Technical Progress Report

PLASMA CONFINEMENT THEORY AND TRANSPORT SIMULATION

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SUMMARY OF PROGRESS

The objectives are: (1) to advance the transport studies of tokamaks, including development and maintenance of the Magnetic Fusion Energy Database, and (2) to provide theoretical interpretation, modeling and equilibrium and stability studies for TEXT-Upgrade. Recent reports, publications, and conference presentations of the Fusion Research Center are listed on attached pages [1-45].

A. Magnetic Fusion Energy Database

The MFE profile database now contains almost 1000 discharges from 6 different tokamaks. In the current period, emphasis has been on the development of tools to access and manipulate the data [18,28,40,44]. The database has been moved to an IBM/RS6000 which allows the data to be accessed via an X-window application. There is also a batch-like procedure using *Netlib*-based software [28], which allows a user to mail an SQL query across the *Internet* and have the results mailed back to the user.

The most recent and powerful solution to the access problem is a new interface, MDI, which uses *Mathematica*® as a front end [18,44]. MDI is a *Mathematica* package that defines a basic set of MFE-database access functions. The package will also accept standard SQL queries. Each function returns *Mathematica*-style lists, which can then be manipulated with any of the *Mathematica* functions. MDI also provides utility functions for plotting and analyzing the data, essentially making the MFE database an extension of *Mathematica*. The user may use any of the many *Mathematica* front-ends including telnet, X-Windows, or a notebook. The MDI.m package may be obtained by anonymous FTP from the MFE-database site or by use of netmfe [28], an E-mail database interface. MDI has also been installed on a workstation at NERSC.

MDI is an example of distributed computing. Behind the user interface, MDI calls an RPC¹ client program that communicates with an RPC server on the MFE-database computer. It relies on the network-communication capabilities of *Mathematica* to connect the user to a workstation running the *Mathematica* kernel. The *Mathematica* kernel is then connected to the MFE-database host workstation by a client/server pair of RPC processes. If the *Mathematica* kernel is to be run on the user's machine, the RPC client program must also be obtained and installed. The MDI-RPC server is also available for users who would like to provide their own client software. The server returns ASCII tables from standard queries and may be accessed and processed by any program on the internet that has access to RPC services.

In order to make it easier for the various laboratories to contribute data, the MFE-database project has been willing to accept ASCII-coded data in almost any format. Reformatting this data for insertion into the MFE database has required writing a separate program to parse each type of file. For example, the output file from the OneTwo code consists of a header, several lines of comments, several NAMELISTs, diagnostic messages, several tables, and summary information. We are developing a tool kit which accepts, as input, descriptions of the OneTwo formats and builds a parser [40]. The parser can then operate on the OneTwo input files and directly enter the data into the database. This tool kit is being constructed using the tools *lex* and *yacc*.²

In the coming period we will focus our efforts on strengthening contacts with experimentalists on the various machines, obtaining additional data, and exploring statistical analysis methods.

¹John R. Corbin, "The Art of Distributed Applications", Springer-Verlag, New York, 1990.

²Tony Mason and Doug Brown, "lex & yacc", Dale Dougherty, ed., O'reilly & Associates, 1990.

B. Support for TEXT-Upgrade and Diagnostics

We have adapted an iron-core version of the equilibrium code EFIT^{3,4} to run on the IBM RS6000 [33]. It was decided to use only public-domain or very easily available software for mathematical subroutines and plotting packages. Preliminary studies, without plots, show that a typical case (only one time slice) can run in 10 to 20 seconds of CPU time on the RS6000, compared to 2 or 3 minutes on the VAX 8600. This could allow the use of EFIT for magnetic analysis in between shots.

We have designed and assembled an apparatus for the measurement of the magnetic-field profile on TEXT-U [19], utilizing successive charge-exchange collisions, as suggested by Valanju. Expected capabilities are 1 cm spatial resolution, 0.1° angular resolution of magnetic field direction and 1 ms time resolution. Tests of calibration and sensitivities are in progress. Additional theoretical work has led to a design for a multi-chord apparatus which can measure a q-profile in a single shot [8].

