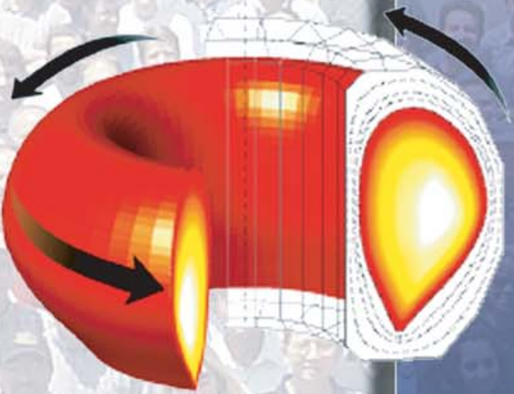
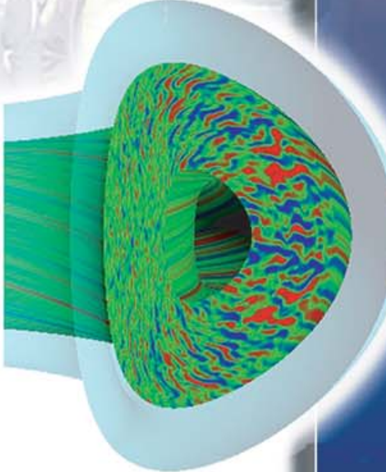
GA-A24319

DIII-D RESEARCH OPERATIONS ANNUAL REPORT



OCTOBER 1, 2001 THROUGH

SEPTEMBER 30, 2002



GENERAL ATOMICS

GA–A24319

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

OCTOBER 1, 2001 THROUGH SEPTEMBER 30, 2002

by
PROJECT STAFF

Scientific Editor
T.E. EVANS

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1. DIII–D NATIONAL PROGRAM OVERVIEW FOR FY02

The mission of the DIII–D research program is: “To establish the scientific basis for the optimization of the tokamak approach to fusion energy production.” The program is focused on developing the ultimate potential of the tokamak by building a better fundamental understanding of the physics of plasma confinement, stability, current drive and heating in high performance discharges while utilizing new scientific discoveries and improvements in our knowledge of these basic areas to create more efficient control systems, improved plasma diagnostics and to identify new types of enhanced operating regimes with improved stability properties. In recent years, this development path has culminated in the advanced tokamak (AT) approach. An approach that has shown substantial promise for improving both the fusion yield and the energy density of a burning plasma device. While the challenges of increasing AT plasma performance levels with greater stability for longer durations are significant, the DIII–D program has an established plan that brings together both the critical resources and the expertise needed to meet these challenges. The DIII–D research staff is comprised of about 300 individuals representing 60 institutions with many years of integrated research experience in tokamak physics, engineering and technology. The DIII–D tokamak is one of the most productive, flexible and best diagnosed magnetic fusion research devices in the world. It has significantly more flexibility than most tokamaks and continues to pioneer the development of sophisticated new plasma feedback control tools that enable the explorations of new frontiers in fusion science and engineering.

Significant progress was made during FY02 in all areas of the DIII–D research program. Some highlights from the operations and research program include:

- Clear demonstrations of current profile control using off-axis electron cyclotron current drive (ECCD).
- Active feedback control of T_e [and, indirectly, J(r)] with electron cyclotron heating (ECH).
- High bootstrap AT plasmas, with $q_{min}{\approx}1.5$ and $q_{min}{>}2$, were sustained for several hundred milliseconds with nearly fully noninductive current $f_{NI}{\approx}90\%$ and $\beta_N{\approx}3$.
- First experimental stabilization of the 2/1 neoclassical tearing mode using electron cyclotron current drive.
- Understanding that the key physics of stabilization of the RWM is plasma rotation with respect to the mode.
- The scaling of the critical rotation for RWM onset is consistent with inverse Alfvén time.

- Successful disruption mitigation technique with real-time trigger of gas jet.
- Geodesic acoustic mode branch of zonal flows identified in DIII–D plasmas.
- Demonstrated isolated inner strike points in double-null divertor discharges — no ELMs, little particle and heat flux.
- TAE mode number scales with $1/q^2$ consistent with theory in DIII–D/NSTX similarity experiments.
- Identified the dependence of the density pedestal width on neutral penetration in both hydrogen and deuterium plasmas.
- Plasma rotation observed in plasmas with no angular momentum input in C–Mod comparison experiments.
- Ran more than 50 DIII–D discharges with 5 fully functioning ECH gyrotrons and obtained incident ECH power levels exceeding 2.3 MW with heating pulse lengths of approximately 2 s.
- Staff played key leadership roles in the preparation and execution of the 2002 Snowmass Fusion Energy Sciences Summer Study, a major step in moving ITER forward.

The ECH and ECCD systems became an integral part of the primary experimental program in FY02 and provided significant advances in key research areas. With the enhanced capabilities and availability of the EC systems, suppression of both the 3/2 and 2/1 neoclassical tearing mode (NTM) has been achieved using a set of active feedback algorithms developed in FY02. These experiments have opened a substantial window of opportunity for the additional optimizations of $\beta_N H$ versus time and have provided significant new insight into the physics of tearing modes in high performance plasmas. In the area of developing new AT operating scenarios substantial progress was made using the new capabilities of the EC systems. Work in this area centered on first application of high power (P_{EC}≈2.5 MW) ECH and ECCD AT plasmas with high bootstrap fraction and on quiescent double barrier plasmas. In both cases, up to 140 kA of current was driven well away from the magnetic axis. Another important objective accomplished in the AT scenario development research thrust was the successful demonstration of kinetic profile control using the ECH system. Thus, substantial progress was made on the near-term AT goal of producing plasmas, with $\beta_N \approx 3.5$, that are sustained noninductively for 2 s.

As in previous years, planning activities associated with the experimental campaign are an important part of the DIII–D research program. This activity starts with an open Research Opportunities Forum in which ideas for a broad spectrum of experiments are presented and discussed. More than 225 experimental proposals were submitted to the FY02 Research Opportunities Forum that results in a 58 day experimental campaign that began on January 28, 2002. The final allocation of experimental run time was made following the Research Opportunities Forum through a series of meetings and discussions between the

DIII–D directors, the Research Thrust and Topical Science Area leaders and the DIII–D Research Council. Twelve run weeks were obtained on DIII–D in 2002.

Members of the DIII–D research team continued to demonstrate a strong commitment to other fusion-related activities during FY02. These activities include providing a leadership role in the International Tokamak Physics Activity (ITPA), the Snowmass Meeting in July 2002 and in the U.S. Fusion Educational Outreach Program. In terms of the ITPA, DIII–D team members hold several International leadership positions including membership in the Coordinating Committee and as international leaders in the Transport and Internal Barrier Physics Topical Group and in the Edge and Pedestal Physics Topical Group. In addition, 12 DIII–D team members are Core Contributors across the seven ITPA Topical Groups and three are U.S. Topical Group Leaders while 14 other DIII–D team members are unofficial ITPA participants. The 2002 Snowmass Meeting represented a major milestone in the process of planning future U.S. Fusion activities. DIII–D team members played a pivotal role in the organization and execution of this meeting. Two DIII–D team members served on the Organizing Committee and 11 of the Subgroup Co-chairs were members of the DIII–D team. The fusion educational outreach team continued to maintain an active program by providing tours of the facility to students and teachers, supporting educational outreach programs at large annual meetings, such as the DPP-APS Meeting in Long Beach, and giving talks and plasma science demonstrations to local schools. In addition, the DIII–D program hosted a group of undergraduate students during the summer as part of the National Undergraduate Fusion Fellowship Program and continues to give a high priority to educating future generations of plasma researchers by hosting undergraduate, graduate and postgraduates throughout the year and providing them with hands-on experience in various fusion research projects.

This report includes a CD that contains additional details about progress made in FY02. Included in the CD are copies of presentations on DIII–D FY02 results that were made at some of the major meetings and a comprehensive list of publications made by DIII–D team members in FY02. Appendix A is also included in which copies of the DIII–D research highlights released during the year are provided.

2. FY02 SCIENTIFIC GOALS AND PROGRESS

The DIII–D research program is organized into focused Research Thrusts (RTs), selected annually to address key physics questions and four standing Topical Science Areas (TSAs) that provide researchers with resources needed to investigate a wider variety of physics and technology issues that are expected to meet the long-term needs of the fusion program. During FY02, there were four active RTs focused on: Pedestal Stability and Control (RT1), Neoclassical Tearing Modes (RT3), Resistive Wall Modes (RT4) and Advanced Scenario Development (RT8). These RTs completed 32 experimental run days. The remainder of DIII–D's run days were dedicated to TSA experiments in the area of: Stability, Confinement and Transport, Heating and Current Drive, and Boundary Physics. Highlights of the results from each of the RTs and TSAs are summarized in this section.

2.1. PEDESTAL STABILITY AND CONTROL — RESEARCH THRUST 1

It is well understood that the confinement and stability properties of the core plasma are intimately coupled to the plasma edge region in high performance tokamak regimes. In particular, the height and width of the edge pedestal region plays a fundamental role in setting the global performance level attainable in high pressure advance tokamak (AT) discharges. Thus, a key area of AT research rests on developing a comprehensive understanding of the mechanisms that determine the detailed distributions of plasma current and pressure across the pedestal region as well as understanding how edge instabilities such as ELMs are affected by changes in these pedestal profiles.

The primary near-term goal of the Pedestal Stability and Control Thrust is to develop and test theory-based predictive models of the edge stability using DIII–D experimental data. This includes testing and improving linear stability codes such as ELITE, GATO and NIMROD as well as evaluating the impact of nonlinear, nonideal, and low n effects in the stability models and developing self-consistent pedestal transport models. A critical element of this development is our ability to make high resolution edge temperature (T_e) and density (n_e) profile measurements, required for assessing ballooning mode stability, in conjunction with edge current density profile measurements needed for validating peeling mode theories. As shown in Fig. 2–1, DIII–D's edge Thomson scattering system provides excellent T_e and n_e profile coverage of the pedestal region.

In addition, a new edge current diagnostic system, based on the measurement of polarized Zeeman split emissions from an energetic lithium beam, was installed and operated on DIII–D for the first time in FY02. These two diagnostic systems are providing data with which to critically test our existing stability codes and with which to develop predictive edge stability models required for investigating AT pedestal scenarios in reactor relevant operating regimes.

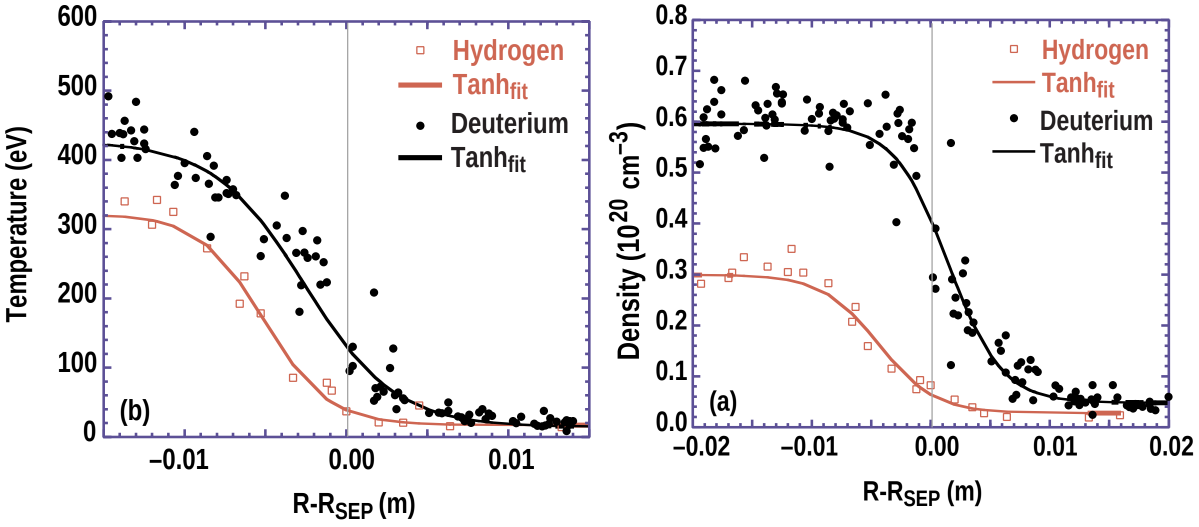

Fig. 2–1. High resolution T_e and n_e Thomson scattering profiles demonstrate the effects of atomic physics on the height and width of the pedestal profiles in DIII–D plasmas with the same dimensionless pedestal ion parameters.

