respectively. The neutral beams were to compare with ICRF and also to provide energetic particles for the ICRF wave-heating studies. Up to 2.5 MW D^0 have been injected in conjunction with ICRF heating experiments to achieve a total auxiliary heating power of 4.5 MW.

Minority-Ion Heating

The central deuterium temperature increments, $\Delta T_d(0)$, obtained for the ^3He -minority, H-minority, and H-minority plus D^0 neutral-beam injection regimes are summarized in Fig. 26(a) for a range of densities and powers up to $\bar{n}_0 \sim 6 \times 10^{13} \text{ cm}^{-3}$ and $P_{\text{AUX}} \sim 4.5$ MW. Both the highest value of $\Delta T_d(0)$, 2.2 keV, and the best ion heating efficiencies have been achieved in the ^3He minority case.² The ion-heating efficiency in this case is $5 \times 10^{13} \text{ eV cm}^{-3} \text{ kW}^{-1}$ as compared with $3 \times 10^{13} \text{ eV cm}^{-3} \text{ kW}^{-1}$ for H-minority heating of plasma with similar I_p and B_T .

Figure 26. Plasma ion-heating efficiency for the (a) minority-fundamental and (b) majority-second-harmonic regimes of ICRF. (83X0477)

Theory predicts that both the negligible charge-exchange loss and the stronger collisional coupling to the deuterium ions of the energetic ^3He ions contribute to better ion confinement and therefore ion heating. Measurements of charge-exchange neutrals indeed show a factor of about 100 reduction in the superthermal flux. Measurements of the energetic ions at the periphery have been made with a particle bolometer^{3,4} located at the limiter radius, and with a fast-ion charge-exchange system.⁵ The bolometer is covered by a carbon cylinder with acceptance slits along its axis, which is oriented along the major radius [insert Fig. 27(a)]. Rotation about this axis provides discrimination between particles having different gyroradii and different ratios of $v_{\perp}/v_{\parallel}$ with respect to the magnetic field. The charge-exchange system discriminates $v_{\perp}/v_{\parallel}$ by scanning in the horizontal midplane of the plasma.

The particle bolometer measurements of energetic ions during ICRF heating of a D plasma with H (42 MHz) and ^3He (25 MHz) minorities are given in Fig. 27(a). The angle-resolved absorbed power, $dI/d\theta$, in the ^3He -minority regime is indistinguishable from its value during ohmic heating and arrives at the probe at $\theta = 0^\circ$

Figure 27. (a) Power to a bolometer probe located in the PLT edge plasma versus probe angle. During H-minority heating the energy to the bolometer arrives at the probe at an angle of 50° with respect to B_T indicating the loss of energetic particles. (b) Charge-exchange flux versus tangency radius. (c) One viewing point of the charge-exchange analyzer superimposed on a large banana orbit whose tips are in the ICRF resonant layer and antenna high voltage points. (83X0496)

and 180°. The observed flux in the H-minority regime is three times greater than the ohmic value, and it peaks at approximately 50° relative to the plasma current direction, representing particles with large gyroradii having $v_{\perp}/v_{\parallel} \sim 1.2 - 1.3$. From geometric considerations, these particles have $E_{\perp}$ of the order of 50 keV and are estimated to give a direct loss of about 15% of the input power, if the flux is poloidally uniform. Tangential NBI (on PLT) results in $df/d\theta$ with the same θ dependence as the He³-minority regime. Perpendicular NBI (on PDX) gives $df/d\theta$ similar to the H-minority case but at 81° with respect to the parallel direction.

Charge-exchange measurements made during H-minority heating at 42 MHz indicate the presence of energetic trapped ions (up to 91 keV). As the line of view intercepts larger major radius the neutral flux decreases [Fig. 27(b)] consistent with banana orbits that just fit inside the outermost PLT ring limiters [Fig. 27(c)]. The tips of the orbits intersect the ion cyclotron layer as well as the high voltage region of the antenna, as verified by seeing the flux at a fixed viewing angle change as the toroidal field is varied. It is possible that these particles could be those measured by the bolometer probes.

In the minority regimes substantial electron heating has been obtained at the higher power levels. For the ³He-minority case $T_e(0) \geq T_e(0)$ has been observed, in contrast to $T_e(0) < T_e(0)$ for the H-minority case. Numerical transport studies indicate that the electron heating can be accounted for by coupling to the

energetic minority ions, although direct wave electron heating could also be occurring.

Density fluctuations at the heating frequency have been observed using a 2-mm microwave scattering system during 42-MHz ICRF heating of D plasmas with H-minority.⁶ The signals produced by fluctuations with $k \approx 3.8 \text{ cm}^{-1}$ in the plasma center are shown in Fig. 28 as a function of the toroidal field for two different minority concentrations. The maxima correspond to conditions where the ion-ion hybrid layer is close to the scattering region, indicating that the observed fluctuations could be produced by electrostatic ion-Bernstein waves mode converted from the ICRF fast wave. This process has recently been proposed to explain both ion and electron heating.

Figure 28. Scattered microwave signal from the plasma center ($k = 3.8 \text{ cm}^{-1}$) for two H concentrations in D plasmas heated with 1.2 MW of rf power at 42 MHz. (83X0033)

Second-Harmonic Heating

The highest rf power coupled into a PLT plasma to date, 3.2 MW, has been reached in the H-second-harmonic regime with the 42-MHz rf system. The central hydrogen energy distribution measured

Figure 29. (a) Central hydrogen distribution function determined by perpendicular charge exchange during second-harmonic H heating (~2.8 MW). (b) T_{eff} versus time for this case. (83X482)

with charge-exchange systems is anisotropic and non-Maxwellian [Fig. 29(a)]; this is in general agreement with the theory of quasi-linear velocity space diffusion. The energy contained in such a distribution can be described in terms of the average ion energy, $\langle E_h \rangle$, or by an effective temperature,^{2,4} $T_{eff} \equiv 2/3 \langle E_h \rangle$. T_{eff} versus time for $P_{rf} \sim 2.8$ MW and $\bar{n}_e \approx 3.8 \times 10^{13} \text{ cm}^{-3}$ is given in Fig. 29(b). A maximum value for T_{eff} of 3 keV was attained. Figure 26(b) illustrates the scaling of ΔT_{eff} with $P_{rf}/\bar{n}_e$ for several combinations of antennae.

ICRF Plus Neutral-Beam Heating

The high-power results reported here are for the H-minority plus D⁺-beam case for which the rf beam-ion interaction is expected to be less than in the previously⁷ measured H⁺-beam case. The ion temperature was determined from Doppler broadening of impurity lines since energetic components are added to both the H and D ion-energy distributions. Toroidal β values in the range of 1.6 - 2.2% were achieved in the H-minority regime at 17.5 kG with ~ 3 MW of combined (25 MHz) plus NB (D⁺) power. These results were obtained at a plasma current of 500 kA giving $q(a) \approx 2.1$. The total plasma-stored energy exceeded 100 kJ, half being in the electrons.^{2,8}

Figure 30. Electron-heating characteristics for the minority-H plus D⁺-beam regimes, (a) Rise in central electron temperature; (b) rise in stored electron energy. The power levels for each heating technique are NB ~ 1.5 MW, ICRF ~ 1 MW, ICRF plus NB ~ 2 MW, ohmic ~ 0.5 MW. (83X0480)

Figure 31. Global (τ_{EG}) and transport (τ_{ET}) confinement times in PLT for auxiliary heating experiments as a function of electron density and heating power. (83X0488)

The properties of ICRF plus NB heating have been studied at higher toroidal field, $B_\phi \sim 28$ kG, for auxiliary power levels up to 4.5 MW and $\bar{n}_e$ ranging up to $\sim 6 \times 10^{13} \text{ cm}^{-3}$. Ion temperature profiles have been obtained by measuring Doppler broadening of intrinsic, e.g., Ti and C, and injected, e.g., Fe and Mo, impurities. The values of $T_d(0)$ deduced for the bulk deuterium component

from Doppler broadening measurements of hydrogen-like titanium-line radiation are plotted in Fig. 26(a). The ICRF plus NB data points lie somewhat above the H-minority curve, indicating an ion heating efficiency of 3.5×10^{13} eV cm⁻³ kW⁻¹ for the conditions studied.

Systematic studies of the electron heating have begun in the H-minority regime, with and without D⁰ beam injection. Results of electron heating in the ohmic, H-minority, and H-minority plus D⁰ beam regimes obtained for similar target plasma conditions are given in Fig. 30 for $\bar{n}_e$ up to 6×10^{13} cm⁻³ and auxiliary power, P_{AUX} , up to 4.5 MW. The rate of central incremental electron heating [Fig. 30(a)] measured by Thomson scattering, ω_{ce} and $2\omega_{ce}$ emission, and X-ray pulse height analysis, is generally higher for the H-minority plus D⁰ beam case and is comparable to the incremental ion-heating rate ($\sim 3 \times 10^{13}$ eV cm⁻³ kW⁻¹). However, the change in electron energy for all three cases [Fig. 30(b)] is roughly linear in power, in keeping with the T_e profile being more peaked for the combined ICRF plus NB-heating regime. An incremental volume heating efficiency, $2\Delta E/3P_{AUX}$ V, of $\sim 1.0 \times 10^{13}$ eV cm⁻³ kW⁻¹ best fits the set of data in Fig. 30(b).

Combining the electron and ion heating results for this case yields the energy confinement times plotted in Fig. 31. The global confinement time, defined as $\tau_{EG} = (E_e + E_d)/(P_{rf} + P_{nb} + P_{oh})$, incorporates all of the energy loss processes. The "transport" confinement time, defined as $\tau_{ET} = (E_e + E_d)/(P_{rf} + P_{nb} + P_{oh} - P_{cx} - P_{rad})$, represents primarily conduction and convection losses. The energy stored in the energetic ions has not been included here. Figure 31(c) suggests that an energy confinement time lower than the ohmic value characterizes the auxiliary-heated discharges at large auxiliary power. However, at the higher densities the "transport" confinement time in the ICRF case approaches that of the ohmic case, and τ_{ET} of up to 40 msec is obtained in the ICRF plus NB case.

LOWER HYBRID CURRENT DRIVE

The benefits of sustained-plasma-burn duration in tokamak reactors have motivated the efforts on wave-driven currents in PLT. Technical improvements, including carbon coating⁹ of the lower hybrid six-waveguide grill and relocation of the PLT limiters, have permitted operation of the 800 MHz LH experiment at power levels up to 600 kW, five times higher than FY81 (Fig. 32). Lower hybrid current drive, "unassisted" by a toroidal electric field, has been extended to discharges of 420 kA for 0.3 sec or 165 kA for 3.5 sec (Fig. 33). The current drive efficiency of ~ 2 A/W degrades rapidly for densities above $\bar{n}_e \sim 0.8 \times 10^{13}$ cm⁻³.

Because of the large reservoir of energy in the poloidal magnetic field, changes in inductance can play a significant role in current maintenance during the LH pulse. In 1982 discharges were successfully created in which up to 90% of the power needed to maintain the

Figure 32. Power-reflection coefficient versus power. Prior to carbon coating the waveguide grill, the forward power per waveguide was limited to approximately 40 kW. With the coating the power throughput is the maximum available from the present power supplies. (83X0131)

Figure 33. Plasma-current and electron density versus time. 165 kA of current were driven with an applied power of 75 kW. (82X0404)

discharge was derived from the rf power itself,¹⁰ as shown in Fig. 34. This fraction was inferred from the constancy of the internal plasma inductance $L_i/2$, measured from the vertical field required to maintain the plasma in equilibrium.

It has been suggested that lower hybrid waves may be useful in maintaining the plasma current in a fusion reactor during the time the ohmic heating transformer is recharged by reversing its primary current. Preliminary tests of this idea¹¹ were conducted on PLT. The plasma current was held almost constant at 150 kA while the current in the ohmic primary winding was reduced at a rate of 1.8 kA/sec (-0.3 V on loop voltage). X-ray studies show that the high-energy electron population is unchanged during the reversal time (~ 0.4 sec).

Detailed X-ray and microwave measurements^{12,13} indicate that the drive current is carried by a high energy (~ 100 keV) electron tail. Figure 35 shows energy spectra obtained from a pulse-height analysis of X rays observed by a NaI detector. The curves are approximately exponential, with an average energy ranging from 25 to 50 keV, depending on the relative

Figure 34. Plasma current, loop voltage, electron density, and internal inductance versus time for three cases: no rf current drive, 300 msec rf current drive, and ~1.0 sec current drive. (83X0485)

Figure 35. X-ray energy spectra for three rf phases during lower hybrid current drive and with no applied rf power. (82X0738)

phasing, $\Delta\phi$, between adjacent waveguides. Model calculations indicate that Maxwellian electron tails with "temperatures" of 50 to 100 keV would produce the observed X-ray spectra.¹⁴ The width of the spectra is in qualitative agreement with the linear theory of lower hybrid wave excitation in which the spectrum excited would correspond to an average energy of 25 keV (at 135° phasing of the LH waveguides) to ~100 keV at 60° phasing. The absence of X rays when no LH power is applied shows that a preformed tail is not required for LH current drive.

The spatial location of the fast electron tail has been determined with a scanning silicon soft X-ray (≤ 25 keV) detector.¹³ The X-ray intensity is peaked at the center of the plasma column. The width of this central peak varied from ~7 cm at low current/high field to ~15 cm at high current/low field. Current profiles inferred from this data, with a number of simplifying assumptions, yield an internal inductance $\lambda_i/2$ from 1.0 to 0.6, in good agreement with those determined from the plasma equilibrium equations.

Measurements of the angular distribution of the X-ray emission with respect to the magnetic field have begun to give definitive results on the shape of the electron distribution function during lower hybrid current drive. The spectra X rays emitted in the direction of the plasma current have approximately the same slope, but with four times lower intensity, as the spectra emitted in the opposite direction. It may, therefore, be assumed that the electron velocity distribution is not a beam in the forward direction, but is comprised of a broad hump that extends beyond 90°. The theoretical curves that have been fitted to the experimental data in Fig. 36 represent bremsstrahlung calculations for an electron velocity distribution, f_0 , which has the energy dependence of a 100-keV Maxwellian and $f = f_0$ in a 60° cone in the forward direction, $f = 0.1 f_0$ in a 60° cone in the backward direction, and $f = 0.55 f_0$ in the remaining region of phase space.

Under certain conditions, usually when an electric field as well as the LH power is impressed on the plasma column, periodic oscillations appear in the intensity of the microwave radiation emitted from the plasma

Figure 36. X-ray spectra emitted parallel and counter to the direction of the electron current. The experimental data can be fit by an electron-distribution function as shown in the inset. (83X0478)

column. A characteristic phase reversal appears (see Fig. 37) in the oscillations of the radiation at frequencies near ω_{pe} , ω_{ce} , and $2\omega_{ce}$, which is consistent with the build-up of an electron tail parallel to the magnetic field, and with the occurrence of an instability which transfers the energy into a direction perpendicular to the field. The instability is similar to that identified in the TM-3 tokamak by Parail and Pogutse, in which the presence of an electron tail is thought to excite electron plasma waves via the anomalous Doppler interaction. The conversion of parallel electron energy into perpendicular energy has been confirmed by hard X-ray measurements. Relaxation oscillations are observed for decaying plasma current, for example, when the LH power is small or when the plasma density is relatively high, $\bar{n}_e \sim 7 \times 10^{12} \text{ cm}^{-3}$.

Studies of the bulk plasma during LH current drive have been made with Thomson scattering for electron temperature profiles and with the low energy neutral atom spectrometer (LENS) for ion temperature profiles (Fig. 38). The classical (collisional) energy transfer from the current-carrying energetic (100 keV) electrons to the bulk electrons has been evaluated. This gives a power input into the bulk plasma of 60 kW and an estimated energy confinement time in the range of $\tau_{Ee} = 5\text{--}20 \text{ msec}$. A comparable energy confinement time is also estimated for the energetic electrons. Ohmically heated discharges with the same $\bar{n}_e$ and I_p have a similar τ_{Ee} . Transfer of energy from the bulk electrons to the ions has been modeled using the standard PLT ion-

Figure 37. Microwave emission at ω_{pe} , $\omega_{ce}(0)$ and $2\omega_{ce}(x)$ showing parallel to perpendicular electron energy transfer during simultaneous application of a loop voltage and lower hybrid current drive. (83X0484)

Figure 38. Bulk electron and ion temperature profiles measured during lower hybrid current drive. Also shown is the calculated T_i profile based on the measured $T_e(r)$ and the standard PLT energy balance code. (83X0475)

power balance code. The predicted T_i profile matches the measured central value of T_i , but underestimates the edge value.

Other experiments using lower hybrid waves included a demonstration of current ramp-up at $\sim 80 \text{ kA/sec}$, a demonstration of preionization and current drive up to 3 kA without any OH assistance, and a demonstration that current drive could be maintained in the presence of ICRF ion heating.

PLASMA TRANSPORT

To understand the physical processes responsible for confinement, studies of microturbulence, and impurity ion, proton, and MeV-ion transport and confinement have been made in ohmic and auxiliary-heated plasmas.

Microturbulence

The frequency spectrum of density fluctuations in PLT during ohmic discharges has been reexamined¹⁵ using a new microwave scattering geometry with improved spatial resolution. The radial extent of the typical scattering region was $\Delta r \approx 10$ cm. Shown in Fig. 39 are the frequency spectra of density fluctuations at three radial locations. These data clearly illustrate three important features of the microturbulence of tokamaks: 1) The spectra are shifted in frequency corresponding to propagation along the electron diamagnetic direction; 2) the spectral width at half intensity is several times (2-4) the value of ω_{ce} ; 3) the spectral width of fluctuations at the boundary of the plasma column is larger than that of fluctuations in the central region. These results indicate that the observed fluctuations evolve to a strong nonlinear state.

Figure 39. Frequency spectrum of density fluctuations: (a) $r=5$ cm, $k=5$ cm⁻¹; (b) $r=16$ cm, $k=7$ cm⁻¹, and (c) $r=30$ cm, $k=6$ cm⁻¹. The plasma parameters were $B=32$ kG, $I_p=420$ kA, $T_{e0} \approx 1.5$ keV, $T_{i0} \approx 0.8$ keV, $Z_{eff} \approx 1$, and $\gamma_e/\gamma_{\text{bounce}} < 1$. (83X0471)

Impurity Transport

A major aim of transport studies in PLT discharges¹⁶ was to examine differences between impurity ion transport during co-neutral-beam injection (co-NBI) and counter-neutral-beam injection (ctr-NBI). It has been known for some time that significant differences exist at comparable injected power levels into identical target plasmas. Recently theoretical work has suggested a strong influence of the beam-induced direction of toroidal plasma rotation on impurity ion transport, with heavy ion accumulation in the plasma core for ctr-NBI and heavy ion expulsion during co-NBI. The theoretical model predicts that the flux of heavy ions should be mass dependent. Hence, for our transport studies, two elements with differing masses were chosen: scandium ($Z=21$) and molybdenum ($Z=42$). Additional reasons for this choice are related to atomic physics and detection techniques.

The tracer elements were injected into discharges by the laser blow-off method.¹⁷ All standard plasma [$T_i(r)$, $T_e(r)$, $n_e(r)$, I_p] and neutral beam parameters were the same from shot to shot during the period of tracer-element radiation observations. The toroidal plasma rotation was determined by the Doppler shift of line radiation, with central plasma rotation determined from the 2665 Å forbidden line of FeXX. These experiments were performed with hydrogen neutral-beam injection into deuterium plasmas ($H^0 \rightarrow D^+$).

Figure 40. Time evolution of ScXI, ScXIX, MoXXXII, and MoXXXIII radiation during co- and ctr-NBI. (83X0072)

The only substantial difference between co- and ctr-NBI was that the amount (~ 10^{18} atoms) of injected Mo had to be reduced a factor of three during ctr-NBI to prevent any significant changes in plasma parameters and to produce the same interior ($r \leq 20$ cm) emissivities as in the co-injected case. The cause of this difference is not yet known, but it is undoubtedly connected with plasma conditions. When the amount of injected Mo was not reduced during ctr-NBI, radiation losses from the plasma core led to such large drops in the central electron temperature that the observed MoXXIII ion

Figure 1 consists of two plots, (a) and (b), showing Mo line intensity and temperature profiles.

Plot (a) shows Line Intensity (arb. units) on the left y-axis (0 to 1.0) and Temperature T_e (keV) on the right y-axis (0 to 2.0) versus Time (ms) on the x-axis (440 to 600). The plot is titled "LARGE AMOUNT OF Mo". It displays three Mo line intensity profiles: Mo XXIII (3553 Å), Mo XXII (176 Å), and Mo XXX (490 Å). A temperature profile T_e is also shown, increasing from approximately 1.5 keV at 440 ms to 2.0 keV at 600 ms. The Mo XXIII intensity peaks at approximately 450 ms, Mo XXII at approximately 470 ms, and Mo XXX at approximately 490 ms.

Plot (b) shows Line Emission on the y-axis (0 to 6) versus Radius (cm) on the x-axis (-30 to 30). It displays three fast radial profiles of the Mo XXIII line emission at different times: $t_1 = 459$ ms, $t_2 = 473$ ms, and $t_3 = 488$ ms. The profiles show a shift in the emission peak from the center (0 cm) to the periphery (approximately 20 cm) as time progresses.

Detailed quantitative evaluation of all the transport experiment data including absolute ion densities, the behavior of the total Mo or Sc density, and the attempts to deduce transport coefficients by comparison with modeling calculations (the MIST code)¹⁸ is in progress. On the basis of these experiments with one and two neutral beams it is concluded that:

- In PLT with trace impurity injection, significant differences were not observed in radial profiles and time evolution of Mo and Sc radiation during co- and ctr-NBI (for $P_{NB} \sim 0.5$ MW and 0.9 MW, H° injection into D° plasma, $B_T \approx 31$ kG).
- For the same amount of injected Mo or Sc, significantly more tracer element ions penetrate the plasma periphery during ctr-NBI than during co-NBI.

The transport of laser blow-off injected low-Z elements, e.g., aluminum and magnesium, during sawtooth MHD activity in ohmic discharges was studied by soft X-ray techniques. During the early injection phase, inverted sawtooth oscillations appear on the signals from the soft X-ray diodes. A typical example

with Al injection is shown in Fig. 43. For these discharges, synchrotron-radiation traces exhibit normal sawteeth with $m = 1$ precursors and no postcursors, in agreement with the "classical" Kadomtsev-reconnection model. The soft X-ray traces exhibit precursors, inverted sawteeth, and, in addition, a postcursor. This indicates that incomplete reconnection might occur much more often than is apparent from radiation without adequate radial selectivity.

Figure 43. Inverted sawtooth at 761 msec in the soft X-ray emission due to Al injection. (83X0472)

Hydrogen Transport During Gas Puffing

The evolution of the density profile during gas puffing experiments on PLT¹⁹ indicates that particle transport could be due to the combination of an inwardly directed velocity ($V^A \sim 10^3$ cm/sec) that is peaked towards the plasma periphery (Fig. 44) and a large anomalous diffusion coefficient ($D^A \sim 10^4$ cm²/sec), as has been suggested previously on the basis of Alcator gas puffing experiments. This conclusion is derived from PLT plasma conditions where the density rises strongly and the plasma is evolving in time. However, these transport coefficients for the hydrogen ions also would explain PLT transport measurements of trace high-Z impurities¹⁸ and trace ³He ions²⁰ which were performed in quasi-steady-state plasma conditions. The results reported here cannot be explained by enhanced neutral penetration coupled with a mildly enhanced Ware pinch, which has previously been used to explain PLT and Alcator density profiles. Charge-exchange measurements of the central neutral-density evolution and the neutral emission from the limiter indicate that neutral-particle penetration did not cause the density rise. The evolution of the ion-energy balance during the density rise indicates that, whereas the usual neoclassical analysis applies during the quasi-steady portions of the discharge, an anomaly exists during the

density rise. Fitting the experimental data requires a five-times enhanced ion thermal conduction, or an energy-dependent convection process, to bring additional energy into the plasma center. There is a fundamental difficulty with the usual treatment of the convection term in the ion-energy balance, since the inward and outward fluxes are much larger than the net flux of particles that is conventionally used to deduce the convective energy flow.

Figure 44. Neoclassical and anomalous pinch velocities required in particle balance calculations to explain penetration of puffed hydrogen into the PLT plasma core. (81X0458)

MeV Ion Confinement

The confinement and slowing down of charged fusion reaction products has been studied²¹ by measuring the fraction of a dilute concentration of 1.0-MeV tritons and 0.8-MeV ³He ions, produced by the d(d,p)t and d(d,n)³He fusion reactions, that undergo subsequent d(t,n) α and d(³He,p) α fusion reactions. To within a factor of three, this "burnup" ratio has been found to be

consistent with classical confinement and slowing down of 0.8-MeV ^3He ions during deuterium neutral-beam injection into 2.2-kG PDX discharge. Similarly, at 32 kG, the 1.0-MeV triton burnup in PLT was near classical. These studies are similar to studies of the burnup of neutral-beam injected 40-MeV deuterons and of 0.2-MeV ICRF heated ^3He ions that also indicated near-classical behavior in PLT. The 0.8-MeV ^3He burnup in low field PDX discharges and the 1.0-MeV triton burnup at 18 kG in PLT differed substantially from classical predictions, however (Fig. 45). The data suggest that anomalous prompt losses of these large gyroradii ions may be responsible for the reduced burnup.

Figure 45. Ratio of experimental to theoretical values of ion burn-up versus ion gyroradius. (82X0753)

DIAGNOSTICS DEVELOPMENT

In support of TFTR, a number of diagnostics devices and techniques were developed on PLT for future studies of plasmas with temperatures exceeding 10 keV.

Electron Cyclotron Emission

A grating polychromator has been built and operated on PLT by physicists from the University of Maryland. The instrument can measure T_e at three different radii. For a 50-kHz bandwidth, the spatial resolution is 4 cm and signal-to-noise 200:1 at $T_e = 1$ keV and $B_T = 32$ kG. For thermal plasmas, its density and temperature ranges are $5 \times 10^{12} \text{ cm}^{-3} < n_e < 5 \times 10^{14} \text{ cm}^{-3}$ and $10 \text{ eV} < T_e < 10^4 \text{ eV}$.

Ultraviolet Spectroscopy

Measurements of hot plasma ion transport, rotation, and temperature profiles are possible through spectroscopic techniques. Ion species with ionization potentials near T_e are needed for these applications.

Long wavelength transitions involving the ground state configurations of highly ionized atoms with $20 \leq Z \leq 50$ are of particular interest. These ion species are predicted to have strong emission lines (required because of the severely limited density tolerance to heavier elements of tokamak plasmas) at relatively long wavelengths (required for efficient and versatile detection techniques). The program consists of

- (1) identifying the appropriate transitions and measuring the wavelengths,
- (2) establishing quantitative correlations between measured absolute emissivities and the corresponding local ion densities,
- (3) developing and improving methods of quantitative emissivity measurements, and
- (4) application to plasma diagnostics.

Laser blow-off (LBO) impurity injection has proven to be an indispensable tool towards accomplishing this program. Over 25 different elements, including gases, have been routinely injected in controlled amounts into the PLT.¹⁷

The first task is nearly complete²²⁻²⁵ for ions of diagnostic interest in plasmas with electron temperatures to 3 keV, the highest temperatures achieved this year in PLT. With the prospective increase of available ICRF power, it is anticipated that the 3-10 keV range of temperatures will become accessible. In this range, progress will be rapid both because of fewer available choices with increasing temperature and because of improved theoretical extrapolations based on our previous work. Considerable progress has also been achieved in the remaining listed tasks, although much work still remains, particularly in part (2). Valuable help has been provided through informal cooperative arrangements with numerous atomic physicists both in the US and Europe, who have undertaken to calculate, or measure the relevant, cross sections or radiative probabilities.

X-ray Diagnostics

X-ray spectra of hydrogen-like ions with $Z > 20$ will be of vital importance for diagnosing central plasma parameters in TFTR discharges. This is true in particular for the measurement of the central ion temperature which will be determined from Doppler broadening of the Lyman- α resonance lines.

Figure 46 presents a spectrum of hydrogen-like titanium, TiXXII, emitted from ICRF heated PLT discharges with electron temperatures in excess of 2 keV. It was obtained with a high resolution ($\lambda/\Delta\lambda = 15000$ at $\lambda = 2.5 \text{ \AA}$) quartz crystal (2023; $2d = 2.7497 \text{ \AA}$) spectrometer in the Johann configuration. The spectrum shows the $1s(^2S_{1/2}) - 2p(^2P_{1/2,3/2})$ fine structure components of the Lyman- α resonance line (features 1 and 2) and the associated dielectronic satellites $1s^2nl - 1s2pnl$ with $n \geq 2$ (features 3 to 8). The high spectral resolution and the small statistical error of the data have permitted the first detailed comparison²⁶ with the theories for high-Z hydrogen-like ions by Vainstein *et al.*, (solid line) and Steenman-Clark. The

intensities of the satellites relative to the resonance line are functions of T_e alone; hence they can be used as an electron temperature diagnostic. In Fig. 46(b) is shown the predicted electron temperature dependence of the satellite to resonance line ratio, I_J/I_H , for the strongest satellite J, and the experimental value of I_J/I_H from the spectrum. This value of T_e agrees with that determined from laser Thomson scattering. The central ion temperature during the period of the cyclotron heating has also been determined from the Doppler width of the resonance lines.

Figure 46. (a) Dielectronic spectrum of hydrogen-like titanium. (b) Electron temperature versus the ratio of dielectronic to resonance emission. (83X0486)

Line spectra of helium-like and hydrogen-like ions of low-Z elements (Ne, Al, Mg, Si) have also been investigated. In typical PLT plasmas, the helium-like spectrum of Mg shows the appearance of the forbidden line [$1s^2(^1S_0) - 1s2s(^3S_1)$], which is important for astrophysics. The experimental data show several significant deviations from a synthesized spectrum (solid curve).¹³ Preliminary observations indicate that the effect of radial profiles may explain some of these discrepancies.

