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TRANSPORT SIMULATIONS OF OHMIC PELLET EXPERIMENTS ON THE TFTR, ASDEX, AND ALCATOR-C TOKAMAKS

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ABSTRACT. Transport simulations of ohmic gas-fuelled and pellet-fuelled experiments have been carried out to test a microinstability-based, profile-consistent model of anomalous transport in tokamaks. Predictions for experiments on the TFTR, ASDEX, and ALCATOR-C tokamaks were found consistent with the observed confinement and temperature measurements.

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1. INTRODUCTION

A central problem in plasma physics is understanding and improving the energy confinement of tokamak discharges. Measurements of the electron thermal confinement time indicate a large anomalous reduction: i.e., τ_{eE} is usually less than one one-hundredth of neoclassically predicted levels. For the ions, the observed confinement times are typically less than one-third of neoclassical estimates.

Transport simulations with recent theoretically based models [1] for these anomalous electron and ion thermal losses have been found in good agreement with ohmic and neutral-beam-heated experiments on TFTR [2,3]. In these simulations trapped-electron drift wave transport at low density was found to give rise to neo-Alcator scaling, and η_i -driven ion transport was found consistent with the onset of density saturation of the total energy confinement time for large plasmas. Initial simulation studies of TFTR pellet-fuelled experiments were consistent with suppression of η_i -driven ion transport and improved confinement during the peaked profile phase following pellet injection. Results from recent measurements of density fluctuation properties [4,5] tend to support the existence of the specific microscopic transport processes underlying the theoretical model studied here.

We have extended the tests of the microinstability-based models to ohmic experiments on ASDEX and ALCATOR-C using the BALDUR code [6]. Simulations of representative gas and pellet-fuelled discharges on these tokamaks have been carried out to see if the TFTR calibration of the theoretical model can be used for simulations of experiments on machines in different plasma parameter ranges. Analysis of pellet-fuelled experiments is of particular importance for developing a fusion reactor because significantly improved confinement has been observed for pellet-fuelled ohmic plasmas [7-9] and because it is the only way to fuel most proposed reactors. Global confinement increases by about a factor of two for each of these tokamaks with pellet-fuelling. At medium densities, where pellet fuelling does not exceed the gas-fuelling density limit, however, improved confinement with pellet injection is not seen [10].

Each of the experiments considered has already been analyzed by the experimental team responsible for the data. The goal of this paper is to attempt to unify the modelling of the experiments using one theoretically

based model with no change in overall numerical coefficients.

2. MICROINSTABILITY-BASED MODELS FOR χ_e AND χ_i

The profile-consistent microinstability-based model for anomalous electron thermal diffusivity, χ_e , was originally introduced in Ref. [1] and represents the effects of the trapped-electron mode in both collisional and collisionless regimes. As none of the experiments simulated fell in the collisionless regime, only the collisional form of the electron diffusivity is discussed here. The model for anomalous ion thermal transport, χ_i , was also presented originally in Ref. [1]. It is based on the excitation of the toroidal ion temperature gradient-driven instabilities (η_i modes).

The simulations in this paper are carried out with improved versions of the electron and ion diffusivities

$$\chi_e^{\text{collisional}}(r) = \frac{4.3 \times 10^3 (1 - 0.25\alpha_n) (P_{\text{tot},e})^{0.8}}{n_{e0} R^{1.2} a^{0.1} Z_{eff}^{0.2} B_T^{0.3} q_a^{0.9}} F_e(r). \quad (1)$$

and

$$\chi_i^n(r) = \frac{5 \times 10^3 (P_{\text{tot},i}/n_{e0})^{0.6}}{(B_T R q_a)^{0.8} a^{0.2}} F_i(r). \quad (2)$$

Here,

$$F_j(r) = \frac{1 - e^{-\alpha_j} [e^{(2\alpha_q r^2/3a^2)} \int_0^{r/a} dx x h_j(x)]}{[n_e(r)/n_{e0}] (r^2/a^2) \int_0^1 dx x h_j(x)}, \quad j=i,e, \quad (3)$$

where $R(m)$, $a(m)$, $B_T(T)$, $n_{e0}(10^{20}/m^3)$, $\alpha_q = q_a - 0.5$. α_n characterizes the density profile, $\alpha_n = n_0(1 - (r/a)^2)^{\alpha_n}$, and $h_j(x)$ is the total electron or ion heating energy deposition profile. $P_{\text{tot},e}(MW)$ is the net electron heating power from all plasma heating sources. In our simulations we subtract the radiated power and the electron-ion temperature equilibration energy loss from the ohmic electron heating contribution. $P_{\text{tot},i}$ is the total ion heating power, and $h_i(x)$ is the ion heating deposition profile. The ion heating energy deposition arises only from the electron-ion energy transfer in this study of ohmically heated plasmas.

The model was derived for steady-state ohmic equilibrium conditions. The normalization constants in these equations were obtained in simulations

of TFTR ohmic experiments [2]. It was found that the microinstability-based χ_i model produces ion thermal transport roughly equivalent to using a factor of 3 for the neoclassical multiplier in the simulation studies of TFTR [2].

Note that this formulation of the model, Eqs. (1-4), differs from that in Ref. [1] in that the diffusivities depend on the species-specific heating power rather than the total heating power absorbed by the plasma. In high density pellet experiments the improved model χ_i will be larger: the toroidal ion instabilities will have increased power available through the exchange term. The improved, species-specific heating forms for χ_e and χ_i have been used to model both ohmic and neutral-beam-heated cases [3] with no change in numerical coefficients.

