PSFC/JA-12-49

Stationary density profiles in the Alcator C-mod tokamak

.

J. Kesner, D. Ernst, J. Hughes, R. Mumgaard, S. Scott*,
S. Shiraiwa, D. Whyte

* Princeton Plasma Physics Laboratory

December, 2012

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge MA 02139 USA

This work was supported by the U.S. Department of Energy, Grant No. DE-FC02-99ER54512. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States government is permitted.

Stationary density profiles in the Alcator C-mod tokamak

J. Kesner[1], D. Ernst[1], J. Hughes[1], R. Mumgaard[1], S. Scott[2], S. Shiraiwa[1], D. Whyte[1]

[1)] *Plasma Science and Fusion Center, Massachusetts Institute of Technology*

[2)] *Princeton Plasma Physics Laboratory*

(Dated: 20 December 2012)

In the absence of an internal particle source, plasma turbulence will impose an intrinsic relationship between an inwards pinch and an outwards diffusion resulting in a stationary density profile. The Alcator C-mod tokamak utilizes RF heating and current drive so that fueling only occurs in the vicinity of the separatrix. Discharges that transition from L-mode to I-mode are seen to maintain a self-similar stationary density profile as measured by Thomson scattering. For discharges with negative magnetic shear an observed rise of the safety factor in the vicinity of the magnetic axis appears to be accompanied by a decrease of electron density, qualitatively consistent with the theoretical expectations.

I. INTRODUCTION

A peaked, stationary density profile is desirable for a fusion based power source and in the absence of core fueling, an inwards pinch is required to peak the density. Plasma turbulence will give rise to both an inwards pinch and outwards diffusion. They are therefore intrinsically related and result in predictable stationary profiles. A pinch has been predicted by a theory known as turbulent equipartition (TEP)[1–7] which assumes the conservation of adiabatic invariants and by more general calculations that follow from quasi-linear and non-linear gyrokinetics[8–11].

In a tokamak, electrons streaming parallel to field lines will average potential fluctuations and therefore have only a weak response to electrostatic turbulence[5,12]. Furthermore deeply trapped particles react more strongly with eigenmodes that are localized in the low field "bad" curvature region of the torus. Stationary profiles consistent with turbulent equipartition theory have been observed in the DIII-D tokamak[5–7] during L-mode operation. Similarly stationary profiles were observed in the JET tokamak[18] in studies that indicated that temperature gradient driven particle transport, known as the thermodiffusion, would not account for the observed profiles. However, the observed density profiles in JET remain monotonically peaked during reversed shear operation, in contradiction with the theory of turbulent equipartition.

A strong turbulent pinch has been clearly observed in a dipole experiment[14]. For a dipole the magnetic field is poloidal and electrostatic modes are flute-like[13] and, as a result, all electrons (trapped as well as passing) see the same wave field. Combined with a strong magnetic field gradient ($B \propto 1/R^3$) this results in a strong pinch and a sharply peaked stationary state. In the Levitated Dipole Experiment (LDX) the potential and density fluctuations producing the turbulent pinch were measured directly[14,15] and were seen to be consistent with a quasi linear flux. The observed pinch was seen to be consistent with results from a gyrokinetic calculation[16,17].

A general treatment of turbulent transport requires a nonlinear gyrokinetic code such as GS2[20]. However a simple estimate can be obtained assuming the conservation of the longitudinal invariant, J, ($J \equiv \oint v_\parallel d\ell$) which requires that the bounce frequency exceeds the wave frequency. This assumption, along with the conservation the magnetic moment μ, ($\mu = v_\perp^2/2B$) is the basis of the simpler turbulent equipartition (TEP) theory[21]. For plasma confined by a strong magnetic field, electrons conserve the longitudinal invariant J whereas ions may not although they are constrained by quasi neutrality to follow the electrons.

The Alcator C-mod tokamak[22] is heated by ion cyclotron resonance heating (ICRF) and the plasma current may be maintained by lower hybrid current drive (LHCD). Densities are an order of magnitude higher than in other tokamaks and fueling is localized at the plasma edge. We report here the observation of stationary density profiles as predicted by TEP theory in the Alcator C-mod tokamak under diverse operating conditions that include L-mode, I-mode[23], and negative magnetic shear operation[24].