Low-Energy Neutral-Atom Spectrometer

The low energy detectability limit of the low-energy neutral-atom spectrometer (LENS)²⁷ has been extended downward by a factor of 3 to 5 eV for H and to 10 eV for D, allowing a detailed study of discharge cleaning²⁸ and other low-temperature discharges. During the normal high-ionization pulsed discharge cleaning, PDC, the flux in the energy range of 5 to 1000 eV varies from $10^{14} \text{ H}^\circ \text{ cm}^{-2} \text{ sec}^{-1}$ to $10^{16} \text{ H}^\circ \text{ cm}^{-2} \text{ sec}^{-1}$ and the average energy from 10 to 80 eV in a manner consistent with the global plasma parameters. Low-ionization TDC (Taylor-type cleaning) produces a 1000 times lower fluence in the same energy range; however, a flux of $10^{16} \text{ H}^\circ \text{ cm}^{-2} \text{ sec}^{-1}$ at energies less than 5 eV is inferred. The production of CH_4 and other pumped gases is similar in both types of cleaning.

References

- ¹D.Q. Hwang, G. Grotz, and J.C. Hosea "Surface Physics Problems During ICRF Heating of Tokamak Plasmas," *J. Vac. Sci. and Tech.* 20 (1982) 1273.
- ²J.C. Hosea *et al.*, "High Power ICRF Heating on PLT and Extrapolation to Future Devices," in *Proceedings of the Third Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas* (Commission of the European Communities, Brussels, Belgium, 1982) Vol. 1, 213 (EUR 7979 EN).
- ³D.M. Manos, R. Budny, T. Satake, and S.A. Cohen, "Calorimeter Probe Studies of PDX and PLT," *J. Nucl. Mater.* 111 & 112 (1982) 130.
- ⁴D.Q. Hwang *et al.*, "High Power ICRF and ICRF Plus Neutral-Beam Heating on PLT," in *Proceedings of the Ninth International Conference on Plasma Physics and Controlled Nuclear Fusion Research* (IAEA, Vienna, 1983) Vol. II, 3.
- ⁵R. Kaita, R.J. Goldston, and J.-P. Bussac, "Observations of Effects of Banana Trapping on Neutral-Beam-Injected Ions in PLT," *Nucl. Fusion* 21 (1981) 953.
- ⁶E. Mazzucato, A. Semel, and J. Olivain, "Observation of Electrostatic Waves During ICRF Heating on PLT by Microwave Scattering," *Bull. Am. Phys. Soc.* 27 (1982) 926.
- ⁷S.L. Davis *et al.*, "Comparison between Neutral Beam and ICRF Heating on PLT," *Bull. Am. Phys. Soc.* 26 (1981) 931.

- ⁸D.Q. Hwang and J.R. Wilson, "Radio Frequency Wave Applications in Magnetic Fusion Devices," *Proc. IEEE* 69 (1981) 1030.
- ⁹J. Timberlake *et al.*, "Surface Modification of the PLT Lower Hybrid Waveguides to Improve Operations," *J. Vac. Sci. and Tech.* 20 (1982) 1309.
- ¹⁰S. Bernabei *et al.*, "Lower Hybrid Current Drive in the PLT Tokamak," *Phys. Rev. Lett.* 49 (1982) 1255.
- ¹¹W. Hooke *et al.*, "Lower Hybrid Heating and Current Drive on PLT," in *Proceedings of the Ninth International Conference on Plasma Physics and Controlled Fusion Research* (IAEA, Vienna, 1983) Vol. 1, 239.
- ¹²F. Jobes *et al.*, "Current Drive Experiments on the PLT Tokamak," *Physica Scripta* T2:2 (1982) 418.
- ¹³S. von Goeler *et al.*, "X-Ray Spectroscopy on Tokamaks," in *Proceedings of the Course and Workshop on Diagnostics for Fusion Reactor Conditions* (Commission of the European Communities, Brussels, Belgium, 1982) Vol. 1, 109 (EUR 8351-1 EN).
- ¹⁴J. Stevens *et al.*, "Hard X-Ray Emission During Lower Hybrid Current Drive on PLT," *Bull. Am. Phys. Soc.* 28 (1982) 1135.
- ¹⁵E. Mazzucato, "Spectrum of Small-Scales Density Fluctuations in Tokamaks," *Phys. Rev. Lett.* 48 (1982) 1828.
- ¹⁶S. Suckewer *et al.*, "Local Emissivity Measurements of Sc and Mo Ion Lines for Transport Studies in PLT Tokamak Discharges During NB and ICRF Heating," *Bull. Am. Phys. Soc.* 27 (1982) 1044.
- ¹⁷J. Timberlake, S. Cohen, C. Daughney, and D. Manos, "Photography of Impurity Injection into PLT Plasmas," *J. Vac. Sci. and Tech. A1* (1983) 841.
- ¹⁸R. Hulse, "Numerical Studies of Impurities in Fusion Plasmas," *Nucl. Tech./Fusion* 3 (1983) 259.
- ¹⁹J.D. Strachan *et al.*, "A Density Rise Experiment on PLT," *Nucl. Fusion* 22 (1982) 1145.
- ²⁰C.W. Barnes, R.L. Dewar, E. Mazzucato, and J.D. Strachan, "Fluctuations in the Runaway Electron Flux to the PLT Tokamak Limiter," *Phys. Lett. A* 81 (1981) 275.
- ²¹W.W. Heidbrink, R. Chrien, and J.D. Strachan, "Burn-up of Fusion Produced Tritons and ³He Ions in PLT and PDX," *Nucl. Fusion* 23 (1983) 917.
- ²²S. Suckewer, C. Hinnov, S. Cohen, M. Finkenthal, and K. Sato, "Identification of Magnetic Dipole Lines above 2000 Å in Several Highly Ionized Mo and Zr Ions on the PLT Tokamak," *Phys. Rev. A* 26 (1981) 1161.
- ²³S. Suckewer and E. Hinnov, "Atomic Processes for Diagnostics of Magnetically Confined Plasmas," in *Proceedings of the XII International Conference on Physics of Electronic and Atomic Collisions*, S. Datz Editor (North Holland Publishing Co., New York, 1982) Invited Papers, 783.
- ²⁴M. Finkenthal, E. Hinnov, S. Cohen, and S. Suckewer, "The 3s² 1S₀ - 3s3p ³P₁ Magnesium Sequence Intercombination Lines from ScX to MoXXXI Observed in the PLT Tokamak," *Phys. Lett.* 91 (1982) 284.
- ²⁵E. Hinnov *et al.*, "Radiated Energy and Impurity Density Changes During Intensive Hydrogen Influx in the PLT Tokamak," *Nucl. Fusion* 22 (1982) 325.
- ²⁶M. Bitter *et al.*, "X-Ray Line Spectra of Hydrogen-Like Titanium, Ti-XXII, from PLT Discharges," *Bull. Am. Phys. Soc.* 27 (1982) 1083.
- ²⁷D.E. Voss and S.A. Cohen, "Low-Energy Neutral Atom Spectrometer," *Rev. Sci. Instrum.* 53 (1982) 1696.
- ²⁸D. Ruzic, S. Cohen, B. Denne, and J. Schivell, "Low-Energy Neutral Atom Spectroscopy During Pulsed Discharge Cleaning in PLT," *J. Vac. Sci. and Tech. A1* (1983) 818.

Poloidal Divertor Experiment

The Poloidal Divertor Experiment (PDX) experimental program in FY82 was focused mainly on achieving high- β plasmas and on gaining a coherent understanding of the energy transport and MHD activity of these plasmas. Most of this work was done with the plasma boundary defined by poloidal rail limiters. However, some of the work was carried out using the inner wall as a toroidal limiter, and some was in the inside-Dee divertor configuration (Fig. 47). Experiments were also carried out to investigate pellet fueling as well as energy and particle flow, and impurity content and transport. Diagnostic techniques were developed in connection with impurity studies. Results of these experiments were presented at the Ninth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, the Third Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas, the Fifth International Conference on Plasma Surface Interactions in Controlled Fusion Devices, and the Ninth Annual Conference on Plasma Physics (Oxford).¹⁻⁵

MAJOR ACTIVITIES

During the month of October 1981, experiments were performed in the areas of low- q operation, scattering of CO_2 laser radiation, plasma rotation, and plasma fueling. The machine was then opened from November to mid-December for routine divertor maintenance, replacing the graphite blades on the limiters, installing new thermocouples, repairing and upgrading machine diagnostics. In mid-January, after two weeks of conditioning, the machine had to be opened again to repair a break in a current lead to the central solenoid of the ohmic heating transformer. Concern about the mechanical support of this lead, even after the break had been repaired, led to a decision to operate the machine at reduced field and current levels until a more complete repair could be implemented. Since low toroidal field (low- q and high- β ; β = plasma pressure/magnetic pressure) operation was planned for FY82, this restriction in operating range did not compromise the experimental objectives for the year.

Low- q operations began in earnest in March 1982, initially on the inner wall. A few discharges with $q \sim 2.5$ were obtained, but the success rate was low, and in late March operations switched to the poloidal graphite rail limiters. By the end of April 1982, PDX was operated at toroidal fields as low as 0.9 T and $q \sim 1.7$ and achieved values of $\langle \beta_1 \rangle$ above 3%. Studies of β -scaling continued through July 1982, with toroidal fields down to

0.7 T. Subsequently, some of these studies were repeated during several weeks of divertor operation carried out in June and July 1982.

In August 1982, plasma operation was stopped in order to upgrade the divertor hardware, including the replacement of the titanium neutralizer plates and liners with stainless steel components, blocking off the outer divertor channels, and taking the outer divertor coils out of circuit for operation in a double null divertor geometry. For the planned electron cyclotron heating (ECH) system, two inside launchers and a window for the outside launcher with an associated polarizing reflector on the inside wall were installed. In addition, a scoop limiter and vertical soft X-ray array were installed. The interlead void of the damaged current lead was packed with an epoxy/glass mixture. Other repairs included replacing the Thomson scattering system shutters, work on the magnetic pick-ups and plasma position loops, and scraping off titanium flakes. Plasma operation resumed in November 1982.

During most of FY82, PDX ran on a nine-hour operating shift for six days per week on alternate weeks. The total period of operation in FY82 was eighteen weeks. During this time, approximately 5500 discharges were made, 40% of them with neutral-beam injection (NBI). About half of both the total and the NBI discharges were high power; $I_p > 200$ kA for more than 0.5 sec. The shot efficiency (number of shots/time of operation) in FY82 was 50% greater than that in FY81. The milestones for FY82 are given in Table IV.

The four duopigatron neutral-beam injection systems of the joint Princeton Plasma Physics Laboratory/Oak Ridge National Laboratory Heating Project provided up to 7 MW of D⁰ power and 5 MW of H⁰ power for pulse lengths of up to 300 msec. The four beamlines inject at a tangency radius of 35 cm, which gives an angle of 14° from perpendicular at the center of the vessel. An important achievement was getting the beam-injection systems under complete automatic control, which generally improved both reliability and reproducibility of beamline operations [Figs. 48(a,b)]. Beamline calorimetry and direct computer processing of temperature sensor waveforms permit an accurate energy calibration to be made within 17 msec after conditioning shots, which occur at a 60-sec repetition rate between the 5-min PDX shot repetition rate.

To provide quick, on-line analysis results of the PDX experiments, a between-shots confinement analysis code (CAAN) was developed. The CAAN is a zero-dimensional code which relies primarily on a magnetic equilibrium analysis providing a time history of

Table IV. PDX Milestones for Fiscal Year 1982.

October 1981	Low-q operation in ohmic plasmas.
November 1981 to December 1981	Machine maintenance and diagnostic repair and upgrade.
March 1982	Low-q inner wall operation. Neutral-beam injection into circular plasmas ($B_T = 1.2$ T).
April 1982	Low-q rail limiter operation. Neutral-beam injection into circular ($a/R = 40/140$ cm) plasmas ($D^0 \rightarrow H^+, D^+$); β -scaling, fishbone, and MHD studies. $B_T = 0.9\text{--}1.4$ T, $q_a = 1.8$, $\langle \beta_1 \rangle = 3.2\%$ achieved.
May 1982 to July 1982	Neutral-beam injection into circular ($a/R = 35\text{--}36/125\text{--}140$ cm) and Inside-Dee plasma; β -scaling, fishbone and MHD, counter- injection studies. $B_T = 0.7\text{--}1.5$ T, 140 kJ of stored energy achieved.
August 1982 to September 1982	Installation of new divertor hardware, scoop limiter, ECH system, vertical soft X-ray array.

Figure 47. Outer flux surfaces for different operating modes of PDX. The surfaces are defined for (a) water-cooled graphite rail limiters ($R = 135\text{--}155$ cm) and (b) water-cooled titanium-carbide coated graphite bumper limiter for inner wall operation ($R = 125$ cm). (c) Inside-Dee diverted configuration ($R \approx 138$ cm). (C3X0027)

Figure 48. Top: PDX neutral-beam operating history. Bottom: PDX neutral-beam ion source fault history. (83X0026)

such quantities as plasma current, surface voltage, line-averaged density, $I_p/2 + \beta_0$, β_0 , and β_T (using an assumed plasma current profile), injected and absorbed beam power, q , and a global confinement time which was generally in good agreement ($\pm 15\%$) with results from a more sophisticated transport analysis code. An example of a CAAN output is shown in Fig. 49. CAAN has proved to be of immense value in guiding plasma operation.

Figure 49. Between shots confinement analysis output (CAAN). (83X2002)

EXPERIMENTAL RESULTS

β -Scaling Experiments

Several techniques were used to obtain $\langle \beta \rangle$ values for the experiments on PDX. They were the diamagnetic loop which yields the volume averaged, perpendicular β ($\langle \beta_1 \rangle$), results from either a full MHD equilibrium code or a determination from the total measured magnetic and kinetic stored energy of the plasma which yielded the "equilibrium" value ($\langle \beta^{eq} \rangle$), and the kinetic transport code, TRANSP.^{6,7}

The transport analysis code, TRANSP, is a data interpretation code which models the ion and electron energy balance using the electron temperature and density profiles measured by the Thomson scattering system, line-averaged density from both 2-mm microwave and far infrared interferometers, the central ion temperature measured by a mass-resolving passive thermal charge-exchange system, the radiated power from a bolometer array, and the plasma and beam characteristics. Beam deposition is modeled using a full Monte-Carlo calculation, and the thermal neutral density is modeled with a neutral transport code⁸ using an assumed gross particle recycling time. An appropriate multiplier of the ion neoclassical conductivity is determined within the code in order to match the measured passive charge-exchange ion temperature. Power losses from the ions and electrons include convection, conduction, classical ion-electron coupling, charge-exchange, and radiation. From the stored energies of the plasma and the beam, the code

computes both the diamagnetic and equilibrium β -values, yielding remarkably good agreement with those values obtained experimentally except at large $\langle \beta_1 \rangle > q$ values ($\geq 4.5\%$). In FY82, 85 well-documented experimental conditions were analyzed using the code.

An example of a diamagnetic $\langle \beta_1 \rangle$ measurement during a four-beam $P_{inj} = 5.5$ MW discharge is shown in Fig. 50. For this shot, deuterium beams were injected into a hydrogen plasma to maximize the beam power absorbed. The $\langle \beta_1 \rangle$ is seen to increase dramatically at the onset of neutral-beam injection and to attain a value of $\geq 3\%$. This value was achieved in the difficult operating regime of limiter q value $< 2(q_a \alpha^2 B_T / R I_p)$.

Figure 50. Measurement $\langle \beta_1 \rangle$ from toroidal-field coil diamagnetic flux loop. (83X0022)

To study the statistical trends of the β -scaling experiments, data from over 1000 PDX discharges, selected on the basis of shot quality and diagnostic coverage, were incorporated into a computer data base. Linked to the data base are several interactive programs enabling the user to read, sort, and display the stored parameters in a variety of fashions, as well as to fit the data to regression curves.

The majority of the β -scaling experiments were carried out in rail limited circular cross-section plasmas with $R = 138$ -143 cm, $a = 40$ -44 cm, and $n_e = 3.6 \times 10^{13}$ cm⁻³. The toroidal field, B_T , was varied from 0.7 - 1.5 T and the plasma current, I_p , from 240-400 kA to study the dependence of $\langle \beta \rangle$ on these variables. Deuterium injection was used in order to maximize the absorbed power. Some size, configuration, and plasma and beam species scalings were performed. Figure 51 is a plot of the distribution of data as a function of B_T and I_p used in the β -scaling studies, and is a subset of the data points contained in the data base. Each circled cluster of points represents a fully documented, controlled power scan at fixed B_T , I_p , and if possible, n_e . Note that this plot contains both the set of points obtained in FY82 for the β -scaling as well as data obtained in FY81 at 2.2 T ($I_p = 200$ -480 kA). No diamagnetic β -values are available for this latter set of data. The experiments were run at currents which would limit the classical bad orbit loss to

$\approx 10\%$. In addition, no discharges were run with $q_a < 1.7$. Below this q -value disruptions prohibited successful discharges. Within this operating regime $\langle \beta_L \rangle$ values of up to 3.2% and β_{pol} values up to 1.8 were achieved.

Figure 51. Range of I_p and B_T covered by PDX β -scaling experiments. Circled points represented fully documented, controlled power scans, $R = 143$ cm, 40 cm $< a < 44$ cm. The $q_{cyl} = 1.7$ line is drawn for $a = 42$ cm. (82X0761)

The β -scaling investigations began with analysis of the behavior of $\langle \beta_L \rangle$ with input power and current at fixed toroidal field. At low power (0-2 beams) $\langle \beta_L \rangle$ was observed to increase linearly with input power and current. However, as the toroidal field was reduced and input power increased, a saturation of $\langle \beta_L \rangle$ with beam power was observed, with greater saturation at lower toroidal fields. The data points from the full range of power scans could be reduced into a single "universal" curve by plotting the product $\langle \beta_L \rangle q_a^{-1}$ as a function of $P_{TOT}/B_T^{1.4}$ for each point, as shown in Fig. 52. The choice of the variable $\langle \beta_L \rangle q_a^{-1}$ reflects that at fixed B_T , $\langle \beta_L \rangle$ increases nearly linearly with plasma current and that the degree of saturation for all currents was the same, while the abscissa, $P_{TOT}/B_T^{1.4}$, reflects the degree of saturation as a function of input power and toroidal field. The curve in Fig. 52 reveals that saturation occurred for $\langle \beta_L \rangle q_a^{-1} \gtrsim 4.5\%$. No variation of $\langle \beta_L \rangle$ with density, at fixed toroidal field, plasma current, and injected-beam power was observed.

The thermal energy confinement and power losses of the nonsaturated ($\langle \beta_L \rangle q_a^{-1} \lesssim 4.5\%$) discharges were studied using TRANSP. The thermal energy confinement time is defined to be the stored energy in the thermal plasma (not including beam stored energy) divided by the power flow out of the thermal plasma. The confinement scaling for a complete power scan (0-4 beams) at four different currents and $\bar{n}_e \approx 4 \times 10^{13}$ cm $^{-3}$ is shown in Fig. 53 for two different toroidal fields. The abscissa is heating power, defined to be the total beam power into the plasma (absorbed beam power less bad-orbit and charge-exchange losses) plus the ohmic heating power. Points with $P_{heat} < 1$ MW were heated solely ohmically. What emerged for both toroidal fields

Figure 52. $\beta_T q^{1.15}$ versus $P_{TOT}/B_T^{1.4}$. Universal curve for all beam-heated PDX diamagnetic data at $R = 143$ cm, $a = 40$ -42 cm. (82X0798)

and all currents is a clear degradation in the confinement time for neutral-beam heated discharges, although there was little variation of τ_E for discharges with two or more beams at a given current. There was essentially no variation of thermal confinement with toroidal field, but there was a strong scaling of τ_E with plasma current, confinement being greater at the higher current, close to a linear fashion. These results confirmed the trends apparent in the scaling of gross confinement as derived directly from the diamagnetic measurements.

Figure 53. Global thermal energy confinement times as a function of total heating power for two toroidal-field cases and four currents for each case. (83X0025)

It was determined from the ion and electron power balances that anomalous electron thermal conduction was the dominant energy loss mechanism; thus, providing understanding of how the electron thermal conductivity scales is the key to understanding the process giving rise to the confinement scaling. The electron thermal conductivity profile was determined from the calculated conduction loss and the measured electron temperature profiles. A comparison between

the calculated conductivities and those predicted by a large number of published theories of anomalous electron thermal transport shows poor agreement. However, another approach taken to understand the conductivity scaling was to perform a regression analysis to find the variables which best order the conductivity values. The dominant scaling variables in such a fit proved to be plasma radius (r) and poloidal field (B_p) with the fit $\chi_e \propto r^{1.7} B_p^{-1.8}$ fitting the conductivity scaling to a high degree of accuracy. Although the magnitudes of the χ_e values were greater, their dependence on B_p is that which is expected from classical diffusion theory.

Fishbone Activity

During high power co-neutral-beam injection (3-4 beams) in discharges with low toroidal fields ($B_T \leq 1.2$ T), a new type of instability was observed on several diagnostics. The instability was observed on all discharges in the saturated β regime, that is, with $\langle \beta_1 \rangle q^{1/2} > 4.5\%$. One of its more distinctive signatures was seen on the Mirnov coils, probes that measure fluctuations in the poloidal magnetic field. The activity was typified on the Mirnov coils by growing bursts of large amplitude oscillations with a repetition period of 2-6 msec and a frequency of approximately 10-15 kHz within each burst. Because of its appearance on the Mirnov signal, these distinctive oscillations have been dubbed "fishbone activity" (see Fig. 54).⁹ No fishbone activity was observed during counter-injection experiments even with $\langle \beta_1 \rangle q$ close to the saturation level.

Figure 54. Mirnov coil signal during fishbone activity. The "outline" is a result of the artist's imagination and was not measured on the Mirnov coil. (83X0023)

Observations of fishbone activity were not confined to the Mirnov coils. Figure 55 is a composite of fishbone activity on two different time scales as observed on the central chord of the soft X-ray (SXR) array, the Mirnov coils, the fast ion charge-exchange detector, and a fast

Figure 55. Typical signatures of strong fishbone activity on central soft X rays, Mirnov coil, charge-exchange flux, and neutron emission on slow (left panel) and fast (right panel) time scales. (82X2203)

neutron flux detector. The SXR signal in the left panel shows the repetitive bursts of high-frequency activity characteristic of the fishbone activity. Similar behavior was also observed in titanium radiation from the center of the discharge. Also seen in the figure is a burst of fast charge-exchange neutrals which escaped from the plasma at the time of each fishbone spike. Coupled to this was a drop in the neutron emission. The right-hand panel in Fig. 55 shows, in an expanded time plot, the phase relation between the signals during one fishbone burst.

During each fishbone burst, density fluctuations of magnitude $\sim 5\text{--}10\%$ were observed by the 2-mm microwave interferometer, and both the microwave and CO_2 laser scattering diagnostics. Other measurements in which fishbone activity was observed were the H_α radiation, impurity radiation, and the thermal charge-exchange energy flux. Transport of injected scandium was different during fishbone activity from that during normal sawtooth activity, showing an enhanced inward diffusion.

As previously mentioned, large bursts of escaping fast charge-exchange neutrals, originating from the beam ion distribution, were phase-coupled to the fishbone spikes. Two examples of charge-exchange spectra are shown in Fig. 56. The top panel exhibits a

Figure 56. Perpendicular charge-exchange spectra for a two-beam (no fishbone) and a four-beam (strong fishbone) case. (82X0853)

spectrum during a 2-beam discharge without fishbones, and it is typical of beam slowing down through classical collisions. The bottom panel is an example of a spectrum observed during a 4-beam discharge with severe fishbones. Fishbone spikes are seen throughout the spectrum. Note that the fast ion charge-exchange detector sweeps in energy as a function of time, so the observed spikes were actually localized in time rather than in energy. Several features of this spectrum are worth mentioning. First, depletion of beam ions is seen from just below the injection energy ($E_{inj} \approx 45$ keV) down to $E \sim E_{inj}/2$. Also seen are spikes of escaping neutrals whose energies are above E_{inj} ; in the most severe cases of fishbones, spikes from thermal energies up to approximately 75 keV were observed. In these cases spikes were also observed in the low energy target species neutrals. During the more moderate cases the bursts were confined to energies between $E_{inj}/2$ and E_{inj} .

Because of the apparent effect of the fishbones on the beam ion distribution, a phenomenological model of ion loss due to fishbones was developed in which a loss

cone of near-perpendicular particles with energies above 35 keV was opened during each fishbone. The ion loss rate was adjusted to bring the predicted charge-exchange and neutron signals into agreement with the measured one. The ion loss model was then incorporated into the transport analysis code from which it was estimated that up to 40% of the beam heating efficiency was lost during the fishbone oscillations. This ion loss could account for the discrepancy in the saturated regime ($\langle \beta_1 \rangle q_a > 4.5\%$) between the measured $\langle \beta_1 \rangle$'s and those predicted by the code when only classical ion loss was considered.

To test the effect of the beam ion precession direction on fishbone activity, a short counter-injection experiment was performed. For counter-injection the beam ions precess in a direction opposite to that for co-injection. Similar $\langle \beta_1 \rangle$ values were obtained during counter-injection as during co-injection with near identical discharge conditions; however, no fishbone activity was observed during the counter-injection discharges.

Fluctuations

A summary of the types of MHD activity observed on PDX is given in Table V. For normal discharges at low $\langle \beta_1 \rangle q_a \leq 1\%$ very little MHD activity is observed on the Mirnov coils, while sawteeth are observed on the soft X-ray signal with a low level of higher frequency activity just before the drop of the sawtooth. For $\langle \beta_1 \rangle q_a \sim 2.5\%$ the sawteeth have increased in amplitude and period; the high frequency oscillations observed on the central SXR signal just before the drop are phase-coupled to those observed on the Mirnov coils. The energy content of the plasma is systematically larger at the top of the sawtooth than at the bottom, with a 5-10% variation in electron temperature and a 2-5% variation in density observed over the course of a sawtooth.

The MHD activity appears to have no further effect on the gross energy confinement of the NBI heated plasma which is, however, already degraded from that of the ohmically heated plasma. The fishbone activity seen during $\langle \beta_1 \rangle q_a > 4.5\%$ discharges has already been discussed (see section on Fishbone Activity for further details).

Higher frequency oscillations (3-200 kHz) in the PDX tokamak have been studied using small-angle scattering of CO₂ laser radiation to measure the chord averaged wave-vector and frequency spectra of density fluctuations in both circular and divertor plasmas. The spatial distribution of the density fluctuations showed a peak at the minor radius, corresponding to that of the limiter or separatrix, and then decreased monotonically from the edge to the center of the plasma (Fig. 57). The peak at ~ 10 cm in the upper panel of Fig. 57 was determined not to be real. Typical fluctuation amplitudes were $\delta n/n \approx 0.5$ at the boundary in both circular and divertor plasmas and $\delta n/n \approx 0.02$ near the plasma center. In divertor plasmas $\delta n/n$ decreased less rapidly away from the edge than in circular plasmas. There was little change in fluctuation

Table V. MHD Activity in PDX with Neutral-Beam Injection.

	DISCHARGES			m=2 DISCHARGES	
	OH	Beams	Beams	OH	Beams
Activity observed on soft X-ray signal
$\langle \beta_1 \rangle q_0$ range	~0.01	~0.025	~0.045	~0.01	~0.025
X rays and Mirnov coil	Sawtooth and m=1; very low level of MHD activity.	Large sawtooth coupling to Mirnov coil at fall of sawtooth; $m \geq 2$.	Fishbone activity; strong coupling of m=1 to Mirnov coil; $m \geq 2$.	m=2 mode. m=2.	Sawtooth, then m=2. Large m=2.
Neutron emission		Decrease (fast-ion disruption).	Decrease ~40%		m=2 oscillations observed on neutron emissivity.
Charge-exchange flux		Sawtooth observed on charge exchange, and spike at drop of sawtooth	Large burst of charge exchange during fishbone and depletion in slowing down spectrum.		m=2 activity on charge-exchange flux. No depletion of the fast-ion slowing down spectra.
Conclusions	No transport effects.	No clear global transport effects observed.	A loss of fast ions from the plasma. A drop in the calculated τ_E .	Decrease in confinement time is observed when m=2 activity is present.	Confinement time one-half to two-thirds the confinement with sawtooth or fishbones.

Figure 57. Density fluctuations amplitude as measured by CO_2 scattering as a function of plasma radius for two different frequency ranges. C_{AB} is the scattered power and is proportional to the square of the frequency fluctuation, $\tilde{n}^2$. (820466)

amplitude, frequency and wave vector spectra during NBI; $\delta n/n$ was constant to within a factor of ≤ 2 . The CO_2 scattering measured by crossed beams has been used to determine the group velocity of the observed waves; for divertor plasmas a propagation velocity of $\sim 1.3 \times 10^5$

cm/sec in the electron diamagnetic drift direction was observed.

The 2-mm microwave scattering system became operational in October 1981, and is capable of measuring density fluctuations in the drift wave parameter regime ($f < 500 \text{ kHz}$). The density fluctuations observed by this system increased up to a factor of two with NBI from their ohmic level, consistent with the CO_2 scattering results, but showed little dependence with injected power at constant line-averaged density. Plasma rotation, inferred from Doppler shifts of the scattered signal, was observed in the electron diamagnetic drift direction during ohmic plasmas. Additional Doppler shifts, consistent with the direction of toroidal rotation, were observed during both co- and counter-injection with $V_\phi \approx 5 \times 10^5$ to 2×10^6 cm/sec.

Impurities and Impurity Transport

A general monitor of impurity radiation in PDX discharges has been the 19-channel bolometer array. However, this diagnostic is sensitive to both impurity radiation and charge-exchange flux. Consequently, several techniques were employed to determine what fraction of the bolometer signal was due to impurity radiation. In Fig. 58, spectroscopic measurements of impurity radiation are compared with bolometric

Figure 58. Total power radiated from a PDX plasma as a function of neutral-beam input power. The dark circles are from the bolometer, and the open circles are from vacuum ultraviolet (VUV) spectroscopy. The inset shows radiation profiles as measured by the bolometer array. (83X0123)

measurements as a function of beam power in circular discharges with carbon limiters. For ohmically heated plasmas good agreement was observed. In beam-heated discharges the spectroscopic measurements accounted for only half of the bolometric power. This conclusion concerning the bolometer signal was corroborated by two other independent techniques. The first technique utilized the beam-orbit simulation in the transport analysis code (TRANSP) to determine the beam charge-exchange efflux as a function of toroidal angle, and this result was compared to bolometer measurements. The second method was to expose samples of poly-methyl-methacrylate (PMMA), which is sensitive to both impurity radiation and impinging particles, during neutral-beam heating experiments. The intercomparison of the results from two samples with different amounts of shielding led to information about the relative amounts of charge-exchange flux and impurity radiation. Both techniques indicated that a substantial fraction ($\geq 50\%$) of the bolometer signal was due to charge-exchange efflux.