Ohmically heated TFTR cases have been simulated [2] with the original model [1]. The improved version has already been used for the neutral-beam-heated cases studied in Ref. [3] and for the one collisionless ohmically heated case in Ref. [2]. For ohmically heated, gas-fuelled plasmas on TFTR this difference in formulation changes only the overall normalization in that simulation results for confinement and plasma temperatures are almost unchanged. However, for neutral-beam-heated plasmas, where the ion heating fraction becomes large, and for high density pellet-fuelled plasmas, where Q_{ei} is significant in the electron power balance, Q_{ei} , these two formulations are no longer equivalent. In Section 4.1 the power balance results for several simulation cases are presented for both of these models.

3. SIMULATION RESULTS

In Table I are shown the plasma parameters for the seven experiments simulated. The TFTR pellet-fuelled experiments simulated here are high current, large R and a , three and five-pellet discharges. The three-pellet experiment was also analyzed in the TFTR ohmic simulations study [2]. This case has been reanalyzed with an improved version of the microinstability-based model.

The TFTR five-pellet case exhibited enhanced confinement for 0.8 sec [9], about $1.5 \times \tau_E$. Since this case did not have time-dependent density profiles available, we have attempted to simulate this shot by using the 76-point Thomson scattering density data (at 200 msec following the last pellet) for

a time-independent "steady-state simulation." The two ASDEX experiments simulated are very similar multiple-pellet-fuelled shots. The ASDEX experiments are of particular interest as a steady-state peaked profile condition is maintained by multiple pellet injection in a divertor tokamak for as long as 1.0 sec., i.e., about $7 \times \tau_E$. Where the relevant data were available, a reference gas-fuelled discharge at the same conditions of current, magnetic field, etc. was also simulated. The experiments on the ALCATOR-C tokamak are high toroidal field, high density scenarios: a lower density one-pellet discharge and a high current, very high density three-pellet discharge.

3.1. Transport Modelling

The BALDUR transport code [6] solves time-dependent radial diffusion equations to simulate the evolution of the current and particle densities and the electron and ion temperatures. Up to two species of hydrogen and four species of impurities can be handled by the multifluid code. Resistivity is assumed to be neoclassical. A Kadomtsev sawtooth model is used with the sawtooth period set to the measured period.

Particle densities are computed for all species. The particle flux includes both diffusive and advective effects. The source of particles arises from ionization of thermal neutrals and from pellet injection modelling [11,12]. Recent analysis of enhanced confinement neutral-beam-heated discharges by Zarnstorff [13] indicates that an upper bound on the central ion convective multiplier is greater than or equal to $5/2$ and the central electron convective multiplier is between $3/2$ and $5/2$. However, at this time there is no general prescription for the convective multiplier appropriate for a particular tokamak in a given experimental scenario. The convective multiplier has been assumed to be $3/2$ in the simulations in this paper.

Except for TFTR shot 20259, for which complete time-dependent data were not available, all experiments were simulated to model the full time evolution of the experimental shot including the pre-pellet gas-fuelled phase and the pellet injection phase, matching pellet size and injection times. Pellet velocities were adjusted to give agreement with pellet penetration as measured on each experiment. These simulations included the evolution of current and line average density. Empirical particle transport coefficients were adjusted to give agreement with measured central and line average electron density.

The BALDUR code was programmed to include oxygen impurities and the impurity transport coefficients were empirically adjusted to match the observed values of Z_{eff} . The particle transport coefficient choices are described in Section 4.3. The measured ratios of radiated to ohmic heating power were used as well as the radiation profiles, which were available for the TFTR and ASDEX experiments. Thus, these simulations represent the most complete and detailed predictions of actual experiments currently possible.

3.2. Simulations of TFTR Experiments

Results from the time-dependent simulations of two TFTR experiments are shown in Table II. The TFTR three-pellet shot 18681 exhibits strong, transient current ramp conditions before pellet injection. However, a corresponding ohmic equilibrium, high current gas-fuelled shot was available for our analysis, shot 18673 (Table I).

These two cases were simulated with the total plasma heating model of Ref. [1] as part of a study [2] of a large number of TFTR ohmic experiments. Results from the simulations in this paper are not very different from those of Ref. [2] (see Section 4.1). The measured and predicted electron temperature and density profiles of the gas-fuelled case are shown in Fig. 1. Confinement results, loop voltages, and electron temperatures are in good agreement for the gas phase.

Since the theoretical models for the diffusivities were based on steady-state assumptions [1-3], difficulties can obviously be expected when attempting to simulate transient phenomena. This is illustrated by the simulation of the nonequilibrium three-pellet-fuelled plasma case at TFTR. The predicted central electron temperature was found to be 1.9 keV, compared to the measured central electron temperature of 1.5 keV. The calculated high electron temperature (Fig. 2) of the postpellet TFTR simulation is attributed to the fact that the plasma is not in steady state. Specifically, the line average density decreases by 20% over an energy confinement time following the last pellet while the plasma is continuing to reheat. In addition, an unstable condition can develop in the species-specific model simulations if $Q_{et} - P_{rad}$ becomes comparable to the ohmic heating power, as can happen for high density pellet-fuelled plasmas. This instability was seen to develop when the simulation of TFTR shot 18681 was run with $\epsilon^{ANOM} = 0$.

