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THE GENERAL ATOMICS FUSION THEORY PROGRAM ANNUAL REPORT FOR FISCAL YEAR 2003

by
PROJECT STAFF

Work supported by
the Department of Energy
under Grant No. DE-FG03-95ER54309

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DISCLAIMER

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ABSTRACT

The dual objective of the fusion theory program at General Atomics (GA) is to significantly advance our scientific understanding of the physics of fusion plasmas and to support the DIII–D and other tokamak experiments. The program plan is aimed at contributing significantly to the Fusion Energy Science and the Tokamak Concept Improvement goals of the Office of Fusion Energy Sciences (OFES).

1. HIGHLIGHTS OF THEORY WORK IN FY03

During the past year, considerable progress was made in each of the important areas of our research program:

- The global gyrokinetic code GYRO simulation of a DIII–D L–mode ρ^{-} pair with full physics (trapped and passing electron, finite-beta and ρ^*, E×B and parallel flow shears, real geometry, and experimental profiles) recovered Bohm scaling and experimental power flows (with a 10% tuned ion temperature profile gradient).
- The GLF23 transport model has been retuned to fit gyrokinetic growth rates for negative central shear (NCS) and H–mode pedestal parameters. Application of the retuned model to DIII–D discharges with boundary conditions inside the H–mode pedestal satisfactorily modeled the experimentally observed particle, thermal, and toroidal and poloidal rotation transport.
- Comprehensive studies of edge stability and resulting pedestal constraints with ELITE and GATO have allowed successful systematic comparisons with experiment, and broad characterization of pedestal stability limits.
- Dynamic simulations of pressure and current driven edge instabilities with the BOUT code have characterized the early nonlinear phases of edge localized mode (ELM)-like crash events, including poloidal narrowing and filament formation.
- The DIII–D I–coils have been found to be more effective than the C–coils in its capability to stabilize the resistive wall mode (RWM) by a factor of 4 to 5 depending on the plasma equilibrium.
- Plasma rotation and feedback have been evaluated to have a mutually synergistic effect on stabilizing the RWM. This effect is most prominent when the rotation frequency approach critical rotation value for stabilization.
- In studying the non-linear aspects of magnetohydrodynamic (MHD) stability theory, the onset and nonlinear evolution of resistive MHD modes in tokamaks with anisotropy and rotational shear, have been shown to be affected by the changing linear stability long after nonlinearity has become significant enough to alter the equilibrium.
- Numerical problems that prevented the 2-D MHD stability code TWIST-R from producing well-behaved linear resistive MHD solutions were resolved and solutions for a toroidal equilibrium test case were obtained with the expected behavior

exhibiting a finite jump in the logarithmic derivative of the perturbed flux at the singular surface.

- Two 3-D magnetic diagnostic codes V3RFUN and V3POST have been developed to support design of compact stellarators such as NCSX and CTH in collaboration with Oak Ridge National Laboratory (ORNL) and Auburn University.
- The Monte-Carlo rf orbit code, ORBIT-RF, has been successfully upgraded to treat steady-state neutral beam injection (NBI) and ion cyclotron range of frequencies (ICRF) absorption at higher harmonics. Experimental observations on DIII–D during RF pulses of neutral beam (NB)-heated plasma are reproduced by ORBIT-RF with reasonable agreement.
- A new flux-tube-averaged vorticity equation was used to solve for the E×B pellet cloud drift and mass deposition profile in toroidal geometry, and favorable agreement with the experimental profile following HFS pellet injection into DIII–D was found.
- A promising new fueling concept was investigated that takes advantage of the conversion of a miniature high-density gas jet into a high-pressure plasma jet near the plasma boundary which, combined with the grad-*B* effect, draws the jet plasma into the plasma core.

As a consequence of this work, scientists from the Theory Group were selected to give a large number of invited talks and colloquia. Below is a summary of the highlights in this regard from the past year. Following this are more detailed descriptions of the advances and achievements made in each of the major areas.

2. SIGNIFICANT PRESENTATIONS IN FY03

- Brennan, D.P., invited talk: "A Mechanism for Tearing Mode Onset Near Ideal Stability Boundaries" presented at 44th American Physical Society Annual Meeting of Division of Plasma Physics, November 11–15, 2002, Orlando, Florida.
- Candy, J., "Computational Challenges in Fusion Plasma Physics" presented at the 2003 Rosenbluth Award Ceremony, General Atomics, July 7, 2003, San Diego, California.
- Candy, J., invited presentation: "Comprehensive Gyrokinetic Simulations of Turbulent Transport in DIII–D with the GYRO Code" presented at 44th American Physical Society Annual Meeting of Division of Plasma Physics, November 11–15, 2002, Orlando, Florida.
- Candy, J., invited presentation: "Effects of Magnetic Shear on Transport Barrier Formation" presented at the JIFT Workshop, University of California, San Diego, September 19–23, 2003.
- Candy, J., invited talk: "Turbulence, transport and self-consistent profiles via global Eulerian gyrokinetic simulations" presented at the 2003 ICNSP Conference, September 7–10, 2003, Falmouth, Massachussetts.
- Chan, V.S., invited talk: "Theory and experiment of electron cyclotron current drive on DIII–D" presented at the 2003 Asian Plasma and Fusion Association Meeting, October 13–16, 2003, Hangzhou, China.
- Chu, M.S., invited talk: " Modeling of feedback and rotation stabilization of the resistive wall mode" presented at 45th American Physical Society Annual Meeting of Division of Plasma Physics, October 27, 2003, Albuquerque, New Mexico.
- Chu, M.S., significant tokamak seminar: "The resistive wall mode, its feedback and rotational stabilization" at JAERI, February 25, 2003, Naka, Japan.
- Hinton, F.L., invited talk: "Effects of electromagnetic turbulence in the neoclassical Ohm's law" presented at 45th American Physical Society Annual Meeting of Division of Plasma Physics, October 27, 2003, Albuquerque, New Mexico.
- Lao, L.L., presentation from GA IR&D: "Physics and Control of ELMing H–Mode Negative-Central-Shear Advanced Tokamak ITER Scenario Based on Experimental Profiles from DIII–D" presented at 19th IAEA Fusion Energy Conf., October 14–19, 2002, Lyon, France.

- Snyder, P.B., invited talk: “Developments in the Peeling-Ballooning Model of ELMs and Pedestal Constraints” presented at the Festival de Theorie Plasma Theory Workshop, July 2003, Aix en Provence, France.
- Snyder, P.B., seminar: “Developments in the Peeling-Ballooning Model of ELMs and Pedestal Constraints” presented at the Culham Science Centre, 29 July 2003, Culham, England.
- Snyder, P.B., seminar: “MHD Stability and Dynamics of the Tokamak Edge, and Implications for ELMs and Pedestal Constraints;” and a theory seminar: “The Role of Toroidal Flow Shear on Ballooning and Peeling Modes,” presented at the University of Wisconsin, Madison, October 13, 2003.
- Snyder, P.B., seminar: “Theory and Modeling of ELMs and Constraints on the Pedestal in Tokamaks,” presented at the University of California, San Diego, January 27, 2003.
- Snyder, P.B., talk: “ELMs and Constraints on the H–Mode Pedestal: A Model Based on Peeling-Ballooning Modes,” presented at the ITPA Joint Pedestal and MHD Group Meeting, October 23, 2002, Garching, Germany.
- Snyder, P.B., talk: “ELMs and Constraints on the H–Mode Pedestal: A Model Based on Peeling-Ballooning Modes,” presented at 19th IAEA Fusion Energy Conf., October 14–19, 2002, Lyon, France.
- Snyder, P.B., talk: “Parameter Dependence of Peeling-Ballooning Pedestal Constraints and Comparison to the Database;” and a summary talk: “Summary of Edge Stability Issues” presented at the ITPA Pedestal Group Meeting, September 29, 2003, San Diego, California.
- Waltz, R.E., reported: “Progress on GYRO: Past, Present & Future” presented at the SciDAC Plasma Microturbulence Project Workshop, August 5, 2003, San Diego, California.