During FY02, work in the pedestal stability and control thrust focused both on commissioning the Li beam edge current density profile diagnostic and on gathering experimental data needed to better understand atomic physics effects on the properties of the pedestal, to determine if the properties of tolerable, so-called Type II, ELMs are similar from one tokamak to another, and to better understand the physics of Quiescent H–modes (QH–modes). Six experimental days were dedicated to the following three areas:

- Hydrogen versus deuterium similarity studies.
- Type II ELM similarity studies.
- QH–mode physics studies.

As shown in Fig. 2–1, the width of the n_e pedestal is about a factor of two larger in hydrogen plasmas than in deuterium plasmas. This data supports the hypothesis that atomic physics is the key factor in setting the width of the pedestal. It was also found that changes in the auxiliary heating by as much as a factor of two did not affect the pedestal pressure.

The goal of the ELM similarity experiments was to match Type II ELMs observed in Asdex–U and study their physics. Results from these experiments demonstrated that:

- Small, Type II-like, ELMs can be obtained with Asdex-U similar discharges in DIII–D although it was not possible to identically match the Asdex-U pedestal.

- D_α measurements are inadequate for small ELM similarity studies — a more appropriate measure is the ELM energy loss normalized to the pedestal energy.
- While the confinement with small ELMs was good at moderate densities, it degraded at higher densities as the T_e pedestal width narrows.

Quiescent H–mode studies continued to be a priority element in the FY02 Thrust 1 experimental plan. These modes are particularly attractive because of their superior confinement quality and the absences of ELMs during the QH–phase. While relatively little experimental time was available for QH–mode experiments (one day of the six completed in Thrust 1) significant progress was made in developing more effective shapes for pumping and density control. As a result, it was found that pumping can be used to control the pedestal pressure by controlling the density in the pedestal region.

2.2. NEOCLASSICAL TEARING MODES — RESEARCH THRUST 3

The goal of this research thrust is to develop a better understanding of the physics involved in the destabilization and growth of Neoclassical Tearing Mode (NTM) islands in high performance plasmas and to explore methods of suppressing these instabilities. NTMs are known to limit the core confinement and normalized plasma pressure (β_N) in both conventional and AT discharges. Research in this area is expected to contribute to a more comprehensive understanding of a broader range of tearing mode physics issues and could help us identify a scaling relation for the onset of NTMs with increasing β_N. Thus, the development of active NTM suppression techniques, such as that demonstrated in DIII–D by driving current in the NTM islands with Electron Cyclotron (EC) waves, is essential both for studying the stability properties of these modes and for enabling better access to long pulse, high performance, AT plasmas.

Substantial progress continues to be made in developing EC Current Drive (ECCD) feedback suppression methods and algorithms for the m/n = 3/2 NTM. This success with 3/2 mode suppression has opened a window for exploring longer duration, high β_N, plasmas with higher confinement (H) factors. Thus, our attention in FY02 was focused on the stabilization of 2/1 NTM and on assessing the extent to which the product of β_N and H may be extended (with and without sawteeth) in NTM quiet discharges.

Specific near-term objectives for this line of research include:

- Maximize performance ($\beta_N H \sim 9$–10) versus time for long pulse discharges.
- Optimize discharge waveforms to attain the highest $\beta_N H$ possible (i.e., >10).
- Develop a better understanding of 2/1 stability physics and eliminate 2/1 NTMs.
- Using 2/1 and 3/2 NTM stable plasmas to optimize $\beta_N H$ versus time.
- Investigate the current profile evolution in NTM stable discharges with high $\beta_N H$.

Significant new experimental results were obtained during FY02 in the NTM research thrust area. Key among these was stabilization of 2/1 NTMs for the first time ever using ECCD. These results are summarized in Fig. 2–2.

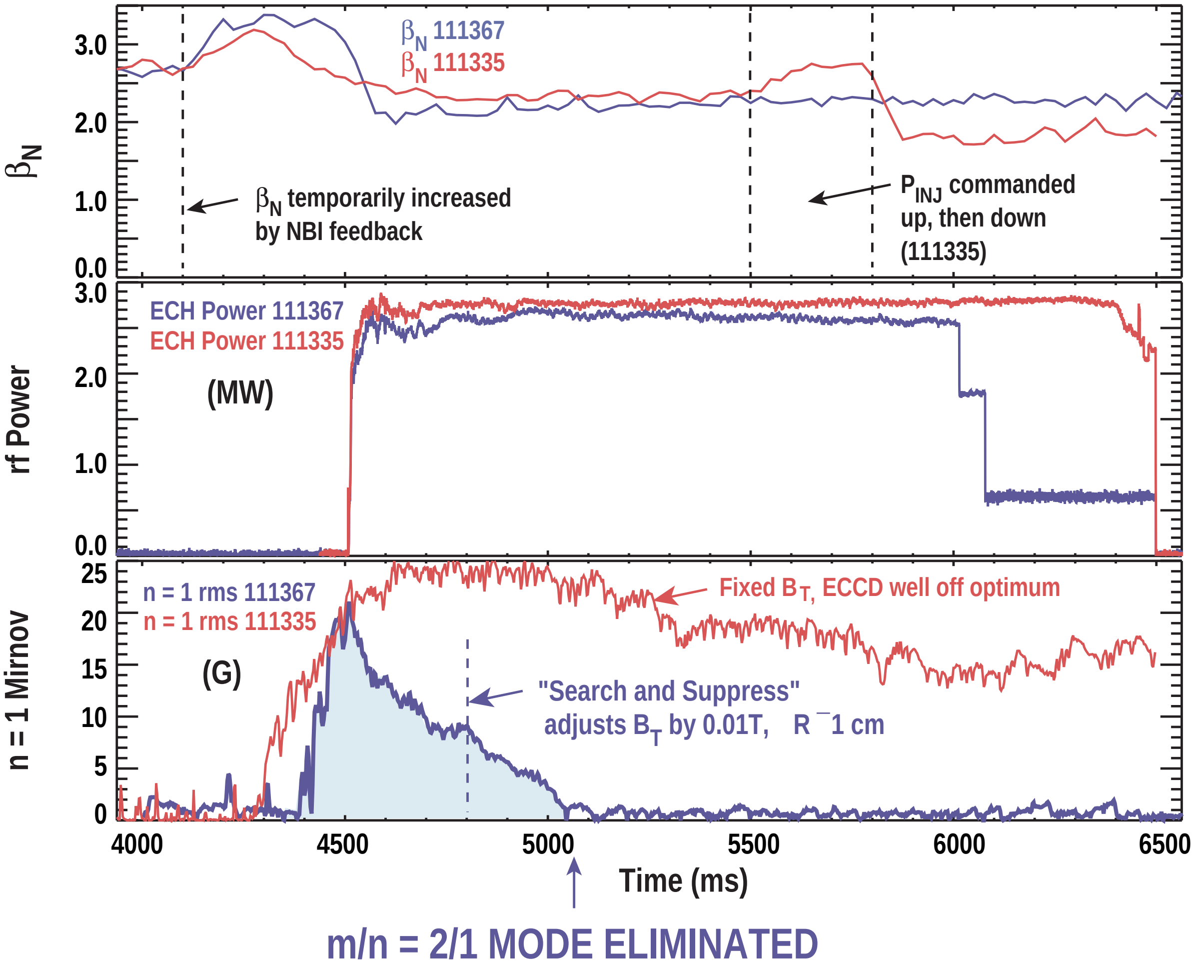

Fig. 2–2. Comparison of a discharge (111367) in which the m/n = 2/1 NTM was eliminated by the ECCD “Search and Suppress” feedback control system to one without ECCD feedback (111335). Note that the discharge without ECCD feedback has a comparable amount of ECH power and a large 2/1 NTM.

Other important accomplishments in this research area include:

- Identification of experimental results that are consistent with a model, i.e., a “pole”, predicting that the tearing Δ' increases with proximity to the ideal wall β limit.
- Incremental progress in a long-pulse scenario (between conventional sawtoothing and a fully noninductive AT plasma) in that: (1) RWM feedback significantly increases plasma rotation, (2) the maximum stable $\beta_N H$ was increased to ~8, (3) the duration was increased to 8 s (limited only by power supplies), and (4) demonstration of ECCD stabilization of the limiting 2/1 NTM.

- Comparison of the threshold in the m/n = 3/2 NTM by slow β_p rampdown in DIII–D and JET to produce an offset rather than an onset in which seeding complicates the threshold evaluation.

2.3. RESISTIVE WALL MODE — RESEARCH THRUST 4

In addition to the Neoclassical Tearing Modes, described in Section 2.2, another class of instabilities that limit the performance of high β_NH plasmas is the Resistive Wall Mode (RWM). Stabilization of these ideal kink modes is essential for developing the full potential of long-pulse AT plasmas. Spinning the plasma with neutral beams provides an effective way to stabilize these RWMs. On the other hand, resonant magnetic perturbations from nonaxisymmetric radial fields produced by nonideal toroidal and poloidal field coil positions try to produce magnetic islands and exert drag forces on the plasma thereby slowing its rotation. By minimizing the size of the magnetic nonaxisymmetries with external control coils, the plasma can be made to spin rapidly with the neutral beams and the metal walls of the vacuum vessel have a stabilizing effect on the RWMs similar to that of a perfectly conducting wall. Thus, maintaining sufficiently high plasma rotation allows the discharge to operate above the no-wall β limit with good confinement properties.

The primary objective of the RWM research thrust in FY02 was to improve our understanding of RWM stability for various plasma conditions and to develop predictive theories for RWM stability thresholds in high β_NH reactor relevant plasma regimes. A specific high priority goal for this thrust was the development of both passive and active control tools that produce sustained DIII–D plasma discharges above the no-wall β limit. Work on the following related topics was carried out during the six experimental run days completed in FY02:

- Continue the development of a better understanding between RWM physics and the properties of the plasmas including:
  - RWM stability versus β_N.
  - RWM stability with plasma rotation or dissipation.
  - RWM stability versus plasma wall separation.
- Assess whether the ideal-wall stability limit can be improved.
- Determine the lower limit on q_{95} for stable RWM operations.
- Operate high β_N RWM stable plasmas with low rotation to benchmark feedback models.
- Assess the impact of ELMs on feedback with internal poloidal field sensors.
- Use active feedback to improve the effectiveness of error field correction.

Experiments in these areas resulted in a broad range of improvements both in terms of understanding key RWM stability physics issues and in controlling the onset of RWM instabilities. The key results obtained in FY02 included:

- Determination that there is no obvious dependence of RWM stability with the plasma-wall separation as shown in Fig. 2–3.

