DIII-D RESEARCH OPERATIONS ANNUAL REPORT

OCTOBER 1, 1999 THROUGH SEPTEMBER 30, 2000

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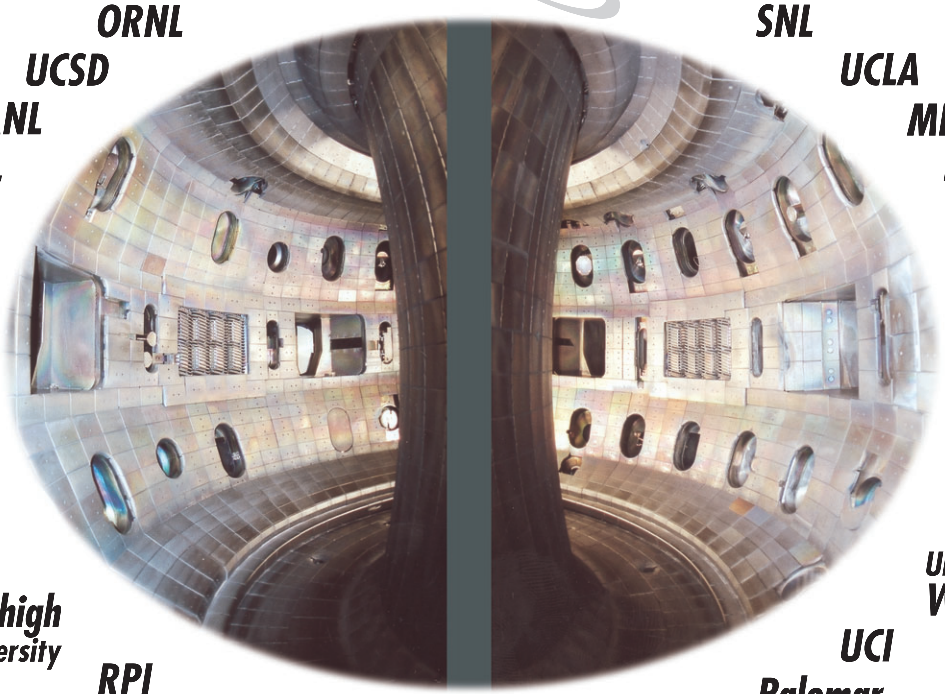

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DIII–D RESEARCH OPERATIONS ANNUAL REPORT TO THE U.S. DEPARTMENT OF ENERGY

OCTOBER 1, 1999 THROUGH SEPTEMBER 30, 2000

by
PROJECT STAFF

Work prepared under
Department of Energy Contract Nos.
DE-AC03-99ER54463, W-7405-ENG-48,
DE-AC02-76CH03073 and DE-AC05-96OR22464

GENERAL ATOMICS PROJECTS
30033, 30034, 30035, 30040
DATE PUBLISHED: AUGUST 2001

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1. DIII–D NATIONAL PROGRAM FY00 OVERVIEW

1.1. THE PLANNING PROCESS

The DIII–D Program is guided by its mission statement: "To establish the scientific basis for the optimization of the tokamak approach to fusion energy production." Presently, the focus of optimization is upon the development of so-called Advanced Tokamak (AT) scenarios which portend increased reactor attractiveness. This focus is bolstered by a broad effort in elucidation of the underlying science of all aspects of tokamak physics, since projections to future facilities are made credible by scientific understanding. The key to AT exploitation is control of plasma internal profiles — primarily the current density profile.

Over the past few years a roadmap has been developed to guide the research program toward its goals. It is modified annually as the results from the previous year are considered. The roadmap entering the FY00 experimental campaign is shown in Fig. 1–1. At present, the AT scenario being pursued is that derived from a number of years of research on negative central shear (NCS) discharges on DIII–D, referred to in Fig. 1–1 as the High Bootstrap Fraction Scenario. This scenario is characterized by a broad profile of the plasma current, well matched to a bootstrap current profile, and requiring off-axis current drive. (The other scenario shown for future investigation has centrally peaked plasma current, the so-called High-ℓ_i scenario.)

The NCS scenario requires the development of "enabling technologies," both in the engineering and scientific sense. The key to off-axis current drive will be the unique DIII–D gyrotron system for electron cyclotron current drive (ECCD). At fixed EC injected power more current can be driven at lower plasma density, so it is important to actively pump these AT discharges to lower the plasma density. Broad current profile discharges can be limited by resistive wall mode (RWM) instabilities, so active feedback control amelioration is beneficial. All of these areas of focused effort are defined as "thrusts" in the FY00 DIII–D campaign. A thrust has clearly defined goals leading toward the AT scenario and involving a group of scientists with expertise in multiple areas of tokamak physics.

For FY00, two major hardware additions came online for these thrusts together with some other improvements. A new upper divertor pump on the inboard side was installed to pump the plasma density in high triangularity AT discharges. And the gyrotron system continued to be expanded in terms of the number of gyrotrons and launching systems.

Also, a highly sophisticated articulating EC launcher built by PPPL was installed and proved to be a very valuable research tool. Additionally, the power supplies used for RWM feedback experiments were upgraded.

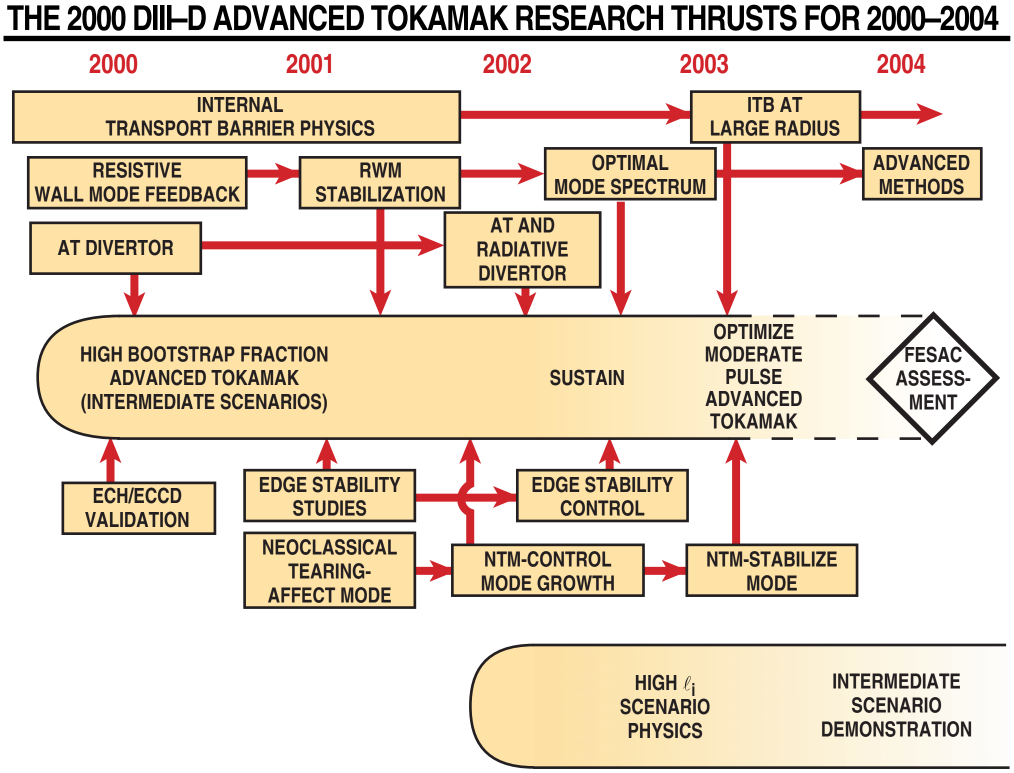


Fig. 1–1. Logic diagram for the DIII–D Advanced Tokamak Program, taken from the DIII–D Program Plan at the start of the FY00 experimental program.

The research thrusts and Topical Science Areas (TSA) for FY00 are indicated in Table 1–1. Another thrust is the internal transport barrier (ITB) thrust, tasked with developing understanding and control techniques for ITBs, useful in all AT research. The four TSAs are Divertor, Confinement, Stability, and Heating and Current Drive (H&CD). Each of these areas was assigned an allotment of experimental days for the FY00 campaign. (H&CD experiments were done under the EC thrust this year.)

With the FY00 research areas established, the annual DIII–D "Brainstorming Session" was held over three days early in the fiscal year. Nearly 200 proposals for experiments in these various areas were received and discussed at this time. In an iterative process between the DIII–D director, the DIII–D Research Council and the experimental area leaders, the FY00 plan was established. This plan scheduled 55 days for physics experiments in the nominally assigned 16-week run plan spread over the research areas. Unassigned days are for contingency and make allowance for the historical 80% DIII–D operational availability.

TABLE 1–1
ACTIVE FY00 THRUSTS

Identifier	Number	Title/Description
AT scenario	2	Progress toward a high bootstrap fraction AT plasma demonstration
RWM	4	Understanding and feedback stabilization of resistive wall modes
EC	9	Electron cyclotron heating and current drive validation
AT divertor	8	Validate and explore closed, pumped divertor operation toward AT applications
ITB	7	Expand the spatial extent and time duration of internal transport barriers
Ongoing Topical Science Areas		
Stability, Confinement and Transport, Divertor/Edge Physics, Heating and Current Drive		

1.2. RESEARCH PROGRESS

A very successful year in terms of experimental results was achieved. The actual run time occupied 17 weeks, more than originally scheduled. In June, July, and August the difficulties of the California power crisis began to appear, causing mandated shutdowns of DIII–D experimental operations midday on about six days in total. The uncertainty of this situation led to modifications in the details of the run schedule.

Progress was made in the AT scenario in extending a candidate discharge to very long duration, showing without question that such a discharge can be maintained indefinitely as far as the core plasma physics is concerned. This discharge (104276) is indicated on Fig. 1–2 together with performance parameters of some significant past DIII–D discharges. This new result greatly extends the duration (horizontal axis). The $\beta_N H$ product (vertical axis) is slightly less than the best case from 1999 (98977). This is due to the changes in plasma shape necessitated by the installation of the new AT cryopump. In working around this somewhat surprising result, a great deal of physics involving shape details and stability limits was revealed. Keys to achieving the long pulse were the new AT divertor cryopump and using active real-time feedback of the neutral beam power on the total stored plasma energy to keep the energy below any instability threshold. To be a truly complete AT candidate, this long pulse discharge needs to have a higher fraction of bootstrap current — a topic for future experiments. [Here , $\beta_N \equiv \beta(aB/I)$ where β is the percentage ratio of kinetic to magnetic energy, B the magnetic field strength, I the plasma current and “a” the minor radius. H is the confinement scaled to low-mode confinement.)