In the one-pellet-fuelled simulation the η_i parameter is seen to have dropped to 1.9, compared to 3.9 in the gas-fuelled reference case. In the three-pellet simulation, as discussed in Ref. [2], η_i dropped to 1.46, but did not exhibit prolonged suppression below the critical value of 1.5. The relatively rapid density pumpout on TFTR and the particle confinement properties of this limiter tokamak caused a temporary drop in η_i , simultaneous with the observed temporary increase in plasma confinement. However, when the magnetic confinement data are averaged over a confinement time, a substantial increase in plasma confinement is not observed. These results are consistent with the η_i model which does predict temporarily improved confinement with transiently peaked plasma density but no significantly improved sustained confinement.

The "steady-state" simulation of the TFTR five-pellet shot 20259 is of particular interest because $\tau_E^{\text{exp}} \sim 550$ msec over 0.8 sec [9]. This should be compared to the 300 msec confinement time of the very high density gas-fuelled deuterium and helium experiments. Figure 9 of Ref. [2] illustrates the improved confinement found for the 72-cm TFTR pellet experiments. Shot 20259 has a very peaked density profile, $\alpha_n \sim 3$, where $n_e = n_o(1 - (r/a)^2)^{\alpha_n}$. At $n_{eo} = 3.0 \times 10^{20}/\text{m}^3$, T_e and T_i are strongly coupled and if T_{eo} is the measured 1.4 keV, η_i is found equal to 0.5, averaged across the $q = 1$ to $q = 2$ surfaces. If the η_i threshold is 1.5, the anomalous ion losses are clearly suppressed in the TFTR five-pellet shot. The steady-state simulations show the increase of global confinement due to suppression of anomalous ion losses is 41% at this density. The measured increase in global confinement for the five-pellet shot compared to the "saturated" confinement level of the high density gas puff cases is 57%. Thus, the improvement in confinement of the five-pellet high confinement shot obtained from the model is comparable to that found for the experiment. We do not present detailed results from the simulations of this case because we have not modelled the nonequilibrium reheating conditions or convective losses, which were about 10% of the total losses in the three-pellet time-dependent simulation.

3.3. Simulations of ASDEX Experiments

Table III shows the simulation results for the two multipellet ASDEX experiments. In Fig. 3 is shown the evolution of the line-averaged den-

sity on ASDEX for shot 18876. The multi-pellet-fuelled, quasi-steady-state allows a more definitive test of the microinstability-based transport model and a quantitative prediction of η -suppressed, improved confinement. The electron temperature profile predictions are compared to Thomson scattering measurements in Figs. 4-7. Predictions agree well with experiment in the ASDEX pellet phases. The overall confinement predictions for the gas phase simulations are within 20% agreement with data analysis results. The predicted electron temperature profile shapes are in clear disagreement with the gas phase observations on this divertor machine. Since the line average density is increasing less than 10% over a confinement time at the end of the gas-fuelled prepellet phase (Fig. 1), this is not expected to be a factor in the temperature profile disagreement between data and modelling. The initial assumption of a Gaussian temperature profile shape is clearly incorrect for these experiments. For the limiter tokamaks studied, the temperature profiles are in reasonable agreement with measurements in both gas and pellet-fuelled phases.

The transient nature of most pellet experiments is the biggest potential drawback in applying the models for χ_e and χ_i , which were derived for steady-state conditions. The ASDEX pellet experiments are not subject to this limitation. These were also experiments which showed a clear and prolonged transition in both η_i and τ_E . η_i drops from 2.0-3.0 in the gas phase to 0.2-1.0 in the pellet-fuelled phase for shot 18716, depending on r/a . The simulation results are close to the experimental values: η_i is predicted to be about 3.0 in the gas phases and 0.3 and 1.0 in the two pellet phases simulated. The simulated confinement improved from 73 ms to 138 ms for shot 18876, and from 84 ms to 166 ms in the simulation of shot 18716. This is in good agreement with the experimentally measured confinement improvement.

Figure 8 shows the electron and ion thermal diffusivities used in the simulations of ASDEX shot 18716 in the gas and pellet phases. In the pellet phase the model predicts the ion diffusivity to be neoclassical. Note that the shape of the ion diffusivity in the gas and pellet phases is very different. Both electron and ion transport coefficients are reduced in the pellet-fuelled phase in the confinement region $a/3 < r < 2a/3$. In ASDEX, the increase in electron confinement time from this model can be traced to the $1/n_e$ behavior of χ_e and the fact that $P_{e,loc}$ was the same in the ASDEX gas and pellet-fuelled phases.

In these simulations where η_i transport is more important during the gas phase than during the pellet phase, the diffusivity profiles (Fig. 8) are similar to the results of Groebner *et al.* [14], who have shown from neutral-beam-heated experiments on D-III where η_i transport is expected to be important [3], that the ion diffusivity profile appears to be more like the $\chi_e(r)$ profile than like the ion neoclassical diffusivity profile. Fonck [15] has reported that for balanced neutral-beam-heated supershots on TFTR, the ion temperature profile measurements indicate that $\chi_i \propto (1-2) \times \chi_e$ is a good approximation. He also finds, from a preliminary analysis of χ_i and χ_e for ohmic experiments at the half radius, that the ratio of χ_i to χ_e increases with plasma density [16]. Although improved diagnostics are being developed, there is, as yet, little actual ion diffusivity data for ohmic experiments, precluding detailed comparisons of model and experiment. We note however that χ_i/χ_e at the half radius increases with the line average density in this case (Fig. 8).

