Transport and turbulence studies in the linear ohmic confinement regime in Alcator C-Mod *

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Abstract. Transport in ohmically heated plasmas in Alcator C-Mod was studied in both the linear (LOC) and saturated (SOC) ohmic confinement regimes and the importance of turbulent transport in the region r/a = 0.5-0.8, was established. After extensive analysis with TGLF and GYRO, it is found that using an effective impurity ion species with Z_i = 8, and moderately high Z_{eff} (2.0-5.6), in the LOC regime electron transport becomes dominant due to TEM turbulence. The key ingredient in the present results is the observation that dilution of the main ion species (deuterium) by impurity species of moderate charge state reduces the dominant ITG turbulence, in contrast to the SOC regime with little, if any dilution. The turbulent spectrum measured with the Phase Contrast Imaging (PCI) diagnostic is in good agreement with predictions of a synthetic PCI diagnostic adopted to Global GYRO. The toroidal rotation in the low density LOC regime is in the co-current direction but as the density is raised, in the SOC regime the rotation reverses to the counter current drive direction. Recently we have measured the impurity content of the plasma and found an effective Z_i of 9.

1. Introduction

In our recent studies of turbulent transport in ohmically heated low density C-Mod plasmas where the energy confinement time $\tau \propto n_e$, the so-called neo-Alcator regime [1] and where $T_e > T_i$. past TRANSP results indicated heat diffusivities such that $\chi_i < \chi_e$, whereas nonlinear gyrokinetic analysis [2] with GYRO [3] indicated that at least for moderate Z_{eff}, $\chi_i > \chi_e$ due to the dominance of ITG modes over TEM or ETG modes. We now know that in this low density regime ($n_e \leq 1x10^{20}$ m^{-3} in Alcator C-Mod, and similar results hold at lower densities in other tokamak experiments worldwide) confinement deteriorates relative to L-mode at higher densities. In particular, the apparent favourable linear confinement scaling ceased to continue at sufficiently high densities, at least in gas fuelled discharges [1], presumably due to ITG turbulence becoming dominant as shown recently in [2]. In our previous experiments [2] the composition of the impurities, Z_i, was not well known and to some extent Z_{eff} was uncertain. In view of this, and given that C-Mod walls are protected with molybdenum tiles while typical plasma operation is performed with periodic boronization, in the transport analysis in [2] an effective Z_i =12 (or higher) was assumed. These experiments were repeated recently with improved diagnostics, in particular with the ion temperature profile measured with X-ray imaging crystal spectroscopy (XICS). In the present work the measured values of Z_{eff} were found to be higher than previously used values. Recently TGLF, the trapped gyro-Landau fluid model code [4], was used very efficiently to model the turbulent transport as a function of density, Z_i and Z_{eff}, and the results indicated that the second (impurity) ion species with moderate Z_i would significantly reduce 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 Z_{eff} while keeping Z_i = 12 or higher, it was verified that increased collisionality alone was not sufficient to explain the experimental results [2]. The key ingredient in the present results is the recognition that dilution of the main ion species (deuterium) up to 30% by impurity ion species of moderate charge state $Z_i = 8$ (Oxygen-like) results in the reduction of ITG turbulence while maintaining, or even triggering TEM dominated turbulence. Initial results were presented at recent conferences [5, 6].

We also present results of measurements of the turbulent spectrum with the Phase Contrast Imaging (PCI) diagnostic [7] and the measurements are in reasonable agreement with predictions of a synthetic PCI diagnostic [8] as applied to the output of global GYRO, as long as the Doppler shift due to the measured E_r is included. Importantly, the measured flow shear in these low beta (< 0.1%) ohmic plasmas is found to be too weak to significantly effect the stability of TEM or ITG modes.

