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THE GENERAL ATOMICS FUSION THEORY PROGRAM ANNUAL REPORT FOR FISCAL YEAR 2002

by
PROJECT STAFF

DECEMBER 2002

DISCLAIMER

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GENERAL ATOMICS PROJECT 03726
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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. Summary of Theory Work in FY02

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

- Development of the continuum global gyrokinetic code GYRO into a production numerical tool (Waltz 2002, Candy 2002).
- Continued development of the GLF23 transport model (Kinsey 2002a), including renormalization using recent gyrokinetic simulations, incorporation of the GKS Gyrokinetic code into the parallel XPTOR transport code, and other contributions to the National Transport Code Collaboration.
- Improved projections for burning plasma experiments using the renormalized GLF23 transport model (Kinsey 2002b).
- Crystallization of a new working model based on ballooning/peeling MHD stability of the plasma edge that explains a wide variety of pedestal and Edge Localized Mode (ELM) behavior (Lao 2002, Snyder 2002a, Snyder 2002b).
- Development and testing of more comprehensive models for active feedback of Resistive Wall Modes (RWMs) and Neoclassical Tearing Modes (NTMs) (Chance 2002, Chu 2002a).
- Construction of analysis tools for making and testing predictions of DIII-D behavior (Turnbull 2002a, Turnbull 2002b).
- Development of a Monte-Carlo Orbit-RF code used to study fast ion effects in ICRH plasmas (Chan 2002a).
- Development of models for describing pellet and gas jet dynamics and interactions with plasma for plasma fuelling and disruption mitigation (Parks 2002a, Parks 2002b).
- Development of several new ideas and models for Innovative Confinement Concepts (Chu 2002b, Parks 2002c).

As a consequence of this work, staff 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 Fiscal Year. Following this are more detailed descriptions of the advances and achievements made in each of the major areas.

2. Significant Achievements in FY02

- The GA Theory Group was selected for two invited presentations at the APS/DPP meeting, Long Beach CA, in November 2001:
  - "Gyrokinetic Turbulence Simulations of Profile Shear Stabilization and Broken GyroBohm Scalin,g" by R.E. Waltz.
  - "The Temperature Pedestal and ELMs: A Model Based on Coupled Peeling-Ballooning Modes," by P.B. Synder.

- Two seminars were given by A.D. Turnbull at the invitation of the Plasma Theory and Computation group at U. Wisconsin, Madison on 26 November 2001:
  - A general plasma seminar on behalf of the DIII-D team to the UWM plasma physics groups on "The Advanced Tokamak Concept", covering the DIII-D view of the Advanced Tokamak and the progress made to date.
  - A seminar on "Predictive Capability of MHD Stability Limits in High Performance DIII-D Discharges" given to the Plasma Theory and Computation group and covering the GA MHD theory work.

- The GA Theory Group was selected for two invited presentations at the Sherwood Theory Meeting April 22 in Rochester:
  - J.M. Candy gave a talk "GYRO Modeling of Anomalous Transport in Tokamaks," describing the recent progress with the continuum global gyrokinetic code GYRO.
  - J.E. Kinsey gave a talk "Renormalization of the GLF23 Transport Model and Burning Plasma Projections on a Universal Curve of Q versus T_{ped}," on the renormalization of GLF23 and the development of a stiff model for fusionQ-scaling.
  - In addition, A.M. Garofalo, from DIII-D, gave an invited talk entitled "MHD Stability in a Tokamak Above the Free Boundary Pressure Limit," which described the recent DIII-D wall stabilization results and included our work on theory/experimental comparisons.