II. THEORETICAL CONSIDERATIONS

Consider a turbulent spectrum of fluctuations in a collisionless plasma that satisfies $\Omega_{cj} \gg \omega_{bj} \gg \omega$ with $\Omega_{cj},\ \omega_{bj},\ \omega$ respectively the cyclotron frequency and bounce frequency for species j and the wave frequency. Under these conditions the adiabatic invariants μ and J are conserved. Note that often $\omega_{bi} < \omega$ for ions as for ion temperature gradient (ITG) modes. The quantity $\psi - mcRv_\phi/e \approx \psi(1 + O(\rho/R))$, proportional to the canonical angular momentum, is conjugate with the toroidal angle ϕ and is a constant of motion for sufficiently low frequency fluctuations. When $\omega \sim \omega_d$ with ω_d the toroidal curvature drift frequency, canonical angular momentum is no longer conserved and we can write a mean field Lagrangian collisionless kinetic equation for $f = f(\mu, J, \psi, t)$[26–29] as follows:

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial \psi}\bigg|_{J,\mu} D^\psi \, \frac{\partial f}{\partial \psi}\bigg|_{J,\mu} + S(\mu, J). \tag{1}$$

$S(\mu, J)$ is the local particle source and we have assumed that the turbulent transport dynamics can be parametrized by a turbulent diffusion coefficient, $D^\psi(\mu, J, \psi)$[5,30]. The source, S, can be ignored in the plasma core when fueling is limited to the plasma edge. The particle flux implied by Eq. (1) is

$$\Gamma = -\iint d\mu dJ \; D^\psi \, \frac{\partial f}{\partial \psi}\bigg|_{J,\mu}. \tag{2}$$

The quasilinear diffusion coefficient, $D^\psi \approx D^{QL}(\psi, \epsilon, \lambda) \propto \Sigma A_\ell |\phi_\ell|^2$ with ϵ the energy and λ the pitch angle variable, $\lambda \equiv \mu/\epsilon$ and ℓ the toroidal mode number.

For a diffusion coefficient that is independent of velocity and considering spatial scales larger than the turbulence correlation length but smaller than the gradient scale length, D^ψ

becomes independent of ψ and we can define $D^{\psi} \approx D$. Integrating Eq. (1) over μ and J noting that $\int\int d\mu dJ = \oint d\ell/B \int d^3v$ we obtain:

$$\Gamma \equiv -D\frac{\partial N}{\partial \psi} = -D(V'\frac{\partial n_e}{\partial \psi} + n_e\frac{\partial V'}{\partial \psi}) \tag{3}$$

with N the particles per unit flux, $N \equiv n_e(\psi)V'(\psi)$ and $V' \equiv dV/d\psi = \oint d\ell/B$ is the specific volume (i.e. the volume per unit poloidal flux). For a stationary profile $\Gamma \approx 0$ and therefore $n_e \propto 1/V'$. Notice that the density profile is independent of the diffusion coefficient, D, and D will only effect the rate at which the plasma approaches a stationary profile. Although D is generally different for ions and electrons (requiring the convective velocity to be different), TEP theory assumes the same D for both species. In Eq. (3) the term proportional to the density derivative is a diffusive term and the off-diagonal term, proportional to density, can be interpreted as a pinch term.

In a tokamak the diffusion coefficient D^{ψ} is a function of pitch angle and "passing" and "trapped" particles respond differently to fluctuations. Equation (2) can be integrated using a diffusion coefficient of the form $D^{\psi} = D(\psi)g_p(\lambda)(\epsilon/T)^{-\alpha}$ with g_p is the ratio of the diffusion coefficient for passing vs. trapped particles[19]. In the usual limit of a large collision rate compared to the diffusion rate the distribution function, f, must be taken as a local Maxwellian, $f_M = (m/2\pi T(\psi))^{3/2}\, n(\psi)exp(-\epsilon/T(\psi))$. An approximation to the solution of the resulting integral has been obtained in which a parameter, η, replaces the function $g_p(\lambda)$[19]. For $\Gamma = 0$ the stationary profile then obtains the form[19]

$$\frac{1}{n_e}\frac{\partial n_e}{\partial \psi} \approx \left(1 - \frac{2}{3}\alpha\right)\left(\eta q H \frac{\partial}{\partial \psi}\frac{1}{qH}\right) + \alpha\frac{1}{T}\frac{\partial T}{\partial \psi}. \tag{4}$$

For an equal response of passing and trapped particles $g_p = \eta = 1$ whereas for no passing particle response $g_p = 0$ or $\eta \approx 0.2$.

