DIII–D RESEARCH OPERATIONS ANNUAL REPORT

OCTOBER 1, 2000 THROUGH SEPTEMBER 30, 2001

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DIII–D RESEARCH OPERATIONS ANNUAL REPORT TO THE U.S. DEPARTMENT OF ENERGY

OCTOBER 1, 2000 THROUGH SEPTEMBER 30, 2001

by
PROJECT STAFF

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GENERAL ATOMICS

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1. DIII–D NATIONAL PROGRAM OVERVIEW FOR FY01

The DIII–D research program is a science program aimed at an energy goal as stated in the mission statement: "To establish the scientific basis for the optimization of the tokamak approach to fusion energy production." The focus is on advanced tokamak (AT) research with a goal aimed at discovering the ultimate potential of the tokamak. The research program is a multi-institutional, collaborative effort involving 60 institutions and about 300 researchers. The DIII–D tokamak has considerable plasma shape flexibility, plasma feedback control tools and algorithms and a full set of mature diagnostics for detailed studies of plasma stability, turbulence and transport, heating and current drive with neutral beams and electron cyclotron power available, and boundary and divertor physics. Along with these broad topical science areas (TSAs) of research several more focused areas of research, called thrusts, are chosen each year. This year the thrusts were on a high bootstrap fraction (f_{BS}) AT scenario, stabilization of resistive wall modes (RWMs), internal transport barrier (ITB) control, understanding and control of the edge pedestal, and stabilization of neoclassical tearing modes (NTMs).

Significant progress was achieved in each of the thrust and topical science research areas this year. Some highlights of the operations and research results include:

- Routine operation of four, 110 GHz gyrotrons was established with >2 MW available for 2 s.
- Improved AT scenario target discharge with error field, RWM, and density control resulting in $\beta_N H_{89} > 10$ for four energy confinement times.
- Demonstration that sustaining plasma rotation and controlling error fields enables higher plasma pressure, β, operation.
- Feedback controlled local electron cyclotron current drive (ECCD) used to suppress the m=3, n=2 NTM, allowing higher β operation.
- Edge pedestal plasmas with the same nondimensional parameters in DIII–D and Alcator C–Mod have similar profiles and microstability properties.
- Simulations of quiescent, coupled core, and edge barrier discharges with the GLF23 transport model reproduce core ion temperature profiles and agree with measurements of reduced but not suppressed ion temperature gradient mode activity.
- Demonstrated controlled plasma termination with high pressure noble gas injection mitigates disruption effects including inhibiting production of fast electrons.

- Measurements of turbulent radial correlation lengths are consistent with gyrokinetic simulations.
- Gained understanding and validation of the theory showing that high electron beta improves the efficiency of ECCD, consistent with AT program requirements.
- Documented enhanced plasma flow to the divertor by intermittent convective transport across the plasma separatrix, accounting for half of the total cross field particle and energy transport.

This year saw the electron cyclotron system come of age with reliable four-gyrotron operation, the physics model for the current drive essentially verified, and EC power demonstrated as a very useful tool in stabilizing the NTMs. The major elements required to achieve integrated, long-pulse, AT operation were demonstrated individually this year. Predictive simulations based on experimental profiles taken from this year's best examples of integrating the required aspects of an AT scenario offer the exciting prospect of sustaining $\beta_N = 4$, $H_{89} = 3.1$ with $f_{BS} = 65\%$ for 10 s with 3.5 MW of electron cyclotron heating (ECH) power, which is expected to be available in 2002. In addition, this year saw a renewed strong interest in the error field from its impact on the location of the last closed flux surface (LCFS), impact on the stabilization of the RWM, and the impact on discharge formation and evolution.

Detailed planning of the experimental campaign is an important part of the research program each year. The process began early in the fiscal year with a Research Opportunities Forum where ideas for all types of experiments were solicited based on a set of experimental goals developed by the thrust and TSA leaders and DIII–D Research Council members. Just over 200 experimental ideas were collected for this year which competed for 17 weeks of experimental run time. Final allocation of experimental run time was obtained through iterative discussions between the DIII–D director, the thrust and TSA leaders and the Research Council. Due to the California power crisis in 2001, DIII–D had to operate 14-h days for all run periods except the last, when staff limitations precluded the longer days. The achieved operations time had 699 scheduled hours of tokamak operation and 526 h of productive physics experiments were accomplished, for an actual availability of 75%. The availability was lower than usual because of the electric supply problems and the 14 h per day operation. But in spite of the California power crisis, DIII–D achieved 16 more hours of productive physics operation in FY01 than had been planned.

Members of the DIII–D research team continued their commitment and involvement in other fusion-related activities including the newly formed International Tokamak Physics Activity (ITPA) which offers the opportunity for the U.S. to participate in international tokamak R&D and an Educational Outreach Program. The DIII–D director is a member of the ITPA coordinating committee and 12 team members are official members of the topical ITPA groups with five members in leadership positions. The DIII–D fusion education team maintains an active program by providing tours of the facility to students and teachers, supporting educational outreach programs at large annual meetings such as American Physical Society, and giving talks and plasma science demonstrations to local schools.

This report includes a CD which contains much more detailed information than could be covered in the summary sections which follow. Included on the CD are FY01 publications and presentations from some of the major meetings.

2. FY01 SCIENTIFIC PROGRESS

The DIII–D research program is organized into four general areas of research called TSAs which consist of plasma stability, turbulence and transport, heating and current drive, and boundary and divertor physics. Along with these broad TSAs of research, several more focused areas of research, called thrusts, are chosen each year. For FY01, the thrusts were on a high bootstrap fraction AT scenario, stabilization of RWMs, internal transport barrier control, understanding and control of the edge pedestal, and stabilization of NTMs. Highlights of the results from each of these areas is summarized in this section beginning with the thrust areas.

2.1. HIGH BOOTSTRAP FRACTION AT SCENARIO — THRUST 2

A major focus of DIII–D research is on AT physics. The overall goal is to achieve a steady-state, high performance discharge which requires an elevated central safety factor, q(0), with weak or negative central magnetic shear which is favorable to local stability, high bootstrap fraction, and reduced thermal and particle transport. The experimental focus this year was on achieving a demonstration of such a discharge while developing the scientific basis as necessary to achieve this goal. This required an emphasis on integrating the various physics elements and control tools to find an optimum operation point. The key physics elements and control tools included:

- RWM stabilization.
- Off-axis ECCD.
- Active density control.
- Understanding/control of transport in the plasma core and edge.
- NTM avoidance and, if necessary, stabilization.

All of these elements and tools are key areas of concern for other thrusts and TSAs in the DIII–D program and, thus, highlights the strong coordination and integration aspects of this area of the program.

Significant progress was made in this thrust. The major elements required in achieving integrated, long-pulse, AT operation were demonstrated this year, though not all simultaneously. They include:

- High plasma pressure, $\beta \sim 4.2\%$, $\beta_p \sim 2$, $\beta_N \sim 4$.
- High performance, $\beta_N H_{89} > 10$ with $q_{min} > 1.5$.

- High bootstrap and noninductively driven currents, $f_{BS} \sim 65\%$, $f_{NI} \sim 80\%$.
- The above conditions were achieved simultaneously and sustained for a significant duration, 4 τ_E.
- Density control ($n_e < 5 \times 10^{19}$ m^{-3}) at $\beta_N \sim 4$.
- ECCD efficiencies consistent with theory and future AT needs.

Experiments demonstrated that the measured ECCD efficiency improves with increasing β_e and the results were consistent with theoretical predictions. Several issues involving the full integration of these elements remain to be resolved. Of particular importance are obtaining high electron pressure, β_e, at high β to maintain a high current drive efficiency and avoiding NTMs at reduced density. The duration of the discharge in Fig. 2–1 was limited by growth of the m/n = 2/1 NTM which was experimentally correlated with q_{min} approaching 1.5. Future experiments will use ECCD to sustain a more favorable current profile with $q_{min} > 1.5$.