- The GA Theory Group was selected for two oral presentations at the Montreux EPS meeting in June 2002:
  - J.M. Candy described the progress made during the past year on our the GYRO code development.
  - A.D. Turnbull presented work on “Detailed Comparison of MHD Stability Theory with Measurements in DIII-D,” describing the Theory Group's recent progress on the MHD stability analysis for DIII-D.
- L.L. Lao co-organized the IEA Workshop on ELMs at JET following the EPS meeting in Montreux. L.L. Lao and A.D. Turnbull also made presentations, which covered our work on developing the new model for Type I ELMs based on ideal stability of intermediate n modes, and complemented the experimental talks by T.H. Osborne and A.W. Leonard from DIII-D.
- V.S. Chan gave an invited talk on “Fast Ion Transport and Plasma Rotation in Ion-Cyclotron Heated Plasmas,” at the Varenna-Lausanne Conference on Theory of Fusion Plasmas, Varenna, Italy, August 27-30, 2002.
- R.E. Waltz gave a talk on the latest results from GYRO at the EU-US TTF Meeting in Cordoba, Spain, September 9-12, 2002.
- The GA Theory Group has also been selected for four presentations at the IAEA Meeting in Lyon, France October 14-19, 2002 describing our Theory Grant work:
  - P.B. Snyder for an oral IAEA presentation on “ELMs and Constraints on H-mode Pedestal: A Model based on Peeling-Ballooning Modes.”
  - R.E. Waltz for a presentation on the latest results from GYRO.
  - J.E. Kinsey for a presentation on the latest results using the GLF23 and Multimode, along with various pedestal models to predict the profiles in experimental H-Mode discharges, as well as the fusion performance in the proposed ITER, FIRE, and IGNITOR tokamak designs.
  - M.S. Chu to present results from the work on resistive wall and feedback modeling.
  - L.L. Lao was also selected to present results from IR&D work on ITER FEAT scenario development.
- D.P. Brennan and J.N. Candy are selected to give invited APS talks at the APS/DPP meeting, Orlando, Florida, in November 2002, respectively describing a

new comprehensive model for onset of Neoclassical Tearing Modes, and turbulence simulations of DIII-D L-mode plasmas with the GYRO code.

- The GA Theory Group devoted considerable effort (30%-40% of staff time during the third Quarter of the FY) to the Snowmass Meeting in July. R.E. Waltz was a convener for the P4 Transport group. J.E. Kinsey, G.M. Staebler and P.B. Snyder contributed to the Transport Group, D.P. Brennan, L.L. Lao, and A.D. Turnbull to the MHD Group, and V.S. Chan to the RF Group. Examples of this work can be found at: http://web.gat.com/snowmass/working/mfe/physics/p4/ & /p3/

- M.S. Chu co-organized, and the GA Theory group successfully hosted, the Magnetofluid Modeling Workshop on August 19 and 20 and the several following satellite workshops for the major national extended MHD modeling efforts: the Center for Magnetic Reconnection Studies (Amitava Bhattacharjee, U Iowa); the Center for Extended MHD Modeling (S. Jardin, PPPL); and the NIMROD Project (D. Schnack, SAIC).

  For details, see http://web.gat.com/workshops/mmw02.

- R.E. Waltz, J.N. Candy, P.B. Snyder, J.E. Kinsey, G.M. Staebler, A.D. Turnbull, L.L. Lao, and V.S. Chan participated in the ISOFS Workshop in San Diego, September 17-18, 2002.

3. Advances in Transport Research

3.1. GYRO Code Development

There have been enormous advances in the development of our full radius continuum gyrokinetic code GYRO over the past year. All of the planned features became operational in January 2002, after a three year development, and the GYRO code has essentially obtained its goal of a physically comprehensive simulation of a large radial slice of a DIII-D plasma with finite beta trapped and passing electrons, and with collisions and real geometry at the actual finite ρ_* (Candy 2002). In the GYRO code, full electron dynamics on the bounce/transit timescale are retained and both E×B and magnetic flutter nonlinearities are computed with fourth-order time accuracy. Arbitrary profiles can be simulated, although one can also use a switchable flux-tube mode of operation that allows precise comparison with GS2 code. As a first application, we completed an ion temperature gradient (ITG) study of profile shear effects. The results were highlighted at the Long Beach American Physical Society (APS) Meeting (Waltz 2002):

- GyroBohm scaling can be obtained when well above threshold and the diamagnetic (ρ_* scaled) rotational shear rates are not large. Otherwise, Bohm-scaling or worse can result.
- An adaptive source used to keep the background temperature gradients from relaxing was shown to avoid “false Bohm” scaling.
- Although the profile stabilization effects were small and a non-cyclic finite radial slice could reproduce the flux tube results in the gyroBohm regime, nonlocal effects are evident in the Bohm regime or very near threshold.