For a shaped tokamak the specific volume takes the form:

$$V' \equiv \oint d\ell/B \approx 2\pi R_0 q(\psi)H(\psi)/B_0 \tag{5}$$

with B_0 (R_0) the field (major radius) at the magnetic axis, ψ the poloidal flux, $q(\psi)$ the safety factor, and $H(\psi)$ is a correction for aspect ratio and shape (H=1 for a large aspect ratio circular cross-section torus). When we can ignore the temperature gradient ($\alpha = 0$), we can combine Eqs. (5) and (4) to obtain

$$n_e = A\ (2\pi R_0 qH/B_0)^{-\eta}. \tag{6}$$

A more general derivation of a pinch can also be obtained from gyrokinetics[8–11]. We can write the quasi linear flux as

$$\Gamma_P^{QL} = -n_e D^{QL} \left(\frac{1}{n_e} \frac{\partial n_e}{\partial \rho} + C_T \frac{1}{T_e} \frac{\partial T_e}{\partial \rho} - \frac{C_P}{R} \right) \tag{7}$$

with R the major radius and the coefficients D^{QL}, C_T and C_P represent respectively the quasi linear diffusion coefficient, and the coefficients for the thermodiffusive and the curvature pinch. These coefficients can be obtained from a gyro kinetic code such as GS2[20]. In a study in which GS2 was run in the electrostatic and linear limit with gyrokinetic electrons and ions the results were seen to agree with expressions derived from the quasi linear approximation[10]. It was found that the ion temperature gradient (ITG) mode and the trapped electron (TEM) mode will coexist and produce a stationary state in which the quasi-linear flux, $\Gamma_P^{QL} \approx 0$.

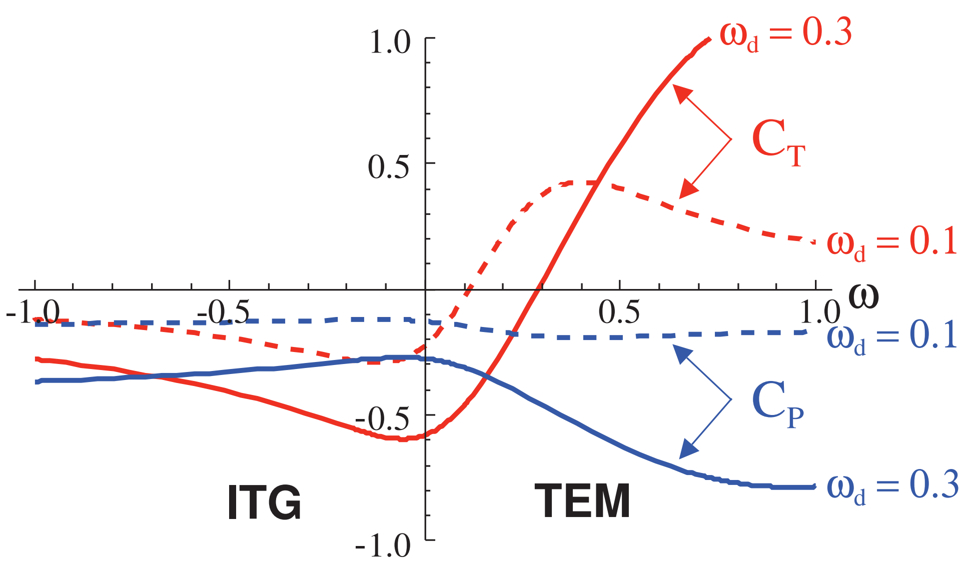

FIG. 1. The quasilinear coefficients (Eqs. 9, 10) vs. ω for $\gamma = 0.2$, $k_y \rho_i = 0.5$ and $\omega_d = 0.3$ (solid lines) and $\omega_d = 0.1$ (dashed lines). 1) Thermo diffusion coefficient, C_T, (red) and 2) Curvature pinch coefficient C_P, (blue). Negative values indicate inwards flows.

A rough approximation to the coefficients may be obtained from quasilinear theory by assuming a single mode and assuming that the dominant part of the pinch derives from trapped particles[10]:

$$D^{QL}(\psi, E, \lambda) \propto \Sigma A_n |\phi_n|^2 \tag{8}$$

$$C_T \approx \frac{Im\left(\int d^3v F_M (E-3/2)/(i\gamma + \omega - k_\parallel v_\parallel - \omega_d \hat{E})\right)}{Im\left(\int d^3v F_M/(i\gamma + \omega - k_\parallel v_\parallel - \omega_d \hat{E})\right)}, \tag{9}$$

