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**PLASMA CONFINEMENT THEORY AND
TRANSPORT SIMULATION**

Final Report

October 1, 1988 - October 31, 1994

David W. Ross

Fusion Research Center

The University of Texas at Austin, Austin, Texas 78712

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The objectives of the Fusion Research Center Theory Program 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 the TEXT-Upgrade tokamak. Publications and reports [1-33] and conference presentations [34-106] for the grant period are listed on attached pages 20-27. Work is described in five basic categories:

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A. Magnetic Fusion Energy Database

We have established a profile-oriented Magnetic Fusion Energy Database (MFEDB) for storing analyzed experimental data and transport-analysis results from toroidal magnetic confinement devices around the world. For the first time, a common set of experimental data sets, with which theoretical models can be compared, is available to the entire magnetic fusion energy community. The fundamental purpose for this database is to provide with complete sets of experimental data from a variety of machines and discharge conditions in order to form a strong physics foundation for ITER.

Work on the MFEDB continued during the current grant period. A new commercial relational database management system (RDBMS) was installed in a modern workstation

environment running the UNIX operating system. We wrote programs for reading data sets from several new machines such as JT-60 and DIII-D, made slight modifications at the request of users, and created new interfaces to the database that allowed easier access to the data. At least two papers were published that referred to data taken from the MFEDB (Barbato, Briguglio *et al.*, 1991; Turner, Allen *et al.*, 1992).

Within the last six months, four events have led to an increased interest in the database. First, members of the H-Mode Working Group, who assembled the Global Energy Confinement H-Mode Database for ITER (Christiansen, Cordey *et al.*, 1992) have decided to assemble a profile database. They have requested that the MFEDB be used as the central storage facility. Secondly, the ITER Central Team wishes to apply the Rebut-Lallia-Watkins empirical transport model (Rebut, Watkins *et al.*, 1991) to other machines in order to corroborate those results and extrapolate them to ITER. Thirdly, the complex geometry of the divertor throat has led ITER scientists to recognize the need for an Edge Database for probe data taken in this region of the discharge. Finally, the participants in the Numerical Tokamak Project (NTP) have recognized the need to compare their numerical simulation results with experimental data.

The basic schema of the MFEDB was derived from the one we developed for the TEXT database. It has proved sufficiently robust that only minor modifications have been required since its inception. This robustness has allowed us to include the ITER Edge Database within the MFEDB as if it were actually a separate database. We can maintain both databases without duplication of administrative effort and software costs (Miner, Tsui *et al.*, 1993). There are currently 924 representative shots in the ITER Profile Database section from nine tokamaks (Table I) and 35 representative shots from five tokamaks in the ITER Edge Database (Table II).

MACHINE	COUNT (MACHINE)
ASDEX	2
DIII-D	8
JET	5
JT-60	55
PDX	320
PLT	333
T-10	29
TEXT	18
TFTR	224
	924

Table I The current contents of the MFEDB profile data.

MACHINE	COUNT (MACHINE)
PHAEDRUS	4
TDEV	3
TEXT	28
TEXT-U	1
TFTR	<u>1</u>
	35

Table II The current contents of the MFEDB edge data.

We have, as a matter of policy, accepted data in any format, usually the one commonly used at the laboratory where the data was taken. Such formats are generally different at each site and are sometimes quite elaborate. We have written at least eight codes to import data. Five of these are still in use; the others were for one-time use only. We currently support input from the PPPL SNAP archive, TRANSP output, ONETWO output, the TEXT database, and data in spreadsheet format.

There are three interfaces actively supporting the database. The first is a tool supplied by the commercial database vendor, the SQLPlus program, which supports direct Structured Query Language (SQL) queries. This program can be accessed via a Telnet connection (over the Internet) to the local host. The user must acquire an account on the local host and become a registered user of the database. More elaborate programs are available from the vendor which would enhance the user's ability to browse and retrieve data. These are not currently available because of their cost.

The most elementary but probably the most widely available interface is communication via electronic mail. We have installed the netlib package (Dongarra and Grosse, 1985) and implemented several queries for which the user simply fills in the necessary blanks to retrieve data (Miner, McCann *et al.*, 1991). Messages are sent to netmfedb@hagar.ph.utexas.edu.