Since Jan 2002, full physics simulations with DIII-D experimental profile input have been performed. The ion and electron energy and particle diffusivities, as well as ion toroidal viscosity, electron-ion energy exchange are computed. A sample movie is available on the web at: http://web.gat.com/comp/parallel/mpeg/d3d.n16.1x_0.5.mpg. The E×B equilibrium shear effects are particularly striking in this movie. Very recently, enormous advances in the computational speed of the GYRO code have been achieved for full physics simulations. Previously, physically comprehensive simulations of DIII-D plasma slices (which are 20 times more expensive than state-of-the-art ITG runs) with trapped and passing electrons, finite-beta, real geometry, profile variation and E×B shear, etc., required 5-24 h restarts on 128ps of seaborg.nersc.gov. This resulted in a formidable 7 to 10 day job turn-around. Advances in the nonlinear transfer algorithm, now allow good scaling to 1024ps, and physically comprehensive simulations of DIII-D plasma slices cases can now be done in a single 24 h run on 512 processors. These full-physics GYRO runs can now be done in production mode; however, this will require a large increase in the MPP time available to us. For larger radial slices, the "box" instability is encountered as a result of the proximity to a singular inversion for the potential for long radial wave lengths of the n=0 zonal flows. The solution is to enforce a radial scale separation and preventing evolution of the longest near equilibrium waves. This allows a 6-fold speed up with time steps up to the electron parallel courant limit, or simulations with the physical $\sqrt{m_i/m_e}$ = 60 instead of 20, at a speed twice that previously possible.

3.2. GLF23 Transport Modeling and Code Development

The original 1997 GLF23 model (Waltz 1997) was fit to gyrofluid ITG simulations and an isomorphic electron temperature gradient (ETG) model. The GLF23 transport model has now been renormalized using an H-mode database comprising nearly 50 discharges from the DIII-D, JET, and C-Mod tokamaks (Kinsey 2002a). This was motivated by recent nonlinear gyrokinetic simulations with adiabatic electrons indicating that the saturation levels for ITG transport are nearly a factor of four lower than the gyro-fluid results that were used to normalize the original GLF23 model and also by the work of Jenko, *et al.* (Jenko 2000), suggesting that ETG streamers can result in significantly larger electron heat fluxes compared with simple isomorphic estimates. Although the DIII-D data is not very sensitive to these renormalizations, reducing the scatter in the fits from 13% to 10%, the ITER projections are somewhat more optimistic.

The renormalized model was also fit to gyrokinetic simulations (Kinsey 2002a) which have found the ITG transport to be less stiff and the ETG transport to be larger than the isomorphic $\sqrt{m_e/m_i}$ scaling. A slightly better fit to H-mode data was obtained and the extrapolations to burning plasmas are slightly more optimistic. The renormalized model is still rather stiff in that Q is proportional to the Volume * P^{2}_{ped}/P_{aux}. This make Q very sensitive to the achievable H-mode pedestal β, but it also suggests that once a pedestal temperature [$T_{ped} = p_{ped}/(3n_{ped})$] is obtained for Q in the range 5 to 10, the auxiliary power P_{aux} could be shut off and the plasma ignited; P_{fus} will remain nearly unchanged if T_{ped} is maintained, which requires $P_{fus}/5 - P_{brem}$ greater than half the LH power threshold possible.

The renormalized GLF23 (Waltz 1997) and MM95 (Kinsey 1996) transport models were used, along with several models for the H-mode pedestal temperature in simulations of H-mode experimental data and burning plasma devices (Kinsey 2002b). Both MHD limit power independent and free-fit power dependent pedestal models were considered.

For 47 H-modes from DIII-D, JET, and C-Mod, the RMS error in the core stored energy using the latest power dependent pedestal scaling (Cordey 2002) has been found to be 20%. Using experimental boundary conditions, an RMS error of 10% was found for the same database. The MM95 model shows less sensitivity to the choice of pedestal temperature by comparison. Using the power dependent pedestal scaling with GLF23 and MM95 leads to significantly more optimistic fusion projections for ITER, FIRE, and IGNITOR than when a power independent MHD type scaling is used.