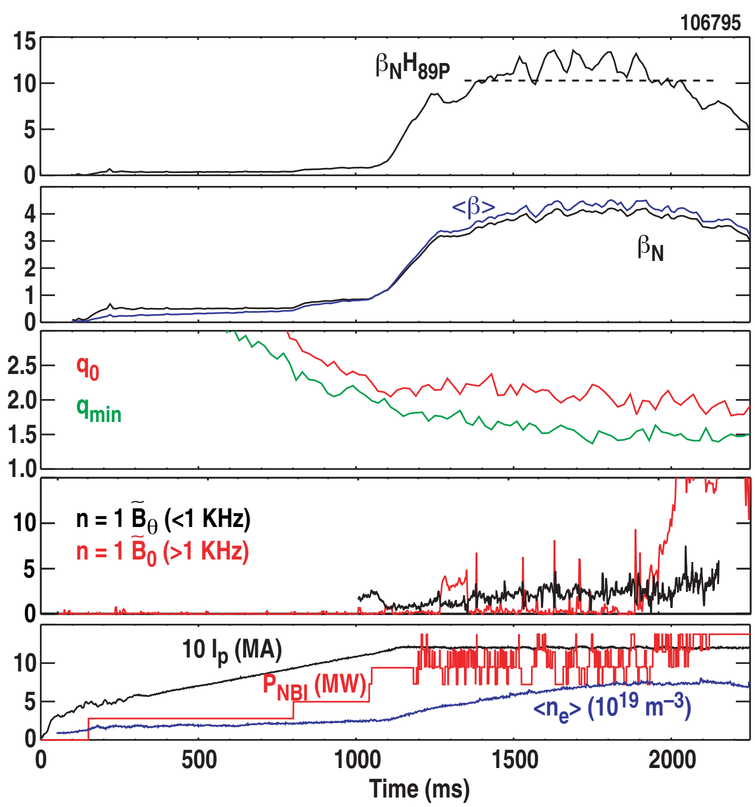

Fig. 2–1. A high performance, $\beta_N H_{89} > 10$, high bootstrap fraction, $f_{BS} \sim 65\%$, discharge sustained for four energy confinement times.

Predictive simulations based on experimental profiles taken from this year's best examples of integrating the required aspects of an AT scenario offer the exciting prospect of sustaining $\beta_N = 4$, $H_{89} = 3.1$ with $f_{BS} = 65\%$ for 20 s with distributed ECH power that will be available next year, 3.5 MW (Fig. 2–2). The ECH power deposition profile can be appropriately distributed by varying the launch angle of the antennas.

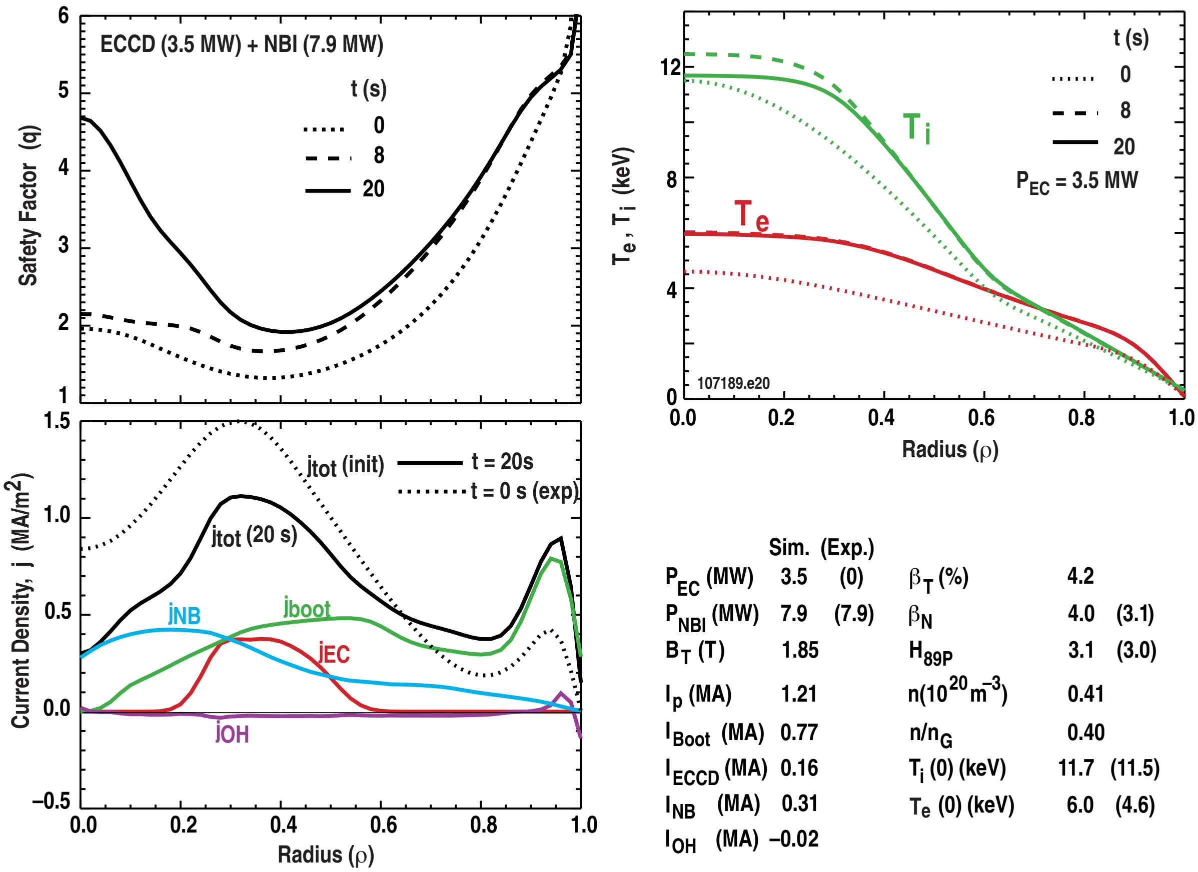

Fig. 2–2. Simulation based on experimental profiles with 7.9 MW of neutral beam injection showing that by adding 3.5 MW of distributed ECH power the q profile evolves in a way that is consistent with an AT scenario and that a high performance discharge can be sustained for 20 s.

2.2. STABILIZATION OF RESISTIVE WALL MODES — THRUST 4

Progress in high performance AT research relies on avoidance and control of magnetohydrodynamic (MHD) instabilities, particularly RWMs and NTMs. The normalized plasma pressure, β_N, is limited by RWMs making stabilization of these modes essential for achieving high performance regimes of operation. Spinning the plasma provides a way to stabilize RWMs and thus make possible operation above the no-wall β limit. When the plasma spins rapidly, an ordinary metallic wall should have the same stabilizing properties as a perfectly conducting wall. Initial experiments on DIII–D which raised the plasma pressure while spinning the plasma resulted in the spin rate slowing down and an unstable plasma.

While utilizing new tools developed this year, including internal sensors for radial and poloidal magnetic field measurements and an active feedback control system, several key discoveries were made:

- Rotation slowing is a consequence of "error field amplification" at β above the no-wall limit.
- Reduction of the nonaxisymmetric (error) fields enables continued plasma rotation at β above the no-wall limit.
- Active RWM feedback detects and minimizes the amplified error field.

Integrated together, the discoveries led to a reduced error field which allowed sustained plasma rotation leading to stable operation well above the no-wall β limit (Fig. 2–3). Along with this impressive demonstration of stable operation above the no-wall limit, the physics in this area was advanced by validation of models of plasma rotation slowdown and RWM stability. Benchmarking of the VALEN model and other feedback models was accomplished.

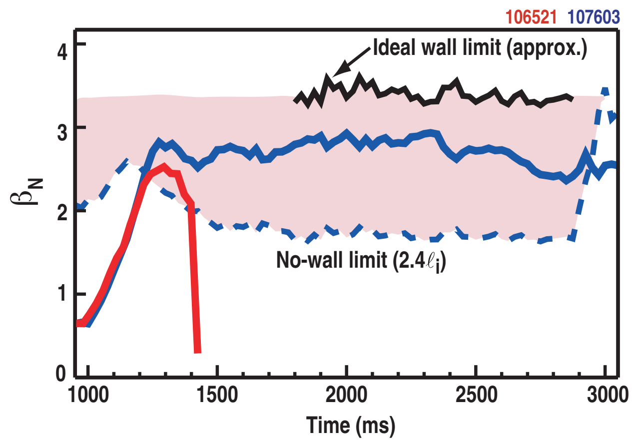

Fig. 2–3. Stable operation well above the no-wall β limit has been demonstrated on DIII–D when the RWM is stabilized by sustained plasma rotation due to active feedback reduction of error fields (shown in blue). The plasma rotation slows and the plasma becomes unstable above the no-wall limit without active feedback (red).

2.3. INTERNAL TRANSPORT BARRIER CONTROL — THRUST 7

The major areas of research for this thrust are to develop profile control tools to vary the position and strength of internal transport barriers and to assess the viability of an ITB-based approach to an AT high performance regime. In 2000, the quiescent double barrier (QDB) mode was discovered to have enhanced performance by virtue of combining an internal transport barrier with an edge localized mode (ELM)-free H–mode edge transport barrier. The edge pedestal elevates the central temperatures beyond the normal values obtained in an ITB with an L–mode edge (Fig. 2–4), thus making QDB an interesting candidate for an AT scenario. There was considerable emphasis on achieving a better understanding of QDB discharges this past year which lead to several highlights:

- Further improvements in QDB performance and duration were obtained, $\beta_N H_{89} \sim 7$ with $\beta = 3.9\%$ for 10 τ_E.
- Expanded QDB operating space with $I_p \leq 1.6$ MA and plasma shape compatible with good divertor pumping allowing density control.