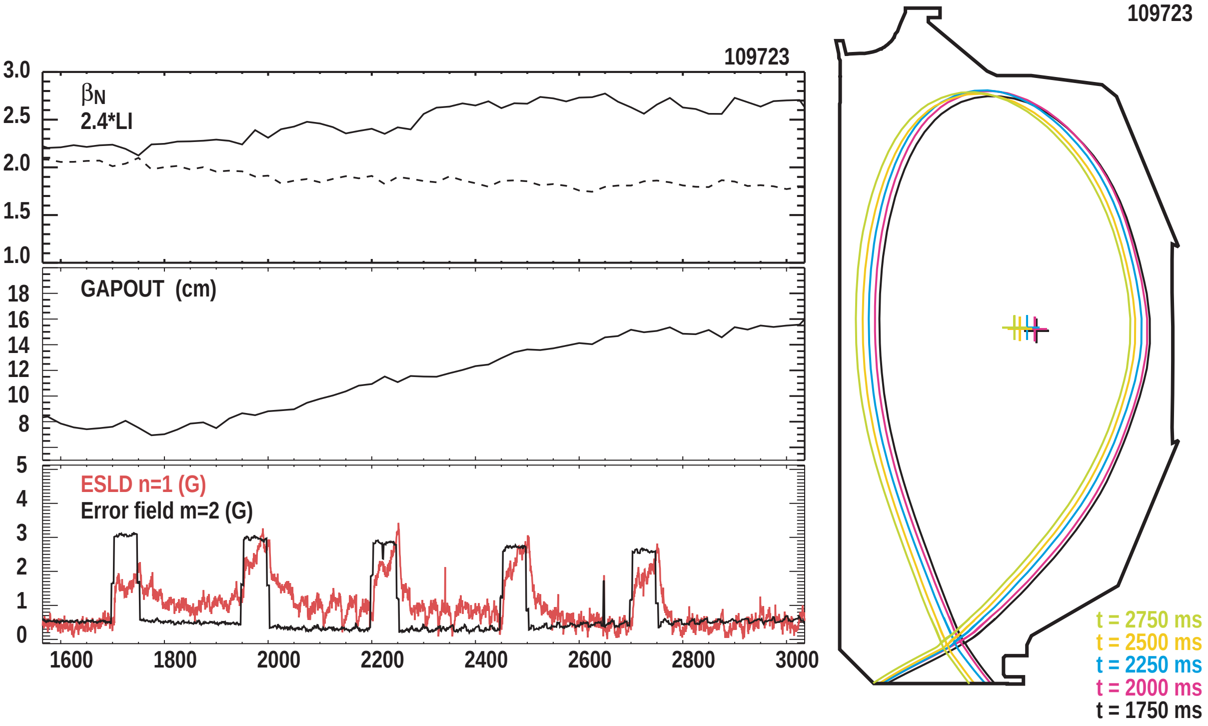

Fig. 2–3. The outer gap (GAPOUT) is scanned from 8 to 15 cm while an n=1, m=2 error field produced by a set of external correction coils is pulsed approximately every 250 ms in an attempt to destabilize an RWM in a rotationally stable discharge. The results indicate that there is no obvious dependence in RWM stability with the distance between the plasma and the wall.

- Demonstration that a relatively shear-free q-profile, with $2 \leq q \leq 3$, can be established in RWM stable plasmas with high β_NH.
- Evidence that RWM stabilization can be achieved in slowly rotating plasmas under some conditions.
- Verification that an externally applied n=3 magnetic field results in a small amount of rotational braking.
- Demonstration of “active n=1 magnetic braking” as a means for producing low-rotation target plasmas for feedback tests.
- Verification that the scaling of critical rotation for RWM onset is consistent with inverse Alfvén time as shown in Fig. 2–4.

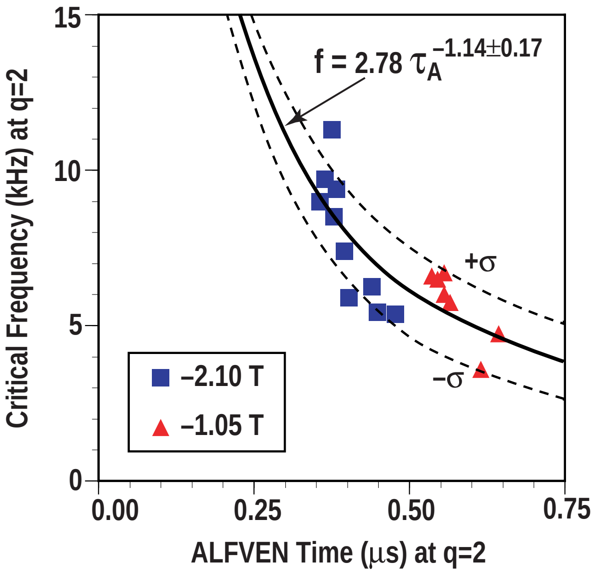

Fig. 2–4. The critical plasma rotation frequency required for the onset of the RWM at the q=2 surface was varied by changing the toroidal field and plasma density and is characterized here by a change in the Alfvén time at the q=2 surface. Note that the critical frequency decreases with increasing Alfvén time in qualitative agreement with the predictions of the RWM theory by Bondeson and Ward [A. Bondeson and D.J. Ward, Phys. Rev. Lett. **72**, 2709 (1994)]. Measuring the critical plasma rotation $\Omega_c=2\_f_c$ at the q=2 surface gives: $\Omega_c^*\tau_A$ ~ 2%.

- Evidence that a modest level of ECH power may affect the shape of the rotation profile and thus the stability of RWMs.
- Indications that a relatively simple MHD model can be used to understand an observed resonant field amplification without RWM rotation.
- Use of a real-time RWM identification algorithm in the plasma control system to control the feedback stabilization coils.
- Evidence that an extended lumped parameter model can be used to predict the effects of combined plasma rotation and active feedback.
- Indications, based on ideal MHD theory, that the error field component dominates RWM stability over a wide range of AT plasma configurations.

2.4. ADVANCED SCENARIO DEVELOPMENT — RESEARCH THRUST 8

The Advanced Scenario Development Research Thrust was initiated in FY02 as a focal point for identification and development of AT scenarios characterized by simultaneous high fusion performance and steady-state operation. High fusion performance requires operation at high toroidal beta β_T (≡ plasma pressure ÷ confining toroidal magnetic field pressure) and high confinement factor H_{89} ($\equiv\tau_E/\tau_{ITER89-P}$). Steady-state operation requires operation at high poloidal beta β_P to maximize the self-generated bootstrap current, and external current drive (provided mainly by electron cyclotron current drive, ECCD, in DIII–D) to supply the remaining plasma current with no current provided by inductive means. Although each of these requirements can be satisfied by itself, a major challenge for the Advanced Scenario Development thrust is integration of these results into a single scenario simultaneously exhibiting high performance and 100% noninductive operation.

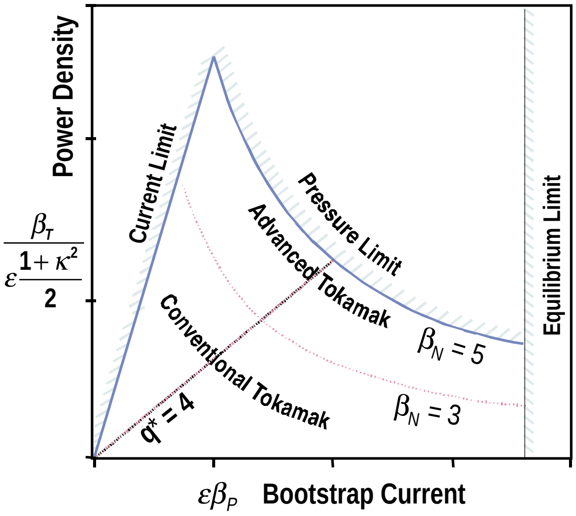

Fig. 2–5. Requirements for simultaneous high fusion power density and high bootstrap current are simultaneously satisfied at high β_N.

Our approach is a comprehensive effort embracing modeling and simulation both to design experiments and to evaluate their results, so that the predictive capability needed to design such regimes for next-step devices improves with experience. Specific performance goals for the thrust exist mainly as a test of this understanding:

- Near-term: Plasmas with $\beta_N \approx 3.5$ sustained noninductively for 2 s.
- Longer term (2–3 years): $\beta_N \approx 4$ sustained noninductively for 4–5 s. Requires long-pulse gyrotrons, fast wave and possible divertor modification.
- Ultimate goal (5–6 years): $\beta_N \approx 5$–6 sustained noninductively for 10 s. Possible operation with nearly 100% bootstrap fraction (with beamline reversed). Requires full 9 MW ECCD system and pulse length improvements.

During FY02, research in the AT thrust centered on first application of high power ($P_{EC}\approx 2.5$ MW) electron cyclotron heating (ECH) and current drive (ECCD) to AT plasmas. Other work included extensive exploration of MHD stability limits with high q_{min}. Significant accomplishments during FY02 include:

- **Current profile modification with ECCD in two different AT regimes.** High power ECCD was applied to both the High Bootstrap Fraction AT and Quiescent Double Barrier regimes. In both cases, up to 140 kA was driven well away from the magnetic axis. Two plasmas in the High Bootstrap Advanced Tokamak regime, one with q_{min}≈1.5 and one with q_{min}>2, were sustained for several hundred milliseconds with nearly full noninductive current (f_{NI}≈90% with β_N≈3; Fig. 2–6). Simulations based on these discharges indicate that with slightly higher power we can sustain similar discharges at higher β for the duration of the ECCD pulse. This will be tested during the 2003 campaign.

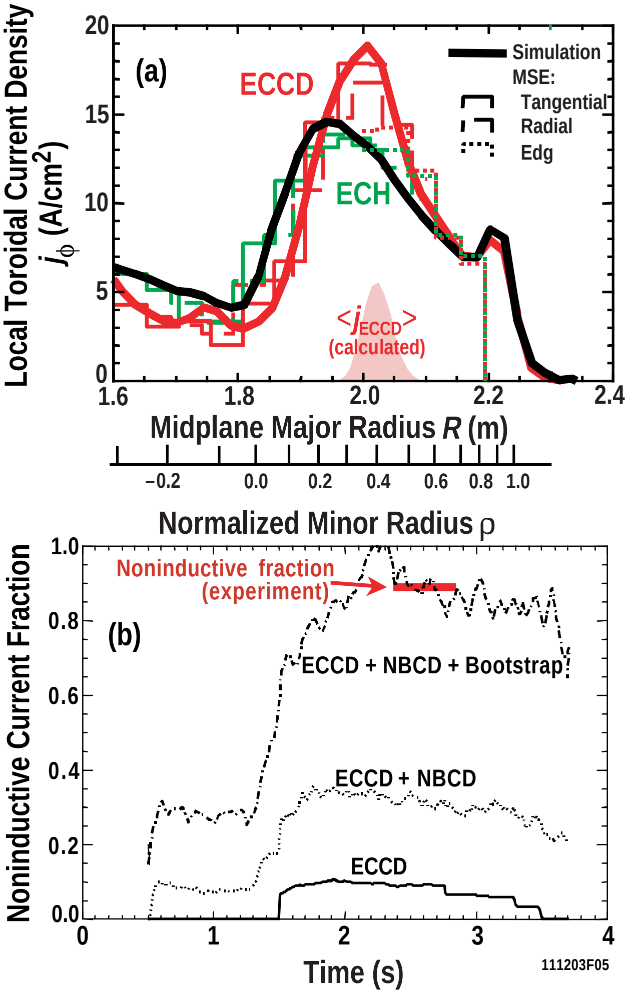

Fig. 2–6. (a) ECCD deposited at r≈0.4 drives current at that radius, consistent with prediction. (b) Plasma with ECCD obtains f_{NI} > 85% for duration of ECCD.

- **Control of kinetic profiles with ECH.** The utility of ECH for controlling kinetic profiles in the AT plasma was demonstrated:

— **Feedback control of T_e.** The plasma control system was used to establish feedback control of the electron temperature profile (Fig. 2–7). In these initial tests, a single ECE channel provided the sensor, while the actuator was several gyrotrons aimed at the same spatial location. Future improvements may expand this to multiple measurement and heating locations, to control the electron temperature profile shape. This technique was successfully applied to the current ramp phase of AT discharges, providing improved reproducibility in forming the AT target.