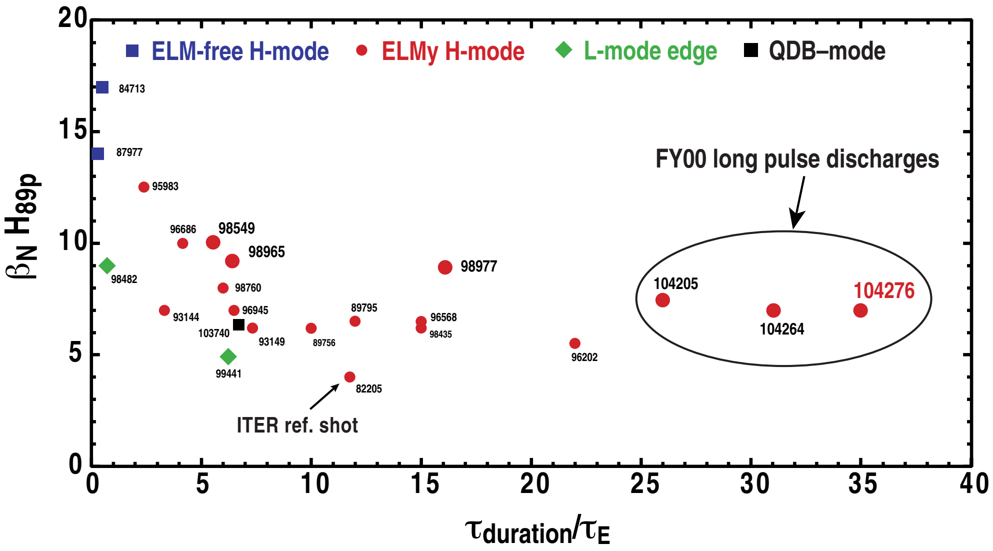


Fig. 1–2. Significant progress has been made in FY00 long-pulse high performance discharges. Exemplary FY00 dischargs are shown in comparison with unstable DIII–D discharges from previous years.

The operational parameter space of the new AT divertor was mapped out in great detail. Enhancements to the digital plasma control system (PCS) were necessary in order to fully exploit the new capability to pump both upper strike points.

The gyrotron systems were used in a number of exciting experiments. Off-axis ECCD was clearly measured for ELMing H–mode discharges. ECCD was used to stabilize neoclassical tearing modes (NTMs). And EC power in current drive or heating mode was seen to produce striking transport barriers in the electron temperature profile.

Progress was made in feedback stabilization of the RWM, increasing the period of active stabilization by a factor of 2 over the 1999 results. The addition of internal sensing loops in the DIII–D vessel should result in an increase in the operating β_N limit with active feedback next year.

The ITB thrust discovered a new mode of operation for DIII–D, now dubbed the Quiescent Double Barrier (QDB) mode. This is an H–mode discharge (H–mode edge) but without ELMs and with an ITB. Despite being “ELM-free”, impurity and density control were achieved in these H–mode discharges. The ELMless H–mode had been seen last year. Keys to achieving the QDB so far are the use of neutral beam injection counter to the direction of plasma current (the plasma current is reversed to achieve this) and active pumping of the plasma density. The QDB may emerge as an ideal AT reactor candidate.

A number of other experiments were done in the TSAs. A great deal of data on the so-called radiatively improved (RI) mode was obtained. Experiments on turbulence characterization in dimensionally similar discharges and on transport via avalanche-like events were completed. An H–mode threshold experiment indicates that changing the direction of the vertical gradient-B drift changes the magnitude of the shear in the electric field prior to the transition. An experiment on the effect of elongation in dimensionally similar L– and H–mode discharges was performed. A detailed experiment on the improvement in core confinement correlated with rational q surfaces was performed. The effect of pumping in discharges with density well above the Greenwald limit was investigated. And many other high density divertor experiments were done in the Boundary TSA as well as experiments to measure the plasma flows and neutral density near the X–point.

1.3. FINAL TALLY

Figure 1–3 displays the final accounting for the DIII–D physics experimental plan for FY00. The open bars on the chart indicate the number of the original 55 days assigned to each area. As the experiments were conducted and results obtained, there were some changes in the planned activities, especially in the thrusts which are working toward a well defined goal, but with a path revealed in the final analysis only by experiment. The solid bars in Fig. 1–3 show the actual time (in days) realized by each area, with the red portion showing that part of the originally defined 55-day plan completed. For example, the AT divertor thrust completed their days just as planned in

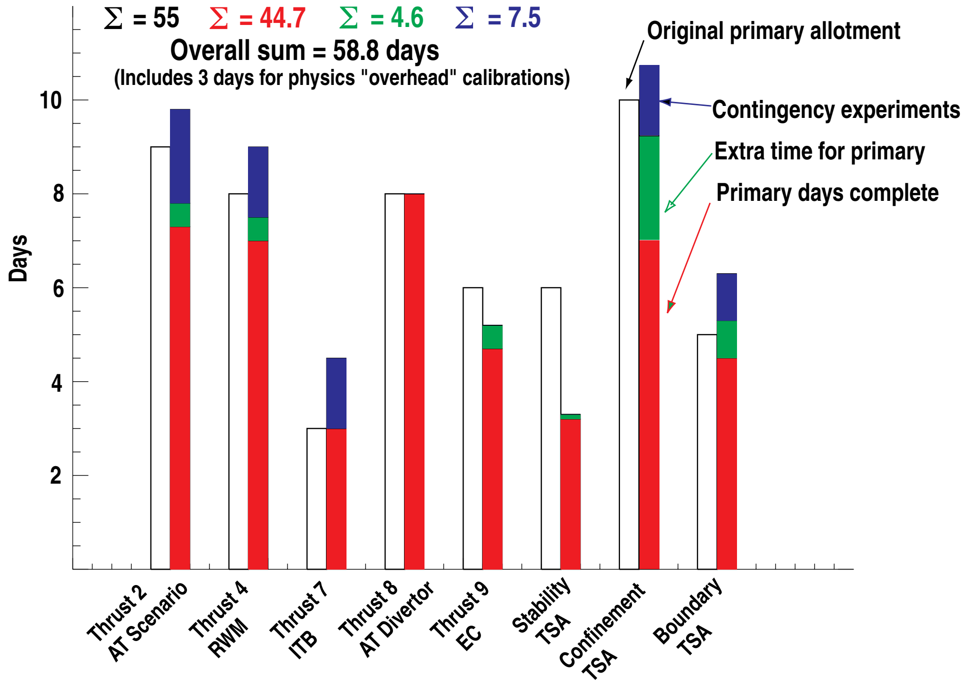


Fig. 1–3. Final tally of DIII–D physics run days accomplished shows FY00 to be a productive year.

their development of an operational checkout and experimental methodology for the new AT divertor. The green portion indicates additional time given to some experiments from the original plan because they had interesting results to explore or more diagnostic coverage was needed. The blue portion indicates additional experimental time given for high priority contingency experiments. These are experiments which emerged from the DIII–D brainstorming process but did not quite make the cut down to the 55 day plan and thus were on a first priority "reserve" list. There were three other days of physics operation not shown by a bar which were days for "overhead" diagnostic calibrations used by most other experiments. DIII–D was operated in full up physics mode for these calibrations. The overall sum of productive days is just under 60, in very good agreement with the 80% historical availability for 17 equivalent weeks (some weeks are scheduled for only 4 day operation).

1.4. THIS REPORT

More detail on the experimental results is given in Section 2. Section 3 gives an overview of the facility operations and the new hardware upgrades.

Readers interested in more detail, or to learn about experiments not covered in this brief text are referred to the accompanying CD which contains most of the publications from FY00 giving a great deal more information on all FY00 topics.

2. FY00 SCIENTIFIC PROGRESS

2.1. ADVANCED TOKAMAK SCENARIO — THRUST 2

Significant progress was achieved in AT scenario research. Shown in Fig. 2–1 is a long pulse, steady state ELMing H–mode discharge with a product of $\beta_N H_{89P}$ of 7. Long pulse means this discharge ran out to 35 energy confinement times, limited in this case only by some nuances of the DIII–D control system at the time of the experiment. This discharge actually appears to be in resistive equilibrium in that the current profile is steady for the final two or three seconds, as measured by the motional Stark effect (MSE) diagnostic. All indications are that this discharge could be maintained indefinitely if the Ohmic transformer drive could be replaced by suitable noninductive current drive.

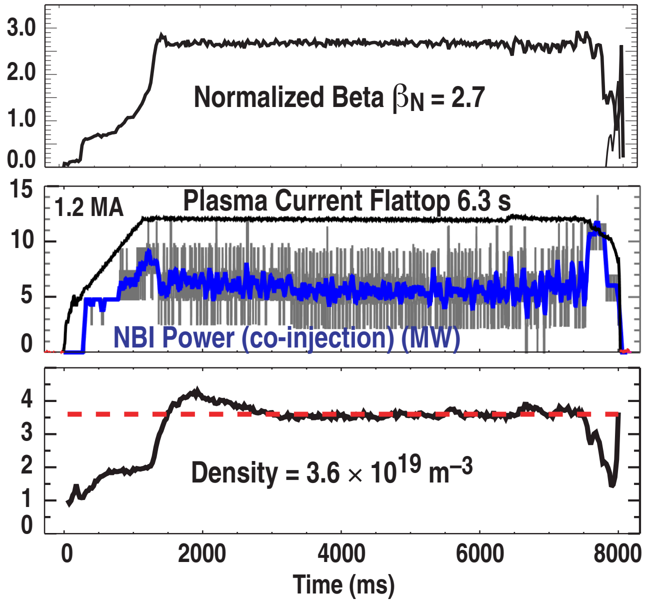


Fig. 2–1. AT progress — Long pulse, steady, ELMing H–mode β_N H_{89P} ~7 τ/τ_E ~ 35. NBI power is feedback controlled on plasma beta at $\beta_N = 2.7$. Density is controlled with divertor pumping.

Density and impurity control with the new AT divertor were critical in achieving this long pulse result. The density could be controlled with gas puffing for particle input while actively pumping to produce a particle sink, with no adverse effect on confinement in either L– or H–mode discharges. Figure 2–2 indicates all the active cryopumps now available on DIII–D. The AT divertor is referred to by the project name “RDP 2000.”

Shown is a comparison of the electron density profiles achieved with the various cryopumps with lower density obtained with each improvement. The AT divertor achieves the lowest ionization rate — a measure of the particle source entering the plasma.

