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THEORY-BASED TRANSPORT SIMULATIONS
OF TFTR L-MODE TEMPERATURE PROFILES

BY

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Theory-Based Transport Simulations of TFTR L-mode Temperature Profiles

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Abstract

The temperature profiles from a selection of TFTR¹ L-mode discharges² are simulated with the 1-1/2-D BALDUR transport code^{3,4} using a combination of theoretically derived transport models, called the Multi-Mode Model.⁵⁻⁹ The present version of the Multi-Mode Model consists of effective thermal diffusivities resulting from trapped electron modes and ion temperature gradient (η_i) modes, which dominate in the core of the plasma, together with resistive ballooning modes, which dominate in the periphery. Within the context of this transport model and the TFTR simulations reported here, the scaling of confinement with heating power comes from the temperature dependence of the η_i and trapped electron modes, while the scaling with current comes mostly from resistive ballooning modes.

I. Introduction

There is a significant demand for predictive transport simulations of tokamak experiments and projections to future tokamak reactors.^{10,11} Predictive transport simulations require a complete transport model for the flow of heat, charged particles, and magnetic flux, from the center to the edge of the plasma. For this purpose, it would be highly desirable to have a theoretically derived transport model expressed as functions of the local thermodynamic variables and valid over a wide range of plasma parameters. Predictive transport simulations could then be carried out with computer codes such as BALDUR,^{3,4} in which the transport is placed in the context of the computed source and sink terms (for heat, charged particles, and magnetic flux) as well as the effects of large scale instabilities such as sawtooth oscillations, ballooning modes, and tearing modes. It would be most desirable if one combination of theory-based models could be made to simulate a wide variety of tokamak operating conditions — Ohmic, density saturated Ohmic, L-mode, supershots, pellet injected plasmas, H-modes, and various transient conditions.

The Multi-Mode Model of transport⁵⁻⁹ is a combination of theoretically derived transport models designed to approximate the thermal and charged particle transport from the center to the edge of the plasma. In the present version of this model, transport due to trapped electron modes and ion-temperature-gradient driven (η_i) modes dominates in the core of the plasma, while transport due to resistive ballooning modes dominates near the edge of the plasma. The resulting effective thermal diffusivity increases nearly monotonically from the core of the plasma to the edge for L-mode simulations.

Version 5.10 of the Multi-Mode Model is used in this paper. The trapped electron mode contribution is based on the model used by Dominguez and Waltz¹² with modifications suggested by Rewoldt, Tang, et al.^{13,14} The Hamaguchi and Horton theory¹⁵ is used for the ion temperature gradient driven turbulence (η_i) contribution. A modification of the Carreras and Diamond model is used for the resistive ballooning mode.^{16,17} This combination was chosen as the best and most completely developed set of theoretically derived transport models available at the time this research was carried out. The coefficients and thresholds for these models were adjusted to match the

experimental data and were then held fixed for a consistent set of simulations.

The success of the Multi-Mode Model depends sensitively on the density profile, since the density gradient appears in each of the contributions to the model. While there has been some success with using the Multi-Mode Model to simulate particle as well as thermal transport in strongly beam fuelled plasmas,^{6,8,9} the resulting density profiles are not as smooth as the experimentally measured profiles and these lumpy density profiles have unpredictable and sometimes adverse effects on the computed thermal diffusivities. Consequently, the simulations in this report were carried out using an empirical particle transport model in which feedback loops were used to adjust the magnitude and width of the electron density profile in order to match the experimentally measured profile. The Multi-Mode Model was then used to compute only the electron and ion thermal transport in order to predict the temperature profiles for these discharges.

The Multi-Mode Model is implemented in the BALDUR transport code^{3,4} in the form of a subroutine which is thoroughly documented using $\text{\LaTeX}$.¹⁸ It is available for use in other transport codes. In addition to trapped electron, η_i , and resistive ballooning modes, there are a variety of other options to include additional transport from rippling modes, high-frequency (η_e) modes, and kinetic ballooning modes. There are also provisions to include trapped ion modes and other models in the future. Options for the detailed implementation of each model, such as the choice of the threshold function for the η_i mode, can all be controlled by input data.

A detailed description of the transport model and the choices made for modelling sawtooth oscillations, boundary conditions, etc., will be given in Section II. The simulations of TFTR L-mode shots will be described in Section III with particular emphasis on the scaling of confinement with heating power and plasma current. Some newly developed numerical techniques, which are needed to produce relatively smooth results given a thermal diffusivity that turns on sharply when the temperature gradient exceeds a given threshold, are presented in the Appendix.