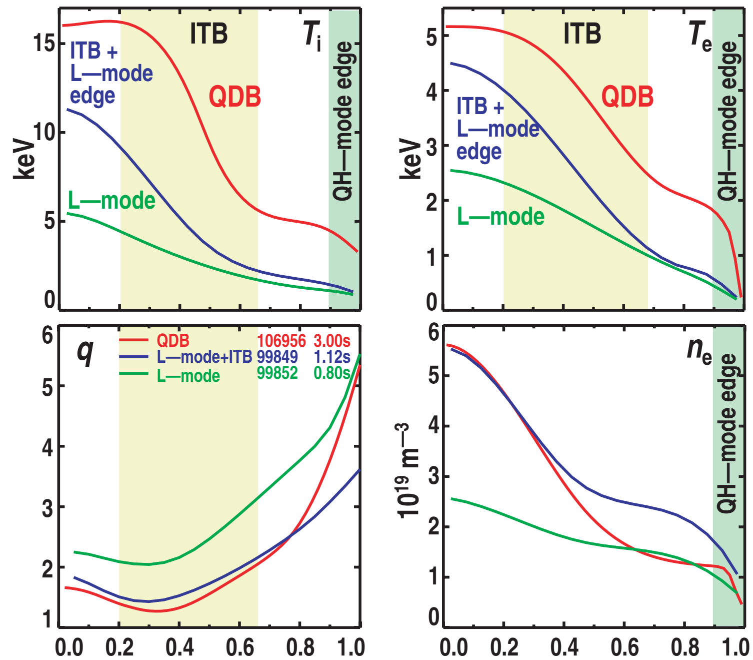

Fig. 2–4. Comparison of profiles in L–mode, ITB + L–mode edge and QDB discharges. The QDB regime combines a core transport barrier with a quiescent edge barrier which elevates both the edge pedestal and central temperatures, improving the fusion performance over ITB discharges.

- Measured neon transport coefficients particle diffusivity and pinch velocity (D&V) in QDB plasmas were much greater than neoclassical levels and impurity density profiles were less peaked than neoclassical predictions.
- Core turbulence amplitudes in QDB were strongly reduced but were not completely suppressed.
- Simulations of QDB discharges with the GLF23 transport model reproduce the core ($\rho \leq 0.7$) ion temperature profiles, also with incomplete suppression of the ITG mode.

2.4. UNDERSTANDING AND CONTROL OF EDGE PEDESTAL — THRUST 1

The long-term goal for this thrust is to develop the scientific basis for predicting the height of the H–mode pedestal and ELM effects on the plasma core. During this fiscal year, efforts concentrated on continuing to develop a model of edge MHD stability and experiments focused on a better understanding of the physics controlling the width of the edge density barrier and ELMs in plasmas with an H–mode edge and the key physics underlying quiescent H–mode (QH) discharges. The QH–mode, discovered in DIII–D in 2000, is an H–mode discharge with good confinement but without ELMs which is a highly desirable characteristic for future reactors where heat loads to the wall caused by ELMs is a concern. Highlights of major results from experiments addressing these issues are:

- Strong evidence was found that neutral penetration controls the width of H–mode density pedestals.
- Edge pedestal plasmas with the same nondimensional parameters in DIII–D and Alcator C–Mod have similar profiles and microstability properties.
- QH–mode plasmas have large edge radial electric fields.
- The QH–mode edge has lower density and higher temperature than conventional ELMing H–mode.
- The edge harmonic oscillation found in QH–mode plasmas is located at the base of the density pedestal, outside the separatrix.

In one of these experiments, a "wind-tunnel" approach was employed to study the confinement and stability conditions of the plasma edge. These conditions are important because they play an important role in determining the confinement and stability of the entire plasma. The experiment tested basic plasma physics theory which predicts that similar plasma phenomena should be observed in two machines if certain "nondimensional parameters" were matched (Fig. 2–5), even though the machines have significantly different sizes and magnetic field strengths. When the nondimensional parameters were matched near the boundary, the edge plasmas in DIII–D and Alcator C–Mod exhibited the same energy transport characteristics; they exhibited the "quasi-coherent mode", a small-scale instability (Fig. 2–6); and they were both found to be very near the threshold for the development of a large-scale edge instability (ELMs). Thus, the experimental results were consistent with the predictions of basic theory and show that the wind-tunnel approach, using nondimensional parameters, is a very productive method to compare results from different tokamaks.

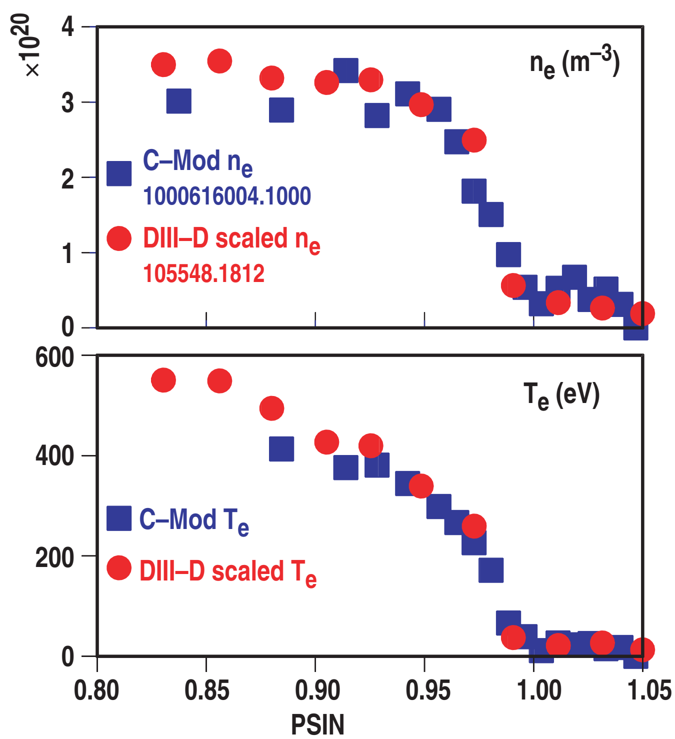

Fig. 2–5. Comparison of DIII–D and C–Mod edge pedestal profiles showing the similarity between the DIII–D and C–Mod pedestals. The DIII–D profiles are scaled to C–Mod values.

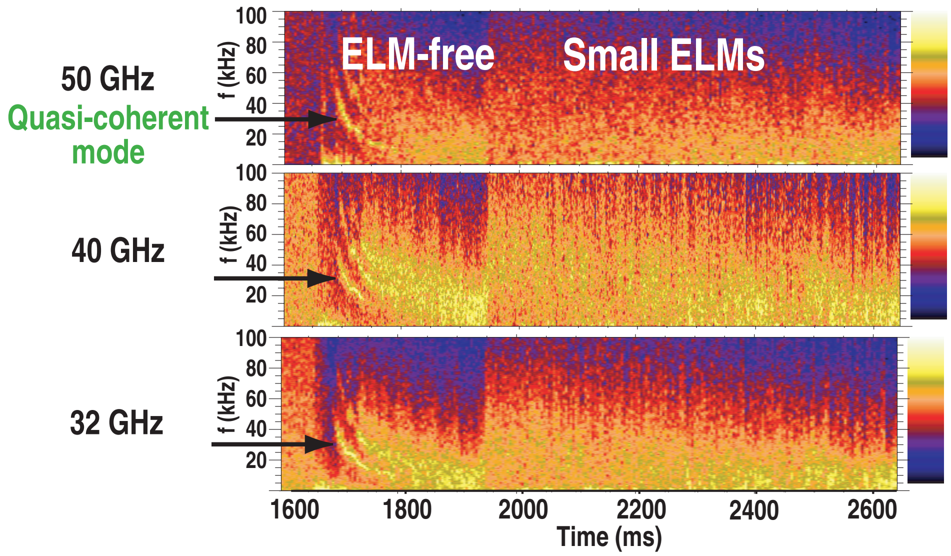

Fig. 2–6. Color contour plots of the density fluctuation power spectra versus time for homodyne reflectometry (UCLA) at 32, 40, and 50 GHz (corresponding to densities in the edge gradient region) showing the presence of a "quasi-coherent" mode in the DIII–D edge during the ELM-free phase.

2.5. STABILIZATION OF NEOCLASSICAL TEARING MODES — THRUST 3

The fundamental goal of this research area is to advance the physics understanding of NTMs, which are magnetic islands that occur at high plasma temperature and pressure, in order to better understand how to predict and thus possibly avoid or otherwise suppress these instabilities.