$$C_P \approx -\frac{1}{k_\perp \rho} \frac{Im\left(\int d^3v F_M (\omega + i\gamma)/(i\gamma + \omega - k_\parallel v_\parallel - \omega_d \hat{E})\right)}{Im\left(\int d^3v F_M/(i\gamma + \omega - k_\parallel v_\parallel - \omega_d \hat{E})\right)}. \tag{10}$$

with $\omega_d = k_\perp \rho [\langle cos\theta \rangle + \hat{s}\langle \theta sin\theta \rangle - \alpha \langle sin\theta^2 \rangle]$, θ the ballooning angle and the angle brackets represent an average over a Gaussian trial function defined by θ_0. The wave vector is $k_\parallel = \langle 1/q d/d\theta \rangle \approx \hat{k}(a/Rq)/2\theta_0$ and $(\hat{s},\ \alpha)$ assume the usual definitions for circular high beta tokamak equilibria. E is the normalized energy, $E = (v_\parallel^2 + v_\perp^2)/2T$, $\hat{E} = v_\parallel^2 + v_\perp^2/2$ and λ is the pitch angle variable, $\lambda \equiv \mu/E$. Frequencies are normalized to the sound frequency c_s/R. Further simplification comes from assuming that only deeply trapped particles ($v_\parallel \approx 0$) contribute to the pinch. The resulting quasi-linear coefficients are shown in Fig. 1 for $\omega_d =$ 0.3 and 0.1. ITG instability corresponds to negative ω while TEM instability corresponds to positive ω values. The coefficient of thermodiffusion, C_T, (Eq. 9) has a subtraction in the numerator and can change signs for different spectra of waves. It is found that C_T will tend to produce a pinch for ITG modes ($\omega < 0$) and an outward flow for TEM modes ($\omega > 0$). Thus the response for a broad spectrum of turbulence requires a detailed non-linear evaluation of the wave spectrum. Except for the curvature drift term, the integrals appearing in the curvature pinch, (Eq. (10) with $v_\parallel \approx 0$), are positive and noting that the flux tube average curvature drift is $\langle \omega_d \rangle = (\ell/e)\ T_e\ d \ln V'/d\psi$[31] and $V' \propto q$ we observe that negative magnetic shear will lead to a reversal in the curvature pinch (C_P) and an outwards flow.

III. ALCATOR C-MOD RESULTS

Alcator C-mod is a D-shaped and diverted tokamak with aspect ratio $A \sim 3$. Since C-mod operates at high density and has auxilliary heating via RF waves, all fueling takes place close to the plasma edge. Under normal operating conditions the geometric factor in Eq. (6) becomes $H \approx -0.46\hat{r}^2 + 0.25\hat{r} + 0.94$ and $\hat{r} = (R - R_0)/a$ with R the midplane radius, $R_0 = 0.67\ m$ the major radius and $a = 0.22\ m$ the minor radius.