An extensive experimental campaign has been carried out very recently to determine spectroscopically the impurity ion content of C-Mod plasmas in the LOC regime and the results verified the hypothesis of significant low Z impurity contamination. At the same time, in these ohmic plasmas we observed a characteristic spontaneous toroidal rotation even without external momentum input [9]. The toroidal rotation in the low density LOC regime is in the co-current direction but as the density is raised, in the SOC regime the rotation reverses to the counter current drive direction. This may be the consequence of the modes switching from TEM to ITG which may generate the toroidal flow through residual Reynolds stress [9]. In order to further quantify the impact of dilution, recently we have also carried out N_2 impurity injection experiments to increase Z_{eff} and were able to induce rotation reversal as the plasma switched from SOC to LOC. Gyrokinetic analysis of these experiments indicates that the turbulence is localized to r/a = 0.5-0.8 and the cause of transport in other regions, in particular in the inner core of the plasma column, or the edge region, is still not understood. In previous presentations [10] we noted that U/C_S up to 6 occurs in the central plasma at the lowest densities (where U is the ohmic electron drift speed J/em_e and $C_S = (T_e/m_i)^{1/2}$ is the acoustic speed), and we speculated on the role of current driven drift wave turbulence. While in past theoretical studies transport due to such acoustic type drift wave turbulence was thought to be unimportant, more subtle phenomena, such as distortions of the electron distribution cannot be excluded as causes of electron drift wave turbulence and transport. Alternate explanations for central heat transport may have to do with mild sawtooth phenomena in part of this regime (r/a < 0.35).

The outline of the paper is as follows. In Section 2 we present modeling results with TGLF, showing the reduction of ion transport as the ion dilution is increased. In Section 3, we present comparisons of TGLF and nonlinear GYRO fluxtube modeling results, showing good agreement. We also show results on how heat transport varies with density throughout the LOC regime, often requiring subtle adjustments of the electron density and temperature gradients to obtain good agreement between experiment and GYRO predictions. In Section 4 we present results of turbulence measurements from an absolutely calibrated PCI diagnostic, showing good agreement between measurements and a synthetic diagnostic method. In Section 5 we discuss typical results from rotation measurements showing how the LOC and SOC regime result in spontaneous toroidal rotation. In section 6, we present very recent results of impurity measurements in the LOC regime, as well as some results of targeted N_2 impurity injections. Finally, in Section 7 the Summary and Conclusions are given.

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

Typical profiles of density and temperature used in these analyses is presented in figure 1. We indicate the impurity species density (about 5% of the electron density) with $Z_i = 8$, which gives $Z_{eff} = 2.7$, the experimentally determined value from loop voltage analysis and neoclassical resistivity models. Note that this value results in a nearly 24 % depletion of the deuteron density relative to electrons. Using the above profiles, simulations with the TGLF code [4] show 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) [figure 2]. The impurity density is varied and the ensuing Z_{eff} is indicated by the different colored curves (see also values in insert box). The experimentally measured Z_{eff} corresponds to 2.7 (see red curve) at this line average density (n_e= $0.64x20^{20}m^{-3}$). We see that at the same time the dilution has a smaller effect on electron transport. The