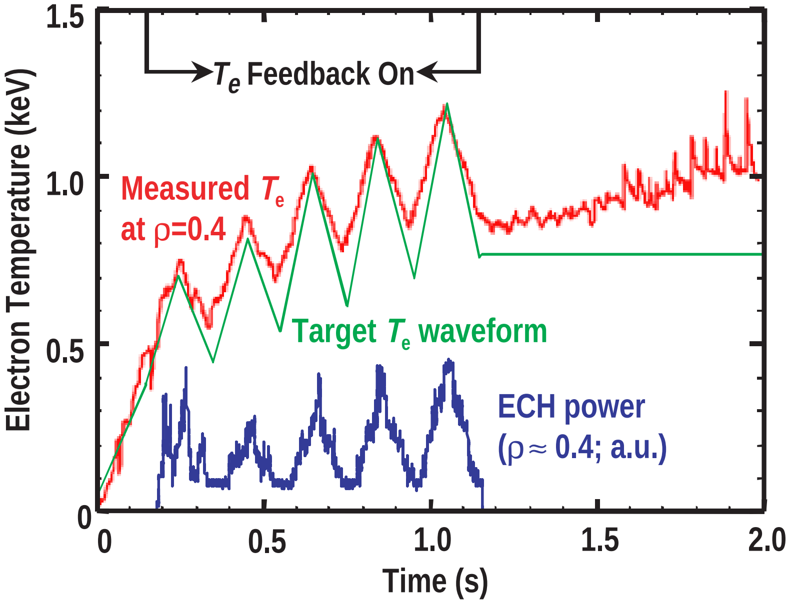

Fig. 2–7. Local electron temperature can be controlled via feedback control of ECH.

— **Density profile control in Quiescent Double Barrier regime.** QDB discharges have highly peaked density profiles, leading to accumulation of high-*Z* impurities, reduced β limits and poor bootstrap alignment. Small amounts of central electron heating can reduce the density peaking and impurity accumulation. Future experiments will study impacts on the β limit and bootstrap current.

— **Target q profile optimization.** Early efforts in 2003 concentrated on developing discharges with high q_{min} due to an expected benefit for high bootstrap fraction. Detailed studies, both experimental and through simulations (Fig. 2–8), found that the achievable β_N decreases at the highest values of q_{min} (>2.5). This may indicate that the optimal q_{min} is somewhat lower than previously thought, perhaps slightly above 1.5. Future work will explore the possibility that high q_{min} operation may still be desirable with broader pressure profiles and/or more strongly shaped plasmas.

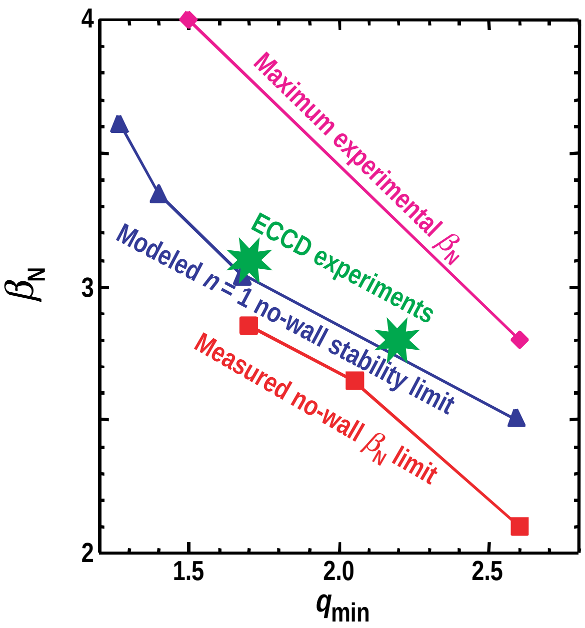

Fig. 2–8. Both experiment and calculations indicate that the β limit decreases with increasing q_{min} in discharges with a pressure profile similar to that of the 2003 AT studies.

2.5. STABILITY TOPICAL SCIENCE AREA

Research activities in the Stability TSA are primarily focused on developing a deeper understanding of MHD physics in high performance DIII–D plasmas. Experience shows that developing a better understanding of basic MHD physics leads to improvements in plasma performance. Over the short term, i.e., the next three years, areas of particular interest for the Stability TSA include: understanding the effects of plasma rotation and wall distance on resistive wall mode stability, investigating edge instabilities driven by large pressure gradients and bootstrap currents, exploring physics issues connected with the active stabilization method for neoclassical tearing modes, understanding nonideal instabilities such as sawteeth, resistive interchange modes and ion drive modes, and developing disruption mitigation or avoidance techniques based on a more comprehensive understanding of disruption dynamics in high power plasmas. Each of these topics has a direct bearing on one of the DIII–D Research Thrusts and thus will help provide information for making rapid progress toward the integrated goals of the DIII–D program. Over the long-term, the goal of the Stability TSA is to establish the scientific basis for understanding and predicting limits to macroscopic stability of toroidal plasmas.

In FY02 experiments on disruption mitigation physics and Alfvén Eigenmode stability were carried out by the Stability TSA group. In addition, Stability TSA group members participated in a wide range of stability related experiments carried out in each of the

Research Thrust areas. Key results obtained during the disruption mitigation experiment included: the first demonstration of a real-time Vertical Displacement Event (VDE) disruption detection system used to trigger a neon gas jet which safely terminates a high power discharge without inducing large halo currents, vessel forces or runaway electrons; and a demonstration that neon impurity radiation provides an optimal mitigation mechanism for reducing excessive thermal loading and vessel forces during high current disruptions. The Alfvén Eigenmode stability experiment was designed as a similarity study for comparing the properties of Toroidal Alfvén Eignemode (TAE) modes in NSTX and DIII–D. The goal of this study was to match the NSTX shape, fast ion energy, and ratio of fast ion velocity to Alfvén velocity to that of DIII–D and to investigate the major radius dependence of the TAE modes, measure their stability threshold, and determine the most unstable toroidal mode number in each machine. The geometry used for these similarity studies is shown in Fig. 2–9. These experiments confirmed that the TAE thresholds are similar in the two machines and that the TAE mode number scales as expected from NSTX to DIII–D.

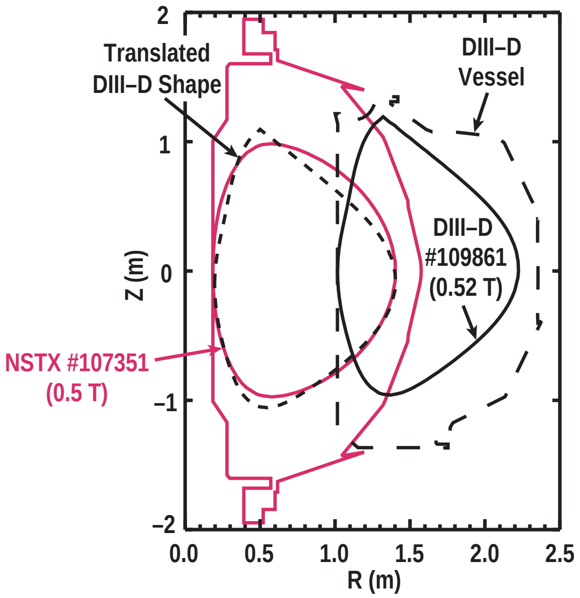

Fig. 2–9. Geometry used for NSTX/DIII–D Alfvén Eigenmode similarity experiments.

2.6. CONFINEMENT AND TRANSPORT TOPICAL SCIENCE AREA

The primary goal of the Confinement and Transport TSA is to develop a predictive understanding of transport in high performance tokamaks by investigating fundamental transport physics issues resulting from research in DIII–D AT plasmas. The activities of this TSA are designed to foster the development of novel transport ideas and create opportunities for making new discoveries in basic confinement and transport physics. During FY02 five experimental run days were completed in this research area covering: core transport physics, H–mode physics, nondimensional transport studies, fundamental turbulence studies, and a test of theory-based transport models. These experiments are representative of the work being done in the three subtask areas that form the basis for the short-term goals of this TSA: core transport, edge physics, and comparisons with numerical modeling.

Significant new and important experimental results, with which to test a rapidly developing array of models, were obtained during FY02. For example, this year's experiment on fundamental turbulence studies verified previous observations of zonal flows in the saturated turbulence near the plasma edge and compared the properties of these flows to characteristics calculated with the BOUT code and a 3D Braginskii code. The experimental results clearly demonstrated a coherent poloidal oscillation in the turbulent flow field and identified a mode frequency that scales with the sound speed divided by major radius. These results are consistent with the frequency scaling displayed by geodesic acoustic modes often seen in simulations carried out with edge turbulence codes.

Other important results in this research area include:

- A demonstration that more than a factor of two increase in ECH power above the NBI power threshold is required for H–mode transitions in plasmas with densities between 1 to 3×10^{19} m^{-3}.
- Measurements of T_e phase lags, in ELMing H–mode ECH modulation experiments, that indicate a lack of profile stiffness. These phase lags are similar to or longer than those seen in previous L–mode experiments (which is consistent with improved H–mode confinement).
- The identification of similar Ohmic H–mode plasma rotation profiles in DIII–D and Alcator C–Mod but significantly different rotation profiles in DIII–D ECH and C–Mod ICRH H–mode discharges (a comparison of the DIII–D Ohmic and ECH H–mode rotation profiles is shown in Fig. 2–10).
- The creation of strong but transient core transport barriers in both the ion and electron loss channels during NCS discharges with L–mode edges by independently varying the E×B shear and Shafranov shift (i.e., with rapid I_p jumps, by creating weak NCS conditions with delayed beam injection and by varying T_e/T_i with ECH to change the E×B shear during constant NBI heating).

In addition, a surprising new result was obtained during the core transport physics experiments, the discovery of a long lasting NCS phase in which q_{min} remained above 2 for more than 2000 ms in some discharges (much longer than in previous NCS experiments).

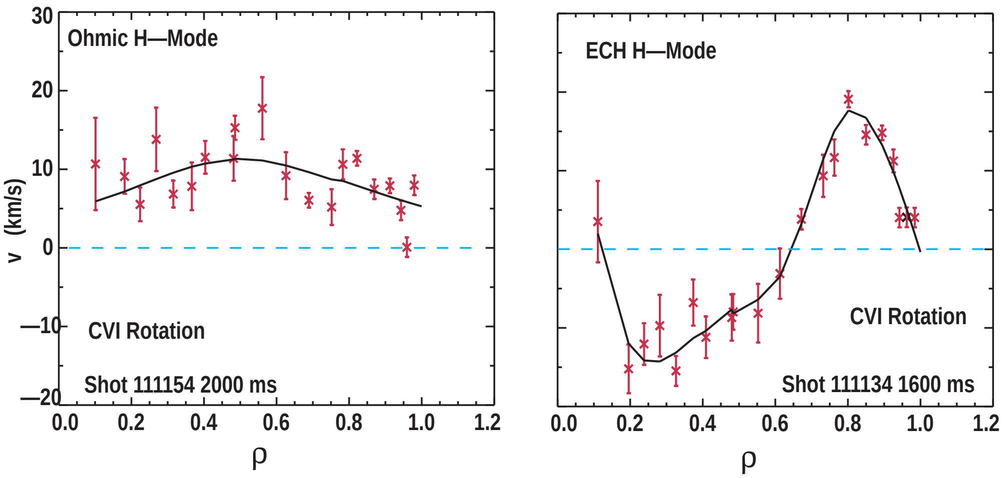

Fig. 2–10. Plasma rotation profiles measured in DIII–D Ohmic and ECH H–modes.