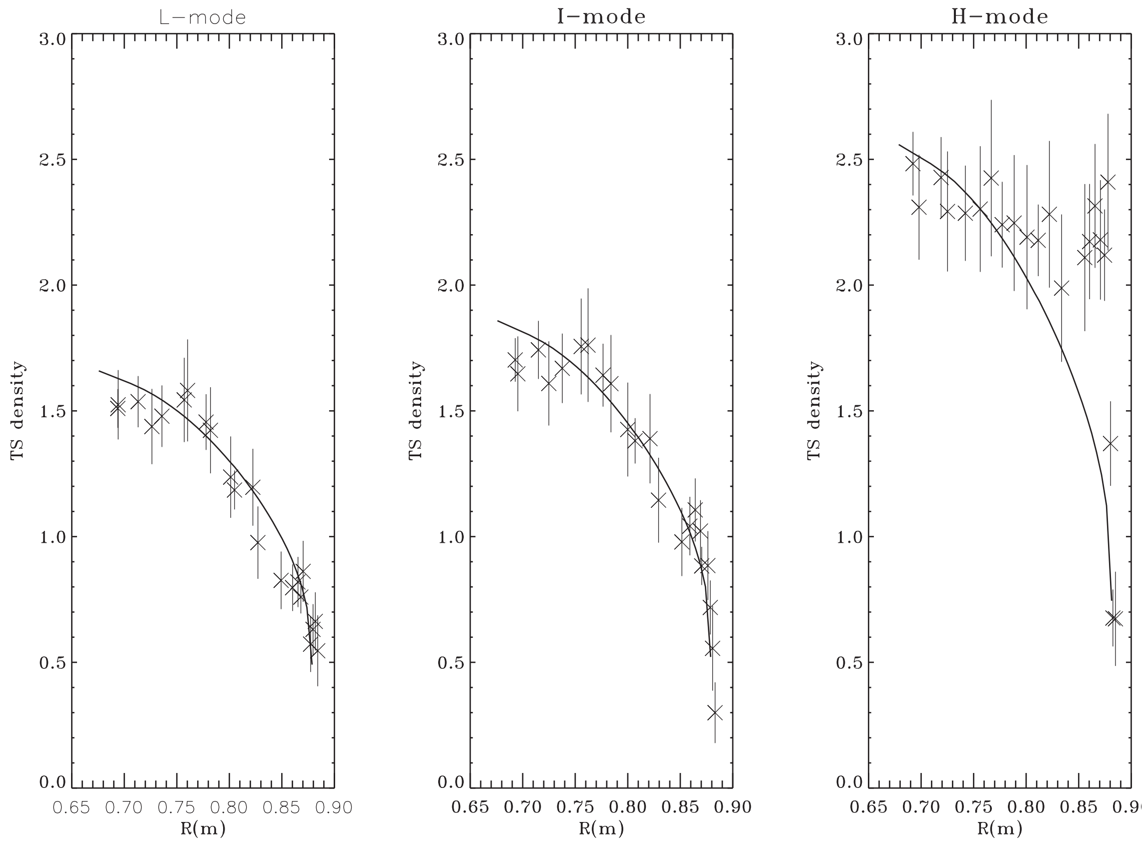

FIG. 2. C-mod density profiles ($10^{-20} n_e$ (m^{-3})) from Thomson scattering for a discharge (1100827029) when the plasma is in L-mode (t=0.9s), I-mode (t=1.25s) and H-mode (t=1.4s) respectively. Solid line is Eq. 6 with $\eta = 0.7$ and A=1.1.

The C-mod experiment has observed a mode of operation known as the "I-mode"[23], in which the density appears to behave as in a low confinement or "L-mode" discharge, (peaked density, low particle confinement time) while the energy is confined as in a high confinement or "H-mode" discharge. Figure 2 displays a C-mod discharge that exhibits successive transitions from L-mode (Fig. 2(a)) to I-mode (Fig. 2(b)) to H-mode (Fig. 2(c)). Considering a range of C-mod discharges we find that L-mode discharges are well fit by Eq. (6) with $\eta \approx 0.7$ which is consistent with results from DIII-D[6]. At the L-I transition the density rises but the profiles remains self-similar and fit by $\eta = 0.7$ as seen by the solid lines in Figs. 2(a) and (b). After a transition to H-mode, however, the edge density rises and the profile is poorly fit by $\eta = 0.7$ (Fig. 2(c)).

An implication of turbulent equipartition, Eq. (6), or alternatively the quasilinear curvature pinch with thermodiffusion subdominant, Eq. (10), is that the axial density would be

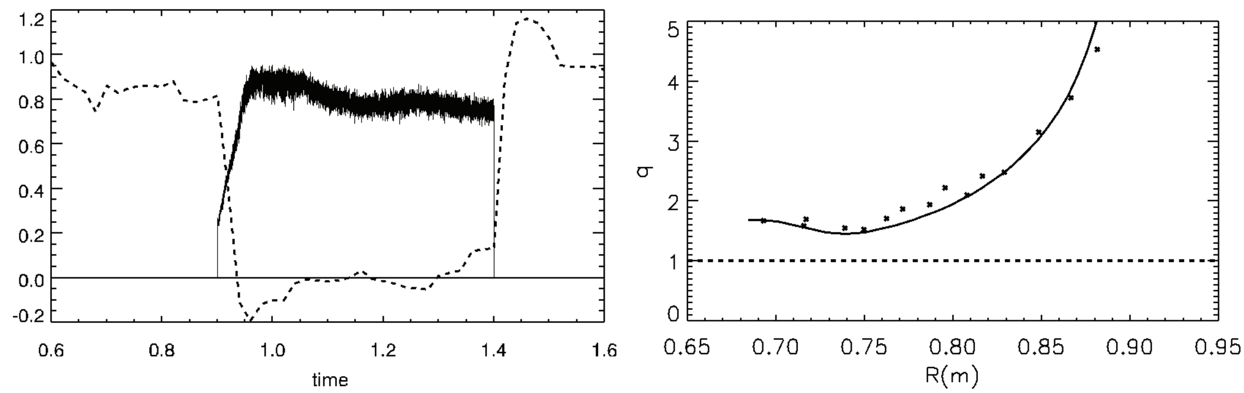

FIG. 3. a) LHCD (solid, MW) and loop voltage (dashed, V) vs. time for discharge 1101019014 and b) MSE constrained q profile at t=1.34 s and experimental values derived from Thomson scattering measurements vs R (m). Magnetic axis at R=0.68 m.