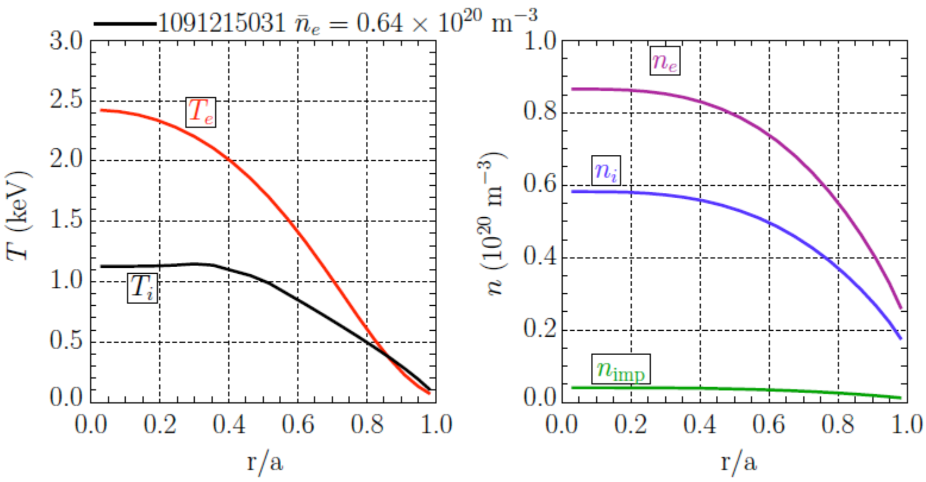

Figure 1. Typical density and temperature profiles determined from Thomson scattering and high resolution crystal X-ray spectroscopy. The ion temperature profile at r/a < 0.4 is uncertain.

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. We see that for the experimentally measured density and temperature profiles, 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,

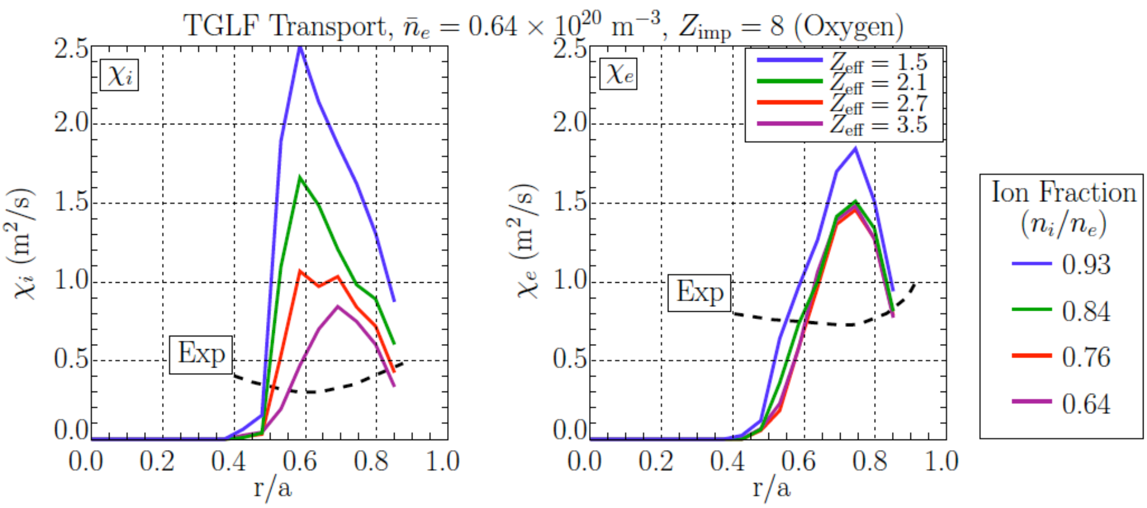

Figure 2. Variation of the ion and electron transport coefficients as a function of ion impurity concentration, assuming Z_i= 8 (oxygen). Predictions based on TGLF. Alcator diverted ohmic discharges, n_e=0.64x10^{20}m^{-3}, B_T=5.2T, I_p= 800 kA. The experimental value of Z_{eff} corresponds to 2.7, the red curves.

with a peak value of $\chi_i = 1.0$ and $\chi_e = 1.5$. This radial dependence is a typical result, and usually we do not see any significant turbulent transport in the core of the plasma, r/a < 0.5, where typical experimental heat diffusivities remain of the order of 0.5 m^2/sec, well above neoclassical values. Note that at this Z_{eff}, $\chi_i < \chi_e$ as desired, although the ion heat diffusivity at r/a = 0.7 is still higher than the TRANSP predicted values. As we shall see later, this kind of discrepancy can be remedied by increases in the ion temperature gradient scale length, and is best done with the more accurate GYRO code. The advantage of TGLF is that it runs very quickly and is an excellent tool for scoping studies which we typically run on the PSFC parallel computational cluster, a 600 core AMD Opteron system. We should note that we have repeated these modeling runs using molybdenum impurity (Z_i= 42) while adjusting Z_{eff} at the above values, and in the absence of ion dilution we found no reduction of χ_i. This is in agreement with the previous results of Lin [2], showing that collisionality is not the key factor in reducing ion transport. We have also repeated the runs by including E_r shear (using the measured radial electric field with typical values of 14 kV/m, including the shear) and found insignificant impact on transport (< 10%). These results motivated us to begin extensive spectroscopic studies to document the impurity composition in ohmic plasmas in the low density LOC regime. We know from previous work that in the SOC regime Z_{eff} decreases toward unity and hence impurity ions cannot deplete the deuteron concentration. The question was whether an "average" Z_i of 8-9 was realistic or not. Section 6 below provides the answer in the affirmative.