We have collaborated in a general review of TEXT fluctuation measurements and transport interpretation [13]. Work is continuing on possible attenuation effects in heavy-ion beam-probe fluctuation measurements for various plasma conditions on TEXT [21]. A simulation code was used to determine the attenuation effect on broad-band fluctuation amplitudes, coherence lengths, and wave numbers. Simulation results and experimental data were compared. The analysis is being extended to other plasma conditions such as modulated-ECH 'non-local' phenomena, sawteeth, and MHD. We also hope to have direct measurements of primary-beam attenuation effects from TEXT-U. For low density plasmas, attenuation effects do not seem to be a significant part of the measured fluctuation signals for any plasma condition other than MHD.

³L. L. Lao, H. St. John, and R. D. Stambaugh et al., Nucl. Fusion **25**, 1611 (1985)

⁴E. R. Solano, G. H. Neilson, and L. L. Lao, Nucl. Fusion **30** 1107 (1990).

C. Instabilities and Transport

1. Oscillating gas puff

A perturbation analysis has been developed which closely couples measurements of oscillating density, temperature, and fluctuation levels with a theoretical model in order to calculate perturbed particle fluxes [16,29]. Perturbation data on TEXT yielded a flux, calculated using a simplified dissipative-trapped-electron (*dte*) model, which did not agree with the directly measured flux. The lack of inward steady-state flux terms in the model may contribute substantially to this disagreement. We also investigated modulated gas puffing using the transport code CHAPO with generic anomalous models that retain the symmetry properties of the quasilinear transport matrix in ∇n and ∇T , but allow for various dependences on plasma parameters [30]. Comparing the amplitudes and phases of the experimental perturbed fluxes, densities, temperatures, etc., with those of the simulation, we attempted to determine the critical features of the model. In particular, in analogy with diffusion-convection models, we asked whether the off-diagonal coefficients must be negative. The results were ambiguous, however, owing to the uncertainty in the particle source in the plasma core at the low plasma densities considered.

Most recently, we have the analysis to higher density cases where the effect of the source is reduced [42]. First results, where we still employed the *dte* scaling, did not reproduce the measured profiles. Further study of the source question is needed.

2. Edge physics and L-H transition

In collaboration with TEXT experimentalists, with the IFS, and with General Atomics, we are pursuing a broad range of edge physics and H-mode studies.

We have calculated impurity flow velocities in the presence of collisionality and charge exchange [20]. We find that ions and impurities move together in the parallel direction. In the perpendicular direction, collisional friction is insufficient to damp their independent diamagnetic motions. The resulting poloidal impurity flow can be opposite to the ion diamagnetic flow. Poloidal and toroidal rotation rates of light impurities have been measured in TEXT using Doppler shift techniques and have been compared with this theory. Besides fueling a tokamak plasma, cold, stationary neutrals near the wall can cause drag on rotating ions via charge-exchange [37]. In addition, charge-exchange produces hot, penetrating neutrals that can enhance plasma viscosity and thermal conductivity, and can diminish ion diamagnetic drift [10]. A cold ion [6] population is also produced that causes further drag while being heated via Coulomb collisions with hot ions. We derive analytical expressions for the drag, viscosity, thermal conductivity and plasma rotation profiles by solving a four-population drift-kinetic model with physical boundary conditions at the wall. The resulting isotopic dependence of energy confinement and the effects of varying plasma profiles near the wall have been studied.

Particle, thermal, and impurity transport in high and low density He discharges were studied and compared with the transport in H and D discharges [31]. Profiles of T_e , T_i , n_e , v_ϕ , v_θ , and P_{rad} were measured along with the impurity confinement time and the particle source distribution. A 1-d transport simulation was used to infer local values for the transport coefficients. In some cases, $\tilde{n}_e$ and $\tilde{\phi}$ were available as HIBP or Langmuir probe

measurements. When combined with the transport results, these allow an examination of the importance of proposed turbulence drive mechanisms including ionization drive and radiation drive.

Traditionally neoclassical transport assumes a poloidally constant poloidal magnetic field. Near an X-point, however, the poloidal field is very small, so the field lines linger at that poloidal location. We have shown this to modify particle orbits, enhancing grad B drifts [43]. In particular, banana orbits that bounce near the X-point have "square tips", due to the grad B drift acting on the particle for a longer time. Computational and analytical calculations of particle orbits allow an evaluation of the importance of this effect (the drifts are proportional to $v_{thermal}$, so hotter ions are more strongly affected). Realistic poloidal fields are used to compute particle orbits. A study of changes in Pfirsch-Schlüter collisional transport due to the X-point has also been initiated.

