Turbulent Transport Studies in Alcator C-Mod Ohmic Plasmas*

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1. Introduction

In our recent studies of ohmically heated low density C-Mod plasmas where $\tau_e \propto n_e$, the so-called neo-Alcator regime [1] where $T_e > T_i$, TRANSP results indicated heat diffusivities such that $\chi_i < \chi_e$, whereas our nonlinear gyrokinetic analysis [2] with GYRO [3] indicated that at least at low Z_{eff}, $\chi_i > \chi_e$ due to the dominance of ITG modes over TEM or ETG. In essence, this relatively low density regime ($n_e \leq 1x10^{20}$ m^{-3} in Alcator C-Mod, and in fact in several other tokamak experiments worldwide) corresponds to a confinement *deterioration* relative to L-mode, in contrast to optimistic expectations in the 1980s that this confinement scaling would continue to very high densities . However, the favorable linear confinement scaling ceased at sufficiently high densities, at least in gas fuelled discharges [1], due to saturation (now we know that this occurs at the L-mode confinement value), presumably due to dominant ITG turbulence[1, 2]. In our previous experiments [2] the composition of the impurities and Z_{eff} was not well known. In addition, the ion temperature profiles were determined from TRANSP using a model χ_i profile, calibrated to the temperature from neutron emission. These experiments were repeated recently with greatly improved diagnostics, and initial results were presented [4, 5]. In the present work the measured ion temperature profiles from x-ray crystal spectroscopy are used, and new values of the measured Z_{eff} were found to be larger than previously assumed. Recently TGLF, the trapped gyro-Landau fluid model code [6], was used with great efficiency to model the turbulent transport as a function of density and Z_{eff}, and the results indicate that the second (impurity) ion species with moderate Z_i reduces significantly the predicted values of χ_i while maintaining the electron diffusivities near the experimental values as Z_{eff} was increased and the density decreased. By varying the impurity Z_i, it was verified that increased collisionality alone was not sufficient to explain these results. New analysis with the nonlinear flux tube GYRO [3] simulations indicates a similar trend and some of the results are presented here.

2. Numerical results with the trapped gyro-fluid Landau fluid model code TGLF

Here we present results with TGLF [6] which shows a significant reduction of the ion energy diffusivity as a two ion species plasma is introduced, with moderate Z_i (= 8 in the present case, corresponding to oxygen impurities) [Fig. 1]. The impurity density is varied (see dilution factors in the vertical bar) and the ensuing Z_{eff} is indicated by the different colored curves. The experimentally measured Z_{eff} corresponds to 2.7 (see red curve) at this line average density (n_e= 0.64x$20^{20}$$m^{-3}$). We see that at the same time the dilution has negligible effect on the electron transport coefficient. Thus, we are now in a position to model the variation of transport at different densities and compare the results with the experimentally measured transport coefficients as determined by TRANSP, using the experimentally measured electron and ion temperatures, density, radiated power, and Z_{eff}. The radiated power measured in these discharges is too low for the majority of the Z_{eff} to originate from molybdenum impurities. In most of the discharges 10% or less of the Z_{eff} being from molybdenum is sufficient to produce the measured radiated power.