3. Comparison of TGLF and GYRO

We have modeled the variation of transport at different densities and compared 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}.

A series of simulations were carried out 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. Plots of the radial profiles of the ion and electron heat diffusivities at a density of n_e=0.64x10^{20} m^{-3} are shown in figure 3.

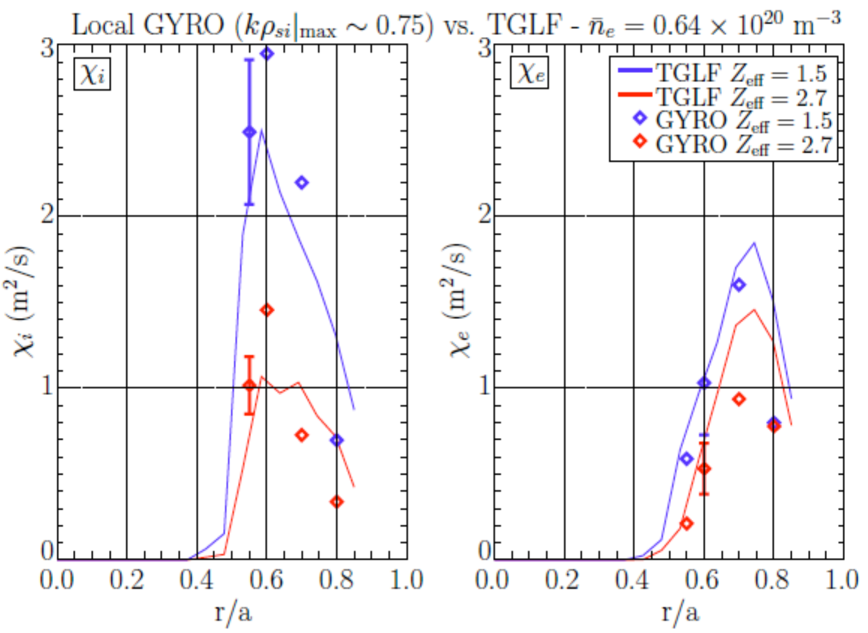

Figure 3. Radial plots of the ion and electron heat diffusivities for both high Z_{eff} = 2.7 (present experimental value) and Z_{eff} = 1.5 (low values used in Ref 2). In the codes we assumed Z_i= 8, n_e=0.64x10^{20}m^{-3}, B_T= 5.2T, Ip = 800 kA.

We see that TGLF and GYRO are in agreement within experimental error when varying the temperature profiles, showing reduction of ion transport by both codes as the dilution increases at the higher values of Z_{eff}. We see that no turbulent transport is predicted for r/a < 0.5 owing to the gradients flattening off and the modes of interest becoming stable. 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 are presented below in figure 4. As can be seen, the results are very sensitive to the exact electron temperature and density gradient scale lengths which are all within experimental error. This was verified by a contour plot of the linear stability regime in the L_{Te} versus L_{ne} plot which showed that the standard gradients measured were often near marginal stability of TEM modes and that a 10 or 20 percent adjustment of L_{Te} and/or L_{ne} had a profound impact on stability and consequent transport. Sensitivity to L_{Ti} in this regime was not apparent. It is clear from figure 4 that the correction to the gradients is not the same for all densities, namely the errors are random and vary from density to density, rather than being some kind of systematic error. Nevertheless, the corrections are all within experimental uncertainty. In the future we will use TGLF iterated with TGYRO, a technique which allows the profiles to be adjusted to match the ion and electron heat diffusivities, or the respective power flux. Once more, the 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 on 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 when E_r shear was included. On the contrary, the Doppler shift of frequencies is substantial and essential to understanding the measured frequency spectrum.