expected to fall in discharges with shear reversal, as are formed by off-axis current drive. Figure 3(a) shows the loop voltage and LHCD power for a discharge in which an 800 kW LHCD heating pulse was applied between 0.9 and 1.4 s. A motional Stark effect (MSE) measurement, used to constrain an EFIT[25] generated equilibria reveals a q profile at t=1.34 s that has an off-axis minimum at R=0.75 and rises 15% from this minimum to a higher value at the magnetic axis (at R=0.67 m), Fig. 3(b)[24].

During non-inductive current drive the plasma develops a local negative loop voltage that opposes a change of the current profile and the modification of the current profile is delayed for a resistive time. Thomson scattering measurements of the density profiles are suggestive of a hollowing of density in the vicinity of the magnetic axis after ∼200 ms of lower hybrid wave heating. The measured density profiles are shown at four times in Fig. 4. and a decrease of density near the magnetic axis is observed after t≈1.2 s. The solid curves in Fig. 4 represent a least squares B-spline fit to the data with error weighting. The error bars represent Monte Carlo error analysis of the fitted profiles, i.e. the standard deviation of the fit based on 100 trials in which the data points are varied according to their experimental error bars. Although the dip in density near the magnetic axis falls within the error bars, the Monte-Carlo analysis indicates that the error weighted average profile is hollow. Conversely, values of the safety factor, q, can be obtained from ($q \propto 1/(Hn_e^{1/\eta})$, Eq. (6), with density obtained from Thomson scattering measurements and $\eta = 0.7$ (averaging 5 similar and consecutive discharges) and are consistent with the measured q profile (Fig. 3b).

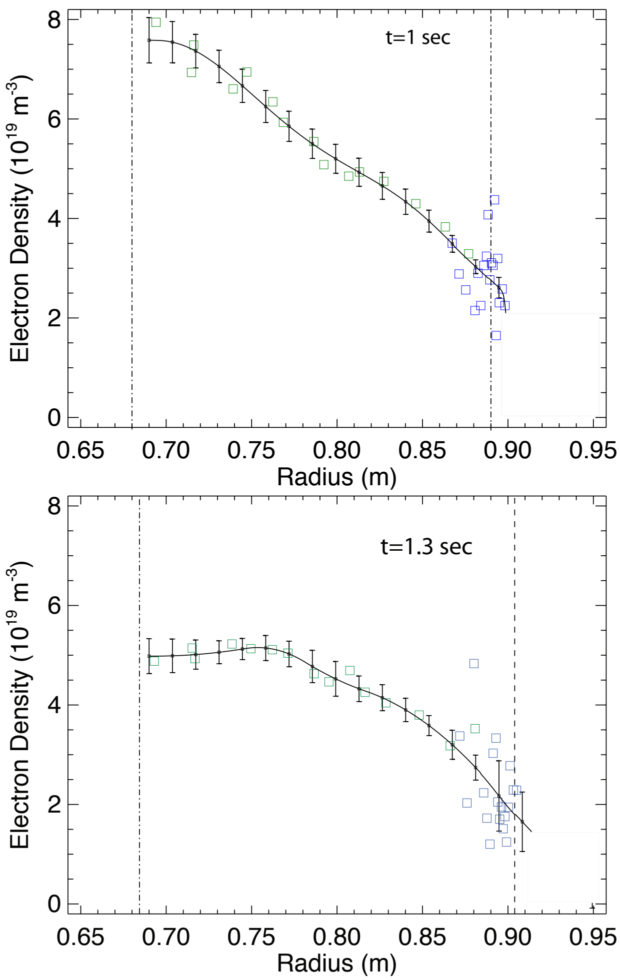

FIG. 4. Electron density profiles from Thomson scattering for discharge 1101019014. a) t≈1 s, b) t≈1.2 s, c) t≈1.3 s. d) t≈1.4 s. Dashed lines indicate the magnetic axis ($R \approx 0.68$ m) and the separatrix ($R \approx 0.88$ m).