The most abundant impurities in tokamak plasmas are usually low-Z elements such as carbon and oxygen. At electron temperatures ≥ 1 keV, these elements are completely ionized and consequently cannot be observed with conventional spectroscopic techniques. Time and space resolved detection of the fully stripped impurities was made possible by a technique utilizing the radiation induced by charge-exchange collisions between the fully stripped ions and neutrals from a tightly collimated, low power (5-10 keV) diagnostic neutral beam (DNB) in the field of view of a grazing incidence spectrometer.¹⁰ Square wave modulation of the DNB allows discrimination of the desired signal from

the background. The DNB can vary its angle of injection so that the beam is scanned across the plasma midplane in the line of sight of the spectrometer.

An example of steady-state radial profiles of CVI^{+} and OVIII^{+} measured by the charge-exchange recombination technique in PDX ohmic discharges is shown in Fig. 59 along with model calculations to be discussed. A noticeable feature of the CVI^{+} and OVIII^{+} profiles is that both species have appreciable densities beyond the limiter radius at 30 cm. The amount of cross-field transport necessary to account for the observed profiles can be estimated by comparing the measured radial profiles to those calculated by a multispecies impurity transport code. The curves in Fig. 59 show results of steady-state calculations assuming either

Figure 59. Radial profiles of fully ionized oxygen and carbon during the steady-state phase of the discharge. Closed circles $R > R_{\text{major}}$, open circles $R < R_{\text{major}}$. The solid lines are radial profiles of CVI^{+} and OVIII^{+} calculated from an impurity transport code. C.E. = distribution expected from coronal equilibrium assuming a constant impurity density. D = constant impurity diffusion coefficient. (82X0246)

coronal equilibrium or relatively simple diffusion models. Both the CVI⁺ and OVIII⁺ show clear deviations from coronal equilibrium, especially at large radii. The measured profiles are in much better agreement with profiles calculated assuming a constant diffusion coefficient of $D = 10^4 \text{ cm}^2/\text{sec}$, which is the value obtained from analysis of earlier scandium-injection experiments.

Vertical poloidal asymmetries in the low-ionization states of carbon (CII, CIII), whose source is not poloidally symmetric and is either the limiter or the wall of the vacuum vessel, have been observed. These impurities were often observed to peak outside the limiter radius, where they were most asymmetric, and the asymmetry itself propagated inward through some anomalous radial diffusion mechanism thus affecting higher charge states.

Power Handling and Limiter Conditioning, Edge Studies, and Plasma Fueling

These studies were carried out in the three different plasma configurations (shown in Fig. 47) in order to assess impurity control techniques as well as the power handling capabilities of the various limiting surfaces. In rail limited discharges, a gas flow rate of 10-12 Torr- L/sec was required to maintain densities of $1-4 \times 10^{13} \text{ cm}^{-3}$.¹¹ In these discharges, the total bolometrically measured power accounted for approximately 30% of the total input power, with approximately half of the bolometer signal due to impurity radiation. The impurities responsible for the impurity radiation over the entire plasma were, in order of importance, oxygen, titanium, and carbon, with the titanium alone accounting for the majority of the central radiation.

With the onset of neutral-beam heating, Z_{eff} (the effective charge state of the plasma ions and thus an indication of plasma impurity) rose from ohmic values of ≈ 2 to values ≥ 4 ; the rise in Z_{eff} presumably was due to an influx of carbon and oxygen. Long-term conditioning of the limiting surfaces was inferred by measuring the Z_{eff} of the plasma over long-term operation (Fig. 60). The limiter clean-up is clearly illustrated in the figure as Z_{eff} approached unity after six months of operation on the top limiter. In comparison, low Z_{eff} was obtained in divertor operation with minimal conditioning.

Short-term power handling and conditioning of the limiter was studied, making use of an array of thermocouples measuring absorbed power 0.5 cm below the surface of the top limiter. Figure 61 shows the fraction of input energy that was deposited on the limiter over a range of toroidal fields and plasma currents. The fraction of input energy that went to the limiter was a function of beam power, initially increasing and then decreasing, but there was little change with current and toroidal field. On the other hand, the bolometer power was a constant fraction of the input power, indicating that the change in the fraction of energy going to the limiter was perhaps due to the local plasma-limiter

Figure 60. Z_{eff} as a function of injected beam power for different periods in fiscal years 81 and 82. (82X1048)

Figure 61. Fraction of input energy that is deposited on limiter as a function of input power for a power and current scan ($I_p = 250-450 \text{ kA}$, 0-4 beams). (83X0019)

interaction and not due to changes in other energy loss channels.

The PDX inner wall bumper limiter, a prototype for the TFTR limiter, consists of titanium-carbon coated graphite tiles (70% of total wall area) with a water-cooled stainless steel backing. The rest of the wall, except for small breaks for diagnostic access, is made of titanium tiles. To maintain a constant density discharge in this configuration ($\sim 2.5 \times 10^{13} \text{ cm}^{-3}$), gas flow requirements increased by approximately 60% over the rail limiter cases. No special conditioning of the inner wall was needed, as $q_a > 3$ discharges were obtained with ease. However, fast disruptions occurred when q_a was lowered. A few discharges with $2.5 < q_a < 3$ were obtained eventually by ramping the current up approximately 40% faster than for $q_a \approx 3$ discharges.

The impurity levels and radiated power in the inner wall discharges were difficult to obtain because of limited diagnostic access; thus the global averages from spectrometers and bolometers were unreliable.

Using the charge-exchange recombination technique, the levels of OVIII⁺ and CVI⁺ were found to be comparable to those in rail limiter discharges. Titanium levels in the core were also comparable to those in rail limiter discharges, as were ohmic and NBI values of Z_{eff} .

A toroidal average of total power incident on the bumper limiter, measured by an array of thermocouples around the machine, indicated that 40% of the input power was deposited on the wall. The vertical power deposition profile was measured by a vertical thermocouple array behind a beam armor section. Figure 62 shows the change in bulk temperature per shot for an ohmic discharge; similar profiles were obtained with NBI, but with the temperature change per shot being a few degrees higher. The cause for the vertical asymmetry and displacement is not yet understood, but the asymmetry was observed to switch to the lower half-plane when the toroidal field direction was reversed.

Figure 62. Bulk temperature change per discharge in bumper limiter for ohmic plasmas. (82X0306)

Inside-Dee diverted plasmas produced cleaner plasmas with less conditioning than either the rail or bumper limiter, with Z_{eff} approaching 1. Responsible for this lowered Z_{eff} was a decrease in the amount of low-Z impurities in the discharge (carbon and oxygen); their levels were 50% of those in rail limiter discharges. However, the radiated power measured by the bolometers was still 30-40% of the total input power, similar to that for circular plasmas. The amount of titanium in the core for medium densities ($\sim 3 \times 10^{13} \text{ cm}^{-3}$) was similar to that for circular discharges, implying that there was little extra titanium influx due to power loading of the neutralizer plates; the titanium in both circular and divertor discharges must have originated

from the same source, presumably the protective titanium liners close to the main plasma. During higher density ($> 6 \times 10^{13} \text{ cm}^{-3}$) Inside-Dee operation, the energy deposition profile on the neutralizer plate was found to broaden, and the peak power loading was reduced. In addition, the core titanium density was reduced by a factor of 5 with respect to the lower density case. An important difference between divertor and limited plasmas is that it took about five times the gas flow (45-50 Torr-ℓ/sec) to maintain a constant density in the divertor than in the limiter plasmas.

To study the energy flux into the edge plasmas, a shielded and rotatable combined electrostatic calorimeter-probe was utilized.^{12,13} During NBI on PDX the integrated heat flux to the edge was measured to be $\sim 1.1 \text{ MW}$, with a peak in velocity space close to the pitch angle and full energy of the injected beam ions. The 1.1 MW is in agreement with the power predicted for loss of beam ions. Thus this edge study indicates that a substantial fraction of the edge heat flux was carried by beam particles and that these ions underwent prompt loss with a minimum of pitch angle scattering. Measurements of the radial variation of the heat flux in the scrape-off plasma were also possible using the calorimeter-probe. The heat flux of both Inside-Dee and circular scrape-off plasmas had e-folding distances of $\sim 2.5 \text{ cm}$. The addition of neutral-beam injection power increased the edge losses in proportion to the total energy input, thus keeping the e-folding distance constant.

To study alternate methods of plasma fueling, a gas-driven hydrogen pellet injection system, built by the Oak Ridge National Laboratory Technology Division and capable of producing and injecting four pellets per discharge, was tested. The pellets are driven by high pressure helium gas. The gas load delivered to the tokamak by the pellet injection system is reduced by using large baffled chambers and Teflon guide tubes. Four straight guide tubes are used, each having a length of $\sim 75 \text{ cm}$ and an aperture of 5 mm. This guide tube system has improved the coupling of the injector and the tokamak, resulting in highly reliable injector operation.

Injection speeds of $\sim 470 \text{ m/sec}$ and penetration lengths of $\sim 16 \text{ cm}$ were achieved in ohmic discharge using pellets that contained $\sim 1.3 \times 10^{19}$ hydrogen atoms. Such pellets, when injected on the midplane, are capable of increasing the discharge column density by $\Delta n_e l \approx 1.2 \times 10^{14} \text{ cm}^{-2}$. An example of a four pellet injection event is shown in Fig. 63. Given in the left-hand panel is the plasma column density as measured by the midplane microwave interferometer. Each pellet is clearly seen by an increase in the column density. In the right-hand panel is a photograph taken through a near tangential viewing port showing the ablation signatures of the four pellets.

Changes in plasma parameters were similar to those found during previous single pellet experiments,¹⁴ indicating that the pellet mass could be increased. Modifications to the injector have begun to increase the pellet mass to about 12×10^{19} hydrogen

atoms per pellet. When the modifications are completed, these larger pellets will be used in conjunction with neutral-beam heating.

Figure 63. Four-pellet injection into a PDX ohmic discharge (left panel) and column density measured by midplane microwave interferometer. Arrows indicate the times of pellet injection. Photo of pellet ablation taken from a near-tangential viewing port (right panel). (B3X0011)

DIAGNOSTIC DEVELOPMENT

Fiscal year 1982 was a fertile year for the development of tokamak plasma diagnostics on PDX. Diagnostics developed for PDX certainly will be adapted for use on larger machines such as TFTR.

The SPRED (Survey, Poor Resolution, Extended Domain) System¹⁵ is a compact, time-resolved multichannel spectrograph developed to provide routinely impurity spectra information for tokamak plasmas. It operates in the vacuum ultraviolet (VUV) spectral region (100-1700 Å), within which the most intense emission lines in high-temperature plasmas fall. The SPRED system has three basic functions. First, it can be used as a machine monitor for observations of intrinsic impurities. Second, it can be operated in a polychromatic mode with high temporal resolution in order to study impurity transport. Third, line intensities from SPRED can be used to estimate impurity radiation loss.

As previously described, the charge-exchange recombination technique allows for the measurement of

low-Z impurities in the plasma core. This diagnostic technique also offers a means of monitoring the space and time evolution of fusion products such as He⁺⁺. In addition, ion temperature profiles and plasma rotation velocities may be obtained by measuring the Doppler broadening of low-Z impurities spectral lines.¹⁶

The plasma Z_{eff} has been determined by a variety of techniques. Simple estimates may be made from discharge parameters such as the loop voltage, plasma current, electron temperature, and an assumed electrical resistivity model. Another method is to use the charge-exchange recombination measurements of fully stripped carbon and oxygen, taking these elements to be the dominant impurity species. A third method is to use visible continuum radiation measured by double interference filtered detectors at 5235 Å which view the plasma through 19-fiber optically coupled telescopes. For near real-time monitoring, the central chord data for this array are combined with an appropriate model for the electron density and temperature profiles to derive a line averaged Z_{eff} , the results being displayed to the operator as a "Z-meter." Data from the entire 19-channel poloidal array are Abel inverted to yield both temporal and radial profiles of Z_{eff} in the discharge.

The last method of measuring Z_{eff} makes use of the diagnostic neutral beam of the Fast Ion Diagnostic Experiment (FIDE) to measure the relative amount of pitch angle scattering of the injected ions. Since the amount of pitch angle scattering depends on the local Z_{eff} , radial profiles of Z_{eff} can be extracted from this measurement. All of the methods show good agreement. Measurements of the orbit shifts of ions injected by the DNB in the FIDE diagnostic provide a method of determining the radial profile of q , and thus the radial dependence of the plasma current.

A new diagnostic was developed to measure *in situ* the species yield of a neutral-beam injection system under operating conditions using the FIDE detectors to measure beam particles Rutherford backscattered 136° from the PDX inner wall armor in the absence of a plasma. This allows fast systematic measurements of species yield across a beam power profile with changing beamline operating conditions.

An electron cyclotron heating (ECH) system is near completion. It will be used to study localized electron heating and electron current drive on PDX.

References

¹D. Johnson *et al.*, "High Beta Experiments with Neutral-Beam Injection on PDX," in *Proceedings of the Ninth International Conference on Plasma Physics and Controlled Nuclear Fusion Research* (IAEA, Vienna, 1983) Vol. I, 9.

²R. Goldston *et al.*, "Confinement Studies with Neutral Beam Injection on PDX and PLT," in *Proceedings of the Third Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas* (Commission of the European Communities, Brussels, Belgium, 1982) Vol. II, 783 (EUR 7979 EN).

³H. Eubank *et al.*, "Neutral Beam Heating Experiments on PDX and PLT," in *Proceedings of the Third Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas* (Commission of the European Communities, Brussels, Belgium, 1982) Vol. I, 15 (EUR 7979 EN).

⁴R. Fonck *et al.*, "Impurity Levels and Power Loading in the PDX Tokamak with High Power Neutral Beam Injection," *J. Nucl. Mater.* 111 & 112 (1982) 343.

⁶S. Davis *et al.*, "Auxiliary Heating Results from PDX and PLT," *Plasma Physics* 25 (1983) 189.

⁶R. Hawryluk *et al.*, "An Empirical Approach to Tokamak Transport," in *Proceedings of the Course on Physics of Plasmas Close to Thermonuclear Conditions*, (Commission of the European Communities, Brussels, Belgium, 1980) Vol. I, 19 (EUR FU BRU/XII/476/80).

⁷R. Goldston *et al.*, "New Techniques for Calculating Heat and Particle Source Rates Due to Neutral Beam Injection in Axisymmetric Tokamaks," *J. Comp. Phys.* 43 (1981) 61.

⁸S. Tamor, "ANTIC: A Code for Calculation of Neutral Transport in Cylindrical Plasmas," *J. Comp. Phys.* 40 (1981) 104.

⁹K. McGuire *et al.*, "Study of High Beta Pressure Driven Modes in PDX," *Phys. Rev. Lett.* 50 (1983) 891.

¹⁰R. Fonck *et al.*, "Spatially Resolved Measurements of Fully Ionized Low-Z Impurities in the PDX Tokamak," *Phys. Rev. Lett.* 49 (1982) 737.

¹¹H. Dylla *et al.*, "Gas-Fueling Studies in the PDX Tokamak," *J. Nucl. Mater.* 111 & 112 (1982) 211.

¹²D. Manos *et al.*, "Calorimeter Probe Studies of PDX and PLT," *J. Nucl. Mater.* 111 & 112 (1982) 130.

¹³D. Manos *et al.*, "TFTR Prototype Electrostatic Calorimeter Probe Head," *J. Vac. Sci. Tech. A1* (1983) 845.

¹⁴S. Milora *et al.*, "Pellet Injection into PDX Diverted Plasmas," *Nucl. Fusion* 22 (1982) 1263.

¹⁵R. Fonck *et al.*, "SPRED: A Multichannel Grazing Incidence Spectrometer for Plasma Impurity Diagnosis," *Appl. Optics* 21 (1982) 2115.

¹⁶R. Fonck *et al.*, "Plasma Ion Temperature Measurements via Charge-Exchange Recombination Radiation," *Appl. Phys. Lett.* 42 (1983) 239.

Spheromak

The spheromak device features a plasma confinement configuration that has its toroidal field generated and maintained entirely by plasma currents, thus eliminating the large toroidal coils necessary in tokamaks and stellarators. This scheme permits a simple and compact design that is a desirable characteristic for a commercial fusion reactor.

The S-1 Spheromak, which will begin operation in early CY83, is the largest device of its kind (compact torus) in the U.S. The S-1 device will have a plasma with a major radius of about 45 cm and a minor radius of about 25 cm. Expected plasma parameters are a plasma temperature of over 100 eV, a plasma density of $\sim 10^{14} \text{ cm}^{-3}$, a magnetic field of 3-5 kG, and a configuration lifetime of over 1 msec (see Table VI).

Table VI. S-1 Spheromak Device Parameters and Expected Plasma Parameters

Plasma Major Radius	0.45 m
Plasma Minor Radius	0.25 m
Plasma Density	$\sim 10^{14} \text{ cm}^{-3}$
Plasma Temperature	$\geq 100 \text{ eV}$
Plasma Lifetime	$\geq 1 \text{ msec}$
Magnetic Field	3-5 kG
Plasma Toroidal Current	0.5 MA
Flux Core Major Radius	1.0 m
Flux Core Minor Radius	0.19 m
TF in the Flux Core	1.4 T
TF Ampere Turns	7.5 MA Turns
TF System Resistance	0.8 m Ω
TF System Inductance	3.6 μH
Maximum TF Inductive Energy	0.45 MJ
PF Ampere Turns	0.5 MA Turns
PF System Resistance	0.38 m Ω
PF System Inductance	3.26 μH
Maximum PF Inductive Energy	0.408 MJ
EF Field Index	$-0.03 \leq n \leq 0.35$
Pulse Length	1 msec

The spheromak configuration is generated at PPPL by a process which transfers poloidal and toroidal flux from a flux core to the plasma in an externally generated quasi-steady equilibrium field.

Two Proto S-1 devices were constructed and operated at the Princeton Plasma Physics Laboratory. The Proto S-1A device successfully demonstrated the validity of the initial PPPL-proposed spheromak formation scheme in 1980. The Proto S-1C device, which is twice as large as the Proto S-1A, extended the experimental study of the spheromak plasma configuration. In the Proto S-1C

device, a spheromak plasma with major radius $R = 12 \text{ cm}$, minor radius $a = 8 \text{ cm}$, and configuration lifetime up to $100 \mu\text{sec}$, has been generated on a slow time scale of $\tau_{\text{form}} \approx 50 \mu\text{sec}$. Toroidal and poloidal plasma currents of 60 kA and 120 kA have been obtained, respectively. Plasma temperature and density (Fig. 64) were measured by laser Thomson scattering with bolometric and spectroscopic monitoring. By reducing the density to less than $2 \times 10^{14} \text{ cm}^{-3}$, a temperature of over 40 eV was obtained.

Figure 64. Electron temperature and density measured by Thomson scattering versus fill pressure (H_2). The total radiated power, which is monitored by a bolometer, is also plotted. The electron density was calibrated, $n_e \geq 1 \times 10^{14} \text{ cm}^{-3}$, at 10 mTorr H_2 fill pressure. (82X0449)

S-1 SPHEROMAK FABRICATION

Fabrication of the S-1 Spheromak device continued on schedule during FY82. A view of the assembled S-1 device is shown in Fig. 65, and device parameters are listed in Table VI.

Figure 65. The S-1 Spheromak device. (83E050B)

The most complex element of the S-1 device, the flux core, was completed toward the end of FY82. It contains pulsed toroidal- and poloidal-field coils and quasi-dc equilibrium-field coils. These coils were potted inside an aluminum shell that has toroidal and poloidal gaps. An epoxy-glass overwrap was then applied to the aluminum shell. Finally, an approximately 0.010-inch thick Inconel liner was placed over the aluminum shell, and the space between the liner and the epoxy-fiberglass overwrapping was potted with urethane. The completed flux-core assembly, in the center section of the S-1 vacuum vessel, is shown in Fig. 66.

Figure 66. Completed S-1 Spheromak flux core. (82E1029)

The vacuum system was assembled without the flux core and pumped down to a pressure of 2×10^{-7} Torr. This is about three times the calculated pressure based on estimated outgassing rates of the construction materials.

Design of the computer control system was completed and a CAMAC DEC LSI-11/23 computer was purchased and delivered. Table VII lists the major features of the control system. The control room is shielded and isolated electrically from the building structure. Fiber optic links provide communications

between the control room computer and the power supplies. Software programming has continued on schedule.

Table VII. Major Features of the S-1 Spheromak Computer Control System.

CAMAC DEC LSI-11/23 computer
256k bytes memory
Floating point hardware
RSX-11M operating system
30M byte hard disk
5 MHz serial highway (fiber optic)
1 MHz sequencer highway (fiber optic)
Watchdog timer at each location
Personnel and machine safety systems duplicated with hardwire system
Water flow, temperature, overcurrent sensing
Touch panel operator interface
Keyboard entry of machine operating parameters
High-speed transient digitizer waveform storage
Plot package for displaying system voltage and current waveforms
Multiple page mimic and operator information displays

The capacitor charging supplies and banks for the toroidal- and poloidal-field coils were constructed at PPPL during FY82. Each capacitor bank will store up to 0.5 MJ of energy. This system is located in the S-1 machine area.

Operation of the S-1 Spheromak in Mode D (field index ≈ 0.4) is scheduled for March 1983, and the completion date for all systems is August 1983.

IMPURITY CONTROL STUDY IN PROTO S-1C DEVICE

In the Proto S-1C device, radiation from low-Z impurities is considered to be the dominant energy loss mechanism. Investigations have identified emission lines from OII, OIII, OIV, CII, CIII, and CIV. The existence of the CIV lines at 5811.98 Å and 5801.33 Å supports the measurement of relatively high temperatures by Thomson scattering (≥ 40 eV). Emission from CV was not found. Nitrogen, iron, nickel, and titanium (from earlier gettering) emission lines were also identified. By intentional introduction of known amounts of O_2 and C_2H_2 , oxygen and carbon impurity concentrations were estimated (without discharge cleaning or gettering) to be about 1-5% oxygen and about 0.5-3% carbon. It was observed that (1) the relative oxygen concentration is reduced by a factor of 2 to 4 by titanium-gettering the vacuum vessel prior to discharges; (2) the removal of magnetic probes inserted into the plasma decreased the carbon content by a factor of 2 to 4; and (3) the oxygen and carbon impurity levels relative to density did not change markedly at different fill pressures. With the observed amount of low-Z impurities for $n_e \leq 2 \times 10^{14} \text{ cm}^{-3}$, the radiation energy loss is estimated to be 10-50 MW, which accounts for most of the ohmic heating input.

When the filling-gas pressure is reduced to below 10-12 mTorr, the radiated power decreases significantly and the temperature rises (Fig. 64), indicating that the ohmic heating input surpasses the radiation barrier caused by carbon impurities and almost surpasses that due to oxygen impurities.

GROSS MHD STABILITY IN PROTO S-1 DEVICES

Both Proto S-1 devices were used to study the gross MHD stability properties of the spheromak plasma configuration. By adjusting the shape of the equilibrium field, spheromak plasmas have been generated in regimes both stable and unstable against the tilting instability. If the flux core currents are adjusted to allow the equilibrium index to become slightly negative [$n^* \equiv -R/B_{\theta} (\partial B_{\theta} / \partial R) < 0$], a tilting instability occurs.

The shift instability was identified in the Proto S-1C device when the field index became appreciably positive ($n > 0.1$). The growth rate of this mode was observed to be about the same as that of the tilt mode: $\gamma_s \approx 3-5 \tau_A$ where $\gamma_s \equiv (1/R) \partial R / \partial t$ and $\tau_A \equiv a/V_A \sim 0.1-0.5 \mu\text{sec}$.

Three types of stabilizing conductors were tested: a figure-8 type, a saddle type, and a center conductor. The design of the figure-8 coils was based on the computed pattern of eddy currents that appear in nearby conductor walls when an $n = 1$ rotation/displacement of the spheromak plasma occurs.

Figure 67 shows the evolution of $|B_z|$ contours measured in the Proto S-1C with and without figure-8 coils for the same operational mode. The coils were positioned with their outer edges 12 cm from the midplane of the core. The figure shows that the coils have stabilized the tilting of the plasma.

In the Proto S-1C device, spheromak plasma lifetime is reduced to less than 30 μsec (even with the figure-8 coils) when the fill-pressure is reduced below 10 mTorr.

References

- ¹W.W. Heidbrink, S.C. Jardin, and M.S. Chance, "Tearing Mode Stability of a Forming Spheromak Plasma," Nucl. Fusion 22 (1982) 459.
- ²S.C. Jardin, "Ideal Magnetohydrodynamic Stability of the Spheromak Configuration," Nucl. Fusion 22 (1982) 629.
- ³M. Yamada et al., "Experimental Investigation of the Spheromak Configuration," in *Proceedings of the Ninth International Conference on Plasma Physics and Controlled Nuclear Fusion Research* (IAEA, Vienna, 1983) Vol. II, 265.
- ⁴Y.C. Sun et al., "Numerical Simulation of the Energy Balance in the Proto S1-C Spheromak," in *Proceedings of the Fourth Symposium on Physics and Technology of Compact Toroids in the Magnetic Fusion Energy Program* (LLNL, Livermore, California, 1981) CONF-811087 p. 114.

Figure 67. Evolution of the toroidal-field (B_z) contour in the r - z plane with (right column) and without (left column) figure-8 coils in the Proto S-1C device. (83X0073)

In this condition, the plasma discharge is often terminated by a disruption-like phenomenon which is characterized by a sudden shrinkage in major radius. It has been found that this termination can be eliminated by inserting an electrically floating cylindrical center conductor along the major axis. In this case the plasma lifetime is extended to over 150 μsec , which is about one-third of the classical resistive decay time, and the plasma terminates gently.

- ⁵Y.D. Sun, S.C. Jardin, and M. Yamada, "Spheromak Formation with Divertors," in *Proceedings of the Fifth Symposium on Physics and Technology of Compact Toroids in the Magnetic Fusion Energy Program* (MSNW, Bellevue, Washington, 1982).

- ⁶J. DeLucia and S.C. Jardin, "Linear and Nonlinear Resistive Instabilities in Spheromaks," in *Proceedings of the Fifth Symposium on Physics and Technology of Compact Toroids in the Magnetic Fusion Energy Program* (MSNW, Bellevue, Washington, 1982).

- ⁷W. Park and S.C. Jardin, "Nonlinear Saturation of Non-Resonant Internal Instabilities in a Straight Spheromak," Princeton University Plasma Physics Laboratory Report PPPL-1893 (April 1982) 12pp.

⁸A.C. Janos *et al.*, "Spheromak Experiments in Proto S-1C," in *Proceedings of the Fourth Symposium on Physics and Technology of Compact Toroids in the Magnetic Fusion Energy Program* (LLNL, Livermore, California, 1981) CONF-811087, p. 137.

⁹C. Munson *et al.*, "MHD Stability Studies in the Proto S-1A Device," in *Proceedings of the Fourth Symposium on Physics and Technology of Compact Toroids in the Magnetic Fusion Energy Program* (LLNL, Livermore, California, 1981) CONF-811087, p. 149.

¹⁰C. Munson *et al.*, "Effects of Passive Coils on Spheromak Gross MHD Instabilities," in *Proceedings of the Fifth Symposium on Physics and Technology of Compact Toroids in the Magnetic Fusion Energy Program* (MSNW, Bellevue, Washington, 1982).

¹¹A.C. Janos *et al.*, "Equilibrium and Stability of Proto S-1 Experiments," in *Proceedings of the Fourth U.S. Japan Workshop on Compact Toroids* (Osaka University, Osaka, Japan, 1982).

¹²C. Munson *et al.*, "Experimental Investigation of the Global MHD Characteristics of Proto S-1 Spheromak Plasmas," in *Proceedings of the Fifth Symposium on Physics and Technology of Compact Toroids in the Magnetic Fusion Energy Program* (MSNW, Bellevue, Washington, 1982).

¹³S. Paul *et al.*, "Experimental Investigation of Spheromak Configurations in Proto S-1C," in *Proceedings of the Fifth Symposium on Physics and Technology of Compact Toroids in the Magnetic Fusion Energy Program* (MSNW, Bellevue, Washington, 1982).

¹⁴R.A. Ellis *et al.*, "Status of Fabrication of the S-1 Spheromak Device," in *Proceedings of the Fifth Symposium on Physics and Technology of Compact Toroids in the Magnetic Fusion Energy Program* (MSNW, Bellevue, Washington, 1982).

Advanced Radio-Frequency Concepts and Technology

ACT-I

ACT-I (Advanced Concepts Torus-I) is a steady-state, 5-kG toroidal device with minor radius of 10 cm and major radius of 59 cm. Research on ACT-I is currently devoted to the investigation of wave physics in the lower hybrid and ion cyclotron range of frequencies (ICRF). Particular emphasis is being placed on advanced concepts in radio-frequency heating, current drive, and plasma diagnostics relevant to fusion reactors.¹

Ion-Thermal Effects on Lower Hybrid Waves

Linear-mode conversion of lower hybrid waves into hot plasma waves and into the ion-Bernstein waves near the lower hybrid resonance layer was predicted theoretically by T.H. Stix in 1965. This process provides a mechanism through which ions may be heated near the conversion layer. Attempts to detect the mode conversion process in several previous experiments were not successful. However, an experiment on ACT-I² has shown the predicted finite-ion-temperature modification of lower hybrid waves, at frequencies $\omega \approx 4-8\omega_{ci}$, close to the lower hybrid resonance layer. Probe and CO₂-laser scans of the wave amplitude show interference patterns at frequencies above each ion cyclotron harmonic (Fig. 68). This periodic repetition of waveform patterns is a signature of the mode conversion process. Modeling with a hot-ion electrostatic ray-tracing code, using Fourier reconstruction of the waveforms, offers additional confirmation that linear mode-conversion into hot plasma waves is indeed occurring.