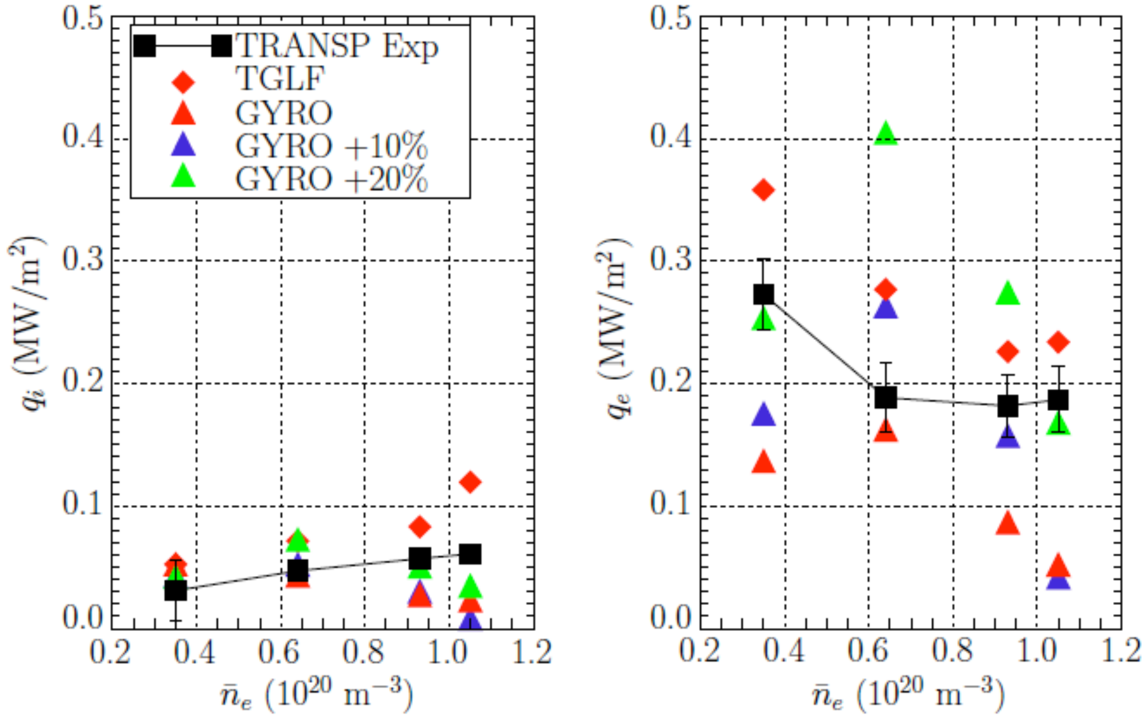

Figure 4. A comparison of the heat flux of electrons and ions and four different densities, at each density the value taken at r/a= 0.7 and averaged over a range of ± 0.05. The black squares are the TRANSP results, the red diamonds are the TGLF results and the red triangle corresponds to GYRO predictions using the nominal gradients. The blue triangles represent GYRO predictions with the electron temperature and density gradient scale lengths reduced by 10%, and the green triangles correspond to the same but with a reduction of 20 %.