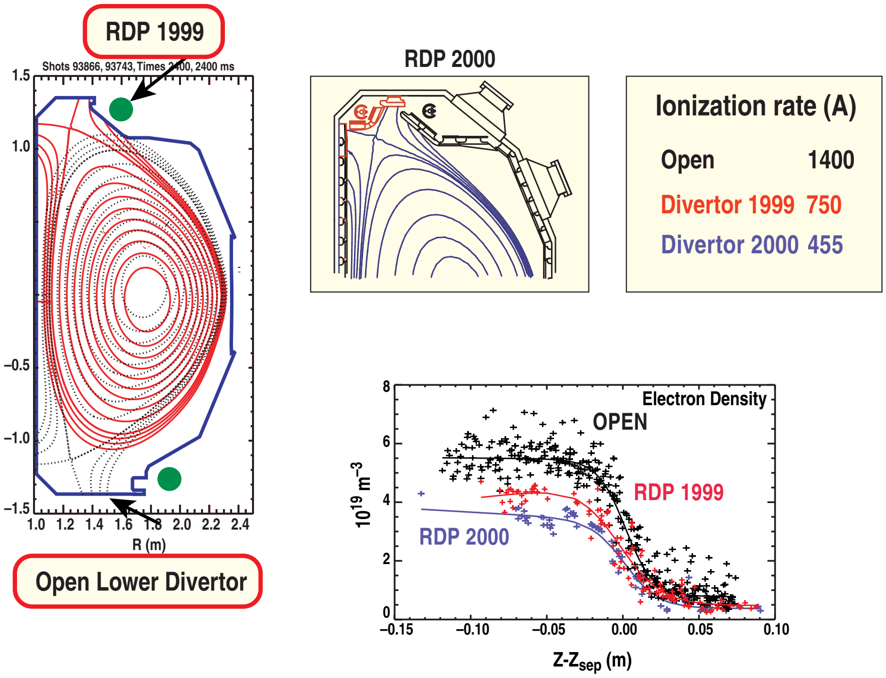


Fig. 2–2. RDP 2000 reduces core ionization source.

In order to effectively use pumping for density control, it was necessary to develop the necessary algorithms for real-time strike point control with the DIII–D digital PCS. Figure 2–3 shows a case in which the upper inner strike point is held fixed while the outer is swept to follow a programmed waveform and shows the sensitivity of the plasma density to the strike point location. A few millimeters matter.

The other key element in achieving the long pulse result was real-time regulation of the neutral beam injection power to control the stored energy in the plasma keeping the energy below any instability threshold. This was also accomplished with the PCS.

In FY00, it was discovered that the relatively small changes to the plasma shape necessitated by the new upper inner AT pump reduced the stability limit for plasma pressure. This was verified by running an inverted discharge where the previous shape could be reproduced in the bottom of the vessel and reversing the direction of the toroidal field to complete the mirror image operation. This discharge largely recovered the former parameters, but of course could not be properly pumped. This effect of shape will be investigated further in the future.

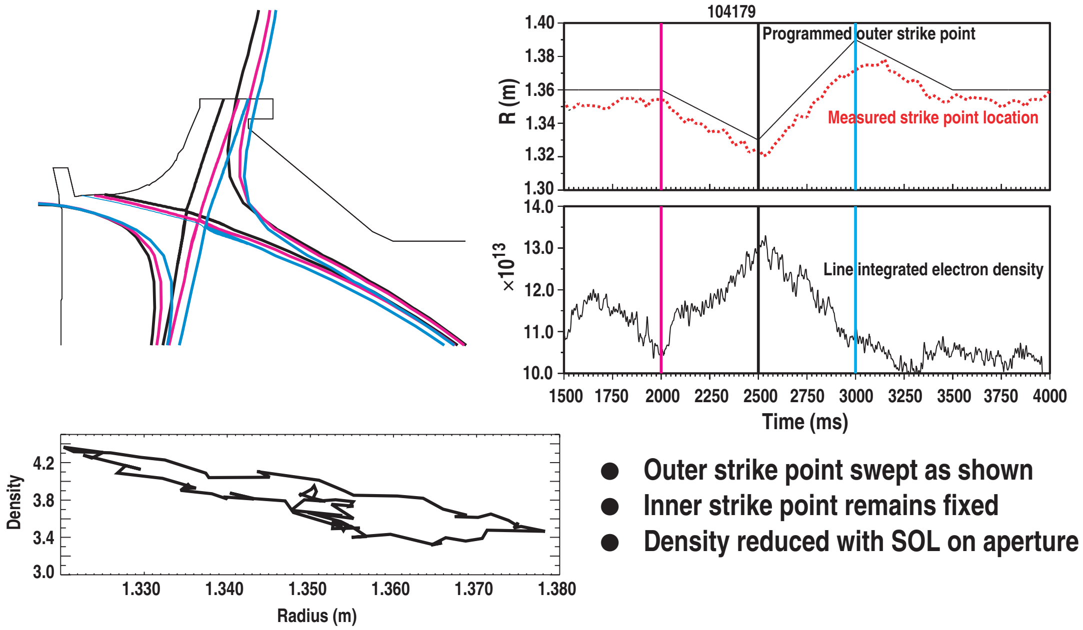
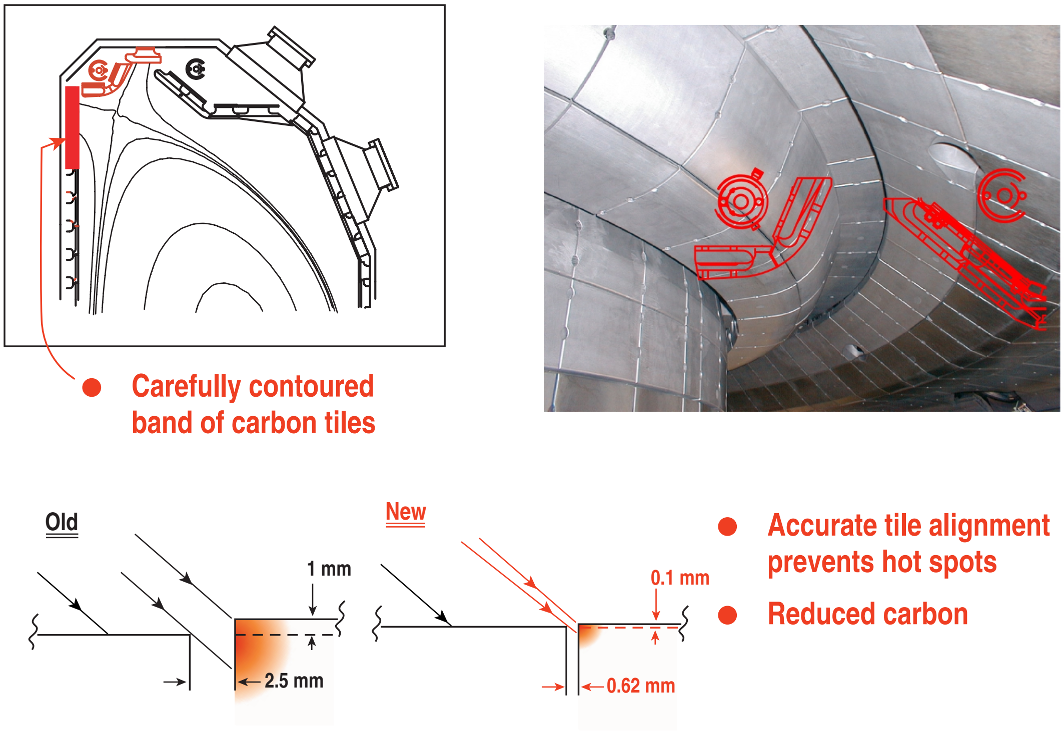


Fig. 2–3. Strike point sweep shows directly the effectiveness of the pumping.

2.2. AT DIVERTOR — THRUST 8

The AT divertor experimental team quickly established the efficacy of the new AT cryopump and developed the necessary operational understanding for the system to be used in experiments. Density control was clearly established as described. Another innovation for the new geometry was careful contouring of the edges of the upper inner wall band of carbon tiles, as indicated in Fig. 2–4, removing the higher edges on the tiles which exist in the normal faceted tile geometry. This resulted in reduction of edge hot spots on the tiles as shown by the IR camera images in Fig. 2–5 which compare tile heating with the strike point on the new smooth tiles with the strike point on the faceted geometry. A reduction in the carbon content in the discharges as compared with former operation was also measured. This band of tiles readily took 50 MJ of integrated input power in the long pulse AT discharge shown in Fig. 2–1 with Z effective remaining below 2 and showing no indication of any thermal runaway in the peak tile temperature.

Some of the other results from the AT divertor characterizations are as follows. The exhaust efficiencies are consistent with those predicted by the first-flights neutral models used at the time of the divertor design. A small shape bias of a nominally double-null plasma upward is sufficient for adequate density control with the upper pumps. Plasma pumping during the plasma current rampup can be used to reduce the wall inventory and reduce the density rise in a subsequent H–mode phase. Gas puffing of deuterium "upstream" from the strike point effectively sweeps impurities out of the plasma as a deuterium flow is established toward the pump.



- Carefully contoured band of carbon tiles

- Accurate tile alignment prevents hot spots
- Reduced carbon

Fig. 2–4. Divertor-2000 controls density and impurity level.

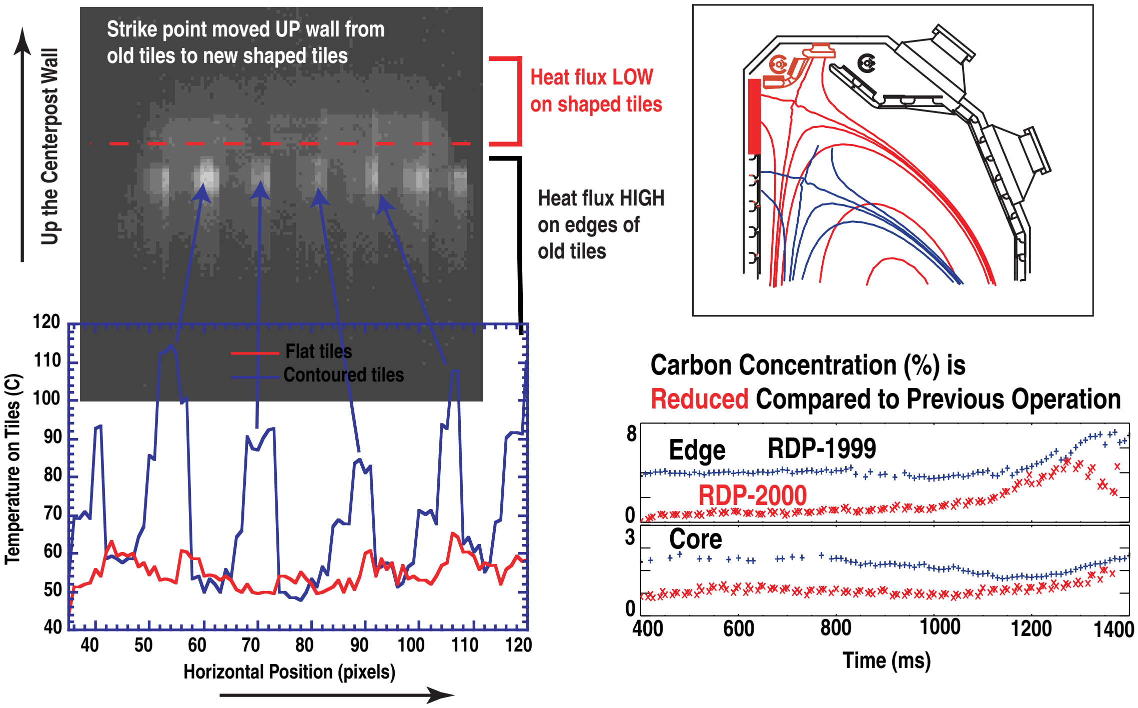


Fig. 2–5. Impurity control in AT plasmas with careful tile shaping.

