TRANSPORT SIMULATIONS OF OHMIC TFTR EXPERIMENTS WITH
PROFILE-CONSISTENT MICROINSTABILITY-BASED MODELS

FOR x_e and x_i

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ABSTRACT

Transport simulations of ohmically heated TFTR experiments with recently developed profile-consistent microinstability models for the anomalous thermal diffusivities, x_e and x_i , give good agreement with experimental data. The steady-state temperature profiles and the total energy confinement times, τ_E , were found to agree for each of the ohmic TFTR experiments simulated, including three high radiation cases and two plasmas fueled by pellet injection. Both collisional and collisionless models are tested. The trapped-electron drift wave microinstability model results are consistent with the thermal confinement of large plasma ohmic experiments on TFTR. We also find that transport due to the toroidal ion temperature gradient (η_i) modes can cause saturation in τ_E at the highest densities comparable to that observed on TFTR and equivalent to a neoclassical anomaly factor of 3. Predictions based on stabilized η_i -mode-driven ion transport are found to be in agreement with the enhanced global energy confinement times for pellet-fueled plasmas.

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1. INTRODUCTION

Anomalous electron and ion conduction losses appear to dominate tokamak energy confinement [1-5]. This is a key problem in designing practical fusion reactors.

Numerous theoretical papers [6-12] have attempted to explain tokamak energy losses on the basis of drift modes and other instabilities. Verification of any of these models depends on testing against actual experimental data. This has motivated the present study in which the BALDUR transport code [13] has been used to simulate TFTR ohmic experiments over a wide range of plasma conditions in order to test the validity of recent profile-consistent theoretically based models [6] for the anomalous electron and ion thermal diffusivities χ_e and χ_i .

A comparison of predictions of the collisional and collisionless χ_e models was made. The collisionless model was found appropriate for interpreting the ohmic phase of a representative low density "supershot" [14]. All other simulations were carried out with the collisional model for χ_e^{TE} . The simulation results are found to be consistent with (i) the TFTR ohmic scaling $\tau_E \propto n_e q_a a R^2$ [15] at low to moderate densities, (ii) the measured degradation of ohmic confinement at high density relative to the low density scaling when the profile parameter, $\eta_i = d \ln T_i / d \ln n_i > 1.5$, and (iii) the experimentally observed behavior in pellet-fueled experiments.

In Sec. 2, we present the thermal diffusivity models tested and their extension to high radiation cases ($P_{rad}/P_{OH} > 60\%$). The main features of the time-dependent, one-dimensional transport code (BALDUR) used in these studies are described in Sec. 3. In Sec. 4, the results of detailed simulations of a large number of actual TFTR experiments, including several high-radiation and pellet-fueled cases, are presented. Section 5 describes similar results for

simulation of a typical PDX ohmic discharge. Confinement results predicted by the simulations are discussed in Sec. 6, and the general conclusions from these studies are summarized in Sec. 7.

2. MICROINSTABILITY-BASED MODELS FOR χ_e AND χ_i

2.1 Profile-Consistent Trapped-Electron Drift Wave Model for χ_e

A number of proposed models for anomalous electron thermal diffusivity are of potential interest for modeling tokamak experiments. The specific model [6] being tested here was formulated from global as well as microscopic theoretical considerations. Experimentally deduced expressions for χ_e , generated from the energy balance analysis of TFTR data, have recently been compared to various proposed models [16]. Results from these studies have indicated that the scaling of the profile-consistent microinstability model [6] is in better agreement with the ohmic data base than the scalings predicted by many other models [7,17-19]. The Coppi-Mazzucato model [18] was also found to give reasonable agreement. With regard to actual time-dependent transport code simulations, Dominguez and Waltz [8] have recently reported that the neo-Alcator-like scaling trend ($\tau_E \propto \bar{n}_e a R^2 q$) in devices, such as the Doublet III tokamak, could be reproduced by using a model for χ_e based on the presence of trapped-electron (TE) drift instabilities. $\bar{n}_e$ is the line-averaged plasma density, q_a is the safety factor at the edge of the plasma, and R and a are, respectively, the major and minor radius of the device.

As discussed in detail in Ref. [6], if realistic profile constraints are enforced, then most of the significant confinement properties in low-beta ohmically heated tokamaks can be accounted for by electrostatic ($\mathbf{E} \times \mathbf{B}_0$) transport due to drift-type microinstabilities. The associated profile-consistent models are based on the presence of trapped-electron drift modes

and/or toroidal ion temperature gradient (η_i) modes in the bulk region of thermal insulation (usually between the $q = 1$ and $q = 2$ surfaces) in the plasma [20]. They incorporate the familiar mixing length estimate for the magnitude of the fluctuations and also impose a temperature "profile consistency" [7] constraint. If the parameter η_i exceeds a critical magnitude $(\eta_i)_c$ (typically from 1 to 2), then the dominant instability evolves from the trapped-electron mode to the η_i -type mode [21].

For the purpose of analytic simplicity, a number of assumptions were made in constructing the basic model. These include invoking parallel Ohm's law to relate the temperature to the current profile in steady state and taking the electron temperature profile to be represented by the Gaussian form,

$$T_e(r) = T_{eo} \exp[-2/3(q_a + 0.5) r^2/a^2] . \quad (1)$$

As noted in Ref. [6], this choice does not imply that other T_e -profiles (exhibiting a monotonically decreasing radial dependence sensitive primarily to q_a) could not be alternatively selected. Solving a simplified cylindrical steady-state energy-balance equation, this yields for the electron thermal diffusivity in an ohmically heated plasma

$$\chi_e = C_F \frac{1.25(1 + 0.25 \alpha_n) 10^4 a B_T^{0.3} Z_{eff}^{0.2}}{n_{eo} R^{1.9} q_a^{1.6}} f(r) , \quad (2a)$$

with

$$f(r) = \frac{\exp[(2/3)(q_a + 0.5)r^2/a^2] - \exp[-(1/3)(q_a + 0.5)r^2/a^2]}{[n_e(r)/n_{eo}] (r^2/a^2)} , \quad (2b)$$

where B_T (Tesla), R (m), a (m), n_{eo} (10^{14}cm^{-3}), and α_n is a value chosen to characterize the steepness of a parabolic density profile. C_F is a scaling coefficient of order unity. This result can also be expressed in terms of the dependent variables, such as the central electron temperature T_{eo} , or the ohmic power P_{OH} . Specifically, in terms of T_{eo} (keV), this becomes

$$\chi_e^{TE}(r) = C_F \frac{(1 + 0.25 \alpha_n) 10^4 a^{0.8} T_{eo}^{0.5}}{R^{1.8} q_a^{1.5} n_{eo}} f(r), \quad (3)$$

and in terms of P_{OH} (MW),

$$\chi_e^{TE} = C_F \frac{0.6(1 + 0.25 \alpha_n) 10^4 P_{OH}^{0.8}}{R^{1.2} a^{0.1} Z_{eff}^{0.2} B_T^{0.4} q_a^{0.9} n_{eo}} f(r) \quad (4)$$

with P_{OH} (MW). It is also of interest to recall at this point the very strong temperature dependence in the expression for the local thermal diffusivity of dissipative trapped-electron modes. However, when the global profile consistency constraint is applied to this local estimate [6], the resultant scaling [Eq. (3)] is actually $T_e^{1/2}$ instead of $T_e^{7/2}$. The particular merit of using Eq. (4) [which is, of course, entirely equivalent to Eqs. (2) and (3)] is that it reflects the unfavorable scaling of anomalous electron thermal transport with increasing input power in ohmically heated plasmas.