3.3. ONETWO 1-1/2 D Transport Code Development

Considerable progress was made in maintaining and upgrading the ONETWO 1-1/2 D transport code.* The renormalized GLF23 confinement model was installed and benchmarked against the XPTOR code for several experimental DIII-D discharges, as well as the proposed burning plasma experiments (BPX) currently under consideration. Several of the BPX simulations included sawtooth modeling in combination with GLF23. The results indicate that agreement between the codes is satisfactory (St John 2002a) and the (small) differences that are observed can be explained in terms of understood differences in the codes.

Several other developments were implemented in the ONETWO code to enhance its applicability to situations of real experimental interest. A new solution method that allows us to generate fully evolved equilibrium states directly, eliminating the long simulation times required to relax the toroidal electric field to a steady state with stiff confinement models (such as GLF23), has now been added to the ONETWO transport code. The new approach uses globally convergent variations of the Newton method to solve the nonlinear time independent transport equations. In favorable circumstances, the required computation time is reduced from about 30 h to about 15 min. This allows the mapping out of steady - state AT modeling scenarios for DIII-D and ITER-FEAT using stiff confinement models to be achieved much more reasonably (St John 2002b). Also, the finite difference forms of the coupled transport equations were rewritten to permit the application of boundary conditions at arbitrary values of the minor radius. In simulation mode, each equation can now have an independent boundary specified as a function of time. This not only allows studies of the effects of various boundary conditions but it also makes possible the L to H transition modeling with GLF23 and provides for a more flexible core/edge coupling methodology. In addition, a new facility was added to the code to limit the growth rate of the safety factor q near the magnetic axis and prevent the formation of multiple magnetic axes, by dynamically adjusting a seed current to flatten the toroidal electric field when the current density is decreasing.

*Progress in transport code development is presented annually at the APS Meeting.

3.4. Neoclassical Transport Theory

Work continued on δf simulation of rotating tokamak plasmas. The poloidal flow with finite orbit width was shown to agree well with a new expression for poloidal flow proportional to the product of toroidal rotation shear and density gradient (Hinton 2003). We are presently implementing a different formulation for the angular momentum and energy fluxes, given by integrals of expressions containing the collision operator, to resolve the major remaining problem in the incorrect sign of the angular momentum flux near the magnetic axis.

4. Advances in MHD Stability Research

4.1. Edge Stability and Pedestal Modeling

The new working model for edge localized modes (ELMs) and constraints on the H-mode pedestal, based on the interaction between MHD ballooning and kink stability and transport at the plasma edge, was matured to the point where the model now successfully describes the qualitative behavior of ELMs in DIII-D, JT-60U, and Alcator C-Mod over a wide range of conditions (Lao 2002, Snyder 2002b). This was coupled with development of the associated numerical tools, especially the ELITE peeling-ballooning edge stability code, ELITE was used to explore edge pedestal stability boundaries in DIII-D in edge current, pressure gradient parameter space. This led to a greatly improved understanding of the physics of the H- mode edge pedestal. Several important results were presented at the APS Meeting in Long Beach (Snyder 2002a):

- The edge bootstrap current profile plays a key role in stabilizing the peeling-ballooning mode well above the zero current ideal MHD ballooning mode stability pressure gradient; increasing edge current opens up second stability access to high-n modes, resulting in a higher pressure gradient limit, and a lower-n for the limiting instability.
- Edge density and temperature parameters are separated by the bootstrap collisionality dependence.
- The effects of squareness and triangularity on DIII-D and JT-60U edge stability limits and ELMs are well explained.
- The finite-n peeling-ballooning modes limiting the pedestal are sensitive not just to local gradients, but to nonlocal changes in the equilibrium. Hence the stability limit is not a simple constraint on the pressure gradient, but rather can be approximately described as a constraint on the pedestal height, which is a sublinear, increasing function of the pedestal width.

A key additional hypothesis, that the ELM depth is related to the radial penetration into the core of the computed linearly unstable edge kink mode, was subsequently tested quantitatively for DIII-D discharge #97887. The radial eigenmode structure of the n=10 peeling-ballooning mode, which is the most unstable mode just prior to the first ELM was calculated with the ELITE code and compared to the observed ELM depth — that is the radial region over which the ELM leads to significant direct loss of energy and particles determined by statistical analysis of Thomson data across the first two large ELMs. The calculated and observed radial widths are in good agreement (Lao 2002, Snyder 2002b). Also, both extend inward well inside the pedestal. The promising agreement in this first studied case encourages further more detailed studies.