Perhaps the most useful interface to the MFEDB is the Mathematica Database Interface (MDI) (Wiley, Miner *et al.*, 1992 (unpublished)). This interface uses client-server technology which allows a Mathematica (Wolfram Research, 1993) client on a remote host to communicate with a server on a machine at the Fusion Research Center (FRC), which in turn communicates with the MFEDB. A remote host running Mathematica can access the data over the Internet, making it appear as if the data were local. The Mathematica interface is part of a more general remote procedure call (RPC) client-server

application (Wiley, Miner *et al.*, 1992). New interfaces can be added by modifying the client end of the application, while leaving the server unchanged. We have demonstrated this technology on remote hosts at NERSC and at JAERI in Japan. This interface allows the user to query the database, retrieve data, and then analyze and visualize it using the powerful tools built into Mathematica. We have also written several Mathematica packages for data analysis.

B. Computational Support and Numerical Modeling

1. Transport modeling

During the current grant period a number of transport-related numerical projects were advanced. In the past, considerable effort was expended on the one-dimensional transport code CHAPO, which has been used by both the theoretical and experimental groups to explore connections between TEXT results and various models and theories. Lately, we have reduced active development and maintenance of this code. One significant modification was the porting of the code from the NERSC Cray's to our local RS/6000 workstation. This made running the code significantly easier and less expensive. CHAPO continues to be used by experimentalists and ourselves for various studies. For example the work on modeling gas puffing made use of the code (Ross, Richards *et al.*, 1992; Ross, Richards *et al.*, 1993). See further description in Sec. D.

We have begun looking at new computational technologies to solve the types of problems that the new modes of operation of tokamaks are making interesting. For example, a simple one-dimensional transport code was developed using object oriented programming (OOP). This C++ code was developed to study the time dependent H-mode model proposed by Hinton (Hinton, 1991; Wiley and Hinton, 1991). This code was given to General Atomics (GA) and has been used to study the H and VH transitions on DIII-D [Staebler, 1993 #527; Staebler, 1993 #419]. See further description in Sec. D.

2. Neutral modeling

We developed a fast 3-D neutral transport code (NUT) (Valanju, 1990) based on the observation that the neutral transport problem can be solved analytically on scale lengths over which plasma variation is small. This allowed us to use rather coarse grids to get accurate answers. The resulting code was much faster than its Monte Carlo counterparts. The current version of NUT can be used to model the neutral penetration profile in TEXT-

U in order to find whether the neutrals penetrate significantly beyond the X-point. We have begun this in collaboration with H_{α} measurements on TEXT-U. The answer to this question is important for the open divertor of TEXT-U, where the X-point is near the inner strike plate. Preliminary investigations suggest that one could control the source (with ECH, for example) to vary from the case where the neutral fueling is inside the separatrix to where it is mostly outside. NUT has also been used in other machines such as TFTR to simulate beam halo effects for use in charge exchange recombination spectroscopy (CXRS). We are currently continuing to help the TFTR group in a similar calculation (Stratton, Fonck *et al.*, 1990).

3. Database interfaces

Much of the numerical effort over the current grant period has been devoted to development of interfaces for the MFEDB database as described earlier in Sec. A.

4. Alfvén code

During this period we have also made significant numerical modifications to the Alfvén code which has been used for many years (see Sec. E). This changes included a new spline package and a reorganization of the code to simplify modification [Li, 1992 #455; Chu, 1992 #333]. This code has also recently been transferred to GA.

5. Other computational support

Software support for the new IBM RS/6000 UNIX workstation cluster has been provided throughout the current period.

As part of the support for TEXT we have supplied a Macintosh network interface library, which was used to build a Macintosh RPC library. This coupled with an RPC TEXT archive service allows several software packages running on any computer to have interfaces to the TEXT archive. This is a major step in archive access since previously the TEXT archive was only available on a VAX. This forced most experimentalists to write analysis codes only on that VAX, preventing them from making effective use of the UNIX workstation cluster. With the RPC service, these codes can now be written on any of our systems. One of the first uses of this technology has been the equilibrium code, EFIT, which can run on one of our workstations while obtaining TEXT archive data from the VAX cluster. This is discussed more fully in Sec. C, below.

