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FUSION PROGRAMS IN APPLIED PLASMA PHYSICS

JULY 11, 1992 THROUGH MAY 31, 1993
TECHNICAL PROGRESS REPORT

by
PROJECT STAFF

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GENERAL ATOMICS PROJECTS 3937 AND 3938
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ABSTRACT

This report summarizes the progress made in theoretical and experimental research funded by U.S. Department of Energy Grant No. DE-FG03-92ER54150, during the period July 11, 1992 through May 31, 1993. Four main tasks are reported: applied plasma physics theory, alpha particle diagnostic, edge and current density diagnostic, and plasma rotation drive. The report also discusses the research plans for the theory and experimental programs for the next grant year. Reports and publications supported by the grant during this period are listed in the final section.

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1. APPLIED PLASMA PHYSICS OVERVIEW

General Atomics' (GA) effort in Applied Plasma Physics consists of a theoretical and an experimental program. The theoretical program comprises of an interconnected series of investigations designed to elucidate the equilibrium, stability, and confinement properties of magnetically-confined plasmas in general; shaped high beta tokamak plasmas in particular. An important component of the program is our research in the application of rf waves and particle beams to enhance the performance of tokamaks. The objectives of the theoretical science program are:

1. To interpret and understand present experiments and predict the outcome of future planned experiments.

2. To improve on existing models and codes and validate against experimental results.

3. To conduct theoretical physics development of advanced concepts with applications for DIII–D and future devices.

GA's experimental effort in experimental Applied Plasma Physics encompasses two advanced diagnostics essential for the operation of future fusion experiments:

1. Alpha particle diagnostic,

2. Current and density profile diagnostics,

and a study to evaluate using plasma rotation drive to control tokamak stability and transport.

In the past 12 months of the grant period, significant progress has been made in both the theoretical and experimental programs. In theory, the model for the Toroidal Alfvén Eigenmode (TAE) has been extensively developed for noncircular, high beta plasmas to a stage where quantitative comparison with the DIII–D measurements is possible. A new beta-induced Alfvén eigenmode has also been discovered. The gyro-Landau fluid code has been applied to simulate saturated steady-state ion temperature gradient mode turbulence in toroidal geometry for the first time. Self-consistent transport simulations have demonstrated that transient current ramp good confinement high-ℓ_i discharges can in principle be stably maintained at steady-state in DIII–D with a combination of bootstrap current and rf and neutral beam driven noninductive currents. In experiments, we obtained initial data for the alpha pellet diagnostic from a high energy neutral analyzer on the Tokamak Fusion Test Reactor (TFTR) in the fall of 1992. Both neutrals from the high energy ^{3}He tail produced during ion cyclotron resonance heating (ICRH) and 1 MeV tritons from D–D reactions were observed. We made our first Li beam measurements of the edge electron density profile on the Texas Experimental Tokamak Upgrade (TEXT–U) in the fall of 1992 before the machine was shut down. These results are encouraging. However, they also point out the need for further improvements in the equipment, which we are in the process of implementing. The plasma rotation drive study has made progress in extending the theoretical model to handle multiple islands. The model has been validated against DIII–D results. Highlights and progress will be discussed in subsequent sections, followed by programs planned for the next grant year.

2. APPLIED PLASMA PHYSICS THEORY PROGRAM

2.1. HIGHLIGHTS

- Two theory papers where presented at the 14th International Conference on Plasma Physics and Controlled Nuclear Fusion [International Atomic Energy Agency (IAEA) Meeting], Würzburg, F.R. G., September 30-October 7, 1992. One invited theory talk and seven contributed papers were given at the Division of Plasma Physics Meeting, American Physical Society (APS), Seattle, Washington, November 16–20, 1992. Eight papers were presented at the International Sherwood Fusion Theory Conference, Newport, Rhode Island, March 29–31, 1993.

- J.M. Greene received the Maxwell Prize for his work on magnetohydrodynamic (MHD) theory and non-linear dynamics at the 1992 APS Meeting.

- A review of the Theory Program was presented to Dr. David Crandall, DOE/ OFE Director of Applied Plasma Physics, at GA, September 14, 1992. This consisted of nine technical presentations.

2.2. PROGRESS

2.2.1. MAGNETOHYRODYNAMICS

A new Alfvén eigenmode induced by finite beta (BAE-mode) was discovered in the MHD stability code (GATO) and verified in DIII–D experiments.

Significant progress was made during the past year in understanding the localized MHD spectrum using the spectral code CONT, with kinetic effects simulated by numerical modifications to the code. These results, combined with low toroidal mode number n calculations from the GATO code, as well as comparisons with experimental observations in DIII–D, have led to a broad understanding of the positive frequency side of the MHD spectrum and the corresponding eigenfunctions [1,2]. Numerical calculations for DIII–D discharges have demonstrated good quantitative agreement with the observed TAE frequencies, including detailed predictions of multiple TAE modes [3], as well as a qualitative understanding of the various damping mechanisms [4]. The calculations also led to the discovery of a distinct set of new modes, the

Beta-induced Alfvén Eigenmodes (BAEs) [5], which provide a plausible explanation of DIII–D observations at high beta. An APS invited paper describing this work was given in November 1992; the paper will also be published in the 1993 Special Issue of Physics of Fluids B [6]. The work on the theoretical aspects of the Alfvén and TAE mode spectra was also combined with results from kinetic calculations, done by the University of Texas group, into an IAEA paper in September 1992 [7].

Steady and significant progress was made in the study of several advanced tokamak configurations. Detailed, systematic stability analysis has been coupled to self-consistent transport and current-drive calculations and a clearer overall picture of the various regimes is now emerging. For the VH–mode and High Poloidal Beta (HPB) regimes, the important physical parameters limiting the low n stability have now been identified [8]. Stability calculations for the High ℓ_i regime and for Second Stable Core (SSC) regime with nonmonotonic safety factor profile, have revealed stable configurations with high normalized beta. Transport calculations have also shown that they can be maintained in a steady state by non-inductive current-drive with reasonable power levels.

A paper describing the new formulation of the tearing mode stability criterion was completed and published [9]. Further work on the tearing mode stability problem has focused on the equations describing the inner tearing layer; some parameter regimes have been found in which the validity criteria of the usual inner-layer equations were violated. It was shown, however, that this can be repaired by modifying the inner-layer equations so that the mass density profile varies on the inner-layer scale. A paper describing this work is in progress [10].

The program to study the effects of plasma rotation on MHD equilibrium and stability has been initiated. In DIII–D, the rotation energy near the plasma edge can be comparable to the thermal energy and this flow is thought to play an important role in the observed enhanced confinement. An existing equilibrium code was modified to solve the Grad-Shafranov equation in the presence of a sheared toroidal flow. It was found that one can tailor the profiles in the edge region to increase the toroidal current density on the outboard side by a factor of two or more, with no appreciable change in the total current. This observation may reduce discrepancies between Motional Stark Effect (MSE) and external magnetic probe measurements in equilibrium fitting of some DIII–D discharges.

2.2.2. TRANSPORT

Gyro-Landau fluid (GLF) model equations were successfully implemented in a novel 3D nonlinear ballooning mode representation (NLBMR) code to simulate saturated steady-state ion temperature gradient mode turbulence in toroidal geometry.