3.4. Simulations of ALCATOR-C Experiments

Simulations of the ALCATOR-C pellet shots (Table I) predict confinement times and electron temperatures which agree with experiment within 20% (see Table IV and Figs. 9 and 10). In ALCATOR-C shot 80, as in the TFTR three-pellet shot, the η_i parameter does not fall below 1.5 for a time long compared to τ_E . Again, although the predictions do not disagree much with measurements, the results still do not constitute a severe test of the model. Like the TFTR three-pellet case, the lower density ALCATOR-C pellet-fuelled case was on the borderline for onset of η_i transport: η_i being 1.6 in our simulations. The higher density ALCATOR-C case had η_i reduced to 0.4, well below the critical value. Unfortunately, the gas phase of this high density shot was obtained during a current ramp. No corresponding ohmic equilibrium gas puff shot at this high current was available for comparison. Note that the model correctly predicts the doubling of confinement for the high current, high density ALCATOR-C experiment compared to the lower density case.

In Table V is shown a comparison of the electron temperatures and confinement predicted for several ion diffusivity models for these two ALCATOR-C cases. The microinstability model predictions can be compared to those for simulations in which ion diffusivity was assumed due to a) Chang-Hinton

neoclassical model only, b) twice Chang-Hinton ion diffusivity, and c) four times Chang-Hinton ion diffusivity. The experimental values are also shown. As found by Wolfe [17], the ALCATOR-C gas-fuelled experiment corresponds to larger ion losses than can be accounted for by the Chang-Hinton theory alone, and pellet-fuelling reduces the anomalous ion losses so that the total ion losses are at about the neoclassical level. The model predictions for T_e and τ_E are similar to those for $1 \times \chi_i^{\text{Chang-Hinton}}$ in the higher density pellet-fuelled phase. The model predictions for T_e and τ_E in the gas phase case are closer to experiment than predictions based on any multiplier of $\chi_i^{\text{Chang-Hinton}}$ for the anomalous ion diffusivity.

4. DISCUSSION

The agreement of τ_E and T_e between simulation and experiment for the ALCATOR-C cases shows that the scaling of the theoretically based models for χ_e and χ_i can be applied to ohmically heated experiments on tokamaks other than TFTR with no significant change in the overall numerical factor. The ASDEX simulations constitute real tests of both the χ_e and χ_i models, as quasi-steady-state cases were simulated with η_i above and below the critical value. For all three tokamaks with high density pellet fuelling, the simulations show improved ion energy confinement time because η_i transport is suppressed. This trend is most clearly evident in the ASDEX simulations.

4.1. Comparison of Original and Improved Diffusivity Models

In Tables VI and VII we see the effect on the energy balance of recasting the original model for χ_e and χ_i [1] so that power heating the electrons drives χ_e and power heating the ions drives χ_i . In Table VI are simulation results using the improved model, Eqs. (4-7), and in Table VII are results obtained from simulations with the original model [1]. The improved model changes the details of the power balance but has little effect on overall confinement and plasma temperatures except for the ASDEX pellet phase, where somewhat better agreement with experiment is seen.

The two models were calibrated [2] on TFTR ohmic data so that simulated confinement times were identical within 5%. Recently, it was discovered that the TFTR Thomson scattering system had been improperly calibrated

due to misinterpretation of a lamp standard. This resulted in an $\approx 17\%$ underestimation of T_e during the run periods 1986-1987. The effect on the 1985 data is more complex. Revised temperature data show that the ohmic cases on which the model was evaluated, from 1985 data, have been underestimated by only a few percent. Thus our overall conclusions and the model normalizations have not changed.

The ASDEX and ALCATOR-C pellet simulations are more sensitive to the change in the form of the power driving the diffusivity model, since ion losses are of more importance in these high density cases. TFTR has weaker electron-ion coupling, is more collisionless than the other two tokamaks, and energy confinement losses are primarily due to χ_e^{ANOM} . On ASDEX and ALCATOR-C the confinement losses are balanced more equally between the electron and ion channels in the gas phase. The power balance in the ASDEX and ALCATOR-C gas puff simulations with the species-specific heating model shows ion losses becoming slightly stronger than with the original model. In the pellet phase on ASDEX and ALCATOR-C, the losses shift to more ion-dominated with the improved model.

4.2. Improvement of Confinement

The effect of the anomalous ion losses on total confinement is about the same in the three tokamaks. The model for anomalous ion losses used in these simulations causes a 15% reduction in the total energy confinement time in each of the TFTR, ASDEX, and ALCATOR-C gas-fuelled cases compared to simulations with only neoclassical ion losses. The confinement time in the high density pellet cases is increased up to 40% (shot 20259) by suppression of the anomalous ion losses attributed to η_i transport.

As the plasma density is increased, the roles of the electron and ion loss channels change. The trapped-electron diffusivity $\chi_e^{TE} \propto \frac{1}{n_e}$ decreases with increasing density and becomes less important. Since the η_i mode diffusivity $\chi_i^\eta \propto n_i^{-0.6}$, it becomes more important than χ_e^{TE} with increasing density. The neoclassical $\chi_i^{neo} \propto n_i$ increases strongly with increasing density and eventually dominates. If the plasma density is peaked relative to the temperature profile so that the η_i mode is stabilized, the transport losses due to this mode can be minimized. With this picture of transport losses, the maximum confinement time for an experiment with fixed a , R , Z , B_z , I_p would

be found for density high enough to minimize trapped-electron mode losses but low enough so that neoclassical losses are kept small and with density profile sufficiently peaked that anomalous ion losses are suppressed.