These equations can continue to be applicable in the lower collisionality end of the plateau regime because the banana regime parameter, ν_{*e} , involves the thermal particles. Hence, the higher energy trapped electrons can still contribute to the instabilities even when ν_{*e} exceeds unity [20,22].

If $\nu_{*e} \lesssim 0.1-0.2$, the collisionless form of the trapped electron drift wave diffusivity should be used [6]

$$\chi_e^{\text{TE-collisionless}}(r) = C_G \frac{10^4 (P_{\text{tot},e} / n_{oe})^{0.6}}{(B_T R_a)^{0.8} a^{0.2}} f(r) . \quad (5)$$

Here $P_{\text{tot},e}$ is the total electron heating power which is also used in calculating the function $f(r)$. The factor C_G is a scaling constant. All cases studied (Table I) except shot 22014 were found to have $v_{*e} > 0.15$ at $q = 1.5$ and could properly be simulated with the collisional formula. The collisionless form of χ_e was used in simulating the very low density ohmic case, in Sec. 4.2.

One example of the errors that can be generated by applying the collisional form of χ_e where the collisionless form should be applied can be seen in the recent results presented by Duchs et al. [23].

Ion losses associated with the presence of the trapped-electron drift modes [in situations where $\eta_i < (\eta_i)_c$] are less important. Local estimates of the magnitude of χ_i^{TE} indicate that it is typically smaller than χ_e^{TE} and exhibits a similar scaling [6]. Consequently, in the higher density ohmic regimes, where the ion loss channel is dominant, the contribution of χ_i^{TE} tends to be masked by the conventional neoclassical ion transport. It would then appear that in such discharges the electron channel is anomalous while the ion confinement is neoclassical.

In Sec. 4.1, we will discuss simulations of experiments for which the fraction of ohmic heating power lost to radiation is greater than 60%. For these simulations we have modified Eq. (4) to account for the reduced total power available to drive the thermal transport associated with the trapped-electron microinstabilities. We have also used the power deposition profile factor F_H appropriate for auxiliary heated discharges [6] to properly include radiation loss for ohmically heated cases.

$$\chi_e^{TE}(r) = C_F \frac{0.6(1 + 0.25 \alpha_n) 10^4 (P_{OH} - P_{rad})^{0.8}}{n_{eo} R^{1.2} a^{0.1} z_{eff}^{0.2} B_T^{0.4} q_a^{0.9}} F_H(r) , \quad (6a)$$

with

$$F_H(r) = \frac{[1 - \exp(-\alpha_q)] \exp(2 \alpha_q x^2 / 3 a^2) \int_0^{r/a} dx x h(x)}{[n_e(r)/n_{eo}] (r^2/a^2) \int_0^1 dx x h(x)} , \quad (6b)$$

where $\alpha_q = q_a + 0.5$, P_{rad} (MW), and $h(x)$ is the total energy deposition profile including ohmic heating minus radiation losses. For auxiliary heated cases $h(x)$ and the factor $(P_{OH} - P_{rad})$ would be replaced by the net heating power from all plasma heating sources including alpha particle heating if present.

2.2 The Profile-Consistent Ion-Temperature-Gradient Drift Wave Model

For situations where the profile parameter η_i is sufficiently large, comprehensive theoretical studies of toroidal microinstabilities [20,21] have concluded that the ion (rather than electron) dynamics are dominant. The resultant toroidal ion-temperature-gradient-driven modes are fluid-like in character and (in contrast to the trapped-electron modes) insensitive to collisions. Following the same general procedure as noted in Sec. 2.1. (and described in detail in Ref. 6), the profile-consistent expression for the associated anomalous ion thermal diffusivity is given by

$$\chi_i^{TE} = C_H \frac{10^4 (P_{tot}/n_{eo})^{0.6}}{(RB_T q_a)^{0.8} (a)^{0.2}} F_H(r) , \quad (7)$$

with $F_H(r)$ given by Eq. (6b). In arriving at this result, it was assumed for simplicity that $T_e = T_i$ and that the parabolic and Gaussian forms (for the density and temperature profiles, respectively) could again be used to formulate the profile constraint condition. The factor C_H is a scaling

constant [6], n_{e0} is the central electron density, and the onset condition is just $\eta_i = d\ln T_i / d\ln n_i > (\eta_i)_c$ with $(\eta_i)_c = 1.5$.

With regard to the anomalous electron thermal diffusivity associated with the η_i -modes, theoretical calculations [2] indicate that $\chi_e^{\eta_i} \approx \chi_i^{\eta_i}$, in a collisionless plasma. However, this electron loss channel, as in the case of trapped-electron modes, remains sensitive to collisions. Hence, for most ohmically heated plasmas of interest, the expression for $\chi_e^{\eta_i}$ will tend to be very similar to χ_e^{TE} . Accordingly, the expressions for χ_e^{TE} given in Sec. 2.1 can continue to be used in simulating ohmic plasmas even when $\eta_i > (\eta_i)_c$.

Recent time-dependent transport code simulations carried out by Dominguez and Waltz [8] have reported favorable correlations with the observed τ_E saturation in a number of high density ohmic experiments and also with results from the neutral-beam-heated Doublet-III tokamak. Although they invoke the presence of the same type of electrostatic microinstabilities discussed in this paper, the actual form of the anomalous thermal diffusivities used in their code is very different from the profile-consistent model. In particular, conventional local expressions for χ_e and χ_i (associated with trapped-electron and η_i -modes) are applied between the $q = 1$ and $q = 2$ regions of the plasma, and a heuristic "venetian blind" model associated with tearing modes is invoked to provide the required strong degradation of confinement outside the $q = 2$ surface. In a qualitative sense, the effect of the "venetian blind" model is to enforce the profile consistency trend characteristic of the model used in the present paper.

Simulations of ohmic TFTR discharges have been carried out using the profile-consistent $\chi_i^{\eta_i}$ model added to the usual ion neoclassical expression. As illustrated in Sec. 4.2.1, the results indicate improved agreement between the simulated and experimental values for central T_e and T_i . Correlation with

the observed saturation of τ_E with increased density in the large plasma TFTR discharges is also demonstrated.

3. THE BALDUR TRANSPORT CODE

BALDUR [13], a multispecies one-dimensional transport code, was used for this series of simulations. BALDUR includes energy and particle sources due to conduction, convection, radiation, recombination, sawteeth, and ohmic heating. All simulations were carried out with neoclassical transport coefficients for diffusion, thermal diffusivity, and Ware pinch in addition to anomalous transport coefficients for energy and particle transport. Specifically,

$$\chi_e = \chi_e^{NEO} + \chi_e^{ANOM}, \quad (8a)$$

$$\chi_i = \chi_i^{NEO} + \chi_i^{ANOM}, \quad (8b)$$

$$D = D^{NEO} + D^{ANOM}, \quad (8c)$$

$$v = v^{WARE} + v^{ANOM}. \quad (8d)$$

The microinstability diffusivity models described in Sec. 2 for anomalous transport are specified up to a coefficient of order unity [6].

3.1 Thermal Transport Coefficients

The theoretical prescription for situations where $n_i < (n_i)_c$, is that the n_i -mode should not be excited and that the transport coefficients should be given by $\chi_e^{ANOM} = \chi_e^{TE}$ and $\chi_i^{ANOM} = \chi_i^{TE}$. As pointed out in Sec. 2, χ_i^{TE} is

usually smaller in magnitude, but exhibits a scaling similar to χ_e^{TE} for most ohmic cases when $\eta_i < (\eta_i)_c$. Hence, in such situations (where the electron losses are dominant), the influence of χ_i^{TE} can be simply approximated by taking $\chi_{TOTAL}^{ANOM} = \chi_e^{ANOM} \propto \chi_e^{TE}$ with $\chi_i^{ANOM} = 0$. We have, in fact, chosen the order unity numerical coefficient C_F to be 0.67 in all the simulations. This choice leads to good agreement with the experimental measurements of central electron temperatures and surface voltages and was calibrated on the low density TFTR large plasma experiments. The anomalous contribution to the ion thermal diffusivity is here neglected to test the predictions of the trapped-electron drift wave model by itself in Sec. 4.1.