Work continued on the development and application of a GLF code in a NLBMR [11]. This has allowed very efficient 3D simulations of ion temperature gradient (ITG) mode turbulence in toroidal geometry. The GLF model equations have been found to reproduce rather well the linear ITG ballooning mode instability spectrum from kinetic theory. The ITG turbulence was found to have a 2:1 outside to inside asymmetry with transport fluxes having a 10:1 asymmetry. The toroidal transport was found to be at least an order of magnitude larger than purely slab transport. The scaling with shear, safety factor and relative temperature gradient was found to be rather similar to simple mixing length models. No evidence of subcritical turbulence has been found. A key feature of the NLBMR was to establish that nonlinear interaction with "image" modes are ballooning at large extended poloidal angles is small. This appears to be the case, although we now have a new way to keep these interactions at minimal expense. The most surprising result from this research has been the recognition that $n = 0$ "radial modes" play a crucial role in limiting the turbulence and transport from the high-n ballooning modes. These modes have been left out of most previous simulations because their evolution is generally difficult to separate from that of the transport equilibrium. The NLBMR is a Fourier transform representation which makes the radial modes easy to retain. The radial modes amount to small scale sheared rotations in the flux surfaces. They give no transport directly, but instead have an $E \times B$ shear stabilization effect on the high-n modes. Any mechanism which damps these mode leads to larger transport. Magnetic pumping appears to be too small to influence their damping. This work is part of a collaboration with National Energy Research Supercomputer Center (NERSC) (G.D. Kerbel) to develop fast parallel methods for turbulence simulations. It is part of the Numerical Tokamak Project which was designated as a "Grand Challenge" in the High Performance Computing and Communications Initiative (HPPCI).

A program to compare transport in tokamaks and stellarators was initiated. Tokamaks have profile resiliency or heat pinch like behavior and at least L–mode scaling is now established to be Bohm-like. These are the two most fundamental and poorly understood features of tokamak transport. By contrast stellarators have no profile resiliency (*i.e.*, heating off axis produces a flat temperature profile suggesting simple diffusion) and further more they appear to have the gyroBohm-like scaling expected from microturbulence. In collaboration with the W7–AS Stellarator group at Max-Planck-Institut für Plasmaphysik (IPP), Garching (U. Stroth and F. Wagner), we are trying to understand if these features are to the presence of the internal tokamak current. Experiments are in progress to introduce current into the stellarator causing to transition to a tokamak state with profile resiliency. Also a general theory program is underway to show that microturbulence in stellarators and tokamaks is fundamentally the same.

In collaboration with the Institute for Fusion Studies (IFS) at The University of Texas at Austin (UTA) (M. Kotschenreuther), we are exploiting a new fast gyrokinetic stability code. This new code contains virtually complete physics for treating the linear stability of high-n modes in a ballooning mode representation suitable for toroidal geometry. We have added many graphic and interactive features to this code as well real noncircular geometry, and quasilinear flow calculations.

Quasilinear calculations of the parallel and perpendicular viscous stresses due to drift waves in the kinetic regime for a sheared slab magnetic geometry were completed [12]. Both parallel and perpendicular ion flows contribute to the gradient of the Doppler shifted mode frequency which stabilizes the drift waves. For very large parallel velocity gradients the destabilizing Kelvin-Helmholtz drive term can dominate. This is not in the range of parallel flow shear observed in present tokamaks. The strong reduction in turbulent perpendicular viscosity with perpendicular velocity shear below the stability threshold was found to be a property of the parallel viscosity as well. These calculations, combined with previous calculations of the quasilinear energy and particle fluxes, were used as the theoretical basis for a local transport model of the H–mode bifurcation discussed below.

A local transport model based on the stabilization of turbulence by the gradient of the Doppler shifted mode frequency has been developed. Beginning with only energy transport [13], the existence of a purely turbulence driven bifurcation was demonstrated due to the feedback between the turbulent transport and the electric field gradient through the temperature gradient. Thus, the suppression of turbulence by a radial electric field gradient was shown to be a sufficient mechanism for a bifurcation without the need for other new physics. This model was extended to include particle transport [14] discovering how particle recycling at the edge can determine the width of the transport barrier in H–modes. Finally, momentum balance was included, so that all of the contributions to the Doppler shift gradient could be computed self-consistently in a time dependent system of transport equations. An explanation for the presence of a very high confinement regime (VH–mode) at high power was uncovered by this theory. The transport simulations compare favorably to DIII–D VH–modes [15]. We made experimental proposals, based on this theory, on how to bring the VH–mode to a steady state which is predicted to have even higher energy confinement due to a much wider transport barrier than has been achieved so far.

The poloidal mass flow and ion heat transport driven by friction between thermal ions and fast ions resulting from neutral beam injection, have been studied [16]. The driven poloidal mass flow can be much larger than the standard neoclassical poloidal rotation. The resulting viscous heating of the ions can be much larger than the standard neoclassical ion heat conduction term in the ion energy equation. The driven ion heat flux is inward (a heat pinch) in the case of co-injection, and can be significantly larger than the standard neoclassical heat flux. There is also a convective contribution to the total energy flux, due to the diffusional mixing of the fast ions and thermal ions, which is even larger than the heat pinch, but outward, when the energy density of the fast ions is smaller than that of the thermal ions. Transport coefficients are derived which relate the poloidal mass flow and the radial ion heat flux, as fluxes, to the fast ion friction and the radial temperature gradient, as forces. An Onsager symmetry condition shows that the coefficient of the fast ion friction in the radial heat flux is the negative of the coefficient of the temperature gradient in the poloidal mass flow. Self-consistent equilibrium temperature profile has been determined including this thermal pinch, beam-driven viscous heating and standard conduction. The solution shows thermal runaway of bulk ion temperature close to magnetic axis, which may explain the rapid increase of central temperature, the peaked ion temperature profile in the core region and the very low inferred ion thermal diffusivity in the hot ion H–modes in DIII–D and other large tokamaks.

New theory of ion rotation has been developed to apply to edge localized bootstrap current which is an important quantity in understanding MHD stability in H– and VH–modes in DIII–D. This theory is valid in the region where radial electric field gradient scale length is comparable to pressure gradient scale length. Preliminary comparison of this theory with He plasma experiment shows excellent agreements both in magnitude and profile (GA Internal Review as of June 3, 1993). The real fundamental difference between this new bootstrap current theory and the standard one is that ion rotation velocities (both poloidal and toroidal) now depends on the electric field shear. Physically speaking, if the electric field shear is strong (squeezing factor is larger than one), ion parallel flow driven by pressure gradient (ion driven bootstrap current) is reduced by this squeezing factor. In the edge region of H– and VH–modes in DIII–D, typical squeezing factor is about 3 to 5. This implies that Hirshman and Sigmar's bootstrap current formula over-estimates bootstrap current by about ~15% to 40% depending on the squeezing factor. Generalization of this theory to full toroidal geometry is under progress.

2.2.3. RF HEATING AND CURRENT DRIVE

Self-consistent transport simulations have shown that transient current ramp good confinement high-ℓ_i discharges can in principle be stably maintained at steady-state in DIII–D with bootstrap current and moderate power fast wave (FW), electron cyclotron (EC) wave, and neutral beam current drive (NBCD).

Since the review by the Office of Program Assessment in January 1992, considerable progress has been made on code dissemination of CQL3D and collaborations with other institutions. A documentation was prepared on CQL3D and published [17]. The code has been extensively applied in collaboration with various institutions including: (1) Shoucri, Tokamak de Varennes (TdeV), for modeling lower hybrid (LH) experiments in PBX–U and TdeV [18]; (2) Colborn, Massachusetts Institute of Technology (MIT), for LH experiments in Versator [19]; (3) Hokim, University of Wisconsin, for electron runaways in RFP; and (4) Fuchs, Bers, and Ram (TdeV, MIT) for Joint European Torus (JET) FW/LH synergism [20]. The code has also been benchmarked against the ACCOME code and the results reported at the Tenth Topical Conference on Radio Frequency Power in Plasmas, Boston, Massachusetts, April 1993 [21]. Applications of the code has been made in simulating experiments in Tore Supra, T–10 [22], JET, and DIII–D. It has been useful in assessing the synergism between rf and ohmic electric fields in DIII–D and T–10 [23], and in evaluating nonthermal effects on ECEs from electrons.