II. Transport Models Used

A. Trapped Electron Modes

The effective thermal diffusivities for the collisionless and dissipative trapped electron modes are similar to the forms used by Dominguez and Waltz¹²

$$\chi_{e,i}^{DR} = 8.33 F_{e,i}^{DR} F_{\beta} \left(\frac{r}{R} \right)^{1/2} \frac{\rho_s^2 c_s}{L_{ni}} \left[1.; \frac{0.1}{\nu_e^*} \right]_{\min}. \quad (1)$$

Here, $F_{e,i}^{DR}$ are adjustable coefficients given in section II.D below. The factor F_{β} is a finite beta correction with a form suggested by the simulations of Rewoldt, Tang, and Hastie¹³

$$F_{\beta} = \frac{1 + \beta'/\beta'_c}{1 + (\beta'/\beta'_c)^3}$$

where $\beta' = \partial\beta/\partial r$ and $\beta'_c = \hat{s}/(1.7q^2R)$. The function F_{β} starts at unity for small β' , then rises to a maximum value of 1.35 before asymptotically approaching zero at large β' . The rest of the notation is described in Tables 1 and 2.

For the transition between dissipative and collisionless trapped electron modes, we have used the form $[1.; 0.1/\nu_e^*]_{\min}$ suggested by reference 14 rather than the form $[1.; \omega_*/\nu_{eff}]_{\min}$ used by Dominguez and Waltz.

The trapped electron effective thermal diffusivities scale like:

$$\chi_{e,i}^{DR} \sim T_e^{3/2} \left(\frac{r}{R} \right)^{1/2} \left| \frac{1}{n} \frac{dn}{dr} \right| \frac{M^{1/2}}{B^2} \left[1.; \frac{\text{Const. } T_e^2}{nqRZ} \left(\frac{r}{R} \right)^{3/2} \right]_{\min}. \quad (2)$$

This scales like $r^3 T_e^{7/2}$ near the magnetic axis and $R^2 T_e^{7/2}/(nqL_n)$ near the edge of the plasma. Hence, these modes dominate deep in the core of the plasma but away from the magnetic axis.

B. Ion Temperature Gradient (η_i) Mode

Expressions based on the Hamaguchi-Horton¹⁵ theory of transport driven by ion temperature gradient (η_i) modes are used:

$$D_{\eta_i} = \frac{\rho_s^2 c_s}{L_n} \max(\eta_i - \eta_i^{th}, 0) \exp[-\min(5L_n, 4L_T)/L_s] \quad (3)$$

$$\chi_i^{IG} = F_i^{IG} D_{\eta_i} \quad (4)$$

$$\chi_e^{IG} = F_e^{IG} D_{\eta_i}. \quad (5)$$

Since the hydrogenic ion density profile is not known accurately while the electron density profile is measured accurately, the value of $\eta_i = \partial \ln T_i / \partial \ln n$ is computed here using the electron density n_e .

The threshold function

$$\eta_i^{th} = \max(1, 5L_n/R) \quad (6)$$

approximates the form derived by Dominguez and Rosenbluth.¹⁹

Since η_i typically drops below the threshold near the center of the plasma and rises to large values well above the threshold near the edge of the plasma, the effective thermal diffusivities from the η_i modes typically rise to their maximum value about two thirds of the way from the center of the plasma, and then, because of the strong temperature dependence, fall to small values near the edge. Hence, the η_i mode transport typically fills in between the trapped electron modes in the core of the plasma and the resistive ballooning modes at the edge.

C. Resistive Ballooning Mode

A modified form of the Carreras-Diamond theory is used for the transport due to resistive ballooning modes.^{16,17}

$$\begin{aligned} D^{RB} &= f_{dia} \Lambda^2 \frac{\beta R q^2}{\sqrt{2} L_p \hat{s} \tau_R} \sim \frac{d(nT)}{dr} \frac{R q^2 Z_{eff} \Lambda^2}{T_e^{3/2} B^2 \hat{s}} \\ \chi_e^{RB} &= F_{e1}^{RB} f_{dia} \frac{\Lambda^{4/3}}{2^{13/6}} \left(\frac{\tau_{hp}}{\langle n \rangle \tau_R} \right)^{2/3} \left(\frac{\beta R q^2}{L_p} \right)^{4/3} \frac{v_{the} r^2}{\hat{s} R} + F_{e2}^{RB} D^{RB} \\ &\sim \frac{n_e^{1/3} [d(nT)/dr]^{4/3} r^{2/3} R q^{8/3}}{T_e^{1/2} B^{10/3} \hat{s}} + F_{e2}^{RB} D^{RB} \\ \chi_i^{RB} &= F_i^{RB} D^{RB} \end{aligned}$$

where

$$\Lambda \equiv \frac{2}{3\pi} \ln \left[\frac{256 (\tau_R / \tau_{hp})^2 L_p}{\beta R \Lambda^3} \left(\frac{\hat{s}}{\langle n \rangle} \right)^4 \right]$$

is typically about 7. Neoclassical resistivity is used to compute the resistive decay time τ_R .