2.7. HEATING AND CURRENT DRIVE TOPICAL SCIENCE AREA

The near-term goals of the Heating and Current Drive TSA are as follows: (1) establish predictive capability for Electron Cyclotron Current Drive (ECCD) and Fast Wave Current Drive (FWCD) that includes all the essential dependencies on density, temperature, β, geometry, power, trapping, and DC electric field; (2) develop long pulse AT discharges, including those with very high bootstrap fraction that are sustained exclusively by noninductively generated current; and (3) advance our understanding of the physics of bootstrap currents and Neutral Beam Current Drive (NBCD). A key activity in this research area is the development of high power Electron Cyclotron Heating (ECH) tools to be used for exploring new AT operating regimes such as those discussed above in the various research thrust areas. During FY02, more than 50 DIII–D discharges were run with 5 fully functioning ECH gyrotrons. Incident ECH power levels exceeding 2.3 MW, with heating pulse lengths of approximately 2 s, were obtained for the first time in FY02. Commissioning of the dual P1999 launcher, with independent toroidal steering but ganged poloidal steering, and the dual P2001 launcher, with fully independent steerability, was completed, along with the testing of a GA launcher with long pulse mirrors.

High power ECH and ECCD operations were achieved late in the experimental year and are now available to support the physics goals of this TSA. The primary research areas to be examined with the high power EC systems over the next few years will be:

- Experiments supporting the development of basic physics concepts involved in understanding ECH and ECCD interactions with high β_NH AT plasmas including:

  — Far off-axis ECCD.

  — ECCD physics in high β_e plasmas.

- The development of discharges with very high bootstrap current fractions.

During FY02 considerable progress was made in preparing for dedicated experiments in this area. For example, it was found that a scan of the parallel index of refraction switches the direction of the ECCD from a co- to counter-current drive orientation. As shown in Fig. 2–11 experimental measurements made for three sets of conditions are in good agreement with predictions from CQL3D Fokker-Planck code simulations.

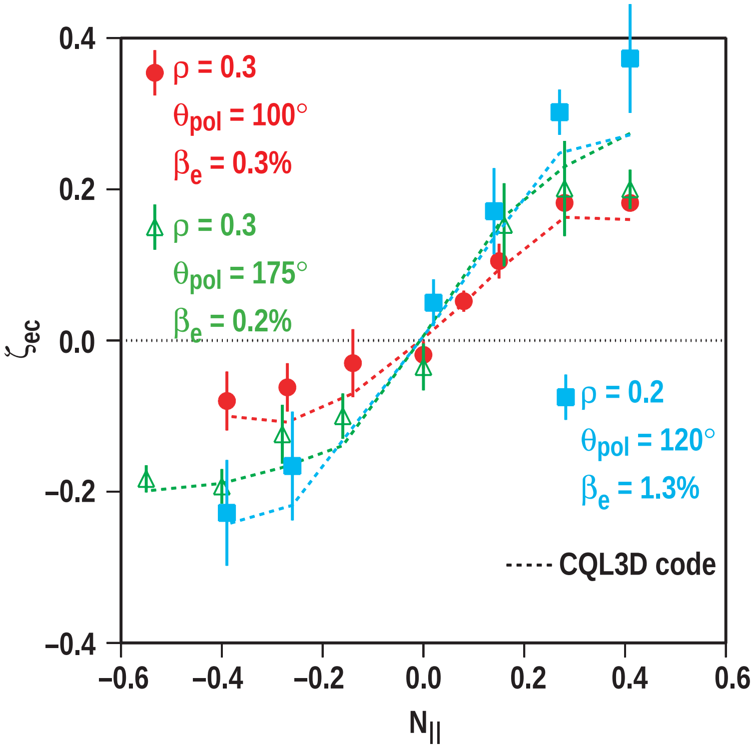

Fig. 2–11. Measurements of the dimensionless ECCD efficiency (ζ_{ec}) versus the parallel index of refraction $N_{||}$ (symbols) compared to CQL3D Fokker-Planck code simulations (dashed lines).

In addition to these basic ECH/ECCD physics studies, the Heating and Current Drive TSA supported key AT physics goals in several research thrusts that resulted in:

- A demonstration of 2/1 tearing mode stabilization with ECCD in Thrust 3.
- The use of ECCD in discharges with high bootstrap fraction as well as in QDB discharges and the use of ECH to provide feedback control of T_e for improving discharge startup conditions during Thrust 8 experiments.

2.8. BOUNDARY PHYSICS TOPICAL SCIENCE AREA

Boundary and divertor plasmas provide a buffer region separating high power core plasmas from solid material surfaces that protect the vacuum vessel walls and a variety of internal experimental components and diagnostic systems. The physics in this region is highly complex due to the diversity of processes involved, the interactions between these processes and the intrinsic 3D nature of the region. Several of the key processes involved in establishing the properties of the plasma in this region include: small-scale electrostatic turbulence, atomic and molecular physics, open-field line heat and particle transport, global MHD stability physics, and plasma material interactions. Understanding both the fundamental nature of these processes and the complicated interplay between them is the primary challenge facing researchers in the Boundary Physics TSA. During 2002, boundary physics experiments on DIII–D addressed aspects of all these processes. These experiments included: open-field line (scrapeoff layer) turbulence and transport studies in H–mode, Edge Localized Modes (ELMs) studies at high time resolution, impurity penetration physics versus plasma density, basic physics studies in simple as possible plasmas, and the effects of magnetic balance on boundary physics.

One of the most striking results obtained in 2002 was that very small changes in the up-down magnetic balance of standard ELMing H–mode plasmas produce substantial changes in the properties of the edge plasma. Among the key observations are:

- Significant changes in the deposition patterns of ELM pulses on plasma facing surfaces are observed with small changes in magnetic balance.
- A sensitive dependence in the divertor target neutral particle recycling in well balanced DN configurations. Of particular interest is the disappearance of ELM particle flux at the inner divertor when operating in well-balanced double nulls.
- Strong variations in the evolution of the core plasma properties observed due to changes in magnetic balance, as shown in Fig. 2–12, are related to the direction of the toroidal magnetic field and not the difference in closure of the upper and lower divertor baffles.

A variety of other important results obtained during these experiments including:

- The first high time resolution images of carbon and deuterium emissions during an ELM cycle show divertor plasma reattaching then strongly detaching and recovering its pre-ELM conditions all within <1 ms.
- The first high time resolution measurement of midplane density profiles during an ELM crash show a front that moves from the separatrix to the wall in ~200 μs.
- Variations in carbon penetration factors during CD_4 puffs show a modest reduction with increasing density but a strong reduction with $V_{\nabla B}$ pointed away from the active divertor.
- Transport bursts, seen with several diagnostics, carrying as much as 50% of the radial particle flux to the midplane wall in L–mode plasmas but are reduced in amplitude and frequency during H–modes.

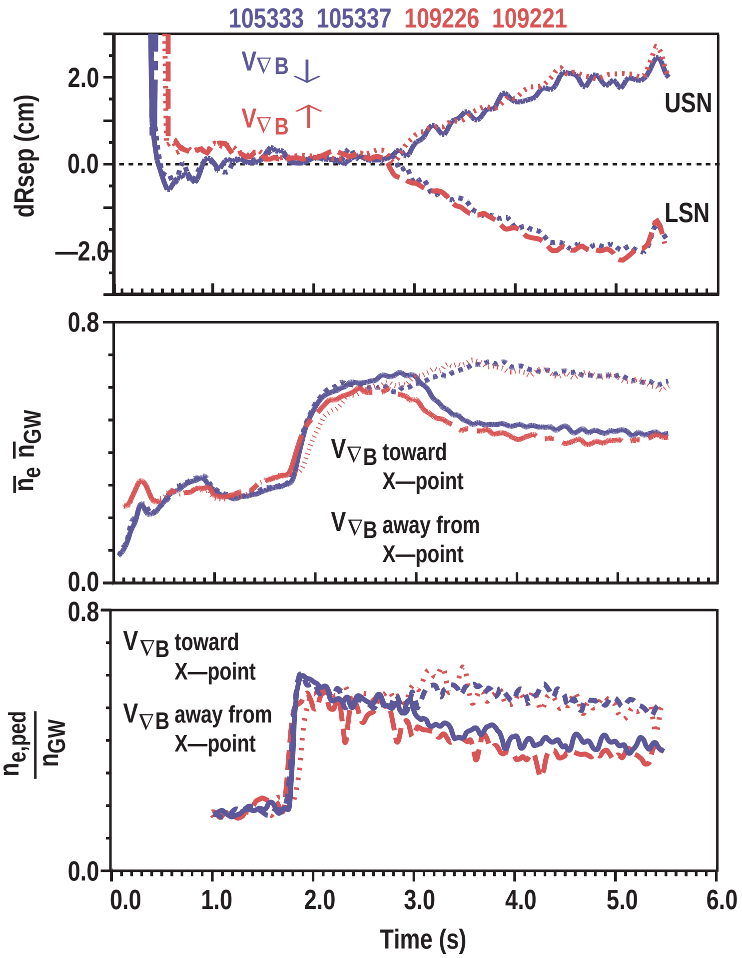

Fig. 2–12. Reversing the ∇B drift direction changes the response of the core and pedestal density with small shifts in the up-down magnetic balance.

In addition to these basic physics studies the Boundary Physics TSA supported the targeted research goals of several thrust areas discussed above. During FY02, group members from this TSA were especially active in the Pedestal Stability and Control Thrust area. Many of the most important results obtained in FY02 are summarized in 18 invited and contributed papers presented at the 15th International Plasma Surface Interactions Conference and will be published in the March 2003 issue of the Journal of Nuclear Materials.

3. FY02 FACILITY OPERATIONS

FY02 was a highly productive year for the Operations Group despite a number of challenges presented by equipment failures. As is usual, the year began with the completion of a major vent and construction period during which time two prototype in-vessel coils for Resistive Wall Mode stabilization were installed and an extensive set of high precision measurements to evaluate magnetic error fields were obtained. Experimental operations occurred during the second and third quarters, but they were terminated nine days early because of a vacuum leak in the vessel wall. The leak was repaired during a short vent. This was followed by an extended down period to install the full set of 12 internal coils. A major task for the electrical engineering group was to install the power cables and data acquisition system for the I–coils. The neutral beams operated with high reliability during the year, but critical ion source parts have started to fail. A task to make these parts from old sources and make completely new ones has been started. All six gyrotrons were successfully operated generating power in excess of 4 MW for pulses greater than 2 s. One gyrotron, CPI–P1, developed a water leak and had to be sent back to CPI, where a new collector was installed.

A timeline for the year with highlights is shown in Fig. 3–1.

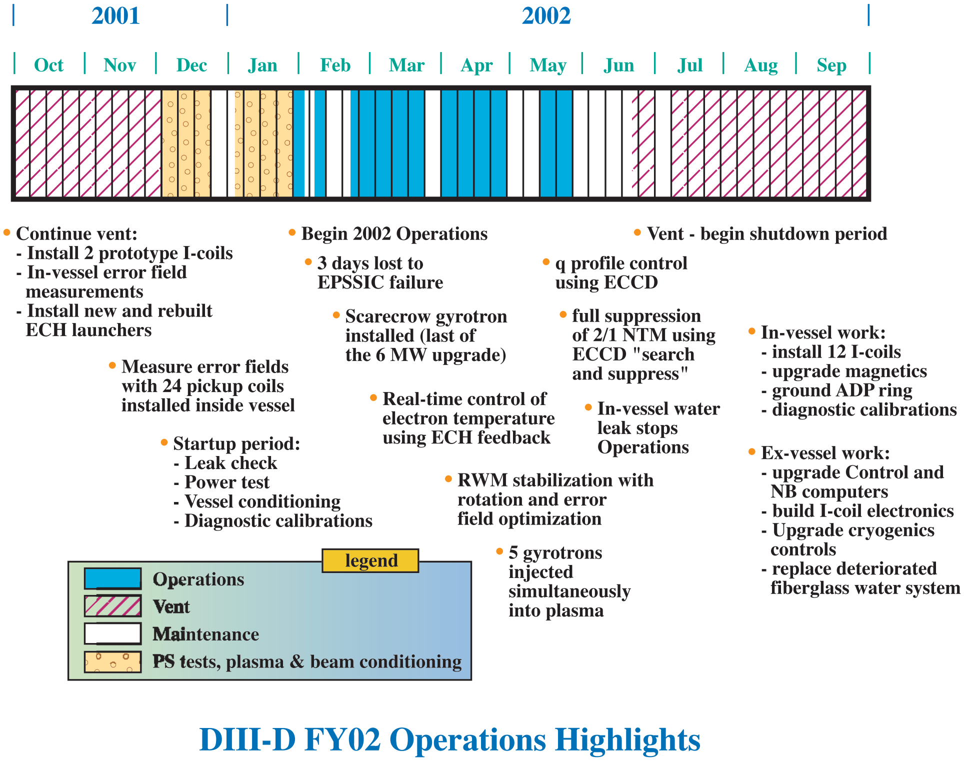

Fig. 3–1. DIII–D FY02 Operations Highlights.