3. ADVANCES IN TRANSPORT RESEARCH

3.1. GYRO CODE DEVELOPMENT

After considerable progress in speeding up the GYRO code [Candy 2003a] by better parallel processing, we ran into difficulties as we attempted to simulate larger radial plasma slices. The problems were associated with the long wavelength n=0 neutrally stable zonal flow oscillations. These were very slowly becoming numerically unstable. Numerical filtering was tried, but in the end we found no satisfactory way to filter the long wavelength modes. We also attempted to limit the maximum $k_{||}$ in the n=0 oscillations. Finally, we had success with second order accurate implicit-explicit Runge-Kutta (IMEXRK). The very stiff electron parallel motion term is treated implicitly and all others explicitly. We are now able to run with physical $(M_i/m_e)^{1/2} = 60$ mass ratio. The IMEXRK schemes were only recently developed by the mathematics community. Essentially, when large implicit time steps are used, the code skips over the problematic electrostatic Alfvén waves. We found third order methods not needed.

As reported in a *Physical Review Letter* [Candy 2003b], the near full radius, full physics GYRO simulations of DIII–D L–mode ρ^* pairs obtain the characteristic Bohm scaling and are within a factor 2 of experimental power flows. Small 10% reductions in the ion temperature gradients can bring the power flows into agreement with experimental flows. The full physics included trapped and passing electrons, finite-β and ρ^*, E×B and parallel flow shears, real geometry and real experimental profiles [Waltz 2003].

Since the core plasma is "stiff" and close to marginal with E×B shear stabilization, the only way to make accurate direct comparison of simulations to experiments is to predict profiles from given power flows. External feedback loops were added to GYRO to "tune" input experimental profiles about a midradius pivot so that simulation energy and plasma flow profiles are matched to the experimental flows. The resultant steady state transported temperature and density profiles are then compared with the experiment. Given the stiff nature of core transport with power flows highly sensitive to ion temperature gradients, and near null plasma flows from thermal gradient pinches, this technique is essential for comparing simulations to experiments within error bars. This new work was reported at the 2003 International Sherwood Theory Conference, which commenced April 28–30, 2003 in Corpus Christi, Texas.

3.2. GLF23 TRANSPORT MODELING AND CODE DEVELOPMENT

The renormalized GLF23 and Multi-Mode (MM95) core transport models have been used together with scaling for the H–mode pedestal height to predict the profiles in H–mode discharges. Using a recently developed power dependent pedestal scaling along with the GLF23 model, an RMS error of 20% in the core stored energy is obtained for 47 H–mode discharges from DIII–D, JET, and C–Mod. In combined core and pedestal modeling of ITER, FIRE, and IGNITOR the power dependence of the pedestal height is found to be a critical issue. Results obtained using the GLF23 and MM95 core models, along with the power dependent pedestal model, are more optimistic than the results obtained using MHD limit pedestal scaling.

Work to improve the GLF23 drift-wave based transport model is continued. The four-moment and six-moment gyro-fluid equations by Beer were implemented into the GLF23 physics module. With a sufficient number of basis functions, the results for growth rate calculations using the Hermite basis function approach were found to be in excellent agreement with the growth rates in Beer's paper. A complete revision of the trapped particle equations in GLF23 has been made. A three moment model for the trapped particles (density, parallel, and perpendicular pressure) has been derived which gives a much better fit to the toroidal drift resonance response than the two moment model of GLF23. The reduction of the Landau damping experienced by the circulating particles due to the bounce averaging of the trapped particles has also been substantially revised and improved. A model for the loss of bounce averaging when the wave frequency exceeds the bounce frequency has been developed. The final equations couple trapped and passing ions and electrons without restriction on the mode frequency. The combined equations allow the electron and ion instabilities to couple and produce transport in the complementary species. This is expected to yield new insight into the role of electron temperature gradient (ETG) modes in producing particle, ion energy and momentum transport. The hypothesis that ETG modes could produce the anomalous transport within a transport barrier will be tested with the new model.

The theoretical basis for solving the parallel momentum transport equation along with the other transport equations rather than invoking the conventional neoclassical ordering has been investigated. It was found that a consistent transport system can be derived. In the process, it was discovered that the turbulent energy exchange can directly modify the neoclassical solution to the poloidal flow. This new source for poloidal momentum can be computed using the GLF23 model and will be tested against the experiment. The toroidal and parallel momentum balance equations have been included in the XPTOR transport code which uses an Implicit-Newton solver we developed for GLF23. Recently, the formation of an H–mode pedestal using GL23 for the core and edge transport has been demonstrated. Here, the density, temperature, and toroidal and poloidal rotation profiles were simultaneously evolved. It was found that the model could reproduce DIII–D H–mode pedestal profiles if the profiles remained marginally unstable to ITG/TEM modes. Boundary conditions were applied midway down the pedestal near $\rho = 0.95$ [Kinsey 2003, Petty 2003].

3.3. ONETWO 1-1/2-D TRANSPORT CODE DEVELOPMENT

To support the DIII–D experimental efforts and development of AT scenarios, a new version 1.60 of the TORAY-GA electron cyclotron heating/electron cyclotron currrent drive (ECH/ECCD) module based on an adjoint formulation that includes collisionality effects has been implemented in ONETWO. A new interface that accepts the ONETWO time-dependent equilibrium data analysis mode has been created. A new recently retuned version of the GLF23 transport model that provides a more accurate treatment of negative central magnetic shear discharges has also been implemented in ONETWO as an interim solution to allow modeling of these configurations. Testing of this new module against results computed using the XPTOR code is in progress.

A new version of the CURRAY ICRF module from NTCC has also been installed on local GA computers and modified to create an uniform interface to transport codes such as ONETWO and TRANSP. This eliminates the awkward, multiple EQDSK interface and combines several other files into a coherent scheme. CURRAY can now be run out of ONETWO with a standard EQDSK interface, with the time-dependent EQDSK mode, and with evolving fixed boundary equilibrium calculations. For DIII–D, a generic input file detailing the antenna spectrum at 60, 83, and 117 MHz was created that is usable for routine DIII–D data analysis.

A major revision of the ONETWO code to incorporate the NTCC-based Monte Carlo fast ion physics package Nubeam was also undertaken during this time period. With on-site collaboration from Lehigh and remote support from Princeton Plasma Physics Laboratory, we were able to successfully build the module on Linux and OSF architectures (but not on HPUX). The package is now functional in ONETWO and extensive benchmarking has started.

Finally, the two-dimensional inverse equilibrium solver TOQ was incorporated into ONETWO. This enhances the ability of the code to do both theoretical simulations coupled with stability calculations and experimental data analysis.