Ion-Bernstein Wave Heating

Ion-Bernstein wave heating or finite-Larmor-radius (FLR) ICRF is a waveguide reactor-heating concept utilizing a full FLR ion-Bernstein wave to carry rf power deep into the plasma interior. FLR-ICRF wave heating appears to scale well and would have several important technological advantages for reactor-plasma heating. In the ACT-I hydrogen plasma, ion-Bernstein wave heating has been investigated for $\omega \approx 1.5\Omega_H \sim 3\Omega_H$.^{3,4} Detailed measurements of wave absorption and of ion-temperature profiles have clearly identified various heating layers near the ion-cyclotron harmonics of deuterium-like (D) and tritium-like (T) ions. In Fig. 69 the measured ion temperature at a given radial position is

Figure 68. Radial probe scans of wave amplitude as a function of applied rf frequency, approximately 120° toroidally from the antenna, which was located radially at $r = 6.5$ cm. Interference patterns can be seen in bands above ion cyclotron harmonics as well as distortion and broadening of the resonance cone (main feature) near each harmonic layer. The innermost features are from waves traveling the long way around the torus. (82X2029)

plotted as a function of wave frequency (ω/Ω_H). Strong heating layers, with comparable heating efficiencies of $10 \text{ eV/Watt}/10^{10} \text{ cm}^{-3}$, can be seen near $5\Omega_T$ [Fig. 69(a)] and $5\Omega_D$ [Fig. 69(b)]. At these layers the ion temperature undergoes a nearly thirty-fold increase from its 1.5 eV unheated value. The position of the ion temperature

Figure 69. Ion temperature versus rf frequency (a) $\omega/\omega_H = 1.6-1.9$ (b) $\omega/\omega_H = 2.4-2.75$. $P_{rf} = 10$ W, $r = 3$ cm, $B_0 = 4.75$ kG, and $n_0 = 2.5 \times 10^{10}$ cm $^{-3}$. (82X1130)

peak is found to coincide closely with the observed region of strong wave absorption and also with the location for power deposition predicted by a ray-tracing calculation. From power balance estimates, nearly all of the applied rf power can be accounted for by the observed ion energy increase, an indication of excellent overall FLR-ICRF heating efficiency. The present ACT-I heating result together with theoretical investigations^{5,6} suggest that a timely experiment could be performed on existing medium-size tokamaks.

CO₂ Laser Scattering on Lower Hybrid Waves

The heterodyne CO₂-laser scattering system⁷ was used to investigate lower hybrid wave propagation, and, by this method, the lower hybrid wave resonance cone⁸ was observed for the first time. The $k_{\parallel}$ -spectra for various antenna phasing were directly measured, and it was found that electron Landau damping produces a filtering effect (for $\omega/k_{\parallel} \leq 3v_{Te}$) on the wave

$k_{\parallel}$ -spectrum.⁸ As the plasma density is raised, the resonance-cone signal disappears when $\omega \leq 1.5\omega_{pi}$. This event is attributed to the scattering of lower hybrid waves by naturally occurring low-frequency density fluctuations ($\delta n/n \approx 20-30\%$) near the plasma edge. At high rf power, the laser signal drops. Careful measurements reveal that the plasma density profile and the wave phase front are distorted at high rf power causing a net decrease in laser signal even though the wave amplitude is increasing.⁹

Finite-Larmor-Radius Effects on the ICRF Fast-Wave Experiments

Finite-Larmor-radius effects on the ICRF fast-wave experiments have been investigated using a Faraday-shielded ICRF induction coil antenna with ceramic insulation. Two dominant FLR-effects induced by the near-field of the ICRF antenna have been observed. With the low threshold electric field of approximately 1 volt/cm, strong parametric instability activity has been observed where the ion-Bernstein wave and ion quasi-mode are excited at the lower sideband and low-frequency mode, respectively. In addition, the antenna electric field has been observed to directly excite the ion-Bernstein wave through an electrostatic field induced by the $\vec{E}_{rf} \times \vec{B}_0$ drift motion in the plasma density-gradient region.

Tokamak Start-Up and Current Drive

A novel tokamak start-up scheme has been proposed by the ACT-I group. This scheme uses low-energy electron injection along helical field lines followed by lower hybrid wave current drive or low-voltage ohmic current ramp-up. A test experiment was carried out with a 500-volt, 200-amp electron beam injected for a period of approximately 50 msec into the ACT-I device, where a small vertical field was applied to provide a spiraling electron orbit into the plasma. The resulting toroidal plasma current (≤ 800 amp) is typically a factor of 5-10 times larger than the injected current due to the beam-stacking effect. A highly ionized plasma ($n \leq 10^{13}$ cm $^{-3}$) was produced. The current induced by a small ohmic heating system (≤ 0.01 volt-second) increased dramatically with the beam-injected current from approximately 50 amp in a low-power discharge to approximately 3000 amp in a high-power discharge. This start-up scheme scales favorably to large tokamaks.

In addition to the experimental progress, some theoretical calculations were carried out for rf current drive in large tokamaks. The wave trajectories for three waveguide-launched modes, namely, lower hybrid wave, fast wave, and ion-Bernstein wave, were analyzed for the Fusion Engineering Device (FED) parameters.¹⁰ A 2-1/2-dimensional ray-tracing code was used in the calculations to evaluate their applicability for steady-state current drive in tokamak reactors. Merits and demerits of each mode were identified. In addition to these ray-tracing calculations,

runaway electron orbits were analyzed in a tokamak magnetic field. It was found that the runaway electrons drift outward along the major radius with a velocity proportional to the ohmic electric field.¹¹ This finding seems to explain the correlation between the hard X-ray flux and the loop voltage in lower hybrid wave current-drive experiments.

RADIO-FREQUENCY TESTING FACILITY

Facilities with a proper plasma environment for testing rf components to be used in high-power rf applications in tokamaks are essential to verify the design limits and to condition the components before installation. The Radio Frequency Testing Facility (RFTF), was under construction in the H-1 area at C-site, during FY82. It will provide a realistic magnetized long-pulse plasma for the testing of the next generation of long-pulse or steady-state advanced rf components for PLT and TFTR.

The RFTF is a steady-state (or long-pulsed) mirror device which can have a 5-kG field in the center cell and up to a 25-kG field in the mirror throat. The plasma will be produced by rf waves to a projected electron density approaching 10^{13} cm⁻³. The central vacuum vessel is in three sections and the present device is a replica of the PLT vessel. The diameter of the vessel is one meter and has four ports that are identical to those on PLT. The initial program will test the PLT-size wave launchers, both antennae and waveguides, for long-pulse high-power operation. Eventually, the center section will be replaced by a TFTR-size vessel with TFTR-type ports and will be used to test antenna arrays. The magnetic field will be produced in the mirror throat by two spare PLT toroidal-field coils, eight FM-1 size coils, and 28 Q-3 coils. Figure 70 shows the PLT and the FM-1 coils in place.

Figure 70. Magnetic coils for the steady-state rf testing facility (RFTF). The mirror field is provided by two PLT coils, eight FM-1 coils, and 28 Q-3 coils (not shown). (82X2236).

In FY82 the H-1 area was cleared, the PLT and the FM-1 coils were installed, and the preliminary vacuum system designs and construction were started. The FY83 schedule includes the coils and vacuum support structures, the electrical connections, and the main cooling system constructions. The device is scheduled to begin operation in March 1983 with a magnetized plasma but with no stability-field coils. The full plasma parameters will be reached in July to August. High-power long-pulse operation will commence in the fall of 1983.

References

- ¹K.L. Wong, M. Ono, and G.A. Wurden, "ACT-I: Steady-State Torus for Basic Plasma Physics Research," *Rev. Sci. Instrum.* 53 (1982) 609.
- ²G.A. Wurden, K.L. Wong, F. Skiff, and M. Ono, "Observation of Magnetized Ion Thermal Effects on Lower-Hybrid Waves," Princeton University Plasma Physics Laboratory Report PPPL-1974 (February 1982) 12pp.
- ³M. Ono, K.L. Wong, and G.A. Wurden, "Harmonic Launching of Ion Bernstein Waves Via Mode-Transformation," Princeton University Plasma Physics Laboratory Report PPPL-1905 (June 1982) 54pp.
- ⁴M. Ono, G.A. Wurden, and K.L. Wong, "Efficient Ion Heating Via Finite-Larmor-Radius ICRF," Princeton University Plasma Physics Laboratory Report PPPL-1981 (February 1982) 14pp.
- ⁵M. Ono, "Absorption of Ion Bernstein Waves by Impurity Cyclotron Harmonics," Princeton University Plasma Physics Laboratory Report PPPL-1900 (May 1982) 9pp.
- ⁶M. Ono, "Effect of Low Frequency Density Fluctuations on Ion Cyclotron Waves," *Phys. Fluids* 25 (1982) 990.
- ⁷G.A. Wurden, M. Ono, and K.L. Wong, "Ion Temperature Measurement Via Laser Scattering on Ion Bernstein Waves," *Phys. Rev. A* 26 (1982) 2297.
- ⁸G.A. Wurden, "CO₂ Laser Scattering on RF Waves in ACT-I," Ph.D. Thesis, Princeton University (1982).
- ⁹J.R. Wilson and K.L. Wong, "Ponderomotive Force Effects on Slow-Wave Coupling," *Phys. Fluids* 25 (1982) 675.
- ¹⁰K.L. Wong and M. Ono, "Radio-Frequency Wave Trajectories for Current Drive in Tokamak Reactors," Princeton University Plasma Physics Laboratory Report PPPL-1967 (December 1982) 29pp.
- ¹¹K.L. Wong, "Leakage of Runaway Electrons from Tokamaks," *Nucl. Fusion* 22 (1982) 1528.

X-Ray Laser Studies

In 1982 the Soft X-Ray Laser Development Experiment progressed to measurement of the radiation of spectral lines in the vacuum ultraviolet (VUV) region for the determination of level populations, and hence population inversions and gains. Recent experimental results include the observation of population inversions in the lithium-like ions CVI, OIV, FVII, and NeVIII, and the strong enhancement of the hydrogen-like CVI 182 Å line in the axial direction of the plasma column which suggests stimulated emission.

Experimental results that indicate the effectiveness of radiation losses for the fast cooling of a magnetically confined plasma column which is first heated by a powerful CO₂ laser (1 kJ, 10-20 GW) were presented in the FY81 Annual Report. The use of radiation losses for fast cooling of the plasma column differentiates our approach¹⁻³ from most X-ray laser experiments, which are based on recombining plasmas where the plasma is cooled primarily by adiabatic expansion. In an expanding plasma the electron density decreases rapidly during the expansion; this has a significant negative effect on gain. In fast cooling of the plasma column by radiation losses the electron density does not change significantly, and the plasma column can be as long as 10-20 cm, and have a diameter of about 1-2 mm.

Two VUV spectrometers, three air monochromators, and an air spectrometer were the principal plasma diagnostic instruments and they were used to measure the density and time evolution of the various excited atomic states in the plasma. The overall space and time development of the plasma was monitored by a fiber optic-streak camera system. One of the VUV spectrometers monitored line radiation from the plasma column in the axial direction (axial instrument); the second monitored line radiation along a diameter of the plasma column (transverse instrument). (Both instruments will also have, in the future, the capability to measure the time evolution of line intensities; in fact, the transverse instrument will be able to measure the intensities of two lines simultaneously.) Two differential pumping stations isolate these instruments from the higher pressure plasma chamber. A system of beam splitters enables absolutely calibrated, 0.5 m air monochromators to view the same points in the plasma. In this way, the VUV instruments can be calibrated for absolute intensities by using the method of branching ratios. The optical arrangement of the experiment and target assemblies⁴ are presented in Fig. 71. In some experiments the plasma was created by focusing the laser beam onto gas puffed by a fast valve into the target chamber. A number of experiments were performed

Figure 71. The optical arrangement of the experiment and target assemblies for the Soft X-Ray Development Laser Experiment. (83X0005)

using two gas limiters: one with a 2-mm orifice to decrease gas flow in the direction of the axial spectrometer and the second one with a 10- or 15-mm orifice located at a distance of ≈ 10 cm upstream from the first orifice (towards the CO₂ laser) to provide a high gas pressure gradient near the laser focus. Also shown in Fig. 71 is a solid target with a small hole in the center. For this target the laser beam was focused on the edge of the hole, and the plasma column was created along the axis through the hole. With a magnetic field of $B > 50$ kG, the plasma column was well-confined and the length of the column was ≈ 5 cm. Until now, carbon targets mainly have been used, although a few experiments were done with a teflon target (for observation of fluorine spectra, particularly lithium-like FVII spectra) and an aluminum target (for lithium-like Al XI).

One of the most promising results from the Soft X-Ray Laser Development Experiment is shown in Fig. 72. The spectrum is obtained in both axial and transverse directions, and the same emission lines can be seen in both spectra. However, when compared to the CVI 33 Å 2-1 emission, the CIV 182 Å 3-2 emission is an order of magnitude stronger in the axial direction than in the transverse direction. If this increase is due to stimulated emission (which still needs to be verified in future experiments), it corresponds to a gain-length product of

STRONG AXIAL EMISSION OF C VII 182.17 Å (H α)

Figure 72. Axial and transverse emission spectra from a carbon target with a 1-mm hole and with an applied magnetic field of $B = 50$ kG, in the vicinity of the C VI 182 Å (3-2 transition) and C VI 33 Å (2-1 transition) emission lines. (Strong enhancement of C VI 182 Å line intensity emitted in the axial direction in comparison to the intensity measured in the transverse direction.) (83X0188)

4 (400%) at 182 Å. This result is potentially very encouraging, and additional experiments are planned that will use different conditions in order to further increase the gain.

The lithium sequence ions C IV, O VI, F VII, and Ne VIII have also been studied. Figure 73 shows two O VI spectra that were observed under different experimental conditions. In these spectra the intensity of a given line is proportional to the product of the upper state population and the transition probability. (The plasma is optically thin to the lines in question. This has been confirmed experimentally by measurements of the fine structure components of the O VI 173 Å line.) Since the transition probabilities are known, ratios of level populations can be obtained from ratios of line intensities. The lower spectrum was taken using a target gas of 2.5 Torr CO₂ with the addition of 5% xenon for

faster radiation cooling. Comparison of the O VI 129 Å 4d-2p line intensity with the O VI 173 Å 3d-2p line intensity shows that the 4d level has one third the population of the 3d level, and thus there is no population inversion. In this case, the addition of xenon seems to provide too much additional radiation cooling. On the other hand, the upper spectrum of 3.5 Torr CO₂ shows stronger 129 Å emission than 173 Å emission, indicating an 8:1 4d/3d population inversion. The 4f level does not have a transition in the same spectral region, but it is within 0.02 eV of the 4d level, and it is expected to have the same sublevel population leading to gain on the 4f-3d transition at 520 Å. The absolute value of the gain was measured by the branching ratio method of absolute intensity calibration using the O VI 3811 Å 3p-3s and the O VI 150 Å 3p-2s lines. The 3811 Å intensity was measured simultaneously with the VUV exposure. The result is an estimated gain of approximately 0.1 (~10%) on the O VI 520 Å transition. This result is subject to some uncertainties with regard to the variation in sensitivities of the VUV spectrograph with wavelength, but it does represent a time-integrated measurement. The peak gain at 520 Å is expected to be much higher. Measurements on other lithium-like ions have also shown 4d/3d population inversions: C IV (4:1), F VII (1.2:1), Ne VIII (4:1) with potential lasing transitions at 1168 Å, 381 Å, and 292 Å, respectively.

In the future it is planned to make VUV time-resolved measurements of the level populations and to further optimize the experimental conditions necessary to increase the gain and progress toward a soft X-ray laser.

Figure 73. The lithium-like O VI spectrum in the region 100-180 Å from a CO₂ gas target. (a) The spectrum with the intensity ratio of O VI 129 Å (4d-2p) and O VI 173 Å (3d-2p) emission lines indicate a population inversion for levels 4d and 3d. The CO₂ gas pressure is $p \approx 3.5$ Torr. (b) The spectrum without the population inversion for levels 4d and 3d. The CO₂ gas pressure $p \approx 2.5$ Torr + 5% xenon. (83X0187)

References

¹S. Suckewer, L.C. Johnson, K. Sato, A. Semet, C.H. Skinner, and D. Voorhees, "First Results from a Soft X-Ray Laser Experiment in a Confined Plasma Column," *Princeton University Plasma Physics Laboratory Report PPPL-1896* (April 1982) 27pp.

²S. Suckewer, "Experiments on Soft X-Ray Lasers at PPPL," *Bull. Am. Phys. Soc.* 27 (1982) 453.

³C.H. Skinner, R. Mullen, K. Sato, A. Semet, S. Suckewer, and D. Voorhees, "Feasibility Study of a 1216 Å Laser," *Bull. Am. Phys. Soc.* 27 (1982) 480.

⁴S. Suckewer, D. Voorhees, L.C. Johnson, H. Milchberg, K. Sato, A. Semet, and C.H. Skinner, "Experimental Arrangement for the Study of Population Inversions in the Soft X-Ray Region," *Bull. Am. Phys. Soc.* 27 (1982) 480.

Theory

Theoretical research at the Princeton Plasma Physics Laboratory continues to play a major role in magnetic fusion research and in the theory of nonlinear continuum physics in general. Both the understanding of current experiments and the performance projections for future magnetic fusion devices are expressed in theoretical terms. Fundamental research in statistical physics is enjoying a renaissance with the discovery that nonlinear classical systems, with a few degrees of freedom, can exhibit statistical behavior. Research at PPPL is contributing to the basic development of this field as well as to the application of the new concepts to the particulars of magnetic fusion devices. At the other end of the spectrum of theoretical research, conceptual engineering studies have provided paradigms for the application of theory to device design. The central part of the PPPL theoretical research effort remains the development and application of the increasingly sophisticated computational codes that deal in a quantitative way with the difficult interplay between nonlinear physics and toroidal geometry that characterizes PPPL's approach to magnetic fusion. The examples below document a portion of our efforts in these areas.

A MODEL FOR "FISHBONES"

One of the key questions for magnetic fusion research has been, "How will the β -limitations of various confinement configurations manifest themselves?" Until recently, only the β -dependent outward Shafranov shift of the magnetic axis had been measured in PPPL's tokamaks. This year, high-power neutral-beam-heated discharges on PDX revealed a second phenomenon—repetitive bursts of MHD oscillations which acquired the name of "fishbones." (See PDX Section.) These oscillations caused the loss of the energetic heating particles with a consequent limitation on the β -value.

The theoretical model for fishbones drew on three separate theoretical developments. First, the motion of the energetic particles in the combined steady-state and oscillating magnetic fields was cast in a Hamiltonian formalism which made the threshold for the transition from true magnetic surfaces to stochastic regions particularly simple to express. (The concept of a stochasticity threshold is a central ingredient in the recent developments in statistical physics.) Second, nonlinear MHD codes were developed to the point where they were able to predict the internal magnetic perturbations resulting from an MHD oscillation when the computed surface oscillation levels were fitted to

observations. The agreement between observed soft X-ray waveforms (which are determined by internal magnetic perturbations) and their theoretical predictions was excellent. These magnetic perturbations were utilized in the Hamiltonian formalism mentioned above. Third, the MHD stability of the heated PDX discharges could be assessed by the PEST linear stability code.

The theoretical picture of the fishbone phenomenon comes from the following results. Both the PEST code and the nonlinear MHD code showed that the heated PDX discharge was close to or at a marginal stability boundary for an ideal, pressure-driven, $m=1$, $n=1$ mode. Figure 74 portrays these results. This instability persists

Figure 74. Stability diagram showing the region of instability to the $n=1$, $m=1$ internal kink mode for a tokamak with aspect ratio (ratio of major to minor radius) 3 and safety factor $q_{\text{edge}}/q_{\text{axis}} \approx 2.5$. The figure shows stability at low β and a second stable region at high β . The cross-hatched area indicates the effective range of operation of PDX when fishbone MHD activity is first observed. The vertical axis shows the product of the inverse aspect ratio and the plasma pressure in relation to the toroidal plasma current ($\epsilon\beta_{\text{pol}}$). The horizontal axis shows the safety factor on axis. (83T0087)

even when the q -value at the magnetic axis is above unity, ruling out the $m=1, n=1$ resistive reconnection mode associated with the low- β sawtooth phenomenon. When the computed magnetic perturbations were introduced into the Hamiltonian formalism as a rotating mode (as observed), both a loss of beam particles and an energization of a few particles above the injection energy resulted. Figure 75 shows the particle loss as a function of mode frequency for various injection parameters, R_T . A clear resonance is seen at the beam precession frequency. Loss is largest for near-perpendicular injection (small R_T). Quantitatively, the agreement with experiment was good.

This research leads to the conclusion that fishbones are a genuine high- β phenomenon. Fortunately, it has also been found that the troublesome $m=1, n=1$ mode can be stabilized by the bean-shaped tokamak described below.

Figure 75. Fraction of beam particles lost during one fishbone period (500 μ sec) as a function of mode frequency for various beam injection angles. The frequency is normalized to the on-axis, beam-particle gyro-frequency ω_0 . The injection parameter R_T is the distance of closest approach of the beam line-of-sight to the center axis of the torus. Thus $R_T = 0$ is perpendicular injection, and $R_T = R_0 = 143$ cm, the major radius, is parallel injection. A monoenergetic 50-keV deuterium beam was used for this example. The resonant frequency for $R_T < 100$ cm, $\omega/\omega_0 = 2.7 \times 10^{-3}$, represents the trapped-particle precession rate, which is approximately independent of injection angle and radial position, and for the PDX parameters used, is about 20 kHz. (83T0081)

SHAPED TOKAMAK STUDIES

The shaping of tokamak configurations is the principal means used to raise the ideal MHD β -limits. Indeed, the most extreme tokamak shape yet built—the Doublet—was chosen for its theoretical high- β properties. More recently, the Big-Dee upgrade of Doublet III and the JET

(Joint European Torus) designs have utilized vertical elongation to provide an increase in the predicted maximum stable β -value.

The prospects for achieving a high- β tokamak rest principally on the ability to enter the recently discovered second stability regime. Several years ago, research at the Massachusetts Institute of Technology (MIT) and PPPL showed that, at sufficiently high- β values, the tokamak became a self-stabilizing configuration wherein increases in the plasma pressure altered the internal magnetic configuration enough to increase the stability properties of the plasma. This regime of self-stabilization was called the second stability regime. But these favorable prospects were tempered by the fact that there still remained a significant range of β for which the tokamak was unstable—at least for conventionally elongated tokamaks. The exciting new discovery is that for a special tokamak shape—the bean tokamak—there is no unstable region separating the regular and second stability regimes. Figure 76(a) depicts the bean tokamak equilibria which have been used and which are parameterized by the indentation length d . Figure 76(b) summarizes the results of stability

Figure 76. Bean tokamak stability studies. (a) Sketch of the poloidal cross section of a bean tokamak equilibrium in terms of the major radius R , minor radius a , and axial extent $2b$. Stability calculations have been performed for a sequence of equilibria parameterized by the indentation length d . (b) Results of PEST stability calculations for ideal MHD fine-scale ballooning modes. (83T0086)

calculations for fine-scale, ideal MHD ballooning modes. Clearly, the second and the regular stability regimes merge at an indentation length $d/2a = 0.3$. Calculations regarding stability with respect to other modes are in progress. In a more general sense, it has been learned that unconventional shapes may hold special promise for achieving high β in tokamaks. For example, the ideal MHD $m=1$, $n=1$ mode associated with fishbone oscillations is stabilized in the bean configuration.

NONINDUCTIVE CURRENT DRIVE

The successes of lower hybrid current-drive experiments on PLT have unequivocally demonstrated that radio-frequency (rf) waves can be used to maintain a steady current in a tokamak with an efficiency in good agreement with theory. The promise of a true steady-state tokamak reactor is quite appealing. In addition, the PLT experiments could actually increase the plasma current, opening up the possibility that the initial plasma current in a tokamak could be created largely by radio-frequency waves.

Theoretical research in current drive has been concentrated in two areas: methods to increase the energy efficiency of current drive, and identification of alternate plasma waves which possess advantages over the lower hybrid waves used in current experiments. The approach to increased energy efficiency starts with the observation that the radio-frequency energy required to build the plasma current up to a specified level is less at lower plasma densities and temperatures. Significant increases in the energy efficiency of current drive can be obtained by a modest oscillation in the current. The current is increased when the plasma is relatively tenuous and cold. Once the current increase has been effected, the plasma temperature and density are increased to fusion reactor conditions where the decay time for the current is very long because of the high plasma temperature. Eventually, the current will decay to a specified level where another build-up cycle must begin. An overall increase of a factor of five in energy efficiency can be obtained.

Turning to the question of other plasma waves, research has identified the fast Alfvén wave [used in Ion Cyclotron Range of Frequencies (ICRF) heating] as a promising alternative to lower hybrid waves. The fast wave provides better penetration into the hot, dense core of true steady-state reactor-level plasmas. But research has also found that there is only a small window for the frequency of the fast wave where it will be effective at current drive. Outside this window, the fast wave energy is absorbed by plasma ions or fusion alpha-particles and is ineffective.

ICRF HEATING OF TOKAMAKS

During the past several years, the physics of ion-cyclotron heating in tokamaks has shown a remarkable agreement between theory and experiment.

High power heating experiments on PLT have recorded good temperature increases and excellent heating efficiencies. As a result, several reactor studies have adopted ICRF heating as the prime bulk-heating method. The focus of ICRF heating theory has similarly moved towards reactor-heating issues. Theoretical research at PPPL has developed modeling codes which permit quantitative studies of the effect of ICRF heating in various large tokamak (e.g., TFTR) and fusion reactor studies. The antennae used to launch the fast Alfvén wave in ICRF experiments must also be improved from the induction loops used in current experiments to modular, all-metal structures recessed behind the first wall in a reactor. A theoretical design which fulfills these requirements has been carried out.

The major ingredients of the ICRF code are a ray-tracing package to calculate the wave fields and a Fokker-Planck code to determine self-consistently the damping of the waves and the evolution of the distributions of particles. The wave fields are determined by using the ray-tracing equations where the dispersion relation is given by the multi-fluid model with a polytropic equation of state. This choice of dispersion relation has the advantage that it may be calculated rapidly (which is obviously important in a transport code), but it does not allow for the treatment of waves which are primarily kinetic. Very fast equilibration of the heat on a flux surface is assumed which, together with the toroidal symmetry, means it is not necessary to keep track of the toroidal position of the rays. This, in turn, means that the ray tracing need only be carried out in two dimensions. The absorption of a particular ray is found by calculating the polarization of the wave, using the fluid equations, and hence finding the flux-surface-averaged quasi-linear diffusion coefficient for the particles under the influence of this wave. From this and the distribution of the particles, the power absorbed by the particles can be determined, which allows the power content of the ray to be determined. By this method, all the collisionless damping mechanisms (Landau, fundamental, and harmonic cyclotron) are treated without the need for special-purpose approximations. The major assumption is that the polarization of the wave is accurately given by the fluid equations.

An example of the output for a minority heating experiment on PLT is shown in Fig. 77. The line-averaged plasma density is $2 \times 10^{13} \text{ cm}^{-3}$ with 95% deuterium and 5% hydrogen. The toroidal magnetic field is 28 kG. A radio-frequency power of 1 MW at 42 MHz was injected using 20 rays, which approximately describes the half-turn antenna used in the experiment.

A novel ICRF antenna was proposed which is based on the concepts of small-gap cavities used in microwave tubes. Figure 78 shows a design carried out for the Big-Dee Doublet III tokamak. In brief, the vertical plates serve both as a capacitor and as part of the current loop which determines the inductance. The rf magnetic field lines encircle the vertical plates and penetrate through the Faraday shield and into the plasma where they produce an oscillating component of the toroidal field. This matches well with the

Figure 77. Calculation of ion temperature rise in a 1-MW ICRF heating experiment on PLT. (83T0099)

Figure 78. ICRF antenna. (a) General view. The large-area Faraday screen is coincident with the first wall. All dimensions are in cm. (b) Cross section of the rectangular, coaxial transmission lines. (c) Horizontal cross section of the small-gap cavity. (d) Vertical cross section showing how the vertical plates form a capacitor. The cavity is excited by magnetic loop coupling to the rectangular transmission line. (82T0219)

polarization of the fast Alfvén wave. The small-gap cavity geometry enables the cavity resonant frequency to coincide with the intended ICRF frequency (55 MHz), even though the cavity dimensions are significantly

smaller than one-half of the electromagnetic wavelength at 55 MHz. In addition, the strong electric fields which arise in the capacitor are oriented perpendicular to the main toroidal field, thus benefiting from a magnetic insulation effect. The computed power-handling capabilities are excellent; a single coupler should be able to launch 20 MW of ICRF power.

ENHANCED NUCLEAR REACTIVITY BY POLARIZATION

It seems possible that, once one has constructed a working fusion reactor, its performance can be improved by the additional step of polarizing the nuclear fuel before it is injected into the reactor. The physics of these plasmas with polarized ions are being studied, from three points of view.

Nuclear Aspect

Deuterium-tritium (D-T) reactions can occur with three different orientations of the nuclei: parallel, across, and antiparallel. For an unpolarized plasma, these three orientations have equal probability. However, the relative chances for a reaction to occur in these three orientations are unequal. The relative probabilities are three, two, and one, respectively. Figure 79 depicts the

Figure 79. In order for a fusion reaction to occur the total angular momentum of the nuclei must be $3/2\hbar$. This angular momentum comes from the spins of the D and T nuclei. If the nuclei are properly aligned, the total spin is $3/2$ and the reaction is likely. If they are improperly aligned, the total spin is $1/2$ and the reaction is unlikely; D and T suffer an elastic collision and depart unchanged. Enhancement is obtained over random nuclear events by making sure the nuclei are aligned with spins parallel. (82X0400)

nuclear spin orientations in a D-T fusion reactor. Thus, by proper choice of orientation of the nuclei, the effective nuclear cross section can be changed and, consequently, the reactivity as well. The optimum choice is a parallel orientation which gives a 50% larger cross section than the mean value. Not only does the cross section vary with orientation but so does the distribution of emission direction for the reaction products, the alpha-particle, and the neutron. This control over emission direction may also be of use in the control of the reactor performance.

Correspondingly, control over other nuclear reactions is possible. It is believed that the deuterium-deuterium (D-D) reaction can be enhanced or suppressed, which could be very useful for the deuterium-helium (D-He³) reactor.