For situations where $\eta_i > (\eta_i)_c$, the η_i -modes are theoretically predicted to be excited, and the thermal transport coefficients become $\chi_e^{ANOM} = \chi_e^{\eta_i}$ and $\chi_i^{ANOM} = \chi_i^{\eta_i}$. As discussed in Sec. 2, $\chi_i^{\eta_i} \propto \chi_e^{TE}$. Hence, the form of the anomalous electron thermal diffusivity remains unchanged; i.e., $\chi_e^{ANOM} \propto \chi_e^{TE}$ as before. For the models used in the simulations and which will be described in Sec. 4.2, we have retained the same numerical factor in χ_e^{TE} , $C_F = 0.67$, and have chosen the numerical factor, C_H , to be 0.1 in the expression for the anomalous ion diffusivity

$$\chi_e^{ANOM} = \chi_e^{TE} \quad , \quad C_F = 0.67 \quad , \quad (9a)$$

$$\chi_i^{ANOM} = \chi_i^{\eta_i} \quad , \quad C_H = 0.1 \quad . \quad (9b)$$

Use of Eqs. (9a) and (9b) in BALDUR have produced simulation results in good agreement with the observed high density confinement time saturation on TFTR.

3.2 Particle Transport Models

The empirical anomalous particle transport coefficients used in most of the simulations were taken to be

$$D^{ANOM} = 1 \times 10^3 \text{ cm}^2/\text{sec} , \quad (10)$$

$$v^{ANOM} = 2D^{ANOM} \tau/a^2 . \quad (11)$$

The exceptions were the pellet injection simulations described in Sec. 4.1.3 and four of the lowest density plasma simulations where the diffusion coefficient was chosen to be proportional to $1/n_e$. These cases required such modification of D and v to match the experimental density profiles. After pellet injection on TFTR, a "density pumpout," with decreasing total particle content, is observed unlike typical gas-fueled experiments. To model the pellet-fueled cases, v^{ANOM} was set equal to zero after pellet injection, and the diffusion coefficient was adjusted to produce the observed decay of line-average density. The plasma recycling coefficient R was set to 0.9 in all simulations.

The convective heat flux was $(3/2) nkTv$ in all simulations, possibly underestimating the convective heat losses. The resistivity was assumed to be neoclassical, and a discrete Kadomtsev sawtooth model [13] was used for the simulations with sawtooth period of 50 msec, which is typical of TFTR large plasma discharges. Especially in the case of future ignition experiments, improved models for properly describing sawtooth behavior are critically needed. As described in Ref. [13], the BALDUR code calculates the temporal evolution of the plasma due to prescribed heating conditions and to specified particle sources and sinks. The empirical particle transport model just

described was adjusted to obtain density profiles similar to those measured in each experiment simulated. Of course, the principal aim here is to test how well the thermal transport properties of the plasma can be reproduced by the profile-consistent microinstability-based thermal diffusivities in Ref. [6]. Hence, the calculated surface voltages, values for the electron temperature across the discharges, and energy confinement times have been carefully compared with experimental results.

4. TFTR SIMULATIONS

The model for χ_e^{ANOM} described in Secs. 2 and 3 has been tested here by the predictive simulation of a set of TFTR large plasma ohmic experiments which vary primarily in density and plasma current. Many accurate and cross-checked diagnostic measurements as well as the relatively wide parametric operating regime in TFTR, have made it possible to test systematically the theoretical model against a variety of actual experiments. Information from the TFTR SNAP and GLOBE [24] data bases was used as input to the code and is given in Table I. SNAP is a time-independent, radial profile, kinetic data analysis code used to obtain transport coefficients, etc. GLOBE is a time-dependent, magnetic data analysis code used between shots on TFTR to analyze global plasma parameters, such as τ_E . Five gas-puff-fueled cases were modeled with the BALDUR code in detail for up to 3.5 sec, after specifying the changing total line-average electron density and the total plasma current as well as the other plasma parameters (Table I). Since the current flat-top times exceeded the energy confinement times, the simulated confinement times and temperature profiles were the same as those calculated when only the time independent conditions of line-average density and total current characteristic of the current flat-top

were specified during the transport simulation. Hence, the simpler time-independent procedure was adopted for simulating the remaining ten gas-fueled TFTR cases. The model was found to overestimate significantly the electron temperature during a current ramp.

The TFTR plasmas simulated here are large plasmas with $R = 2.55$ m, and $a = 0.72$ m, or $a = 0.82$ m. Both low and high density cases at high currents of 1.4 to 2.2 MA were modeled. The Gaunt-factor-corrected [25] value for Z_{eff} from visible bremsstrahlung was used in the model for x_e and also in the calculation of the impurity fraction specified as input to the code. The value of Z_{eff} consistent with neoclassical resistive ohmic equilibrium was within 20% of the corrected visible bremsstrahlung value. Precise experimental results for Z_{eff} profiles are extremely difficult to obtain. For the TFTR cases considered here, the radial dependence is thought to be flat from the plasma center to at least 40 cm and then to rise gently. Since the impurities were also assumed to follow the same particle transport laws as deuterium, their profile is similar to the electron density profile. The impurity particle transport model prescribed to the BALDUR code produced a Z_{eff} profile in agreement with this picture. Fully ionized oxygen was the only impurity species considered, consistent with trends reported by Dylla et al. [26] for TFTR large plasmas at high density.

In the original theoretical model [Eqs. (2-4)], impurity radiation effects were not taken into account. However, since Z_{eff} falls between 1.2 and 6 in the TFTR plasmas studied here, such effects should not be ignored. The important problem of including realistic impurity radiation profiles in the simulation was treated by fitting the measured radiation power profiles by a linear rise of $P_{\text{rad}}(r)$ to 0.9 a and by a quadratic cut-off region at the plasma edge. The ratio of total radiated power to total ohmic heating

obtained from each experiment was also specified to the code. Most experiments had less than 35% radiated power, but three cases were found to have 60% or more radiated power. These will be discussed in detail in Sec. 4.1.

4.1 Simulations with χ_e^{ANOM} and χ_i^{NEO}

The simulations were initially carried out using the form of χ_e^{TE} given by Eq. (2) with the numerical factor of 0.67 and with the Chang-Hinton neoclassical ion thermal conductivity. Comparisons of the temperature profiles measured by Thomson scattering to those predicted by the BALDUR simulations indicated good agreement with respect to both magnitude and shape. In particular, for nine ohmic gas-fueled cases, which were not radiation dominated, the agreement was within 10% experimental error. These simulated electron temperature profiles are compared to Thomson scattering data in Fig. 1. The sawtooth phases of the simulations have been adjusted to agree with the phases of the measured X-ray sawtooth traces at the time of the Thomson scattering temperature measurements.