3.4. TURBULENCE-NEOCLASSICAL TRANSPORT THEORY

We have formulated the problem of transport in tokamaks including both turbulence and neoclassical effects. The standard neoclassical drift kinetic equation is replaced with one containing turbulence driving terms as well as ∇B drifts and collisions. The fluxes of particles and energy obtained from the solution of the drift kinetic equation are the sums of purely neoclassical fluxes and terms containing the parallel momentum transfer from turbulence. These are to be added to the standard quasi-linear expressions for the turbulent fluxes. Using the analysis leading to the reduced electron kinetic equations, an expression was derived for the fluctuation-induced parallel force which appears in the drift kinetic equation, in terms of the fluctuations in magnetic field, parallel electric field, scalar potential and magnetic field line displacement. These fluctuations would need to be calculated separately using a code such as GYRO. The transport problem is formulated in terms of four fluxes, related to particle and energy transport, parallel current and parallel heat flux, and four driving terms, related to the electron pressure gradient, temperature gradient, an average of the effective parallel electric field, and an average of the effective parallel temperature gradient. The Onsager-symmetric transport coefficients can be calculated using a variational principle that corresponds to the effective entropy production. An ensemble averaged Ohm's law contains the turbulent corrections to Ohmic and bootstrap current.

The turbulent Spitzer problem, calculating the current driven by these nonlinear fluctuation terms, has been solved in the Lorentz gas limit, without using the massless electron approximation. The current is given in terms of correlations of moments of the fluctuating distribution function with the field fluctuations. This avoids the appearance of line integrals of two-point correlations in the expression for the current, which would be difficult to evaluate computationally. The more general expression can be more easily evaluated using the nonlinear electromagnetic turbulence code GYRO. The standard neoclassical Ohm's law (current — voltage relation) with neoclassical resistivity and bootstrap current is preserved with the addition of a turbulent dynamo EMF. This dynamo EMF (volts/meter) results primarily from two mechanisms: (1) the divergence of radial flow of parallel electron current, and (2) the beating of parallel electric field and density fluctuations. In scaling from DIII–D to ITER, a gyroBohm scaling of these dynamo EMFs would decrease (e.g., 6-fold) but the transformer EMF will be smaller (e.g., 20-fold). Thus a dynamo within the 10% experimental error on DIII–D could extrapolate to a 30% effect in ITER. From a GYRO simulation of a 1 T DIII–D L–mode, we find that the first dynamo type generates no net current but strong small scale (few ion gyroradii) peaks and compensating dips in current densities centered on low order rational surfaces. These will have an effect on delta-prime and tearing mode stability. The secondary dynamo can drive (or degrade) net current at the 1% level. A paper on this subject has been accepted for presentation as an invited talk at the APS meeting in October 2003 [Hinton 2003].

3.5. NEOCLASSICAL TRANSPORT IN SMALL AND LARGE ROTATION LIMIT

A comprehensive description of neoclassical transport theory in the banana regime for large-aspect ration flux surfaces of arbitrary shapes and small rotation has been developed [Wong 2003a]. The method of matched asymptotic expansions is used to obtained solutions for plasma distribution functions and to compute transport coefficients. The method provides justification for retaining only the part of the Fokker-Planck operator that involves the second derivative with respect to the cosine of the pitch angle for the trapped and barely circulating particles. It leads to a simple equation for the freely circulating particles with boundary conditions that embody a discontinuity separating particle moving in opposite directions. Corrections to the transport coefficients are obtained by generalizing an existing boundary layer analysis. The system of moment and field equations is consistently taken in the cylinder limit, which facilitates the discussion of the treatment of dynamic constraints. It is shown that the nonlocal nature of Ohm's law in neoclassical theory renders the mathematical problem of plasma transport with changing flux surfaces nonstandard.

A formulation of the neoclassical transport theory for tokamak plasmas with large toroidal velocities that can be comparable to the ion thermal velocity is developed [Wong 2003b] using the drift kinetic equation as a starting point. In this formulation, the motion of the guiding centers is the same as in the small rotation theory, but the radial electric field is considered stronger. A complete set of transport coefficients for both electrons and ions is calculated in the large-aspect-ration limit in the banana regime for flux surfaces of arbitrary shape. The calculation also utilizes the method of matched asymptotic expansions for particle and energy fluxes and a simple perturbation for the angular momentum flux.

4. ADVANCES IN MHD STABILITY RESEARCH

4.1. EDGE STABILITY AND PEDESTAL MODELING

A series of pedestal stability studies was carried out for JT–60U discharges which used current ramps and impurity injection to modify ELM behavior. Small or “grassy” ELMs on JT–60U were found to generally correspond to instabilities with a dominantly peeling mode structure and narrow radial eigen function. Results were presented at the American Physical Society Annual Meeting of Division of Plasma Physics meeting. Additional pedestal stability studies were carried out for numerous DIII–D and Alcator C–Mod discharges.

Work continues on a systematic study using model equilibria to characterize peeling-ballooning pedestal stability bounds as a function of pedestal width, density, triangularity δ, magnetic field, current, and aspect ratio. Maximum stable pedestal height is found to increase with width to roughly the 0.7 power. The sublinear increase with width is the result of finite *n* modes sensitivity to profiles and to natural magnetic shear decreasing with width. Current and magnetic field dependencies can be approximately characterized as a β_N dependence, though complexities exist due to *q* variation and second stability. Higher triangularity opens second stability and leads to pedestal height increases of roughly $(1+\delta)^{1.7}$ at moderate density. While many multiple parameter dependencies make a simple parameterization difficult, significant progress has been made toward a broad characterization of peeling-ballooning stability limits in shaped tokamak geometry [Snyder 2003a, Snyder 2003b]. These studies can also be used to systematically compare calculated pedestal height stability limits to experimental values just before ELMs, and good agreement has been found, both in absolute value of the pedestal height, and in trends with triangularity, current and density [Snyder 2002b, Snyder 2003b].

Compression and toroidal rotation shear effects on peeling-ballooning modes have been studied using the ELITE code [Wilson 2002, Snyder 2002a]. The code has been rewritten to allow for compression and complex eigenvalues and optimized to yield a factor of two improvement in performance for up-down asymmetric equilibria. ELITE with compression has been successfully benchmarked against MARS. The lowest order rotation terms have been implemented in the code and are used in preliminary studies of rotation impact on peeling-ballooning stability. Subsonic rotation studies find that subsonic toroidal flows cause radial narrowing and shearing of the modes, and can either decrease or increase growth rates, though the change in growth rates is generally modest. A new formulation allowing larger sonic flows has been developed and will be implemented in ELITE in the near future.

4.2. EDGE STABILITY AND TURBULENCE SIMULATIONS

A nonlinear evolution of peeling-ballooning type instabilities in DIII–D equilibria was studied using the BOUT reduced Braginskii edge turbulence code. Initial behavior of the modes is well characterized qualitatively by the expected linear growth rates and poloidal and radial mode structure. In the early nonlinear phase, a variety of more complex behavior is found in some cases. The initial unstable mode may saturate briefly and be followed by a faster growing, longer wavelength mode. As the crash phase of the instability progresses, it narrows poloidally and begins to extend radially from the pedestal across the separatrix and into the scrape-off layer (SOL). At the latest phase of the simulations, the structures extend radially all the way across the simulation domain. A number of techniques will be explored to allow simulations to continue beyond this phase, including modified boundary conditions and damping, initialization at smaller growth rates, and eventually pushing the equilibrium slowly across the mode instability threshold using sources rather than initializing the simulation with a strongly unstable equilibrium.

4.3. ROTATION AND FEEDBACK STABILIZATION OF RESISTIVE WALL MODE

A new general equation for the RWM in rotating plasma and in the presence of an external resonant field has been derived [Chu 2003a]. An analysis shows that the growth and damping of the RWM result from the balance of the energy flux and the dissipation torque from both the plasma and the resistive wall. However, in steady state, only the dissipation in the plasma to the damped RWMs contributes to the phase shift between the external resonant field and the resonant plasma response. Further, the phase and amplitude of the plasma resonant response is related to the damping rate and mode frequency of the RWM through a complex amplification factor. These conclusions can provide an explanation of the experimental observations of the resonant field amplification phenomenon.