Depolarization

A principle cause for concern is the rate of depolarization which might occur to the ions subject to all the plasma processes in a reactor. The depolarization processes that occur during binary collisions were examined. These consist of spin-orbit, spin-spin, and electric quadrupole interactions. In all cases, cross sections for depolarization by binary collisions are minute compared to nuclear fusion cross sections. Another possibility for depolarization is by interaction with the magnetic fluctuation in various plasma waves, the most dangerous waves being those in the neighborhood of the deuteron ion-cyclotron frequency. A first consideration of these processes indicates that they, too, are negligibly small. However, since they depend on the nonlinear behavior of various plasma instabilities, it is difficult to be certain of this. Research on this problem is continuing. Finally, the inhomogeneous character of the reactor fields can also lead to the possibility of depolarization. Again, first estimates indicate that, although it is larger than depolarization by binary collisions, it is still quite negligible. Thus, it is reasonable to conclude that there are good grounds for believing that a polarized plasma, once formed, will remain polarized to a high degree for the time necessary for it to fuse.

Sources

This aspect is not of direct concern to theoretical plasma physics. However, it is necessary that abundant cheap sources of polarized particles be found that can supply a reactor if the polarization process is to have any reality. Fortunately, such sources are now potentially available and are currently being developed to produce substantial quantities of polarized nuclei.

STELLARATOR EQUILIBRIUM AND STABILITY

The current revival of interest in stellarator configurations rests on three developments. First, European and Japanese experiments have demonstrated excellent confinement in the current-free regime. Second, steady-state, disruption-free operation alleviates many

Figure 80. Equilibrium properties of the ATF-1 device. (a) Zeroth-order magnetic surfaces for $\beta = 2.5\%$. (b) Rotational transform as a function of $x = R/a$, where R is the major radius and a , the fixed, reference minor radius. Dashed curves are for $\beta = 0$ and solid curves are for $\beta = 2.5\%$. (c) $V'_{vac}(\phi)$ is the rate of change of volume per unit toroidal flux. At $\beta = 0$, $V'_{vac}(\phi)$ has a minimum at the plasma center corresponding to a destabilizing average magnetic hill, which is stabilized by the shear in the spatially varying rotational transform χ . But even at low pressure, a stabilizing magnetic well develops. (8370254)

reactor engineering and reliability problems. Third, high- β values appear to be possible in optimized field designs. PPPL's research contributes to this last area.

A general theory of the β -limits for inherently three-dimensional configurations, such as stellarators, is extraordinarily difficult. Fortunately, most stellarator devices have large aspect ratios which permit the use of the stellarator expansion to investigate equilibrium and stability. Using the stellarator expansion, the equilibrium can be expressed mathematically in a two-dimensional, rather than a three-dimensional, representation. The key concept is to average over the many field periods of the helical fields that a large-aspect-ratio stellarator typically possesses. When the equilibrium is expressed two-dimensionally, then the powerful computational methods of the PEST equilibrium and stability codes can be brought to bear on the question of the ideal MHD β -limits for stability.

Appropriate modifications were made to the PEST codes, and the new stellarator versions were applied to the Japanese Heliotron E, the German Wendelstein VII-A, and the proposed Oak Ridge ATF-1 (Advanced Toroidal Facility) device. Initial studies showed the onset of instability at low β -values in Heliotron E and Wendelstein VII-A—1% and 0.3%, respectively. With a peaked pressure profile, the ATF-1 device was much better—no instabilities were present at a $\langle\beta\rangle$ -value of 2.5%, the largest value investigated to date. Figure 80 shows the equilibrium properties for the high- β ATF-1.

ADVANCES IN THEORY OF HAMILTONIAN SYSTEMS

Many problems of plasma physics can be described by systems of differential equations of low order. In the absence of dissipation, the equations can be put into so-called Hamiltonian form. Examples of such problems are magnetic-field-line wandering, acceleration of ions by radio-frequency fields, the transport of particles in toroidal systems, and the position of a ray in the geometric optics limit.

Very often, interest is in the long-time behavior of the systems which are perturbations of the soluble systems. For example, the nested magnetic surfaces of an idealized tokamak constitute the soluble system, and magnetic fluctuations arising from internal MHD oscillations are the perturbation. Interest then centers on the question: Will the perturbed magnetic field lines continue to remain close to the original magnetic surfaces, or will they wander off and eventually fill a finite volume? The transition between these two classes of behavior is called the stochastic instability.

About 20 years ago, Kolmogoroff, Arnold, and Moser (KAM) showed how to construct a convergent series for certain solutions which showed that the orbits may be stable for sufficiently small perturbations. However, numerical evidence indicated that there were stable solutions for much larger perturbations (by many orders of magnitudes) than were covered by KAM theory. Recently, renormalization techniques were applied to show that the results of KAM theory do indeed hold out

to the point at which the stochastic instability was observed. It also is possible now to describe completely the motion close to the border of the instability.

In a generalized mathematical sense, finding the magnetic-field-line trajectories of idealized tokamaks can be considered as a nonlinear oscillator because of its recurrence properties. The new results represent a significant advance in classical mechanics: Newton and Lagrange solved the problem of a nonlinear oscillator; the advances of the last year enable us to see the outlines of the solution of two coupled, nonlinear oscillators. Applications abound throughout all of physical science.

APPLICATIONS OF MAGNETIC COORDINATES

The important mathematical results described above rest on expressing orbits (of particles or magnetic field lines) in terms of a Hamiltonian system of equations. For particle orbits in magnetic confinement devices, PPPL interest centers on the guiding-center drifts and on magnetic coordinates.

Magnetic coordinates reverse the customary representation of magnetic coordinates (ψ, x, α) interpretations in systems with good magnetic surfaces— ψ is the magnetic flux inside the surface, x parameterizes the distance along a field line, and α labels the field line within a surface. The actual geometry of a magnetic field then comes by expressing the usual Cartesian coordinates in terms of magnetic coordinates.

Magnetic coordinates are extraordinarily useful in dealing with toroidal, magnetic confinement devices. First, in following particle orbits computationally, the very rapid motion of a particle along a field line is one-dimensional and can be evaluated accurately without numerical errors which could produce spurious motion transverse to the field. Second, magnetic surfaces are surfaces of constant electric potential ϕ , so ϕ is a function only of the magnetic coordinate ψ .

Several important advances have been made in the application of magnetic coordinates. First, the guiding-center equations have been formulated in terms of a Hamiltonian system based on magnetic coordinates. This formulation remains valid even for systems which do not possess nested flux surfaces. The key approximation rests on the fact that, in all interesting toroidal configurations, the magnetic field values (as opposed to the eventual trajectories of magnetic field lines) are very close to a reference field which does possess nested flux surfaces. The reference magnetic field forms a basis for setting up magnetic coordinates. The new Hamiltonian system of guiding-center equations provided a key capability in assessing the consequences of fishbone oscillations on energetic particles, described above. Second, computational procedures have been developed to express Cartesian coordinates in terms of magnetic coordinates for real stellarator fields. This capability is essential to our studies of single-particle confinement in

stellarators and was used in the ATF-1 design. Third, magnetic coordinates provide the natural starting point for the evaluation of ergodic field regions. Fourth, these coordinates are useful in the study of equilibrium. Theoretical research at PPPL has played a central role in bringing this new, powerful technique to bear on problems of toroidal fusion research.

SPACE PLASMA PHYSICS

The cross-fertilization between magnetic fusion and space plasma research is particularly productive. Under the sponsorship of the National Science Foundation, PPPL has been applying its capabilities in theoretical research to the fundamental properties of space plasmas.

Theoretical space plasma research has focused on auroral field line plasmas at an altitude of one earth radius ($1R_E$) and which exhibit rich and complex plasma physics phenomena. Some examples are potential double layers, precipitation of energetic auroral electrons and upward accelerated ions, and large amplitude electrostatic hydrogen cyclotron waves. During the past year, research at PPPL has concentrated on the study of electrostatic ion-cyclotron (EIC) waves, formation of conical ion velocity

distributions, and the associated density striations aligned in the east-west direction.

Inspired by the spacecraft and rocket observations on EIC waves and by ion velocity distributions on auroral field lines, detailed analytical and numerical simulation studies on the EIC waves and their effects on particles were conducted. A new simulation model was developed in order to incorporate ionospheric boundary conditions. Simulation results confirmed the importance of the ionospheric electrons, which are essential for producing observed ion energization and large amplitude EIC waves. In addition to bulk ion heating, simulations revealed the presence of a high energy tail whose temperature can be two orders of magnitude larger than the original ionospheric temperature. An analytic theory was developed to predict the maximum attainable ion heating based on a marginal stability analysis.

In addition to energizing ions, recent two-dimensional simulations on EIC waves indicate that EIC waves may be responsible for generating thin auroral arc elements. Results of two-dimensional simulations show that large density striations, $n_{\max}/n_{\min} \lesssim 2$, aligned in the east-west direction, appear to be associated with the EIC waves. The distance between the density maxima is a few ion gyroradii, and thus resembles the thin auroral arc elements.

TOKAMAK MODELING AND DIVERTOR STUDIES

The tokamak and divertor modeling program consists, in part, of the development and application of large computer simulation programs, the analysis and collection of atomic physics processes relevant to tokamak plasmas, and the comparison of theory with experimental results through collaboration with the experimental staff. The work on divertor modeling and impurity control concentrates on a two-dimensional fluid calculation of a diverted plasma and on a Monte Carlo calculation of the transport of neutrals. Tokamak modeling is based on the one-dimensional BALDUR code, which was upgraded with models for ICRF, ECRH, and lower hybrid heating, and the new one- and one-half-dimensional equilibrium/transport code GOSPEL. In FY82 these codes were applied to PLT, PDX, TFTR, D-III, and INTOR/FED.

Tokamak Modeling

The 1-1/2-dimensional equilibrium/transport code GOSPEL has been used to simulate and analyze low-Q ohmic discharges in PDX.¹ Both free- and fixed-boundary simulations were made for disruptive and non-disruptive cases. It was found that (1) image currents are important in the simulation of actual tokamak discharges (2) disruptive discharges show a marked peaking of the current profile, in agreement with measurements, and (3) disruptive discharges require an anomalous resistivity at high-current densities.

A modeling code was developed to determine the optimum beam energy and plasma temperature in beam-driven steady-state tokamak reactors.² It was found that such reactors could produce large net electrical power, with $Q \sim 10-20$ (Q = fusion power/beam power) for an INTOR-size device. The optimum beam energy is 1-2 MeV, and the optimum plasma temperature is about 15 keV for deuterium beams.

Steady-state reactor performance, furthermore, can be greatly improved upon by driving the current continuously with an "internal transformer."³ Alternately, the plasma current is increased during a low-density, higher-resistivity drive period, and then it is allowed to decay slowly during a longer high-density, lower-resistivity fusion burn period. With this method, a time averaged Q of 90 can be achieved with about 60 MW of 200-400 keV neutral deuterium beams in an

INTOR-size device. Figure 81 compares the costs for operating a reactor with an "internal transfer" versus one with other current driving schemes.

Figure 81. A comparison of the cost of generating electricity versus the critical beta for various current drive options in a tokamak reactor. (82P0202)

Contributions were made to the Fusion Engineering Device A (FED-A) design study. It was determined that approximately 50 MW of 400-800 keV D^0 injection would be sufficient to fulfill the FED-A design values for plasma current fusion power in strictly steady-state operation. By using the internal transformer mode, the beam requirements can be reduced to about 20-40 MW of 200-400 keV D^0 beams.⁴

Pellet injection in TFTR compression discharges was studied using the BALDUR transport code.⁵ It was found that injection of a tritium pellet immediately before compression of a beam-heated plasma results in a large burst of neutron production while the total neutron production is minimized. Injection of a large, solid deuterium pellet followed by a small, solid tritium pellet gives a burst of neutrons from the plasma core and further minimizes the total neutron production. These studies provide understanding of how to achieve fusion in TFTR with a minimum of neutron activation of the vacuum vessel.

Impurity Transport

In FY82 the multispecies impurity transport code MIST was expanded to include more atomic processes and to operate ten times faster, and thus allow wider application. The MIST code was used to analyze the transport of injected impurities in experiments with ohmic and neutral-beam discharges on PLT and PDX.⁶ It was also used to model transport of low-Z materials in conjunction with charge-exchange diagnostics (Fig. 82).⁷

Figure 82. The time dependent behavior of an oxygen impurity in a plasma at $T_e = 50$ eV and $n_e = 2 \times 10^{14} \text{ cm}^{-3}$. The charge-state distribution is shown in (a) and the radiative cooling-rate coefficient in (b) for the case when the oxygen is neutral at $t=0$. (82P0143)

The transport of molecules at the plasma edge in tokamaks has been investigated in order to compare how light impurities enter the plasma if they are released in molecular rather than atomic form. Differences in their transport arise because of the dissimilarities between atomic and molecular reactions with the bulk of the plasma. It was found that recycling of carbon to the walls is more efficient if it is released in molecular form (as methane, for example).⁸

Modeling and Diagnostics

The measurement of the ion temperature is crucial to the understanding of plasma physics experiments. In conjunction with the PDX experimentalists, a new technique for measuring ion temperature was proposed⁹ which uses the Doppler-broadened line profiles of transitions excited by charge-exchange recombination reactions between fast hydrogen atoms and fully ionized low-Z ions. Expected line intensities were modeled for TFTR and PDX for states of CVI, OVIII, and HeII. The models were used to diagnose measurements from PDX using HeII radiation, and to measure the density of CVII, OIX, and HeIII.⁹

The possibility of seeding a fusion plasma, with nuclei which can undergo nuclear reactions with energetic alpha particles, to produce radioactive product nuclei was investigated.¹⁰ (Information about the presence of fast alpha particles can be obtained if a fraction of the product nuclei can be collected and measured.) It was found that the reaction $^{10}\text{B}(\alpha, n)^{13}\text{N}$ is a feasible diagnostic for studying fusion-produced alpha particles in machines such as TFTR and JET.

Divertor/Scrape-off Studies

The two-dimensional model for plasma and neutral transport was used to study poloidal divertor operation (Fig. 83).¹¹ Three operating regimes were identified. These regimes are characterized by the recycling, which in turn depends on the geometry of the divertor, the input energy and particle flux, and the pumping near the neutralizer plate. The recycling can be parameterized by $R = \Gamma_D / T_0$, the ratio of particle flux striking the neutralizer plate to the particle flux entering the divertor. It was found that large pumping rates (i.e., low recycling where $R \sim 1$) result in high-temperature, low-density divertor plasmas. When recycling is raised to 5-10 by decreasing the pumping, the plasma temperature decreases and the density increases by the ratio R . Further decrease of the pumping to where R is 20 results in a temperature decrease by 20 and a

Figure 83. Model calculations for the expanded boundary divertor in D-III showing plasma flux (Γ), density (n_e), and temperatures (T_e and T_i) along the field line for the center of the divertor. (82P0222)

density increase by 90. Such high-density, low-temperature regimes have been observed on D-III and appear to offer the most promise for impurity and particle control for large tokamaks.

The Monte Carlo model of neutral-particle transport in diverted plasmas was extended to treat general two-dimensional wall and plasma geometries. It was used to follow the transport of deuterium, tritium, and helium atoms formed by recombination at the walls. The geometries modeled include the PDX scoop, the UCLA probe experiment, and the INTOR/FED poloidal divertor design (Fig. 84).¹²

Figure 84. Cross sections of some divertor geometries modeled for the INTOR poloidal divertor, the PDX scoop, the UCLA probe experiment, and the INTOR/FED design proposal. (82P0113)

References

- ¹D.A. Larrabee *et al.*, "Simulation of PDX Low-Q Ohmic Discharges," *Bull. Am. Phys. Soc.* 27 (1982) 1034.
- ²D.R. Mikkelsen and C.E. Singer, "Optimization of Steady-State Beam-Driven Tokamak Reactors," Princeton University Plasma Physics Laboratory Report PPPL-1919 (September 1982) 52pp.
- ³C.E. Singer and D.R. Mikkelsen, "Continuous Tokamak Operation with an Internal Transformer," Princeton University Plasma Physics Laboratory Report PPPL-1936 (October 1982) 35pp.
- ⁴L.D. Stewart *et al.*, "Neutral Beam Driven Current Options," in *FED-A, An Advanced Performance FED Based on Low-q and Current Drive*, editors Y.-K.M. Peng and P.H. Rutherford, Oak Ridge National Laboratory Report ORNL/FEDC-83/1.
- ⁵C.E. Singer, D. Heifetz, and D.E. Post, "Pellet Injection in TFTR," *J. Vac. Sci. Tech. A* 1 (1983) 964.
- ⁶R.A. Hulse, "Numerical Studies of Impurities in Fusion Plasmas," Princeton University Plasma Physics Laboratory Report PPPL-1917 (September 1982) 38pp.
- ⁷R.J. Fonck *et al.*, "Spatially Resolved Measurements of Fully-Ionized Low-Z Impurities in the PDX Tokamak," *Phys. Rev. Letts.* 49 (1982) 737.
- ⁸W.D. Langer, "Penetration of Molecular Impurities at the Edge of Tokamaks," *Nucl. Fusion* 22 (1982) 751.
- ⁹R.J. Fonck *et al.*, "Plasma Ion Temperature Measurements via Charge Exchange Recombination Radiation," *Appl. Phys. Lett.* 42 (1983) 239.
- ¹⁰L.R. Grisham, D.E. Post, and J.M. Dawson, "A Nuclear Diagnostic for Fast Alpha Particles," Princeton University Plasma Physics Laboratory Report PPPL-1962 (August 1982) 12 pp.

The two-dimensional neutral transport code, in conjunction with a description of the plasma scrape-off calculated with BALDUR, was also used to study pumping and erosion rates for the TFTR and INTOR/FED limiter design.¹³ It was found that only about 7% of the charge-exchange power was deposited on the first wall in a proposed toroidally symmetric "bumper" limiter. For this reason, the first wall will not have to be replaced as often as the limiter.

The impact of particle and energy transport on the limiter design was evaluated for TFTR in a similar calculation.¹⁴ In this work, however, the recent Langmuir probe and calorimeter measurements of PLT and PDX were used to determine scaled-up transport coefficients for TFTR. Using the predicted particle and energy fluxes in TFTR, the limiter scrape-off was modeled in a slab geometry, and the neutral transport was evaluated using the SPUDNUT algorithm. The modeling results indicate that the optimum limiter should have a concave shape when viewed from the plasma.

Recent experiments on PDX, D-III, and ASDEX, as well as design work on INTOR, illustrate the need for a theory of collision-dominated transport in the scrape-off region where the plasma flows on open magnetic flux surfaces to a divertor or limiter plate. To study this regime the fluid equations in toroidal flux coordinates were analyzed for subsonic flows in an axisymmetric tokamak divertor.¹⁵ By using a self-consistent estimate of the magnitude of each term in the fluid equations, it was found that radial particle flows are dominated by Pfirsch-Schlüter currents. The scrape-off thickness could be estimated from the radial particle flow, and it was found to be in good agreement with experimental determinations for the high-density diverted plasmas in D-III. This analysis also will provide a basis for constructing simplified fluid equations to be used in the two-dimensional numerical modeling of such divertors.

¹¹D.E. Post, D.B. Heifetz, and M. Petravic, "Models for Poloidal Divertors," J. Nucl. Mater. 111 & 112 (1982) 383.

¹²D. Heifetz *et al.*, "A Monte-Carlo Model of Neutral-Particle Transport in Diverted Plasmas," J. Comp. Physics 46 (1982) 309.

¹³D. Heifetz *et al.*, "Pumping and Erosion Rates for the TFTR and INTOR/FED Limiter Designs," J. Nucl. Mater. 111 & 112 (1982) 298.

¹⁴M. Ulrickson and D.E. Post, "Particle and Energy Transport in the Plasma Scrapeoff Zone and Its Impact in Limiter Design," J. Vac. Sci. and Tech. A1 (1983) 907.

¹⁵C.E. Singer and W.D. Langer, "Axisymmetric Scrapeoff Plasma Transport," Phys. Rev. A 28 (1983) 994.

Design Studies for New Devices

HELIAIC

Recent stellarator experiments at Garching and Kyoto have shown approximately neoclassical transport in stellarators with planar magnetic axes. Studies conducted at PPPL indicate that stellarators with helical axes show potential for higher equilibrium betas. Preliminary engineering design analyses and numerical calculations have been completed for an experimental helical axis device called the Heliac (see Fig. 85). A promising feature of such a device is that it can be built from plane circular coils with reasonable stress levels if the toroidal field is in the range of 1-2 T.

Table VIII shows the parameters of a three-field period ($N = 3$) Heliac. With further optimization of the design an $N = 4-6$ Heliac could possibly be achieved. Table IX is a list of possible research objectives for the Heliac program.

Additional numerical studies of stability and transport by 3-dimensional computer codes and design refinement will be necessary before selection of final device parameters. A proposal will be prepared when this work is completed, and device construction could begin in about two years.

Figure 85. Schematic of the Heliac. (82E0153)

TFET

An upgrade of the TFTR facility has been considered that would focus the tokamak experimental program of

Table VIII. Heliac Parameters.

Major radius (R)	120 cm
Minor radius (a)	25 cm
Plasma volume (V)	$1.5 \times 10^6 \text{ cm}^3$
Safety factor (q)	1.0
Magnetic field on axis (B_0)	10 kG
Magnetic field on ripple (δ) at $r = a/2$	10%
Plasma beta value (β)	10%
Plasma Density (n)	$10^{14} - 5 \times 10^{14} \text{ cm}^{-3}$
Plasma temperature (T)	1.2 - 0.25 keV
H^+ ion gyroradius (ρ_i)	0.35 - 0.16 cm
Ion banana width (Δr_b)	1.5 - 0.7 cm
Ion collision time (τ_i)	0.43 msec - 8.3 μsec
Ion thermal velocity (v_{Ti})	$4.8 - 2.2 \times 10^7 \text{ cm/sec}$
Ion mean free path	$2.1 \times 10^4 - 18 \text{ cm}$
Energy confinement times	
Classical (τ_{EA}^C)	0.37 sec - 34 msec
Alcator (τ_E)	20 msec - 0.1 sec
Trapped electron (τ_E^I)	6.7 msec - 8.1 sec

Table IX. Preliminary Heliac Research Program.

1. Produce a hot dense plasma in the Heliac configuration.
2. Investigate transport in the long-mean-free-path regime in Heliacs.
3. Demonstrate large critical beta for equilibrium and stability.
4. Investigate the physics of heating plasmas in the Heliac geometry.
5. Investigate the characteristics of current-free toroidal plasmas.
6. Expand the theoretical understanding of Heliacs.

the late eighties and early nineties on the development of the individual components and the integrated technologies necessary for the next step in the overall evolution of a tokamak fusion reactor. An important part of such a program would be the demonstration of engineering feasibility in a number of critical areas of tokamak performance. This upgrade of TFTR has been named the Tokamak Fusion Engineering Test (TFET).

Other possible upgrades of TFTR were also

considered. Their elements are incorporated, to a greater or lesser extent, in the TFET. One such low-cost alternative, called "Q-2," would maximize Q utilizing existing TFTR hardware plus the addition of 30 MW of ICRF, remote handling hardware, fast alpha-particle diagnostics, and shielding.

The overall objective of the TFET project would be to provide a long-pulse test facility that would integrate nuclear testing (and the associated remote handling) with rf heating and current drive, and would include the necessary long-pulse capabilities for heat and particle removal. These elements and their integration are critical to the development of a tokamak fusion reactor. The TFET project would also provide the necessary development and integration of many of the important reactor technologies expected to be demonstrated on the FED. While the TFET is not nearly so ambitious as the FED, it could help sustain the forward momentum of fusion reactor technology in the near term, and it would provide a solid base for a subsequent, more advanced FED.

The TFET project could proceed with design and fabrication, in parallel with TFTR operation, during the period from 1983 through the first quarter of CY88. The TFET hardware would then be installed on TFTR, with TFET operation beginning in late 1989. The necessary data base for the TFET design would be provided by a research and development program carried out over the next several years as a part of U.S. tokamak research (including research on the TFTR itself). Component development would be done at U.S. fusion laboratories and in industry. The TFET project would be able to draw on a well-tested facility (the TFTR) and on the extensive data base provided by the U.S. tokamak experimental program. Accordingly, the overall cost and risk associated with TFET would be minimized.

Objectives and Program Elements

The objectives of TFET would be to

- Demonstrate reliable, high-level, deuterium-tritium operation and perform experiments utilizing the fusion products.
- Demonstrate remote handling of tokamak components.
- Demonstrate long-pulse energy and particle control and plasma handling in a highly conductive vacuum vessel.
- Demonstrate ICRF heating in a large D-T tokamak.
- Provide a facility to demonstrate current drive as an approach to steady-state tokamak operation.

The overall objective of the TFET program would require operation with pulse lengths that are significantly longer than the 1.6 sec for the full-field (5 T) baseline for TFTR discharges. Due to the thermal limitation of the coils and the stored energy limitation of the two motor generators, the toroidal field and associated plasma current would need to be decreased appropriately for increasing pulse length. Two pulse lengths would be featured as part of the TFET program. Six-second pulses would be used to study high-power rf

heating and its effect on limiter operation, while producing high neutron fluxes for nuclear studies. These discharges would be characterized by toroidal fields of 4 T, plasma currents of about 2.5 MA, and plasma betas of 2.5-4.0%. In addition to the 6-sec pulse lengths, 20-to 30-sec pulses would be used to study rf and neutral-beam current drive at reduced field and plasma current. Because of the implicit reduction in volt-seconds associated with the current-drive experiments, an increase in ohmic-heating capability would not be required to realize these very long discharges. Long-pulse operation could be used to demonstrate the ability to provide particle and energy control with a large-area pumped limiter, and a vacuum vessel with efficient heat removal capability. The 30-sec discharges would be characterized by toroidal fields of 2.0-2.5 T, plasma currents exceeding 1 MA, and betas of 2.5-4.0% (limited by the MHD stability of these discharges). The parameters for the 6-sec and 30-sec pulses are summarized in Table X. A pictorial representation of the possible ranges of plasma currents and pulse lengths is shown in Fig. 86.

Table X. TFET Parameters.

Parameter	Moderate Pulse	Long Pulse
Pulse length (sec)	6	30
Major radius (m)	2.61	2.61
Minor radius (m)	0.85	0.85
Toroidal Field (T)	4	2.2
Plasma current (MA)	2.5	1-1.4
Limiter q	2.4	3.3-2.4
Average beta (%)	2.5-4.0	>2.5
Auxiliary heating required (MW)	40	20
Heating available* (MW)		
ICRF	30	30
Fast Wave Current Drive	10	10
Neutral Injection	10	10
LHRH Current Drive	5	5
Thermonuclear energy (MJ)	100-200	75-150
Neutron wall loading (MW/m ²)	0.2-0.4	0.25-0.05
Limiter load (MW/m ²)	2	1

*All the heating power would not be available simultaneously. The fast wave current drive, neutral injection, and lower hybrid resonant heating (LHRH) current drive would share dc power supplies and therefore could not be used simultaneously.

Figure 86. Ranges of plasma currents and pulse lengths for TFET. (82P0170)

Because reliable operation with D-T mixtures would be a large part of the TFET research program, remote-handling considerations would play a major role throughout the project. Remote-handling techniques would be used for all operations following installation of components, and the program would emphasize efficient remote handling of components that are most likely to need replacement.

The high-current (2.5 MA, 6 sec) discharges would produce between 100-200 MJ of thermonuclear energy per pulse, at a wall loading between 0.2-0.4 MW/m², when operated with an optimum D-T mixture. Up to four large-area nuclear test bays, with a minimum of vacuum vessel structure between the plasma and test modules, would be available for nuclear testing. The nuclear testing capability provided by the large test volume and high neutron flux would form an important part of the TFET program. A total of 40 MW of auxiliary heating would be provided for these discharges (30 MW of ICRF and 10 MW of neutral injection). The neutral-injection heating would be a long-pulse upgrade of the existing system.

A pumped limiter would absorb, at the power density of about 2 MW/m² (characteristic of the FED limiter), the approximately 30 MW of plasma heat flow to the edge. This toroidally symmetric pumped limiter would also be used to control the density and to remove the helium ash. Due to the high temperatures and long pulses, macroscopic sputtering, erosion, and redeposition of limiter and first-wall materials would be encountered for the first time in the fusion program. Materials test areas would be provided to study this important phenomenon.

Forty megawatts of heating power would be available for heating the 30-sec pulses; however, 20 MW would probably be sufficient to reach the beta limit at the reduced field for these pulse lengths. Plasma heating would be provided either by a combination of 10 MW or more of ICRF and 10 MW of fast-wave current drive, or by a combination of 10 MW or more of ICRF and 10 MW of neutral-injection current drive.

A low-power (5 MW) lower hybrid resonant heating (LHRH) system would provide current initiation and ramp up to the 1-MA level. The 5 MW of LHRH would be sufficient if the plasma density is maintained at 5×10^{12} cm⁻³ during the current ramp up, with about 10 sec allowed for the current-rise phase. The ohmic-heating system would be available to produce more rapid rates of plasma-current increase. As a result of the lower toroidal field and associated plasma pressure characteristic of the 30-sec pulses, they would have much lower neutron flux and somewhat lower neutron fluence than the 6-sec pulses.

A new type of vacuum vessel would be required to accommodate the high-power, long-pulse heat and particle removal systems, the high-power heating apparatus, and the nuclear testing. On the basis of experience with the operation of large tokamaks gained since the time of the original TFTR design phase, the vacuum vessel resistance would be made much lower than that of the present vessel. This would simplify the design of the vessel by eliminating the bellows sections,

and it would facilitate the pumped-limiter design, the remote handling, and the heating system interfaces. The associated low-voltage startup technique would provide direct experience in this type of operation for the FED, which was designed with a low-resistance vacuum vessel.

There would be about 10,000 TFET pulses per year. Approximately 1500 of these pulses would be with full-power neutron production.

FED-R—A FUSION ENGINEERING DEVICE UTILIZING RESISTIVE MAGNETS

A preliminary conceptual design of the FED-R device was carried out in FY82 by the Fusion Engineering Design Center (FEDC), under the design direction of PPPL. The mission of the FED-R tokamak facility is to provide a substantial quasi-steady flux of fusion neutrons irradiating a large test area in order to carry out thermal, neutronic, and radiation effects testing of experimental blanket assemblies having a variety of configurations, compositions, and purposes.