There is strong effect from diamagnetic stabilization of these modes

$$f_{dia} = \left[1 + \left(\frac{C_{dia} \mu_o \omega_{ci} \rho_i^3}{\eta \beta q^2 L_{ni}} \right)^2 \right]^{-1/6},$$

which typically decreases two to three orders of magnitude from the edge of the plasma to the center, reflecting the non-fluid nature of the modes in a hot plasma. There is considerable uncertainty in the theory of this diamagnetic stabilization term. Choosing the adjustable coefficient $C_{dia} = 0.1$ in this expression improves the fit with experimental data.

Since many modes are allowed in the high shear region near the edge of the plasma, the root mean square toroidal mode number $\langle n \rangle$ is chosen to be 2.0 here.

The first contribution to the resistive ballooning mode effective electron thermal diffusivity comes from parallel transport along magnetic field lines with magnetic flutter. This contribution typically peaks a few centimeters in from the edge of the plasma and then becomes small at the very edge of TFTR plasmas, because $[d(nT)/dr]^{4/3}$ diminishes faster than $T_e^{1/2}$. The second contribution comes from the $E \times B$ interchange driven by resistive ballooning modes, which produces comparable thermal and particle transport for both the electrons and ions. It is important to retain this contribution because it increases monotonically out to the edge of the plasma.

D. Calibration of the Model

All the results shown in this paper were computed using the following set of coefficients:

	χ_e	χ_i
Trapped Electron Modes	$F_e^{DR} = 0.2$	$F_i^{DR} = 0.2$
η_i Mode	$F_e^{IG} = 3.0$	$F_i^{IG} = 6.0$
Resistive Ballooning Mode	$F_{e1}^{RB} = 1.0$	
	$F_{e2}^{RB} = 4.0$	$F_i^{RB} = 4.0$

Additional calibration choices have already been discussed in previous subsections for the diamagnetic stabilization of resistive ballooning modes and the threshold for η_i modes. Future calibrations are expected to refine these choices of coefficients.

It should be noted that all the heat transport is represented by *effective* thermal diffusivities $\Gamma_e = n_e \chi_e \nabla T_e$ and $\Gamma_i = n_i \chi_i \nabla T_i$. Since the theories do not make a clear distinction between conductive and convective heat losses, all the heat losses are folded into these effective thermal diffusivities and there is no separate convection term.

E. Sawtooth Oscillations

The temperature and density profiles are redistributed during each sawtooth crash according to the Kadomtsev model. However, in these simulations, the current density is *not* redistributed during sawtooth crashes in order to be approximately consistent with experimental observation that the magnetic q -value at the magnetic axis remains well below unity while sawtooth oscillations are taking place. Hence, this model leaves considerable magnetic shear within the sawtooth mixing region, which stabilizes ideal ballooning modes as the central plasma reheats between each sawtooth crash (which is more important in elongated plasmas).

The sawtooth period is prescribed in order to approximately match the experimentally observed sawtooth period. The sawtooth period is made longer after the beam heating power is turned on, as observed. Both the experimentally measured profiles and the simulated profiles are taken from near the top of the sawtooth oscillations, just before a crash.

F. Boundary Conditions

A relatively high pedestal density is used in these simulations in order to match the experimentally observed density profile in the core of the plasma (see density profiles in section III). Actually, there is a relatively narrow boundary layer (less than 10% of the plasma minor radius) at the edge of the plasma in which there is a considerable inboard/outboard asymmetry in the observed electron density profile in TFTR. Since this effect is beyond the scope of the flux-surface-averaged simulations of the BALDUR transport code, this boundary layer was excluded from consideration in the work

presented here. The density boundary condition and corresponding profile characterizes the observed density profile only in the core of the plasma.

The electron and ion temperature boundary conditions were arbitrarily fixed at 10 eV on the grid point placed half a grid space outside of the plasma. As a natural result of the simulations, the temperature rises above 100 eV within the outer 5 cm of the plasma. Since the grid points are equally spaced about 1.8 cm apart and the computed thermal diffusivity rises rapidly near the edge of the plasma, the transport calculation is not very accurate in this edge region. However, for L-mode simulations, it is observed that the overall profile does not depend sensitively on the choice of the boundary temperature (for values well below 100 eV). Different choices of boundary temperature merely shift the overall temperature profile in or out by a few centimeters, at most. In H-mode or supershot simulations, however, the choice of boundary temperature (at the top of the pedestal in H-modes) is found to be much more important.