On the other hand, two TFTR shots, 11603 and 11606, were not simulated very well by Eq. (2). The main reason is that these cases have $Z_{eff} = 5.0$ and are radiation dominated ($P_{rad}/P_{OH} > 60\%$). Temperature profiles from simulations, using the model of Eq. (2) for the three radiation-dominated experiments 11603, 11606, and 11609, are compared to Thomson scattering measurements in Figs. 2(a) - 2(c). Since these three shots have a large fraction of heating power lost through radiation, the model for χ_e was modified consistent with the ideas of the original theory. As indicated by Eq. (6), this involves the inclusion of a power deposition profile factor and a reduction of the ohmic power by the radiated power. This radiation-

corrected model was found to give good agreement with the Thomson scattering measurements for all three cases [Figs. 2(d) - 2(f)]. Shots 11603 and 11606 have $Z_{\text{eff}} = 5$; Shot 11609 has $Z_{\text{eff}} = 3$. The radiation correction is of more importance for high Z_{eff} plasmas with greater than 60% radiation. The simulation of shot 14618, which had only 35% radiation, was rerun with the radiation-corrected model. No significant differences were found. Increased radiation can cause improved electron thermal confinement in this model due to the reduction in energy available for driving the microinstabilities.

The simulations in Fig. 2 have not been sawtooth phased. The simulations in Figs. 2(a) and 2(d) are at the bottom and top of a sawtooth. This decreases the difference in T_e^{MAX} by 0.2 keV for these simulations of shot 11603.

For comparison, a simulation using an empirical INTOR-like scaling for $\chi_e = (2.4 \times 10^{17}/\text{cm}^{-3})/n_e(r)$ was carried out. As shown in Fig. 3, the results also indicate good agreement with temperature profile shape. It should be compared to Fig. 1(c). For this particular simulation, radial dependence of the temperature is controlled predominantly by the radial variation in density.

As discussed in Sec. 3, the empirical particle transport model used in these studies of anomalous, thermal transport was constructed to produce density profiles approximating the Thomson-scattering-measured density data. The error in simulating $n_e(r)$ has little effect on the electron conduction heat loss calculation because the product, $\chi_e n_e$ used in solving for the plasma thermal energy flux, is independent of n_e . A dynamic particle transport model for the density profile was used rather than a steady-state $n_e(r)$ function, so as to retain in the simulations the energy and particle fluxes (due to electron and ion convection) as well as neutral recombination losses.

4.2 Simulations with χ_e^{ANOM} and χ_i^{ANOM}

4.2.1 Large Plasma Ohmic Results

The effects of η_i -mode-driven χ_i [specified by Eq. (7) with $C_H = 0.1$] on the simulations of the TFTR large plasma gas- and pellet-fueled experiments have also been studied. Additional simulations of the experiments of Sec. 4.1 were carried out with the ion thermal transport given by $\chi_i = \chi_i^{NEO} + \chi_i^{\eta_i}$. The parameter η_i was evaluated across the confinement region from $q = 1$ to $q = 2$ as $(\Delta T_i / T_i)(n / \Delta n)$. $\eta_i = 2$ is characteristic of all the TFTR ohmic gas-fueled experiments studied here.

As shown in Table II, comparisons with the previous simulations for three representative cases which ignored the anomalous ion conductivity, indicate that the new results for the central ion and electron temperatures as well as the total energy confinement times exhibit better agreement with experimental results. The modest saturation of the confinement time at high density for large plasmas on TFTR produced by this model is shown in Fig. 4 (closed circles). The open circles are results of simulations using only the neoclassical Chang-Hinton ion diffusivity, and the crosses are the SNAP data base analysis confinement times for each experiment. The η_i -mode model produces a 20% reduction in τ_E at $n_e = 5 \times 10^{19}/m^3$. Figure 4 presents results for all the large plasma experiments of Table I with q_a between 2.7 and 2.9. Simulation of the highest density shot 14618 with $\chi_i = 3 \chi_i^{NEO}$ produced $\tau_E = 443$ ms, a result very similar to the observed confinement time $\tau = 438$ ms and the η_i model $\tau_E = 439$ ms.

Figure 5 shows the total ion thermal conductivity compared to the Chang-Hinton neoclassical ion thermal conductivity and to $\chi_e(r)$ for high density shot 14618. Efthimion et al. [15] have reported that the saturation of confinement time with increasing density for small plasmas on TFTR ($a = 41$ cm,

55 cm) was found to be consistent with neoclassical ion thermal conductivity. We find that for the large plasmas, high-density saturation of r_E on TFTR cannot be accounted for by neoclassical ion conduction alone. The present simulation results indicate that this saturation is consistent with the predictions of the profile-consistent η_i -mode transport model for χ_i .

Figure 6 shows the three remaining gas-fueled experiments simulated with the χ_e^{ANOM} and χ_i^{ANOM} models. Figure 6(a) shows a comparison of the simulated electron temperature profile with that from the TRANSP analysis code [27] for an $a = 72$ cm gas puff plasma (studied in connection with pellet-injection cases). Figure 6(b) shows temperature profiles for a small a and R plasma considered in size-scaling studies. The solid line in Fig. 6(c) shows the temperature profile predicted for a high- q experiment, the ohmic phase of a TFTR "supershot" with the collisional model. In Table III, we show the simulated central electron and ion temperatures, the confinement times and surface voltages for these simulations with and without η_i as well as the experimental values for each experiment.

The collisional model predicted temperature profile for shot 22014 (Fig. 6c) is not in as good agreement with experimental data because at the radius for which $q = 1.5$, $v_{*e} = 0.1$, and the collisional form of χ_e^{ANOM} would hold for $v_{*e} \geq 0.1-0.2$. We have simulated shot 22014 with the collisionless model for trapped-electron drift wave electron thermal diffusivity Eq. (5). Here the power deposition profile factor given in Eq. (6b) was used with $h(x)$ and $P_{\text{tot},e}$ including the electron heating power only. Use of the collisionless model for analysis of shot 22014 required the coefficients $C_F = 0.72$ and $C_H = 0.5$ because the model has been recast so that the diffusivities χ_e and χ_i depend on the net heating power of each plasma species. The factor $C_G = 0.60$ was obtained by equating the collisionless and collisional diffusivities at

the minor radius for which $q = 1.5$ in simulating ohmic shot 14618, for which $v_{*e} = 0.2$ at the $q = 1.5$ radius.

The collisionless and collisional models give nearly identical results for simulation of the ohmic shot 14618. Simulation with the collisionless χ_e is in better agreement with experiment for the ohmic phase of the supershot 22014 as shown in Table III. The temperature profile is now also in good agreement with Thomson scattering data (dashed line in Fig. 6c). Confinement results of these simulations are discussed in Sec. 6.

4.2.2 Pellet Injection Simulations

The peaked density profiles characteristic of pellet-fueled experiments affect the models of Sec. 2 in two ways. First, the microinstability model for χ_e includes a weak dependence on the density gradient through the exponent α_n of a reference parabolic-shaped density profile. Second (and more significantly), the peaked density profiles characteristic of multipellet-fueled plasmas will reduce η_i and, hence, possibly eliminate the η_i -driven anomalous ion energy transport. The role of the density gradient in electron thermal conduction of ohmic plasmas and stabilization of η_i -mode transport was tested by simulating two deuterium pellet-fueled TFTR experiments.

In order to model more accurately the evolution of the density profile, the pellet simulations required a more complex particle transport model than the nonevolving density profiles of ohmic gas-fueled experiments given by Eqs. (10) and (11). To simulate the measured evolution of the line-averaged density, which exhibits pumpout after injection, the anomalous inward particle pinch, v_{*e}^{anom} , was set to zero after injection of the pellet. As noted earlier, the particle transport models used throughout this study were chosen

only to reproduce reasonable agreement with empirical density profiles and were not based on any particular theoretical model.

Simulation results for $T_e(r,t)$ and τ_E with $x_i = x_i^{NEO} + x_i^{\eta_i}$ were found to be almost identical to those from the simulation which had $x_i = 3x_i^{NEO}$ with $x_i^{NEO} \equiv x_i^{\text{Chang-Hinton}}$. However, this by no means suggests that the models are equivalent, since x_i^{NEO} has a dramatically different scaling from $x_i^{\eta_i}$ at higher temperatures (and lower collisionality).