Progress has also been made in new developments of CQL3D. A new way of calculating bootstrap current from the Fokker-Planck solutions have been benchmarked against existing results. The new method promises the possibility of calculating bootstrap contributions from rf power. Development of $\mathrm{CQL}_{\parallel}$ is underway. This code solves for the distribution in 2D velocity and 1D spatial (along B-field) variables and the work is being done in collaboration with Dr. Olivier Sauter, a postdoctoral fellow from the National Science Foundation of Switzerland. The code will be useful in examining rf and trapping effects in arbitrary collisionality regimes, and can also be useful in transport studies of divertors.

Further transport simulation studies using ONETWO were carried out for two advanced tokamak scenarios on DIII–D: (1) fast wave current drive (FWCD) sustained high Li H–mode, (2) VH–mode with a second stable core. It is found that the high Li H–mode can be sustained by FWCD at the 1 MA level and a Li of about 1.4 with the near term capability (1994) of rf system upgrade on DIII–D. For the scenario of VH–mode with a second stable core, the quasi steady state could be maintained non-inductively using a combination of bootstrap current, on-axis FWCD (6.5 MW), off-axis electron cyclotron current drive (ECCD) (7.0 MW), and NBCD (2.5 MW).

Considerable work has been done in the past on the theory of FWCD in support of DIII–D experiment and reactors with collaborative efforts from Prof. M. Porkolab of MIT and Dr. C.F.F.Karney of Princeton Plasma Physics Laboratory (PPPL). In collaboration with Dr. T.K. Mau of University of California, Los Angeles (UCLA) [24], the theory has been implemented into the transport code ONETWO, and simulations have shown general agreement between theory and DIII–D experiment [25]. Further progresses have been made in the theory in this area. We have generalized previous theory to include relativistic and toroidal effects which can be of importance in reactors and high temperature plasmas in general [26]. Also, since synergistic effects between ohmic field and rf can be important in most of existing current drive experiments and probably at the earlier stages in reactors, we have, in collaboration with Karney, developed a code 'MADJR' to investigate this effect. This code generalizes earlier work by Karney and Fisch to include relativistic and toroidal effects which give important modifications to the previous theory. These works were developed with the aim that they will be implemented into ONETWO for simulations with self-consistently evolving MHD equilibrium.

A collaborative effort has been started between GA, M. Brambilla (IPP), and P. Bonoli of MIT on development of fast-wave full-wave code. The aim of the effort is to implement non-Maxwellian physics into the full-wave code. A formalism has been worked out which is consistent with both the full-wave formulation and quasilinear theory. More efforts shall be devoted to implementing the formalism.

The damping of rf waves can exert forces on selective species of plasma particles. This can be used to drive steady-state currents, generate rotations in tokamaks, and induce enhanced or reduced particle and energy transport. Quantitative knowledge of these forces is thus essential to evaluate the importance of various effects. Further work has been carried out to solidify a physical picture of the existence of non-resonant rf forces and a systematic theoretical development is obtained using a Hamiltonian formulation in which both resonant and non-resonant forces are considered in a unified approach [27]. We find that a net toroidal non-resonant force can exist in a tokamak for waves with finite parallel electric field and damped across the ambient magnetic field. Unlike resonant forces, non-resonant forces can interact with electrons to drive plasma currents while depositing most of the wave energy to the ions. This is explicitly illustrated in the case of wave helicity current drive. RF rotation drive is also considered and the power requirement is roughly the same order of magnitude as neutral beam injection. This work unifies all previous theoretical results and establishes a correlation between rf helicity injection and MHD turbulence theory. New areas where these effects may be prominent include situations where there is strong inhomogeneity in plasma parameters such as in low-frequency resonances and ion-Bernstein wave (IBW) experiments. Physics of non-resonant forces shall be investigated in these situations.

2.3. PROGRAM PLAN FOR BY94

2.3.1. MAGNETOHYDRODYNAMICS

2.3.1.1. TAE Modes. Although a broad understanding of the MHD properties of the TAE and BAE modes has been achieved, reliable kinetic models that can accurately predict their stability are not yet so well developed. We plan to investigate kinetic effects and to systematically incorporate them into our models. Here, we especially plan to focus on the stability of the new BAE mode but we will also consider the Elongation-induced Alfvén Eigenmode (EAE), which has also been observed now in DIII–D. A collaboration with L. Villard [Centre de Recherches en Physique des Plasmas (CRPP), Ecole Polytechnique Fédérale de Lausanne, Switzerland] has been initiated for the study of damping of TAE, BAE, and EAE modes in DIII–D discharges. Collaboration with C.T. Hsu (MIT) is also underway to study the effects of these modes on fast particle confinement.

2.3.1.2. Advanced Tokamak Configurations. In the coming year, we expect to continue the systematic stability studies of the advanced tokamak configurations. In particular, we plan to use our new understanding of the important stability parameters in the VH–mode and HPB configurations to optimize them and search for more reactor-relevant scenarios. We will continue the self-consistent transport/current-drive calculations in the high ℓ_i and SSC scenarios and we also plan to extend them to the VH–mode and HPB studies. Collaborations with B.J. Lee (UCLA), J. Ramos (MIT), and the Lawrence Livermore National Laboratory (LLNL) experimental group are already underway and we are initiating a new collaboration with O. Sauter and his colleagues in the MHD group at the CRPP in Lausanne.

2.3.1.3. Stability of Resistive Modes at Finite Beta. Our goal remains the construction of a numerical program for evaluating resistive MHD stability at finite beta on an equal footing with the ideal MHD computations from GATO. A reasonable goal for the coming year is to make further improvements in the inner-layer equations and to develop further develop further estimates of the results of such calculations.

2.2.1.4. Effects of Sheared Plasma Flows on MHD Equilibrium and Stability. At this stage of the program, we are considering purely toroidal rotation. We are, however, including shear in the rotation profile. An initial value ballooning mode code is under construction. With it, we plan to investigate the effect of toroidal flow on the first and second ballooning stability boundaries. The next stage will incorporate poloidal flow. MHD is, however, inadequate for this problem and at least a Guiding Center Plasma model will be required. Extensive collaborations are planned in various phases of this work with A. Bhattacharjee (Columbia University), A.B. Hassam (University of Maryland), and F.L. Waelbroeck (IFS).

2.3.1.5. Stabilization of Kink Modes. We are also initiating a new study of the possibilities of stabilizing resistive tearing and ideal kink modes by various means. These include wall stabilization from resistive walls and passive plates and driving of currents in the plasma scrape-off layer. We plan to evaluate simple arguments and models to determine the feasibility of the various schemes and are also considering modifications to the existing stability codes.

2.3.2. TRANSPORT

2.3.2.1. Transport Code Modeling of Tokamak Experiments. The thrust of our work on transport modeling will be to use the new fast gyro-kinetic stability code for general high-n ballooning modes to analyze DIII–D transport code data. Since this code has the most realistic and complete physics (collisional, electromagnetic, multi-species) and MHD geometry imaginable, we hope to find some correlation with the experiment. Despite its generality however it can only compute linear physics quantities, e.g., linear growth rate spectra, linear mixing length diffusivity, critical temperature thresholds, and quasilinear flow ratios. We can ask whether there always exists a critical temperature gradient in DIII–D L and H–mode plasma? Whether energy pinches can be found in addition to plasma pinches? Does the mixing length diffusivity correlate with the experimental effective heat diffusivity? We also hope to do confinement optimizations studies, *e.g.*, do discharges with the highest critical beta or falling into second stability also have lower mixing length diffusivity?

2.2.2.2. Numerical Simulation of Turbulent Transport. We anticipate that simulations of ITG mode turbulence in toroidal geometry using the GLF NLBMR code will be largely concluded. More elaborate and more exact gyro terms are being explored by the PPPL group (G. Hammett, B. Dorland, M. Beer) and at some point we will adopt these models. We have begun to explore the stabilizing effect of externally imposed sheared $E \times B$ rotation in toroidal geometry. This appears to be a difficult and very subtle topic for numerical methods but we hope to have a quantitative understanding of its effect on the actual heat diffusion.