An enhanced version of the MARS MHD code with RWM feedback, MARS-F [Liu 2000], was obtained from Bondeson and Liu of Chalmers University. A set of TOQ equilibria was used to test MARS-F. In the absence of flow, results from MARS-F agree well with those computed using the DCON-VACUUM plus feedback package [Chu 2003b]. In the presence of toroidal flow, the two ion sound wave and the kinetic damping models give results within a factor of two of each other. Finally, to evaluate the effectiveness of the new DIII–D internal coils (I–coils), the VACUUM [Chance 1997] code has been improved and extended to include the I–coils. Analyses indicate that the I–coils are nearly four times more effective in stabilizing the RWM than the external C–coil.

4.4. NON-LINEAR TEARING MODE ANALYSIS

The effects of the Δ' pole on tearing stability in the presence of non-linear mode coupling are analyzed using the 3-D MHD code NIMROD. The effects due to ramping of the NB are modeled by multiplicatively ramping the pressure profile. Preliminary results confirm the validity of the effect of the linear drive at small island size, and suggest that even in the presence of non-linear coupling from sawteeth, the linear drive component is important for determining the nonlinear evolution. Additionally, several model equilibria with DIII–D experimental characteristics have also been generated and used in an exploratory campaign into the nonlinear phase with a time-dependent background pressure. The nonlinear evolution of the spontaneous tearing modes driven by the ramping pressure exhibit super-exponential growth in the linear phase, confirming the effect of approaching a pole in the linear resistive stability index independent of an asymptotic matching procedure. Both the interchange and the tearing parity go sharply unstable as a pole is approached in Δ' and Γ', with one or the other being dominant depending on the equilibrium.

4.5. DIII–D STABILITY ANALYSIS

The data analysis on the experiment to measure the effect of poles in Δ' on tearing stability has been completed. Three discharges (109144,109145,109151) were analyzed which have different ramp rates in $d\beta/dt$ leading to onset of the 2/1 neoclassical tearing mode (NTM). In addition to previous agreement found between the experimental data and the island evolution modeling, a lull in the growth rate of the islands shortly after onset was also reproduced in the model. This lull is due to the onset of the polarization effect as the island grows larger than the ion banana orbit width. Also predicted by this form of the model are trace elements of the mode shortly before onset. In the presence of coupling from sawteeth, the effects of toroidal rotational shear on the nonlinear driving of the 3/2 mode were shown to be small for some typical DIII–D cases, and the evolution of the background linear stability remains a dominant factor in the nonlinear evolution.

The convergence studies for the comparative stability study of an old DIII–D VH–mode discharge (#75121), the high performance NCS H–mode discharge (#87099), and a conventional H–mode discharge (#92001) were completed and confirmed the results reported previously for these discharges, namely that the severity of the ELM depends on the radial penetration of the linear ideal MHD edge instability, and that the edge stability of the two high performance discharges is remarkably similar, despite significant differences in the time evolution of the discharges and the internal equilibrium geometry.

Some effort has been devoted to resolving some apparent discrepancies in the RWM electron cyclotron emission (ECE) fluctuation amplitudes within the plasma and the Magnetic signals at the wall for Thrust 4. The ratio of the perturbed B in the plasma to that at the wall appears to be a factor 20, of which a factor 5 is easily accounted for between the wall and the plasma boundary. But GATO calculations with no wall suggest the ratio between the plasma boundary and interior is near one. One possibility is that this ratio is sensitive to other conditions, such as the actual presence of a partly conducting wall. The issue is important since it strongly affects the outcome of measurements and calculations of the momentum drag exerted on the plasma by the RWM.

4.6. RESISTIVE LINEAR STABILITY CODE (TWIST-R) DEVELOPMENT

The numerical problem that has prevented the 2-D TWIST-R code from producing well-behaved linear resistive MHD solutions was resolved by a systematic investigation of the code. The calculation of all the metric elements was tested by comparison with analytic derivations of those elements for the 2-D analytic Solovev equilibrium. Some terms near the singularity at the magnetic axis were found to be inaccurate but none were the cause of the numerical problems. The matrix solver was also found to be working well and the boundary conditions shown to not be the cause of the spurious solutions, leaving the Fourier decomposition and the actual matrix construction as the only remaining possible source of error. A group of terms in the original equations, however, was ultimately identified as missing from the matrix construction for the 2-D case. New routines for calculating these terms were developed and solutions for the Solovev equilibrium test case were obtained with the expected behavior and exhibiting a finite jump in the logarithmic derivative of the perturbed flux at the singular surface. Checking of this solution against the PEST-III code is presently underway — this requires some additional work to accurately extract the matching conditions produced by PEST-III and extraction of the large and small solution components of the eigenfunction in a form from PEST-III suitable for comparison between the two codes. Several other relatively minor numerical problems, related to the calculation of numerical coefficients with singular behavior near the magnetic axis that were avoided in the test case, also remain to be resolved ultimately. It is expected then that the TWIST-R code will be able to produce robust numerical solutions for arbitrary values of the Mercier index.

5. ADVANCES IN RF HEATING AND FUELING RESEARCH

5.1. ICRF AND NBI FAST ION INTERACTIONS

To investigate the interaction between energetic particles generated by NBI and ICRF waves self-consistently and its effects on NBI driven current, a NBI physics package has been added to the ICRF guiding-center orbit code ORBIT-RF [Chan 2002]. The NB-injected fast ions are modeled as a test particle source. A first comparison of the new ORBIT-RF NBI physics module using 1000 particles on a single processor against the NBI results computed using ONETWO has been completed. The NBI-driven current from ORBIT-RF agrees well with the ONETWO results. To improve the statistics and to test the accuracy of the calculations, the ORBIT-RF code has been fully converted to Fortran 90 and successfully paralleled to run with 8000 particles on the 43-processor Stella Linux cluster. These new simulations indicate that results from the previous calculations using 1000 particles are qualitatively correct.

ORBIT-RF was also improved to allow study of the absorption of ICRF waves by NB ions at high harmonics. Analysis of a DIII–D ICRF discharge indicates that the tail energies of the beam ions are extended above the injected beam energy due to the resonant heating by the ICRF wave at the fourth harmonic resonance. Additionally, there is also an enhancement of the neutron production rate [Heidbrink 1999]. Both of these features are observed experimentally. The calculations assume a simple model for calculating the wave electric field $|E_+|$. ORBIT-RF will be coupled to a full wave code to allow a more self-consistent treatment of $|E_+|$.

5.2. PELLET FUELING ANALYSIS

A 2-D time-dependent simulation of pellet ablation carried out in collaboration with R. Ishizaki from National Institute of Fusion Studies (NIFS) indicates that ionization causes the formation of a stationary shock front in the supersonic region of the ablation flow that is followed by a “second” sonic surface farther out as previously conjectured. Anisotropic heating caused by the directionality of the magnetic field also leads to a non-uniform pressure distribution over the pellet surface. This can deform the “soft” hydrogen pellets, causing them to become highly elongated in the cross-field direction as previously conjectured. It is found that this 2-D effect can shorten the pellet lifetime by a factor of two from that assuming 1-D spherically symmetric heating.

The model of ∇B and curvature induced drift of pellet cloud material problem has been reformulated using the vorticity equation and is now more rigorous. This facilitates the introduction of effects due to toroidicity and strong parallel flow velocity along the curved magnetic field. A special field line following coordinate system attached to the moving cloud flux tube is also used to facilitate the calculations.