The emphasis on reliable nuclear testing capability demands that the plasma physics characteristics and technological features of the fusion machine be chosen as close as possible to mid-1980s state-of-the-art. Hence the specified plasma parameters for initial (Stage I) operation are selected to be near those expected in TFTR or D-III Upgrade, with the important exception that FED-R demands high-duty-factor operation using a single-null poloidal divertor for particle control and heat removal. Neutral-beam injection is to be used for plasma heating and current drive in the steady state, as well as for partial fueling and for enhancing fusion neutron production.

The plasma has major and minor radii of 3.5 m and 0.85 m, respectively, with a vertical elongation of 1.5 m. The nuclear test region is located on the outboard side of the plasma, and it is 80-cm deep with approximately 70 m² of exposure area (see Fig. 87). To ensure maximum flexibility and reactor availability, the test region is located outside the vacuum boundary. The outboard vacuum boundary is a stainless steel double wall with 20-atmospheres helium coolant. This wall allows more than 80% transmission of 14-MeV neutrons, with adequate heat removal and acceptable stresses caused by the atmospheric pressure load, and accepts a steady non-nuclear thermal load up to 60 W/cm².

The toroidal-field coils are fabricated of water-cooled copper plates insulated with magnesium aluminate, and they are sufficiently massive so that they can be operated steady state with a power dissipation of 180 MW in Stage I (0.4 MW/m² at $Q_p = 1.5$) or 280 MW in a Stage II upgrade (1.3 MW/m² at $Q_p = 2.5$). The toroidal-field coils have demountable joints to facilitate maintenance access to all the in-bore components, and to allow installation of outsized nuclear assemblies. The demountable joints also permit an option for the Stage II

Figure 87. Elevation view of the FED-R. (83P0535)

upgrade wherein the coil bore is enlarged for installation of a new vacuum vessel with nearly complete blanket coverage to serve as a full-scale engineering test reactor.

The total electrical power consumption of the FED-R facility is approximately 425 MW in Stage I and 600 MW in Stage II. The total direct cost for Stage I is estimated to be \$810 million (1982), and an additional \$220 million of direct cost is estimated for Stage II upgrade with the same toroidal-field coil bore.

Reference

D.L. Jessby and S.S. Kalsi, editors, "FED-R, A Fusion Engineering Device Utilizing Resistive Magnets," Oak Ridge National Laboratory Fusion Engineering Design Center Report ORNL/FEDC-82/1 (April 1983).

Advanced Project Design and Analysis

The Advanced Projects Design and Analysis Division (APDAD) supports the Laboratory's physics program and the national fusion effort by providing planning and evaluation of new and upgraded experiments, conceptual and preliminary design services, and systems integration services. In addition, APDAD develops and maintains computer programs for design and analysis, and performs engineering and scientific analyses in specialized areas of technology, such as radiation, solid and fluid mechanics, heat transfer, vacuum and cryogenics, superconductivity, and magnetics and coil design.

The Division consists of an administrative unit and five technical branches; the latter are further divided into sections according to specialty.

MAJOR ACTIVITIES

Analysis Branch

The Analysis Branch carries out specialized analysis activities critical to the development of the fusion program. The staff utilizes advanced equipment and a library of state-of-the-art computer programs. Three principal specialties are identified: magnetic field analysis and design, radiation and nucleonics analysis, and finite element analysis.

TFTR Eddy Current Analysis

Eddy current analysis continues to be a major effort in magnetic studies at PPPL. In TFTR and other fusion devices, both normal operation of the coil systems and plasma disruptions can induce large electrical eddy currents in the surrounding metallic components. These eddy currents create undesirable parasitic fields and also interact with the background fields to produce significant mechanical forces.

A major goal of the work in this area has been the development of a highly automated, general geometry computer program called SPARK. In addition to calculating transient eddy currents and their resulting fields, SPARK produces mechanical loads in a form compatible with existing structural analysis programs, such as NASTRAN. This feature enables efficient interfacing of the eddy current and mechanical analyses.

A preliminary version of SPARK was used to analyze several designs of the TFTR internal vacuum vessel hardware, including limiters and protective plates. Figure 88 illustrates some SPARK results; this figure shows the streamlines of the eddy currents in a

Figure 88. Streamlines of the eddy currents in a protective plate showing changes in time as a plasma disruption occurs. (83E0010)

protective plate changing in time as a plasma disruption occurs.

An overall model was developed for analyzing the combined effect of the principal eddy currents that arise during normal TFTR operation. This model consists of axisymmetric coils (representing all the coil systems), the vacuum vessel, and the major support structures. The boundary constraints of the model are adjusted to compensate for noncontinuous elements, such as the toroidal-field coils. Both transient and steady-state ac responses were investigated using this model.

During the year APDAD was host to a visiting fellow from the Max-Planck Institute für Plasmaphysik, Garching, Federal Republic of Germany. He developed a separate computer code for eddy current calculation on the NMFEECC (National Magnetic Fusion Energy Computer Center) Cray, which was used to analyze the effect of the TFTR toroidal-field coil system in more depth.

Magnetic Design for Heliac

The proposed Heliac device is a modular stellarator with circular coils, rather than with helical windings, placed along a helical axis. To aid in designing an optimum magnetic configuration, a computer simulation was written to model the coils and calculate the vacuum magnetic field attributes such as rotational transform, magnetic well depth, and location of the magnetic surfaces. The simulation program was then used to optimize the design in several ways. Figure 85

Figure 89. Calculated Helic magnetic surfaces at different positions within one field period along the axis. (82E0166)

shows the Helic geometry, and Figure 89 shows magnetic surfaces calculated for Helic at different positions along the axis for one optimum design.

Radiation and Nucleonics Analysis

The major projects that the radiation analysis group worked on during FY82 included the development and compilation of material activation data for TFTR, a review of the meteorological monitoring program for TFTR, investigations of fundamental aspects of fusion neutron transport, and the establishment of a consistent radiation analysis system on the MFEC computer. The group also provided a wide range of radiation data and analyses for various projects and programs in the Laboratory.

Work for the development of the activation data for TFTR included calculations of the decay profile for a set of isolated baseline materials and the derivation of factors which can be used to adjust the data for any pulsing history and material thickness.^{1,2} Methods and examples of interpolating the data for different materials were also determined. To incorporate the non-symmetric large components around the machine, a two-dimensional scalar flux remeshing scheme was developed and applications of this approach to include the vacuum pumping duct in the background calculation were developed.³

In studying the fundamental aspects of fusion neutron transport, two major tasks were accomplished. With the investigation of deuterium-deuterium (D-D) fusion neutrons penetrating through a thick layer of concrete

lead, it was concluded that the correct representation of the cross section near the oxygen 2.3-MeV anti-resonance in the multigroup calculation is one of the most important factors that needs to be considered.^{4,5} The applicability of the concept of the removal cross section for 14-MeV neutrons was investigated.⁶ Removal cross sections were generated and tabulated, and the systematics of these cross sections with respect to the atomic numbers were derived. These data provide a designer with an adjustable parameter for making an initial assessment of the shielding required to achieve design objectives.

Most of the PPPL radiation analysis software system, including multigroup cross sections and a wide variety of codes, was moved to the NMFECC, establishing the first consistent set of software packages for performing fusion neutronics analysis.

In the support of radiation analysis work at PPPL, tasks were performed for the conceptual designs of LITE and TFET (Tokamak Fusion Engineering Test) and in support of the mechanical designs for the penetration filter, the coil lead stem filler, and the diagnostic equipment shielding. Work was also performed for neutron diagnostics, such as the calibration of the fission detector system used for plasma time profile measurement.

Finite Element Analysis

The finite element method (FEM) was used to perform a dynamic simulation and analysis of the TFTR diagnostic support structure whose performance is very sensitive to vibration and motion.⁷ It was decided to improve the Tokamak Fusion Test Reactor Flexibility Modification (TFM) vacuum vessel finite element dynamic simulation so that behavior above 200 Hertz (see Fig. 90) could be predicted. This was necessary for the adequate mechanical design of diagnostic equipment which eventually would be attached to the vacuum vessel.

The design and analysis of the TFTR Phase II bumper limiter, which shields the vacuum vessel from plasma damage and is subjected to a number of dynamic loading conditions, was upgraded. Based on the results of the analysis, an adequate design of the structure's various components was determined. A detailed analysis of the TFTR toroidal-field coil lead stems was performed to ascertain the limits of the existing design and to suggest modifications that could be used for its optimization. An extensive FEM analysis, which surveyed a variety of machine configurations and supporting conditions for the Helic device, was also performed.

Other applications of the finite element method include an analysis of the TFTR vacuum pumping duct and the examination of the behavior of fusion coil bundles. Examination of the behavior of fusion coil bundles was performed in part by a visitor to APDAD from the Toshiba Corporation of Yokohama, Japan.

Figure 90. Finite element method (FEM) model of Sector C of the TFTR vacuum vessel.

Mechanical Branch

The Mechanical Branch covers a broad spectrum of mechanical engineering, with an emphasis on engineering mechanics and mechanical design. Applications include dynamic analysis, materials engineering, stress analysis, fracture mechanics, and analysis and design of vacuum vessels, structures, and magnetic coils.

During FY82 Mechanical Branch engineers were engaged principally in engineering support for the TFTR systems, including diagnostics, and for the S-1 Spheromak.

TFTR Diagnostics

Mechanical engineering support for TFTR Diagnostics was provided in several areas: (1) The detailed design of the MIRI support structure was completed and a major subcontract for its fabrication was awarded. (2) The designs for a diagnostics cooling water system and compressed air system were completed, and the components were installed. (3) A design for support of the vacuum vessel "organ pipes" (vertical diagnostics access tubes) was completed. (4) The detailed design of the Thomson scattering viewing dump was completed and its fabrication was initiated.

Spheromak Mechanical Systems

Design and engineering efforts for the mechanical subsystem of the S-1 Spheromak device continued throughout the year. Design and structural analysis were completed for the machine platform and structure. A mechanical analysis of the S-1 equilibrium field coils was performed, correctly predicting the laminated beam behavior.

Electrical Branch

The Electrical Branch provides capabilities in the planning, design, and electrical systems analysis of pulsed power systems, large motor generators, and rectifier systems and their control. During the year, work was primarily focused on the TFTR neutral-beam power supply and controls, the electrical energy systems for the S-1 Spheromak device, and the Fusion Engineering Device (FED).

TFTR Neutral-Beam Power Supply, Controls, and Instrumentation

Technical management was provided for a number of key TFTR subcontracts, including the system's standardized electrical connectors, cables, and vacuum feed-throughs. Significant cost savings and schedule improvements were achieved by system-wide standardization, generic specification, and single subcontract purchase.

Electrical Branch personnel provided technical management of subcontracts for the TFTR neutral-beam power supplies and for the high-voltage switch tubes. During the year, procurement of the decel power supplies was completed. In addition, engineering coordination was provided for construction of the power supply facility, and work was continued on installation and testing of the TFTR neutral-beam power supplies.

In the areas of TFTR neutral-beam instrumentation and control, project engineering was provided in a number of areas: cryogenic and water system control, system operational interlocking and fault analysis, personnel and equipment protection from induced voltage transients, sweep magnet instrumentation, and vacuum system control and instrumentation.

A computer program was developed to route cables, inventory by type, calculate container fill, and provide work aids. At present, the system accounts for twenty thousand wires.

TFTR Integrated Systems Tests

In anticipation of the TFTR first plasma, Electrical Branch engineers participated in the integrated systems testing effort for TFTR. This involved preparing test procedures, investigating protective features, and directing and participating in the engineering tests prior to the commissioning of the TFTR machine. In parallel, efforts in preparation for TFTR first plasma included the electrical design and implementation of the site radiation monitoring and site security systems.

Spheromak Device Electrical Energy Systems

Electrical Branch engineers contributed to the electrical design integration of the S-1 Spheromak device. Specifically, an integrated test plan was developed, a safety analysis report was initiated, and groundwork was started on an operating manual. Contributions were made to the continued design and supervision of ongoing construction. These efforts resulted in improvements in the schedule within budgeted costs.

Fusion Engineering Design Center

A member of the Electrical Branch provided electrical-function management for projects at the Fusion Engineering Design Center in Oak Ridge, Tennessee. This full-time assignment included responsibility for developing engineering design concepts for electrical power, controls, plasma diagnostics, plasma heating systems, and fuel injection. The projects considered were the International Tokamak Reactor (INTOR), FED-R, FED-A, Fusion Engineering Device (FED) Baseline, and Technology Development Facility (TDF).

In addition, calculations were performed and designs generated relative to torus electromagnetics. Concepts

that were investigated included a copper shell for FED-A to prevent or greatly reduce disruptions. For the other tokamak designs, configurations were selected to prevent the current decay disruption energy from doing damage to the torus and limiters. These studies led to the conceptual designs of long time-constant toruses. The resultant effects on startup and position control energy were calculated for the FED Baseline Project.

HX-1 Heliac

The electrical energy systems part of the Heliac proposal was prepared by members of the Electrical Branch of APDAD. The PLT and PDX power supplies were adapted for this proposed device, resulting in a projected cost savings.

Integration Branch

The Integration Branch is concerned with unification of the overall design of fusion devices, including considerations of assembly, remote handling, diagnostics, experimental access, and auxiliary systems. Represented technologies include diagnostics, vacuum pumping systems, vacuum seals, vacuum materials, and cryogenic systems.

Integration Branch staff contributed to the TFTR integrated systems testing effort,⁸ and in the engineering, design, and procurement of a number of major components of the TFTR neutral-beam system. Components included the pivot point bellows, the ceramic break and the absolute valve for the torus connecting duct, the ion sources and valves of the source neutralizer terminal, the water and gas systems of the auxiliary subsystems, and the 120-kV flexible transmission lines for the high-voltage power systems.

Drafting Branch

In addition to serving APDAD needs, the Drafting Services Branch of APDAD provides mechanical drafting services to other PPPL Divisions. The Branch also maintains the back-up tracing files for all of PPPL.

References

¹L. Ku and J. Kolibal, "Estimated Neutron Activation Data for TFTR, Part II, Biological Dose Rate from Sample Material Activation," Princeton University Plasma Physics Laboratory Report PPPL-1898 (June 1982) 60pp.

²L. Ku and J. Kolibal, "A Systematic Investigation of Material Activation on the TFTR," *Trans. Am. Nucl. Soc.* 41 (1982) 167.

³J. Kolibal and L. Ku, "A Two-Dimensional Scalar Flux Remeshing Technique for Tokamak Nucleonics," *Trans. Am. Nucl. Soc.* 41 (1982) 514.

⁴L. Ku and J. Kolibal, "Analysis of DD Fusion Neutron Transport in Thick Concrete," *J. Nucl. Tech./Fusion* 4 (1983) 69.

⁵L. Ku and J. Kolibal, "Transport of DD Fusion Neutrons in Thick Concrete," Princeton University Plasma Physics Laboratory Report PPPL-1914 (July 1982) 30pp.

⁶L. Ku and J. Kolibal, "Effective Dose Removal Cross Section of 14 MeV Neutrons," Princeton University Plasma Physics Laboratory Report PPPL-1970 (January 1983) 28pp.

⁷J. Zatz, L. Lontai, and S. Goldfarb, "Design and Analysis of a Stable Support Structure for TFTR Diagnostics," in *Proceedings of the Ninth IEEE Symposium on Engineering Problems of Fusion Research* (New York, N.Y., 1982) 1122.

⁸S. Goldfarb and C.O. Ward, "Preoperational Testing of TFTR Systems," in *Proceedings of the Twelfth Symposium on Fusion Technology*, (Jülich, Federal Republic of Germany, September 1982).

Engineering

The Engineering Division consists of over 150 engineers and technicians organized into three major branches, eight sections, two tech-service centers, an Administrative Office, Computer Aided Drafting and Design (CADD) Program, and Quality Assurance Program.

Two major reorganizations of the Engineering Division took place in FY82. The Radio-Frequency (rf) Section was reorganized into the Radio-Frequency Branch, with two sections: The Low-Frequency Section and the High-Frequency Section. The Low-Frequency Section is responsible for the design, construction, and operation of all high-power rf generators and transmission equipment operating at frequencies below 500 MHz, and the High-Frequency Section is responsible for equipment operating at frequencies of 500 MHz and above.

The second reorganization took place late in the fiscal year with the creation of a new branch, the Systems Branch. This branch is responsible for large diagnostic systems and their design and construction. The third branch of the Engineering Division, the Diagnostics Branch, is responsible for machine diagnostics with special emphasis on electro-optics, controls, and electronic systems.

CADD PROGRAM

Specifications for a Computer Aided Design and Drafting System (CADD) were determined during FY82. This system will be used to assist in the design, development, and fabrication of new diagnostics and will provide for their integration into existing PPPL fusion devices. The system will be purchased in conjunction with four other fusion laboratories: Lawrence Livermore National Laboratory (LLNL), GA Technologies Inc. (GA), Los Alamos National Laboratory (LLNL), and Oak Ridge National Laboratory (ORNL). Compatible systems for each site will be procured to allow for the easy exchange of design data and to facilitate the use of existing large-scale computing resources for complex analysis calculations. This is in recognition that 1) current design features of individual laboratory programs will be incorporated into future machines, and 2) future fusion devices will be so large that they will require extensive cooperation among laboratories. Upward compatibility of successive generations of computer hardware and software will be of equal importance.

The system will be used initially for electrical and mechanical engineering drafting and design. These

capabilities will be applied to all projects in the Engineering, APDAD, and FOM Divisions. Initial areas of work will include TFTR diagnostics, TFTR neutral beams, TFTR power systems, and S-1 Spheromak diagnostics. Future applications will include piping, facilities design and management, and numerical control.

Mechanical engineering requirements consist of engineering mechanics, mechanical design, and mechanical drafting services. The technical specialties represented cover the mechanical design aspects for fusion devices, including support structure, coils, vacuum vessel, and materials. The electrical engineering requirements include the full spectrum of electrical design, analysis, drafting, and product fabrication.

QUALITY ASSURANCE PROGRAM

The Quality Assurance Program was involved in a number of efforts designed to improve the quality of equipment fabricated by the Engineering Division. Areas included in this program were workmanship standards, establishment of National Bureau of Standards (NBS) traceability in the calibration of test equipment, and on-site inspection of electronic hardware.

A major ongoing effort was the establishment of a Preferred Parts List for the Engineering Division. Inasmuch as the Engineering Division output is mainly diagnostic systems involving electronic hardware, electronic components were the first to be researched and for which a list was compiled. In order to cover effectively the broad spectrum of components used, a committee composed of Engineering Division representatives, CICADA group representatives, and the PPPL stockroom management was formed. The purpose of this committee was to research and submit information on preassigned component categories in order to establish a specific level of reliability for the subject components and to determine from which manufacturers these components should be purchased. These efforts will provide for improvements in the standardization of parts and in cost-effective savings. These savings will be realized through improved diagnostic reliability and lower maintenance, reduced component inventory and lower inventory carrying costs, and improved ability to determine usage and therefore better economy in component purchases.

On September 14, 1982, the first edition of the Engineering Division Preferred Parts List was released.

In coming months, additional electronic components will be added to the list, and a procedure to revise and update the list will be established. The Preferred Parts List will become an increasingly important tool in the procurement of quality parts as quality procurement procedures are implemented.

ELECTRONICS SECTION

A Diagnostic Vacuum Controller (DVC), Fig. 91, was designed for use with the TFTR vacuum diagnostic systems. Each DVC provides control and monitoring of the pumps, valves, and gauges associated with each diagnostic vacuum system. All pump and valve sequencing and protection features are provided by the controller. The DVC is a microcomputer-based unit that is extremely flexible and may easily be configured for variations in the vacuum systems. Control may be from the front panel or via the CICADA system.

Figure 91. Diagnostic Vacuum Controller (DVC) for use with TFTR vacuum diagnostic systems. (B3E0524)

The precise determination in real time of the plasma position within the TFTR vacuum vessel is achieved through the B-theta Electronics System which was designed and partially fabricated in FY82. Twenty-six coil pairs, which are spaced equally around the minor circumference of the vacuum vessel, are used to sense the current which flows in the plasma. Errors due to vacuum vessel eddy currents and to other undesired couplings are electronically compensated. A separate function of the B-theta Electronics System is to detect and measure expected distortions of the plasma shape.

Carbon-glass resistors (CGRs) are used on the TFTR neutral-beam cryopanel to measure the temperature of the panels. A system to measure the resistance of the carbon glass resistors was designed and constructed. Each CGR electronics unit has the capability of operating with up to 30 CGFs, and each provides outputs to both the CICADA system and the local readout which is located in the electronics unit. The resistance is measured by injecting a known 100 Hz ac current into the CGR and measuring the voltage drop across the device. There are two current ranges

which can be used, depending on the value of the CGR resistance. The range switching is done automatically to provide increased dynamic range for the system. An ac measurement is used since it greatly reduces the drift and offset errors that were a problem on previous designs.

The Laser Interferometer System on PDX was modified to provide a real-time analog output signal. A feedback controller was constructed which uses this signal to regulate the gas pressure in PDX during a pulse. The Laser Interferometer System has two signal outputs. One signal comes from a Far-Infrared Interferometer (FIR) which responds to plasma density plus vibration, and the other comes from a Visible Interferometer (VIS) which responds to vibration only. Subtracting the VIS signal from the FIR signal yields the plasma density. During FY82, the VIS phase comparator, operating at 40 MHz, was modified to provide a direct real-time analog signal with an expanded range to prevent foldover during a shot. The FIR phase comparator, operating on a 1-MHz signal, was modified in the same way.

A Langmuir Probe Controller for use on PLT was also designed and constructed. This unit controls the voltage and polarity of an external power supply and transmits probe voltage of ± 100 volts and currents ± 2 amps, while maintaining electrical isolation of the probe from the power source and output lines. The current sensitivity is 20 mA, 200 mA, or 2 A full scale, and the output signal rise time is less than 10 microseconds.

ELECTRO-OPTICS SECTION

The first of three periscopes for viewing the TFTR plasma and vacuum vessel interior was installed and used along with a 100 by 100 pixel, 400 frame-per-second solid state TV camera to record the first plasma in TFTR. The periscope was also used with a 35 mm film camera to photograph the vessel interior and plasma. The two remaining periscopes will be installed in early FY83.

Another major subsystem of the TFTR Plasma TV System which was designed and fabricated during FY82 is VDAS, Video Data Acquisition System. Its one megabyte memory captures the digitized video at rapid frame rates, and it converts the video signal to standard 60 field-per-second TV rates so that the signal can be displayed on the CICADA closed circuit TV network. Figure 92 is a photograph of a TV monitor displaying the TFTR First Plasma. The video data can also be recorded on analog video cassette recorders.

An Infrared TV System employing a Schottky-Barrier type Infrared Charge-Coupled Device (IR-CCD) is under development and will be installed on one of the periscopes in the spring of 1983. This digital television camera will be used primarily to measure the temperature of various areas within the TFTR vacuum vessel.

Work on the TFTR Bolometer System has continued with emphasis on calibration of the thin platinum foil detectors and on the fabrication of bolometric arrays for

Figure 92. TV monitor displaying TFTR first plasma. (83X2010)

"Day 1" plasma. A 20-channel set of bolometer electronics was provided to the Lawrence Livermore National Laboratory for use in their magnetic mirror fusion program.

The Intensified Charge-Coupled Device (ICCD) camera systems for the TFTR Thomson Scattering diagnostic were completed, and a number of auxiliary electronic subsystems for control and telemetry of the overall instrument were designed.

CONTROLS SECTION

The Controls Section was almost totally involved with the specification, design, and construction of the man-machine interface and system controls for the S-1 Spheromak device during FY82. This work included design and construction of all controls for the three major power systems, the poloidal- and toroidal-field coil capacitor banks with their associated ignitron switching circuits and charging power supplies, and the equilibrium-field coil motor generators. Many subsystem controls were also included in this work: the personnel and equipment safety subsystem; the sequence timer system; the operator display subsystem (Fig. 93); the water flow and temperature monitoring system; the vacuum controller; and the control room facility design and construction.

The computer system and related CAMAC modules (I/O ports, display drivers, transient digitizers, and watchdog timers) were purchased in June 1982. A Digital Equipment Corporation LSI-11/13 micro/mini-computer was chosen because of its greater speed compared to the 8-bit CAMAC-based microcomputers initially under consideration, and because the RSX-11 operating system and PDP-11 type architecture computer are in wide use throughout PPPL. The computer was supplied by Kinetic Systems and was fully integrated with CAMAC. It includes 256K bytes of memory, hardware floating-point option, and a 30M byte Winchester hard disk with a 1M byte floppy disk backup. The real-time multiuser operating system allows

Figure 93. S-1 Spheromak operator console. (83E0473)

several engineers to develop software simultaneously and provides a fast real-time control environment. When in operation, the S-1 Spheromak device requires the continuous scan of over 300 digital points, over 32 analog signals at a rate of five times per second, and servicing of many lower priority tasks. These tasks include operator inputs via a CAMAC-based touch panel and standard Qwerty keyboard, the simultaneous display of five system-display pages, and the calculation and display of 12-coil current waveforms using an available Fortran plot package.

The noncomputer hardware for S-1 includes six remotely located CAMAC crates, a fiber-optic 5-MHz

serial highway, a 1-MHz serial clock highway and timer system based on the TFTR CAMAC timer modules, six remotely located relay panels containing over 100 standard and time-delay relays, a closed circuit TV system, a Kirk key and door interlock personnel safety access system, a complete "hardwire" backup system for equipment and personnel safety, a standard station class protective relay system including 1 $\frac{1}{2}$ instantaneous overcurrent and undervoltage relays, and an Instrumentation Section designed four-channel active ground loop monitor. Of special interest is the vacuum controller based on the Intel 8749 single chip microcomputer. Designed and built by the Electronics Section, these units provide all fail-safe control and monitoring, with battery backup, for the S-1 device vacuum systems.

At the end of FY82 approximately 75% of all hardware has been designed and installed. A version of the real-time scan software was running, and initial time measurements showed that a 200-msec scan was possible. If several of the Fortran display routines are recoded in the Macro assembly language (when time and manpower become available), the scan time could be reduced to as low as 100 msec.

INSTRUMENTATION SECTION

A milestone accomplished by the Instrumentation Section in FY82 was the completion and temporary installation in PLT of a 1-mm Double Pass Interferometer (Fig. 94) for an extensive testing program. The system performed successfully with varied plasma conditions and was then permanently installed, as originally intended, in TFTR as a first plasma diagnostic.

This instrument is a TFTR primary control diagnostic that provides (a) line-averaged electron density measurements of densities up to $2 \times 10^{14} \text{ cm}^{-3}$, (b) a permissive signal for control of neutral-beam firing, and (c) an input signal for the gas feedback control system that regulates the electron density level.

The interferometer is designed to measure up to 500 fringes as the transmitted power level varies up to 50 dB during pulsed plasma conditions. Heterodyne detection was chosen because continuous wave operation of the transmitting source eliminates swept-frequency operation and its inherent amplitude modulation problems, and high intermediate-frequency operation is allowed, thus reducing noise sidebands in the mixer output. Second harmonic mixing was adopted to avoid the added expense and complexity of a 1-mm local oscillator source.

Because of the high power losses at 200-325 GHz of WR-3 waveguide components, quasi-optical components were preferred. Since these components are not available commercially, many were built—power splitters, diplexers, E and H bends, a phase shifter, and a mode suppressor.

In heterodyne receiving systems the local oscillator is usually locked to the transmitter by an automatic frequency control (AFC) circuit. It has been found that electromagnetic interference from sources associated

Figure 94. One millimeter interferometer oscillator and radio-frequency racks. (82E1129)

with tokamak operation makes AFC locking unreliable. To overcome this difficulty a broadband super-heterodyne tracking circuit was developed.

To calibrate the system, a fringe simulator was provided to generate programmable intermediate-frequency phase changes up to 1024π radians. The interferometer is designed to be controlled automatically and to be monitored through the CICADA system.

Another major accomplishment for FY82 was the construction of two waveguide runs which allow launching of 200-kW microwave power from the inner wall region of the tokamak. These waveguide runs were part of the Electron Cyclotron Resonance 60-GHz Microwave Heating Program (ECRH heating) on PDX.

These waveguide runs (Fig. 95) were fabricated of precision-honed, corrugated copper-plate, 2.5-inch inner-diameter steel tube. The waveguide was corrugated to allow launching of the HE_{11} mode microwaves. Each run was terminated near the inner tokamak wall by a water-cooled beryllium oxide vacuum window and followed by two mirrors for launching microwave power in the desired direction inside the tokamak. The waveguides had to be electrically isolated from PDX by ceramic voltage breaks and to be shock isolated by bellows. Since the inside of the waveguide was gas-filled (to allow microwave penetration through the cyclotron resonance absorption region of the tokamak) and the window

Figure 95. Electron Cyclotron Range of Frequencies in-torus launcher. (82X2374)

water-cooling lines ran inside the machine, ultrahigh vacuum integrity of the waveguide runs was mandatory.

MECHANICAL ENGINEERING SECTION

The Mechanical Engineering Section provides conceptual and final design, fabrication, and project engineering support of diagnostics for use on the TFTR, PLT, PDX, and S-1 Spheromak. During FY82, major diagnostics projects were completed for use on TFTR. Among those projects was the first of two X-Ray Imaging Systems (XIS) (Fig. 96). The integration of XIS into TFTR is scheduled to begin in the spring of 1983.

The XIS is a "Day 1" diagnostic which will be used to measure line-integrated soft X-ray emission intensity from different chords of the plasma. These data will provide information about plasma position, magneto-hydrodynamic activity, disruptions, and confinement conditions. The plasma emission is viewed through a narrow slot aperture and an array of X-ray detectors. This equipment is essentially a one-dimensional, slot-hole, imaging camera analogous to the historic "pinhole" photographic camera. Each of the 76 silicon surface barrier detectors measures chord-integrated and wavelength-integrated X-ray emission along a narrow ray bundle emitted from a chord of the plasma

Figure 96. X-ray imaging assembly (top) and lower housing (bottom); they form the major mechanical structure of the X-Ray Imaging System (XIS). (83E0404)

minor radius. The typical energy range of interest falls in the 0.5 to 20 keV region.