More recently, in work prepared for the IAEA Meeting in Lyon, it was shown that it is possible to predict pedestal trends in both present and future experiments by constructing series of model equilibria and calculating the stability boundaries with ELITE. This technique was employed for DIII-D, and the expected pedestal trends with plasma shape and density were directly compared to appropriate data from the more than 20,000 points in the DIII-D pedestal database. Good agreement was found, lending strong confirmation that the pedestal is limited by peeling-ballooning stability in DIII-D (Snyder 2002b).

4.2. Nonlinear Edge Stability and Turbulence Simulations

A complete understanding of edge physics requires studies of the nonlinear evolution of edge profiles and instabilities. X. Xu at LLNL has developed the BOUT code (Xu 2002) for simulation of nonlinear edge dynamics, by solving a set of reduced Braginskii equations in a realistic edge and divertor geometry. The simulations allow equilibrium profiles to evolve and can produce L-H mode-like transitions. In collaboration with Xu, we are endeavoring to enhance and use this code to study ELM dynamics by including the physics of current driven instabilities in the code. The parallel current term in the vorticity equation was incorporated into the code and a series of runs with and without this parallel current term carried out using equilibria from the ELMing H-Mode DIII-D discharge 92001. For this case, which lacked second stability access in the edge, including the parallel current leads to only a slight increase in the instability growth rate. However, by also including the dominant parallel current terms in the reduced Braginskii equations, instabilities that are clearly current driven were found in both H-mode and L-mode equilibria. These instabilities exhibit qualitative features in the linear and early nonlinear phases that are distinctly ELM-like, namely, Alfvénic growth rates, with initial growth inside the separatrix, followed by transport of particles and heat across the separatrix.

We are currently pursuing numerical methods, such as hyperviscosity and damping at the boundaries, to achieve nonlinear saturation and allow more thorough study of the nonlinear behavior of current-driven edge modes, and compare it to the behavior of previously studied pressure-driven modes. Meanwhile, we are continuing to run the enhanced BOUT code to characterize the earlier phases of edge current driven instabilities. Growth rates and saturation amplitudes have been calculated as a function of the edge current. As edge current is increased, the instability changes from a slowly growing resistive ballooning (or resistive X-point) mode to a peeling mode, with an order of magnitude faster growth rate. We plan to further characterize these current-driven peeling modes in BOUT, including comparisons of linear growth rates with ideal MHD calculations from ELITE and GATO, and assess the importance of non-ideal effects on these modes. The numerical properties of BOUT also make it most amenable to the study of collisional L-mode edge plasmas. We are studying the impact of enhanced current on an L-mode discharge. In the future, we plan to add collisionless damping terms, and eventually other kinetic effects, to the formalism to better allow treatment of hot H-mode plasmas, which tend to have a large bootstrap current and large, possibly current-driven, ELMs.

4.3. Resistive Wall and Feedback Stabilization

We have continued with investigations of stabilization of the ideal MHD kink mode above the β limit obtainable with no wall, using both passive and active wall stabilization. In a study using the normal mode approach for active feedback, the comparative effectiveness of off-midplane feedback coils and poloidal and radial field sensors on the stabilization of the resistive wall mode (RWM) was studied in DIII-D geometry (Chu 2002a). The study found that:

- With poloidal field sensing, a single central band of external feedback coils is sufficient for stabilization of RWMs with growth rates up to 30 times as fast as the rate of flux diffusion through the resistive wall.
- Extra upper and lower bands of feedback coils will provide substantial additional stabilization effect on the RWM; the strength of the RWM that can be stabilized is then increased by a factor of up to 30.
- Poloidal field sensing is much more effective than radial field sensing.