In addition to the relatively coarse radial grid and the poloidal averaging of the charged particle density at the edge, there are two other simplifications used in these simulations that would affect the boundary conditions. First, a prescribed core radiation model was used to approximate the experimentally observed radiation from the plasma. If the more complex non-equilibrium impurity radiation model were used, (which is available in the BALDUR code) the rate of radiation from the edge region would be much higher, as impurities move into and out of the higher temperature regions of the plasma before achieving their equilibrium ionization level. Second, recycling and the neutral gas density were kept much lower in the simulations than is believed to be present in the experimental reality. Hence, energy losses due to charge exchange and ionization are low in these simulations. The problem with properly implementing each of these two phenomena is that accurate predictive models for hydrogen and impurity transport are not yet available. Hence, there would be a large uncertainty in the predicted energy loss rates near the edge of the plasma from these two phenomena. The consequences of using a finer radial grid near the edge of the plasma and using more realistic models for impurity radiation and recycling would be to reduce the effective thermal diffusivity needed from resistive ballooning modes.

III. Simulations

Five simulations of TFTR L-mode shots will be presented in this report in order to demonstrate the way in which the Multi-Mode Model transport scales with heating power and plasma current. These five simulations are shown as a function of auxiliary heating power and plasma current as the solid points in Figure 1. (The simulations shown as open circles were among those used in the calibration of the model.)

The values of the externally controllable parameters that characterize these five shots are given in Table 3. These shots are uniquely identified by a TFTR shot number followed by the number of the SNAP code analysis of the data. SNAP is a computer code used to analyse TFTR experimental data at a given instant during the discharge.²⁰ Since these shots are mostly beam fuelled, the density climbs rapidly from the time the beams are turned on until it reaches quasi-steady-state by the time of the SNAP analysis. The magnetic q -value at the edge of the plasma, the estimated Z_{eff} , and the thermal energy confinement time from the SNAP analysis are also given. Finally, the designation of the BALDUR simulation is given.

The results from these simulations are presented in Figures 2 through 12. At least five panels are presented for each simulation: The first three panels (Figures 2, 5, 7, 9, and 11) show the computed electron temperature, ion temperature, and electron density, compared with the measured values as a function of major radius. The electron temperature was measured by Electron Cyclotron Emission radiometry²¹ for all the cases shown, except for TFTR shot 41326-05 shown in Figure 2 where the electron temperature was measured by a Thomson scattering diagnostic called TVTS. The error in the Electron Cyclotron Emission measurements of electron temperature is estimated to be 5–10%, and the agreement with Thomson scattering is generally good. The ion temperature was measured by charge exchange recombination spectroscopy (CHERS). The electron density was measured by the Multi-channel Infrared Interferometer system (MIRI).^{22,23} The next two panels for each simulation (shown in Figures 3, 6, 8, 10, and 12), show the computed electron and ion thermal diffusivity broken down into the contributions from trapped electron modes (χ^{TEM}), η_i modes (χ^{η_i}), resistive ballooning modes (χ^{RB}), and the sum of these (χ^{TOT}). Finally, Figure 4 shows a typical example of the profiles of η_i and the threshold value η_i^{th} used in Eq. (3) for

$\chi_{e,i}^{\eta_i}$.

In each case, it can be seen that the total effective thermal diffusivities increase nearly monotonically from the core to the edge of the plasma. Neoclassical transport is negligible compared to the anomalous contributions except in a very narrow region near the magnetic axis, where the other contributions all scale like r^α with $\alpha \geq 1$. Trapped electron modes dominate deep in the core of the plasma in some shots (as in the high power shot 45585 shown in Figure 8) or remain subdominant to the other modes in other shots (as in the low current shot 45966 shown in Figure 12). The η_i mode then rises with increasing minor radius to a broad peak between $0.5 \leq r/a \leq 0.9$, and then dies at the edge. The effective thermal diffusivity due to resistive ballooning modes then rises steeply at the edge of the plasma, where it completely dominates. Most of this is due to the $E \times B$ contribution of the resistive ballooning mode, which applies to both ions and electrons. The region of dominance of resistive ballooning modes is much wider in the low current (high q) discharge 45966, because of its q^2 dependence.

The value of η_i is much larger than the threshold value for instability (η_i^{th}) near the edge of the plasma (Fig. 4). However, the transport due to the η_i mode decreases sharply near the edge because of its $T_e^{3/2}$ dependence. Working in from the edge, the values of η_i and η_i^{th} converge until they nearly coincide over a range of radii. Contrary to popular notions, the region of marginal stability is relatively narrow and deep in the core of the plasma.