2.3. RESISTIVE WALL MODE STABILIZATION — THRUST 4

The RWM is a limiting factor in the achievable β_N in the NCS AT scenario discharges. The long term goals of this thrust are to advance the physics understanding and delineate the parametric scaling of the RWM instability and to achieve sustained plasma operation above the no-conducting-wall beta limit through active or passive stabilization of the RWM.

For active stabilization, the outer waist of DIII–D is configured with a set of feedback driven picture-frame-like coils, known as the C–coil, as indicated in Fig. 2–6. Sensor loops detect the relatively low frequency RWM and active feedback mode suppression is done with the C–coil. Enhancements to the C–coil power supplies this year and progress in the real-time algorithms led to improvements in the duration of suppression, lasting for greater than 20 characteristic wall times. The red trace in Fig. 2–6 shows a discharge with a beta collapse due to RWM growth with no active C–coil feedback. In the green trace, active feedback is applied to an otherwise identical discharge and the mode and beta collapse are suppressed for about 100 ms. Modeling is in reasonable agreement with the experimental results given the FY00 hardware configuration and predicts that in 2001 another 15% or so will be gained in the beta threshold for instability due to the addition of in-vessel sensor loops, a project designed in FY00.

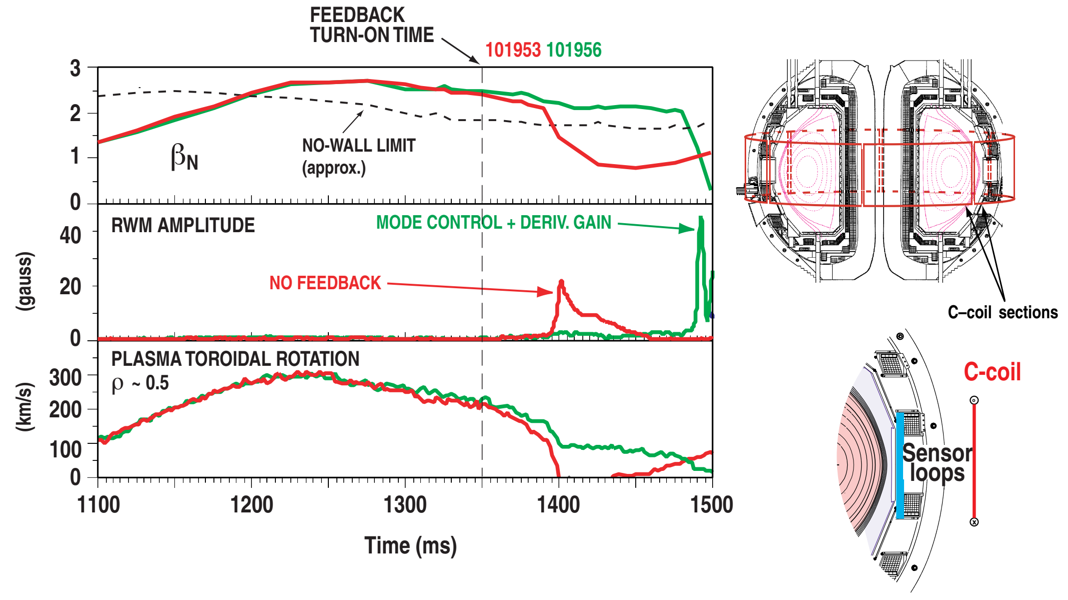


Fig. 2–6. Progress in feedback stabilization of the RWM. Modeling agrees with experiment. Higher β_N with internal sensors, future upgraded C–coil.

The C–coil is also used to correct magnetic error fields on DIII–D and extensive scans led to an improvement in the nominal C–coil settings for error field correction. The reduction in error fields led to more robust toroidal rotation of the plasma, which in turn enhances the resistance of the plasma to the RWM instability. Other interesting physics results were that there is evidence that near the stability boundary the plasma amplifies any static error fields, and the mode appears to be an ideal n = 1 kink in character. A 1–D feedback simulation code accurately predicts the dynamics of the feedback process, useful for planning and interpretation of the results. A very nice experimental demonstration was done of the effectiveness of the feedback wherein it was gated off briefly and the resultant mode regrowth was measured.

2.4. ELECTRON CYCLOTRON SYSTEM — THRUST 9

The AT scenario will require off-axis current drive for steady state, noninductive, operation. This is to be done with ECCD.

The EC thrust was tasked with the engineering and physics validations of the gyrotron systems. Figure 2–7 shows one of the new CPI gyrotrons and some ancillary equipment. It has a diamond output window and so the tube is specified to do 10 s pulses with a nominal 1 MW of EC power at the tube output. We also used two Russian-made gyrotrons obtained from the TdeV tokamak formerly in Canada. Experiments in FY00 were done with two or three gyrotrons. Figure 2–7 also shows a photograph of the Princeton articulating launcher that proved very valuable in EC physics productivity this year. Mirrors allow the EC waves to be redirected toroidally between shots, so one shot can have co-current drive (driven current in the direction of the plasma current) and the next counter current drive. Formerly a counter current drive shot required the plasma current to be reversed.

Commissioning of the gyrotron systems was successful in determining the steering and polarization of the launched wave. It was found that the polarization calculations are fairly accurate for setting the mirrors which determine the direction of the launched wave electric field, certainly adequate for the majority of applications.

In the physics validation there were some very nice results, notably the measurement of localized, off-axis current drive in ELMing H–mode discharges. The measured toroidal ECCD driven current is shown in Fig. 2–8. This is derived from the MSE measurement of the poloidal field in discharges with and without ECCD and simply differencing Ampere’s law, as indicated in the figure. Two current peaks off the magnetic axis are indicated, consistent with the CD profile shape prediction from the ray tracing code Toray-GA, showing the agreement in profile location. There had been some concern that high wave refraction from the steep edge H–mode density gradient might be problematic, but no indications of this were seen.

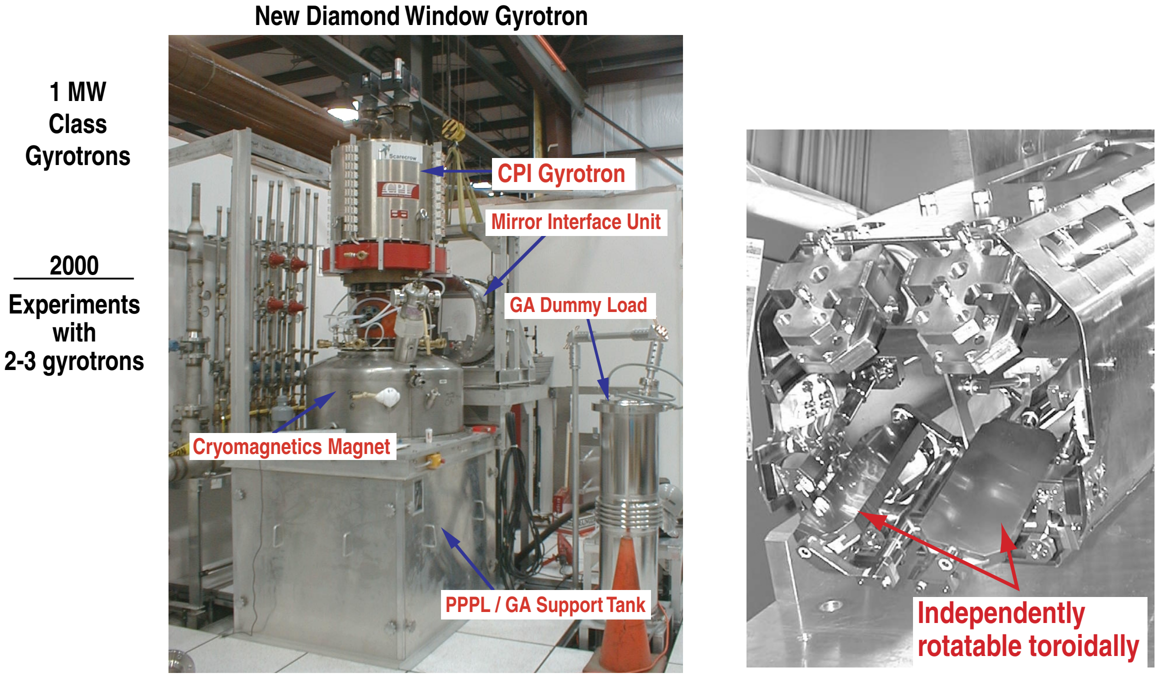


Fig. 2–7. High power EC system (110 GHz) for AT profile control coming online. PPPL articulating launcher invaluable for physics productivity — necessary to exploit EC as an AT tool.

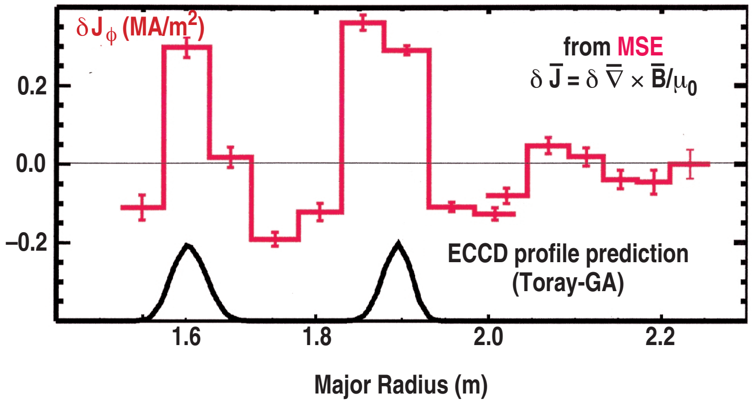


Fig. 2–8. Localized, off-axis ECCD in ELMing H–mode.

Also experiments were done to test the effect on ECCD of varying the toroidal wavenumber of the launched wave. The power deposition location moved as expected with the varying Doppler shift and these data are being analyzed in detail.

2.5. INTERNAL TRANSPORT BARRIER — THRUST 7

The ITB thrust discovered an exciting new mode of operation this year, which has been dubbed the QDB mode. It has two transport barriers, the usual edge H–mode barrier but without any ELMs, and an ITB. Traces from a QDB discharge are shown in

Fig. 2–9. In the QDB there are no sawtooth oscillations; q in the core remains above 1 for the duration of the QDB discharges run thus far. Operational keys to realizing the QDB thus far are the use of counter NBI and active plasma pumping. NBI counter to the direction of the plasma current can only be achieved on DIII–D by reversal of the direction of the plasma current. The density and temperature profiles from a timeslice in this discharge clearly show the edge and core barriers in Fig. 2–10 (in red). Profiles from a comparison L–mode ITB discharge are shown also. Experiments next year will focus upon determining the parameters necessary to realize the QDB. The ELMless H–mode was seen last year in counter-NBI operation. Perhaps the new active pumping configuration this year and greater injected power triggered the additional ITB. Unlike standard ELM-free H–modes, density and impurity control were achieved with divertor pumping.