NTM islands can be reduced or eliminated by applying a small electrical current in the island. The current must be located very precisely at the island in order to be effective. The key experimental result this year was a demonstration of the first automatic, real-time control of the current drive location to suppress m/n = 3/2 NTMs with ECCD (Fig. 2–7). The plasma control system (PCS) was put into a "search and suppress" mode that makes either small shifts of the plasma position (~1 cm) while the current drive location remains fixed, or small shifts in the current drive location while the plasma position remains fixed. The optimum position in either approach is based on detecting and minimizing the size of the magnetic island. With this approach, the island can be suppressed in a routine way despite possible changes to its location. In the final experiment of the year, the plasma heating power was programmed to rise gradually after the island was suppressed. With the added stabilizing effect of ECCD, the normalized plasma pressure, β_N, was increased 20% higher than the point where the island had originally appeared and 55% higher than the sustainable pressure when the island had grown to full size.

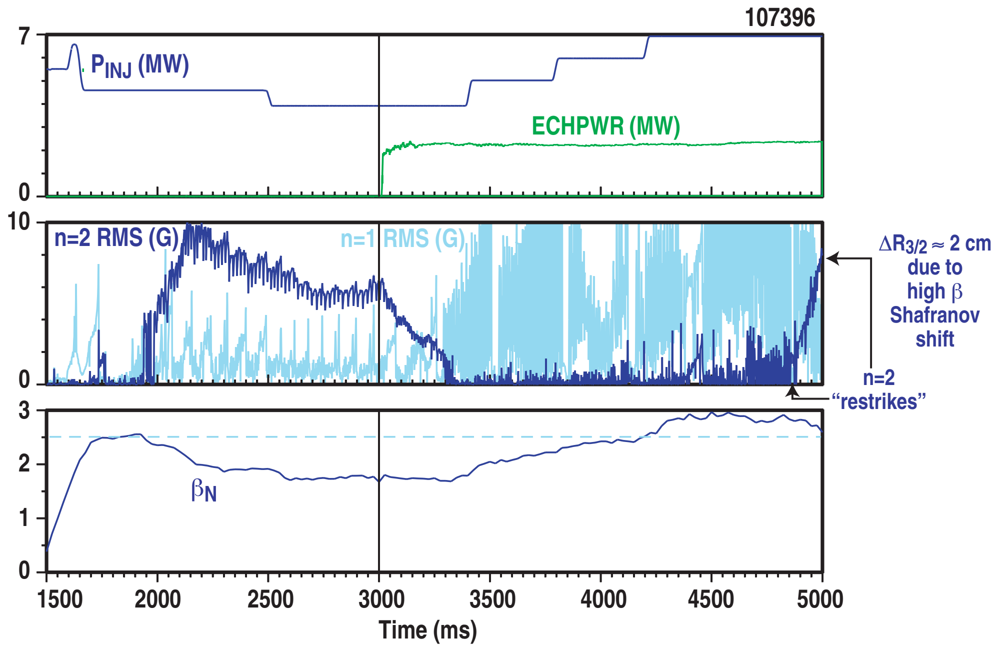

Fig. 2–7. Full suppression of the 3/2 NTM mode occurs at 3300 ms as a result of ECH power applied at 3000 ms and the PCS finding the 3/2 mode surface. At this point, the PCS is fixed. Suppression is maintained even during fishbone and sawtooth activity (see n=1 trace) and β_N increases by 55%. An n=2 mode returns later in the discharge because the 3/2 mode moves out radially by about 2 cm due to the Shafranov shift at high β and thus the ECH resonance is no longer at the mode surface.

2.6. STABILITY TOPICAL SCIENCE AREA

The areas of interest in the stability TSA span both basic and applied MHD stability physics and focused effort on key issues in several research thrusts including RWM stabilization (T4), NTM physics and stabilization (T3), and edge pedestal stability (T1, T7). The major basic and applied MHD stability physics areas studied this year included ideal and resistive MHD, disruption dynamics and mitigation, stability of high performance plasmas, and advanced control systems improvements. Highlights of the experimental results include:

- Successful mitigation of disruptions by a high pressure gas jet was demonstrated.
- Resistive interchange mode structure was documented and some data on threshold conditions were obtained.
- Sawtooth behavior appears correlated with the Mercier stability criterion.
- Stability analysis suggested that some NTMs may be classically destabilized.
- Many PCS capabilities were improved or expanded.

High-pressure injection of neon and argon was used to simultaneously mitigate disruption thermal loading and control runaway electron amplification. The jet pressure exceeded the plasma pressure with the result that it effectively penetrates to the central portion of the plasma in a few milliseconds, increasing the total particle content in the plasma volume by a factor of 50. As a result, the plasma energy is then dissipated uniformly by ultraviolet radiation from the gas species, spreading the heat evenly over the wall area and avoiding local hot spots. The plasma cools quickly, leading to rapid decay of the plasma current (Fig. 2–8) while minimizing wall currents and mechanical stresses. More importantly, the impurity remains in a low charge state — that is, only one or two of the electrons have been removed from the impurity atoms. These electrons still bound in atoms slow down the ultra-high energy electrons (runaway electrons), reducing greatly or eliminating the rapid multiplication of these runaway electrons otherwise experienced in the rapid decay of hydrogenic plasma.

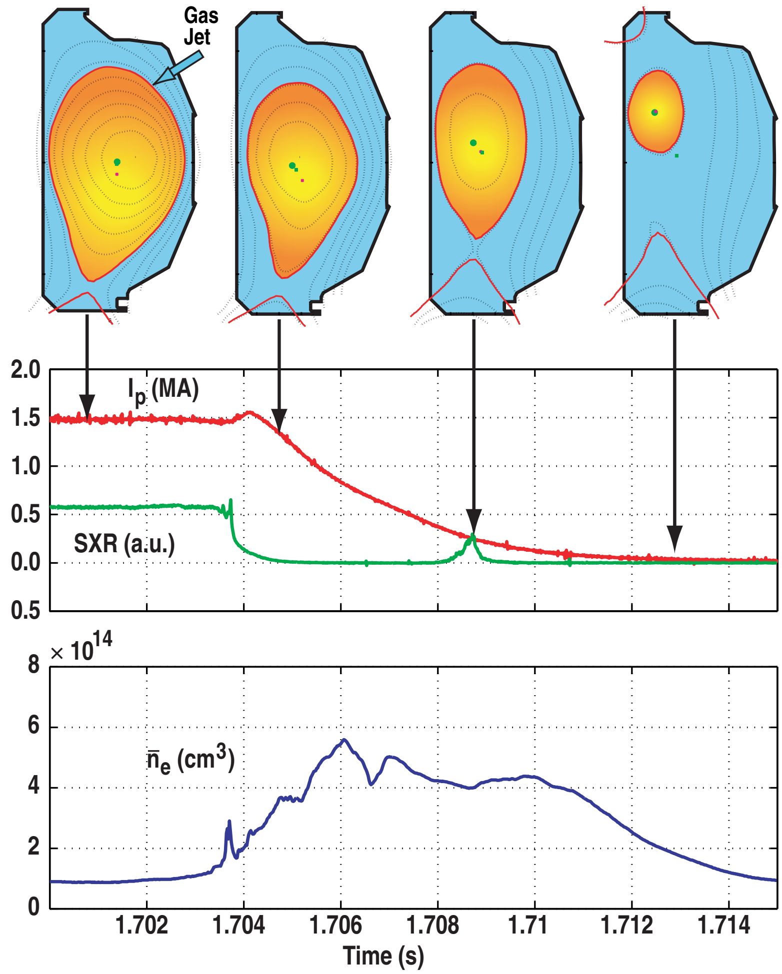

Fig. 2–8. Controlled plasma termination in DIII–D induced by noble gas jet.

2.7. TURBULENCE AND TRANSPORT TOPICAL SCIENCE AREA

The long-term goal of this TSA is to develop a predictive understanding and control of cross-field plasma transport in tokamak plasmas. This is a very active area of research on DIII–D with many more experiments proposed each year than can be accommodated within the experimental run time; 9 out of 50 experiments proposed this year were performed. Continued improvement to modeling capabilities is an essential activity in parallel with experiments and has resulted in the capability to compare measured turbulent fluctuations and correlation lengths with those predicted from gyrokinetic simulations. Figure 2–9 shows radial correlation lengths from gyrokinetic simulations that are comparable to measured values in a QDB discharge. Correlation lengths for L–mode discharges are 5–10 times the gyroradius based on the sound speed velocity (shaded region in Fig. 2–9). The radial correlation lengths are considerably shorter for QDB discharges compared to L–mode discharges and consistent with reduced transport in the QDB mode. The simulations also indicate the importance of zonal flows as a turbulence stabilization mechanism with flow magnitudes of the order of observed E×B flows.