3.1. TOKAMAK OPERATIONS

A total of 58 days of operations were obtained with an average availability of 59%. The availability statistics are shown in Table 3–1. The largest source of lost time (Fig. 3–3) was due to a vacuum leak that developed between the vessel and a vessel cooling channel which resulted in operations for the year ending nine days early. The second largest source of down time was due to water leaks in the beam lines. A total of 36 days of power testing and 15 days of plasma checkout were used to prepare for operations, condition the machine and recover from vents. Also performed were 14 bakes, 3 boronizations, and 8 Rayleigh scatterings. There were 157 vessel entry vent days and clean vents on 3 days.

Table 3–1
DIII–D FY02 Availability Statistics

Availability Statistics	Year Total (h)
Initially scheduled	593
Canceled loss (see note below)	115
Power shut down loss	5
Rescheduled operation	17
Extra operation	0
Actual obtained	348
Availability	59%
Availability excluding power shut down	59%

Note: Canceled loss is initially scheduled operation that was canceled for reasons other than power shut downs while power shut down loss is scheduled operation that was not done because of power cost or power availability.

The upgrade project for the control system for the ohmic coil and switches, EPSSIC, continued and the new EPSSIC CPU system was successfully tested and used. Work on an upgraded F–coil over-current system progressed well, but after 14 of the 18 coils had been calibrated and successfully tested a problem with noise pickup on the remaining coils was found and it was decided a design change was required. Manpower requirements for other projects, however, have delayed completion of both the EPSSIC upgrade project and the F–coil over-current project.

A new RGA was installed, tested, and reliably used during the year in place of the old RGA system that was failing and not repairable.

The FICS system of automatic between shot fault analysis was expanded and improved.

3.2. VENTS

The vent that started during July of 2001 continued and was completed in early December — approximately 7.5 weeks after the initially estimated close date due to delays in the delivery of two ECH antennas, problems with ECH power supplies, and by the addition of an extensive set of error field measurements. A total of 12 days were spent on measuring error fields inside the vessel by powering various coil systems. While the machine was vented, the two new prototype I–Coils installed during the 2001 vent were successfully powered and tested under load. The old n=1 coil was permanently removed from the top of the machine during the error field measurement task. The vent was successfully completed within the radiation guidelines.

The major problem that ended FY02 operations early was a vacuum leak in the machine that occurred at the end of May after the last shot of a day scheduled to study the mitigation rapid plasma terminations with massive gas puffs. After identifying that the leak originated in the vessel wall-cooling channel the approximate location was determined, the vessel was vented, entered, and the leak located. The leak occurred in the port area where one of the ADP bias ring electrical feeds enters and was caused by an arc, probably during a disruption between the ring and the vessel wall. Inspection revealed that the failure was likely due to a ceramic insulated that slipped out of position. The leak was repaired. However, because of the excessive damage to the insulators that occurred from the arc and the infrequent use of the bias ring, it was decided to permanently ground the bias ring at each of its 24 support points.

The major vent for 2002 started in July with setup, inspections, and a week of diagnostic back calibrations. The major vent task of installing 12 I–Coils then commenced and made significant progress with all 12 coils installed and 90% complete. An interference was discovered between the I–Coils in the R–1 plane and the lower divertor baffle gas seals that led to the removal of all 24 baffle plates and a task to redesign the gas shields, modify the baffles, and reinstall them. The new design eliminated the interference and also improved the sealing efficiency of the gas seals. The A set of 14 new magnetic probes were installed to replace old probes that were removed and an additional set of 12 magnetic probes were designed and built and will be installed for use with the 12 new I–Coils. A large number of diagnostic tasks were also performed during the vent, including: a redesign of the Phase Contrast Imaging diagnostic mirrors, a modification to the FIR scattering system, upgrade to the Thomson Scattering in-vessel alignment and calibration “dangling chain” system, replacement of all SXR detector arrays, and refurbishment of the ASDEX fast pressure gauges.

3.3. PLASMA CONTROL

Work on the plasma control system (PCS) during FY02 was focused in two areas: development of new control algorithms to support the DIII–D research program and implementation and testing of a portion of the PCS hardware upgrade.

A key new feature added to the PCS was the ability to control the output power of the DIII–D gyrotrons. This will in the future allow implementation of feedback algorithms to control electron temperature and toroidal current density. During FY02, an algorithm to feedback control the electron temperature at one radial position was implemented. The electron temperature was measured with a single ECE channel and the gyrotron power was adjusted so that the temperature met the target time evolution. Using this technique, it was shown that by modifying the time evolution of the electron temperature during the rampup of the plasma current, the safety factor profile at the end of the current ramp could be reproducibly determined.

Other new control features supported key physics experiments. The fast gas valve was triggered upon detection of a vertical displacement event in order to mitigate the effect of the disruption caused by the vertical instability. Detection of undesirable features in long pulse discharges, such as a large amplitude neoclassical tearing mode, was used to terminate the discharge early in order to reduce neutron production. New features were added to the resistive wall mode control algorithms including the capability to simultaneously but separately, provide error field correction and RWM feedback control.

Development continued of the hardware upgrade of the PCS, which is planned for completion in FY03. In the PCS upgrade, the real time computers and data digitizers will be replaced. The increased processing power and flexibility will enable control of advanced tokamak discharges that requires algorithms with increased complexity and additional diagnostics. During FY02, a hybrid of the existing and upgraded system was operated to test the concepts for the complete PCS upgrade. The new computers and digitizers were acquired and assembled to be ready for use in FY03.

3.4. INTERNAL COILS (I–COILS)

Following the installation of the two prototype internal coils in October 2001, the coils survived 12 vessel bake cycles to 350°C and testing of the coils to maximum current (4.5 kA DC) and AC frequencies to 1 kHz in high magnetic fields. Based on this success, 12 new I–coils were designed, fabricated, and 90% installed through September 2002. The 12 coils are nearly 60 deg in toroidal length and are located inside the vessel arranged in two sets of six located above and below the midplane of the vessel. The I–coils are single-turn, wall-mounted saddle coils comprised of hollow water-cooled copper conductor insulated with ductile polyamide insulator material housed inside a stainless steel tube vacuum barrier with power and water cooling delivered through a concentric lead.

Six vessel ports were required to provide access for the 12 concentric leads required for the coil set. These ports were obtained with a minimum number of changes by sharing three lower ports with the vessel vacuum system, reuse of the upper port used by the prototype coils and the use of two other upper ports with minimal impact on existing diagnostics. Cutting and welding on special adapters for the coils modified the three lower ports.

In-vessel installation completed by the end of FY02 included the following subtasks:

- Modifications to lower ports.
- Removal and modification of plasma facing tiles.
- Removal of conflicting magnetic sensors and replacement with new, individual sensors including a sensor for each I–coil.
- Rerouting of vessel wall mounted thermocouples and diagnostic wiring.
- Installation of coil mounting studs.
- Assembly and attachment of most coils including welding of the vacuum penetrations.

The coil installation including taking off and reinstalling the plasma facing tiles and external connection to power and fluid systems will be completed in FY03.

In parallel with the mechanical work on the I–coil, there was considerable progress on the design and fabrication of the electrical system for the coils. Designs were completed on the cabling, patch panels, shorting and grounding switch, data acquisition and instrumentation system, coil thermal and water flow interlock system, and over voltage protection system. Fabrication and installation of the patch panel, cable trays, and much of the instrumentation was completed in FY02. The full electrical system will be ready for use at the start of the FY03 device commissioning period in January 2003.

3.5. MECHANICAL SYSTEMS

3.5.1. High and Low Pressure DI Water System

Increasing levels of fiberglass debris entrained in the flowing water necessitated the replacement of aging fiberglass return and supply manifolds on the high and low pressure DI water systems with stainless steel manifolds. The replaced sections were above ground sections outside of the DIII–D building. Inspection of the remaining fiberglass parts of the system did not reveal any deterioration. This replacement has significantly reduced the debris problem.

The instrumentation of the DIII–D vessel and coil cooling water system was completed. This system is used to monitor and control the vessel deionized water, the prototype I–Coils, the Neutral Beam closed loop, and the Neutral Beam Ion source systems. This completes the instrumentation of all of the major water systems on DIII–D that was started in 2000.

3.5.2. Cryogenic System

Improvements were made to the Cryogenics control system. Revisions to the He liquefier Programmable Logic Controller (PLC) code were completed along with greatly expanded documentation. The modified PLC code was thoroughly checked against the original code, tested offline, and then was successfully tested after the end of operations. The modifications included rectifying significant errors introduced by the vendor in his porting of the code, and rewriting the control loops to simplify their implementation. The cryopump recool sequence that occurs after every shot at the end of the glow period was also made more efficient. Good progress was also made on the remaining cryogenics PLC upgrade project that includes removing the last of the aging and unsupported hardware. This included replacement of the Westinghouse PLC, incorporating its functions into the existing Siemens PLC, porting over PLC logic, developing graphical user interfaces, generating wiring/documentation spreadsheets, tracing out wiring, cleaning up cabinets, and removing unused equipment. The upgrade has also provided data trending, which has allowed for improved tuning of the system. This tuning has produced more reliable operation and appreciable energy savings.

3.6. COMPUTER SYSTEMS

During FY01, 835 GB of raw data were acquired from DIII–D, with the largest shot being 611 MB. A number of computer system upgrades were done to meet the ever-increasing computing needs of the Fusion Division. The new HP L3000 CPU server, HYDRA, was installed and turned over to the users. The new 1.3 TB disk array for raw shot data was implemented to greatly enhance the amount of raw data available on magnetic disk. This was the first step in a plan to put all raw data on disk. Installation of new network fibers to the DIII–D facility was completed. This will enable network upgrades to Gigabit Ethernet. A dual Xeon Intel computer was purchased running Linux to provide high performance computing cycles to the users for general data analysis. A 12 port Gigabit Ethernet switch was installed and Gigabit capable computers and peripheral devices were attached to it. A new 2 TB disk array was purchased and installed for raw shot data. However, its initial use has been for user space.

Computer security issues continue in importance as the frequency and intensity of Cyber intrusion attempts continues to escalate. Updates were made to the firewall operating system to aid in blocking the latest attacks and more ports were restricted. FTP remote access is now blocked at the firewall except for anonymous FTP. Secure Shell outside access was reduced to a restricted set of computers and protocol 1 was disabled. A Cyber security database is being developed to address Cyber Security data management issues. Reports detailing various probes/scans are routinely reported to CIAC. The project to implement SecurID for protected remote cyber access was completed and cross-realm authentication with PPPL for SecurID was demonstrated.