Steady state solutions have been found for a set of equations describing the transport of particles and energy in a tokamak plasma [22]. A model of transport by turbulence is used in which the turbulence is assumed to be suppressed by shear in the equilibrium $E \times B$ flow. The equilibrium radial electric field which drives this flow is determined by radial ion pressure balance. An energy source is used which represents central heating by an unspecified mechanism. The particle source is given in terms of the neutral density which is calculated from a simplified neutral transport equation. The density and temperature profiles are of two types, depending on the particle and energy source strengths. For a fixed particle source strength, they are: (1) profiles with small gradients, when the heating power is below a threshold value, and (2) profiles with large gradients near the plasma edge, when the heating power is above this threshold value. The particle and energy confinement times, as functions of the heating power, are discontinuous at the power threshold, suggesting comparisons with experimental results for the L- to H-mode transition. The time dependent behavior of the same proposed transport model exhibits confinement bifurcation [35]. The bifurcation is due to the nonlinear nature of the proposed transport coefficients. Here, the equations are extended into the time domain, and numerical solutions are presented which illustrate the nonlinear behavior.

Effects of ionization on the linear drift wave instability is generally complicated, because the equilibrium assumed in a generic slab model (the spatial variation of the plasma density only in the radial direction, and zero radial particle flow) cannot be achieved owing to the presence of ionization [12,36]. We have considered several equilibrium models, including a quasi-equilibrium state, wherein the bulk plasma density evolves slowly compared to the characteristic time scale of the mode frequencies. In this case an analytical solution is obtained for the collisionless drift wave; the contribution from ionization to the temporal evolution of the spatial eigenmode is algebraic rather than exponential.

3. Other transport studies

We have collaborated with the IFS in ion-temperature-gradient mode simulation studies that compare transport predictions with experiment [14]. This has proved to be a useful application of the MFE database.

In addition, we are beginning to benefit from work carried out in the former Soviet Union and continued at FRC. This includes, first, a new transport mechanism appearing specifically under cyclotron wave heating of plasma in toroidal devices [41]. This mechanism

can explain the deterioration of particle confinement in the resonant zone and other experimentally observed phenomena that accompany electron cyclotron heating. The driving force for the new transport process is the poloidally asymmetric electrostatic potential. This potential arises due to the enrichment of the population of suprathermal banana electrons bouncing at the resonance position.

Secondly, a new approach to plasma transport is described where the toroidal drift is considered as a perturbation to the motion of particles in electromagnetic oscillations, $u_d \ll \tilde{v}$ [45]. From the analysis of particle trajectories it is shown that there is a small group of particles that move in the direction of the toroidal drift, even if $u_d \ll \tilde{v}$. This small group of particles also plays a major role in anomalous transport processes. Percolation theory is used to determine the scaling of the diffusion coefficient, D , which is larger than the neoclassical plateau coefficient, D^{pl} , in both banana and plateau regimes: $D \sim D^{pl}(\tilde{v}/u_d)^{4/7} \gg D^{pl}$. Numerical simulation results support the theoretical scaling arguments.

E. Alfvén Waves

We have investigated heating of tokamak plasmas by toroidal Alfvén eigenmodes and toroidicity-modified global Alfvén eigenmodes [25,39]. In tokamak plasmas, the Alfvén wave spectrum is strongly affected by the variation of the equilibrium magnetic field along the major radius, giving rise, for example, to the toroidal Alfvén eigenmodes (or gap modes). These modes may be viewed as resulting from the coupling of cylindrical poloidal harmonics. We have modified a previously constructed antenna-driven cylindrical code,⁵ which takes into account electron inertia and Landau damping and finite ion Larmor radius, to study this numerically. Assuming realistic profiles, we have investigated the toroidicity-induced Alfvén eigenmodes as well as the effects of toroidicity on the cylindrical global eigenmodes. These are identified as resonances in the impedance $Z(\omega)$. We plot the wave electric field, energy deposition, energy flow, and current drive as functions of minor radius.

⁵D. W. Ross, G. L. Chen, and S. M. Mahajan, Phys. Fluids **25**, 652 (1982).

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Names underlined are those supported by the contract.

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