4.4. Resistive MHD Stability Theory

Development of a more computationally accurate and robust resistive MHD theory continued following the asymptotic matching approach, as implemented in the TWIST-R code (Galkin 2000). The resistive inner layer code developed to solve the inner layer resistive MHD equations was modified to include a spatially varying density profile within the inner layer (Galkin 2002). The results confirm that the analytic varying density model developed by Greene and Miller (Greene 1995) yields physically meaningful results over almost the full range of normalized growth rates, not just in the ideal limit where the analytic model is tractable. Provided care is taken to normalize the density profile so that the total mass within the inner layer is fixed, the dispersion curves are insensitive to the form of the density profile. The single significant exception to this is the appearance of an additional pole in the interchange parity matching data at high ideal-like growth rates and with high inertia. The physical significance of this is not fully understood. The new pole appears to be a real effect of the model but is only important at very high growth rates, well above the usual ideal range so it is likely to be irrelevant in practice. Also, the calculations revealed that there are parameter regimes where the dispersion relations for the tearing parity matching data do not depend on certain key equilibrium parameters. This is being investigated further.

4.5. DIII-D Stability Analysis

MHD stability analysis of DIII-D discharges has matured in recent years to the point where direct comparisons of, not just instability limits, but also mode structures and growth rates is yielding new insights (Turnbull 2002a, Turnbull 2002b). Much of this work was highlighted at the oral talk at the European Physical Society (EPS) Meeting in Montreux. Two recent results, in particular, have resolved longstanding puzzles in tokamaks.

Several DIII-D discharges have in the past exhibited apparent phase reversals, or "phase folding" in the Mirnov signals on the inboard side; that is, a signal that superficially appeared to be a simple m = 3 structure but with a region along the inboard side where the mode seemed to be m = –1. These apparent phase reversals had prompted a number of somewhat complicated and non-standard explanations. However, in collaboration with the FARtech group, a re-analysis of the comparison of the Mirnov prediction from the ideal mode computed by the GATO code with the measured signal for DIII-D discharge 87009, revealed that there is, in fact, no mystery and no non-ideal processes need be invoked. The phase reversal is only apparent, and is due to the rich poloidal spectrum of the unstable ideal mode, coupled with the noncircular discharge geometry and relative placement of the Mirnov loops.

In DIII-D discharge 86166 and many other discharges, successive decaying 3/2 modes are triggered by a series of saweeth, until one becomes unstable (Brennan 2002a). Detailed analysis has shown now that both the decay rates of 3/2 islands and the onset time of the final unstable island can be quantitatively explained by the Modified Rutherford Equation (MRE) from changes in Δ' calculated from PEST-III (Pletzer 1994), thus answering the longstanding question as to why the n^{th} sawtooth sets off the 3/2 while previous sawteeth did not (Brennan 2002b). From a PEST3 analysis of this discharge at several times between sawteeth, the background Δ' was found to be increasing on the approach to the 3/2 onset. Taking the computed linear Δ' values from the reconstructed equilibria at eight time slices, plus the calculated neoclassical terms and the measured island widths w at the same time slices, the island growth rates, dw/dt, were calculated from the MRE. These were compared directly to the dw/dt values inferred from the measured island decay rates. The resulting growth and decay rates agree very well, including the change in sign from a decaying to a growing mode. A single free parameter was retained in the polarization term. This was assumed to be constant throughout the discharge and adjusted to obtain the best fit. The best fit value is stabilizing, and also agrees well with the most commonly used theoretical polarization model (Wilson 1996). This is strong confirmation that the MRE, including the often-disputed polarization model, and linear Δ', is a valid quantitative model for island evolution.

NIMROD simulations (Glasser 1999) of this DIII-D discharge were also completed in collaboration with SAIC, and these capture the nonlinear extended MHD dynamics of the NTM seeding by sawteeth and spontaneous NTM generation. The results from these simulations were also made publicly available via MDS+. These results are now being analyzed with advanced 3-D visualization tools using the SCIRun package developed in collaboration with the University of Utah.

5. Advances in RF Heating and Fueling Research

5.1. Rotation Induced by ICRH

Minority ion cyclotron heating can produce energetic ions with banana orbits that are finite compared with the minor radius of a tokamak. The radial transport of the fast ions in the presence of Coulomb collisions results in a radial current and a corresponding J×B torque density on the bulk plasma. Collisions between the minority ions and majority ions provide an additional frictional torque that adds to or opposes the magnetic torque. Using the Orbit-RF code (Chan 2002a), which follows the particle drift trajectories in a tokamak geometry under the influence of rf fields and collisions modeled with rf-quasilinear and Monte-Carlo operators respectively, it was shown that a finite central rotation velocity can result even when the volume integrated torque density is small.