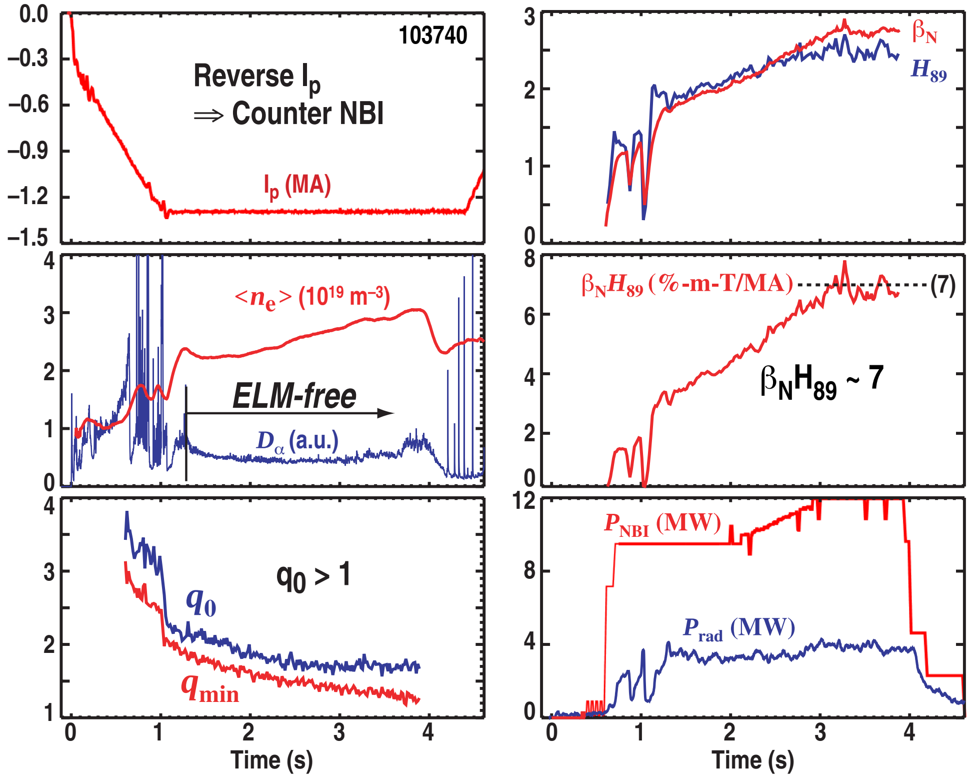


Fig. 2–9. ITB thrust uses counter-NBI discovering new operating mode Quiescent Double Barrier (QDB) — two barriers, no sawteeth, no ELMs (QH–mode edge).

Perhaps illuminated by the ELMless H–mode, an edge nonlinear coherent oscillation in the magnetic probes is clearly seen which appears to be in some way related to the ELM phenomena. With this electromagnetic mode, the edge particle confinement is reduced possibly allowing pumping to be effective. The nonlinearity is manifested by the spectrum that shows a large number of harmonics of the fundamental mode frequency, typically around 2 kHz. In retrospect, this mode has been identified as existing transiently in ELMing H–mode discharges also. Several experiments in 2001 will seek to learn more about the nature of this mode and its role in regulating the edge.

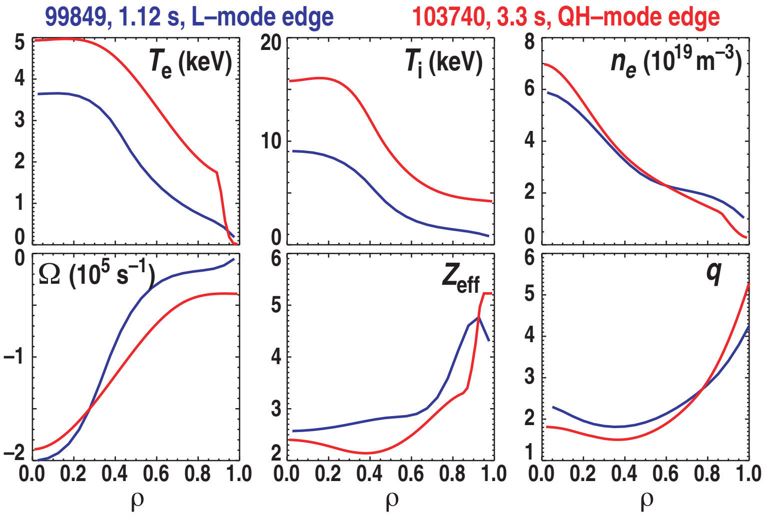


Fig. 2–10. QDB regime combines distinct core and edge barriers. QH–mode edge adds pedestal to temperature profiles, core profile shape otherwise almost unchanged from operation with L–mode edge.

EC power was used to drive ITBs in the electron channel, evidenced by large gradients in the electron temperature profile. It was found that creation of the transport barrier does not depend upon the toroidal directivity of the EC wave, that is, co, counter and perpendicularly launched waves created a barrier. Figure 2–11 shows a discharge in which co-ECCD is applied early during the ramp up of the plasma current. The electron temperature, T_e, is measured with an array of electron cyclotron emission (ECE) channels. The peak in T_e rises up to 15 keV and large gradients in the T_e profile develop, indicated by the large T_e difference in adjacent ECE channels.

ITBs were also stimulated by the injection of solid, frozen deuterium pellets and with the injection of impurities such as neon, as in the RI–mode experiments.

2.6. STABILITY TOPICAL SCIENCE AREA

The premier result from the Stability TSA this year was from a series of experiments on stabilization of NTMs by the injection of localized ECCD. Complete stabilization of NTMs was achieved. In keeping with theoretical predictions, only co-ECCD resulted in this stabilization as the bootstrap current lost by the formation of a magnetic island by the tearing mode must be replaced by ECCD. Figure 2–12 shows this stabilization. Shown is a target discharge with no ECCD with the NTM amplitude measured by edge magnetic probes. In the discharge with co-ECCD, the mode is suppressed with the amplitude driven down to the noise level of the measurement. The location of the added ECCD must be just right relative to the location of the NTM magnetic island layer.

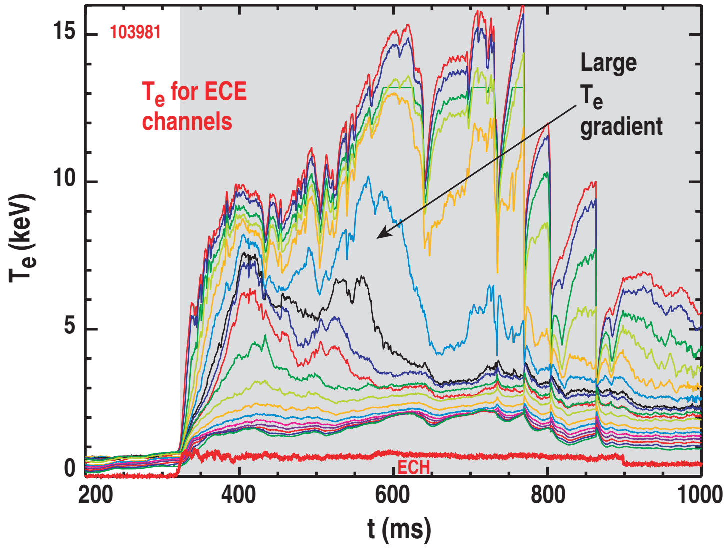


Fig. 2–11. EC heating drives electron ITB. 0.8 MW ECH applied to ρ ~ 0.4; no NBI. Co-ECCD in this case; counter and radial ECH also drive ITB.

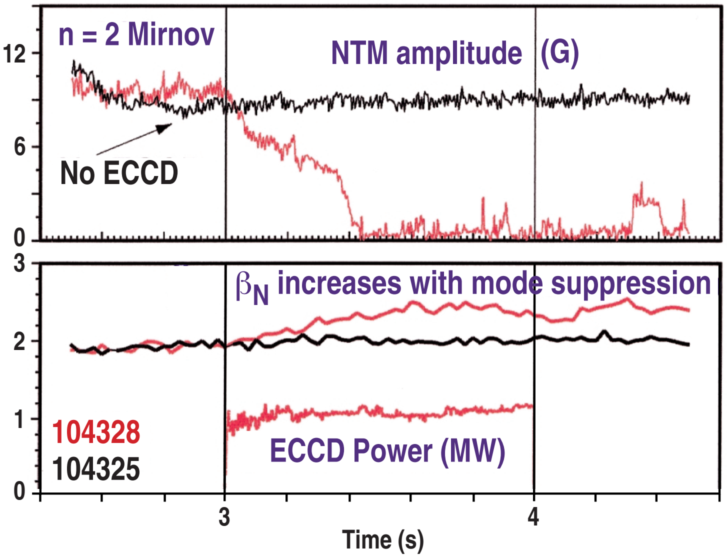


Fig. 2–12. Complete NTM stabilization with co-ECCD. Complete suppression of NTM with co-ECCD. Precise localization of ECCD required for NTM stabilization.

NTMs are observed to degrade the core confinement of the plasma, so stabilization of these modes results in enhanced stored energy in the core. This is indicated in Fig. 2–12 by the recovery of β_N with the suppression of the mode.

2.7. BOUNDARY (DIVERTOR) TOPICAL SCIENCE AREA

The Boundary TSA conducted a number of experiments which were in some sense complementary to those of the AT divertor thrust, working with the new divertor pumps in high density operation rather than the low density mode required for the AT research. As in 1999, very high density operation was achieved together with good confinement. Densities up to 1.4 times the Greenwald density were achieved at H_{89P} approximately equal to 1.9. The new work established that active pumping is not necessary to obtain this mode of operation, but the high densities are easier to achieve if pumping is utilized. New measurements on particle transport were done in these very high density discharges. At high density, a pinch of the plasma density takes place as shown in Fig. 2–13. The measurements of diffusivity, D, and radial flow velocity, V, were obtained with injected helium test particles. As the density approaches the Greenwald density, D decreases and most significantly V changes sign becoming negative and indicating an inward flow or pinch.

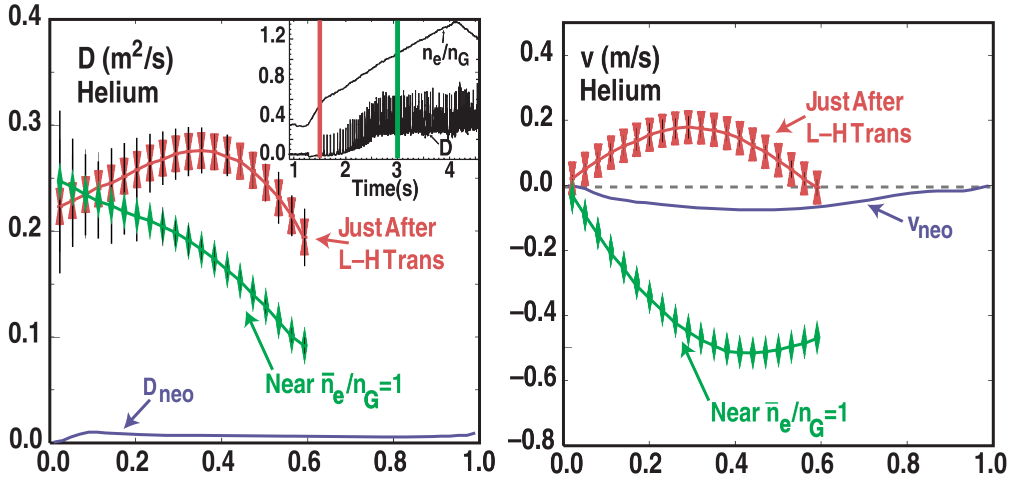


Fig. 2–13. AT high density particle diffusivity decreases and a large particle pinch develops. D and v measurements from He puff. Helium pinch is much larger than neoclassical (Ware) value.