The imaging subassembly of the XIS can be seen in the top portion of Fig. 96. Two rows of 38 detectors are evenly staggered to allow fine or coarse resolution. Remotely positionable attenuator foils directly in front of the detectors allow resolution selection. To obtain fine resolution all 76 detectors will use the same thickness attenuator foil. Coarse resolution may be obtained by allowing one row of 38 detectors to have different thickness foils from the other row. The lower chamber shown in the same photo completes the structural and ultrahigh vacuum chamber in which the detectors operate. The midsection (not shown) contains the slot aperture. Internal baffles prevent cross talk between adjacent detector rows.

A second major X-ray diagnostic fabricated in FY82 was the TFTR Pulse Height Analysis System (PHA). This system will be used initially in the horizontal mode to measure plasma soft X-ray emission in the 1 to 60 keV region and will provide a measure of electron temperature and high-*z* impurity concentrations.

Design and fabrication of the Horizontal Charge-Exchange System and 19-Channel Bolometer Array for use on TFTR was completed. The Horizontal Charge-Exchange System will measure the ion energy in the plasma and will be able to distinguish between atoms of hydrogen, deuterium, and tritium; the Bolometer Array

System will measure TFTR plasma temperatures. In addition, a TV Thomson Scattering System with 76 special recording stations was designed during FY82.

The Mechanical Engineering Section also produced the 15 horizontal TFTR equatorial cover plates that connect the diagnostics to the TFTR Torus. Shutter and pneumatic shutter actuator mechanisms were provided on cover plates for spectroscopy and plasma TV windows.

RADIO-FREQUENCY BRANCH

Low-Frequency Section

The 25-MHz ICRF (Ion Cyclotron Range of Frequencies) System was regularly operated at a power level of 1.5 MW into PLT for the first half of the year. This system was then modified to shift frequency to 30 MHz. The modification was completed and successfully tested into a dummy load at a 2-MW power level.

The 42-MHz ICRF System has been operating routinely throughout the year. This system achieved a power output of 4.0 MW into a dummy load and 3.1 MW into the PLT machine at pulse widths up to 300 msec. The 42-MHz System has also been used to support tests on the recently completed PLT tests.

The Low-Frequency Section will design and construct an 80-MHz amplifier chain that will supply 2 MW for hydrogen second harmonic heating and fast-wave current drive experiments on PLT. Figure 97 shows the 300-kW cavity amplifier driver stage which is under construction. A 30-kW driver stage has been installed and tested; control, supply, and modulation equipment is nearing completion. This equipment, in conjunction with an existing high-voltage, high-power supply, will support the cavity amplifier. Two high-power final amplifier stages were acquired from Continental Electronics Manufacturing Company for use in this program. These will be installed and integrated with the 30-kW and 300-kW driver stages to provide the final 2-MW output power.

The Low-Frequency Section of the Radio-Frequency Branch has been doing advanced development engineering on several rf coupling techniques in preparation for TFTR and other advanced applications. High-voltage bushing development is continuing in the section, and prototype testing is expected next year.

Investigations have been started on the application of dielectrically loaded waveguides as plasma couplers at frequencies as low as 90 MHz. These studies will continue, in preparation for fast-wave current drive experiments on PLT and TFTR, with the development of practical transitions, vacuum windows, and suitable high-power fabrication and bonding techniques.

High-Frequency Section

Work continued on the ECRH System, which will provide two 200-kW channels at 60 GHz for operation into PDX. The rated pulse width is 100 msec at one pulse per minute. The equipment procured from Continental Electronics Manufacturing Company (gyro-

Figure 97. The 90-MHz 300-kW cavity amplifier for PLT. (83E0311)

tron tanks, modulator-regulator, capacitor bank, crowbar, and control and fault sensing circuits) was delivered in early August 1982, is now installed, and will be tested in FY83. Figure 98 is a photograph of the modulator-regulator. One gyrotron and one magnetron were received in September 1982, and these will be tested after checkout of the Continental equipment. The second gyrotron was completed by Varian but failed because of output window arcing during testing at Varian. It is being rebuilt, and delivery is expected early

*Figure 98. The 80-kV modulator regulator assembly.
(82E1074)*

next fiscal year. Operation of this system into PDX is expected by January 1983.

Authorization was received in June 1982 for construction of a 0.5-MW, 2.45-GHz system to be used for current-drive experiments on PLT, and additional authorization was received in September to expand the system to 1.5 MW. Initial operation will share the high-voltage power supply and modulator procured for ECRH. Later options, not yet authorized, may allow a new modulator/HVPS (High Voltage Power Supply) dedicated to the 2.45-GHz System and two additional 0.5-MW stages. At the end of this fiscal year, the first Varian 0.5-MW klystron was on order, and other long-lead parts were in various stages of the procurement cycle. The first channel (0.5 MW) of this system is scheduled for initial operation in September 1983.

The 800-MHz System continues to operate routinely in support of PLT lower hybrid and current-drive experiments. In July 1982, high-power circulators were ordered for the 800-MHz klystrons. Receipt and installation of these circulators will enable substantial operation power (50 to 60 kW in each of the six channels) at long-pulse widths up to ten seconds. The circulators are due in May 1983.

Fabrication, Operations, and Maintenance

The Fabrication, Operations, and Maintenance (FOM) Division provides the services indicated in its name. The Division presently consists of five branches, one independent section, a quality control function, and a special projects group. The Division's major efforts and activities during FY82 were for the TFTR while the needs of the remaining research programs were met as required.

The five branches of the FOM Division are Administrative, Coil Systems, Energy Systems, Installation and Maintenance, Vacuum and Cryogenic Systems. The Engineering Services Section reports directly to the Division Head and provides skilled technicians who work, on request, for the various branches and other groups at PPPL.

The Quality Control Group provides inspection and control functions for all designated activities in FOM. The major effort of this group in FY82 was in the fabrication of the TFTR large poloidal-field coils. More recently the Quality Control Group has become involved in the fabrication of the bellows cover assemblies and other components inside the TFTR vacuum vessel.

The Special Projects Group is available to FOM and others for technical support as requested. Major efforts this past year concerned studies on various aspects of the TFTR lead connections and toroidal-field (TF) coils, and a review and modification of the lifting fixtures required for the TFTR assembly. In addition, a study was made of the PDX coil leads and buswork that resulted in modifications to the support system. The Special Projects Group also provided support for the preoperational testing of the TFTR water cooling systems.

MAJOR ACTIVITIES

Coil Systems Branch

During FY82, the major activity involved completing the poloidal-field (PF) coils and bus required for the TFTR Program. The last three large PF coil stacks were cast, and all of the PF coils were delivered to the machine site (Figs. 99 and 100). All lead stems were attached to both the PPPL manufactured coils, as well as to those from the Brown Boveri Corporation (BBC), utilizing the special fixturing shown in Fig. 101. A series of electrical tests was performed on all the coils, both in the coil shop and at the machine site. In addition, Coil Systems engineers witnessed the assembly of the inner support structure (ISS), manufactured by the Rockwell International Corporation, and its associated coils from BBC. The assembly process is shown in Fig. 102, and

Figure 99. Poloidal-field Stack #9 on the coil shop transporter arriving at C-Site. (82E0683)

Figure 100. Poloidal-field Stack #9 on the transfer fixture entering the TFTR Test Cell Building. (82E0406)

the final placement of the ISS at the machine site is shown in Fig. 103. Coil Systems engineers together with the coil shop electrical test group supervised the

Figure 101. Poloidal-field Stack #4 with lead stem attachment fixture. (81E0860)

Figure 102. Partial assembly of the inner support structure (ISS) plus coils. (83E0349)

Figure 103. The inner support structure (ISS) assembly being placed—a 52,000 pound lift. (82E0562)

Figure 104. The toroidal-field coil flex lead stem assembly mounted in place on a toroidal-field coil. (82E0984)

delivery and on-site testing of the TF coils, manufactured by the Westinghouse Electric Corporation. Twenty special flexible bus sections were designed and fabricated for the TF coils. Each of these assemblies was custom made for a TF coil, permitting motion of the coil while relieving stress on the coil leads. Figure 104 shows one of these assemblies mounted on a TF coil.

The final fabrication and assembly of components for the S-1 Spheromak device were also completed. Figure 105 shows the details of the bus switching panel. The flux core with the inner support ring and the final potting with urethane are shown in Figs. 66 and 106. Partial machine assembly with the equilibrium-field (EF) coils in place is shown in Fig. 107.

Design efforts for the Helic Proposal were also accomplished. The proposed design would reuse the TF coils from the old Adiabatic Toroidal Compressor (ATC) device. The resulting configuration is shown in Fig. 85.

Figure 105. S-1 Spheromak switching panel. (82E1027)

Figure 106. S-1 Spheromak flux core during urethane casting. (82E1061)

Energy Systems Branch

The AC power Section continued a significant level of activity in testing various elements of the ac power and energy conversion systems for the TFTR. Alternating current power tests included control circuit functional checks, insulation tests, and protective relay tests for all of the 13.8-kV circuit breakers, feeders, and transformers supplying the TF, EF, ohmic heating (OH), and variable curvature (VC) systems required for TFTR first plasma. Energy conversion system tests included

Figure 107. Partial assembly of the S-1 Spheromak device with equilibrium-field coil shown in place. (82E0487)

control and insulation tests for the safety disconnect switches (SDS), continuity and insulation tests of the dc power leads between the SDS and power supplies, and control checkout of the hardwire control system. Preoperational tests related to Motor Generator No. 1 were completed, and manpower was provided to assist the General Electric Company in their efforts to complete installation and acceptance testing of the motor generator itself. In addition, technical liaison was provided for all activities related to the repair and installation of Motor Generator No. 2.

Conceptual design for the 138-kV switchyard modification was completed. This modification included the addition of a second 138-kV breaker and reconfiguration of the 138-kV and 4-kV system. This modification provides maximum power distribution flexibility thereby minimizing the possibility of a lengthy Laboratory power shutdown due to the failure of a single piece of equipment.

The AC Power Section was also involved in construction activities at TFTR. This included Title III inspection and supervision of 50 installation packages and 200 field change requests. In addition, a major design and drafting effort was undertaken to produce complete construction documentation and drawings, and to procure all construction materials for first-plasma diagnostics.

Support for a number of maintenance and upgrade tasks was also provided by the AC Power Section.

These included the upgrading of the operating mechanism of the main 138-kV oil circuit breaker, replacement of the leaking 138-kV cable potheads, and improvements in the emergency power generation and distribution system for the Laboratory. Parallel operation capability was added to the TFTR 2.6-MW diesel generator, permitting regular exercising of the diesel under load. With this capability, the entire Laboratory can be powered down without shutting down TFTR housepower, resulting in peak power shaving and other energy cost savings. The Section also contributed technical input to the energy conservation program and to the selection of a computer-aided drafting and design system (see Engineering). Assistance was provided in the start-up of a 1-kW helium refrigerator test stand and a transformer oil processing system was specified and procured.

The MG Operations Section became heavily involved with the TFTR program during FY82. The foremost activity centered on the generation of maintenance manuals for the TFTR apparatus, including the motor generator set, its CO₂ fire protection system, and the diesel emergency generator. The Section provided ongoing manpower support to the TFTR preoperational test program and contributed computer routines for plotting of shaft run-out and MG load simulations.

The Section operations staff continued to support the experimental operations of PLT/PDX involving the C-Stellarator MG Sets and the OH and EF power supplies. Load performance studies for the EF system of the S-1 Spheromak were completed, and the corresponding disconnects were installed. Several significant upgrades of MG-related instrumentation were accomplished. The staff continued to execute its responsibilities for the power dispatch function serving the entire Laboratory. Included in this were significant contributions to the Laboratory's energy management program.

The Section's maintenance staff will assume responsibility for the periodic maintenance of the TFTR equipment as it achieves operational status, in addition to the ongoing maintenance of C-Site equipment. A number of upgrade or corrective tasks were completed. These include the commissioning of a 50-kW propane generator, improvements to the controls of the C-Site V-12 diesel generator, and the installation of co-generation equipment on the TFTR diesel.

The Rectifier Section of the Branch continued to provide support for the PLT and PDX machines as well as for the Proto S-1C device. Five of the high-power rectifiers for the TFTR program were upgraded, tested, and made available for operation. The fault protection system of these rectifiers was completely redesigned in order to improve reliability and functional performance. Ten of these systems were produced and tested. An inductive dummy load was installed near the base of the machine for testing the rectifiers.

The TFTR EF compression/discharge cleaning systems, which include charge/discharge power supplies and capacitor banks, were made operational during the year. This required extensive modifications in

order to meet safety and reliability standards.

The power systems for the S-1 Spheromak were constructed and installed, including the capacitor circuits, the capacitor charge circuits, the switching circuits, and the cable system and the control circuit. This system includes two power supplies, each capable of providing 500,000 A from a 20-kV capacitor bank. The stored energy in each capacitor bank is 480 kJ. These units are being tested for proper operation.

The TFTR ground fault detection system has been upgraded and used for machine protection. The Halmar current monitors were calibrated and made operational along with the I²t coil protection system. The TFTR Kirk Key system was redesigned and installed in preparation for first-plasma operations. The Section assisted in the testing and conditioning of the cycloconverter, exciter, and liquid rheostat portions of the TFTR MG set. A power supply was designed for the surface pumping system. This unit was tested, and a total of four units have been built.

The Neutral-Beam Power Engineering Section continued to provide operation and maintenance support for the PLT and PDX neutral-beam systems. This included diagnostic neutral beams as well as the four heating beams for each tokamak. Main accelerating supplies for the heating beams were upgraded from 40 kV at 70 A to 50 kV at 100 A.

Detailed design and specification of the electrical power portion of the TFTR diagnostic neutral beam was completed. A final design review was held and procurement was initiated. The system will be ordered during FY83.

Figure 108. Ion source auxiliary power supply enclosure for the TFTR neutral-beam power supply. (82E0925)

Difficulties experienced by the vendor of the TFTR neutral-beam power supply systems brought about a descoping of the contract with the vendor. As a result, PPPL was required to complete the manufacture and test of three major subsystems. A facility was prepared, suitable tools and jigs were provided, and the manufacturing operation was started during the last six months of FY82. Part of this operation is shown in Fig. 108.

Delegated to the Section was the responsibility of preparing all necessary specifications and procedures for the subcontracting of the installation and wiring of the twelve heating neutral-beam power supply systems for TFTR. Work was started toward the end of FY82 and will continue through most of FY83.

The Section continued to support operation of the prototype TFTR neutral-beam power supply throughout FY82. Initially this effort required a relatively high level of resource commitment. This commitment has diminished substantially during the year as operation personnel have assumed this support.

Because the skills required for field coil power conversion and charge/discharge apparatus start-up are similar to those required for neutral-beam systems, several Section engineers were temporarily assigned to assist in achieving the TFTR first plasma.

Installation and Maintenance Branch

During FY82, the major effort of the Installation and Maintenance (I&M) Branch was support of the TFTR Program. The TFTR-related activities can be grouped into several broad categories including preoperational testing, radiation shielding, neutral-beam systems, vacuum vessel internal components, and structural instrumentation and testing.

Preoperational testing of the TFTR machine cooling water systems was completed. Six separate systems were involved; they included the field coil power conversion system, the vacuum and gas delivery systems, the field coil systems, and the neutral-beam ion dump and ion source systems. Testing was also completed on the makeup water demineralizer. The I&M Branch coordinated the installation of the mechanical systems in the Test Cell Basement, which included the cooling water distribution piping and the torus vacuum pumping system. Test procedures for the vacuum vessel heating and cooling system were also completed.

The engineering design of all of the radiation shielding components required for first plasma was completed during FY82. These components include the wall panels, the labyrinthian roof beams, the door beams, and the labyrinthian support structure. The installation procedures and tooling were also completed for the first-plasma shielding. The materials and methods for filling the TFTR columns and lintels were developed by the I&M Branch, which also supervised their installation. The fabrication and installation of the shielding structure in the Neutral-Beam Test Cell were completed in FY82. The design of this shielding featured precast posttensioned structural components.

The prototype neutral-beam transmission line connector was successfully tested. Two of the neutral-beam water systems were completed and tested and the other two systems were partially fabricated. The magnetic shielding for the neutral-beam sources was designed, and about 90% of the fabrication was completed. The duct components for the first neutral beamline were fabricated, and the SF₆ systems for the neutral beams were designed and the fabrication started.

Design and fabrication of the vacuum vessel preliminary limiter was completed during FY82. This system was designed to protect the vacuum vessel bellows. Installation of the preliminary limiter, shown in Fig. 109, will be completed prior to first plasma. Meanwhile, liaison continued on the movable limiter systems which are being fabricated at GA Technologies Inc. The movable limiter will be completed and installed in FY83. A position control system for the movable limiter, including stepping motors, power supplies, and controls, has already been delivered. In addition, PPPL took over the technical supervision of an outside contract for fabricating and testing of the limiter actuators. Work continues on the supporting systems for the movable limiter including cooling, fixturing, and C/CADA interface.

Figure 109. Installation of the TFTR preliminary limiter in the vacuum vessel. (B2E1120)

Fabrication of components for the vacuum vessel bellows cover assemblies is scheduled for March 1983. A development program has resulted in a specification for flame-spraying alumina on the ribs of the insulated rails. The design of an internal work platform for the vacuum vessel was completed. The platform will be used together with special installation fixtures to assemble the vacuum vessel bellows covers. Liaison continued with GA Technologies Inc. on the design of the vacuum vessel bumper limiter and protective plates.

During FY82, the Materials Testing Laboratory performed a total of 263 tasks for various groups at PPPL. Approximately 90% of the total task time involved TFTR associated projects. Major tasks for TFTR included the strain gauge instrumentation of the inner support structure (ISS), two TF coil cases, and eight

shear compression panels. Installation of the ISS instrumentation was performed during assembly of the ISS at the Brown Boveri Corporation, located in North Brunswick, New Jersey. Over 900 strain gauges were installed on TFTR components. Figure 110 shows the strain gauge installation on one of the TFTR TF coils. The Materials Testing Laboratory obtained the use of the old Printed Circuit Laboratory, which had previously been destroyed by fire. Renovations were completed, and the area is now fully utilized for strain gauge and data acquisition actuators.

Figure 110. Strain gauge installation on a TFTR toroidal-field coil. (82E0835)

The I&M Branch provided supervision and other services to assist in and expedite the final assembly of the TFTR machine, and its associated systems, during FY82. This effort will be continued into FY83.

Vacuum and Cryogenics Branch

The major efforts of the Vacuum and Cryogenics Branch during FY82 were the preparation and testing of the TFTR vacuum vessel segments; the repairing, assembly, and testing of the TFTR torus vacuum pump ducts; the completion of the acceptance tests for the 1-kW helium refrigerator system; the continuation of the assembly of the TFTR neutral-beam mechanical systems, and the completion of the S-1 Spheromak vacuum vessel and vacuum pumping system.

The first of ten TFTR vacuum vessel segments was received from the Chicago Bridge and Iron Company of Greenville, Pennsylvania, on November 13, 1981. It was the responsibility of the Branch to prepare the surface of the nozzles for metal gaskets, clean and assemble the metal gaskets and the cover plates to the nozzles as shown in Fig. 111, perform the vacuum leak checks, assist Ebasco Services Incorporated on the heating and cooling system, and ship the segment to the TFTR Test Cell. Figure 112 shows a neutral injection segment ready for the helium mass spectrometer leak check. The tenth segment was delivered to the test cell on September 13, 1982.

Early in June 1982 the Vacuum and Cryogenic Branch was requested to receive and check the TFTR

Figure 111. Assembly of the cover plate to the TFTR vacuum vessel nozzle. (82E0813)

Figure 112. TFTR neutral injection segment ready for leak check. (82E0810)

Figure 113. Torus vacuum pumping duct set-up on milling machine. (82E0688)

vacuum pumping ducts. Repairs were required on some of the flanges to correct for weld distortion. Figure 113 shows a duct elbow being positioned on a milling machine. The repaired sections of the "C" duct were then cleaned, assembled with the pumps and valves, leak-checked, and shipped to the Test Cell. In late August 1982, the Vacuum and Cryogenic Branch was asked to install a new bellows and finish the remaining work on the "R" duct for TFTR. The assembly and repairs were completed, and the "R" duct was delivered to the TFTR site in September 1982.

The 1-kW helium refrigeration system for the TFTR neutral beams was temporarily installed in the 1-H Building. This system was operated into a dummy-load to establish its refrigeration capacity at 4.5 °K and 3.8 °K. The system, shown in Fig. 114, was also operated into a 1500-gallon dewar to determine its liquification capacity which is 225 liters per hour.

Figure 114. The 1-kW helium refrigerator with 1500 gallon storage dewar. (82E1094)

Assembly of the TFTR neutral-beam mechanical systems continued. Several additions to the scope of the work were made. Figure 115 is a view of the neutral beamline showing the end of the system where the ion sources are attached. Beamline #2 was 70% complete at the end of FY82, and its cryosystem was used to test the 1-kW helium refrigerator.

The S-1 Spheromak vacuum vessel and pumping system was also completed during FY82. Figure 116 shows the assembly of the vacuum vessel, the vacuum pump line, and the EF coil system.

Figure 115. Neutral beamline #2 with ion-source ends exposed. (83E0427)

Figure 116. S-1 Spheromak assembly vacuum vessel and pump line. (82E1020)

Engineering Services Section

This Section provides tradesmen for all branches of FOM and for any group requesting experimental activities at PPPL. Trades available include carpenters, electricians, metal smiths, plumbers, welders, millwrights, and general technician service. As in the previous year, the majority of Engineering Services work was on TFTR projects; however, support of Research Department projects continued. The latter category included the installation and assembly of S-1 Spheromak components.

Planning and Resource Management

Several significant changes were made to the Projects Office in FY82. The administration of the Electron Cyclotron Resonant Heating (ECRH) Project for the PDX machine was shifted to the Radio-Frequency Branch of the Engineering Division and is reported there. The purview of the Projects Office was altered to cover several critical areas in planning and safety. To reflect this change in responsibility, the office has been renamed the Planning and Resource Management Office. The office has six primary responsibilities: Project Management Support, Automatic Data Processing Equipment Planning, Resource Planning, Project Management Systems, Project and Operational Safety, and Technology Transfer.

PROJECT MANAGEMENT SUPPORT

The office assists line personnel to assure that each project is set up in a uniform manner, with a management plan and organization suited to the project scope of work.

AUTOMATIC DATA PROCESSING EQUIPMENT PLANNING

Work was started on a coherent Automatic Data Processing Equipment (ADPE) planning strategy for the Laboratory. A long-range ADPE plan was prepared and several specialized plans for specific program areas were produced. The office served as the single point of contact for ADPE matters with the Department of Energy. All ADPE procurements were reviewed by the office to assure that they were consistent with overall planning.

RESOURCE PLANNING

A system was implemented for determining the anticipated work load on the technical labor force. This system enables management to compare the work load to the staff and to make adjustments to work load and staff so that a match is achieved. Data from the Field Task Proposals are used to produce this comparison for the current fiscal year, the next fiscal year, and the budget fiscal year.

PROJECT MANAGEMENT SYSTEMS

Work was started on a Laboratory-wide Project Management System (PMS). The PMS-IV system will be used to produce a full set of earned-value cost and schedule reports.

The office also assumed responsibility for the integrated schedule for activities leading up to the TFTR first plasma. At the end of the fiscal year, over 1000 tasks had been built into a logical network which was being used to highlight critical paths for management action. Concurrent with this effort, a rollover schedule was developed which enabled TFTR project management to eliminate interferences between construction activities.

PROJECT AND OPERATIONAL SAFETY

Early in the reporting period, the Laboratory shifted its policy of having safety activities concentrated in a central organization to a policy of having safety activities the responsibility of the line management action. In order to fulfill this responsibility, an organization was set up to work directly with project personnel. Heavy emphasis is placed on day-to-day interaction and close support of project personnel.

In addition, this office worked extensively with other elements of the Laboratory in developing a complete set of Health and Safety Directives which delineate the Laboratory's safety policies and procedures.

TECHNOLOGY TRANSFER

The Laboratory cooperated with the Office of Fusion Energy in establishing a data base of technical innovations which are being or have the potential of being used by other laboratories or industry.

Computer/Cicada Division

In FY82 the Computer/CICADA (Central Instrumentation, Control, and Data Acquisition) Division was formed by a merger of the Computer Division, which reported to the head of the Engineering Program, and the CICADA Section, which reported to the head of the TFTR Operations Division. The new division reports to the Head of the TFTR Project.

The primary purpose of this Division is to provide planning, operations, engineering, and programming support for PPPL's major computer systems. These systems are the TFTR CICADA System, the PLT, PDX and S-1 Data Acquisition System (DAS), the User Service Center (USC), and the VAX 11/780.

The Division is composed of a division office and four branches. The Division Office is responsible for administrative operations, quality assurance, and documentation. The Computer Operations Branch maintains and develops enhancements to computer operating systems and communications networks, and provides operational support and computer security for the major systems. The Hardware Engineering Branch coordinates TFTR control, instrumentation, and data acquisition hardware activities, PLT, PDX and S-1 data acquisition activities, and overall data communication activities. The CICADA System Software Branch provides CICADA user and device support, and the Software Applications Branch provides scientific programming support for TFTR, PLT, PDX, and S-1 data acquisition and data analysis.

TFTR SUPPORT

During FY82 several major milestones were reached by the TFTR Diagnostics Application Programming Section. These milestones took two forms: the development of management aids to help in software implementation, and the actual integration of diagnostic software with the CICADA system.

Management aids that were developed include a Software Quality Assurance Plan, a format for diagnostic functional specifications, a generalized design for diagnostic interfaces to CICADA, and a software package to provide a standard terminal-based user interface to the diagnostic software. Using these tools, software was designed, developed, and integrated with the CICADA system to support several prototype or preoperational diagnostics. Among these

were the Diagnostic Vacuum Controller, the Electron Beam, the Rogowski Loops, and the PLT X-Ray Imaging. Additionally, requirements analysis and design were completed to support diagnostics for TFTR first-plasma operations.

PLT/PDX/PROTO S-1C SUPPORT

During FY82, approximately 25 billion bytes of data were acquired by the DAS Computer System from over 20,000 PLT, 10,000 PDX, and 7,000 Proto S-1C plasma discharges. The amount of data taken per discharge steadily increased, and the capacity of the DAS computer system was saturated totally. (PLT averaged over one million bytes per shot, and PDX averaged close to two million bytes per shot.) In order to keep pace with these steadily increasing requirements for data acquisition and analysis, the DAS computer system was upgraded. Additional computer memory, more disk storage, and numerous operating system enhancements were added. This resulted in more data acquisition per plasma discharge and more real-time analysis capability.

USER SERVICE CENTER

The processing capacity of the USC more than doubled during the past fiscal year, with the installation of additional main memory and a faster central processing unit (CPU). Service to users was also improved with the installation of a 1500 line per minute impact printer. In addition, PPPL users of the National Magnetic Fusion Energy Computer Center (NMFECC) benefited from the installation of a Remote Users Service Station (RUSS). The RUSS is used for teletype traffic and for previewing plots and graphs before printing.

VAX 11/780

The VAX system, which is largely used for Transport Analysis Programs, was upgraded in FY82 when the latest version of the vendors operating system was installed, and a VAX version of MSC/NASTRAN was leased to assist PPPL engineers in doing stress analysis studies.

Administration

During FY82, a Laboratory-wide effort existed to reduce indirect expenses. Toward this end, the total staff in the Administration Department was reduced from 335 to 311 people. Similar efforts were made to reduce expenditures for materials, supplies, and services. The indirect cost reduction program was highly successful. Efforts were made to maintain the quality and level of support through improved management and improved operational procedures.

The total Laboratory staff showed a slight increase from 1209 to 1237 employees. The composition was as follows:

Faculty	2
Physicists	114
Engineers	253
Technicians	535
Other	333
Total	1237

PLANT MAINTENANCE AND ENGINEERING

The following is a summary of the more significant activities in which Plant Maintenance and Engineering were involved during FY82.

New Facilities

Turnover of the TFTR facilities to PPPL during 1982 and preparations for first plasma in December created substantial interaction between the Plant Maintenance and Engineering (PM&E) Division and other areas of the Laboratory. Operating within limited budget and manpower, PM&E supported the start-up of the TFTR facilities and also provided improved responsiveness to the rest of the Laboratory. A key factor that contributed to the improvement in responsiveness was the creation of the new position of Manager of Maintenance Control within the PM&E organization. This position allowed for greater professional attention to the planning of maintenance repairs and minor alterations. Another important factor was the completion of a 5,100 square-foot addition to the Maintenance Building at C-Site. This addition relieved the cramped conditions which had severely limited the effectiveness of the entire organization. The additional space provided for a newly expanded project engineering group and allowed for a much improved area for the maintenance control center with an adjoining staging area for materials. Several shops and offices were also relocated to allow for better coordination and supervision.

The new central chillers and boiler plant were given full load testing during FY82. Environmental control for TFTR, which requires around-the-clock dehumidification and steam reheat, was started in July, 1982.

Energy Conservation

In October 1982, top management at the Laboratory endorsed an aggressive Energy Conservation Program for its energy as well as budget savings implications. Three Energy Management Committees—Administrative, Electric Power, and Employee Awareness—were formed in FY81 and were given the task of finding ways to reduce the Laboratory's projected electric bill from \$4.7 M to \$3.0 M. These energy cost savings were accomplished through various unique and innovative engineering techniques implemented during the year. Controlling electrical demand by avoiding coincidental start-up of large process and utility equipment, adjustment of electrical loads through seasonal work-place temperature policies, implementation of energy cost avoidance projects (such as an extensive facility delamping program), temperature limiting thermostats for the motor-generator sets, and off-hour Security Department light-extinguishing tours contributed to the overall Laboratory Energy Conservation Program. The Laboratory recognized the efforts of those employees most responsible for the energy conservation efforts by presenting to them letters of commendation and memento pictures (Fig. 117).

Figure 117. PPPL Staff most responsible for energy conservation efforts. Sitting left to right: Raymond Pressburger, Bob Longmuir, John Wallace, Dick Terhune, Carl Potensky, John Grabowski. Standing left to right: Dick Farley, Ben Velivis, Mark Kijek, Steve Ragolia, Bob Gulay, Frank Fumia, Henry Chandler, Marvin Richey, John Pacula, Ed Rogers, Connie Stout, Ernst de Haas, Harold Furth (Laboratory Director), Bob Smart (Associate Head of Administration Department). Absent: Tom Hurley, Dave O'Neill, and Bob Goodwin.