In some cases, (eg χ_i for shot 45585 shown in Fig. 8) there is enough of a gap between the η_i mode and the resistive ballooning mode to produce a small region of nonmonotonic radial dependence of the total thermal diffusivity — a slight thermal barrier. This results in a somewhat steeper temperature gradient there than is observed experimentally, which leads to the speculation that one or the other mode should actually be broader than the present theory allows or that there may be a missing piece in the theory.

Scaling with heating power is shown most clearly by comparing shots 41326 (Figs. 2 and 3) with 45359 (Figs. 5 and 6). These two shots have the same plasma current, geometry, and nearly the same density and Z_{eff} . It can be seen from Figs. 3 and 6 that the resistive ballooning mode contribution is nearly unchanged between these two shots. The effective thermal diffusivities due to η_i and trapped electron modes are strongly reduced as the heating power is reduced. The values of η_i and the threshold η_i^{th} are found to be nearly

unchanged in the outer half of the plasma. Hence, the change in thermal diffusivities as the heating power is changed comes from the temperature dependence (mostly $T_e^{3/2}$) of the η_i and collisionless trapped electron modes. In fact, most of the effect comes from the η_i mode in this model.

The results shown in Figures 7 and 8 for shot 45585 carry this trend to still higher power at lower plasma density, and consequently higher temperatures.

Simulations of TFTR shots 41313 and 45603, (not shown) which represent low and high power shots at lower current, yield profiles that also agree well with the experimentally measured profiles. Hence the transport model described in this paper produces correct results for different levels of heating power at low current as well as at high current. However, since the density profile and toroidal magnetic field were different between these two shots, they can not be used to elucidate scaling with heating power alone. In this case, it turns out that the thermal diffusivities due to both the η_i and resistive ballooning modes are noticeably larger in the high power shot (45603), which also had the larger value of q_{edge} (8.2 vs 6.5) and a flatter density profile.

Scaling with plasma current is illustrated by comparing the relatively high current shot 45980 (Figs. 9 and 10) with the lower current shot 45966 (Figs. 11 and 12). These two shots have the same heating power and plasma density (and nearly the same density profile). At low current (high q_{edge}), the resistive ballooning modes clearly extend more deeply into the plasma. This would be true of any edge mode that scaled like q^2 or $q^{8/3}$, as the resistive ballooning modes do here. In this case, the $E \times B$ interchange contribution from resistive ballooning modes dominates over the magnetic flutter part near the edge of the plasma. In fact, a simulation of the low current shot 45966 omitting the magnetic flutter contribution from resistive ballooning modes yields nearly the same results for the temperature profiles as the full model.

As the current is reduced, (comparing shots 45980 and 45966) the thermal diffusivities due to both the η_i and trapped electron modes are reduced, going counter to the trend of the resistive ballooning modes. Further investigation reveals that the η_i and trapped electron modes are reduced merely because the electron temperature is lower (as a result of resistive ballooning modes extending further into the plasma). The shear-dependent factor ($\exp[-\min(5L_n, 4L_T)/L_s]$) in the Hamaguchi-Horton η_i mode model is in the range 0.90 to 0.96 and does not change much between these two shots.

Hence, this explicit shear dependence in the η_i mode model does not play an important role in current scaling for these simulations.

IV. Conclusions

Version 5.10 of the Multi-Mode Transport Model has been used to predict TFTR L-mode temperature profiles over a wide range of conditions. The combination of trapped electron, η_i , and resistive ballooning modes results in effective thermal diffusivities that generally increase monotonically from the center of the plasma to the edge, which is consistent with experimental observations. It is found that scaling with heating power results from the temperature dependence of the η_i and trapped electron modes. Scaling with plasma current, in this model for the TFTR simulations reported here, results from the strong q -dependence of the resistive ballooning modes near the edge of the plasma.

It is important to note that all the results presented here are essentially steady state simulations of L-mode plasmas, aside from the time it takes to heat the plasma and the periodic nature of the sawtooth oscillations. There are preliminary indications that the transport models used here do not adequately predict the results of transient experiments such as density perturbations and fast current ramps. Also, better models are needed to cope with hot ion mode plasmas, such as the "supershots" on TFTR. As improved theory-based transport models become available, they will be implemented in the BALDUR transport code and used to extend the range of applicability of the simulations.

Work is also under way to extend the transport model to predict the density profile as well as the temperature profiles. This is a considerably more difficult task since gradients of the density appear in most of the transport coefficients. Hence the computed density profiles must be both smooth and accurate in order to maintain the good predictive results already obtained for the temperature profiles. In addition, an improved predictive model is needed for the edge region, where a high density pedestal develops in L-mode as well as H-mode, and there is a strong inboard-outboard asymmetry.

In spite of the fact that better theoretically derived transport models are needed, the present version of the Multi Mode Model does predict the temperature profiles for a wide range of data.