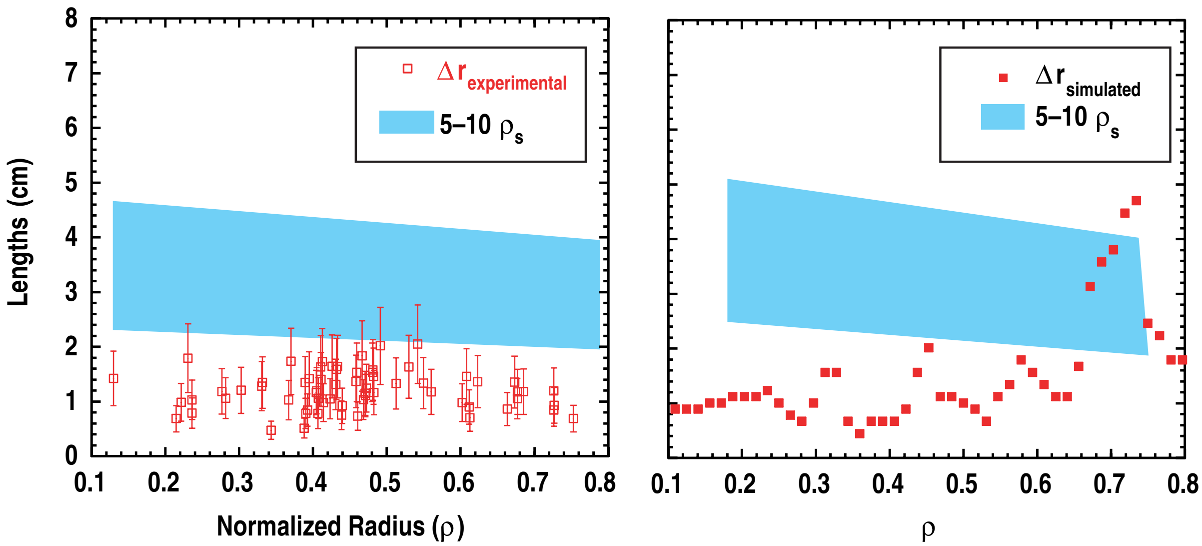

Fig. 2–9. Measured and simulated turbulence radial correlation lengths for a QDB discharge showing good agreement between simulations and experimental values. Values for L–mode discharges (shown as shaded region) are considerably larger.

Additional highlights from research in this area this year include:

- Demonstrated that increased poloidal velocity shear measured prior to the L-to-H transition correlates with lower H–mode power threshold in plasmas where the threshold is varied by changing the plasma shape from lower single null to balanced double null to upper single null.
- Preliminary analysis of experiments confirmed the existence of a heat pinch in the electron channel.
- Demonstrated a strong reduction in plasma transport with increasing vertical plasma elongation.
- Expanded the heat pulse propagation database for comparison with transport theories and demonstrated that the existence of a critical gradient scale length in the electron channel does not necessarily lead to a stiff or clamped local T_e response to local heating.

2.8. HEATING AND CURRENT DRIVE TOPICAL SCIENCE AREA

This year saw the electron cyclotron system come of age with reliable four-gyrotron operation that was utilized in many different experiments. The major highlights in this area included:

- Validation of operation, aiming, and polarization control for gyrotrons in new antenna configurations.
- Validation of the theory showing that high electron beta improves the efficiency of ECCD, consistent with AT program requirements.
- Demonstration of discharges with very high bootstrap fraction, f_{BS} ~ 70%, and nearly fully noninductive current sustainment using ECH and neutral beam heating.

Theoretical analysis showed that the improvement of efficiency of ECCD with electron pressure can be attributed to the changes in the relativistic Doppler-shifted electron cyclotron resonance in velocity phase space. Stronger damping of the second harmonic extraordinary mode, which is due to higher density or temperature, increases the Doppler shift, and higher temperature causes stronger curvature of the resonance due to relativistic effects. Both of these effects tend to move the interaction of the wave with the particles further away from the trapped-passing boundary, thereby reducing the effect of trapping of the current-carrying electrons in the magnetic well. The measured ECCD efficiency over a wide range of plasma conditions was consistent with Fokker-Planck code predictions and indicated that the efficiency increases in high β plasmas (Fig. 2–10). For the discharge at β = 3.7%, the ECCD efficiency is consistent with that required for an AT scenario.

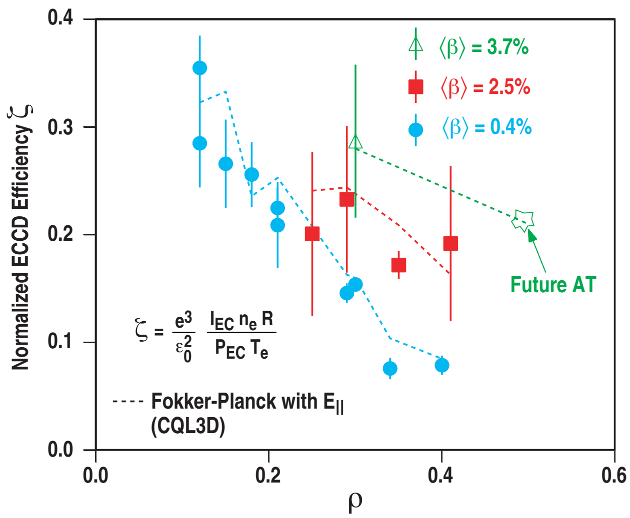

Fig. 2–10. Off-axis ECCD efficiency agrees with theory and increases in high β plasmas.

2.9. BOUNDARY PHYSICS TOPICAL SCIENCE AREA

The major goal of the boundary physics research is to develop predictive capability for the scrapeoff layer (SOL) and divertor plasma and to test new divertor ideas and materials. One interesting highlight from experiments this year challenges the conventional picture of plasma flow to the divertor where plasma crossing the separatrix should flow quickly along the field lines in the SOL to the divertor. Enhanced radial transport in L–mode plasmas was documented with Langmuir probes and beam emission spectroscopy measurements and indicated that the particles and energy crossed the separatrix as intermittent plasma objects (IPOs) that travel rapidly towards the walls (Fig. 2–11), accounting for 50% of the total cross field particle and energy transport. The frequency and intensity of the IPOs increases as the plasma density is increased. Although it is not known yet under which conditions these phenomena are dominating the SOL transport, this finding is consistent with previous observations of an anomalously thick SOL in the ALCATOR C–Mod tokamak.

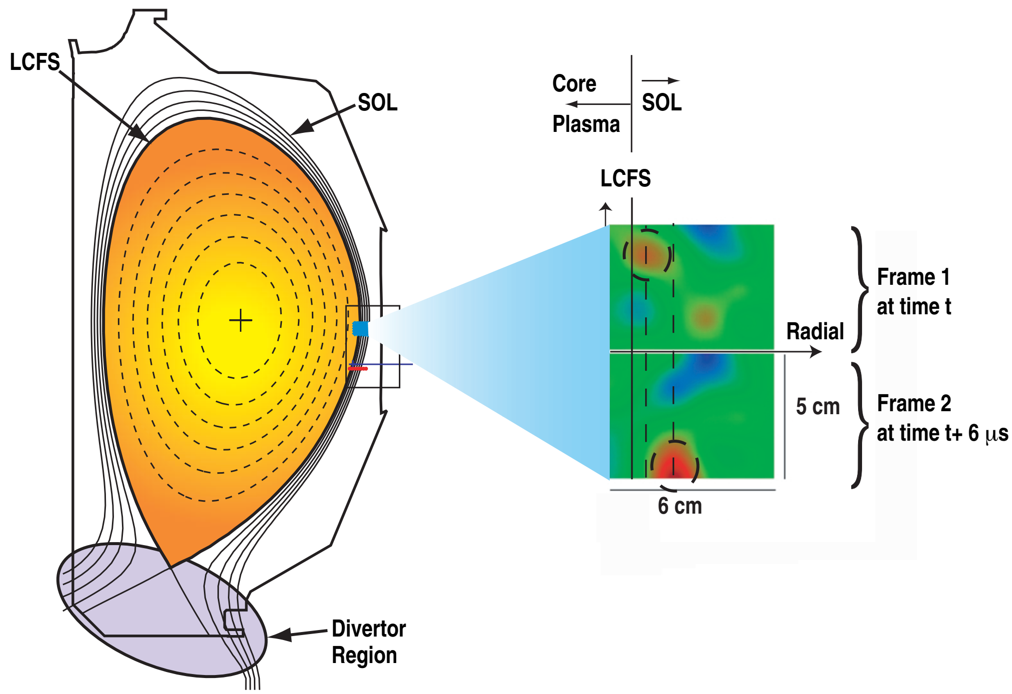

Fig. 2–11. Beam emission spectroscopy measurements show rapid radial transport of an IPO (see red object for instance) across the LCFS and in the SOL.