Higher confinement will be correlated with minimization of ion neoclassical losses as long as anomalous electron and ion losses are also minimized. In the model, χ_e^{TE} is reduced at high density, Eq. (1), and will be reduced at the high densities produced by pellet-fuelling. The relative importance of ion neoclassical losses in these three tokamaks can be estimated from the loss parameter $\xi = \frac{n_e a^2 \sqrt{a/R}}{I_p}$. This loss parameter can be obtained from the estimates $\tau_E^{-1} \propto \frac{\chi_i^{neo}}{a^2}$ and $\chi_i^{neo} \propto \frac{\delta^{1/2} \rho_{i0}^2}{\tau_i}$ [18], $\tau_i^{-1} \propto n_e T_i^{-3/2}$, $\rho_{i0}^2 \propto T_i / B_{p0}^2$, and $B_{p0}^2 \propto \frac{I_p^2}{a^2}$. We can evaluate ξ with the parameters from the pellet phase data in Table 1: I_p (MA), R (m), a (m), n_e ($10^{19}/m^3$), and $T_i \sim T_e^{exp}$. For these experiments on TFTR, ASDEX, and ALCATOR-C, $\xi = 1.3, 6.5, 1.2$. Comparing ξ among these tokamaks, we see that the TFTR and ALCATOR-C designs minimize neoclassical losses. For the proposed Compact Ignition Tokamak (CIT) [19]: $I_p = 11$ MA, $R = 2.1$ m, $a = 0.65$ m, $n_e = 4.5 \times 10^{20}/m^3$, $T_i = 20$ keV, so that $\xi = 0.02$. This suggests significantly improved confinement would be seen on CIT, with a suitable pellet injector and divertor to maintain quasi-steady-state peaked density profiles.

4.3. Particle Transport and Radiation Modeling

The particle transport models used here, Table VIII, are consistent with the premise that, following pellet injection, limiter and divertor tokamaks exhibit quite different particle transport processes. Experiments on all three tokamaks were simulated with particle transport coefficients which varied inversely as the electron density. These coefficients gave simulated densities which were within 20% of the measured profiles in the plasma core region. The ratio v/D at the half-radius is shown in Table VIII for the simulations. On ASDEX, v/D increases by a factor of four following pellet injection and is four times as large as in the simulations of the TFTR or ALCATOR-C experiments.

In pellet experiments on ALCATOR-C [20] particle confinement was found to be correlated with ion energy confinement and not with electron thermal confinement. We found that pellet fuelling at high density was corre-

lated with reduced ion losses for each tokamak and that the particle transport was improved in that the ratio v/D was increased during the pellet phase. Experiments on JET [21] and ALCATOR-C [20] indicate that an anomalous inward particle velocity develops for pellet-fuelled discharges. In these simulations although v/D does increase after pellet injection, neither TFTR nor ALCATOR-C required a high ratio of anomalous inward pinch to particle diffusion coefficient in either gas or pellet-fuelled phases. As in Ref. [22], we modelled ASDEX particle transport with a strong inward pinch during gas-fuelling (Table IX). During pellet-fuelling on ASDEX, particle confinement further improves. During the high recycling divertor operation, ASDEX edge recycling is expected to be less than 30%. TFTR and ALCATOR-C edge recycling was assumed to be 90%.

The functional form of the particle transport coefficients is not prescribed by theory and is not unique. Hulse [23] has found that a density-dependent diffusion coefficient is less satisfactory for modelling the postpellet density transport of several TFTR pellet shots than a density-independent model with an $(r/a)^2$ dependence. On Jet [24] D and v are reported not to depend on the density $n_e(r)$ although they do typically increase toward the plasma edge as $(r/a)^2$.

If we rewrite the transport coefficients used in this study to be of the form $D \propto A \frac{n_e(0)}{n_e(r)}$ so that near the edge, decreasing density causes an increase in D , we find that the coefficient A is $\sim 10^4 - 10^5 \text{ cm}^2/\text{sec}$ for the TFTR and ASDEX cases, as was found for JET, but is higher by an order of magnitude for the ALCATOR-C simulations. Data from JET indicate that D may be inversely proportional to I_p [24]. If we rewrite

$$D \propto B \frac{n_e(0)}{n_e(r) I_p}, \quad (4)$$

we find that the TFTR and ASDEX cases are modelled by $B \sim 10^4 - 10^5 \text{ cm}^2/(\text{sec} - \text{MA})$ but that for the ALCATOR-C cases, B is again an order of magnitude higher. We propose that Eq. (5) roughly describes particle transport in the plasma core of large tokamaks. In smaller tokamaks where edge fuelling and scrape-off loss effects are of more importance, the core particle transport model would have to be modified.

A comparison of the Ware pinch and the anomalous pinch effects in the simulations is shown in Table IX. In the TFTR simulation, at the half-radius

we find the anomalous and neoclassical pinch velocities to be small, less than 6 cm/sec . Hulse 23 has successfully modelled TFTR pellet shots with $v^{ANOM} = 0$. We find that the ALCATOR-C simulations show a larger Ware pinch ($12-20\text{ cm/sec}$). The anomalous pinch is only 1/3 to 1/5 of the neo-classical pinch for these cases. The ASDEX simulations were also found to show large Ware pinch ($10-20\text{ cm/sec}$) and here the anomalous pinch is large and comparable to the neoclassical pinch at the half-radius.