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Appendix A. Numerical Techniques

Simple methods have been found to reduce the numerical instability associated with a thermal diffusivity that has a sharp threshold as a function of the temperature gradient, as in the case of transport driven by η_i modes. An example of this instability is shown in Fig. 13. This instability appears in regions where the temperature gradient just equals the threshold value over an extended region. A perturbation that increases the temperature gradient at a point in this region, causes the diffusivity to increase to a high value at that point. Then, on the next time step, the temperature gradient at that point is flattened and the diffusivity drops to a low value, while the gradient at the next grid point over is increased sharply above the threshold. Hence, the temperature gradient and the diffusivity overshoots and undershoots.

This numerical instability can be eliminated by taking sufficiently small timesteps. For the simulations shown here, the timesteps would have to be at least a hundred times smaller, which would be impractical. It was found that spatially smoothing the profiles or their gradients just increased the wavelength of the instability without appreciably reducing its amplitude.

Two new methods were developed for reducing this numerical instability:

1. Increase the implicitness parameter θ to 4.0 or more in order to reduce overshooting when there is a sharp turn-on function for the diffusivity, as in the implementation of the η_i mode.
2. Limit the local rate of change of the diffusivity.

A. Implicitness Parameter Greater Than Unity

The idea of using values greater than 1.0 for the implicitness parameter θ appears to be new. Numerical analysis textbooks²⁴ normally recommend $\theta = 0.5$, (called the Crank-Nicholson method) because the linear diffusion equation is both numerically stable and second order accurate in time with this choice. For nonlinear diffusion equations (in which the diffusivity is a function of the solution of the equation), a greater margin of stability is usually needed and, consequently, values of θ between 0.6 and 1.0 are usually chosen.

However, we were finding symptoms of numerical instability with any choice of $0.5 < \theta \leq 1$. whenever the diffusivity had a form which increased sharply as a function of the temperature gradient above a threshold value (as in the case of the η_i mode). In particular, under these conditions, the temperature profile developed spatial undulations which would propagate out from the core toward the edge of the plasma. These undulations were traced back to wide swings in the diffusivity as the temperature gradient was rising above and then falling below the threshold for the onset of the η_i mode. The amplitude of this effect could be reduced by decreasing the timestep to extremely small values. A more efficient alternative is to increase the implicitness parameter to values above 1.0. The reason this works will be illustrated with the following example:

Consider a simple temperature diffusion equation

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \chi \frac{\partial T}{\partial x},$$

where the diffusivity χ has a sharp turn-on as a function of $(\partial T / \partial x)$, as shown in Fig. 14. Consider three grid points (with the end points fixed) on which the temperature gradient goes from below the threshold to above the threshold as shown in Fig. 15. Then, an implicit finite difference scheme for the central grid point has the form

$$\frac{T_j^{N+1} - T_j^N}{\Delta t} = -\frac{\chi_H}{(\Delta x)^2} [\theta(T_j^{N+1} - T_{j-1}^{N+1}) + (1 - \theta)(T_j^N - T_{j-1}^N)].$$

Note that the heat flux between gridpoints j and $j+1$ is zero for this timestep, since the temperature gradient there is below the threshold and, hence, the thermal diffusivity there is zero. For large values of $\chi_H \Delta t / (\Delta x)^2$ we have

$$T_j^{N+1} \longrightarrow \frac{T_{j-1}^N + (\theta - 1)T_j^N}{\theta}$$

For the choice of $\theta = 1$ (fully implicit), it can be seen that the value of T on the central grid point just oscillates up and down from one time step to the next, as shown in Fig. 16. (From one timestep to the next, the region of zero thermal diffusivity oscillates from one side of gridpoint j to the other.) However, for the choice $\theta = 2$, after one time step the central grid point becomes the average of the two end points and the gradient becomes

smooth, as shown in Fig. 17. For values of $\theta > 2$, the central grid point rises more slowly and the steep part of the gradient (on the left) approaches the threshold value more gradually. Hence, in a driven system with a steep threshold, taking the implicitness parameter $\theta \geq 2$ will allow the gradients to relax to the threshold value, damping out any overshoots.

In practice, this method does not work perfectly. Sharply defined processes such as sawtooth crashes or the noise from Monte Carlo computations tend to drive the temperature gradient well above the threshold in some locations transiently. Also, with long time-steps, the temperature gradient can increase well above the threshold during one time step. It then takes a while to relax back to a smoother profile.