Additional research highlights include:

- An L–mode plasma with no MHD or ELM activity was carefully documented to benchmark modeling codes.
- A predator prey model was used successfully to model certain L–H transitions.
- Open and closed divertors using gas puffing to achieve high density showed little difference in the maximum achieved density or H–L transition density.
- Sputtering data on solid lithium was obtained and MHD induced macroscopic ejection of liquid Li caused a radiative collapse.
- Sublimation at the edges of carbon tiles protecting the vacuum vessel walls was not important to core carbon contamination

3. FACILITY OPERATIONS

FY01 was a highly productive year for the Operations Group despite considerable challenges presented by the uncertainty of power availability and pricing in California throughout the year. By operating on a 14-h extended day and compressing the operation into the period from February through June in order to avoid the anticipated summer power shortages, the facility was able to operate effectively and support a vigorous and productive research program (Fig. 3–1). In addition to operations, we pursued a series of continuing facility and equipment upgrades, modernizations, and refurbishments. As in previous years, the vessel was vented prior to the start of the fiscal year and the vent continued until the end of November 2000 for installation of the internal saddle coils for detection of the RWM, repair of the E–coil lead tensioning device and installation of the Li beam diagnostic optics. Following new system commissioning and startup, the research program resumed in February operating until the end of June. Another vent period began in August 2001 with the primary task of installing two internal control coils for stabilization. In addition to the vent and operational periods, the highlights for the year include:

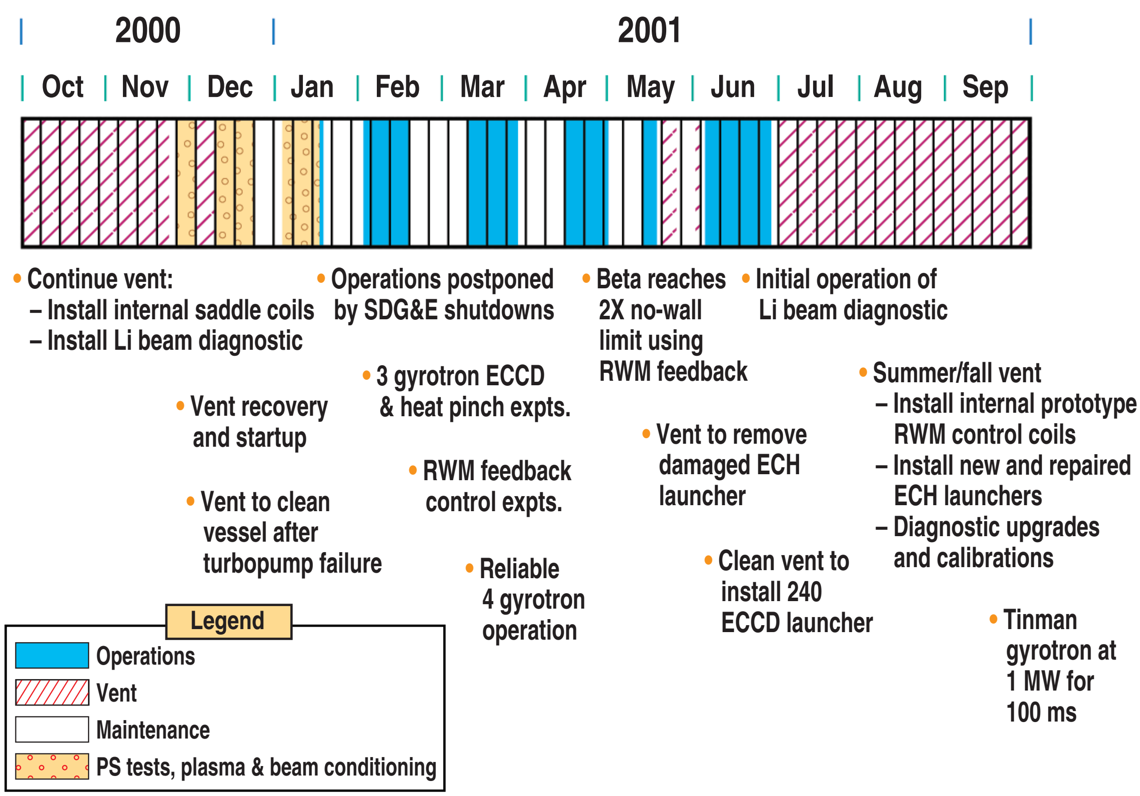

Fig. 3–1. DIII–D FY01 operations highlights.

3.1. TOKAMAK OPERATIONS

The entire operation schedule for the year was completed in an intense run period during the second and third quarters. The operation days were mostly on 14-h double shifts with some 10-h single shifts scheduled in order to reduce electricity costs and avoid power shutdowns. A total of 58 days of operations were obtained (40 scheduled, 14 rescheduled, 4 extra) during which time the availability was 72% (75% excluding power shut downs). The availability statistics are shown in Fig. 3–2. The largest source of lost time (Fig. 3–3) was due to failure of an ECH launcher that required a vessel entry vent to remove the launcher and clean up aluminum debris from the launcher. A total of 16 days of power testing and 14 days of plasma checkout were used to prepare for operations, condition the machine, and recover from vents. Also performed were 23 bakes, 5 boronizations, and 6 Rayleigh scatterings. There were 126 vessel entry vent days and clean vents on 3 days.

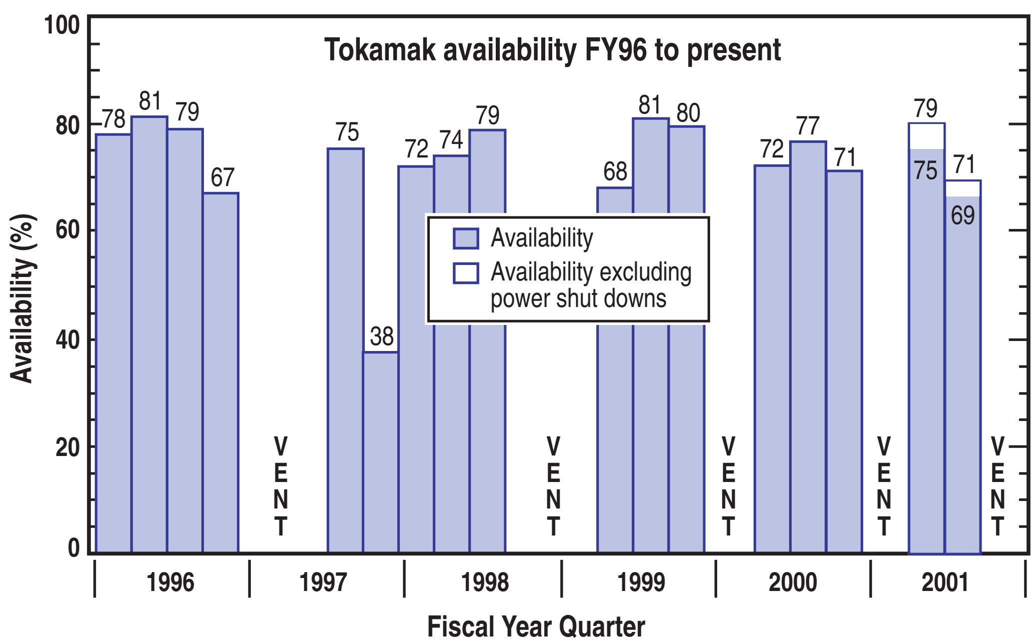

Fig. 3–2. DIII–D availability by fiscal year quarter.

3.1.1. Vents

There were four vessel vents involving personnel entry during FY01. The first vent which started during the summer of 2000, was continued at the start of the fiscal year and successfully completed both on schedule and within the radiation guidelines established by management. The major task completed during the vent was the installation of the RWM internal sensor coils. The full sensor set installed beneath the tiles included 18 picture frame coils to provide full toroidal coverage in three poloidal planes and four poloidal magnetic

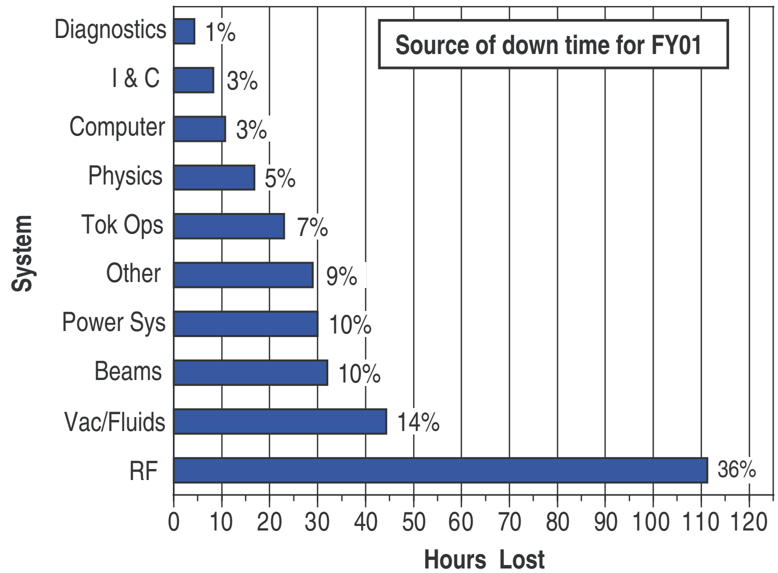

Fig. 3–3. FY01 source of down time.

probes. Three technicians from Princeton Plasma Physics Laboratory (PPPL) were used in support of this effort. Additional work performed during this vent included repair of the Ohmic heating coil lead tensioning device and installation of the optics for the Li beam diagnostic.