4.2.2.1 Single-Pellet Ohmic Experiment

TFTR shot 14371 is similar in many respects (I_p , R , B_T , Z_{eff} , see Table 1) to gas-fueled shot 14454, included in the first set of ohmic TFTR simulations presented in Sec. 4.1. BALDUR uses a modification of the neutral gas shielding pellet ablation models developed by Milora and Houlberg [13,28]. Sawteeth were included in the simulation during the pellet phase as observed in the experiment.

A deuterium pellet (7×10^{20} D⁺, 2.67 mm diameter) was injected at 2.0 sec. The model pellet velocity was adjusted to obtain pellet penetration to the observed radius of 35 cm. The empirical model used here has the form

$$D^{ANOM} = \frac{4.0 \times 10^{16} \text{ cm}^2/\text{sec}}{n_e(r) (\text{cm}^{-3})}, \quad (12)$$

with

$$v^{ANOM} = 2 D^{ANOM} r/a^2, \quad (13a)$$

but with

$$ANOM = 0$$

(13b)

after pellet injection.

The density profiles generated by Eqs. (12) and (13) are very similar to those from multichannel infrared interferometer data. In this shot, the central density was increased by only 30%. The η_i -parameter of the single pellet-fueled case at 2.5 sec is 2.5, so that η_i -mode stabilization was not achieved.

Since the theoretical model used here was derived with steady-state approximations, it cannot be expected to reproduce accurately transient time scale phenomena, such as plasma evolution, during current ramp or plasma behavior immediately following pellet injection. The central temperature is overestimated by about 15%. Confinement times are in good agreement with experiment (see Sec. 6).

4.2.2.2 Three-Pellet Experiment

Pellet experiments for 72 cm plasmas show enhanced confinement at the highest densities [29]. The particle transport in Shot 18681, a 72 cm three-pellet ohmic shot, was modeled with $D = (3 \times 10^{16}/n_e)\text{cm}^2/\text{sec}$, $v = 0$ after pellet injection. Sawteeth were not included in the simulation as they were not present in the experiment. The simulation plasma was found to exhibit $\eta_i < \eta_c$ after pellet injection. A typical TFTR ohmic gas puff shot 18673 (the no-pellet reference case) was found to have $\eta_i = 1.9$, typical for TFTR ohmic gas-puff-fueled experiments. The three-pellet shot was found to have $\eta_i = 0.9$, 0.25 sec after the third pellet, rising to $\eta_i = 2.6$, 1.8 sec after injection. Thus, η_i -driven transport was suppressed in model simulations immediately following injection but was included afterwards when η_i exceeded

1.5.

The central electron temperature predicted by the model after the third pellet is injected is consistently 10% higher than electron cyclotron emission (ECE) measurements. However, when the pellet-fueled plasma has reached a new quasi-steady-state density profile with central density varying less than $3 \times 10^{13}/\text{cm}^3\text{-sec}$, the model for χ_e gives good agreement with measured ECE temperature profiles. Confinement predictions of suppressed η_i mode transport are found in good agreement with the experiment as discussed in Sec. 6.

5. TRANSPORT SIMULATIONS OF PDX OHMIC EXPERIMENTS

A similar set of simulations was carried out for a series of nearly identical ohmic plasmas observed on the PDX machine (shots 61610, 61617, 61621, 61623, 61626, 61627, and 61629). The characteristic parameters for these deuterium plasmas were $B_Z = 1.7$ T, $R = 1.4$ m, $a = 0.39$ m, $q_a = 2.55$, and $Z_{\text{eff}} = 1.8$ with the plasma impurity concentration being primarily oxygen, 1.6%. Since these plasmas had not reached a final steady state, χ_e^{ANOM} overestimates the electron temperature by 20% (Table 3). As in the TFTR simulations, the anomalous diffusivities here were again taken to be $\chi_e = \chi_e^{\text{TE}}$, $\chi_i = \chi_i^{\eta_i}$ with scaling coefficients $C_F = 0.67$, $C_H = 0.1$. For this simulation the predicted steady-state confinement time of $\tau_E = 0.040$ sec is in agreement with the experimental confinement time of 0.045 ± 0.005 sec. The ion conduction losses at $a/2$ are only 25% of the electron conduction losses. The total ion diffusivity at $a/2$ is $2.3 \chi_i^{\text{NEO}}$.

6. DISCUSSION

At low to moderate densities, experimental results from the large plasma ohmic TFTR discharges have generally exhibited the familiar scaling of energy

confinement time with line average density observed in smaller ohmically heated tokamak discharges. This is illustrated on Fig. 4 which plots the simulation results for τ_E versus n_e for $x_e = x_e^{TE}$ and $x_i = x_i^{NEO}$ (open circles). However, at higher densities, we found the observed 20% saturation of τ_E could be reproduced by including the η_i -driven effects. The dashed line indicates neo-Alcator scaling. Favorable correlation is found between the data-base (SNAP) results and the simulated energy confinement times. Figure 4 presents results for large plasmas with q_a between 2.7 and 2.9.

As shown in Ref. [6], the neo-Alcator or Pfeiffer-Waltz [30] scaling of τ_E ($\propto n_e a R^2$) can be analytically derived from the profile-consistent microinstability models used in the present studies. It is therefore not surprising that this trend can be reproduced in the simulations of the TFTR discharges. This is illustrated on Fig. 7 where the simulated values for τ_E (open circles) and the experimental values from SNAP (x) are plotted against the TFTR ohmic scaling parameter [15], $\bar{n}_e q_a R^2$, for all the experiments of Table I. Approximate linear scaling is apparent over a range of this parameter from 3×10^{19} to 8×10^{20} . This figure also provides a useful summary of results from this series of simulations. In particular, the solid circles depict the simulation results for the ohmic gas-puff plasmas where ion thermal transport is modeled with the toroidal η_i -drift mode diffusivity and where the saturation of confinement time is accordingly reproduced. With regard to the PDX ohmic simulation, the anomalous x_i -model was again employed. Although the experiment has not reached a steady state, the simulation of this case does provide a size scaling for the model at a low value of the TFTR ohmic scaling parameter.

Results from simulations of a single-pellet-fueled TFTR discharge are included in Fig. 7. The two open diamonds represent experimental confinement

times at two points in time for the evolving 82 cm single-pellet-fueled case [$n_e q_a a R^2 = 6.6 \times 10^{20}$ ($t = 3.0$ s) and 8.3×10^{20} ($t = 2.5$ sec)]. Here, the higher value of τ_E corresponds to the period soon after injection and the lower value to a later time in the discharge. The simulation results (solid circles) are in good agreement with the experimental confinement times.

Figure 8 shows confinement times from predictive simulations with no η_i -driven ion thermal transport. In these simulations, the highest density, ohmic gas puff simulation of shot 14618, with line average density $4.8 \times 10^{13}/\text{cm}^3$, was modified to have higher line average densities, so that neoclassical ion transport became dominant over the trapped electron conductive transport. Figure 8 shows the behavior of this model for values of the $n_e q_a a R^2$ parameter up to 76.0×10^{20} . $\tau_E \approx 0.9$ sec represents a maximum confinement time for a gas-puff-fueled experiment on TFTR at these plasma parameters q_a , R , n_e , I_p , Z_{eff} if ion thermal transport were neoclassical and electron thermal transport were described by Eq. (6).