A physical picture has now emerged that explains the co- and counter-rotation with low- and high-field resonance respectively as a consequence of finite orbit width (Chiu 2002). For an asymmetric spectrum, it was found that when $n_{\phi\_}$ is in the co-current direction, the rf produces a net co-direction torque leading to co-rotation for both low- and high-field side resonance. With negative $n_{\phi\_}$, the rotation reverses to the counter-current direction. This study (Chan 2002b) calls attention to the possibility of an asymmetric power spectrum with a symmetric antenna array phasing due to an intrinsic antenna loading that is asymmetric perpendicular to the ambient magnetic field. The conditions for a spectral peak in the co-current direction are identified. Under this occurrence, the ICRF can indeed cause a co-current rotation for HFS resonance with Alcator C-Mod parameters. Moreover, for peaked density profiles corresponding to an internal transport barrier, the ICRF-induced rotation reverses its direction. Finally, with a finite positive $n_{\phi\_}$, a co-rotation peaked off-axis was demonstrated for LFS resonance heating for JET parameters. However, our study still cannot explain why there is no significant difference in the observed rotation on JET with different antenna phasing. This is one avenue for future work.

5.2. Pellet Fueling Analysis

Pellet injection into tokamak discharges has found many applications as a fueling method and a control tool, and understanding the pellet-plasma interactions is one of the main challenges of fusion research. In a new analysis of pellet cloud drift dynamics (Parks 2002a), it was found that the effect of toroidicity becomes increasingly important as the cloudlet elongates with time. With toroidicity, different segments of the cloudlet start drifting on different flux tubes and the differential slippage causes the cloudlet to fragmentize in a rather orderly fashion; beginning with the outermost fluid cells, the cells are sequentially shed, one by one. The remaining cells, being fairly well aligned within a common magnetic flux tube at any given moment, continue to drift coherently in the large–*R* direction until the next end cell is shed. The mass shedding model was incorporated into our pressure relaxation Lagrangian (PRL) code, which obtains the mass deposition profile in the plasma. This can then serve as the source profile in any tokamak transport code. A preliminary comparison was made to the experimental profile from DIII-D shot 98796 and good agreement was found. The results of the comparison can be seen at http://web.gat.com/theory/weekly_highlights/attachments/pellet_cloud.pdf.

The adverse effects of disruptions in tokamaks can be mitigated by rapid density increases using cryogenic liquid jets instead of solid pellets. However, a gas jet would be simpler to use and recent experiments on massive gas jet injection into DIII-D achieved the goal of quenching the poloidal magnetic field without generating runaway electrons. We have now developed a new theoretical model for the penetration of such a gas jet (Parks 2002b). The equations describing the (z, t) dependence of the jet radius, density, pressure, and velocity were derived using the long slender jet approximation as previously done in the liquid jet penetration model. A fairly straightforward solution was found when jet cooling of the background plasma is neglected; such cooling may be necessary for good penetration.

6. Advances in Innovative Confinement Concept Research

6.1. Current Hole Equilibria

Recent results from neutral beam heated DIII-D, JET and JT-60U discharges, in which equilibria exhibited a "current hole" near the magnetic axis with virtually zero current (Hawkes 2001, Fujita 2001), have generated considerable attention; these discharges appear to have interesting confinement and stability properties. It is well known that a steady-state tokamak with zero loop voltage can be sustained by an outward particle flow only if the particle source is singular at the axis, which is unphysical. However, a current hole opens the path to a new steady state regime, since a finite sized hole allows one to "fit" a mass source inside the hole in the form of ionized neutral beam particles or pellets and keep the current and poloidal flux from collapsing towards the magnetic axis. Once formed, virtually no toroidal loop voltage would be necessary thereafter. Several competing models were developed at GA to explain these observations and we are presently discussing ways to test these models with the experimental groups.