Finally, parallel computing on a Transputer array was continued with the development of a UNIX Device Driver for a Translink II Transputer Board (Wiley, 1991). This allows a transputer array to be used with the A/UX operating system.

C. Support for TEXT-Upgrade and Diagnostics

1. Equilibrium and position control in TEXT-U

TEXT-U can generate non-circular limited or diverted plasmas (Edmonds, Solano *et al.*, 1989). For diagnostic interpretation it becomes imperative to reconstruct the plasma flux surfaces accurately. We chose the fitting and equilibrium code EFIT (Lao, St. John *et al.*, 1985) and adapted it to include the effect of the TEXT iron core (Solano, Lao *et al.*, 1990). That work led to a collaboration with General Atomics (GA) and the Joint European Tokamak (JET) to adapt EFIT to the JET iron core (O'Brien, Lao *et al.*, 1992). We have written new subroutines (Solano and St. John, 1993), which are now in wide use, to make the code completely portable and to allow its transfer to fast workstations, where it can run in about 15 seconds. A portable subroutine library has been developed to allow access to the TEXT archive and database (resident on a slow VAX) from the UNIX workstation.

A set of magnetic probes will be used for plasma shape reconstruction in TEXT-Upgrade. We have started a study to determine the minimum number of coils necessary to achieve acceptable magnetic reconstruction (Xu, Solano *et al.*, 1992) using EFIT. The optimum placement of the probes is being investigated, taking into account the variety of plasma shapes to be produced and the effect of measurement errors. Another application of EFIT has been to assist the study of magnetic structure with the HIBP (Schwelberger, Crowley *et al.*, 1993)

Plasma position stability in TEXT-U depends on a number of effects. Active feedback stabilization of the plasma position is necessary, because these combine to produce unstable plasmas. Each has been modeled with different assumptions, and the most pessimistic ones were combined to guide the design of a digital feedback system. First, we have studied the destabilizing effect of the iron core theoretically with a 2-D model (Solano, Lao *et al.*, 1990). Initial experiments support the model: a circular plasma is both up-down and in-out unstable. In the model, the height of the core is a free parameter, adjusted to match experimental measurements of poloidal fields. Second, a geometrical constraint may dominate flux conservation in computing in-out stability, particularly in an iron core tokamak (Solano, 1990). If this is so, the plasma would be stable if the last closed flux

surface is determined by an inside limiter or X-point, and unstable for an outside limiter or X-point. Third, the vacuum vessel acts as a passive stabilizer and also delays penetration of the external control fields. Two extreme 2-D models of the vessel have been considered (Sloan, 1990): a solid vessel with no holes, and a vessel with continuous toroidal slits at the poloidal port locations. Work is in progress, in close collaboration with TEXT position measurements, to combine these into a realistic model of position stability and control (Craig, Phillips *et al.*, 1993; Solano, Uglum *et al.*, 1993).

2. Magnetic profile diagnostic using neutral beam

We have invented (Valanju, Bengtson *et al.*, 1990) a new, direct way of measuring the B_p profile in a tokamak by using a diagnostic neutral beam (DNB) to inject (via charge exchange and ionization) high energy ions transverse to the total magnetic field. TEXT has just such a vertical DNB. The beam energy ions thus injected are ripple-trapped in orbits with very small parallel speed, $V_{||} \approx 0$. While drifting upward, many of them still stay in the beam column and are re-neutralized by charge exchange with the many beam neutrals. These beam neutrals come out of the plasma in a plane at right angles to the local magnetic field. The pitch angle of the field can be found directly by detecting the angular location of the maximum signal of these neutrals at beam energy. The signal is very clean, and the angular resolution is also very high (< 0.1 deg). This singular $V_{||} = 0$ location in phase space protects this method from any disturbing plasma effects.

Our invention of this method has led to a very active and close collaboration between TEXT and FRC Theory. We have designed, built, tested, and successfully installed a scannable single-chord detector on TEXT-Upgrade. The magnitude of the signal is large enough to get better than 1 ms time and 1 cm spatial resolution (Duraiappah, Bengtson *et al.*, 1993).