The one-pellet case simulated did not exhibit η_i stabilization ($\eta_i = 2.5$). The relatively low confinement of this one-pellet shot 14371 relative to the ohmic gas-fueled experiments can be understood by detailed comparison of the simulated energy losses in the one pellet shot to ohmic gas-puff shot 14618 at the same density. These cases are represented by the two solid circles in Fig. 7 at $\tilde{n}_e q_a a R^2 = 7 \times 10^{20}$. The time of interest in shot 14371 here is at 2.5 sec. At this time the two plasmas have similar densities, Z_{eff} , and ohmic heating (Table IV). They are both $\tilde{R} = 2.56$ m, $a = 0.82$ m plasmas.

The difference in confinement is consistent with the fact that the central energy balance is different in the two plasmas. In particular, for the pellet-fueled case, the center is losing energy by convection and

radiation at a faster rate than the gas-fueled plasma. This can be seen by comparing the integrated heating and losses in the two cases at $r = a$ and at $r = a/2$ (Table V). The inward pinch in the particle transport model of shot 14618 causes negative total convective losses within the confinement region at $r = a/2$. The 18% lower global confinement of the one-pellet case results from 18% greater power losses, due primarily to convection and radiation, at $a/2$. Hence, the decrease in the central electron temperature for the pellet-fueled case can be associated with increased radiative and convective losses.

Confinement results for a three-pellet-fueled experiment (a 72 cm plasma) are shown with 72 cm gas puff data (derived from magnetic measurements of the plasma stored energy) in Fig. 9. The x's denote deuterium gas-fueled experiments, the crosses (+) denote helium gas-fueled experiments, and the asterisks (*) denote deuterium pellet injection data points. The solid line indicates the density saturation of confinement for 72 cm gas-fueled discharges.

We note that the helium and deuterium gas puff confinement times saturate at about 300 msec for 72 cm plasmas compared to 400 ms for 82 cm plasmas. The neoclassical χ_i depends on ion mass and effective charge so that since

$$(\chi_{i,neo}^{deu} / \chi_{i,neo}^{helium}) = \frac{1}{2\sqrt{2}}$$

for the same n_e , we would not expect neoclassical ion transport to produce the same saturated confinement time for helium and deuterium plasmas at high density. On the other hand, since the n_i -driven χ_i used here has no dependence on Z_{eff} and no explicit strong dependence on ion mass, it would roughly show the same saturated confinement for helium and deuterium if electron and ion transport were described by the models of Sec. 2. This is

the behavior seen in experiments on TFTR. The η_i -mode saturated confinement time [6] scales as

$$\tau_E \propto \left(\frac{n_0}{P_T} \right)^{0.6} R^{1.8} I_p^{1.0} a^{0.2} B_T^{-0.2}.$$

For the 72 and 82 cm plasmas (Table I), with similar densities and heating, this leads to $\tau(a=82)/\tau(a=72) = 1.3$, approximately the ratio of the observed saturated confinement times.

We have carried out a number of simulations of the 72 cm three-pellet experiment to study the effect of different ion transport models. Results shown in Fig. 9 depict simulations with $\chi_i = \chi_i^{\text{neo}}$ (closed circles); $\chi_i = \chi_i^{\text{neo}} + \chi_i^{\eta_i}$; [$\chi_i^{\eta_i}$ turned off $\eta_i < \eta_i^C$] (open circles); $\chi_i = 3 \chi_i^{\text{neo}}$ (open squares); $\chi_i = \chi_i^{\text{neo}} + \chi_i^{\eta_i}$, [$\chi_i^{\eta_i}$ left on even if $\eta_i < \eta_i^C$] (solid squares), and $\chi_i = \chi_i^{\text{neo}}$ with $Z_{\text{eff}} = 1$ and no impurity radiation (open triangles). The simulation confinement times shown have been averaged over a confinement time.

Experiments show enhanced confinement for the 72 cm pellet-fueled plasmas relative to gas fueling. The simulation results are consistent with this being due to stabilization of the η_i -driven ion transport; we found η_i well below 1.5 after pellet injection (Sec. 4.2.2). The η_i parameter rises to 1.5 just prior to 1.8 sec after which η_i -driven transport becomes important. The averaged confinement time drops from 0.36 seconds (at 2.8 sec) to 0.32 sec (at 3.6 sec.). If η_i transport is suppressed throughout the discharge, the simulated confinement time is higher, 0.37 sec (at 2.85 sec) to 0.36 ms (at 3.6 sec) throughout. Thus, the value of $\eta_i^C = 1.3$ seems consistent with experimental measurement of confinement.

We cannot clearly distinguish between neoclassical anomaly factors of 1-3 on the basis of these simulations and the magnetic confinement time. The

quoted experimental confinement times have been effectively averaged over one confinement time. However, the instantaneous measured confinement times are higher by about 40 ms. Our time-dependent simulation results show that $\chi_i = \chi_i^{NEO}$ is consistent with the kinetically measured τ_E (TRANSP) and with the instantaneous magnetic confinement time averaged over a shorter time period. These data are not found to be consistent with $\chi_i = 3 \chi_i^{NEO}$. Simulations with anomalous η_i ion transport retained or with $\chi_i = 3 \chi_i$ are found equivalent for the three-pellet case as for the other experiments modeled. The simulation results for open triangles indicate the best confinement expected for a pure deuterium pellet-fueled plasma with no impurity radiation loss, and with trapped electron transport and neoclassical ion transport. The data point at $\bar{n}_e = 1.4 \times 10^{20}/m^3$ is from a 5 pellet experiment [29] which has not been simulated.

A set of simulations for 72 cm plasmas was carried out analogous to the gas-fueled simulations of Fig. 4 predicting $\tau_E = 630$ ms for a gas-fueled experiment with $n_e = 9 \times 10^{13}/cm^3$ and neoclassical ion losses. The model prediction for shot 18681 was $\tau_E = 336$ ms at $n_e = 10.7 \times 10^{13}/cm^3$. Lower τ_E for the pellet simulation reflects the lower central plasma temperature. The TFTR pellet case does not maintain increased density long enough for the plasma to reheat back to ohmic-like temperatures. The reduced temperature causes lower thermal energy and also higher resistivity, hence, higher ohmic heating power. $\tau_E = nT/P_{OH}$ is reduced for both these reasons. Because the increased ohmic heating power causes increased electron transport [Eq. (6a)], the simulations show an increase of $\chi_e(r=a/2)$ to $5.2 \times 10^3 cm^2/sec$ for the three-pellet simulation compared to $2.0 \times 10^3 cm^2/sec$ for an ohmic gas puff simulation at similar plasma parameters R , a , Z , I_p , and n_e . The total energy confinement time of the pellet simulation is much less than that for the

simulation of the ohmic gas puff case with $1 \times \chi_i^{\text{NEO}}$ for this reason. In the pellet simulation, convective losses are small and radiation losses account for about 20% of the heating power.

As noted earlier, since the models for the anomalous thermal diffusivities used in the simulations were based on steady-state approximations, they cannot be expected to describe accurately the relatively rapid detailed evolution of the plasma immediately following pellet injection. Nevertheless, the simulation does show some qualitatively significant features found in the experiment - namely, increased central confinement time after pellet injection. Our simulations of the single pellet injection experiment show the confinement time at $a/4$ increasing from 0.35 sec to 0.5 sec over the first 500 msec after pellet injection. The fractional increase in the central confinement was found equal to that of the global confinement for both pellet cases studied. No additional increase in the central confinement due to the more peaked density profile was found. For example, in the three-pellet case, when the volume average density is increased by a factor 3 and the central density is increased by a factor 7, both the global and central confinement increase by 75%. This increase in central confinement time is of special interest with respect to the goal of obtaining an ignited plasma at the lowest global density and temperature [31].