During LHCD we observe a turn-on of MHD activity centered at 650 kHz which begins at t=1.1 s and rises after t≈1.3 s. The increase in MHD activity is accompanied by a decrease in ECE emission near the machine axis indicating a loss of of hot electrons and an increase in axial loop voltage is observed. After LHCD shutoff at t=1.4 s the density profile was seen to return to a peaked profile similar to the earlier profile (i.e. at t=1 s, before the q profile has formed reverse shear), Fig. 4d. The temperature profile remains peaked during the lower hybrid heating for these discharges. During lower hybrid current drive the electron temperature exceeds the ion temperature and it is expected that the trapped electron mode (TEM) becomes dominant[32,33]. Shear reversal would be expected to stabilize the TEM (ITG turbulence is still present). Diffusion alone would produce a flat density profile and only an outwards flow, as is predicted to accompany negative magnetic shear by turbulent equipartition (Eq. (6)), can explain an inversion of the density profile.

IV. DISCUSSION

Turbulent equipartition represents a simple subset of gyrokinetic theory, valid when the adiabatic invariants j and μ are conserved. Turbulent equipartition is seen to create a tendency toward a density profile characterized by an equal number of particles per unit flux which, for a tokamak implies that $n_e \propto 1/q^\eta$. A density profile having this character is seen under some circumstances in Alcator C-Mod. More detailed analysis would indicate that temperature gradients can play an important role in establishing the density profile in a turbulent plasma.

I-mode discharges are interesting for tokamak fusion because they exhibit excellent ("H-mode") energy confinement. We have seen that they also exhibit peaked stationary profiles as are predicted by turbulent equipartition. In standard H-mode plasmas a flat density profile is usually observed which implies the reduction or absence of a pinch. H-mode plasmas have higher densities and lower levels of turbulence as well as an altered turbulence spectrum, all of which can serve to reduce the pinch. For sufficiently low collisionality a peaked density profile has been observed in H-mode discharges[34] indicating the presence of a pinch.

Negative magnetic shear can result from bootstrap current or from off-axis current drive. The turbulent equipartition theory predicts that $n_e \propto 1/q$ and therefore one would expect that the local density falls if q rises near the magnetic axis. This is indeed observed in C-mod experiments.

In experiments with monotonic q profiles on the JET tokamak the density profiles were seen to peak in manner consistent with turbulent equipartition[18]. Furthermore it was observed that this peaking was not consistent with thermodiffusion and was independent of collisionality for $0.06 < \nu_* < 0.4$. However, in JET current drive experiments with negative magnetic shear (as measured by Faraday rotation) the density was not observed to fall in the vicinity of the magnetic axis.

The turbulent pinch requires a sufficient level of turbulence such that turbulence becomes the dominant transport mechanism. A higher turbulence level would stiffen but not change the density profile although it would reduce energy confinement. Since $n_e \propto 1/(V')^\eta$ from

TEP theory, it is clear that a radially increasing specific volume, V', will lead to a centrally peaked density profile. In a vacuum field $\nabla V' > 0$ implies bad curvature (as in a dipole or an axisymmetric mirror) whereas in the presence of plasma current (i.e. a tokamak) the gradient of V' is determined by the q profile ($V' \propto q$).

Acknowledgements

The authors would like to thank the Alcator C-mod experimental team. This work was supported by the US DoE Office of Fusion Energy Sciences.

REFERENCES

[1] H.P. Warren, A. Bhattacharjee and M.E. Mauel, Geophys. Research Lett. **19**, 941 (1992).

[2] M.B. Isichenko, N.V. Pervisshvili, Phys. Plasmas **2**, 3650 (1995).

[3] V.V. Yankov, JETP Lett. **60** 171 (1994).

[4] H.P. Warren and M.E. Mauel, Phys. Plasmas **2**, 4185 (1995).

[5] D. Baker and M.N. Rosenbluth, Phys. Plasmas **5**, 2936 (1998).

[6] D. Baker, Phys. Plasmas **9**, 2675 (2002).

[7] C. Estrada-Mila, J. Candy, R.E. Waltz, Phys. Plasmas **13**, 074505 (2006).

[8] M. A. Beer, G. W. Hammett, G. Rewoldt, E. J. Synakowski, and M. C. Zarnstorff, Phys. Plasmas **4**, 1792 (1997).

[9] F. Miskane, X. Garbet, A. Dezairi and D. Saifaoui, Phys. Plasmas **7**, 4197 (2000).

[10] E. Fable, C. Angioni, O. Sauter, Plasma Phys. Control. Fusion **50**, 115005 (2008).

[11] C. Angioni, J. Candy, E. Fable, M. Maslov, A. Peeters, Phys. Plasmas **16**, 060702 (2009).

[12] C. S. Liu, D. C. Baxter, and W. B. Thompson, Phys. Rev. Lett. **26**, 621 (1971).