Three new computers, one Intel Linux and two Alpha Linux, were installed into the plasma control system for FY02 operations. A first fault problem initially plagued the system, but a solution was found. Initial problems with the new DTACQ digitizers were solved. The initial version of a real-time digital scope monitor was developed to provide real-time displays of signals to multiple terminals, thus replacing aging oscilloscopes. Since operations ended, all the old I860 computers have been eliminated from the PCS system. Setup test, software test, and simulation modes now work with the new system as well as synchronizing during a software test shot. New Myrinet fiber switches were installed for the PCS communication. Watchdog monitoring codes for monitoring faults in PCS upgrade system were developed.

Excellent progress was made on the upgrade of the tokamak operations and neutral beam control computer systems to the point that they are essentially complete. The new computers use Intel processors running Linux. The Kylix development software proved to be easy to use and led to rapid completion of work. A configurator database management utility was created for viewing and editing database points. Sequencing procedures (POPS) and data acquisition software were ported to the new computers. CAMAC highways were moved to the new systems and CAMAC scanning was successfully tested. The main control screens were built. Timing chains, data acquisition shots, and calibration shots can now be run from the new operations computer and data acquisition shots have been run on the new neutral beam computers. Synchronization coding was added to the beam POPS procedures to improve the reliability of the computed beam power (PINJ).

3.7. ECH OPERATIONS

All six 110 GHz gyrotrons of the ECH system have been operated successfully with total generated power in excess of 4.0 MW for pulse lengths greater than 2.0 s. Two of the gyrotrons, equipped with low loss artificially grown diamond output windows, were tested to output power of 1.0 MW for 5.0 s pulse length, and a third, also with a diamond window, was tested to 550 kW, 10.0 s.

The system was operated 80 days during the year, of which 23 were in support of DIII–D experiments specifically requiring the ECH system.

Primary activities during the year focused on increasing the flexibility of the gyrotron controls, getting the full complement of gyrotrons operating and verifying the characteristics of the rf beam and the accuracy of the system diagnostic measurements. For the first time, analog command signals generated by the DIII–D plasma control system were used to modulate the rf output power of the gyrotron complex. The system tracked the electron temperature at a particular location in the tokamak, compared the measurement with a predetermined desired value and then increased or decreased the gyrotron output power to maintain the desired temperature. Direct measurements of the polarization of the injected beam verified the proper operation of the remotely controlled polarizers. An automatic system for generating and archiving calorometry data was developed, tested and brought into regular use. All six systems were fitted with the new compact mode conversion dummy loads, which had been tested successfully the previous year.

At the end of plasma operations, the launcher assemblies were removed from DIII–D and inspected. In a few places, slight damage was found in the stainless steel launcher waveguides. This led to silver plating the inside bore of the waveguides, which should reduce the thermal load on the guides from the rf beam. The second high speed articulating launcher, PPPL02, was received from Princeton, calibrated and installed in the tokamak. The Prototype articulating launcher, PPPL99, was refurbished and reinstalled along with the PPPL01 launcher.

The operation of the various elements of the system was investigated. A series of experiments was performed to understand and calibrate the monitors for the launcher mirror temperatures. In addition, thermal measurements of the characteristics of the gyrotron diamond output windows were performed. The operation of the calorimetry system was compared with the system used by the gyrotron manufacturer, CPI, by temporarily installing the CPI system on a gyrotron at DIII–D.

One particular gyrotron, CPI-P1 (Scarecrow) developed a small air leak in the collector during conditioning to the level of 800 ms pulse length. This tube was returned to the manufacturer. The collector was removed, analyzed and replaced with new parts. The gyrotron was then returned to DIII–D for conditioning leading to service.

The gyrotron installation achieved reliability levels comparable to other tokamak systems, demonstrating >90% availability on typical experimental run days.

3.8. ELECTRICAL ENGINEERING

The largest single project for the group was the installation and testing of the power cabling and data acquisition system for the newly installed I–coil. This task involved running 12 quadrature cable pairs from the power supplies to the various coil connection points around DIII–D while a new data acquisition system based on cPCI architecture was installed with the capability of gathering 128 MB of data. Another major task involving the group was the design and partial implementation of a new E Power Supply System Integration and Control (EPSSIC) system to replace an aging and troublesome system. Full implementation is scheduled to take place next summer (FY03).

While supporting these major projects, the group was able to complete over 2500 man-hours of preventative maintenance tasks associated with the facility’s primary power and both High Voltage and Magnet Power Supply systems. Both of the ECH Power supplies (#1 and #2) were operational for much of the year and were used to support Gyrotron operations. The high voltage group continued to support Neutral Beam operations at a high level of availability. As part of a facility longevity initiative program, work was continued by the Power Systems and High Voltage systems group on upgrading various interface and control circuits that over time have become a reliability concern. The Instrumentation and Control group spent considerable time and resources in both supporting existing systems and implementing new designs to support the plasma control and I–coil systems. In an effort to extend the useful life of the existing CAMAC DAQ system, a new fiber optic highway operating at double the previous speed has been installed and is now fully operational. In support of a major upgrade to the PCS system, a new bank of over 150 filters, operating at several predefined frequencies, was designed, fabricated, and tested. These filters were a key component of this upgrade.

Several new procedures and initiatives were put in place to help in the design and documentation process for new projects within the ESE group. In particular, a new reference procedure was written whereby an engineer can refer to a single document to determine the documentation and review requirements for projects. This is meant to make the process easier and less confusing in the future. The electrical engineering group has also standardized on a single software package to handle the schematic, board layout and circuit analysis tasks. This package should allow for designs to be inputted into the company’s documentation control system with a reduction of labor/time. In addition, all future drawings will be made available for review from any terminal in the facility, thus hopefully reducing troubleshooting time.

3.9. 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 95.3% of the time, despite problems associated with the aging (in service since 1986) of the ion sources and the power supply system. Failures of the critical ion source components became more frequent this year; there were no longer enough parts to make even one full spare source. A task to acquire spare parts for ion sources was started and has made significant progress. The program has developed and demonstrated the capability of repairing the failed ion source accelerator grid modules and has procured new parts for the grid modules from vendors. This effort will continue with the goal of developing the required technique and capability of producing new accelerator grid modules. It is not only very crucial to our continued success at DIII–D, it can also be very beneficial to other fusion research institutions that employee (or plan to) use neutral beam systems.

A number of projects were completed this year that improved the maintainability and availability of the beam system. Back flush of water cooling channels of all the ion sources was performed this year after damage of Langmuir probes caused by blockage in the cooling line were observed. This was a very time-consuming project, however, wherever a blockage was found in a water cooling channel it was cleared; this should greatly reduce the risk of component damages caused by over heating due to blockage of a cooling line. A new computer system for neutral beam system operation and data acquisition was installed with all new operation and control software in the summer of 2002. This new computer system is much faster and has enhanced capability. A new timing system, to replace an obsolete and hard to maintain 20-year system, was also installed during the same time period when the new computer system was installed. This new timing system should make troubleshooting easier and will require less maintenance. Changes were made to the beam timing system to extend the window from 8 to 10 s within which the beam can pulse to support long-pulse physics experiments. Data acquisition and calculation software of the beam power measurement diagnostics was also upgraded to improve efficiency of annual measurement of the beam power flow.

3.10. EDUCATION PROGRAM

Through a grant from DOE/OFES and General Atomics, the fusion education team continues to provide engaging science experiences for middle school and high school teachers and students through facility tours, workshops, and classroom visits. Team members presented demonstrations on plasma science to more than 4000 students at many different schools, conferences, and public events. Each of over 400 students, teachers, and professional engineers gained a first-hand look at the DIII–D Tokamak as they toured the facility and were engaged in many science activities. Workshops on plasma science, the electromagnetic spectrum, computer use, and radiation were given to over 160 teachers at 4 different scientific and educational conferences. The education team will continue to actively engage the community with exciting and innovative presentations and curricular materials.

4. FY02 PUBLICATIONS

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.

— Return to Previous Page in pdf documents:

- Hold down the Command () (Macintosh) or Control (PC) key and click the Left Arrow (←)

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5. ACKNOWLEDGMENT

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APPENDIX A
RESEARCH HIGHLIGHT FROM THE FY02 DIII–D PROGRAM

DIII-D
NATIONAL FUSION FACILITY
Research Highlights
MARCH 2002 No.27

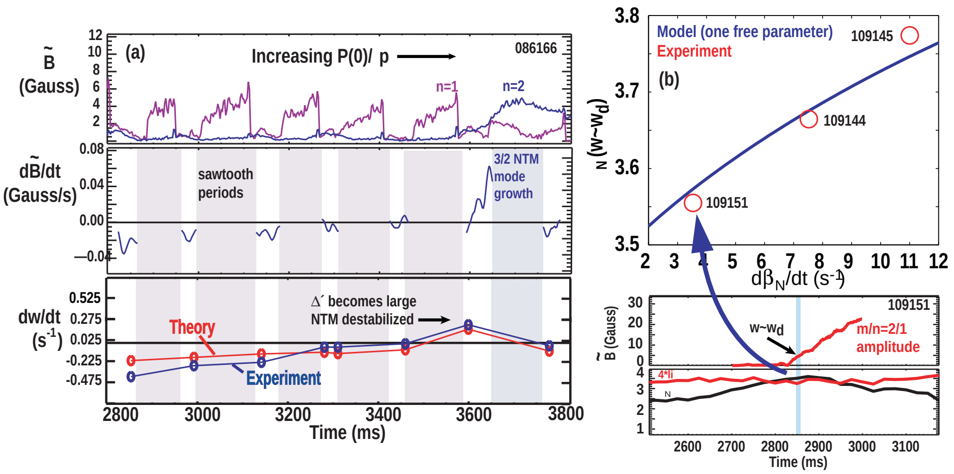
The Effect Of Poles In Δ' On Neoclassical Tearing Mode Onset

Neoclassical tearing modes (NTMs) can severely degrade the confinement properties of tokamak plasmas. It is therefore important as well as interesting to obtain a predictive understanding of their onset and evolution. These modes are inherently nonlinear, requiring a finite size seed island for destabilization. However, one of the main NTM puzzles is that sometimes they appear suddenly without a seed island. They often appear capriciously during a sequence of sawtooth oscillations, or even spontaneously without an apparent driving mechanism.

An interesting hypothesis has been formulated at General Atomics (GA) to explain the onset of NTMs. In this model, the tearing stability index Δ' rapidly becomes large due to profile evolution and the approach to a pole discontinuity at the ideal limit. This rapid increase in Δ' is proposed as the driving element of a mechanism for the onset of NTMs. Instead of being seeded by mode coupling, NTMs can arise as a continuation of the growth of an unstable classical tearing mode, giving the appearance of spontaneous growth without a seed.

This hypothesis is supported with both theoretical analysis and detailed examination of experimental data. For cases with spontaneous NTMs, one directly measurable theoretical prediction is that the point in β space at which the magnetic islands reach a size commensurate with the thermal diffusion length scale should increase monotonically with the time rate of change of beta. This prediction is in qualitative agreement with a new DIII-D experiment designed specifically to test this hypothesis

In general, analyses based on the island evolution equation and detailed simulations of the nonlinear dynamics using the NIMROD code are in agreement with the experimental observations. NIMROD simulations of a sawtooth seeding case show a 1/1 mode driving a 3/2 which is only destabilized further when the core pressure approaches the ideal limit. These are very interesting and important results which explain a mechanism for the onset of NTMs in tokamak discharges that operate near the ideal stability boundary.



Results from a previous sawtoothing experiment (a) and a recent NTM experiment (b) are in agreement with theoretical models.