4. Measurement of the turbulent spectrum

The turbulent spectrum has been measured with the phase contrast imaging diagnostic (PCI) [7]. An expanded CO-2 beam propagating through the C-Mod plasma vertically, through two ports at the top and the bottom of the vacuum chamber detects fluctuations in the plasma below and above the midplane with dominant poloidal mode numbers which propagate perpendicular to the laser beam in both the clockwise and counter clockwise direction. A 32 channel cryogenically cooled detector array is used to detect the fluctuation pattern after the laser beam reflects off a phase plate. A masking plate was used to separate the directions of propagation [7] and results confirm that propagation is in agreement with the $E_r x B_T$ direction. Because localization along the beam is not achieved, the PCI diagnostic picks up fluctuations not only in the core of the plasma but also at the edge region. Because of Doppler shift due to Er in the core of the plasma is significant, the high frequency part of the spectrum (f >100 kHz) represents turbulence from the plasma core [9]. In particular, for typical k values of 5 cm^{-1}, the Doppler shift is of the order of 250 kHz. This will dominate the frequencies of unstable modes which in the rest frame are 20-100 kHz (GYRO predictions). Meanwhile, we expect edge fluctuations to be in the range of 100kHz or less. A sample of the measured spectrum is shown in figure 5, a predicted spectrum by the synthetic diagnostic technique from global GYRO is shown in figure 6, and an integrated spectrum from 100 kHz to 400 kHz is shown in figure 7, providing a comparison between the synthetic spectrum and the measured spectrum. Figure 7 is on an absolute scale using a calibrated PCI technique [7]. We see reasonable quantitative agreement of the magnitude of the measured and predicted turbulent spectrum. Doppler shift with the measured E_r was included in the synthetic spectrum. Note that the experimental PCI spectrum in figure 7 is broader than the synthetic spectrum even though the magnitude on an absolute scale compares very well with the synthetic values. Contributions near the 100 kHz frequency range cannot be ruled out.

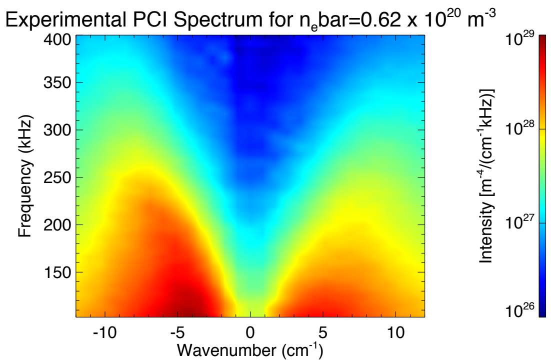

Figure 5. Experimental PCI spectrum

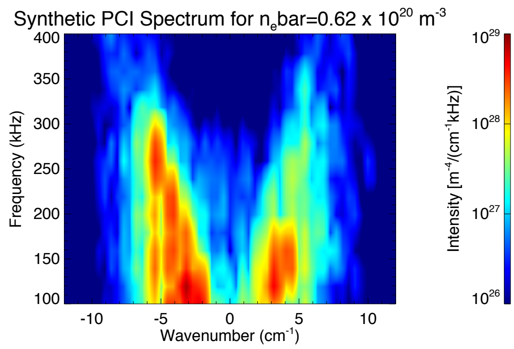

Figure 6. Synthetic spectrum from global GYRO

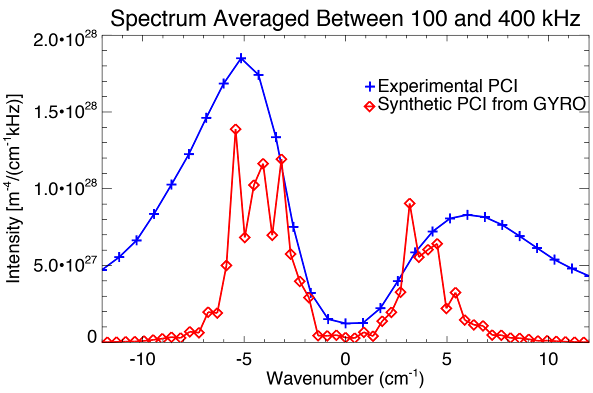

Figure 7. Integrated frequency spectrum

We have recently carried out experiments with a masking plate to verify the direction of rotation which is determined mostly by $E_r x B_T$. Given that the PCI responds to the turbulent spectrum from both the top and the bottom of the plasma column, a masking plate technique [9] is essential to determine the direction of wave propagation. The asymmetry of the spectrum in figure 7 is noteworthy and will be studied in the future. It may represent asymmetry of the spectrum originating from the top and bottom of the plasma column.