Work was done on a new fueling concept for next-step large-scale tokamaks such as ITER and beyond. The idea is to inject a nitrogen-cooled supersonic gas jet which is very slender, i.e., tightly collimated to ensure very high-density when it impinges on the plasma. The moment a fluid element of the jet enters the plasma, it becomes quickly heated and ionized, converting the gas jet into a *high-energy-density plasma jet*. The pressure of the jet can quickly reach a maximum value ~10 to 20 times the ambient plasma pressure. In toroidal devices, such “excess” pressure leads to an excess grad-B and curvature drift current inside the jet that results in E×B convection of the jet material towards the plasma core, much like in the case of an ionized pellet ablation cloud. During this period, a self-similar solution to the hydrodynamic equation describing the jet expansion was found. Temporal profile of the key jet quantities show the dimensionless pressure peaks and then decays because the expansion cooling outweigh the heating caused by energy deposition of the plasma electrons streaming through the jet.

6. ADVANCES IN INNOVATIVE CONFINEMENT CONCEPT RESEARCH

6.1. FIELD REVERSED CONFIGURATION

As reported in 2002, we have found a new class of analytical field reversed configuration (FRC) equilibria "doublet FRC" that contain double magnetic axes and two teardrop shaped private flux regions contained within a figure-eight-shaped, internal separatrix. A common flux region lies between the internal separatrix and the outer separatrix. The common flux surfaces have the familiar "doublet" shape. Doublet FRCs may possess more favorable stability properties: the common flux region near the internal separatrix has favorable average curvature, while finite pressure on the internal separatrix provides interchange stability in the private flux regions. We studied the interchange stability of these new configurations and our results are consistent with our expectations. The paper "Analytical equilibrium and interchange stability of single- and double-axis field-reversed configurations inside a cylindrical cavity" by P. Parks and M. Schaffer, GA Report GA–A24220, was written on this topic and submitted to *Physics of Plasmas* in December 2002. We found that the interchange stability within the private flux region, enclosed by the inner separatrix, is most difficult to achieve at the magnetic axis. This is for the same reason as in single axis equilibria. We found that with a fixed indentation, stability improves when elongation E gets smaller. For a given E, stability improves as the indentation weakens and the flux surfaces near the O–point elongate, but at the same time, the private flux core region shrinks. This property has similarities to interchange stability of a periodically extended magnetic island-chain equilibrium in 2-D planar geometry reported elsewhere. Stability improves when the closed-field island region becomes more elongated, but only at the expense of shrinking the size of the island. Surprisingly, we found that with sufficiently small indentation, all the core flux surfaces inside the internal separatrix can be stable to the interchange mode, even with zero pressure on the boundary separatrix. Just outside the internal separatrix, the interchange mode is stabilized by a favorable average curvature and compressibility stabilizes the mode again near the boundary separatrix. We have not yet quantified interchange stability on the possibly unstable intermediate surfaces between the outer and inner separatrices, but if instability were limited to a narrow set of these surfaces, the consequences to confinement might only be a local flattening of the pressure profile, without affecting the core equilibrium and its good stability.

We have not studied co-interchange modes (incompressible ballooning modes or Newcomb modes) in our paper. These modes represent a rigid incompressible translation of closed flux surfaces in either axial or radial directions, and thus resemble m = 1 kinks. Possibly the conducting walls in our configurations can stabilize the low-n global kink modes. However, high-n kink modes localize near the O–point, where wall stabilization would be ineffective. Future work will concentrate on finite Larmor orbit stabilization of these co-interchange modes that localize near the O–point.

In configurations with open field lines outside an external separatrix the average curvature is favorable and co-interchange modes are usually stable. For example, in a 2-D planar geometry with p′/p = constant everywhere, these modes are stable in the open field region outside the closed-field magnetic “islands”. It might, therefore, be speculated that in the doublet configuration co-interchange modes would also be stable in the common flux region outside the internal separatrix where the average curvature is also favorable. The special advantage of the doublet configuration is that these common flux surfaces are closed; they have the potential for robust stability *and* confinement.

The doublet FRC could face a more serious challenge, because without passive or active feedback stabilization, the private flux regions are susceptible to a global axisymmetric coalescence instability resulting from the attraction of like toroidal currents. In the 2-D planar island-chain equilibrium, an initial value MHD code found that this instability was always present because the negative attractive potential energy of like currents in adjacent islands overcomes the positive-definite stabilizing energy of magnetic field compression against the X–point situated between the islands. In our doublet configuration, however, this instability might be suppressed by passive stabilization, because either a conducting wall conforming to the outer indented separatrix or an external magnetic field coil set is implied in our equilibrium solution, whereas the island-chain equilibrium model has no wall image currents or coil currents.

6.2. 3-D EQUILIBRIUM RECONSTRUCTION

An important goal of the Stellarator 3-D Equilibrium Reconstruction Project is the development of a computational tool to evaluate the magnetic signals for various stellarator equilibria and diagnostic sets. A computer code V3POST that computes magnetic diagnostic signals for 3-D stellarator equilibria based on the efficient EFIT response function approach and Fortran 90/95 has been written jointly with ORNL and Auburn University [Hirshman 2003]. V3POST reads the response function tables from V3RFUN and computes the magnetic signals for various VMEC equilibria. Magnetic signals calculated using V3POST agree well with those computed using EFIT and the Wendelstein DIAGNO code for both DIII–D and W7–AS test cases. The first version of V3POST has been released and is being applied to support design of magnetic diagnostics for NCSX and CTH compact stellarators.

A surface approach to compute the plasma contribution to the external magnetic diagnostics has also been implemented into V3POST. The volume method computes the plasma contribution to a magnetic signal by integrating over the entire plasma volume, whereas the surface approach computes the plasma contribution by integration over the plasma boundary surface only. A convergence study comparing the surface to the volume approach has been completed using the DIII–D and the NCSX magnetic diagnostics. The results indicate that the surface method is more sensitive to the number of V3POST poloidal grid points used in the integration than the volume approach, particularly when the diagnostics are close to the plasma boundary. Thus, although the surface approach is ~15 times faster than the volume approach for 99 radial zones, when taking into account the larger poloidal grid required for similar accuracy, it is only ~3 times faster than the volume approach.

This completes the first phase of the V3FIT stellarator equilibrium reconstruction project. Iteration schemes to integrate the response approach into VMEC and regression algorithms to search for the equilibrium solution that best fits the magnetic data will be developed in the second phase to build the 3-D reconstruction code V3FIT.

7. PUBLICATIONS

7.1. PRIMARY THEORY AUTHORS

7.1.1. Primary Theory Authors for FY01

Candy, J., R.E. Waltz, “An Eulerian gyrokinetic-Maxwell solver,” J. Comp. Physics **186** (2003) 545; General Atomics Report GA–A23876 (2001).

Popov, A.M., R.J. La Haye, Y.Q. Liu, M. Murakami, N.N. Popov, and A.D. Turnbull, “Simulation of Neoclassical Tearing Modes in the DIII–D Tokamak Part II — Suppression by Radially Localized Electron Cyclotron Current Drive,” Phys. Plasmas **9** (2002) 4229; General Atomics Report GA–A23587 (2001).

Popov, A.M., R.J. La Haye, Y.Q. Liu, M. Murakami, N.N. Popova, and A.D. Turnbull, “Simulation of Neoclassical Tearing Modes in the DIII–D Tokamak Part I – Neoclassical Tearing Mode Excitation,” Phys. Plasmas **9** (2002) 4205; General Atomics Report GA–A23586 (2001).