To this point almost all 3D numerical simulations (at GA and elsewhere) have dealt only with electrostatic passing ion dynamics. We hope to begin adding trapped particles, electromagnetic physics and electron dynamics. We believe that new numerical methods in Kotschenreuther's initial value gyrokinetic code will make it possible to do electron dynamics. The time advance algorithms are completely implicit allowing the fast electron transit time scale to be passed in following the slower waves. This work will involve taking moments of the gyro-kinetic equations in a way which preserves the distinction between trapped and passing particles and can still allow the implicit time advance.

2.2.2.3. H–mode and Divertor Studies. There are several problems of a fundamental physics nature we plan to study. The electric field determination as the separatrix is crossed is an outstanding problem. The energy and particle fluxes to a solid surface tangent to magnetic flux surfaces is an important topic for slot divertor design. The transport of current across magnetic flux surfaces as observed in divertor biasing experiments needs a more complete theory. The stability of a neutral plasma interface is important for understanding divertor detachment and testing the gas target divertor concept envisioned for the International Thermonuclear Experimental Reactor (ITER). A Monte Carlo impurity transport code is being developed at GA and will need theory support.

2.3.3. RF PHYSICS

2.3.3.1. Simulations of Advanced tokamak Scenarios and DIII–D Experiments. We shall continue to explore and investigate different rf-generated advanced tokamak scenarios with self-consistently evolving MHD equilibrium. simulations of DIII–D experiments will also be made. The ray-tracing code CURRAY will be upgraded for these purposes. Full wave simulations will be carried out in parallel.

2.3.3.2. Synergistic Effects of RF and Ohmic Field. The codes CQL3D and MADJR will be used to further study the synergistic effects of rf and ohmic field. We plan to interface MADJR with ONETWO to investigate the synergism between ECH, FW, and Ohmic field. We shall also look in approximations of rf-produced distributions. This should lead to the capability to simulate CD experiments which have not reached steady-state (in collaboration with C.F.F. Karney).

2.3.3.3. Full-Wave Code Development. Our plan is to upgrade the FISIC code to have more consistent CD calculations and to accommodate non-Maxwellian distributions. This will be used to address current CD problems and interaction of waves with energetic ions. We also plan to implement FW ion absorption at high harmonics into the code (work to be done in collaboration with P. Bonili and M. Brambilla).

2.3.3.4. Effects of RF-Forces. The effects of rf-forces on plasma rotation and current diffusion will be investigated for realistic plasma profiles. The rf forces are generated by wave damping across singular surfaces. This study will examine the damping mechanisms due to collisionless and kinetic effects across these surfaces by extending a Vlasov-Hamiltonian technique we used previously to study uniform plasmas.

2.3.3.5. ECH and Fokker-Planck Code. We shall continue to develop, jointly with NERSC and Dr. Olivier Sauter (CRPP, Lausanne) CQL3D and $\text{CQL}_\parallel$ to extend the sophistication and versatility of the Fokker-Planck code. With the availability of TORAY EC ray-tracing code and CURRAY FW/LH ray-tracing code, we shall continue to carry out the theoretical study of ECH, ECCD, and combinations of different rf heating and CD techniques. The effect of fast electron cross-field transport on CD will be studied using CQL3D.

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3. ALPHA PARTICLE DIAGNOSTIC

3.1. SUMMARY

In a collaboration between GA, the Ioffe Physical-Technical Institute, and PPPL, we have installed a high energy neutral particle analyzer on TFTR. We obtained our initial data in the fall of 1992. During deuterium operations, we observed neutrals from the high energy ^{3}He tail produced during ion cyclotron radio frequency (ICRF) minority heating interacting with the ablation cloud surrounding a Li pellet. We have also observed the energy spectrum of 1 MeV tritons from D–D reactions slowing down in TFTR. We are modifying the analyzer to measure the energy distribution of the 3.5 MeV alpha particles during D–T operation beginning in the fall of 1993.

3.2. PROGRESS

3.2.1. EXPERIMENTAL OVERVIEW

The Alpha Charge Exchange (ACX) diagnostic that has been assembled on TFTR uses a high energy (1 to 3.5 MeV ^{4}He) neutral particle analyzer that was designed and fabricated by the Ioffe Institute and previously used on the JET tokamak [1]. The Ioffe E||B type mass and energy analyzer has eight signal channels with CsI(Ti) or ZnS(Ag) scintillator detectors whose light emission is measured by phototube/amplifier electronics operated in the analog mode. The Lithium Pellet Injector (LPI) that was used in conjunction with the analyzer was built by MIT and is capable of injecting Li, B, and C pellets. For the experiments reported here, only cylindrical Li pellets with dimensions $1.7\,\mathrm{mm}\,\Phi \times 3\,\mathrm{mm}\,L$ containing $\sim 3.7\times10^{19}$ atoms were injected with velocities in the range of 550 ± 150 m/sec.

A schematic of the ACX diagnostic is given in Fig. 3-1 and the field-of-view relative to the LPI pellet trajectory is shown in Fig. 3-2. The LPI axis lies on a major radius of TFTR and the ACX axis makes a selectable oblique angle of 2.75, 13, or 18.37 deg with the LPI axis, to allow viewing of the cloud at different toroidal distances from the pellet. The ablated lithium leaves the pellet surface as neutrals but quickly ionizes to Li^+ and begins to expand along the magnetic field lines. Further from the pellet, the cloud will become doubly, Li^{++}, and triply, Li^{+++}, ionized. One

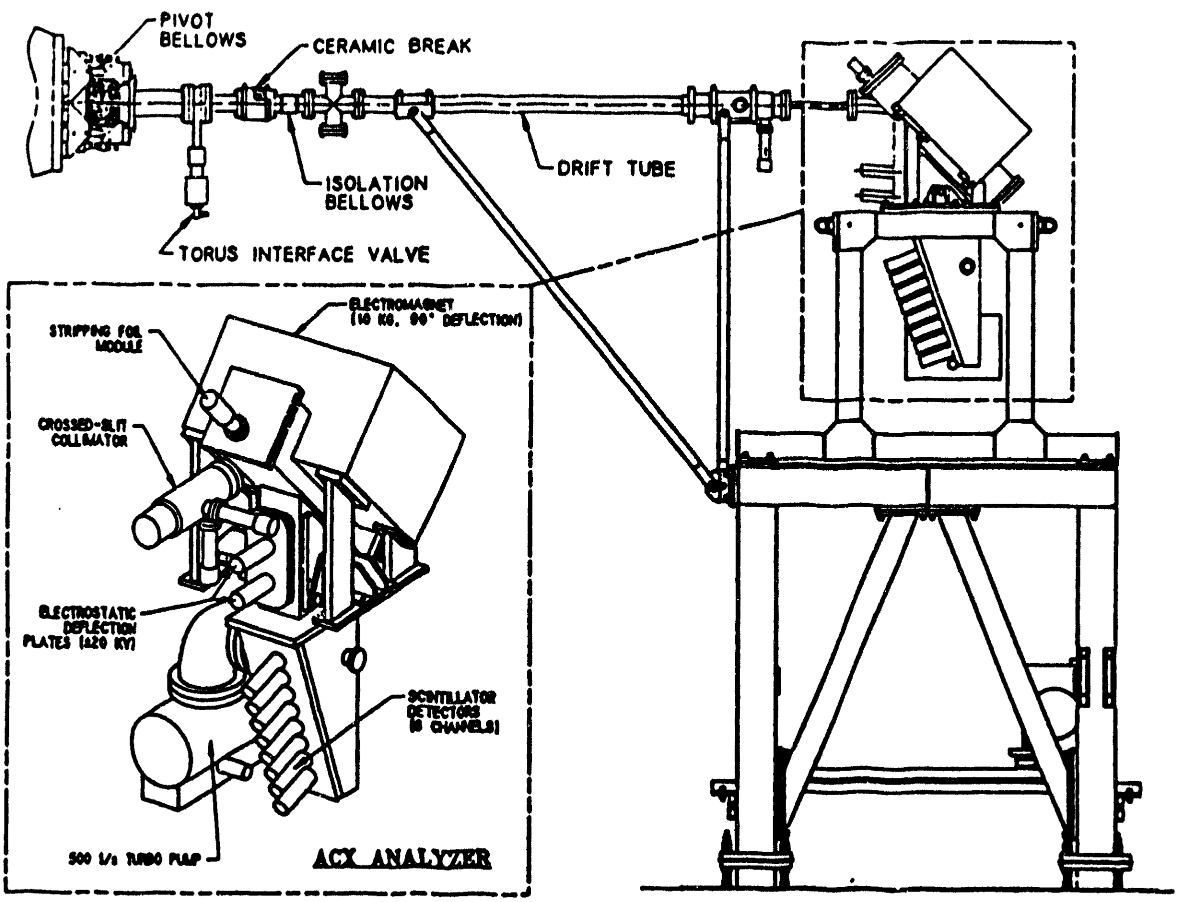

FIG. 3-1. Schematic of the ACX diagnostic on TFTR.