B. Limit the Local Rate of Change of Diffusivity

In order to implement this method, a copy of the diffusivity array is kept from the previous timestep, and the difference is taken between the new and the old diffusivities $\chi^{N+1} - \chi^N$. The idea is to limit the growth of local spikes while leaving the diffusivity free to change on larger scales. The following transform accomplishes this objective:

$$\chi^{\text{New}} = \chi^N + \frac{\chi^{N+1} - \chi^N}{1 + C|\chi^{N+1} - \chi^N - \langle \chi^{N+1} - \chi^N \rangle|},$$

where $\langle \dots \rangle$ represents spatial smoothing. (Here I use $\langle A \rangle = (A_{j+1} + 2A_j + A_{j-1})/4$). Choosing the constant $C = 10$, for example, limits the growth of diffusivity spikes to about 0.1 during each time step. Since there are typically 10 to 20 time steps during each sawtooth period and hundreds of time steps during the entire simulation, the temperature gradient then has a chance to adjust gradually and damp out any tendency to overshoot.

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Table 1. Notation: Fundamental Variables

Symbol	units	Meaning
B	tesla	toroidal magnetic field at major radius R along flux surface
M	kg	average hydrogenic ion mass
n_e	m^{-3}	electron density
n_i	m^{-3}	thermal ion density
q		magnetic q value
r	m	minor radius (half-width) of flux surface
R	m	major radius of flux surface
T_e	keV	electron temperature
T_i	keV	ion temperature
Z		Z_{eff}

Table 2. Notation: Derived Variables

Symbol	Name (units)	Formula
β	beta	$(2\mu_o k_b / B^2)(n_e T_e + n_i T_i)$
c_s	sound speed (m/s)	$[k_b T_e / (m_p A_i)]^{1/2}$
η	resistivity (Ohm-m)	(Neoclassical correction) $\times \nu_{ei} / (2\epsilon_o \omega_{pe}^2)$
η_j		$L_n / L_{T_j}; j = i, e$
$k_\perp$	wave number (m^{-1})	$\approx 0.3 / \rho_s$
$\ln(\lambda)$	Coulomb logarithm	$37.8 - \ln(n_e^{1/2} T_e^{-1})$
L_n	density scale length (m)	$-n_e / (\partial n_e / \partial r)$
L_p	press. scale length (m)	$-\beta / (\partial \beta / \partial r) \equiv \beta / \beta'$
L_s	shear length (m)	$Rq / \hat{s}$
L_σ	η^{-1} scale length (m)	$L_{T_e} / 1.5$
L_{T_j}	$T_e; T_i$ scale lengths (m)	$-T_e / (\partial T_e / \partial r); -T_i / (\partial T_i / \partial r)$
ν_e^*	electron collisionality	$\nu_{ei} q R / (\epsilon^{3/2} v_e)$
ν_{eff}	effective coll. freq. (s^{-1})	ν_{ei} / ϵ
ν_{ei}	electron coll. freq. (s^{-1})	$4(2\pi)^{1/2} n_e (\ln \lambda) e^4 / [3(4\pi\epsilon_o)^2 m_e^{1/2} (k_b T_e)^{3/2}]$
ν_{ii}	ion coll. freq. (s^{-1})	$4\pi^{1/2} n_e (\ln \lambda) e^4 / [3(4\pi\epsilon_o)^2 (m_p A_i)^{1/2} (k_b T_i)^{3/2}]$
ρ_i	ion gyroradius (m)	$= v_i / \omega_{ci}$
ρ_s		$= c_s / \omega_{ci}$
$\rho_{\theta i}$	poloidal gyroradius (m)	$= \rho_i q / \epsilon$
$\hat{s}$	shear	$(r/q)(\partial q / \partial r)$
τ_A	toroidal Alfvén time (sec)	R / v_A
τ_R	resistive diffusion time	$r^2 \mu_o / \eta$
v_A	Alfvén speed (m/s)	$B / (\mu_o n_e m_p A_i)^{1/2}$
v_e	elect. therm. vel. (m/s)	$(2k_b T_e / m_e)^{1/2}$
v_i	ion therm. vel. (m/s)	$(2k_b T_i / m_p A_i)^{1/2}$
ω_{ci}	ion cyclotron freq. (s^{-1})	$eB / (m_p A_i)$
ω_e^*	diamagnetic freq. (s^{-1})	$k_\perp \rho_s c_s / L_n$
ω_{pe}	plasma frequency (s^{-1})	$[n_e e^2 / (m_e \epsilon_o)]^{1/2}$