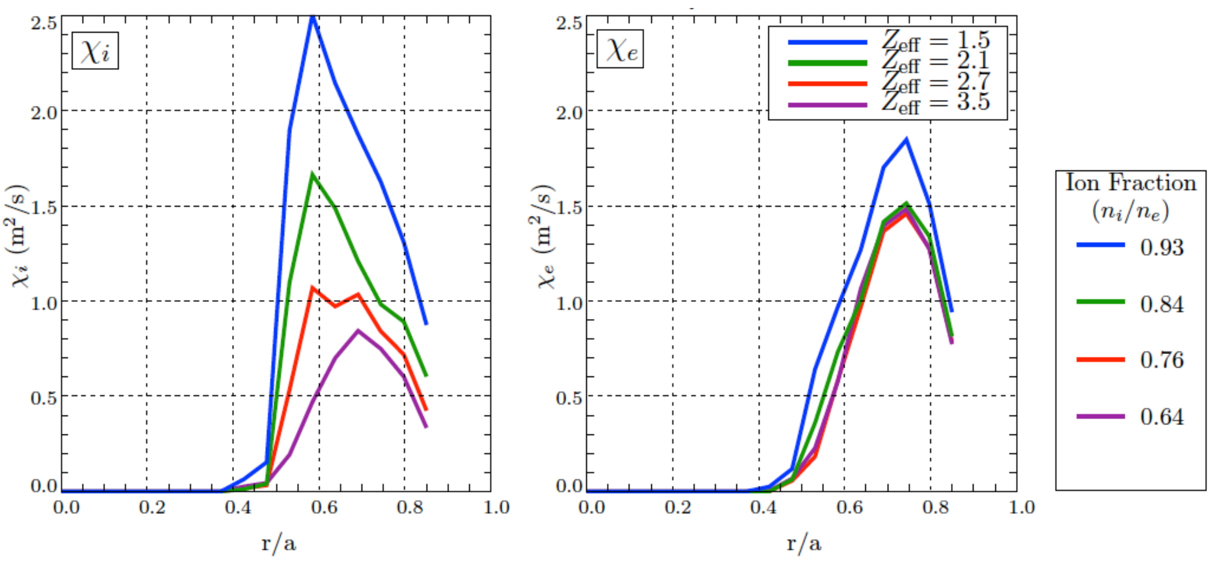

Figure 1. Variation of the ion and electron transport coefficients as a function of ion impurity concentration, assuming Z_i= 8 (oxygen). Predictions based on TGLF. Alcator diverted ohmic discharges, n_e=0.64x$10^{20}$$m^{-3}$, B_T=5.2T, I_p= 800 kA. The experimental value of Zeff corresponds to 2.7, the red curve.

We see that for the experimentally measured density and temperature profiles [5], at the experimental value of Z_{eff} = 2.7 (red curve) the turbulent heat diffusivities are localized to regions of maximum temperature and density gradients r/a = 0.5 - 0.9, with a peak value of χ_i = 1.0 and χ_e = 1.5. This is a typical result, and we almost never see any significant turbulent transport in the core of the plasma r/a < 0.5, where typical experimental heat diffusivities are of the order of 0.5 m^2/sec. Note that at this Z_{eff}, $\chi_i < \chi_e$ as desired.

3. Numerical results with TGLF and GYRO

We have carried out a series of runs on the MIT PSFC parallel computing network LOKI (600 processors) with the nonlinear flux tube GYRO code at 4 different densities, including studies of the total heat flux q and heat diffusivities χ as a function of radius, at both low and high Z_{eff} and compared the results with TGLF. Values of $k_\theta\rho_s$ in GYRO are in the range 0.1-1.2, with little contribution to electron transport from higher values when tested. A plot of the radial profile of the total heat flux q is shown for both ions and electrons in Fig. 2 at a density of n_e=0.64x10^{20} m^{-3}. The TRANSP runs (experiment) are shown by the dashed lines, the blue curves and symbols correspond to the low Z_{eff} = 1.5 used in the past modeling of Lin et al [2] and the red color corresponds to Z_{eff} =2.7, which is the presently believed experimental value and used in the most recent GYRO and TGLF modeling. While the predicted values of total q_i (D and O combined) are higher than the experimental values by factors of two, using slightly modified gradients and lower Z_i (6) and by using TGYRO to iterate density and temperature profiles, reasonably good agreement between experiment and modeling is found in the radial range 0.5 <r/a< 0.8. Within experimental error bars, in no cases could we find