of the goals of the TFTR experiments is to confirm that a large spatial region of the cloud is dominated by the He-like ionization state Li^+, because of the jump in ionization potential to the next higher level. In the work reported here, the ACX was positioned at the 13 deg angle which views $\sim$ 15 cm from the pellet at $R = 3$ m. This position was chosen based on picture of 5845 Å line radiation from pellet clouds on TFTR showing Li^+ clouds that extended $\sim$ 30 cm from the pellet. By measuring the neutrals at different distances from the cloud, we hope to confirm a large Li^+ region and justify using a neutralization fraction for alphas incident on a Li^+ target.

During D–D operations prior to the D–T phase on TFTR, preliminary experiments were conducted to observe neutrals from the high energy ^3He tail produced during ICRF minority heating interacting with the ablation cloud from Li pellets. In the fall of 1992, we obtained about 30 shots with ^3He heating and Li pellet injection. Many exhibited some evidence of a ^3He neutral signal, but only one tokamak shot, where the pellet penetrated the farthest, showed a neutral signal much larger than

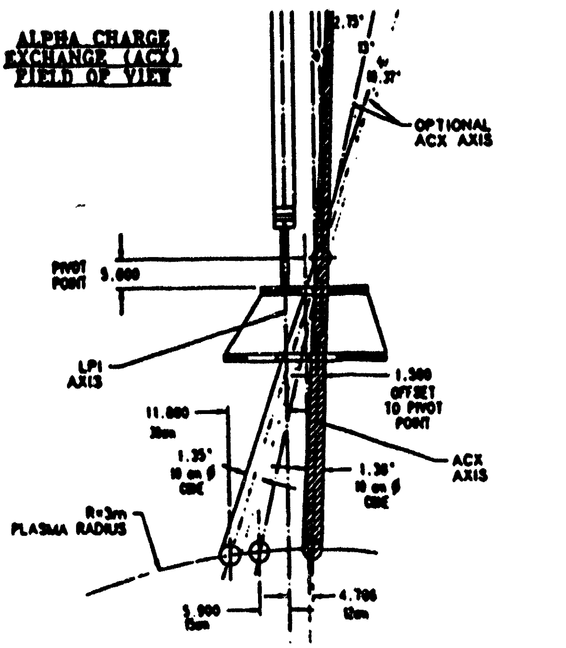

FIG. 3-2. Layout of the field of view for the LPI and the ACX diagnostic.

the measured background due to visible light from the pellet cloud. This shot is illustrated in Fig. 3-3, where the pellet penetrated to $R = 2.74$ m and during the last $\sim 150\ \mu$sec or ~ 9 cm of its travel, resulted in large increase in signal level. The spectrum was obtained during the 2.5 sec flattop phase of a deuterium discharge having salient parameters as follows: $B_T = 4.8$ T, $I_p = 1.8$ MA, $R = 2.62$ m, $a = 0.92$ m, $n_e(0) \sim 6 \times 10^{19}\ \mathrm{m}^{-3}$, and $T_e(0) \sim 2.8$ keV. The rf heating was applied from 3.0 to 4.0 sec and reached a launched power of $P_{rf} = 2.4$ MW, but faulted to 1.1 MW from 3.6 to 4.0 sec. The Li pellets were injected at 3.8 sec (200 msec after the drop in rf power) and at 3.9 sec. The first pellet was used for the ACX data, and a multichord photodiode array for measuring the pellet trajectory showed that this pellet had a velocity of $v = 586$ m/sec and penetrated to $R = 2.74$ m (87% of the plasma minor radius). Hence the neutral signal was large only when the pellet cloud came within ~ 13 cm of the ICRF resonance layer at $R = 2.70$ m. Two virtually identical shots were taken, the first with the analyzer fields configured to measure the $^3He^{++}$ ions and the second with the analyzer fields zeroed to obtain a background shot used to correct the raw data for interference of pellet light scattered into the detectors. After correcting for this effect, the residual signal was analyzed using the expression:

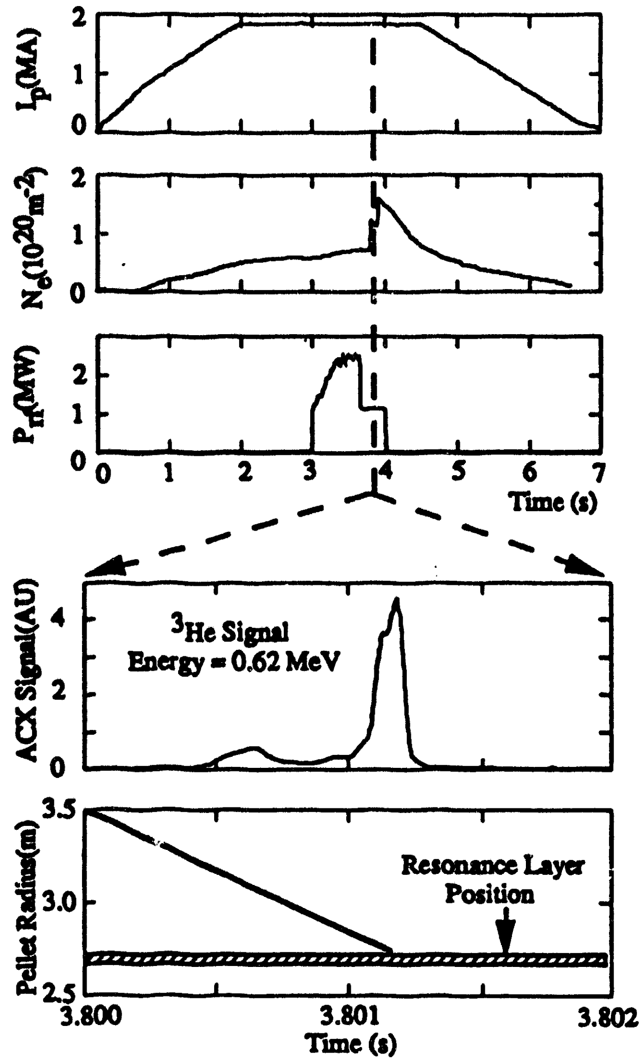

FIG. 3-3. Selected plasma discharge and ACX signal waveforms during ^{3}He minority heating. Also shown is the pellet position versus time.

$$dN(^3\mathrm{He}^{++})/dE = K(E)\, dN(^3\mathrm{He}^0)/dE \quad ,$$

$$K(E) = [F_0(\mathrm{E,Li}^+)\,\eta(E)\,\Delta E \Omega / 4\pi\, v_{\mathrm{He}} A_{\mathrm{cloud}}]^{-1} \quad ,$$

where $dN(^3\mathrm{He}^{++})/dE$ is the ion distribution in the plasma in the direction of observation, $dN(^3\mathrm{He}^0)/dE$ is the measured signal, $F_0(\mathrm{E,Li}^+)$ is the neutral equilibrium fraction for ^{3}He incident on Li^+, η(E) and ΔE are the calibrated efficiency and channel energy width of the analyzer, $\Omega/4\pi$ is the solid angle of the collimator, v_{He} is the ion velocity, and A_{cloud} is the area of the portion of the cloud observed by the analyzer.