In the gas phase, the three tokamaks have similar impurity and bremsstrahlung radiation, $P_{rad}/P_{OH} < 35\%$. The TFTR pellet case had significantly greater radiation losses. The effect of the variation in radiated power among these experiments has been included in the total heating power dependence of the models.

For the TFTR cases, the electron temperature calculation is not sensitive to the details of the density profile since electron conduction losses are dominant and $n_e\chi_e$ is used in the calculation, not χ_e alone. For the other simulations, where ion losses dominate the power balance, the effect of an imperfect match of the density profile to experimental data becomes more important.

As noted in Section 2, the model was derived under the assumption of steady-state conditions for plasma current, densities, and temperatures. The model, being based on an assumption of ohmic equilibrium, is not valid for current ramp cases. We have found inverse correlation between the accuracy of τ_E predicted and the percent density change over a confinement time. The ASDEX gas-fuelled and the ALCATOR-C and TFTR pellet-fuelled simulations exhibit a change in the line average density of less than 10-20% over a confinement time, and are not far from ohmic equilibrium. The density variation in these simulations is seen to cause the confinement and electron temperature predictions to be less than 30% in error. This should be compared to the less than 20% error found in the quasi-constant density cases: the ASDEX pellet-fuelled cases, the TFTR and ALCATOR-C gas puff cases, as well as the TFTR gas puff cases studied earlier [2].

4.4. Comparison of Measured and Simulated Neutron Rates

In Table X are presented the simulated and measured neutron rates for the TFTR and ALCATOR-C experiments. The observed trend of increased

neutron rate with increased density via pellet fuelling is seen also in the simulations. The ALCATOR-C data are overestimated by a factor of 4 and the TFTR data are overestimated by a factor of 4-6 by the simulations. The simulations' overestimate of the neutron rates may be due either to the simulated ion temperature profiles being broader than the actual ion temperature profiles, or to the simulated plasma temperatures being higher than in the experiments. The D-D neutron rate calculation is a sensitive function of temperature. If the electron and ion temperatures are raised (from 1.9 keV to 2.2 keV for shot 20259, for example, the predicted neutron rate is increased a factor of 2, from 1.2×10^{14} neutrons/sec to 2.1×10^{14} neutrons/sec. The measured neutron rates are accurate to within about a factor of 2. It appears that the model systematically overestimates the ion temperatures by 10% to 20%. Whether this is because of an overall scaling and/or a profile effect can only be determined when the model predictions can be compared with measured ion temperature profiles.

5. SUMMARY

The microinstability-based models for χ_e and χ_i have been used for simulation of gas and pellet-fuelled discharges on the TFTR, ASDEX, and ALCATOR-C tokamaks. The TFTR calibration of the model gives reasonable agreement with measured temperature profiles and confinement times for both gas and pellet-fuelled ohmic discharges on these machines for quasi-steady-state conditions. It was found that the trapped electron and η_i -driven transport models were consistent with the experimentally observed confinement of gas-fuelled discharges and that suppression of η_i -driven transport could account for significantly improved energy confinement in pellet-fuelled discharges on the TFTR, ASDEX, and ALCATOR-C tokamaks.

The model has recently been found to produce correlation between observed plasma fluctuation signals and significant η_i -driven anomalous ion losses [25,26]. A detailed comparison of the model diffusivities to those derived from the measurements of electron and ion temperature profiles will be an important future test of this theory.

ACKNOWLEDGMENTS

We gratefully acknowledge the physicists whose measurements of TFTR, ASDEX, and ALCATOR-C experimental data made possible these simulations. The authors especially wish to thank F. Wagner for his interest in the simulations of the ASDEX pellet data and F. Mast, R. Muller, A. Eberhagen, O. Gehre, H. Murmann, K.-H. Steuer, and R. Lang, plasma diagnosticians for the ASDEX pellet shots. We are also glad to acknowledge valuable conversations with D. R. Mikkelsen, G. L. Schmidt, and D. Stotler.

This work was supported by U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

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TABLE 1. Simulation Input Parameters

	SHOT	I_p (MA)	B_z (T)	R (m)	a (m)	$\bar{n}_e$ ($10^{19}/m^3$)	P_{rad}/P_{OH}	Z_{eff}	q_a
TFTR	18681	1.6	5.2	2.4	0.72	3.4(13.0)*	0.65	1.6(1.2)*	3.4
	18673	1.6	5.0	2.4	0.72	3.4	0.27	2.0	3.4
	20259	1.6	4.9	2.4	0.71	14.1*	0.65	1.8	3.3
ASDEX	18876	0.38	2.17	1.6	0.4	3.5(9.3)*	0.2-0.4	1.1	2.8
	18716	0.38	2.17	1.6	0.4	3.8(9.5)	0.2-0.4	1.1	2.8
ALCATOR	80	0.38(0.36)*	8.1	0.64	0.16	18.(28)*	0.35	1.2(1.1)*	4.5(4.8)*
	62	0.78	11.3	0.64	0.16	50.(70.)*	0.35	1.1(1.0)*	3.1