Another feature of the high density operation is that the energy dumped by an ELM is relatively less than in the more typical density discharges. This is important for reactor divertor components. These discharges are subject to NTMs. The Boundary team also did experiments comparing high density operation in the new closed divertor geometry with the open geometry still existing in the bottom of DIII–D.

Several experiments were done with the Divertor Materials Evaluation Study (DiMES) system, wherein a sample with various surface coatings is inserted into the floor of DIII–D and removed for evaluation after exposure to plasma. Together with general spectroscopic measurements, data were obtained for experiments to determine the source of carbon in DIII–D discharges, whether from physical or chemical sputtering and whether from the divertor region or the main chamber carbon wall. These data are very interesting and undergoing detailed analyses. A lithium DiMES sample was also used and a number of conclusions were drawn even though the lithium became molten and was rapidly removed from the sample.

2.8. CONFINEMENT TOPICAL SCIENCE AREA

Perhaps the greatest variety of experiments within the DIII–D program is found in the Confinement TSA. A large number of parameters are known to affect confinement — there are multiple modes of plasma operation with different confinement properties and there are a variety of ways to attack the experimental investigation. To better deal with these experiments, the Confinement TSA has four main sub-areas. These are listed in Table 2–1 along with the experiments in each sub-area executed in FY00. The interested reader is referred to the presentations and papers in the accompanying CD. Here we will mention only two of these experiments.

TABLE 2–1
CONFINEMENT AND TRANSPORT EXPERIMENTS IN THE 2000 CAMPAIGN

- **Fundamental turbulence studies**
  - **Avalanches in L–mode plasmas**
- **H–mode physics**
  - **Edge E_r structure and ∇B effect on L to H transition**
  - **Pellet-triggered H–modes**
  - **Edge neutral density measurements**
  - **Edge poloidal asymmetries and the L to H transition**
- **Nondimensional transport studies**
  - **Nondimensional scaling of turbulence**
  - **Elongation and dimensional similarity**
- **Core transport physics**
  - **Core barrier formation and integer q values**
  - **Controlled density ELM-free H–mode**
  - **Core electron transport barrier formation with counter ECCD**
  - **Effect of impurity injection on transport — RI–mode**

In the H–mode physics working group, an experiment was performed to investigate the effect of the direction of the vertical gradient B drift on the power threshold for the L– to H–mode transition. It is well established in divertor tokamaks that if this drift is toward the dominant X–point, the threshold power is lower (about a factor of 3 lower on DIII–D) than an oppositely directed drift away from the X–point. In this experiment, the gradient B drift direction was fixed to be downward and the dominant X–point was varied between top and bottom with the DIII–D's flexible shaping capability. The most striking result was that three diagnostics which measure edge density fluctuations showed a reversal of the turbulence flow direction in the edge, prior to the transition, for the low threshold power situation. These data are shown in Fig. 2–14 together with a sketch of the plasma shapes. The flow velocity a few centimeters inside the separatrix is reversed for the lower X–point. This reversal means greater velocity shear than for the upper X–point case. Shear in plasma flow is known to suppress turbulence and lead to transport barriers. This greater shear precursor is therefore consistent with a lower power threshold. Now it remains to understand what aspect of the drift versus X–point physics is controlling the velocity profile, presumably by controlling the electric field profile.

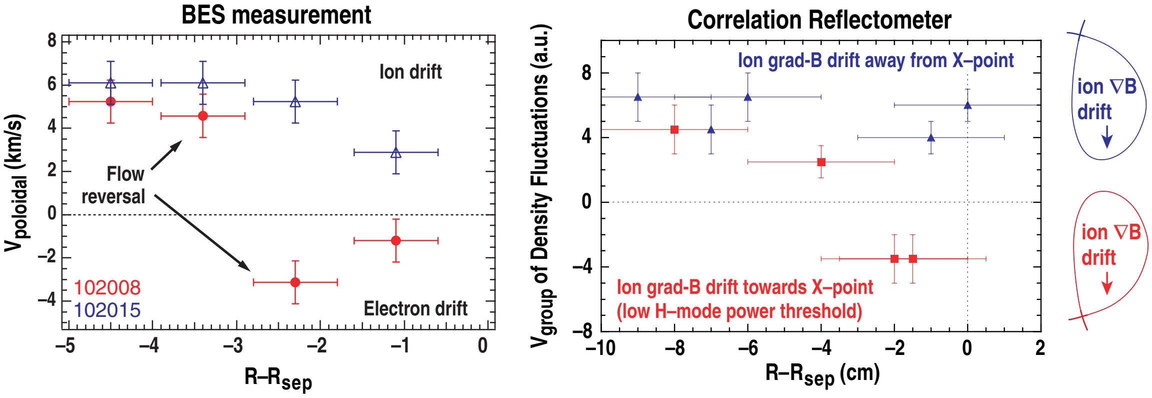


Fig. 2–14. Experiment on L to H transition. L–mode discharges, 1 MA, 2.1 T, NBI = 1.9 MW. Three turbulence diagnostics observe flow reversal in target discharge. Midplane Langmuir probe also sees flow reversal.

For a number of years, a team at DIII–D has done experiments in the area of transport in dimensionally similar discharges, that is, discharges having the same kinetic profiles of appropriately scaled physics parameters and varying one parameter. This year an experiment was nearly completed on the effect of varying the vertical elongation in both L– and ELMing H–mode discharges, actually running both confinement modes in the same shots with shape changes. The resultant data are still in detailed analysis but the control room level result was clear — global confinement in L–mode discharges degrades with elongation while it improves with elongation for ELMing H–mode. This effect is shown by the traces in Fig. 2–15. In the L–mode phase of the discharge, greater NBI power is required in order to match the profiles as nearly as possible. That is, to achieve the same stored energy when elongated, greater NBI power is required. However in the H–mode phase, less NBI power is required for a match, indicating better global energy confinement. Theoretical transport simulations scale the confinement with elongation and this experiment will serve as a test of these models.

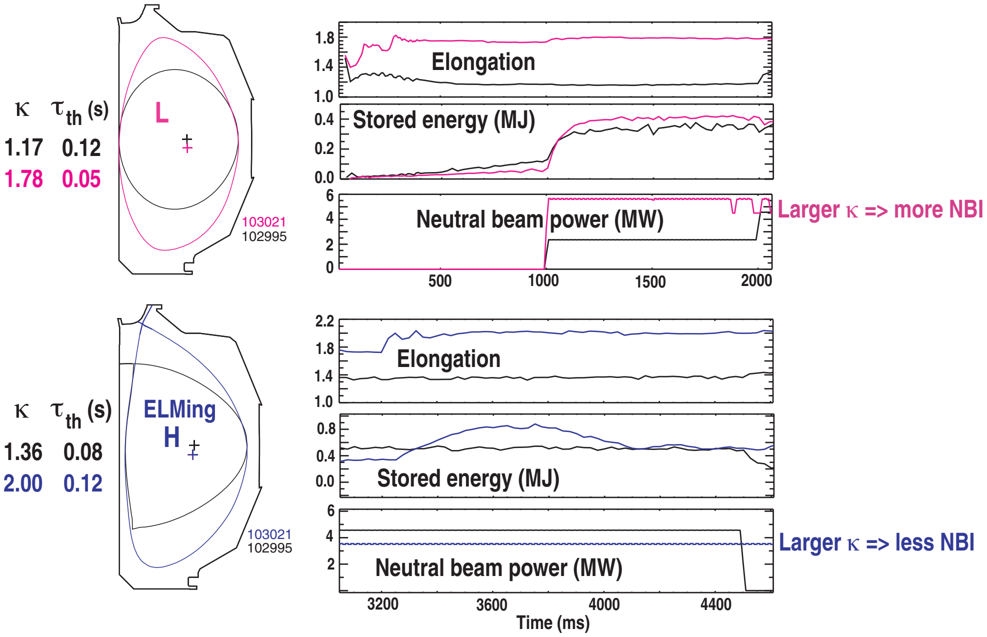


Fig. 2–15. L–mode confinement degrades with elongation, H–mode improves. Confinement TSA experiment — dimensionally similar discharges. Each pair has same I, B, n, R, a, T(ρ) (heating power varied).

3. FACILITY OPERATIONS

3.1. OVERVIEW

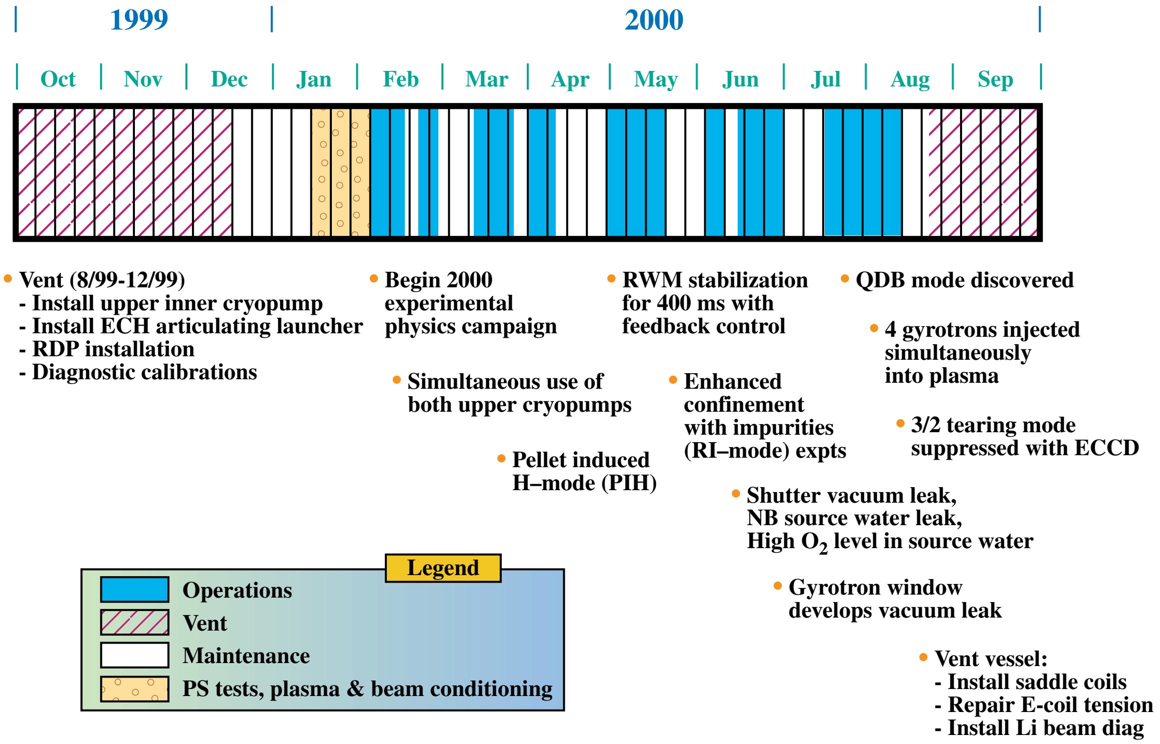
FY00 was a highly productive year for the Operations Group. The facility continued to operate effectively and support a vigorous and productive research program through an aggressive operations schedule and a series of continuing facility and equipment upgrades, modernizations, and refurbishments. As in previous years, the vessel was vented prior to the start of the fiscal year and the vent continued until the end of December for installation of the upper inner cryopump and baffle structure along with numerous other diagnostic upgrades and calibrations. Following new system commissioning and startup in January, the research program resumed in February operating 75 days until mid-August. Another vent period began in September with the primary task to install a set of in-vessel saddle coils for resistive wall mode detection.