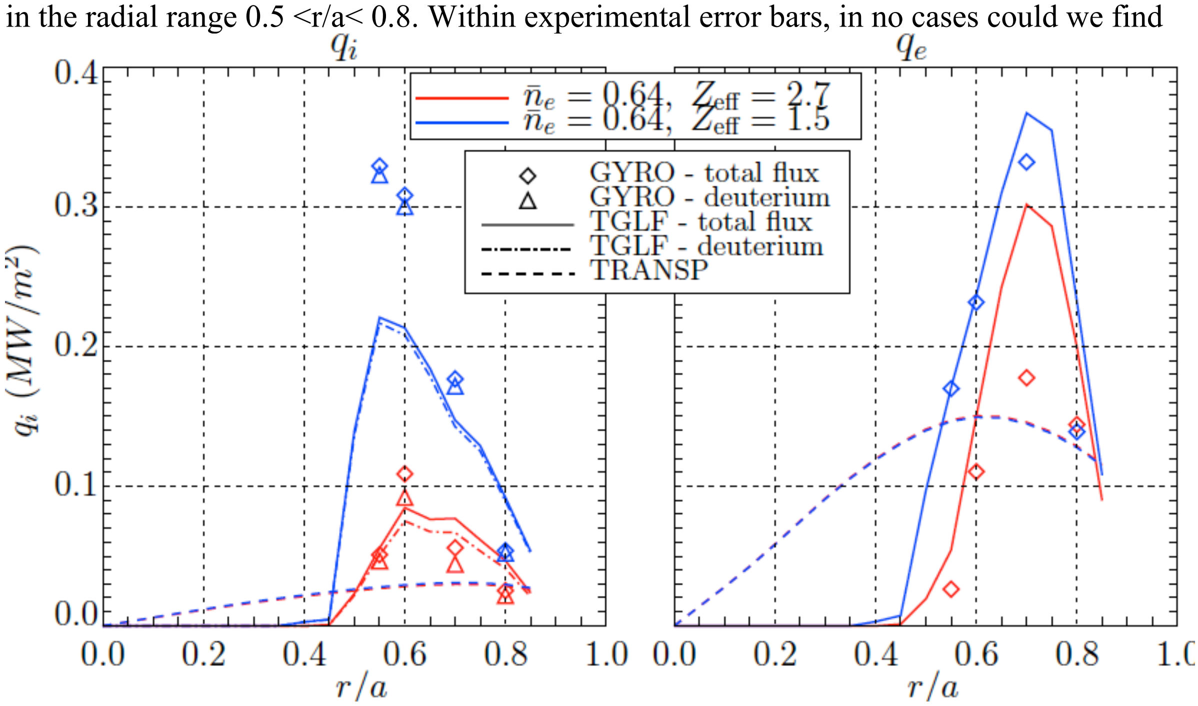

Figure 2. Radial plots of the ion and electron heat flux as obtained from experiment (TRANSP, dashed curves) and TGLF (solid curves) and GYRO, (symbols) for both high Z_{eff} = 2.7 (present experimental value) and Z_{eff} = 1.5 (low values used in Ref 2). In the codes we assumed Z_i= 8, n_e=0.64x$10^{20}$$m^{-3}$, B_T= 5.2T, Ip = 800 kA.

agreement for r/a < 0.5. Similar comparisons have been made between TRANSP predictions and TGLF and GYRO at 4 different densities in the range n_e=(0.35-1.05) $\times 10^{20}$ m^{-3} and the results will be presented in a later publication. Furthermore, we have now obtained even better agreement with experiments with both nonlinear flux tube GYRO, and TGLF iterated with TGYRO, a technique which allows the profiles to be adjusted to match to q_i and q_e, the ion and electron power flux. One question in such modeling is the role of stabilization of the ITG modes by shear flow. Recent measurements in similar discharges [7] indicated a maximum E_r of the order of 14 kV/m. Using the measured E_r radial profiles, we found at most a 10% reduction in the predicted ion transport.

3. Summary and Conclusions

Extensive gyrokinetic studies of low density ohmic plasmas in Alcator C-Mod revealed the important role of deuterium depletion in the presence of a second (impurity) ion species with moderate Z_i, resulting in reduced ion transport and dominant electron transport in the outer half of the plasma column. Additional examination of linear growth rates is in agreement with this observation. The radial electric field shear does not play a dominant role in the stability of these plasmas. Transport in the inner half of the plasma core is not explained by the gyrokinetic codes. Potential physical mechanisms to give the enhanced transport in the plasma core include mild sawteeth (although the inversion radius is typically $r/a \leq 0.35$), or drift waves driven by ohmic electron drift which at the lowest densities considered here can attain values as high as $U/C_s = 6$ near the center, and diminish radially in accordance with the electron temperature profile [4].

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