*after pellet injection

TABLE II.
Comparison of TFTR Simulations and Experiments

	Gas Fueled		3 Pellets (2.8 sec)	
	<u>SIM</u>	<u>EXP</u>	<u>SIM</u>	<u>EXP</u>
$r_E(\text{sec})$	0.28	0.29±0.03	0.36*	0.32±0.03*
$T_e(0)(\text{Kev})$	2.9	2.9	1.9	1.4
$n_e(0)(10^{20}/\text{m}^3)$	0.47	0.45	2.9	2.6
$V_{\text{loop}}(\text{v})$	0.9	0.8	1.2	1.3
$\nu_{*e}(q = 1.5)$	0.2		0.7	
η_i	3.9		1.5	
*averaged over time r_E				

TABLE III.
Comparison of ASDEX Simulations and Experiments
Shot 18876 (17 Pellets)

	Gas Phase		Pellet Phase	
	1.0 sec		2.0 sec	
	<u>SIM</u>	<u>EXP</u>	<u>SIM</u>	<u>EXP</u>
r_E (sec)	0.07	0.07	0.14	0.15
$T_e(0)$ (keV)	1.0	0.77	0.74	0.70
$n_e(0)$ ($10^{19}/m^3$)	5.2	5.1	16.0	16.0
V_{loop} (V)	1.5		1.2	
ν_{*e} ($q = 1.5$)	1.8		1.2	
η_i	2.9		0.3	

Shot 18716 (11 Pellets)

	Gas Phase		Pellet Phase	
	1.4 sec		1.8 sec	
	<u>SIM</u>	<u>EXP</u>	<u>SIM</u>	<u>EXP</u>
$r_E(0)$	0.08	0.09	0.17	0.15
$T_e(0)$	0.92	0.76	0.58	0.58
$n_e(0)$	6.3	6.0	20.	20.
V_{loop}	1.4	1.2	1.6	1.5
ν_{*e}	2.3	> 1.	5.1	> 4.
η_i	3.5	2.-3.	1.0	0.2-1.

TABLE IV.
Comparison of ALCATOR Simulations and Experiments

SHOT 80	Prepellet		Post-Pellet			
	$t = 0.200 \text{ s}$		$t = 0.350 \text{ s}$		$t = 0.400 \text{ s}$	
	<u>SIM</u>	<u>EXP</u>	<u>SIM</u>	<u>EXP</u>	<u>SIM</u>	<u>EXP</u>
r_E (sec)	0.035	0.030	0.028	0.030	0.042	0.028
$T_e(0)$ (keV)	1.9	1.8	1.2	1.3	1.5	1.3
$n_e(0)$ ($10^{20}/\text{m}^3$)	2.7	2.8	5.0	5.0	4.8	4.5
V_{loop} (V)	1.3	1.8	1.9	2.0	1.5	2.0
ν_{*e} ($q = 1.5$)	0.6		2.8		1.2	
η_i	1.6		1.5		1.0	

Post-Pellet		
SHOT 62	$T = 0.55 \text{ s}$	
	<u>SIM</u>	<u>EXP</u>
r_E	0.054	0.048
$T_e(0)$	1.5	1.5
$n_e(0)$	16.0	16.
V_{loop}	2.0	2.0 ± 0.3
ν_{*e}	1.3	
η_i	0.4	

TABLE V.
Comparison of T_e and τ_E for Several Ion Diffusivity
Models for ALCATOR Cases

<u>SHOT 80</u>				
MODEL	Prepellet		Post-pellet (t=0.35 sec)	
	T_e (keV)	τ_E (sec)	T_e (keV)	τ_E (sec)
η_i	1.9	0.035	1.2	0.028
$4X^{CH}$	1.6	0.040	1.1	0.030
$2X^{CH}$	2.0	0.064	1.5	0.057
$1X^{CH}$	2.5	0.102	2.1	0.088
Exp	1.8	0.030	1.3	0.030

<u>SHOT 62</u>			
MODEL	Post-Pellet		
	T_e (keV)	τ_E (sec)	
η_i	1.5	0.054	
$4X^{CH}$	1.1	0.039	
$2X^{CH}$	1.3	0.048	
$1X^{CH}$	1.5	0.056	
Exp	1.5	0.048	

TABLE VI.

Energy Losses at $a/2$ - Heating Species Dependent Model

	$T_e(0)$ (KeV)	$T_i(0)$ (KeV)	Q_e^{cond} (MW)	Q_i^{cond} (MW)	P_{rad} (MW)	P_{Oli} (MW)	Q_{ei} (MW)	τ_{eE} (sec)	τ_{iE} (sec)	τ_E (sec)
<u>TFTR</u>										
gas	2.9	2.5	0.51	0.10	0.09	0.72	0.11	0.20	0.48	0.28
Shot 18681										
pellet	1.9	1.8	0.76	0.08	0.26	1.17	0.12	0.24	1.20	0.40
<u>ASDEX</u>										
gas	1.0	0.8	0.10	0.12	0.03	0.27	0.13	0.070	0.077	0.073
pellet	0.7	0.7	0.06	0.09	0.05	0.26	0.12	0.081	0.499	0.138
<u>ALCATOR</u>										
Shot 80										
gas	1.9	1.3	0.14	0.14	0.04	0.31	0.14	0.030	0.044	0.035
pellet	1.2	1.0	0.06	0.28	0.05	0.43	0.30	0.023	0.038	0.028
Shot 62										
pellet	1.5	1.4	0.26	0.20	0.19	0.89	0.33	0.034	0.141	0.054

TABLE VII.