In addition to the vent and operational periods, the highlights for the year include: simultaneous operation of the two upper cryopumps, commissioning of a new high voltage power supply for the ECH gyrotrons, installation and conditioning of five megawatt-class gyrotrons, installation of a fully articulating ECH launcher, and stabilization of the neoclassical tearing mode using the new ECH system (Fig. 3–1).

3.2. FALL 1999 VENT

At the beginning of FY00, the vessel was open for installation of a number of new systems. The primary vent tasks included: addition of a new upper inner cryopump and baffle system, installation of new contoured tiles with reduced tile separation in the upper divertor region, installation of a PPPL designed ECH launcher with two poloidally and toroidally moveable mirrors, installation of an extensive gas puff system in the divertor region, and numerous new diagnostics. The combination of the contoured tiles, improved edge-to-edge alignment of the tiles, and reduced spacing between tiles reduced the carbon concentration by about a factor of two compared to similar operation in FY99. An extensive set of new diagnostics was also installed during the vent with particular emphasis on permitting careful documentation of the upper divertor region (Table 3–1).

Following closure of the vessel on schedule at the end of December, measurements confirmed that the extensive modifications made to the Thomson scattering diagnostic had reduced the stray light of the divertor system and improved the laser alignment of all three Thomson laser systems. The reduced stray light significantly reduced the uncertainty in the divertor density measurement.



- Vent (8/99-12/99)
  - Install upper inner cryopump
  - Install ECH articulating launcher
  - RDP installation
  - Diagnostic calibrations
- Begin 2000 experimental physics campaign
- Simultaneous use of both upper cryopumps
- Pellet induced H–mode (PIH)
- RWM stabilization for 400 ms with feedback control
- Enhanced confinement with impurities (RI–mode) expts
- Shutter vacuum leak, NB source water leak, High O_2 level in source water
- QDB mode discovered
- 4 gyrotrons injected simultaneously into plasma
- 3/2 tearing mode suppressed with ECCD
- Gyrotron window develops vacuum leak
- Vent vessel:
  - Install saddle coils
  - Repair E-coil tension
  - Install Li beam diag

Fig. 3–1. DIII–D FY00 operations highlights.

TABLE 3–1
DIAGNOSTIC UPGRADES/ADDITION

Diagnostic	Measurement
Langmuir probe array (28 probes)	n_e, T_e in upper divertor
ASDEX pressure gauges (2)	High speed pressure measurement in critical divertor regions (X–point, under baffle)
Magnetic probes in divertor region	Improved X–point location and control
Visible, tangential TV in upper divertor	Impurity measurements in upper divertor
External saddle loop array	Improved detection of resistive wall mode
New motional Stark effect channels	Improved separation of E_r and j(r)
CER detector upgrade	Improved signal/noise level
Thomson scattering	Improved beam alignment and reduced stray light for the divertor system

3.3. TOKAMAK OPERATIONS

During FY00, the facility was used for a total of 283 days with physics experiments conducted on 75 days. The tokamak was operated for an additional 44 days for a combination of startup, power testing, diagnostic calibration, and plasma cleaning following the vent. An additional 11 days were used for vessel conditioning including high temperature baking and boronization. A full breakdown is shown in Fig. 3–2.

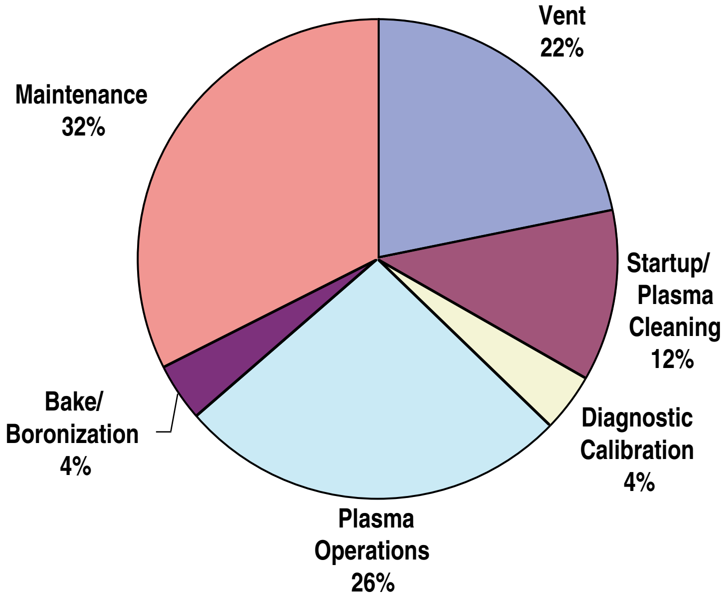


Fig. 3–2. DIII–D facility utilization in FY00.

Machine availability for the year was 74%, consistent with our historical level. A total of 2298 plasma shots were fired. Major causes of down time during the year involved problems with the water system, both in quality and reliability, and an explosive failure of the S1/S2 switches in the Ohmic heating system. The water system problems included a filter failure in a resin bottle, a broken pressure gauge in a water pipe, and a continuing problem with excessively high oxygen level in the high-pressure water system. This latter problem has significant implications for the longevity of the neutral beam ion sources since elevated levels of oxygen in the ion source cooling water is associated with rapid corrosion of critical and irreplaceable ion source components. The high failure rate of the neutral beam systems due to water leaks this past year may have been related to the high dissolved oxygen level. A series of Significant Event Reviews following these incidents, followed by recommended procedural changes, instrumentation repairs, engineering modifications to the system, and improved preventive maintenance led to significantly improved water quality and reliability for the remainder of the year. A major system-wide review of the water system also recommended the addition of a modern instrumentation and alarming system that is being installed in early FY01 and will be ready for the next operating campaign. A review of the damaged switches identified some control logic changes that significantly reduce the likelihood of this failure from ever reoccurring.

Operations was also impacted this year by the deteriorating power situation in California. DIII–D was shut down because of insufficient power as early as June and for parts of five additional days in the July and August period. In anticipation of power shutdowns, operations during the summer were started one hour earlier and extended by one half hour. By “banking” these additional hours and operating on one additional Saturday, we were able to finish all critical experiments on our schedule.

3.3.1. Mechanical Systems

A key cost saving feature of the design of the new upper, inner cryopump had been to utilize the single, existing cryostat on the top of DIII–D to service both pumps. A series of tests following the pump installation and repeated operation throughout the year demonstrated that the two pumps could be operated both independently and simultaneously without any instability. Additional modifications to the control logic also permitted rapid, between shot defrosting of all three in-vessel cryopump systems without any upsets to the gas management system that had been observed in previous years.

A large number of modifications were made to mechanical subsystems throughout the year. During the 1999 vent, repairs were completed on the Ohmic heating coil lead coolant tube. This had been damaged in previous years and by bypassing the cooling lead, operations had resumed but with limited thermal capability. Following this year’s repairs, 90% of the water flow was restored, nearly returning the thermal capability of the coil to its design value.

In addition to the quality related changes to the water system discussed earlier, a number of other energy savings measures were implemented on that system. Variable frequency drive motors were added to the cooling tower fans and the high pressure pumps, and a higher efficiency boost pump was added to the low pressure system. In addition, a smaller, recirculation pump was added to the deoxygenation system to permit continuous polishing and conditioning of the water without the need for large, high power pumps to be operating continuously to maintain high water quality.

Two major system refurbishments were undertaken this year in the area of control systems. The replacement of the vacuum system programmable logic controller (PLC) was started in FY99 and following success of that preliminary phase of the project, the majority of that system was replaced during FY00. This project was successfully completed by the end of FY00 and this effectively eliminates all out-of-date and custom hardware on that critical system. A similar refurbishment was undertaken on the He liquifier PLC. The original PLC was no longer made or supported by the manufacturer, so the replacement of that system with a modern PLC and the addition of a user interface has resulted in a significant improvement in the reliability and operating efficiency of that system.

3.3.2. Computer Systems

The computer systems continued to operate in a highly reliable manner throughout the year. Of particular note was that after considerable preparation for the Y2K changeover, no significant problems occurred. Demands for increased computer resources increased considerably during the year. The largest shot size increased from 305 MB per shot in FY99 to 503 MB per shot in FY00 resulting in a total of 820 GB of shot data obtained during FY00. In response to the increased user demand for resources, a number of changes were implemented: (1) memory available to users on the analysis computer was doubled to 200 GB; (2) raw shot data memory was doubled to 200 GB; (3) a new central data acquisition UNIX-based Alpha machine was installed; and (4) a new, high-speed 12 processor LINUX cluster was developed for between-shot equilibrium analysis.

In response to an increase in the number and severity of attacks on our computer systems, a major security initiative was undertaken during the year. The Cyber Security Program Plan was developed, peer reviewed, and approved by DOE. The objective of the plan is to provide a reasonable level of additional security while maintaining an open environment for scientific collaboration. The first phase of the plan, including a Cisco network security firewall was implemented at the end of August. Along with a number of other security features, the initial results of these changes has been to decrease the number of external scans of the Fusion computers.

Progress has also continued throughout the year on the Plasma Control System (PCS). An algorithm to control both strikepoints in the upper divertor was developed and this was used extensively during the year's experimental program. As part of our program of advanced plasma control development, we successfully demonstrated control of the shape and position of a single-null divertor using a model-based multiple input, multiple output (MIMO) controller. The upgrade to the PCS hardware also continued this year. A major test of the system was performed using the GA customized LINUX operating system to control a high speed Alpha processor and a VME-based Pentium. The new system should provide a factor of 20 increase in performance for the plasma shape control.

3.3.3. Electron Cyclotron Heating and Current Drive

FY00 was a year with both significant successes and disappointments in the development of the ECRF system. The primary goal for the year — achieving the milestone of injecting four gyrotrons into DIII–D including one of the new, long pulse, diamond window gyrotrons — was met at the end of the third quarter. Unfortunately, shortly after that promising event, both CPI tubes developed leaks in the diamond windows. Despite this, the experimental program was able to continue using the strong performance of the two Gycom units.