The results are shown in Fig. 3-4 where a straight line fit to the data yields an effective $^3He^{++}$ temperature of T_{tail} = 170 keV. The measurement is in favorable agreement with rf code modeling calculations which give an effective tail temperature of 170 to 200 keV. However, the amplitude of the measured signal in this preliminary operation of the ACX is significantly below our initial estimates. More detailed analysis remains to be done to obtain consistency between the measured and calculated signal levels. Along the effects that need to be studied are the anisotropy on the pitch angle distribution of the ^3He ICRF tail ions, better calibration of the scintillator/ detector sensitivity, and the effect of multiple pass ion orbits in the calculation of the neutralization fraction.

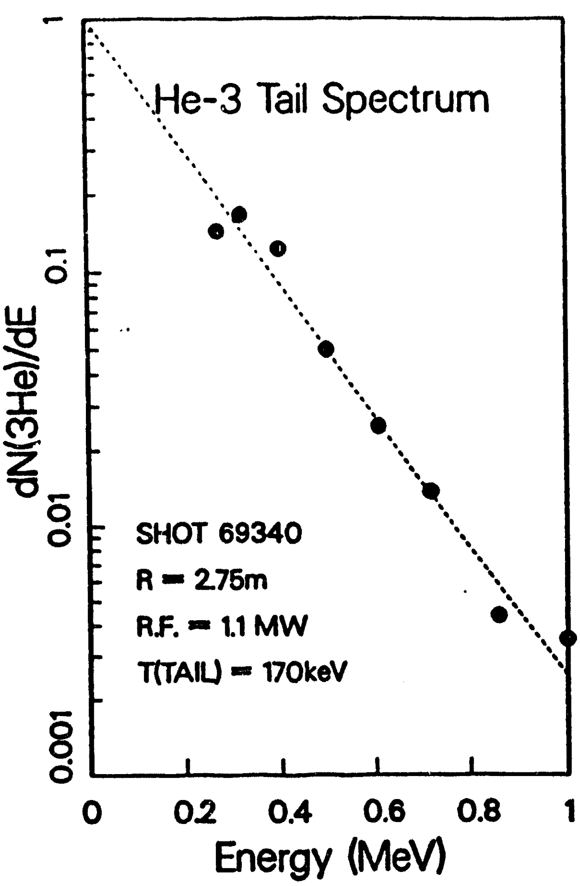

FIG. 3-4. Measured energy spectrum for the ICRF-generated ^3He minority ion tail in TFTR.

During this experimental run, the slowing down spectrum of tritons produced during beam-heated discharges was also measured and is shown in Fig. 3-5. The measured spectrum is consistent with the classical slowing down distribution $f(v) \sim 1/(v^3 + v_c^3)$ where v_c is the critical velocity. The signal to background ratio for the triton spectrum was very small, however, so this data needs to be confirmed.

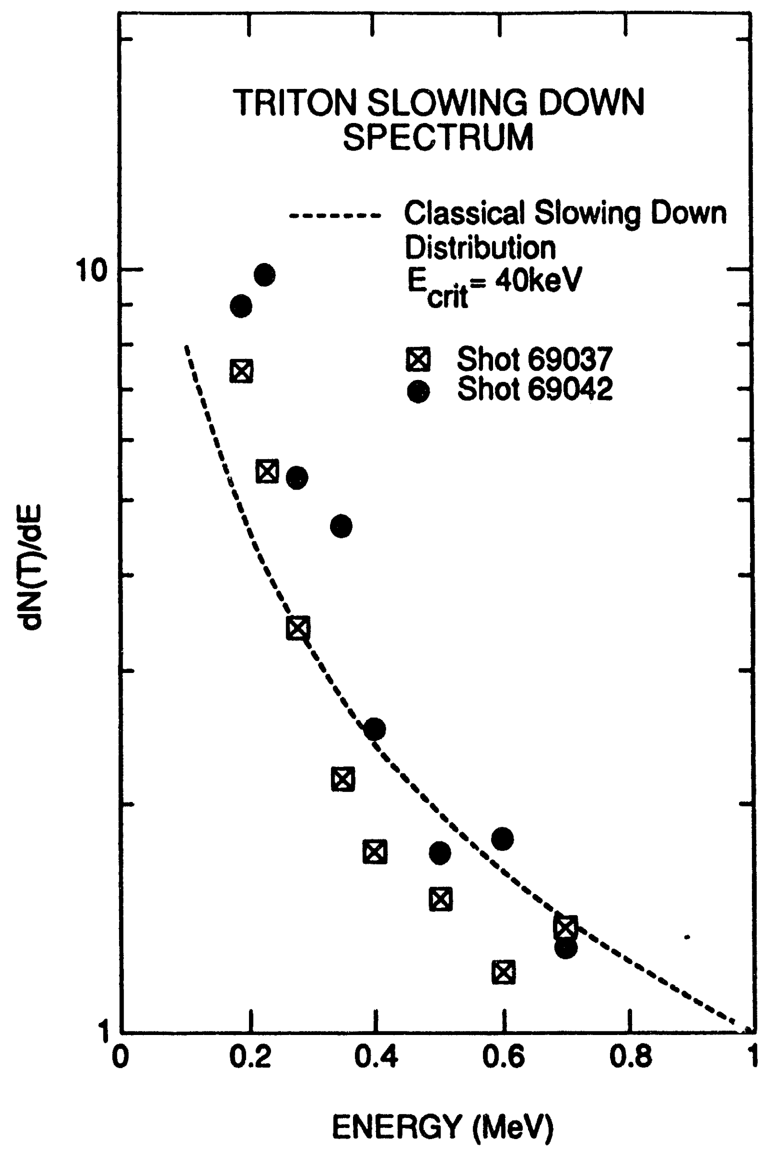

FIG. 3-5. Measured slowing-down distribution of 1 MeV tritons from D–D reactions in TFTR.

The initial operational goals on TFTR, which were to demonstrate the feasibility of the alpha particle measurements using impurity pellet injection and to certify operation of the performance of the ACX diagnostic system, have been achieved. At the present time, the diagnostic is being prepared for the D–T operating phase of TFTR. This preparation includes installing a neutron and gamma radiation shield consisting of a wall of 4 in.-thick Pb encapsulated in a 6 in.-thick outer wall of 5% borated polyethylene giving approximately 100× attenuation of the radiation flux. In addition, the detection system has been modified so that the scintillator light emission is now coupled by fiber optics to phototubes located in a benign radiation environment.

3.3. PROGRAM PLAN FOR BY3

TFTR D–T operation will begin in the fall of 1993. The principal goal during BY3 is to demonstrate the capability of the diagnostic to measure the energy distribution of the fast confined alpha particles produced during D–T operation of a fusion tokamak.

Using the results of the TFTR experiment, we would also examine in more detail the possibility of applying this diagnostic to ITER. JET has also expressed an interest in this diagnostic and would provide an opportunity to perform any tests not possible to complete during the TFTR D–T experiments.

3.4. REFERENCE FOR SECTION 3

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4. EDGE AND CURRENT DENSITY DIAGNOSTIC

4.1. INTRODUCTION

General Atomics has installed a Li beam diagnostic on the TEXT–U tokamak at the University of Texas Fusion Research Center at Austin, Texas, for the measurement of edge electron density profiles and of edge electron density fluctuations. A Li ion source, accelerator, and neutralizer produce a beam of neutral Li atoms with an intensity of 2 to 4 mA and a beam energy of about 25 keV. The beam penetrates about 10 cm into the plasma. Collisions with plasma particles excite some of the Li atoms from the ground Li(2s) state to the excited Li(2p) state. These excited state atoms can then decay via the emission of a visible photon at 670.8 nm. These fluorescence photons are detected with both spatial (about 1 cm) and temporal (about 1 μsec) resolution, giving a measurement of the edge fluorescence profile and edge fluorescence fluctuations. These fluorescence measurements can be unfolded to give the electron density profiles and fluctuations which caused them.