A reduction in fuel oil usage through conservation efforts amounted to a \$90,500 savings during FY82. The reduction in fuel oil usage was achieved by a Laboratory boiler efficiency testing program, a program versus load optimization operation, and the deactivation of an obsolete steam absorption chiller.

Total gasoline consumption for FY82 was 33,692 gallons. This was a slight increase over FY81 (33,300 gallons), but well below the mandated goal of 35,429 gallons. This objective was achieved through the continued use of gasoline rationing coupons and through other conservation measures now in effect at the Laboratory.

An Energy Survey and Study Program generated 15 energy projects with an installation cost of two million dollars. Requests for supplemental funding for these projects have been submitted to the Department of Energy, and, if approved, will result in an annual savings of hundreds of thousands of dollars for the Laboratory. One such project, an Energy monitoring and Control System, was approved earlier, and when completed in 1984, this system will provide for a number of automatic computerized energy functions, such as equipment duty cycling, electric demand limit start-stop control, space night setback, and an electrical metering module.

Training

In-house training programs received much attention again in FY82. Ten mechanics attended the in-house classes in this fifth year of vendor-designed courses given by Plant Maintenance. In addition, four PM&E employees participated in the newly developed apprentice program that was initiated in October 1982. This program, developed by a group of PM&E managers, supervisors, and technicians, may be one of the first of its kind. It is specifically designed to produce well-rounded general maintenance mechanics. The program has received State and Federal certification.

The construction of the TFTR has expanded further PM&E's requirements for training. Weekly classes are conducted on-site by Robertshaw personnel to train technicians in the intricacies of the heating, ventilation, and air conditioning (HVAC) systems. These classes began in July 1982 and will run through April 1983.

Other training efforts included sending two staff members to a Pyrotechnics (fire protection) school and several other employees to various courses on crane inspection, rigging, etc.

Implementation of a Janitorial Services Program, designed by Daniels Associates, allowed for a substantial reduction in the janitorial crew while improving housekeeping standards. A programmable system of computerized work loading, based on the industrial cleaning production standard of 3,000 square feet per man per hour, allowed management to increase or decrease the level of cleaning in any area based on necessity. Additionally, the janitorial crew undertook an environmental program of collecting recyclable paper. The total amount of paper collected was as follows:

Type of Paper

Total in Pounds

Computer	18,040
White Ledger	8,000
Tab (card stock)	600

LIBRARY

Several new automation systems were added to Firestone Library's resources, thus enabling the PPPL Library to expand its services. Through the Research Libraries Information Network (RLIN), a consortium of 26 libraries, the Library now has access to four million books and journals. In addition, this system also enables the Library to track its book orders, and the time between ordering and cataloging has been decreased by several weeks. Through its contracts with the Original Article Test Services (OATS) and the National Technical Information Service (NTIS), the Library is able to order technical reports and non-Firestone Library journal articles on-line, thus reducing the normal period of delivery. Computerized literature searching for Laboratory staff has increased by 20%.

Library operations were reviewed to determine less costly methods of operation. This resulted in the elimination of external distribution of the two monthly publications and cancellation of six journals of peripheral interest.

Circulation has increased by 8% while borrowing from within the Firestone system has decreased by 30%, an indication that the collection development policy is continuing to meet the demands of the PPPL staff. The Library now has 9,113 bound volumes, 16,400 technical reports and 27,800 microfiche.

TELECOMMUNICATIONS

The role of the Telecommunications Office is to provide to the Laboratory voice communication services that are cost-effective and efficient. With this as its goal, the Telecommunications Office

- Processed over 1600 requests for telephone, radio, and pocket pagers;
- Planned and installed cable and conduit in the TFTR complex;
- Undertook extensive studies to provide radio communications within and beyond TFTR;
- Installed computer access telephones in the homes of employees where it was shown that this service would be advantageous to the Laboratory;
- Worked in conjunction with the Emergency Services Unit in the planning and installation of its Emergency Preparedness Plan Communication System;
- Initiated work with American Telephone and Telegraph and New Jersey Bell in order to prepare for the divestiture planned for January 1, 1983.

Increases were levied on communication charges despite strong efforts to control costs. The General Services Administration increased the cost of using the Federal Telephone Service (FTS) by 500%, and New Jersey Bell was granted a rate increase that escalated the Laboratory costs by 25%. Therefore, the cost of Telecommunication Services has become a significant factor in the PPPL budget.

INFORMATION SERVICES

The Information Services Branch of the Administration Department includes all Laboratory services supporting the preparation and dissemination of information pertaining to PPPL's program. Service areas include photography, graphics arts/technical illustration, word processing, printing, technical information, and public/employee information. Various administrative services, specifically, reception, mail, travel, and food services, are also provided.

Public and Employee Information

As in previous years, the Public and Employee Information Section maintained an up-to-date information package which describes PPPL's fusion program to lay audiences. The *Information Bulletins* were updated as necessitated by new experimental results on the Laboratory's operating tokamaks, by construction progress on TFTR and S-1 Spheromak. Three editions of the *PPL Digest* were published, providing the public with information on plasma heating by radio-frequency waves, tritium handling on TFTR, and radiation basics relating to PPPL research. In an effort to communicate up-to-date program and administrative information to PPPL staff, 13 issues of *PPL Hotline* were published.

The Laboratory's tour program experienced significant growth during FY82. By year's end, a total of 230 Laboratory tours were arranged for technical societies, and industrial, educational, and public interest groups. This represents a 50% increase over FY81.

A technical exhibit describing PPPL's fusion program was constructed for display at the American Vacuum Society meeting at Anaheim, California in November 1981. Public and Employee Information staff manned PPPL's traveling fusion energy display at the New Jersey Research and Development Council's Science Exposition at Rutgers in March 1982.

During FY82, plans were drawn up for the implementation of a PPPL Community Outreach program. A committee—chaired by PPPL Associate Director J.W. Clark, with members H. Allen, A.R. DeMeo, Jr., R.A. Ellis, Jr., and H.J. Howe, Jr.—was established to make recommendations to university and PPPL management in early FY83. The goal of the program is to foster a broad base of local public understanding of the work at PPPL and to forge closer communication links with local government, industry, and educational groups.

By the end of FY82, the first draft of the PPPL Public

Affairs Emergency Plan was submitted to the U.S. Department of Energy, Chicago Operations Office for review. This document defines policies and procedures relating to the release and dissemination of public information in the event of an emergency at PPPL. Following a review of several plans in effect at major national laboratories and in industry, the Emergency Plan was designed with a target date for its completion in early FY83. The final plan will be an addendum to the PPPL Emergency Preparedness Plan.

Word Processing

The Word Processing Center increased its productivity 37% over FY81. The successful and efficient use of the Center prompted the Word Processing Committee to conduct a Laboratory survey in order to develop long-range plans for the Laboratory.

In August 1982 the purchase of an NBI OASys 64 was approved, enabling old and new users of NBI equipment at C-Site to be linked into a centralized system. Standard equipment, with a centralized organization, will provide more capability and flexibility to users, as well as better personnel and machine backup, and on-site training. The initial configuration will contain 60 Mb of hard disk storage and ports for 16 peripherals (work stations and printers).

Plans called for the new network to be operational early in FY83. Expansion of the central system will occur gradually, with A- and B-Sites to be connected by communications within the next two years.

Patent Awareness Program

The first complete year of the Patent Awareness Program showed a marked increase in the number of invention disclosures submitted to DOE. Twenty-nine invention disclosures were filed during FY82, an increase of 123% over FY80. In order to promote the objectives of the program, the Committee on Inventions established a system of awards, publicity, and recognition of PPPL inventors intended to raise the patent-mindedness of the Laboratory staff. Forty-eight individuals received awards for their contributions.

Administrative Services

Administrative Services played a significant role in the planning and organization of the Ninth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, sponsored by the International Atomic Energy Agency (IAEA), and held in Baltimore, Maryland.

The IAEA Conferences on Plasma Physics and Controlled Nuclear Fusion Research are held biennially and are recognized as the major forums in the exchange of information among scientists working in this field. The host government for the 1982 Conference was the United States, and the Conference was organized in cooperation with the U.S. Department of Energy and PPPL.

PERSONNEL

The Personnel Division continued to implement services and programs autonomous from Princeton University.

- A Benefits Administrator was hired by the Laboratory to provide more rapid processing of insurance claims and also to respond to employee inquiries regarding the various aspects of the University Benefits Program.
- A new Salary Classification System was implemented for the Senior Lab and Shop Staff as part of the continuing effort to develop salary systems that are designed to best meet the needs of the Laboratory.
- The Laboratory established a Grievance Panel, solely consisting of members of the Laboratory, to hear employees' grievances and to recommend appropriate action to the Laboratory Director. Half of the members of the Panel are appointed by the Laboratory Director and half are elected by their respective staffs.
- A Complaint and Grievance policy was developed which provides the employees of the Laboratory with the mechanism to resolve employee complaints.
- The Compensation Section of Personnel created an Audit Report of all Personnel transactions that occurred during the Fiscal Year. This Report is reviewed by the University Oversight Committee. If necessary, the Committee offers constructive comments to the Laboratory with respect to revising its Personnel Policies and Practices.
- The Human Resources Section created the Laboratory's first extensive Supervisory Training and Development Program geared toward offering first-line supervisors practical tools for resolving day-to-day personnel problems.
- Training programs covering such topics as tritium handling, electromagnetic interference (EMI) shield design, and analog circuits were offered by the Personnel Department to various staff members.

HEALTH AND SAFETY

The emphasis on line responsibilities for safety within the Laboratory continued during FY82. Departmental programs were expanded to include a Safety Coordinator who reports to the Department Head through the Departmental Safety Officer (DSO) and is responsible for buildings/areas. In addition, the Health and Safety Directives (HSD) of the Laboratory Safety Implementation Plan were completed and promulgated, thus establishing a firm, formal statement of Laboratory policy.

Support was provided to the Tokamak Fusion Test Reactor (TFTR) efforts to achieve first plasma by the following actions:

- Completion of the Final Safety Analysis Report (FSAR).
- Participation in a Pre-Startup Safety Appraisal (PSA).
- Participation in the TFTR Operational Readiness Review.

In addition, Health and Safety took part in the preparations for first plasma in the S-1 Spheromak device, which involved reviews, inspections, and analyses.

The Health and Safety Branch and the Laboratory continued to be concerned about the rising trend in the Laboratory's accident statistics. The lost workday case index (LWC) rose from 1.4 in 1980 to 2.55 in 1981 to 2.83 in 1982; the lost workday index (LWD) rose from 10.9 in 1980 to 30.1 in 1981 and dropped to 26.25 in 1982. Temporary rises in such indices during periods of expansion and change are common and the Laboratory is actively emphasizing the need for closer and more extensive attention to safety on the part of all employees.

Health and Safety efforts were expanded in the areas of training, inspection and monitoring, specification reviews, and facility reviews.

EMERGENCY SERVICES

In anticipation of the completion of TFTR, the Emergency Services Unit (ESU) grew from a work force of one permanent Fire Chief and 30 volunteers to a work force that now includes five permanent Fire Captains and 16 temporary fire fighters. This unit provides the Laboratory with round-the-clock, weekend, and holiday fire protection. Its members are divided into five-person crews with the responsibility of providing fire safety throughout the facility. This is accomplished by inspection of fire detection and suppression systems, of hazardous material locations, and of emergency equipment functions and tests.

The Unit formulated and implemented the Laboratory's Emergency Preparedness Plan, and the TFTR Addendum, with 27 Supplements. In addition, the ESU undertook the responsibility of training selected personnel in an on-going course of Cardio-Pulmonary Resuscitation (CPR) with future plans for training all interested personnel. To date, 60 employees have been certified in this procedure. The ESU also operated fire safety and first aid sessions for Department personnel.

During FY82, the ESU responded to 17 more calls than in FY81. The First Aid Squad responded to 53 calls, four of which required life-saving efforts. The Heavy Rescue Unit, assisted by the First Aid Squad, was credited with two vehicle extrication rescues—both rescues occurred on U.S. Route 1 adjacent to the Laboratory. The Fire Department responded to 12 small fire calls.

ACCOUNTING AND FINANCIAL CONTROL

Automated transmission of Tech Center pay data for direct entry into the Laboratory Payroll and Cost

Distribution System was expanded during FY82. As part of the simplification of the reconciliation process (which will lead to the direct computer transmission of accounting information from the PPPL system to the Main Campus system), System, Table, and Computer Programs were designed that convert the coding of PPPL cost distribution data to the coding used in the Princeton University Accounting System. The Cost Control System was expanded to meet the tighter requirement of DOE funding constraints experienced early in the fiscal year and to accommodate the shortened time allowed for filing the Year-End Report. Also, the format of monthly DOE Report 65 was expanded to include Annual Budgets, Interim Cost

Projections, Commitments Outstanding, and Requisitions in Process. In addition, the Manager's Manual portion of the Accounting and Financial Control Manual was completed.

A new project begun during FY82 was the design of a Payroll Cost Distribution System that will improve the capability of payroll projections and allow for the commitment of Tech Center Labor at the job level. Accounts Payable processing was further automated by installing additional software for on-line, instant inquiry.

Table XI is a financial summary for the Laboratory for the last five years.

TABLE XI. PPPL Financial Summary.
(Millions of Dollars)

	<u>FY78</u>	<u>FY79</u>	<u>FY80</u>	<u>FY81</u>	<u>FY82</u>
OPERATING (Actual Costs)					
Department of Energy					
Research & Development Operations	\$ 11,669	\$ 12,230	\$ 4,744	\$ 2,314	\$ 2,945
Facility Operations	289	1,578	5,587	11,832	10,424
Tokamak Flexibility Modification	151	1,535	4,885	13,951	13,033
CICADA	331	493	1,184	2,437	4,044
Neutral Beams	—	—	—	1,870	6,253
TFTR Experimental Research	640	975	1,768	2,081	2,835
TFTR Diagnostics	—	2,595	5,832	7,706	8,973
PLT/PDX	23,306	23,105	21,050	23,271	18,893
ACT-I	545	666	398	438	443
S-1	—	141	1,569	3,223	3,254
Theory	2,379	2,459	2,437	2,643	2,488
Applied Physics	577	358	396	807	1,280
Other Research	360	419	290	364	495
Fusion Engineering Device	—	—	—	125	412
Inventories	948	5,519	2,305	1,922	(237)
X-Ray Laser Development	—	—	160	251	266
SRSA	101	37	1	—	—
Department of Defense	88	88	88	280	297
Other Contracts	18	48	491	563	565
Total Operating	<u>\$41,402</u>	<u>\$52,246</u>	<u>\$53,185</u>	<u>\$76,078</u>	<u>\$76,663</u>
EQUIPMENT (Budget Authorization)					
Capital Equipment not					
Related to Construction	<u>\$ 5,140</u>	<u>\$ 4,295</u>	<u>\$ 6,974</u>	<u>\$ 8,237</u>	<u>\$ 9,272</u>
CONSTRUCTION (Budget Authorization)					
TFTR	\$54,689	\$35,778	\$19,361	\$25,000	\$31,600
PDX Neutral Beams	—	—	1,100	—	—
General Plant Projects	1,350	1,250	1,000	610	1,400
Energy Management	—	60	558	285	197
Total Construction	<u>\$56,039</u>	<u>\$37,088</u>	<u>\$22,019</u>	<u>\$25,895</u>	<u>\$33,197</u>

MANAGEMENT INFORMATION SERVICES

During the past fiscal year, the Management Information Systems (MIS) Branch continued to provide routine maintenance and enhancements to the existing Administrative Systems and to develop new systems. Accomplishments included:

- The definition and first-stage implementation of a major system for the record keeping of capital equipment items (ETACS).
- The installation of a more efficient backup and recovery procedure for the major files in the Budget and Accounting Information System (BACIS). This allows system restarts to be achieved more rapidly.
- The creation of a PPPL/University accounting subsystem which provides a method for computerized reconciliation of PPPL accounts to the University.
- The completion of the second phase of the On-line Automated Stockroom Inventory System (OASIS) with additional reporting capability for minimum/maximum balances and consumption levels of stockroom items by time periods.
- The creation of a facility to obtain reports on Engineering jobs for remote users on an interactive basis. This capability was established at the request of the Program Management System (PMS) subcommittee.

PROCUREMENT

A significant achievement during FY82 was the settlement of the claim involving the TFTR Motor Generator Stator No. 2 accident. Extensive negotiations by the Laboratory and the DOE were completed which allowed the acquisition of a replacement generator to meet a scheduled date of October 1984. The settlement provided for full recovery of costs.

During the year, 9,819 procurement actions were placed with a total value of \$37,658,485. This represents a 10% reduction in number of actions and a 24% increase in procurement dollars over FY81. The reduction in number of actions is the result of opening more "blanket orders"—a procurement procedure whereby authorized individuals, selected by Division Heads, may make direct buys of low value from specific suppliers.

Throughout the year, there was a continuing effort to upgrade and improve the Procurement Automated Data System (PADS). The most significant effort in the PADS activity in 1982 occurred in the last quarter of the year and will carry over to FY83. It is the automatic or simultaneous printing of the purchase order at the time it is entered into the accounting system. This effort will be on line during the second quarter of FY83. Additional activities included making presentations to Laboratory staff on the PADS capabilities, bringing on line new screen presentations and reformatting others for a more meaningful data read-out, and development of the capability to run various reports relating to purchase order/vendor activities.

In April 1982, the construction subcontract administration activities were reassigned from the Facilities and Support function to the Procurement Division.

MATERIAL CONTROL

In 1982, Material Control initiated two major improvement projects—the Equipment Tracking and Control System (ETACS) and the installation of modular storage cabinets in the stockrooms:

- The ETACS computerized equipment records and expanded the data base of property records. The System generates a variety of management and user reports tailored for a particular use or application. File information provides for an exact location of property and results in faster and more accurate inventories of the 12,000 pieces of capital equipment, valued at \$60 M, at PPPL. A new system of capital equipment control and physical inventories has been approved.
- Stockroom sales of \$1.1 M with over 200,000 transactions in the fifteen commodities stored created a need for additional space in the stockrooms. Modular storage cabinets were installed which make available over 1,200 additional square feet of storage space at the B- and C-Site Stockrooms, thus offsetting possible future construction costs. A mezzanine is being added to the B-Site Stockroom and will provide another 400 square feet of space.

Through the efforts of the newly appointed Hazardous Material Control Coordinator, 2,500 capacitors containing polychlorinated biphenyl (PCB) were discarded.

In the past, items excess to the needs of PPPL were sent to the Government Services Administration's Raritan Depot. Because the Depot was closed in March 1982, PPPL had the responsibility of storing all excess items awaiting disposition, donation, and/or sale. A portion of the Annex Building was turned over to the Excess Property Section for this purpose. At that time, 164 line items with a value of \$350,000 were retired and 160 line items with a value of \$1.5 M awaited final disposition. As a result of the sale of scrap, the Excess Property Section also received and credited to various cost centers \$8,000.

As of April 1982, Receiving #4, formerly under Ebasco, was officially transferred to Material Control for the receipt, storage, and disbursement of items purchased by Ebasco/PPPL for the construction/assembly of the TFTR. Since the warehouse was full, a mezzanine was erected to accommodate the small items requiring storage and disbursement.

The latest revision to the Material Control Manual was distributed on November 1, 1982. Revisions were made as a result of new systems established in order to facilitate efficient service to PPPL users.

In conjunction with the safety program established at PPPL, a Material Control Branch Safety Coordinator was appointed, and steps were initiated to make work areas safe, including the rearrangement of Receiving #3's racks to meet with safety regulations.

Graduate Education: Plasma Physics

Benefiting from the physical proximity of PPPL and the academic departments on the main campus of Princeton University, a program of graduate studies in plasma physics has been pursued in Princeton's Department of Astrophysical Sciences since 1959. This program has had a major impact on the entire field of plasma physics. Nearly 100 physicists have now received doctoral degrees in this field, and many hold leadership positions for plasma research and technology in academic, industrial, and government institutions. To the research community, the graduate program brings highly qualified young scientists; to PPPL, the program presents teaching opportunities that offer constant challenge and stimulation; to the University, the program represents an international center of excellence in a branch of scholarly research with large potential for social service.

The teaching faculty for the plasma physics program currently numbers seventeen members who offer a variety of courses to the forty-three graduate students in residence this year. In addition to the formal coursework, there is strong interaction between PPPL staff scientists and engineers and the Astrophysical Sciences Department's graduate students. Most students hold Assistantships in Research at PPPL through which they participate in the continuing experimental and theoretical research programs. With

PPPL staff members serving as their advisors, first-year students this past year were working with PPPL's various experimental groups including TFTR diagnostics development, PLT, PDX, ACT-I, Proto S-1, and the x-ray laser project. In a similar fashion, second-year students worked closely with members of PPPL's Theoretical Division. In addition, in a student-run Tuesday afternoon seminar PPPL physicists shared their expertise each week with the graduate students. The students, of course, are regular attendees at the Laboratory's own seminars and colloquia. All of this experience provides a strong base for doctoral thesis research which, also, is carried out in collaboration with PPPL staff members. Twenty-four students in the plasma physics program are now engaged in their thesis projects—fifteen on experimental topics, eight on theoretical topics, and one in fusion technology.

In Table XII are listed the Departmental courses offered this past academic year. This curriculum is supplemented by teaching in other University departments, including graduate courses in quantum mechanics, electricity and magnetism, and statistical mechanics in physics. The teaching faculty is identified in Table XIII; Table XIV lists the doctoral thesis projects completed this fiscal year under the plasma physics program.

Table XII. Plasma Physics Courses Offered and Instructors.

Fall 1981		
AS551	General Plasma Physics I	S.E. von Goeler and T.H. Stix
AS553	Plasma Waves and Instabilities	F.W. Perkins
AS556	Advanced Plasma Dynamics	H. Okuda and G. Rewoldt
AS557	Advanced Mathematical Methods in Astrophysical Sciences	M.D. Kruskal
AS558	Seminar in Plasma Physics	C.R. Oberman
Spring 1982		
AS552	General Plasma Physics II	R.M. Kulsrud and Tang
AS554	Irreversible Processes in Plasma	P.K. Kaw and J.A. Krommes
AS558	Seminar in Plasma Physics	C.R. Oberman
AS561	Special Topics in Magnetic Confinement	P.H. Rutherford and S. Yoshikawa

Outside support for the graduate program came this year from the Westinghouse Educational Foundation. A grant from this Foundation has permitted the Astrophysical Sciences Department to offer prizes (which supplement the research assistantships) to outstanding applicants to the plasma physics program.

Academic work in plasma physics is broadly based in modern physics. The study of plasma physics requires the folding together of knowledge from electricity and magnetism, atomic physics, hydrodynamics, statistical mechanics and kinetic theory, and applied mathematics, together with diagnostic and data-handling methods from state-of-the-art laboratory physics. Techniques from many disciplines within theoretical and experimental physics find immediate application in plasma research and, by the same token, experience

with plasmas can be transferred back to other areas in physics. But equally important, plasma physics is itself a large field, a young field, and a challenging field where success in research will have enormous impact on reaching a satisfactory long-range solution of the world's energy problems. At Princeton University and at PPPL, the graduate students in the Department of Astrophysical Sciences feel this responsibility and enjoy this challenge to scholarship.

Table XIII. Astrophysical Sciences/Plasma Physics Faculty.

FACULTY MEMBERS	TITLE
Thomas H. Stix	Associate Chairman, Department of Astrophysical Sciences, and Associate Director, PPPL, for Academic Affairs
Liu Chen	Principal Research Physicist and Lecturer with rank of Professor
Harold P. Furth	Professor of Astrophysical Sciences
Raymond C. Grimm	Principal Research Physicist and Lecturer with rank of Professor
Charles F. Karney	Research Staff and Lecturer in Astrophysical Sciences
Predhiman K. Kaw	Visiting Lecturer
John A. Krommes	Research Physicist and Lecturer with rank of Associate Professor
Martin D. Kruskal	Professor of Mathematics and Astrophysical Sciences
Russell M. Kulsrud	Principal Research Physicist and Lecturer with rank of Professor
Carl R. Oberman	Principal Research Physicist and Lecturer with rank of Professor
Hideo Okuda	Principal Research Physicist and Lecturer with rank of Professor
Francis W. Perkins, Jr.	Principal Research Physicist and Lecturer with rank of Professor
Gregory Rewoldt	Research Physicist and lecturer in Astrophysical Sciences
Paul H. Rutherford	Principal Research Physicist and Lecturer with rank of Professor
William M. Tang	Principal Research Physicist and Lecturer with rank of Professor
Schweickhard E. von Goeler	Principal Research Physicist and Lecturer with rank of Professor
Shoichi Yoshikawa	Principal Research Physicist and Lecturer with rank of Professor

Table XIV. Recipients of Ph.D. Degrees.

Robert S. MacKay		September 1982
Thesis:	Renormalisation in Area Preserving Maps	
Advisors:	John L. Johnson, Martin D. Kruskal	
Employment:	Queen Mary College, London	
Eliezer Rosengaus		November 1982
Thesis:	Renormalization of Perturbation Theories for Action-Angle Transformations	
Advisor:	Robert L. Dewar	
Employment:	University of California, Berkeley	
Carl Göran Schultz		July 1982
Thesis:	Tearing Modes in Tokamak Plasmas With and Without Ion Beam Driver Currents	
Advisor:	Predhiman K. Kaw	
Employment:	Cornell University	
Glen A. Wurden		August 1982
Thesis:	CO ₂ Laser Scattering on rf Waves in ACT-I	
Advisors:	Masayuki Ono, King-Lap Wong	
Employment:	Los Alamos National Laboratory	

Graduate Education: Fusion Reactor Technology

PROGRAMS

Now entering its eleventh year, the Fusion Reactor Technology Program is a collaborative effort between the Department of Chemical Engineering in Princeton University's School of Engineering and Applied Science and the Princeton Plasma Physics Laboratory. Four students are currently in residence in this Program; another student (unsupported) will remain a fifth year to complete his thesis. Table XV lists the current status of the students, their thesis topics, and their advisors.

Princeton University is participating in the Magnetic Fusion Energy Technology Fellowship Program, administered for the U.S. Department of Energy by the Oak Ridge Associated Universities. Currently, two DOE Fellows—P. Bertone and J. Isaacson—are enrolled in Princeton's Graduate School, while a third—I. Shokair, a graduate student at the University of California at Los Angeles—chose to complete his practicum assignment at PPPL.

An innovation this past year was the establishment of the Industrial Training Program in Fusion Reactor Technology. This program provides an opportunity for mid-career engineers to gain an academic introduction to the fundamental principles of fusion power combined with practical experience in working in the field. The first two Industrial Fellows, D.J. Amos and D.A. Dilling, are now in residence at Princeton. Mr. Amos is a Westinghouse Electric Corporation employee and recipient of their B.G. Lammé Fellowship. He is working with TFTR's Technical Systems Division as engineer-in-charge of the redesign and procurement of the Engineering Test Station and with some aspects of the lithium blanket module studies. The second participant, Mr. Dilling, is from Bechtel Group, Inc. in San Francisco, California. He has been working on Program Manage-

ment Systems, specifically the Laboratory Work Breakdown Structure.

The Fannie and John Hertz Foundation has listed PPPL as willing to provide research facilities for Hertz Fellows working in applied physical sciences.

The Department of Civil Engineering continued its cooperative research program with PPPL's Tokamak Fusion Test Reactor Flexibility Modification (TFM) Project. A Civil Engineering graduate student, D. Tao, is conducting an analytical and numerical investigation of thermal and dynamic responses of the first wall tile plate assemblies when subjected to thermal shockloads and to electromechanical loads caused by plasma disruptions.

Preparation of a small Chemical Engineering Laboratory adjacent to the neutron generating facility was undertaken this past year. When completed, it will be used by three graduate students.

DEPARTMENT CURRICULUM

In addition to the graduate education program, the Chemical Engineering Department offers a strong undergraduate curriculum to stimulate interest in fusion. A minicourse on fusion is included in Engineering 101, a divisional course of the School of Engineering and Applied Science. Junior and Senior independent work in fusion is also sponsored in keeping with Princeton's tradition of undergraduate thesis work. The undergraduate course Introduction to Fusion Power is suitable for both undergraduate and graduate students.

Each year, Chemical Engineering 417 welcomes a few members of the professional engineering staff of the Laboratory as auditors. These people are specialists seeking a broader understanding of aspects of the Laboratory work that differs from their own. To date,

Table XV. Graduate Students in The Fusion Reactor Technology Program.

Student	Thesis Topic	Degree	Advisor	Status
H.H. Tseng	Molten Fluoride Blankets	Ph.D.	E.F. Johnson	Imminent
P.C. Bertone	Tritium Recovery from Li_2O Blanket	Ph.D.	R.G. Mills D.L. Jassby	1985 (expected)
T.M. Kasturirangan	Li_2O Slurry Blankets	Ph.D.	R.C. Axtmann	1985 (expected)
J.A. Isaacson	Fusion Neutron Energy Spectrum and Flux Measurements	M.S.E.	R.G. Mills	1984 (expected)

about 20% of the engineering staff have participated. This arrangement provides a unique opportunity for students to associate with working professionals in the topic of the course. To reinforce this opportunity, a key feature of the course is a machine design project. The class is divided into two teams for a competition. The professional staff members are divided into three

groups, two sets of consultants for the teams and a selection board to evaluate the final designs. Oral presentations before the board are a fairly realistic preview of the "real world's" contract selection procedures.

The Engineering Faculty and related fusion engineering courses are given in Tables XVI and XVII.

Table XVI. Engineering Faculty.

Faculty	Title
R.C. Axtmann	Professor of Chemical Engineering
E.F. Johnson	Professor of Chemical Engineering
R.G. Mills	Deputy Head, Engineering Department, Princeton Plasma Physics Laboratory and Lecturer with Rank of Professor

Table XVII. Chemical Engineering Courses Relating To The Fusion Technology Program.

Course Number	Title	Faculty
351, 352	Junior Independent Work	Staff
451, 452	Senior Independent Work	Staff
417	Introduction to Fusion Power	R.G. Mills
418	Nuclear Engineering	R.C. Axtmann
550	Fusion Reactor Technology	R.G. Mills, Staff