7.1.2. Primary Theory Authors for FY02

Brennan, D.P., R.J. La Haye, A.D. Turnbull, M.S. Chu, T.H. Jensen, L.L. Lao, T.C. Luce, P.A. Politzer, E.J. Strait, S.E. Kruger, and D.D. Schnack “A Mechanism for Tearing Onset Near Ideal Stability Boundaries,” Phys. Plasmas **10** (2003) 1643; General Atomics Report GA–A24205 (2002).

Candy, J., R.E. Waltz, “Anomalous transport scaling in DIII–D tokamak matched by supercomputer simulations,” Phys. Rev. Lett. **91** (2003) 045001; General Atomics Report GA–A24138 (2002).

Chu, M.S., V.S. Chan, M.S. Chance, D.H. Edgell, A.M. Garofalo, A.H. Glasser, S.C. Guo, D.A. Humphreys, T.H. Jensen, J.S. Kim, R.J. La Haye, L.L. Lao, G.A. Navratil, M. Okabayashi, F.W. Perkins, H. Reimerdes, H.E. St. John, E. Soon, E.J. Strait, A.D. Turnbull, M.L. Walker, and S.K. Wong, “Modeling of Feedback and Rotation Stabilization of the Resistive Wall Mode in Tokamaks” Nucl. Fusion **43** (2003) 196; General Atomics Report GA–A24133 (2002).

Chu, M.S., M.S. Chance, A.H. Glasser, and M. Okabayashi, "Normal Mode Approach to Modeling of Feedback Stabilization of the Resistive Wall Mode," Nucl. Fusion **43** (2003) 441; General Atomics Report GA–A24048 (2002).

Chu, M.S., R.J. La Haye, L.L. Lao, A. Pletzer, C. Ren, E.J. Strait, T.S. Taylor, and F. Waelbroeck, "Study of Low Beta Classical Tearing Mode in DIII–D," Phys. Plasmas **9** (2002) 4685; General Atomics Report GA–A23910 (2002).

Chu, M.S., P. Parks, "Tokamak Equilibria with Central Current Holes and Negative Current Drive," Phys. Plasmas **9** (2002) 5036; General Atomics Report GA–A23962 (2002).

Hinton, F.L., M.N. Rosenbluth, and R.E. Waltz, "Reduced equations for electromagnetic turbulence in tokamaks," Phys. Plasmas **10** (2003) 168; General Atomics Report GA–A24023 (2002).

Kinsey, J.E., T. Onjun, G. Bateman, A. Kritz, A. Pankin, G. Staebler, and R.E. Waltz, "Burning Plasma Projections Using Drift Wave Transport Models and Scalings for the H–mode Pedestal," presented at 19th IAEA Fusion Energy Conf., October 14–19, 2002, Lyon, France, to be published in Nucl. Fusion; General Atomics Report GA–A24125 (2002).

Kinsey, J.E., G. Staebler, and R.E. Waltz, "Burning Plasma Confinement Projections and Renormalization of the GLF23 Driftwave Transport Model," submitted to Fusion Sci. and Technol.; General Atomics Report GA–A24180 (2002).

Lin Liu, Y.R., A.D. Turnbull, R.L. Miller, V.S. Chan, and P.A. Politzer, "A Class of High $\varepsilon\beta_p$ Equilibria in Strongly Shaped Finite Aspect Ratio Tokamak Plasmas," Phys. Plasmas **10** (2003) 790; General Atomics Report GA–A23820 (2002).

Parks, P.B., M.J. Schaffer, "Analytical Equilibrium and Interchange Stability of Single- and Double-Axes Field Reversed Configurations Inside a Cylindrical Cavity," Phys. Plasmas **10** (2003) 1411; General Atomics Report GA–A24220 (2002).

Project Staff, "The General Atomics Fusion Theory Program Annual Report for Fiscal Year 2002," General Atomics Report GA-A24232 (2002).

Waltz, R.E., J. Candy, and M.N. Rosenbluth, "Comprehensive gyrokinetic simulations of tokamak turbulence at finite relative gyroradius," Proc. 19th IAEA Fusion Energy Conf., October 14–19, 2002, Lyon, France (International Atomic Energy Agency, Vienna, 2002) CD-ROM; General Atomics Report GA–A24102 (2002).

Wong, S.K., V.S. Chan, "The Large-Aspect-Ration Limit of Neoclassical Transport Theory," Phys. Rev. E **67** (2003) 066406; General Atomics Report GA–A24103 (2002).

7.1.3. Primary Theory Authors for FY03

Brennan, D.P., S.E. Kruger, A.D. Turnbull, M.S. Chu, T.A. Gianakon, R.J. La Haye, L.L. Lao and D.D. Schnack "Nonlinear Modeling of the Onset and Evolution of Resistive Instabilities in DIII–D," 30th European Physical Society Conference on Controlled Fusion and Plasma Physics, July 7–11, 2003, St Petersburg, Russia; General Atomics Report GA–A24348 (2003).

Choi, M., V.S. Chan, S.C. Chiu, Y.A. Omelchenko, Y. Sentoku, H. St. John, "Interaction of Neutral Beam (NB) Injected Fast Ions with Ion Cyclotron Resonance Frequency (ICRF) Waves," 15th Top. Conf. on Radio Frequency Power in Plasmas, May 19–21, 2003, Moran,Wyoming, to be published in Radio Frequency Power in Plasmas; General Atomics Report GA–A24318 (2003).

Hinton, F.L., R.E. Waltz, and J. Candy, "Effects of electromagnetic turbulence in the neoclassical Ohm's law," presented at 45th American Physical Society Annual Meeting of Division of Plasma Physics, October 27, 2003, Albuquerque, New Mexico, to be published in Phys. Plasmas; General Atomics Report GA–A24511 (2003).

Hirshman, S.P., E.A. Lazarus, J.D. Hanson, S.P. Knowlton, L.L. Lao, "Magnetic Diagnostic Responses for Compact Stellarators," submitted to Phys. Plasmas (2003).

Holland, C., P.H. Diamond, S. Champeaux, E. Kim, O. Gurcan, M.N. Rosenbluth, G.R. Tynan, N. Crocker, W. Nevins and J. Candy, "Investigations of the role of nonlinear couplings in structure formation and transport regulation: experiment, simulation, and theory," Nucl. Fusion **43** (2003) 761.

Ishizaki, R., N. Nakajima, M. Okamoto, P.B. Parks, "Two-dimensional simulation of pellet ablation with atomic processes," to be submitted to Nucl. Fusion (2003); General Atomics Report GA–A24314 (2003).

Lin-Liu, Y.R., V.S. Chan. and R. Prater, "Electron Cyclotron Current Drive Efficiency in General Tokamak Geometry," Phys. Plasmas **10** (2003) 4064; General Atomics Report GA–A24257 (2003).

St. John, H., M. Murakami, T.K. Mau, M. Choi, "Review of Ray Tracing Code Curray," report submitted to the NTCC.

Snyder, P.B., H.R. Wilson, "Ideal Magnetohydrodynamic Constraints on the Pedestal Temperature in Tokamaks," Plasma Phys. Control. Fusion **45** (2003) 1671; General Atomics Report GA–A24279 (2003).

Snyder, P.B., H.R. Wilson, J.R. Ferron, L.L. Lao, A.W. Leonard, D. Mossessian, M. Murakami, T.H. Osborne, A.D. Turnbull, X.Q. Xu, "ELMs and Constraints on the H–Mode Pedestal: A Model Based on Peeling-Ballooning Modes," Proc. 19th IAEA Fusion Energy Conf., October 14–19, 2002, Lyon, France (International Atomic Energy Agency, Vienna, 2002) CD-ROM.; General Atomics Report GA–A24148 (2003).