Table 3. TFTR L-mode Simulations

Shot	41326-05	45359-02	45585-01	45980-02	45966-05
Type	standard	low power	high power	high current	low current
Beam Power					
(MW)	16.8	4.5	19.8	11.34	11.3
I (MA)	1.80	1.79	1.79	1.99	1.0
B (tesla)	3.76	3.75	3.75	4.76	4.76
R (m)	2.58	2.58	2.58	2.45	2.45
a (m)	0.92	0.93	0.93	0.80	0.80
Beam time					
on (sec)	2.8	3.5	3.5	3.0	3.0
Diagnostic					
time (sec)	3.65	4.4	4.17	3.47	4.9
$\bar{n}_e$ ($10^{19}m^{-3}$)	4.26	4.5	3.2	3.34	3.3
q_{edge}	4.3	4.2	4.5	3.61	7.54
Z_{eff}	3.3	1.4	2.8	2.3	2.1
τ_E (sec)	0.086	0.146	0.058	0.099	0.052
simulation	TL02Y1	TL08A1	TL01A4	TL07A6	TL10A1

Figure 1: The TFTR L-mode shots that have been simulated with the Multi-Mode Model plotted against auxiliary heating power and plasma current. Solid points indicate the shots presented in this report.

Figure 2: Profiles of electron temperature, ion temperature, and electron density as a function of major radius from BALDUR simulation TL02Y1 (solid curve) compared with experimental data points from TFTR shot 41326 SNAP run 5 at time 3.65 seconds.

Figure 3: Electron and ion thermal diffusivities as a function of minor radius from BALDUR simulation TL02Y1 of TFTR shot 41326 at time 3.7 seconds. Contributions to the effective thermal diffusivities from trapped electron modes χ^{TEM} , η_i mode χ^{η_i} , and resistive ballooning modes χ^{RB} are shown as well as the sum of these χ^{TOT} .

Figure 4: Radial profile of η_i and the threshold value η_i^{th} used to compute η_i mode transport in BALDUR simulation TL02Y1 of TFTR shot 41326 at time 3.7 seconds.

Figure 5: Profiles of electron temperature, ion temperature, and electron density as a function of major radius from BALDUR simulation TL08A1 (solid curve) compared with experimental data points from TFTR shot 45359 SNAP run 2 at time 4.4 seconds.

Figure 6: Electron and ion thermal diffusivities as a function of minor radius from BALDUR simulation TL08A1 of TFTR shot 45359 at time 4.4 seconds. contributions to the effective thermal diffusivities from trapped electron modes χ^{TEM} , η_i mode χ^{η_i} , and resistive ballooning modes χ^{RB} are shown as well as the sum of these χ^{TOT} . Note, $\nu_e^* > 0.19$ throughout the plasma in this simulation.

Figure 7: Profiles of electron temperature, ion temperature, and electron density as a function of major radius from BALDUR simulation TL01A4 (solid curve) compared with experimental data points from TFTR shot 45585 SNAP run 1 at time 4.17 seconds.

Figure 8: Electron and ion thermal diffusivities as a function of minor radius from BALDUR simulation TL01A4 of TFTR shot 45585 at time 4.17 seconds. Contributions to the effective thermal diffusivities from trapped electron modes χ^{TEM} , η_i mode χ^{η_i} , and resistive ballooning modes χ^{RB} are shown as well as the sum of these χ^{TOT} .

Figure 9: Profiles of electron temperature, ion temperature, and electron density as a function of major radius from BALDUR simulation TL07A6 (solid curve) compared with experimental data points from TFTR shot 45980 SNAP run 2 at time 3.47 seconds.

Figure 10: Electron and ion thermal diffusivities as a function of minor radius from BALDUR simulation TL07A6 of TFTR shot 45980 at time 3.5 seconds. contributions to the effective thermal diffusivities from trapped electron modes χ^{TEM} , η_i mode χ^{η_i} , and resistive ballooning modes χ^{RB} are shown as well as the sum of these χ^{TOT} .

Figure 11: Profiles of electron temperature, ion temperature, and electron density as a function of major radius from BALDUR simulation TL10A1 (solid curve) compared with experimental data points from TFTR shot 45966 SNAP run 5 at time 4.9 seconds.

Figure 12: Electron and ion thermal diffusivities as a function of minor radius from BALDUR simulation TL10A1 of TFTR shot 45966 at time 4.9 seconds. contributions to the effective thermal diffusivities from trapped electron modes χ^{TEM} , η_i mode χ^{η_i} , and resistive ballooning modes χ^{RB} are shown as well as the sum of these χ^{TOT} . Note, $\nu_e^* > 0.14$ throughout the plasma in this simulation.

Figure 13: The electron thermal diffusivity for a numerically unstable BALDUR simulation. Physically, the conditions are the same as in Figs. 7 and 8 but the numerical methods described in Appendix A are turned off.

Figure 14: Thermal diffusivity with steep threshold.

Figure 15: Initial temperature on finite difference grid.

Figure 16: One time-step with $\theta = 1$.

Figure 17: One time-step with $\theta = 2$.

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