One limitation of the existing detector is that it is single-chord; to get a profile, one needs many shots. After building this detector, we discovered (Valanju, 1991) that a simple modification can convert it into a multi-chord instrument capable of producing full radial pitch angle profiles in one shot in real time. Such an instrument would be valuable in any active current-profile control scheme.

3. Interpretation of fluctuation diagnostics

We have collaborated in general reviews of TEXT fluctuation measurements and transport interpretation (Bravenec, Ross *et al.*, 1991; Ross, Bravenec *et al.*, 1991; Bravenec, Gentle

et al., 1992). Following initial studies of the drift-wave interpretation of the Heavy-Ion Beam Probe results, including the effects of finite sample volume (Ross, Schoch *et al.*, 1991), we investigated possible attenuation effects in heavy-ion beam-probe fluctuation measurements for various plasma conditions on TEXT (Ross, Sloan *et al.*, 1992). A simulation code was used to determine the attenuation effect on broad-band fluctuation amplitudes, coherence lengths, and wave numbers (Heard, Crowley *et al.*, 1992). Simulation results and experimental data were compared. For low density plasmas, attenuation effects do not seem to be a significant part of the measured fluctuation signals. Experiments are underway to test this prediction by measuring fluctuations of the primary beam directly (Ouroua, Crowley *et al.*, 1993). These effects decrease with increasing beam energy and should be negligible in measurements carried out by the new 2 MeV beam now being installed on TEXT.

4. TEXT impurity rotation and transport

Extensive measurements of impurity rotation in TEXT were reported for Ohmic plasmas (Meigs, Rowan *et al.*, 1992). Comparison with simple neoclassical theory suggests that rotation can be predicted (Hazeltine, 1974). Comparisons of rotation velocities of different impurities (C^{+4} , O^{+4} , He^{+1}) were made. With this work as background we have attempted to understand perturbations of rotation by EML, ECH and biased electrode. We have also collaborated in a general review of rotation in Ohmic plasmas (Rowan, Meigs *et al.*, 1993). Collaboration has continued, for example, on impurity flow during electrode biasing (Meigs, Rowan *et al.*, 1993). The theoretical aspects of this work are described more fully in Sec. D1.

We have derived closed-form Green's functions for convective-diffusive systems in cylindrical geometries. These solutions can be used to model a variety of time-dependent transport experiments, such as pulsed impurity transport, oscillating gas puff, perturbative rf heating, and sawtooth heat pulse propagation. We have presented successful comparison of the derived profiles with pulsed impurity-injection experiments on TEXT (Mahajan, Valanju *et al.*, 1992).

D. Transport Studies

1. Edge physics and L-H transition

In collaboration with TEXT and the IFS, we have pursued a broad range of edge physics and H-mode studies, many of which are related to the experiments described above.

We have developed a kinetic theory of the neutral distribution function, including charge-exchange (CX) and ionization, in the long CX mean-free-path (mfp) limit. This theory was used to calculate the contribution of CX to the plasma viscosity and toroidal acceleration (Ware, Hazeltine *et al.*, 1991; Hazeltine, Calvin *et al.*, 1992). We analytically calculated the toroidal acceleration in a tokamak plasma which has been biased by a radial probe, as in TEXT experiments. The toroidal acceleration is found to be affected by: (i) viscosity, (ii) space-charge, (iii) current in metallic conductors, and (iv) changes in total enclosed charge. The contribution of CX viscosity in the long mfp limit is the dominant feature in determining toroidal acceleration.

The study of transport near a separatrix has become very important now that many tokamaks are diverted. We studied this problem inside the last closed flux surface [Solano, 1993 #403]. Near an X-point of the confining field of a diverted plasma, the poloidal field is small, causing guiding centers to linger at that poloidal position. Indeed, the poloidal transit frequency approaches zero near the separatrix, so that the collisionality ν^* becomes locally large for any plasma temperature. We solved the drift kinetic equation in the plateau regime for a general flux surface configuration. As an example, a model poloidal flux function with an X-point was used to show that the plateau particle and thermal diffusion coefficients can change considerably (a factor of 2 higher). When correctly interpreted, ion rotation is rather unaffected by the X-point: it is locally proportional to the poloidal magnetic field; hence, it is small near the X-point.