4.2. CHANGES TO THE EXPERIMENTAL APPARATUS

The ion source, accelerator, and beam neutralizer have all consistently worked well and have not had to be changed, although the control and isolation circuitry was overhauled to solve a problem with occasional arcs in the accelerator causing noise in timing circuits. The optical detection system, however, was initially tested in proof-of-principle experiments with unoptimized optics and borrowed data acquisition. Several major improvements were made to this hardware during the period from July 1992 through May 1993. Leftover S20 photomultipliers were replaced with ten new Hammatsu GaAs photomultipliers, which have a much better sensitivity to light at 670.8 nm. These better tubes are necessary to collect enough photons to have reasonable statistics at the high sampling rates (1 MHz) planned for fluctuation measurements. 1 MHz CAMAC digitizers and memories were also purchased and installed, replacing slower modules which had been on short-term loan from DIII–D.

Using these ten new detectors (with associated electronics: power supplies, amplifiers, anti-aliasing filters, etc.), we participated in a number of experiments in July and August of 1992, just prior to TEXT–U shutting down for the replacement of its divertor coil. Sample results from these experiments (reported at the 1992 APS Division of Plasma Physics Meeting in Seattle) are reviewed in the next section.

4.3. RESULTS FROM EXPERIMENTS IN JULY AND AUGUST 1992

During this experimental period we made our first Li beam measurements of the edge electron density profile on TEXT–U. In Fig. 4-1, the black dots are experimental measurements of the Li beam fluorescence intensity as a function of position in the plasma at one particular time during a shot. As previously reported, we have developed a computer program which, given the electron density profile, predicts the Li beam fluorescence as a function of position. Using this program, we were able to find the electron density profile which gave the best fit to the observed fluorescence profile. The electron density profile is shown as the dashed line in Fig. 4-1, and the fluorescence profile calculated by the computer program for the density profile is shown as the solid line. A more sophisticated data unfolding procedure will be used when the quality of the data (number of points, and signal-to-background ratio) warrant.

We repeated the process of fitting an electron density profile to the measured Li fluorescence profile for a number of different times for the same shot. The results are shown in Fig. 4-2. In this figure, the solid line is the line averaged electron density measured by a midplane microwave interferometer. The solid points are the Li beam measurements of the electron density at a minor radius in the plasma of $r = 20$ cm. The dots are lower than the solid line because the density at the edge channel $r = 20$ cm is less than the line averaged density. Where the two sets of data are not parallel, the shape of the electron density profile is changing.

These initial results are encouraging. However, they also point up the need for some further improvements in the equipment if the TEXT–U Li beam is to become a useful diagnostic. These are addressed in the next section.

4.4. FURTHER IMPROVEMENTS TO THE EXPERIMENTAL APPARATUS

After the TEXT–U tokamak shut down in 1992 for replacement of its divertor coil, work continued at GA in San Diego to improve the Li beam diagnostic. More GaAs photomultipliers (and PMT housings, amplifiers, filters, etc.) were ordered to bring the total number of detector channels up from 10 to the design value of 20. All 20 channels will be used when experiments resume in the fall of 1993.

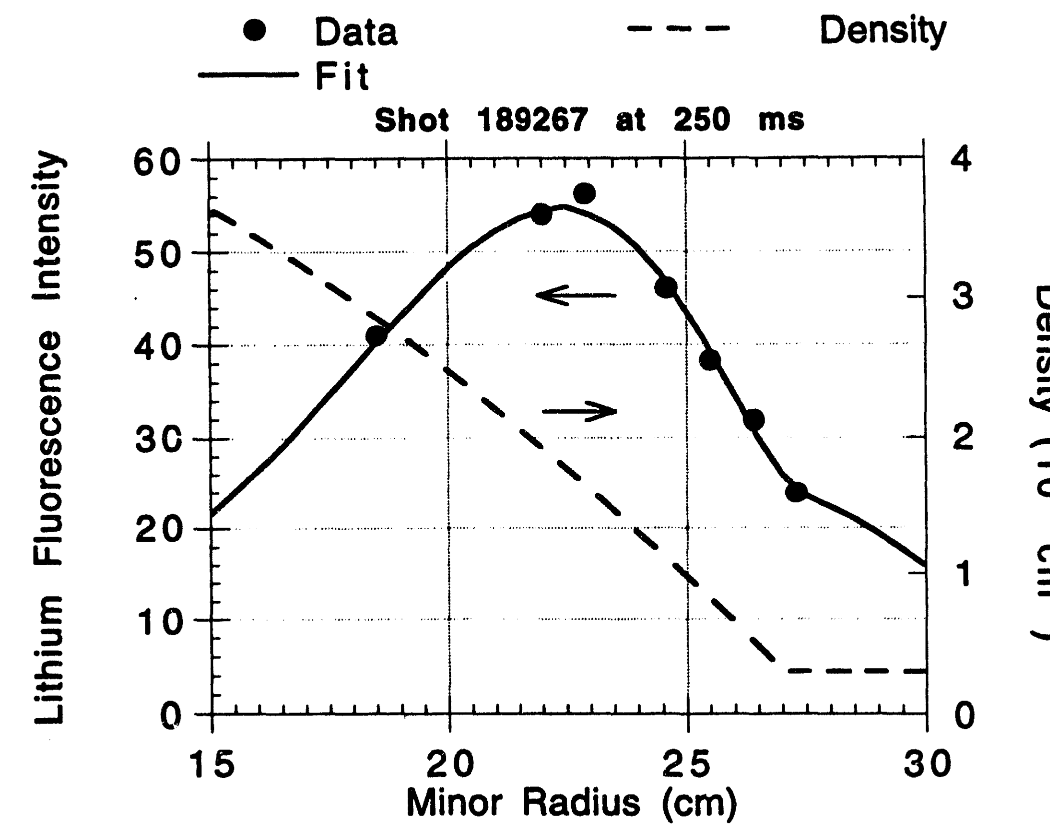

FIG. 4-1. A sample Li beam fluorescence intensity profile and the edge electron density profile inferred to have caused it. The solid dots are measured 670.8 nm fluorescence intensities as a function of position in the plasma, including a relative but not an absolute calibration. For a given edge electron density profile (dashed line), a Li fluorescence profile (solid line) can be calculated from the known atomic cross-sections. The inferred actual edge electron density is that which gives the best fit between the calculated and measured fluorescence profiles. A more sophisticated unfolding algorithm will be used when the quality of the data warrants.