It should also be pointed out that when the pellet-fueled plasma has reached a new steady-state density profile, the model for thermal diffusivity leads to good agreement with TRANSP-derived diffusivity profiles. Good agreement was found for the predicted radial variation of χ_e in the simulations compared to that obtained from the data analysis code in all cases for which TRANSP runs were available. Comparison plots are shown in Fig. 10 for shot 14454, a gas-fueled discharge.

The Gaussian-temperature-based χ_e model produces an approximation to a "sawtooth average" temperature profile in simulations. Addition of a sawtooth model to the calculation flattens the central temperature periodically, but does not significantly affect the overall shape. Figure 11 shows the simulated temperature profile and the Gaussian form, both normalized to $T_e(a/2)$ for shot 14618.

Recent analysis of TFTR temperature profiles by Fredrickson et al. [32] suggests that the apparent q_a -dependence of $T_e(r)$ actually results primarily from the effect of sawteeth at the center, and not from changes in $T_e(r)$ outside $q=1$. They find that electron temperature profile data outside $r = a/3$ do not show any q_a -dependence, and that the q_a -dependent Gaussian form, used in deriving the model χ_e , is a good approximation at low- q (~ 3), for plasmas in ohmic equilibrium. At high- q and during current ramps, the Gaussian form was found to differ significantly from the measured electron temperature profile shape.

Comparison of the measured and simulated temperature profiles indicates that the model predictions at low q_a are in best agreement with data and that the model overestimates the anomalous losses near the edge at high q_a (see Figs. 1,2,6).

The local expression for the drift wave diffusivity on which this model is based exhibit no q_a -dependence. The analytic τ_{Te} obtained for this model is found proportional to $q_a^{0.5}$ [6]. This q_a -dependence arises entirely from the particular choice of temperature profile which reflects temperature profile trends observed in numerous experiments. Our simulation results, which included a sawtooth model, are consistent with $\tau \propto q_a$. How the q_a scaling of τ_e is related to sawtooth modeling and the choice of a temperature profile will be the subject of future investigations.

It is of interest to consider how greatly the numerical factors $C_F = 0.67$ and $C_H = 0.1$ in χ_e^{ANOM} and χ_i^{ANOM} can be changed while keeping good agreement with the plasma temperatures. If $C_F = 0.5$ and $C_H = 0.3$ were used, the high density ohmic results are unchanged, but the low density cases are found to be simulated with central electron temperatures about 15% too high.

7. SUMMARY AND CONCLUSION

We have shown that for large plasmas on TFTR covering a wide range of plasma parameters using the profile-consistent trapped-electron drift wave model for χ_e in BALDUR leads to simulation results in good agreement with the empirical TFTR ohmic scaling for τ_E . The model has been extended to apply to experimental cases with high radiation, and has been used in a large number of detailed transport simulations to predict successfully the electron temperature magnitudes and profiles and the total plasma energy confinement times of actual TFTR experiments.

As also observed in a number of other ohmically heated tokamaks, the energy confinement times at the highest densities on TFTR show a saturation with increasing density. The toroidal η_i -mode has been proposed as a mechanism by which increased thermal transport may be driven at high plasma densities provided the density profiles are sufficiently flat to cause $\eta_i > (\eta_i)_c$. We have shown that the observed saturation of τ_E at high density for large plasmas on TFTR is consistent with the profile-consistent model for η_i -driven transport.

The order-unity numerical factor in χ_e [Eq. (6)] and the one in χ_i [Eq. (7)] have been calibrated only once for TFTR large plasmas. No subsequent adjustments were made in the successful simulations of not only a wide variety of TFTR cases, but also of a set of PDX ohmic discharges.

Confinement time results are consistent with η_i -mode-driven transport being suppressed in high-density pellet-fueled plasmas. Specifically, if the density profile has been peaked by pellet fueling, the η_i -parameter, $d[\ln T_i(r)]/d[\ln n_i(r)]$, may be less than the critical value. The microinstability model simulations presented here are in good agreement with this picture for both a single-pellet ($\eta_i > \eta_i^c$) and a three-pellet injection ($\eta_i < \eta_i^c$) experiment.

The next phase of these systematic studies simulating TFTR plasmas will deal with the investigation of auxiliary heated discharges. In particular, experiments involving strong ion-heating processes (e.g., neutral beam injection and ICRF) generally exhibit significantly lower thermal confinement than the ohmically heated plasmas. Identifying the physics primarily responsible for such effects is clearly of vital importance. To this end, simulations of NBI-heated TFTR experiments (with and without pellet fueling) have been carried out using the models for anomalous thermal transport described in the present paper. Initial results indicate encouraging agreement with observed trends [33]. By building on research efforts of this type (including coordinated theoretical, experimental, and computational studies), it is hoped that a sufficient understanding of tokamak confinement physics can be gained to help significantly in designing the next generation of ignition machines.

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Table I.
Parameters of Simulated Ohmic TFTR Shots

SHOT	I_p (MA)	B_z (T)	R(m)	a(m)	$\bar{n}_e(10^{19}/m^3)$	P_{rad} (MW)	P_{OH} (MW)	Z_{eff}^b	q_a
11603	1.8	3.9	2.56	0.82	2.1	1.2	1.9	4.71	2.9
11606	1.8	3.9	2.56	0.82	2.1	1.4	1.97	5.13	2.9
11609	1.8	3.9	2.56	0.82	3.05	1.2	1.74	3.2	2.9
13638	1.4	3.9	2.59	0.8	2.46	0.6	1.11	3.0	3.5
14038	2.2	4.7	2.59	0.8	3.46	0.7	1.96	2.6	2.7
14041	2.2	4.7	2.59	0.8	4.26	0.75	1.95	1.97	2.7
14043	2.2	4.7	2.59	0.8	4.71	0.8	1.96	1.76	2.7
14371	1.8	4.7	2.56	0.82	3.2(5.1 ^a)	1.2	2.0	2.(1. ^a)	3.4
14454	1.8	4.7	2.59	0.82	3.2	0.6	1.67	3.12	3.3
14616	2.2	4.7	2.57	0.82	3.58	0.8	2.06	2.62	2.7
14617	2.2	4.7	2.57	0.82	3.89	0.8	1.97	2.31	2.8
14618	2.2	4.7	2.57	0.82	4.77	0.9	1.96	1.76	2.8
14619	2.2	4.7	2.57	0.82	3.2	0.8	1.97	3.19	2.7
17871	0.7	2.9	2.25	0.60	1.6	0.4	0.6	1.8	3.3
18673	1.6	5.0	2.37	0.72	3.4	0.7	1.4	1.3	3.5
18681	1.6	5.2	2.37	0.72	3.4(13. ^a)	1.0	1.5	1.6(1.2 ^a)	3.4
22014	0.8	4.6	2.56	0.81	0.8	0.16	0.5	3.4	7.2

^aafter pellet injection

^bfrom visible bremsstrahlung measurements

Table II.