Snyder, P.B., H.R. Wilson, J.R. Ferron, L.L. Lao, A.W. Leonard, D. Mossessian, M. Murakami, T.H. Osborne, A.D. Turnbull, X.Q. Xu, "ELMs and Constraints on the H–Mode Pedestal: A Model on Peeling-Ballooning Modes," submitted to Nucl. Fusion (2002); General Atomics Report GA–A24149 (2003).

Staebler, G.M., "Poloidal Momentum Transport due to Turbulence in Toroidal Geometry", submitted to Phys. Plasmas; General Atomics Report GA–A24001 (2003).

Staebler, G.M., J.E. Kinsey, R.E. Waltz, "GLF2003: a Theory Based Transport Model for the Edge and Core," presented at 9th Tech. Mtg. on H–mode Physics and Transport Barriers, San Diego, submitted to Plasma Phys. Contr. Fusion (2003); General Atomics Report GA–A24481 (2003).

Turnbull, A.D., L.L. Lao, T.H. Osborne, O. Sauter, E.J. Strait, T.S. Taylor, M.S. Chu, J.R. Ferron, C.M. Greenfield, A.W. Leonard, R.L. Miller, P.B. Snyder, H.R. Wilson and H. Zohm, "Edge localized modes in DIII–D high performance discharges," Plasma Phys. Contr. Fusion **45** (2003) 1845; General Atomics Report GA–A24284 (2003).

Wong, S.K., V.S. Chan, "A drift-kinetic approach to neoclassical theory for plasmas with large toroidal rotation" submitted to Phys. Plasmas; General Atomics Report GA–A24459 (2003).

7.2. DIII–D/OTHER PUBLICATIONS WITH SIGNIFICANT THEORY CONTRIBUTIONS

7.2.1. DIII–D/Other Publications with Significant Theory Contributions for FY01

Garofalo, A.M., T.H. Jensen, L.C. Johnson, R.J. La Haye, G.A. Navratil, M. Okabayashi, J.T. Scoville, E.J. Strait, D.R. Baker, J. Bialek, M.S. Chu, J.R. Ferron, J. Jayakumar, L.L. Lao, M.A. Makowski, H. Reimerdes, T.S. Taylor, A.D. Turnbull, M.R. Wade, and S.K. Wong, "Sustained Stabilization of DIII–D Plasmas Above the No-wall Beta Limit", Phys. Plasmas **9** (2002) 1997; General Atomics Report GA–A23864 (2001).

Garofalo, A.M., E.J. Strait, L.C. Johnson, R.J. La Haye, E.A. Lazarus, G.A. Navratil, M. Okabayashi, J.T. Scoville, T.S. Taylor, and A.D. Turnbull, "Sustained Stabilization of the Resistive-Wall Mode by Plasma Rotation in the DIII–D Tokamak," Phys. Rev. Lett. **89** (2002) 235001; General Atomics Report GA–A23849 (2001).

7.2.2. DIII–D/Other Publications with Significant Theory Contributions for FY02

Gohil, P., J. Kinsey, V. Parail, X. Litaudon, T. Fukuda, T. Hoang, for the ITPA Group on Transport and ITB Physics and for the International ITB Database Group, “Increased Understanding of the Dynamics and Transport in ITB Plasmas from Multi-Machine Comparisons,” presented at 19th IAEA Fusion Energy Conf., October 14–19, 2002, Lyon, France, Nucl. Fusion **43** (2003) 707; General Atomics Report GA–A24113 (2002).

Jayakumar, R.J., M.E. Austin, D.P. Brennan, M.S. Chu, T.C. Luce, E.J. Strait, A.D. Turnbull, “Observation and Analysis of a Resistive Interchange Mode in Negative Central Shear Plasmas in the DIII–D Tokamak,” Phys. Plasmas 9 (2002) 5043; General Atomics Report GA–A24008 (2002).

Lao, L.L., V.S. Chan, T.E. Evans, D.A. Humphreys, J.A. Leuer, M.A. Mahdavi, T.W. Petrie, P.B. Snyder, H.E. St. John, G.M. Staebler, R.D. Stambaugh, T.S. Taylor, A.D. Turnbull, W.P. West, and D.P. Brennan, “Physics and Control of ELMing H–Mode Negative-Central-Shear Advanced Tokamak ITER Scenario Based on Experimental Profiles from DIII–D,” Nucl. Fusion **43** (2003) 1023; General Atomics Report GA–A24157 (2002).

Leonard, A.W., T.H. Osborne, M.E. Fenstermacher, R.J. Groebner, M. Groth, C.J. Lasnier, M.A. Mahdavi, T.W. Petrie, P.B. Snyder, J.G. Watkins, and L. Zeng, “Transport of Edge Localized Modes Energy and Particles into the SOL and Divertor of DIII–D,” presented at 44th American Physical Society Annual Meeting of Division of Plasma Physics, November 11–15, 2002, Orlando, Florida, Phys. Plasmas **10** (2003) 1765; General Atomics Report GA–A24204 (2002).

Murakami, M., M.R. Wade, J.C. DeBoo, C.M. Greenfield, T.C. Luce, M.A. Makowski, C.C. Petty, G.M. Staebler, T.S. Taylor, M.E. Austin, D.R. Baker, R.V. Budny, K.H. Burrell, T.A. Casper, M. Choi, J.R. Ferron, A.M. Garofalo, I.A. Gorelov, R.J. Groebner, R. La Haye, A.W. Hyatt, R.J. Jayakumar, K. Kajiwara, J.E. Kinsey, L.L. Lao, J. Lohr, D. McCune, R.I. Pinsker, P.A. Politzer, R. Prater, H.E. St. John, and W.P. West, “Advanced tokamak profile evolution in DIII–D,” Phys. Plasma **10** (2003) 1691; General Atomics Report GA–A24209 (2002).

Murakami, M., M.R. Wade, C.M. Greenfield,, T.C. Luce, M.A. Makowski, C.C. Petty, J.C. DeBoo, J.R. Ferron, R.J. Jayakumar, L.L. Lao, J. Lohr, P.A. Politzer, R. Prater, H.E. St. John, “Modification of the Current Profile in High Performance Plasmas Using Off-Axis Electron-Cyclotron-Current Drive in DIII–D,” Phys. Rev. Lett. **90** (2003) 255001; General Atomics Report GA–A24171 (2002).

Okabayashi, M., J. Bialek, M.S. Chance, M.S. Chu, E.D. Fedrickson, A.M. Garofalo, R. Hatcher, T.H. Jensen, L.C. Johnson, R.J. La Haye, G.A. Navratil, H. Remierdes, J.T. Scoville, E.J. Strait, A.D. Turnbull, M. Walker, and the DIII–D Team, "Stabilization of the Resistive Wall Mode in DIII–D by Plasma Rotation and Magnetic Feedback," Phys. Plasmas **44** (2002) 339; General Atomics Report GA–A24014 (2002).

Petrie, T.W., J.G. Watkins, L.L. Lao and P.B. Snyder, "The Role of Magnetic Balance on the Poloidal Distribution of ELM-induced Peak Particle Flux at the Divertor Targets in DIII–D," Nucl. Fusion **43** (2003) 910; General Atomics Report GA–A23895 (2002).

Petty, C.C., R. Prater, T.C. Luce, R.A. Ellis, R.W. Harvey, J.E. Kinsey, L.L. Lao, J. Lohr, M.A. Makowski, "Physics of Electron Cyclotron Current Drive on DIII–D," Nucl. Fusion 43 (2003) 700; General Atomics Report GA–A24137 (2002).