Recent DIII-D and TEXT experiments show a sudden increase in plasma poloidal rotation as a signature of L to H transition. We have emphasized that shear in the radial electric field near the plasma edge indicates a non-neutral space charge distribution (Xiao, Hazeltine *et al.*, 1993). For such space charge a natural source is the "halo" effect: the relatively large ion (poloidal) gyroradius precludes perfect tracking between n_i and n_e . We built a simple model, including the halo, to find the relation between plasma poloidal flow and radial electric field. The resulting integro-differential equation shows that a Maxwell-Boltzmann

electron distribution (no flow) does not allow space charge. Only in the presence of a sheared velocity can space charge develop.

2. Instabilities and anomalous transport

Interpretation of fluctuation measurements in terms of turbulence theory has proved to be extraordinarily difficult. Not only do the diagnostics themselves have intrinsic limitations, as noted above, but the theories are not well-enough developed to be distinguishable one from another in the experimental context. Observed spectra tend to have similar phase velocities (drift-wave like), and similar frequency and wave number spreads. The HIBP, however, does find a mode in the electron diamagnetic direction that is much too fast to be a drift wave (Ross, Bravenec *et al.*, 1991). As noted in Sec. C3., we have investigated experimental artifacts which might account for this, but so far the mode remains unidentified.

An important question is by what mechanism or mechanisms is the turbulence driven? An important feature of the broad-band turbulence is the strong rise of the fluctuation level toward the plasma edge. This suggests that a strong role might be played by neutrals and impurities, but we have found that current theories of turbulence driven by ionization or radiation are inadequate [Ross, 1993 #405; Ross, 1993 #483] and these sources need to be re-examined. The modes in question cannot, by themselves, account for the steady-state transport.

In the core, on the other hand, the dissipative trapped electron instability (DTE) is the main driving mechanism that has been investigated. A quasilinear model of this mode yields modest agreement with steady-state transport (Bravenec, Ross *et al.*, 1991; Bravenec, Gentle *et al.*, 1992), but fails to describe a perturbation experiment, the oscillating gas puff (OGP) (Richards, Austin *et al.*, 1992).

Perturbation experiments, such as the OGP and modulated ECH, provide us with a great amount of detailed information about plasma transport. The amplitude and phase of the oscillating components of density, temperature, *etc.*, greatly constrain the acceptable theories. For example, in a simple diffusion-convection (D-V) model, we know that inward flux terms are required to match the OGP data (Gentle, Richards *et al.*, 1992). Using CHAPO, we have carried out one-dimensional transport simulations of such experiments in an attempt to develop a non-diagonal model of the transport coefficients based, at least in part, on turbulence theory. The quasi-linear DTE theory mentioned earlier includes off-

diagonal terms, *e.g.*, temperature-gradient driven terms in the particle flux, but they are all in the outward direction. Therefore, the failure of this theory to fit the OGP data (Richards, Austin *et al.*, 1992) should not be surprising. We have continued these transport simulations (Ross, Richards *et al.*, 1992; Ross, Richards *et al.*, 1993), using scalings corresponding to trapped-particle mode theory, but with *ad hoc* changes of the sign of the off-diagonal coefficients. Because of nonlinear functional dependences on plasma parameters, the amplitude and phase of the perturbed density are quite different from those of a simple D-V model and tend to be insensitive to variations in numerical factors in the transport coefficients. The amplitudes and phases in the simulation results seem to disagree with the data in contradictory ways, particularly at higher density. Work continued with a variety of models to attempt to resolve the discrepancies and fit the data. Even with heuristic modifications to include scalings other than DTE, however, we have as yet been unable to fit the full OGP data set. There is clearly something important missing in the available theories.

In the H-mode, it is expected that the derivative of the radial electric field will play an important, possibly decisive, role in suppressing the turbulence, and thereby improving the containment. A number of theories and numerical calculations have exploited this idea, known as shear flow stabilization. We have collaborated in work showing that heuristic models of these can lead to bifurcations occurring in numerical transport simulations. This has been studied using the code HMODE, as described earlier in Section C. First, steady state solutions were found for a set of equations describing the transport of particles and energy in a tokamak plasma (Hinton, 1991; Hinton and Wiley, 1991). A model of transport by turbulence was 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. The density and temperature profiles are of two types: (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 [Wiley, 1991 #507; Staebler, 1993 #527; Staebler, 1993 #419]. The bifurcation is due to the nonlinear nature of the proposed transport coefficients.