Energy Losses at $a/2$ - Total Heating Dependent Model

	$T_e(0)$ (KeV)	$T_i(0)$ (KeV)	Q_e^{cond} (MW)	Q_i^{cond} (MW)	P_{rad} (MW)	P_{OH} (MW)	Q_{ei} (MW)	τ_{eE} (sec)	τ_{iE} (sec)	τ_E (sec)
<u>TFTR</u>										
gas	3.0	2.6	0.60	0.11	0.13	0.86	0.12	0.20	0.59	0.29
Shot 18681										
pellet	1.7	1.7	0.74	0.08	0.26	1.20	0.14	0.23	1.16	0.38
<u>ASDEX</u>										
gas	1.0	0.83	0.15	0.07	0.03	0.27	0.08	0.059	0.086	0.069
pellet	0.6	0.6	0.09	0.07	0.06	0.28	0.10	0.064	0.482	0.112
<u>ALCATOR</u>										
Shot 80										
gas	1.8	1.4	0.18	0.10	0.04	0.31	0.09	0.023	0.068	0.034
pellet	1.2	1.0	0.16	0.18	0.05	0.43	0.19	0.021	0.131	0.036
Shot 62										
pellet	1.4	1.3	0.33	0.17	0.19	0.91	0.29	0.030	0.130	0.048

TABLE VIII.
Empirical Particle Transport Models

$$D = D^{ANOM} + D^{NEO}$$

$$v = v^{ANOM} + v^{Ware}$$

	Recycling	$D^{ANOM} \propto \{1/n_e(10^{20}/m^3)\}$ (m ² /sec)	$v^{ANOM} \propto (r/a)\{1/n_e(10^{20}/m^3)\}$ (m/sec)	$v/D _{r=a/2}$ (m ⁻¹)
<u>TFTR</u>				
gas	0.9	0.04	0.025	0.3
pellet	0.9	0.03	0.045	0.3
<u>ASDEX</u>				
gas	0.3	0.1	0.2	1.0
pellet	0.3	0.05	0.4	4.0
<u>ALCATOR</u>				
gas	0.9	0.03	0.15-0.20	1.1
pellet	0.9	0.1-0.2	0.30	1.0
Energy of recycled neutrals 20-40 eV				

TABLE IX.
Anomalous and Neoclassical Pinch Results from Simulations

		$v_{(a/2)}^{\text{ANOM}}$	$v_{(a/2)}^{\text{WARE}}$	$v_{(a/2)}^{\text{ANOM}}/v_{(a/2)}^{\text{WARE}}$
TFTR	gas	3.4 cm/s	5.5 cm/sec	0.7
	pellet	3.0	5.2	0.6
ASDEX	Shot 18716			
	gas	20.	18.	0.9
	pellet	16.	9.5	2
	Shot 18876			
	gas	22.	20.	1
	pellet	14.	13.	1
ALCATOR	Shot 80			
	gas	3.7	19.	0.2
	pellet	4.6	16.	0.3
	Shot 62			
	gas	---	---	---
	pellet	2.2	12.	0.2

TABLE X.
DD Neutron Rate

	DATA	SIMULATION
TFTR		
18673	$0.36 \times 10^{13} \text{ n/s}^*$	$1.5 \times 10^{13} \text{ n/s}$
18681	1.0*	6.2×10^{13}
20259	2.5*	1.2×10^{14}
ALCATOR-C		
80 (gas phase)	1.0×10^{11}	3.4×10^{11}
80 (pellet phase)	3.4×10^{11}	7.3×10^{11}
62	5.5×10^{12}	2.3×10^{13}

*Accurate to +50%/-35%

Figure Captions

- 1a. TFTR temperature profiles for gas puff shot 18673 compared to simulation results.
- 1b. TFTR density profiles for gas puff shot 18673 compared to simulation results.
- 2a. TFTR temperature profiles for pellet shot 18681 compared to simulation results.
- 2b. TFTR density profiles for pellet shot 18681 compared to simulation results.
3. Line averaged electron density time evolution for ASDEX shot 18876.
- 4a. ASDEX temperature profiles for gas phase 18876 compared to simulation results.
- 4b. ASDEX density profiles for gas phase 18876 compared to simulation results.
- 5a. ASDEX temperature profiles for pellet phase 18876 compared to simulation results.
- 5b. ASDEX density profiles for pellet phase 18876 compared to simulation results.
- 6a. ASDEX temperature profiles for gas phase shot 18716 compared to simulation results.
- 6b. ASDEX density profiles for gas phase shot 18716 compared to simulation results.
- 7a. ASDEX temperature profiles for pellet phase shot 18716 compared to simulation results.
- 7b. ASDEX density profiles for pellet phase shot 18716 compared to simulation results.
- 8a χ_e from simulation of ASDEX gas and pellet phases for shot 18716.
- 8b χ_i from simulation of ASDEX gas and pellet phases for shot 18716.
- 9a. ALCATOR-C temperature profiles for gas phase shot 80 compared to simulation results.
- 9b. ALCATOR-C density profiles for gas phase shot 80 compared to simulation results.
- 10a. ALCATOR-C temperature profiles for pellet phase shot 80 compared to simulation results.

10b. ALCATOR-C' density profiles for pellet phase shot 80 compared to simulation results.

11a. ALCATOR-C' temperature profiles for pellet shot 62

11b. ALCATOR-C' density profiles for pellet shot 62 compared to simulation results.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

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