Strait, E.J., J. Bialek, N. Bogatu, M. Chance, M.S. Chu, D. Edgell, A.M. Garofalo, G.L. Jackson, T.H. Jensen, L.C. Johnson, J.S. Kim, R.J. La Haye, G. Navratil, M. Okabayashi, H. Reimerdes, J.T. Scoville, A.D. Turnbull, M.L. Walker, and the DIII–D Team, "Resistive Wall Stabilization of High Beta Plasmas in DIII–D," presented at 19th IAEA Fusion Energy Conf., October 14–19, 2002, Lyon, France, Nucl. Fusion **43** (2003) 430; General Atomics Report GA–A24142 (2002).

Wade, M.R., M. Murakami, T.C. Luce, J.R. Ferron, C.C. Petty, D.P. Brennan, A.M. Garofalo, C.M. Greenfield, A.W. Hyatt, R. Jayakumar, J.E. Kinsey, R.J. La Haye, L.L. Lao, J. Lohr, P.A. Politzer, R. Prater, E.J. Strait and J.G. Watkins, "Integrated, Advanced Tokamak Operation on DIII–D," Nucl. Fusion **43** (2003) 634; General Atomics Report GA–A24151 (2002).

7.2.3. DIII–D/Other Publications with Significant Theory Contributions for FY03

Fenstermacher, M.E., A.W. Leonard, P.B. Snyder, J.A. Boedo, R.J. Colchin, R.J. Groebner, D.S. Gray, M. Groth, E. Hollmann, C.J. Lasnier, T.H. Osborne, T.W. Petrie, D.L. Rudakov, H. Takahashi, J.G. Watkins, L. Zeng, and the DIII–D Team, "ELM Particle and Energy Transport in the SOL and Divertor of DIII–D," Plasma Phys. Contr. Fusion **45** (2003) 1597; General Atomics Report GA–A24273 (2003).

Jardin, S.C., C.E. Kessel, J. Menard, T.K. Mau, R. Miller, F. Najmabadi, V.S. Chan, L.L. Lao, Y.R. Lin Liu, R.L. Miller, T. Petrie, P.A. Politzer, A.D. Turnbull, "Physics Basis for a Spherical Torus Power Plant," Fusion Engineering and Design **65** (2003) 165.

Li, J., B.N. Wan, J.R. Luo, G.L. Kuang, et al., "Long Pulse Enhanced Confinement Discharges in the HT–7 Superconducting Tokamak by Ion Bernstein Wave Heating and Lower Hybrid Wave Current Drive," Phys. Plasmas **10** (2003) 1653.

Mossessian, D.A., P.B. Snyder, A. Hubbard et al., "High-Confinement-Mode Edge Stability of Alcator C–Mod Plasmas," Phys. Plasmas **10** (2003) 1720.

Petty, C.C., J.E. Kinsey, T.C. Luce, T.L. Rhodes, and R.E. Waltz, "Safety Factor Scaling of Energy Transport in L–mode Plasmas on the DIII–D Tokamak," submitted to Phys. Plasmas; General Atomics Report GA–A24407 (2003).

8. REFERENCES

[Candy 2003a] J. Candy and R.E. Waltz, J. Comp. Physics **186** (2003) 545–581.

[Candy 2003b] J. Candy and R.E. Waltz, Phys. Rev. Lett. **91** (2003) 045001–1.

[Chan 2002] V.S. Chan, et al., Phys. Plasma **9** (2002) 501.

[Chance 1997] M.S. Chance, Phys. Plasmas **4** (1997) 2161.

[Chu 2003a] M.S. Chu, V.S. Chan, M.S. Chance, et al., "Nucl. Fusion **43** (2003) 196.

[Chu 2003b] M.S. Chu, M.S. Chance, A.H. Glasser, and M. Okabayashi, Nucl. Fusion **43** (2003) 441.

[Heidbrink 1999] W.W. Heidbrink, et al., Nucl. Fusion **39** (1999) 1369.

[Hinton 2003] F.L. Hinton, R.E. Waltz, and J. Candy, "Effects of electromagnetic turbulence in the neoclassical Ohm's law," presented at the 45th Annual Meeting Division of Plasma Physics, October 27–31, 2003, Albuquerque, New Mexico.

[Hirshman 2003] S.P. Hirshman, E.A. Lazarus, J.D. Hanson, S.P. Knowlton, L.L. Lao, "Magnetic Diagnostic Responses for Compact Stellarators," submitted to Phys. Plasmas (2003).

[Kinsey 2003] J.E. Kinsey, G.M. Staebler, and R.E. Waltz, "Burning Plasma Confinement Projections and Renormalization of the GLF23 Drift-Wave Transport Model," submitted to Fusion Sci. and Technol. (2003); J.E. Kinsey, G. Bateman, T. Onjun, et al., "Burning Plasma Projections Using Driftwave Transport Models and Scaling for the H–mode Pedestal," presented at 19th IAEA Fusion Energy Conf., October 14–19, 2002, Lyon, France, to be published in Nucl. Fusion (2003).

[Lao 2003] S.P. Hirshman, E.A. Lazarus, J.D. Hanson, S.P. Knowlton, L.L. Lao, "Magnetic Diagnostic Responses for Compact Stellarators," submitted to Phys. Plasmas (2003).

[Liu 2000] Y.Q. Liu, A. Bondeson, C.M. Fransson, B. Lennartson, C. Breitholtz, Phys. Plasmas **7** (2000) 3681.

[Petty 2003] C.C. Petty, J.E. Kinsey, T.C. Luce, T.L. Rhodes, and R.E. Waltz, "Safety Factor Scaling of Energy Transport in L–mode Plasmas on the DIII–D Tokamak," submitted to Phys. Plasmas (2003).

[Snyder 2002a] P.B. Snyder, H.R. Wilson, et al., Phys. Plasmas **9** (2002) 2037.

[Snyder 2002b] P.B. Snyder, H.R. Wilson, et al., "ELMs and Constraints on the H–Mode Pedestal: A Model Based on Peeling-Ballooning Modes," Proc. 19th IAEA Fusion Energy Conf., October 14–19, 2002, Lyon, France (International Atomic Energy Agency, Vienna, 2002) CD-ROM.

[Snyder 2003a] P.B. Snyder and H.R. Wilson, Plasma Phys. Control. Fusion **45** (2003) 1671.

[Snyder 2003b] P.B. Snyder, H.R. Wilson, T.H. Osborne, and A.W. Leonard, "Characterization of Peeling-Ballooning Stability Limits on the Pedestal," submitted to Plasma Phys. Control. Fusion (2003).

[Waltz 2003] R.E. Waltz, J. Candy, and M.N. Rosenbluth, "Comprehensive gyrokinetic simulations of tokamak turbulence at finite relative gyroradius," Proc. 19th IAEA Fusion Energy Conf., October 14–19, 2002, Lyon, France (International Atomic Energy Agency, Vienna, 2002) CD-ROM.

[Wilson 2002] H.R. Wilson, P.B. Snyder, R.L. Miller, and G.T.A. Huysmans, Phys. Plasmas **9** (2002) 1277.

[Wong 2003a] S.K. Wong and V.S. Chan, Phys. Rev. E **67** (2003) 066406.

[Wong 2003b] S.K. Wong and V.S. Chan, "A drift-kinetic approach to neoclassical theory for plasmas with large toroidal rotation" to be submitted to Phys. Plasmas (2003).

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