A five-day vent successfully cleaned up a very large amount of dust and debris that had covered the inside of the vessel after a turbopump failed explosively following the end of the 2000 vent. The entire vessel, ceiling to floor, was cleaned. Results from operations showed that the cleanup of the metal was very successful; there were no major metal impurities and very few impurity bursts.

A seven-day vent was required to remove and clean up the debris from a failed ECH launcher during operations in the third quarter.

The summer 2001 vent started at the end of July after a five-week radiation decay period. The initial vessel entry and inspection found the vessel to be in very good condition with no damage and no splattered metal or deposit evident. Also, an air sample analysis showed no detectable levels of lithium or beryllium, which was considered a possible concern due to their use during operations. The major vent task was installation of two prototype RWM control coils. The installation was completed in early FY02 followed by three weeks of extensive diagnostic calibration.

3.1.2. Vacuum Programmable Logic Controller Upgrade

The final phase of the upgrade of the vacuum system Programmable Logic Controller (PLC) was successfully completed in time for the machine pump down and startup at the beginning of the fiscal year. This task involved moving the wiring of more than 900 signals from the old PLC to the new one, rewriting the entire PLC code on the new platform, and creating new graphical interface screens. This project eliminated most of the outdated and unsupported equipment in the vacuum control system while providing for improved monitoring and interface controls.

Also among the many improvements in the vacuum PLC is new logic control for bakes that provides for a faster temperature rise to the final bake temperature while also reducing the power cost for the bake.

3.2. MECHANICAL ENGINEERING

The desire to stabilize the RWM up to the ideal wall beta limit, spurred an effort to study the feasibility of installing in-vessel control coils as an upgrade to the existing external C–coil. The scope was expanded to compare the programmatic risk/benefit of in-vessel versus ex-vessel coils. The in-vessel concept evolved into a design for single turn, wall-mounted saddle coils comprised of a hollow water-cooled copper conductor insulated with ductile polyimide material housed inside a stainless steel tube vacuum barrier.

A parallel analysis effort using the VALEN code indicated that a set of 12 single-turn internal control coils above and below the midplane (R±1) could stabilize the RWM to greater than 97% of the ideal wall limit. This represented a significant improvement over the existing C–coil and over an alternative proposal for a set of 18 external coils. The selection of the in-vessel design over the ex-vessel design was made in early May based on improved performance projections, less intrusive space requirements, and projected equal costs.

An aggressive development effort was conducted to develop successful designs that would allow for high temperature copper brazing and welding of the stainless vacuum jacket without overheating the polyimide insulation. Two prototypes were successfully built and installed during the summer/fall vent. Based on the tremendous progress this year in RWM stability research, the importance of this research to the AT program, and the success of the prototypes, a full set of 12 internal control coils will be installed in the fall 2002 vent.

Considerable progress was made this year on improving the performance and reliability of the water systems. Continuing problems in maintaining water quality with the water system supplying high pressure to both the ECH gyrotrons and the neutral beam sources was resolved by separating the water into two systems to better meet the different requirements of each user. The new neutral beam system was operational in December 2001 and has reliably provided deoxygenated and deionized high pressure water required for beam operations. The separated ECH water system began operation in September and provides a steadier flow of deionized cooling water that is essential for the accurate calorimetry performed on that system.

The DIII–D water system that supplies coil and vessel cooling was also improved with added instrumentation and PLC control and monitoring. This provides improved alarms, trend monitoring, and control room system control and status display.

3.3. COMPUTER SYSTEMS

During FY01, 855 gigabytes of raw data were acquired from the DIII–D experiment, with the largest shot being 514 megabytes. To meet the growing needs for data storage, user disk space, and computational capabilities, a number of upgrades to computer systems were made. A 400 gigabyte magnetic disk array was added for raw shot data, and later a 1.3 terabyte disk array was added. These were initial steps towards the goal of storing all raw data on magnetic disk permanently. Four hundred gigabytes of disk space was added to the Network Appliance Filers for use by the user community. The aging central processing unit (CPU) server, Hydra, continued to run out of CPU and memory resources under intense usage. A new HP L3000 computer was ordered that has four CPUs, each approximately four times more powerful than the current ones and an increased memory capacity of eightfold. The network link to the DIII–D facility was converted from FDDI to Fast Ethernet, which will permit further expansion to greater bandwidth.

Computer security issues have become increasingly important as the frequency and intensity of Cyber intrusion attempts escalates. The new Cisco firewall has been of substantial aid in defeating such attempts. There was a dramatic reduction in unauthorized FTP network access after FTP was blocked at the firewall for most systems. Numerous security patches have been applied to various operating systems in order to plug security vulnerabilities. Initial work began for implementation of RSA SecureID.

Substantial progress was made in FY01 on a major upgrade to the PCS. This upgrade was motivated by the need for newer capabilities and by the need to eliminate unsupportable hardware. A custom Linux kernel was installed and tested on an Alpha-Linux computer. Near the end of FY01 operations, a significant milestone was achieved when the upgrade computers were used to perform shape control using the isoflux method for a second of the plasma ramp down phase for several shots. This demonstrated the successful integration of the upgrade computing hardware with the old system. Work then progressed towards a first phase system that would be used for FY02 operations and would include three upgrade computers running Linux working in conjunction with three old i860 computers. Other work on the PCS system included completing RWM changes, implementing an NTM algorithm, enhancing the neutral beam substitution code, providing bean shape control, and rearranging code to make it more generic and thus more portable to other systems.

Work began on a project to upgrade the aging tokamak operations and neutral beam control computer systems. A working group was formed to explore different options and to provide proof of principle for various components. The upgrade path is based on a customized Linux control system utilizing much of the existing codes. Other work included developing a Linux CAMAC driver for the Kinetic Systems 2115 CAMAC driver hardware and evaluating the Kylix Visual tool for developing control screens under Linux. The system is expected to be ready for FY03 operations.

Software work continued for the Thomson scattering diagnostic, in particular, for data reanalysis resulting in a first practical version of the reanalysis code. Six fit evaluation plots and multiple displays for the analysis were completed. A new version of the Thomson software was released that had corrected problems regarding access of calibration data. A new program for managing calibration data was written and installed.

3.4. ELECTRON CYCLOTRON HEATING AND CURRENT DRIVE

The 110 GHz gyrotron system reached a level of performance and reliability during FY01 which approached that of the mature neutral beam systems. The three Gycom gyrotrons were available routinely, each generating at least 700 kW at 2.0 s pulse length. The CPI–P2 gyrotron added to the installation an additional 800 kW generated rf power for 2.0 s pulses. The typical power injected into the tokamak was 2.2 MW from all four gyrotrons, for the full 2.0 s pulse length. In Fig. 3–4, the total power traces for 14 consecutive tokamak shots with these parameters are presented.

Following the year's experimental operations, the CPI–P2 gyrotron was conditioned to operate at 81 kV, 42 A and demonstrated 1 MW operation at 5.0 s pulse length, thus qualifying the design of the gyrotron and the ancillary equipment to these high performance levels. Prior to operating at this level, the diamond window was diagnosed *in situ* with Raman scattering and a graphite surface contamination, which probably had been deposited during manufacture of the tube, was removed by alumina grit blasting. Infrared measurements of the window temperature during pulse length extension showed a peak temperature of 150°C, consistent with modeling of these performance levels. This temperature produces stresses well within the yield for diamond with a safety factor of two.

The CPI–P3 gyrotron was tested to factory acceptance performance and delivered to DIII–D. Installation began immediately. The CPI–P1 gyrotron, which had shown a window seal failure during initial operation at DIII–D, was repaired at CPI and is ready for factory testing. The new power supplies for the ECH system, which had suffered from problems with the crowbars, were modified and performed very well during the experimental campaign, making possible the reliable operation of the complete installation. The 2002 experimental campaign should begin with a four-gyrotron system to which two more gyrotrons will be added. Waveguide hardware and control system electronics and software are on track to support the full six-gyrotron system during the campaign.