5. Observation of toroidal rotation

In ohmic C-Mod plasmas significant toroidal rotation has been observed and details have been published [9, 11]. Understanding such phenomena is of considerable importance since it possibly sheds light on the source of intrinsic rotation in plasmas without significant external momentum input. This may have relevance to ITER and reactor regimes where MeV level NBI injection may not be efficient in producing significant momentum input. It has been observed that in the LOC regime toroidal rotation is in the co-current direction, of order 10 km/sec, leading to a radially outward E_r (relative to a B_T field in a cylindrical coordinate system) and thus the $E_r x B_T$ rotation is in the ion diamagnetic (clockwise) drift direction. Typical E_r values deduced are of order 14 kV/m, leading to an $E_r x B_T$ Doppler shift of about $3x10^3$m/sec. In the SOC regime a reversal of the rotation is observed, in the counter current direction, and the direction of E_r should also reverse, resulting in a Doppler shift in the electron diamagnetic direction. By ramping the density up or down, it has been possible to trigger rotation reversal. It has been postulated that the source of momentum for intrinsic rotation is the residual (Reynolds) stress and the stress comes from the ITG and/or TEM turbulence [9]. As the direction of wave propagation changes from the electron diamagnetic direction for TEM modes, to the ion diamagnetic direction for ITG modes, the direction of intrinsic toroidal rotation would change. This hypothesis needs verification by comparing quantitatively the rotation speed with predictions of the residual stress using the measured fluctuation amplitudes. This has not been attempted in either this or in previous works [9, 11] and remains a topic for future investigation. It is noteworthy that reversal of toroidal rotation seems to be the most sensitive indicator of the switching form the LOC to the SOC regime [9, 11]. Based on the results of this paper, we do not have a good understanding of the physics behind the total net energy confinement τ and hence cannot predict the transition from the LOC to the SOC regime. While earlier work indicated the dependence of the LOC regime also on the safety factor q, recent work by Rice et al has found that rotation reversal may also be triggered by changing q (for example, by I_p and B_T ramp) suggesting that collisionality may be an important factor on transiting from LOC to SOC [11,12]. In contrast, in GYRO based transport studies presented here, as well as in earlier work by Lin [2], collisions did not play an important role in triggering either TEM or ITG.

6. Experimental measurements of the impurity content in C-Mod plasmas

Subsequent to the previous analysis, very recently we have carried out a series of experiments to measure the impurity content of C-Mod plasmas in the LOC regime. In tokamaks with graphite plasma facing components (PFCs), the carbon impurity dominates the dilution, $n_D=n_e-Zn_i$, (where n_D is the deuterium ion density and n_i is the carbon ion density) as well as the increment in the effective charge, $\delta Z_{eff}=Z(Z-1)n_i/n_e$. For machines with high-Z PFCs, $\delta Z_{eff}\sim 1$ can be reached without meaningful change to the dilution. Alcator C-Mod has both low-Z (B, C, O and F) and high-Z (Fe, Mo) intrinsic impurities, and commonly uses extrinsic seeding of Ar for X-ray Imaging Crystal Spectroscopy (XICS). In these experiments we also used extrinsic N_2 seeding to modify the dilution, typically after the first boronization of the campaign, resulting in negligible levels of Fe and C [13]. Boron concentrations have also been shown to be less than 0.5% in C-mod ohmic plasmas with negligible