A more detailed chronology of the gyrotron progress is shown in Fig. 3–3. Five separate megawatt class tubes were conditioned and made ready for operations during the year: CPI development tube No. 1, CPI production tubes No. 1 and No. 2, and Gycom tubes Nos. 2 and 3. The installation of the two Gycom tubes from TdeV was completed early in FY00 and following conditioning in the second quarter, they were routinely used at the 700 kW level and were the workhorses of the ECRF experimental program. In the second half of the year, both CPI tubes developed leaks in the aluminum braze to the diamond window and were removed from operational use. Following acceptance testing of CPI production No. 2 at CPI (0.5 MW, 10 s), the tube was installed and reconditioned at GA and was available for use during the last week of the physics program. After physics operations ended in August, we attempted to complete the acceptance testing of the second production tube. However, the testing was halted at the 600 kW, 5-s pulse

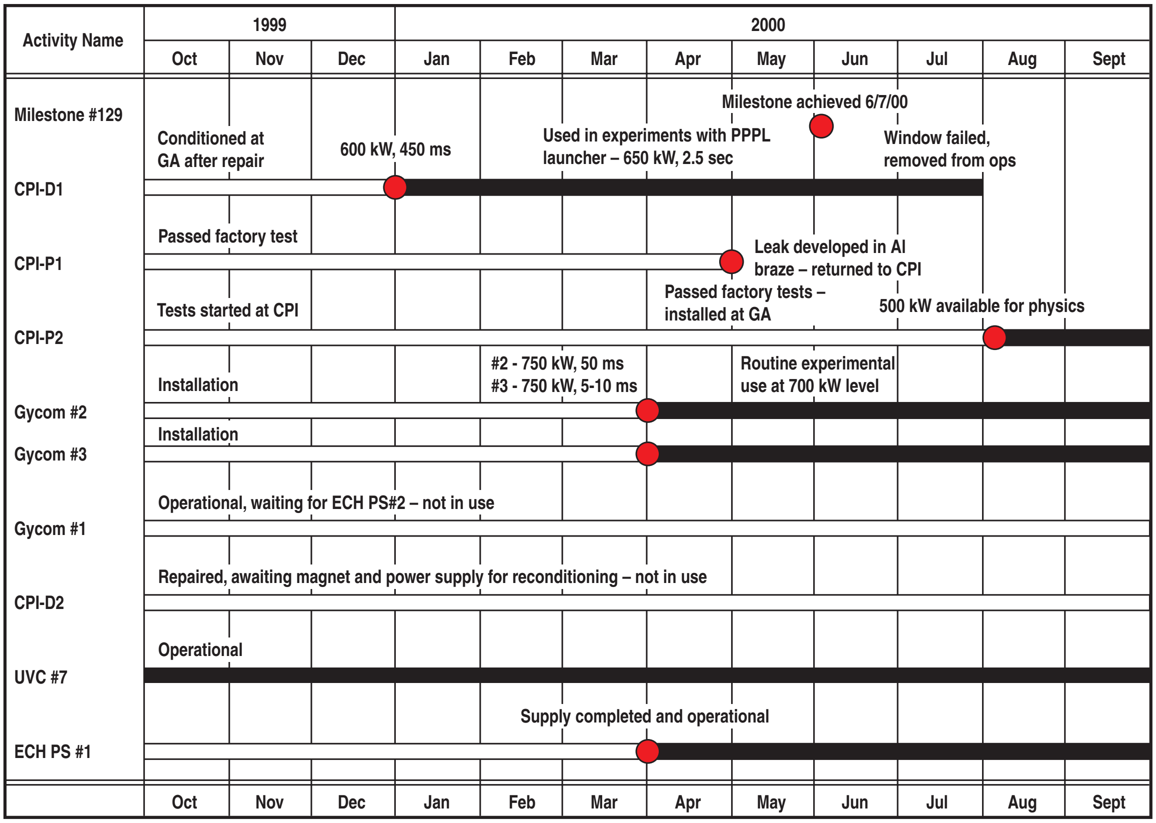


Fig. 3–3. ECRF system progress in FY00.

level in order to improve the performance and reliability of the support systems for the gyrotrons that were hindering the conditioning process.

Two additional highlights of the ECRF program involve the coupling of the power to the plasma. The new L-Box scheme for coupling the Gaussian rf beams from the diamond window gyrotrons to the waveguides was tested and found to increase the power coupled to the plasma by 10% compared with the previous scheme which used phase reconstruction and the two mirror Matching Optics Unit. Considerable progress was also made in the launcher systems. The newly installed PPPL launcher that can be moved both poloidally and toroidally proved extremely valuable for the physics program because of the ability to do both co- and counter-current drive experiments in subsequent shots. Previously, this had required reversing the direction of the plasma current, a process that is typically only done once per year. In addition, a design for upgrading the mirrors in the fixed GA designed launchers to survive 10 s plasma and ECH pulses was completed and two prototype mirrors will be installed in early FY01.

3.3.4. Electrical Engineering

The crowning achievement of the Electrical Engineering group this year was the completion of the ECH Power Supply No. 1. This supply was fully tested up to 120 kV at the end of the second quarter producing well regulated pulses at 80 kV/25A. However, the system developed a problem in the crowbar circuit that used a newly designed thyrotron. The thyrotrons deconditioned after a number of shots and then could not hold off high voltage without considerable reconditioning. An interim solution using ignitrons in parallel was quickly implemented and this worked successfully and allowed the program to continue. We worked with the thyrotron vendor during the remainder of the year and the improved units are being installed in the next ECH power supply.

In support of the diagnostic program, a new variable gain integrator was designed to be used with the new set of resistive wall mode saddle loops installed in Fall 1999. A new design was needed since the older integrators used components that are no longer manufactured. The new integrator has a decade lower drift and less noise than the old units and thus will provide considerable improvement in performance if we extend the shot duration to 10 s.

3.3.5. Neutral Beams

The neutral beam systems continued to operate with high availability. They provided the requested beams (or comparable substitute beams) to the physics experiments 97.7% of the time, despite numerous problems associated with the aging of the sources and other beamline components. Two problems surfaced during the year: degrading water hoses and corrosion of critical ion source components. The 14 year old water hoses were replaced on all four beamlines, but the corrosion issue remains unresolved. The high O_2 levels in the water system in the early part of the year may have accelerated the corrosion of the components, although those levels are now well below the ion source requirements. Failures of both the ion source masking plates and the gradient grid modules occurred on numerous sources during the year and at the end of the year, there were no longer enough parts to make a full spare. We are working with a local vendor to manufacture spare masking plates, however, no vendor has yet been identified that can make the spare grid assemblies.

A number of projects were completed this year that improved the maintainability and availability of the beam system. A new RGA system was tested and installed on the 330° beam line and this test system will be replicated on the other beamlines next year. This new system should allow us to more rapidly identify and remedy vacuum problems on the beamlines. An upgraded beam substitution algorithm more effectively provides a real-time substitution of comparable beams if one of the requested beams fails to fire. In addition, a new hardware/software system permits the beams to fire multiple short pulses to more rapidly condition the beam ducts or perform diagnostic calibration.

3.3.6. Safety and Radiation Management

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

The total neutron radiation at the site boundary for FY00 was 8.3 mrem, the total gamma radiation was 4.2 mrem, giving a total site dose for the year of 12.5 mrem. This is below the SAN DOE annual guideline limit of 40 mrem and the California annual limit of 100 mrem.

The total dose exposure of personnel was kept below the DIII–D procedural limits of 30 mrem/day, 100 mrem/week, and 400 mrem/quarter. The highest personnel dose for the year measured by the radiation monitoring film badges was 170 mrem of gamma radiation. A total of 10 individuals had measurable film badges with a total person-rem for the year of 1.04. Personnel entry into the DIII–D vessel occurred twice during FY00 for a total of 84 days. The initial dose rate in the vessel was 5 to 6 mrem/h. The highest dose accumulated and measured by the personnel digital dosimeter by an individual from pit runs and vessel entries (but not operations) for FY00 was 381 mrem. A total of 126 individuals received doses with 66 of the doses being below 25 mrem.

The DIII–D ALARA committee met and reviewed both the site radiation production and personnel doses for the previous year. The CY99 ALARA goals for a maximum individual dose from vent work of 360 mrem /quarter was met (324 and 296 for third and fourth quarters) and a second ALARA goal of 720 mrem for all of CY99 was met (577 mrem).

As in previous years, some of the site boundary film badges showed neutron doses of 20 to 30 mrem. To understand these measurements, a set of duplicate badges were mounted at these locations and these have not shown any dose. The conclusion is that these nonzero neutron doses on the badges do not represent doses due to DIII–D operation.

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 FY00, there were 17 safety indoctrinations, 25 safety meetings, 41 Hazardous Work Authorizations reviews, and 25 training classes. There were two incidents that involved no injuries, seven accidents that involved minor offsite medical treatment and one lost time accident. Our Fusion Safety Manual was rewritten to make it easier to use and to integrate and update all references to GA and DIII–D safety documents in one central document. DOE Oakland reviewed our Ergonomic Program and gave it good reviews.

4. PUBLICATIONS FY00

NOTE: Access to the GA Web site is limited to employees of GA, their collaborators, and affiliated institutions. Due to this limited access, we have included pdf files for all GA-A reports.

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4.3. MEETINGS http://fusion.gat.com/pubs/browse.html

4.3.1. IAEA 1998 (Publications) and 2000 (preprints) http://fusion.gat.com/pubs/browse.html

4.3.2. APS 1999 (invited publications) and 2000 (preprints, abstracts) http://fusion.gat.com/pubs/browse.html

4.3.3. 14th Int. Conf. on Plasma Surface Interactions in Controlled Fusion Devices 2000 (preprints) http://fusion.gat.com/pubs/browse.html

4.3.4. 27th European Conf. on Controlled Fusion and Plasma Physics 2000 http://fusion.gat.com/pubs/browse.html

4.3.5. 10th International Toki Conf. on Plasma Physics and Controlled Nuclear Fusion 2000 http://fusion.gat.com/pubs/browse.html

4.3.6. 21st Symposium on Fusion Technology 2000 (http://fusion.gat.com/pubs/browse.html)

4.3.7. 13th Topical Conf. on High Temperature Plasma Diagnostics 2000 http://fusion.gat.com/pubs/browse.html

4.3.8. 14th Topical Meeting on Technology of Fusion Energy 2000 http://fusion.gat.com/pubs/browse.html

4.3.9. 18th IEEE/NPSS Symposium on Fusion Engineering 2000 (http://fusion.gat.com/pubs/browse.html)

4.4. OTHER

4.4.1. Overview

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5. ACKNOWLEDGEMENT

This report of work was prepared for the U.S. Department of Energy under Contract Nos. DE-AC03-99ER54463, W-7405-ENG-48, DE-AC02-76CH03073 and DE-AC05-96OR22464.