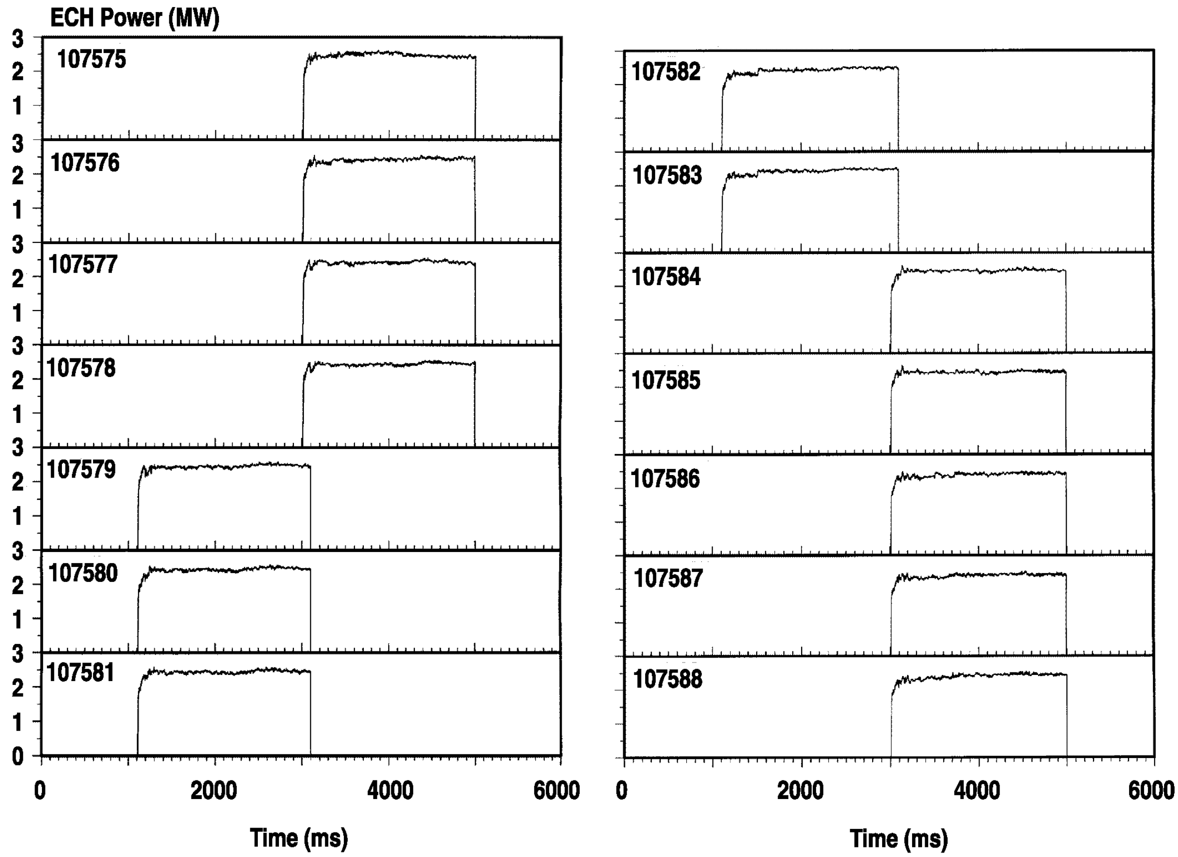

Fig. 3–4. 110 GHz ECH system performance. Fourteen consecutive four-gyrotron shots with >2 MW for 2 s.

3.5. ELECTRICAL ENGINEERING

The largest single project for the group was the completion of the ECH high-voltage power supply No. 2. Both ECH power supplies Nos. 1 and 2 were operational for much of the year and were to support gyrotron operations. The high voltage group also continued to support neutral beam operations at a high level of availability. The power systems group began upgrading various interface and control circuits that, over time, have become a reliability concern. A new F–coil over current trip circuit was designed and fabricated while a new design for the F power supply control system was initiated. The group also supported tokamak operations and testing of the new prototype internal correction coils. The instrumentation and control group spent considerable resources in both the support of existing systems and implementing new designs to support the PCS and the ECH system. In particular, a new watchdog system that monitors proper PCS operation was implemented and a new control system for a steerable ECH launcher (provided by PPPL) was designed, fabricated, and tested.

3.6. NEUTRAL BEAMS

The neutral beam systems continued to operate with high availability in supporting DIII–D physics program. They provided the requested beams (or comparable substitute beams) to the physics experiments 93.7% of the time, despite problems associated with the aging of the ion sources and the power supply system. Failures of the critical ion source components continued this year; there were no longer enough parts to make two full spare sources. A local vendor has manufactured spare masking plates, however, efforts (by outside vendors and internal group) to make the spare grid assemblies have yet to produce any units. Reducing the pressure of the source cooling water from 150 to 115 psi may have helped prevent failures of the masking plates in FY01. The auto-transformer of one beam power supply system failed in the third quarter and was replaced by a loaned unit from PPPL.

A number of projects were completed this year that improved the maintainability and availability of the beam system. A new water cooling system for ion sources was constructed and has been in service, separating the ion sources from the water system cooling the ECH gyrotrons. This system is smaller in size and its water quality (dissolved oxygen level and conductivity) is much easier to maintain. A new upgraded beam pulse shaping module has solved the intermittent spurious beam control problem. Changes were made to the beam timing system to extend the window from 6 to 8 s within which the beam can pulse to support long-pulse physics experiments. New functions were added to the neutral beam workstation, which provide remote monitoring of the source water pressure and quality, the pressures of the source gas system (inlet line and gas bottle), and warning when beamline cooling is switched between the three water systems.

3.7. RADIATION MANAGEMENT AND SAFETY

Radiation management tasks include monitoring the site boundary radiation; monitoring the dose exposures of individuals; ensuring compliance with legal limits, DOE guidelines and DIII–D procedures; monitoring material for activation; maintaining and operating the radiation monitoring detectors (neutron and gamma); and maintaining a database of dose exposures for both the site boundary and for personnel.

The total neutron radiation at the site boundary for FY01 was 7.9 millirem; the total gamma radiation was 3.9 millirem; giving a total site dose for the year of 11.8 millirem. This is below the SAN DOE annual guideline limit of 40 millirem and the California annual limit of 100 millirem.

The total dose exposure of personnel was kept below the DIII–D procedural limits of 30 millirem/day, 100 millirem/week, and 400 millirem/quarter (1600 millirem/year). The highest personnel dose for the year measured by the radiation monitoring film badges was 270 millirem of gamma radiation. A total of 26 individuals had measurable film badge doses with a total person-rem for the year of 2.34. The highest dose accumulated and measured by the personnel digital dosimeters by an individual from pit runs and vessel entries (but not operations) for FY01 was 440 millirem. A total of 122 individuals received doses with 54% of the doses being below 25 millirem. All doses were logged in the database of personnel radiation doses.

Four DIII–D radiation training classes were given as part of the radiation and refresher training. A total of 126 people received training. Five (5) fusion personnel also attended the general radiation training classes given by General Atomics (GA) Health Physics for new personnel.

The DIII–D ALARA committee met and reviewed both the site radiation production and personnel doses for the previous year. Items of note from CY00 included: the total site dose for the year of 12.5 millirem set a new record, the total site dose in a day also set a new record (0.61 millirem), and 4 days from 2000 are among the top radiation producing days. The personnel doses, however, were less than in 1999 and there were no neutron doses received. The CY00 ALARA goals were met and ALARA goals for the summer vent were chosen.

Waste disposal during the year consisted of 16 gallons of mixed waste (oil contaminated with tritium) sent to an off-site vendor for disposal. The total contamination estimate of the disposed waste for the year was less than 0.14 milliCurie of tritium.

An annual inspection and audit by GA Health Physics was held. No action items were generated. A tritium survey of the radiation survey area and the diagnostic lab "hot" shop yielded no detectable contamination.

There continues to be a strong emphasis on personnel safety in the DIII–D program and we pursue an aggressive program of task preparation including safety evaluation, training, and an ongoing system of tracking and reviewing all safety incidents to learn from all events and proactively prevent future occurrences. In FY01, there were 4 safety indoctrinations, 24 safety meetings, 32 Hazardous Work Authorizations reviews, and 32 training classes. There were three incidents that involved no injuries, one accident that involved minor off-site medical treatment and no lost time accidents.

A major upgrade of the equipment alarm system was performed this year. The new system has room for many more alarm points and the alarms are sent to the GA Security station where the nature of the different alarms are displayed. The new system thus gives a better coverage of the equipment status and allows a faster response when alarms come in to the security station.

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