Table 1: Impurity Analysis Summary

n_e (10^{20} m^{-3})	N_2Puff	Z_{eff} [a]	n_N/n_e	n_O/n_e	n_{Ar}/n_e	n_{Mo}/n_e	Z_{eff} [b]	n_D/n_e	Z_i [c]	n_i/n_e [c]
1.08	No	1.4	0.1 %	1.0 %	0.03 %	6 x 10^{-6}	1.65	92 %	9.1	0.88 %
1.08	Yes	1.6	1.4 %	0.6 %	0.03 %	2 x 10^{-6}	2.0	87 %	8.7	1.5 %
0.83	No	1.65	0.3 %	1.3 %	0.06 %	3 x 10^{-5}	2.0	88 %	9.3	1.3 %
0.82	Yes	2.4	3.2 %	0.6 %	0.04 %	7 x 10^{-6}	2.8	75 %	8.2	3.0 %
0.65	No	2.5	0.1 %	1.8 %	0.07 %	2 x 10^{-5}	2.2	86 %	9.6	1.5 %
0.70	Yes	3.2	3.4 %	0.4 %	0.02 %	9 x 10^{-6}	2.7	76 %	8.1	3.3 %
0.50	No	3.0	0.2 %	2.5 %	0.06 %	6 x 10^{-5}	2.7	80 %	9.5	2.1 %
0.53	Yes	3.4	4.4 %	0.7 %	0.06 %	2 x 10^{-5}	3.4	68 %	8.5	3.8 %

[a] Z_{eff} from neoclassical conductivity

[b] Z_{eff} from least-squares solution of line brightness

[c] Impurity charge and density consistent with both Z_{bright} and n_D/n_e

contribution to either dilution or Z_{eff} . The impurities are identified via soft X-ray (SXR) and vacuum ultraviolet (VUV) line emission (1-6 nm, [14] and 10-30 nm [15], respectively). While these instruments currently are not absolutely calibrated, they can be used to track the relative inter and intra-shot changes in impurity levels by observing the H-like and He-like emission of B, N, O and F, the Li like and Be- like emission of Ar and Na-like and Mg-like charge states of Mo. The absolute high Z impurity density is constrained using resistive bolometry and SXR tomography. The total low-Z impurity density is constrained by comparing the measured neutron rate and that modeled using the measured ion temperature profiles. The measured line brightness of the different impurities was compared to Z_{eff} computed from neoclassical conductivity to get absolute impurity densities. The resulting analysis showed an average impurity ion charge (i.e. one consistent with both dilution and Z_{eff}) of between 9.6 and 9.1 without Nitrogen seeding and between 8.7 and 8.1 with Nitrogen seeding. A summary of the results is given in Table 1. In our earlier TGLF and GYRO modeling we used a Z_i of 8, and Z_{eff} was varied as deduced from neoclassical resistivity, consistent with loop voltage measurements. The present work shows that it is essential to include dilution of deuterons to reduce the otherwise dominant ITG turbulence and dominant ion transport [2] in the LOC regime.

7. Summary and Discussions.

Extensive nonlinear gyrokinetic studies of turbulence and transport in low density ohmic plasmas in Alcator C-Mod were carried out in order to understand the underlying physics responsible for the linear ohmic confinement regime (LOC). As shown here, the majority deuteron ion depletion relative to the electron density due to medium charge state impurities has a profound impact on reducing ion transport. In particular, as the deuteron ions are depleted by a few tens of percent relative to electrons, the ion transport coefficients can be reduced by factors of three or more, making electron transport dominant in the LOC regime, in agreement with experiments. In the present work we report new spectroscopic measurements of impurity ions, supporting the prediction of medium Z_i ions being the dominant impurity species (Oxygen-like). The turbulent transport based on the ITG/TEM modes is dominant only in the radial region $0.5 < r/a < 0.8$. At smaller radii the electrostatic turbulence stabilizes due to the shallow gradients, while at larger radii the gyrokinetic analysis is not valid. Thus, it is not possible to deduce a global energy confinement time based on these results. 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. We have also carried out specific experiments with nitrogen injection, increasing the deuteron ion depletion and increasing Z_{eff}. The impact of such dilution experiments on transport and turbulence is under study.

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