Another issue is the ratio of the signal (Li fluorescence light) and the background (plasma light from all other sources) measured by the detectors. For the experiments during 1992, it was necessary to average the fluorescence measurements for periods of a few ms before they could be used to unfold the electron density profiles. A better signal-to-background ratio means a shorter required averaging time. We hope to improve this ratio to the point that profiles can be unfolded on microsecond instead of millisecond time scales. As part of this effort, we have been making measurements using the Li beam diagnostic on DIII–D since TEXT–U is not available. These tests have shown that the signal-to-background ratio can be improved at least a factor of

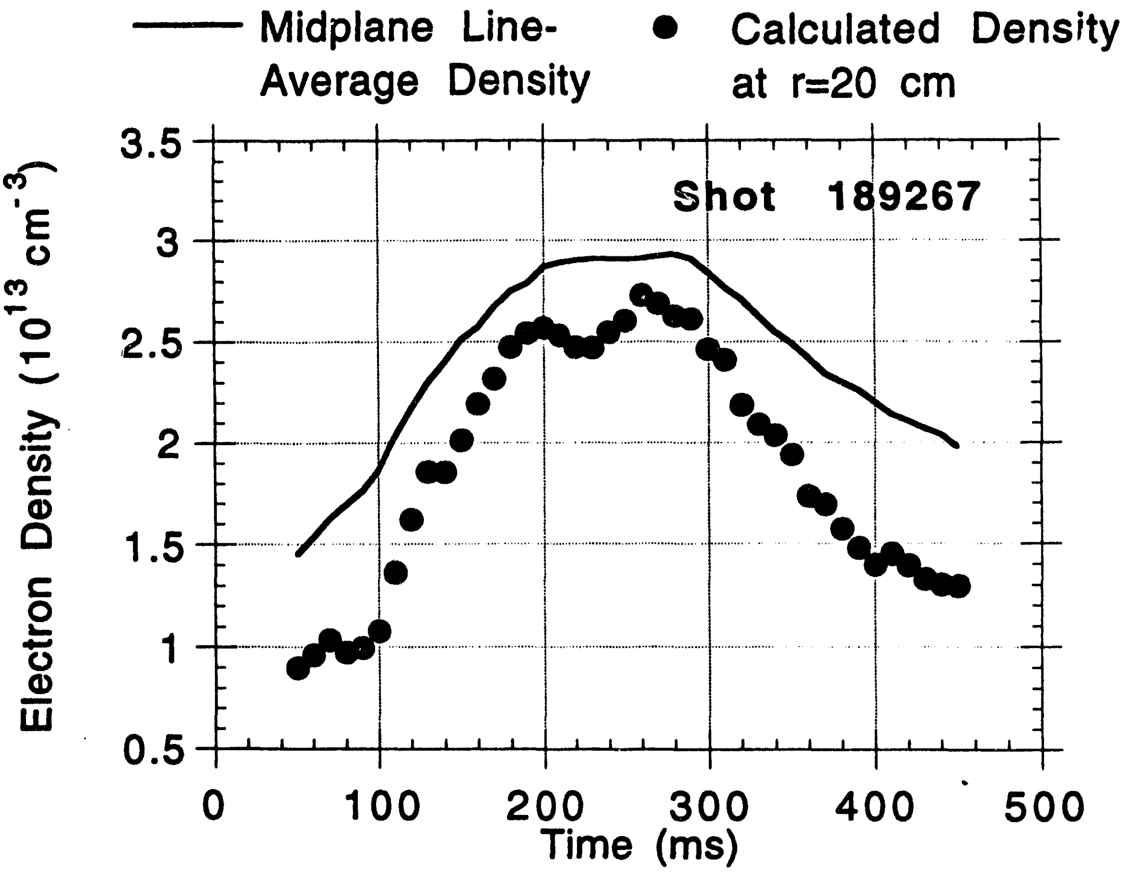

FIG. 4-2. A comparison of the edge electron density at $r = 20$ cm inferred from Li beam measurements (solid dots) with the line-averaged density measured by a microwave interferometer (solid line). The density at the edge position $r = 30$ cm is less than the line-averaged density. Where the two curves are not parallel, as occurs between 230 and 260 msec, and again between 300 and 400 msec, the shape of the density profile is not constant. One of the major goals of this experiment is to improve the time resolution of the Li beam density data.

2 with a change of interference filters. Just how much more it can be improved (and just which new filters to order) awaits tests which will be done during the next DIII–D run period.

An additional improvement is expected from re-designed light collection optics which will give better image quality (resulting in less crosstalk between channels) and higher light throughput.

4.5. DATA UNFOLDING ALGORITHMS

The electron density profile can be unfolded from the measured Li beam fluorescence profile by a number of techniques [*e.g.*, Schweinzer *et al.*, Plasma Phys. and Contr. Fusion 34 (1992) 1173 (1992]. Our work in this area has concentrated on the development of algorithms which have the potential to process large numbers of profiles quickly, as will be needed when we collect data on microsecond time scales, requiring the calculation of up to 100,000 profiles per shot. Since we are interested in fluctuations, such an algorithm must also explicitly include the effect on the fluorescence fluctuations at a given point of density fluctuations at all upstream points. This work is being done in cooperation with DIII–D since the results will be directly applicable to the analysis of data from both TEXT–U and DIII–D.

4.6. PROGRAM PLAN FOR BY3

The program plans are essentially unchanged from those in the original proposal, with a delay caused by the delay in the installation of the TEXT–U divertor coil. Our current schedule calls for making measurements with the full 20 detector channels and at 1 MHz sampling rates starting when TEXT–U resumes operation during the fall and winter of 1993. Measurements of radial electron density profiles and fluctuations will be made on the outer midplane. The goal will be to document changes in the profiles and fluctuations for various plasma conditions and at the L– to H–mode transition. These measurements will be compared with other fluctuation diagnostics on TEXT–U, and with Li beam results from DIII–D.

5. PLASMA ROTATION DRIVE

5.1. PROGRESS

A paper which describes a model for driven islands appeared in Physics of Fluids B [1]. Also a poster [2] on it was presented at the American Physical Society's Division of Plasma Physics Annual Meeting in Seattle in 1992. Another poster [3] was also presented at the same meeting; it describes "magnetic braking" experimental results for DIII–D and a comparison between experimental results and results from our model. Progress is made on writing a paper on this comparison. This work was delayed by unanticipated difficulties of describing simultaneous braking by more than one island surface; these difficulties are believed overcome by now. It appears that a large resistivity anomaly is needed to match experimental and model results.

Not funded by the Grant, but related to its subject, an effort was made to obtain funds for island drive experiments in the Caltech $m = 1$ tokamak under the "Innovations in Tokamak Improvement and New Confinement Systems" initiative. The effort failed, but encouraged by the reviewers' comments we have begun exploring the possibilities of a cooperation with Columbia University on the subject.

A cooperation is beginning now with Adil Hassam of the University of Maryland (presently at GA on sabbatical leave) and Omar Hurricane of UCLA (presently at GA as a summer student). The key tool for the planned work is the Maryland simulation code. The planned work centers around demonstrating that a special layer is formed at the surface of a driven island in the 2D approximation. In the limit of a small resistivity, pressure gradients in this special layer are expected to become large so that the 2D equilibria are unstable to symmetry braking instabilities. This may help to substantiate our view that the driven island problem inherently is a 3D problem of turbulence.

The key assumption of our model [1] can be used to investigate nonlinear stabilization of tearing modes of a plasma with a flow relative to a resistive wall; such an investigation is an extension of a previous model [4] for linear stabilization. A poster on this subject (in cooperation with M.S. Chu) is planned for the the 1993 Annual Meeting of the Division of Plasma Physics of the American Physical Society.

5.2. PROGRAM PLAN FOR BY3

Our first goal is to publish a paper comparing DIII–D magnetic braking experimental results with those of our model. We will also finalize plans for cooperation with Columbia University and prepare a proposal to DOE. We expect that the results of the simulation code work (with Hurricane and Hassam) will substantiate our belief that the driven island problem (in the interesting parameter regime) is inherently one of turbulence.

Because of the similarity between the driven island problem and the problem of tearing mode stability of a plasma with a flow relative to a resistive wall, work under the Grant will help understanding tearing mode stability. An effect, similar to that of a plasma with flow relative to a s resistive wall, occurs when toroidal coupling is included and a moderate shear in the flow exists; this effect is expected to make a plasma more stable toward tearing.

5.3. REFERENCES FOR SECTION 5

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6. PUBLICATIONS

6.1. THEORY PUBLICATIONS FUNDED BY DOE GRANT DE-FG03-92ER54150

Candy, J. (University of California, San Diego) and M.N. Rosenbluth (University of California, San Diego), *Nonideal Theory of Toroidal Alfvén Eigenmodes*, GA Report GA-A21190, submitted to Physics of Fluids B.

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Chan, V.S., L.L. Lao, and T.S. Taylor, *Confinement and Performance Limits for Advanced Tokamaks*, Bull. Am. Phys. Soc. **37** (1992) 1508 (Abstract).

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