In the simplest model, the current hole is supported by a flux of hot beam ions into the core and the resulting outward mass flow (Jensen 2002). This successfully describes the major features of the JT-60U equlibria. The model predicts that, given sufficient ion flux, this configuration could be maintained indefinitely, which opens up the possibility of a steady state tokamak. An alternative model was also proposed that, while still ensuring a true steady-state equilibrium, removes some of the restrictions of the earlier model (Chu 2002b). Specifically, the new model is not restricted to unity β_p and includes the neoclassical bootstrap current effect. This results in a Grad Shafranov equation with two prescribed flux-surface functions — the total particle source rate within a flux surface and the parallel bootstrap current distribution. Since the mass flow is ineffective right at the hole boundary where q is infinite, a diffusive-like hyper-resistivity (Boozer) term is included in Ohms law that effectively replaces the loop voltage and allows for true steady state. An expansion analysis near the hole edge finds a Bessel function solution for the fields, without a singular current at the hole boundary; these profiles also satisfy the 1994 Hegna-Callen high m tearing instability criterion (Hegna 1994), thus justifying the use of the Boozer term.

The theory of Greene, Johnson and Weimer (Greene 1971) for tokamak equilibria was also extended to include equilibria with a central current hole region (Chu 2002b). The current hole region is shown to be connected with the external region with a regular equilibrium profile through a contact singularity where the magnetic field is continuous, with the possibility of a discontinuous current density distribution but no singular currents. However, equilibria with a negative current density region between the current hole and an external positive current region have been shown to not exist in general. These conclusions are consistent with the observation of current holes in tokamaks and the fact that negative currents have never been observed to develop in the current holes (Hawkes 2001, Fujita 2001).

6.2. Field Reversed Configuration Theory

In collaboration with several universities engaged in field reversed configuration (FRC) research, including the University of Washington and Swarthmore College, we have been considering a different FRC formation concept that would produce FRCs with an oblate shape as a replacement for the conventional θ pinch formation method that leads to elongated prolate FRCs. The oblate shape is tilt stable in the MHD (large – *s*) regime, relevant to reactors. Oblate shapes are also more compact than elongated configurations, assuming equal confinement times. Large–*s*, oblate-shaped FRC configurations then have the potential of making superior fusion reactors. In the new formation method, the FRC will be produced by merging spheromaks with counter toroidal magnetic fields and co-toroidal currents. External coils will control the degree of spheromak reconnection and thus the spatial distribution of the internal toroidal magnetic field. Partially reconnected CTs will form “doublets”.

We have found a new class of analytical “doublet FRC” equilibria that contain double magnetic axes and two teardrop shaped private flux regions contained within a figure-eight-shaped, “doublet” internal separatrix (Parks 2002c). A common flux region lies between the internal separatrix and the outer separatrix. Simple stability analyses of these analytic solutions have verified an earlier speculation that these configurations possess more favorable stability properties than standard FRCs. General expressions for the interchange functions V' and V'' at the O-point — the least interchange stable point — were derived, and the stability criteria compared, for the standard and doublet FRCs; this also revealed a correction to the published expression for V'' in work by Sparks and Sudan (Sparks 1984). For the proposed Swarthmore SSX-FRC experiment (elongation ~1.5), stability requires a minimum ratio of edge separatrix-to-O-point pressure of 0.4, compared to 0.58 for a conventional FRC with the same pressure profile. However, more oblate doublet FRCs, or increased indentation at the waist, can lower the edge pressure required for interchange stability, making doublet FRCs a more viable fusion configuration.

6.3. 3-D Equilibrium Reconstruction

In the Stellarator Equilibrium Reconstruction project, a dual processor, 2 GHz Xeon Linux PC workstation has been ordered and a work plan to develop the 3-D response function code V3RFUN has been formulated. The project has been formally initiated with a weekly teleconference between GA and ORNL. The work plan includes evaluation and tabulation of the response functions between the external coil and the magnetic diagnostics and between the plasma and the magnetic diagnostics. For the plasma response, an alternate dynamic approach to evaluate the response function on the fly will also be attempted. Both the vector potential and the magnetic field forms of the Biot-Savart law will be used for evaluation of the flux loop and the magnetic probe responses.

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