[13] J. Kesner, J. Hastie, Phys. Plasmas **9** 395 (2002).

[14] A.C. Boxer, R. Bergmann, J.L. Ellsworth, D.T. Garnier, J. Kesner, M.E. Mauel and P. Woskov, Nature Phys. **6**, 207 (2010).

[15] J. Kesner , M. S. Davis, J.L. Ellsworth, D. T. Garnier, J. Kahn, M. E. Mauel, P. Michael, B. Wilson and P. P. Woskov, Plasma Phys. Contr. Fusion **52**, 124036 (2010).

[16] S. Kobayashi, B. Rogers, W. Dorland, Phys. Rev. Lett. **103**, 055003 (2009).

[17] S. Kobayashi, B. Rogers, W. Dorland, Phys. Rev. Lett. **105**, 235004 (2010).

[18] H. Weisen, A. Zabolotsky, X. Garbet, D. Mazon, L. Zabeo, C. Giroud, H. Leggate, M. Valovic, K.-

D. Zastrow and contributors to the JET-EFDA Workprogramme, Plasma Phys. Control. Fusion **46**, 751 (2004).

[19]D.R. Baker, M.R. Wade, C.C. Petty, M.N. Rosenbluth, T.C. Luce, J.S. deGrassie, B.W. Rice, R.J. Groebner, C.M. Greenfield, E.J. Doyle, C.L. Rettig, T.L. Rhodes, M.A. Mahdavi, Nucl. Fusion **40**, 1003 (2000).

[20]M. Kotschenreuther, G. Rewoldt, W.M. Tang, Comput. Phys. Commun. **88** 128 (1995).

[21]C. Angioni, R.M. McDermott, E. Fable, R. Fischer, T. Ptterich, F. Ryter, G. Tardini and the ASDEX Upgrade Team, Nucl. Fusion **51** 023006 (2011).

[22]E. Marmar et al., Fusion Sci. Technol. **51**, 261(2007).

[23]D.G. Whyte, A.E. Hubbard, J.W. Hughes, B. Lipschultz, J.E. Rice, E.S. Marmar, M. Greenwald, I. Cziegler, A. Dominguez, T. Golfinopoulos, N. Howard, L. Lin, R.M. McDermottb, M. Porkolab, M.L. Reinke, J. Terry, N. Tsujii, S.Wolfe, S.Wukitch, Y. Lin and the Alcator C-Mod Team, Nucl. Fusion **50**, 105005 (2010).

[24]S. Shiraiwa, O. Meneghini, R.R. Parker, G. Wallace, J.Wilson, I. Faust, C. Lau, R. Mumgaard, S. Scott, S.Wukitch,W. Beck, J. Doody, J. Irby, P. MacGibbon, D. Johnson, A. Kanojia, P. Koert, D. Terry, R. Vieira and the Alcator C-Mod team, Nucl. Fusion **51**, 103024 (2011).

[25]L. Lao, H. St. John, R. Stambaugh, A. Kellman, W.Pfeiffer, Nuclear Fusion, **25**, 1611 (1985).

[26]T. Birmingham, J. Geophys. Res. **74**, 2169 (1969).

[27]I.B. Bernstein and K. Molvig, Phys. Plasmas **26** , 1488 (1983).

[28]M.B. Isichenko, A.V. Gruzinov, P.H. Diamond, Phys. Rev. Lett. **74**, 4436 (1995).

[29]M.B. Isichenko, A.V. Gruzinov, P.H. Diamond and P.N. Yushmanov, Phys. Plasmas **3**, 1916 (1996).

[30]X. Garbet, L. Garzotti, P. Mantica, H. Nordman, M. Valovic, H. Weisen, C. Angioni, Phys. Rev. Lett. **91**, 035001 (2003).

[31]N. Krasheninnikova and P.J. Catto, Phys. Plasmas **13** 052503 (2006).

[32]D. Ernst, P. T. Bonoli, P. J. Catto, W. Dorland, C. L. Fiore, R. S. Granetz, M. Greenwald, A. E. Hubbard, M. Porkolab, M. H. Redi, J. E. Rice, K. Zhurovich, and the Alcator C-Mod Group, Phys. Plasmas **11**, 2637 (2004).

[33]Y. Podpaly, " Rotation Generation and Transport in Tokamak Plasmas", MIT Ph.D. Thesis, MIT PSFC Report PSFC/RR-12-2 (2012).

[34]M. Greenwald, C. Angioni, J.W. Hughes, J. Terry and H.Weisen, Nucl. Fusion **47**, L26 (2007).