Effect of η_i -Mode-Driven Anomalous Ion Conduction on Central
Ion and Electron Temperatures, Loop Voltages, and Confinement Times

$$\text{with } \chi_i = \chi_i^{\text{NEO}} + \chi_i^{\eta_i}(C_H).$$

	C_H	V_{loop}	$T_e(0)$	$T_i(0)$	τ_E	$\bar{n}_e$
TFTR SHOT 14618						
EXPERIMENT	--	0.9	2.4 keV	2.3 keV	438 ms	$4.7 \times 10^{19}/\text{m}^3$
BALDUR	0.	0.9	2.7	2.6	520	
	0.1	1.0	2.6	2.4	439	
	1.2	1.6	1.8	1.6	179	
TFTR SHOT 14038						
EXPERIMENT	--	0.9	3.05	2.9	331	3.5×10^{19}
BALDUR	0.	0.95	3.1	2.8	380	
	0.1	1.0	3.0	2.6	323	
	1.4	1.5	2.3	1.6	164	
TFTR SHOT 11603						
EXPERIMENT	--	1.1	3.8	2.57	211	2.4×10^{19}
BALDUR	0.	1.2	3.8	3.2	210	
	0.1	1.2	3.7	2.9	188	
	1.0	1.6	3.0	1.8	120	

Table III.
Comparison of Confinement Times, Loop Voltages, Electron and Ion
Central Temperatures from Experiment and Simulation

Shot	Experiment				Simulations x_e^{ANOM}, x_i^{NEO}				Simulations x_e^{ANOM}, x_i^{ANOM}			
	τ_E	V	T_e (keV)	T_i (keV)	τ_E	V	T_e	T_i	τ_E	V	T_e	T_i
PDX ^b	0.045	1.4	0.75	--	0.052	1.0	1.1	0.80	0.043	1.2	0.96	0.70
TFTR												
11603	0.211	1.1	3.8	2.6	0.210	1.2	3.8	3.2	0.188	1.2	3.7	2.9
11606	0.199	1.1	3.5	--	0.195	1.3	3.5	3.1	0.178	1.4	3.5	2.9
11609	0.280	1.0	2.8	--	0.295	1.1	2.8	2.6	0.255	1.2	2.9	2.5
13638	0.333	0.8	2.8	--	0.391	0.87	3.1	2.8	0.338	0.93	3.0	2.6
14038	0.331	0.9	3.05	2.9	0.380	0.95	3.1	2.8	0.323	1.03	3.0	2.6
14041	0.407	0.9	2.7	--	0.483	0.90	3.0	2.8	0.404	0.99	2.8	2.6
14043	0.415	0.9	2.5	--	0.521	0.88	2.7	2.6	0.435	0.98	2.7	2.5
14454	0.300	0.9	3.2	--	0.433	0.87	3.8	3.3	0.378	0.93	3.6	3.9
14616	0.344	0.9	2.9	--	0.413	0.95	3.3	3.0	0.353	1.0	3.1	2.8
14617	0.384	0.9	3.0	--	0.468	0.89	3.3	3.0	0.412	0.97	3.2	2.9
14618	0.438	0.9	2.4	2.3	0.520	0.91	2.7	2.6	0.439	0.99	2.6	2.4
14619	0.339	0.9	3.5	--	0.367	1.0	3.7	3.3	0.320	1.1	3.6	3.1
17871	0.134	0.87	1.9	--	0.157	0.88	2.3	1.8	0.140	0.93	2.2	1.6
18673	0.290	0.8	2.9	--	0.330	0.85	3.1	2.9	0.280	0.91	2.9	2.6
22014	0.199	0.57	4.5	--	0.111	0.87	3.9	1.9	0.126	0.82	3.8	1.8
									0.176	0.68	4.5	2.0 ^a

^aSimulated with collisionless model for x_e^{ANOM} .

^bAverage of PDX shots 61610, 61616, 61621, 61623, 61626, 61627, and 61629.

Table IV.

Comparison of a Gas-Puff and a Single-Pellet Experiment

	TFTR Shot 14618 (at 3.4 sec)	14371 (at 2.5 sec)
	Gas Puff	Pellet
$\bar{n}_e$	$4.7 \times 10^{19}/\text{m}^3$	$4.4 \times 10^{19}/\text{m}^3$
$P_{\text{GH}}^{(a)}$	2.1 MW	1.8 MW
$P_{\text{Loss}}^{(a)}$	2.0 kW	1.9 MW
τ_E	0.44 sec	0.35 sec
T_e	2.5 keV	2.4 keV

Table V.

Total Integrated Losses and Heating at $a/2$ for a
TFTR Gas-Puff and a Single-Pellet-Fueled Experiment

	$(P_{\text{cond}})_e$	$(P_{\text{conv}})_e$	$(P_{\text{cond}})_i$	$(P_{\text{conv}})_i$	P_{rad}	P_{OH}	dW/dt
<u>at $r = a/2$</u>							
Gas Puff	0.75 MW	-0.02	0.16	-0.01	0.18	1.2	0.16
Pellet	0.75	+0.04	0.19	+0.04	0.24	1.2	-0.03

FIGURE CAPTIONS

FIG. 1. Comparison of temperature profile data from Thomson scattering to BALDUR simulations for nine ohmic TFTR shots with a radiation-uncorrected model for x_e : (a) shot 13638, (b) shot 14043, (c) shot 14618, (d) shot 14038, (e) shot 14616, (f) shot 14619, (g) shot 14041, (h) shot 14617, (i) shot 14454.

FIG. 2. Comparison of Thomson scattering temperature profile data to BALDUR simulations for plasmas with greater than 60% radiation. Figures 2(a) - 2(c) (shots 11603, 11606 and 11609) with model uncorrected for radiation; Figs. 2(d) - 2(f), (shots 11603, 11606 and 11609) with radiation-corrected model.

FIG. 3. Predicted BALDUR temperature profile for TFTR shot 14618 simulated with an empirical INTOR-like model.

FIG. 4. Saturation of energy confinement time for TFTR large plasma experiments (crosses) compared to simulations with profile-consistent models with (solid circles) and without η_i -driven anomalous ion thermal transport (open circles).

FIG. 5. Comparison of Chang-Hinton neoclassical ion conductivity, η_i -mode ion conductivity plus neoclassical, and x_e^{ANOM} for simulation of TFTR shot 14618.

FIG. 6. Electron temperature profiles from simulations (solid lines) with collisional x_e^{ANOM} and x_i^{ANOM} for (a) shot 18673 compared to TRANSP analysis ECE data (dashed line), (b) shot 17871, and (c) shot 22014 both compared to Thomson scattering data (solid circles). Dashed line in (c) is from simulation with collisionless x_e^{ANOM} and x_i^{ANOM} .

FIG. 7. Plot of total energy confinement time versus a neo-Alcator-like parameter for PDX and TFTR cases from toroidal η_i -drift mode model

simulations (solid circles) and from experimental results (crosses, open diamonds). The purely ion neoclassical results from BALDUR are also given for comparison (open circles). All simulations were carried out with the collisional trapped electron drift wave model for χ_e .

FIG. 8. Total energy confinement time from simulations with χ_e^{TE} and χ_i^{NEO} versus the neo-Alcator-like TFTR ohmic scaling parameter. Representative points from experiments with gas puff (crosses) and pellet (diamond) are shown (compare Fig. 7).

FIG. 9. Simulated and experimental confinement times for TFTR 72 cm discharges. Data points: x indicates deuterium gas fueling, + indicates helium gas fueling, * indicates deuterium pellet injection. Simulations: open circles indicate ion transport $\chi_i^{neo} + \chi_i^{\eta_i}$, [with $\chi_i^{\eta_i}$ turned off $\eta_i < \eta_i^C$], closed circles indicate χ_i^{neo} , open squares indicate $\chi_i = 3\chi_i^{neo}$, closed squares indicate $\chi_i = \chi_i^{neo} + \chi_i^{\eta_i}$, [with $\chi_i^{\eta_i}$ not turned off $\eta_i < \eta_i^C$], open triangles indicate the same simulation parameters as open circles, with $Z_{eff} = 1$ and no impurity radiation.

FIG. 10. Comparison of electron thermal conductivity from simulation to that from TRANSP analysis, for TFTR shot 14454.

FIG. 11. Comparison of a typical temperature profile calculated by BALDUR with a Gaussian profile defined by Eq. (1).

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

#86P0071

FIG. 11

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