3. Other transport studies – collaborations

Theoretical studies on the edge-plasma turbulence in TEXT were conducted in collaboration with the IFS (Zhang and Mahajan, 1992). Effects of ionization on the linear drift-wave instability is complicated, because the equilibrium assumed in a generic slab model cannot be achieved owing to the presence of ionization (see also [Ross, 1993 #405] and Sec. 2, above). We considered a quasi-equilibrium state, wherein the bulk plasma density evolves slowly compared to the characteristic time scale of the modes, and obtained an analytical solution for the collisionless drift wave. The contribution from ionization to the temporal evolution of the spatial eigenmode is algebraic rather than exponential. We also included the effects of the thermal-rippling drive, impurity condensation, and charge exchange in the eigenmode analysis.

We have shown that there are stringent limitations on the use of the usual ballooning representation to describe two-dimensional eigenvalue problems (Zhang and Mahajan, 1991). As a result, the stability predictions of the ballooning equation must be accepted with caution. One example is the drift wave driven by electron dissipation, which can acquire a global structure, in contrast to the local ballooning structure. We developed an analytical-numerical hybrid approach to study the original 2-D eigenvalue equation for the high n drift wave.

We have developed an approach to turbulent diffusion in tokamaks where the toroidal drift is considered as a perturbation to the particle motion in electromagnetic fluctuations. The analysis of the simplest single-scale case (Yushmanov, 1992), when the width of the neoclassical trajectory, D , was equal to the characteristic perpendicular scale of electromagnetic oscillations, L , was later extended to an arbitrary ratio of D/L (Smolyakov and Yushmanov, 1993). The diffusion mechanism can substantially differ from that of the single scale case. We showed that the neoclassical diffusion coefficient in a turbulent plasma generally determined by the scale length of the fluctuations, L .

We assisted in the investigation of the electrostatic wake of a superthermal test electron in a magnetized plasma (Ware and Wiley, 1993). The potential is determined for a test electron with $v_{||} \gg v_{Te}$ in a uniform magnetized plasma ($\omega_{ce} \gg \omega_{pe}$). In the frame of the test electron, part of the spatially oscillatory potential has spherical symmetry to the rear of the electron and is zero ahead of the electron. A second part, which makes the potential continuous at the plane containing the electron, is oscillatory radially but decreases almost monotonically in the axial direction.

E. Alfvén Waves

The FRC program of Alfvén wave studies, which is of long duration, has wound down during the current grant period. A small effort, using the toroidal code described below, will continue in the IFS. We have also delivered the code to researchers at General Atomics and the University of Wisconsin for their use.

We investigated the numerical calculation of toroidal Alfvén eigenmodes (TAEs) and toroidicity-modified global Alfvén eigenmodes (Li, Mahajan *et al.*, 1991; Li, Mahajan *et al.*, 1992) in tokamak plasmas. These modes may be viewed as resulting from the coupling of cylindrical poloidal harmonics. We modified a previously constructed antenna-driven cylindrical code (Ross, Chen *et al.*, 1982), which takes into account electron inertia and Landau damping and finite ion Larmor radius. Assuming realistic profiles, we investigated the TAEs as well as the effects of toroidicity on the cylindrical global eigenmodes (GAEs). We identified these as resonances in the impedance $Z(\omega)$ and plotted the wave electric field, energy deposition and energy flow as functions of minor radius.

We have recently rewritten the code to make use of improved numerical methods and to include coupling to more than three poloidal harmonics [Chu, 1992 #333; Li, 1992 #455] and a new effective kinetic resistivity model (Mett and Mahajan, 1992). Mode structure, energy deposition profiles, and damping rates were investigated as functions of this model. We compared results with analytical calculations (Mett and Mahajan, 1992),* and, in collaboration with General Atomics [Chu, 1992 #333], began the comparison with non-ideal MHD calculations.

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