About DIII–D

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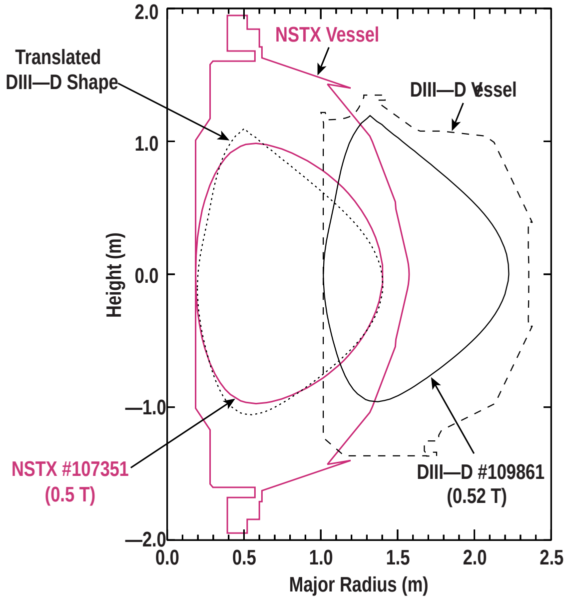
DIII-D
NATIONAL FUSION FACILITY
Research Highlights
APRIL 2002 No.26

Similar Experiments on DIII–D and NSTX Advance the Understanding of Instabilities Driven by High Energy Ions

High energy helium nuclei ("alpha particles") are one of the reaction products in a fusion reactor. These helium nuclei must transfer their energy to the background plasma. If the alpha particles drive instabilities instead, their energy could be lost and the plasma will stop "burning."

The mathematical term for a doughnut shape is "toroidal." The DIII–D tokamak is a toroidal device. There is a tokamak at Princeton called NSTX that is so fat that it looks almost like a sphere. A dangerous instability that can be driven unstable by high-energy ions relies on toroidal curvature; it is called the "toroidicity-induced Alfvén eigenmode" or TAE. In recent experiments, the flexibility of the DIII–D facility was exploited to produce nearly identical plasmas with nearly identical populations of high-energy ions in both DIII–D and NSTX. Since NSTX is twice as fat as DIII–D, this provided a sensitive test of TAE instability physics.

In both facilities, the TAE instability appeared when the pressure of high-energy ions was similar. Another important result concerns the spatial shape of the TAE instability. It was found that the TAE in DIII–D has many more bends toroidally than in NSTX. This finding is consistent with a theory that predicts that future "burning plasma" experiments will have 10–15 toroidal bends. Another finding is that the instabilities in NSTX often change frequency rapidly like a chirping bird, while only a single "pitch" is measured in DIII–D. This observation could have important implications for the amplitude of TAE instabilities in a reactor and may determine whether the high-energy helium nuclei successfully transfer their energy to the plasma.



The boundary of the plasma in recent experiments on DIII–D and NSTX. The cross-sectional shapes are similar but the radius is twice as large on DIII–D.

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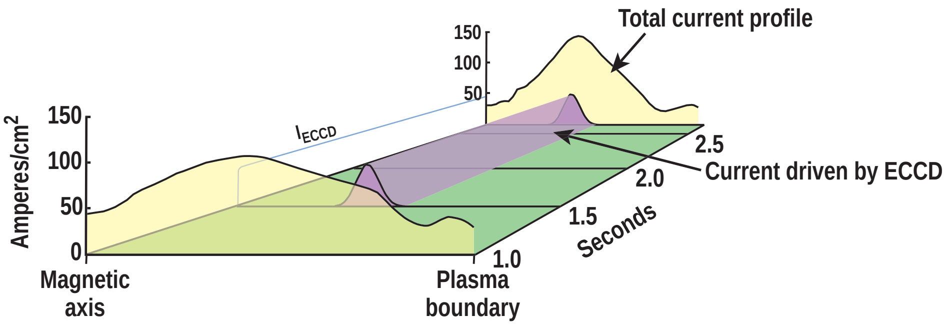
DIII-D
NATIONAL FUSION FACILITY
Research Highlights
MAY 2002 **No.28**

High Power Microwaves Control Plasma Current Profile

Much of the confinement in the tokamak is provided by magnetic fields driven by electrical current flowing in the plasma. In "conventional" tokamaks, this current is provided mainly by a pulsed transformer, inherently limiting the plasma's duration to hundreds or thousands of seconds. Advanced Tokamak (AT) research seeks to eliminate this pulsed plasma constraint by replacing this pulsed inductive current with current drive scenarios that are compatible with steady-state operation while maintaining high fusion performance. Recent experiments in the DIII–D tokamak have produced demonstrations of such scenarios. The broad high pressure profiles in these plasmas produce two advantages: high fusion performance, and a large self-generated "bootstrap" current that accounts for over half of the total plasma current. An additional 30% of the current is driven by the neutral beam heating system. With no other current drive, the plasma's current profile would relax and become more peaked near the magnetic axis, ultimately triggering magnetohydrodynamic instabilities in the plasma. In order for this high performance plasma to become steady state, the remaining inductive current, concentrated near the half-radius of the plasma during the high performance phase, must be replaced with something else. In DIII-D this current can be generated by an electron cyclotron current drive (ECCD) system, comprised of a number of gyrotrons capable of producing megawatts of microwave power at 110 GHz. These microwaves can be aimed to drive current at a desired location in the plasma. In the recent experiments, 120 kA, about 10% of the total current, was driven by ECCD in this region. The combination of bootstrap, neutral beam and ECCD resulted in a high performance plasma with over 90% of the current driven noninductively and with the current profile relaxation significantly slowed. Similar results have been observed in two different AT regimes in DIII–D, indicating that the promise of ECCD is ubiquitous and is not confined to a particular set of parameters. This first demonstration of a large ECCD effect in a high pressure tokamak plasma is an indication of the promise of the planned full gyrotron system. Calculations based on these results indicate that this planned system, in conjunction with neutral beam and bootstrap driven current, will be capable of sustaining the current profile in a high performance plasma for the full duration of the DIII-D plasma.



Without the ECCD, the plasma current would normally "shrink" toward the magnetic axis. Off-axis current driven by ECCD slows this evolution and can maintain a nearly steady current profile with the maximum value away from the axis, favorable for high fusion performance and bootstrap current.

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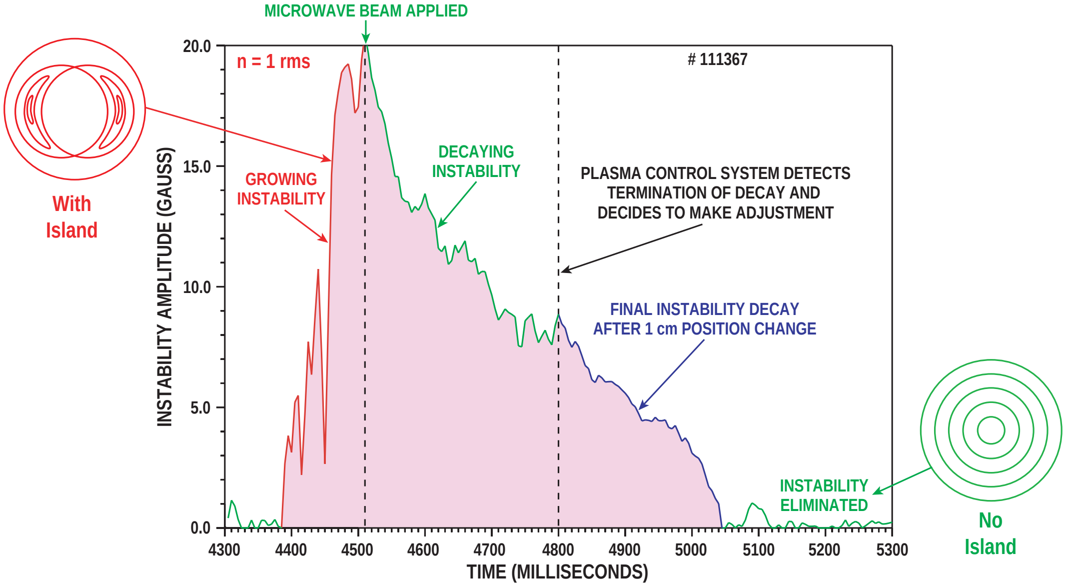
DIII-D
NATIONAL FUSION FACILITY
Research Highlights
JULY 2002 No.24

Microwave "Search And Suppress" Elimination Of A Growing Long Wavelength q=2 Neoclassical Tearing Mode

Magnetically confined plasmas are subject to helical perturbations known as magnetic islands. These islands break up the magnetic surfaces that confine the plasma, leading to more rapid loss of heat from the plasma and making it more difficult to sustain the high temperatures needed for fusion. Neoclassical tearing modes are magnetic islands that occur at high plasma temperature and pressure, and thus pose a potential problem for fusion plasmas. Experiments have confirmed theoretical predictions that the 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. This is done in the DIII–D tokamak by using a narrow beam of microwaves that interacts with the electrons in the plasma to drive the desired current.

Long wavelength modes such as m/n=2/1 (the magnetic field wraps twice around poloidally and only once around toroidally at safety factor q=2) are particularly deleterious. DIII–D experiments this year demonstrated the first automatic, real-time control of the current drive location to suppress a growing 2/1 instability. The plasma control system is put into a "search and suppress" mode that makes small shifts (about 1 cm) in the current drive location while the plasma position remains fixed. The optimum position 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 in its location.



Applying and adjusting the precise position of microwave power stops the growth of a long wavelength tearing mode and then completely eliminates it.

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Research Highlights
OCTOBER 2002 No.29

Smooth Flows Emerge from Chaotic Plasma Fluctuations

Like rapidly flowing gases and liquids, magnetically-confined fusion plasmas exhibit a high degree of turbulence. This turbulence is generally detrimental to plasma performance since it moves hot particles from the center of the plasma to the edge rapidly, thus cooling the plasma or degrading its energy confinement. A fascinating feature of this turbulence is that as a consequence of the magnetic geometry and pressure variations, it can generate its own flows that act as a self-regulating mechanism. These flows, which are predicted theoretically and have been observed in computer simulations of plasma turbulence, create a shearing or tearing action. This shearing action can tear up the turbulent eddies and thus limit the degree of turbulence, as indicated by the figure. Such flows are not unlike the large-scale zonal jets seen in the atmospheres of large outer planets in our solar system; these flows are believed to arise from essentially two-dimensional turbulent systems, in that case driven by solar energy.

Evidence for such turbulence flows has been clearly observed in recent experiments at the DIII-D tokamak using a turbulence imaging system, Beam Emission Spectroscopy. The flows show up as well-defined cycles in the velocity of the turbulence that fluctuate at near 15,000 oscillations per second. The imaging measurements are obtained at a rate of one million frames per second and have a spatial resolution of about 1 cm, thus readily resolving these turbulence flows. A snapshot of the measured flow pattern is shown in the second figure, superimposed on an image of typical turbulence eddies. Experiments have shown that the frequency of these oscillations varies with plasma temperature, agreeing closely with theoretical predictions. Observing and identifying these unique turbulence flows experimentally, and comparing their characteristics with theory, is helping to advance our understanding of this complex and crucial phenomena taking place in high temperature fusion plasmas.

This diagnostic development and research program is a collaboration between the University of Wisconsin-Madison, and the DIII-D National Fusion Facility.

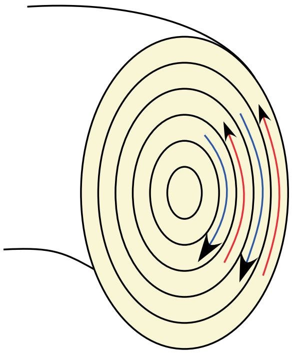

Fig. 1: Theoretical picture of self-generated turbulence flows in a tokamak cross section.

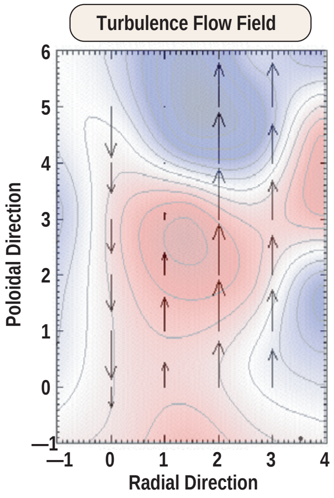

Fig. 2: Measured flow field.

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