Correlations of heat and momentum transport in the TFTR tokamak*

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Measurements of the toroidal rotation speed $v_\phi(r)$ driven by neutral beam injection in tokamak plasmas and, in particular, *simultaneous* profile measurements of v_ϕ, T_i, T_e, and n_e, have provided new insights into the nature of anomalous transport in tokamaks. Low-recycling plasmas heated with unidirectional neutral beam injection exhibit a strong correlation among the local diffusivities, $\chi_\phi \approx \chi_i > \chi_e$. Recent measurements have confirmed similar behavior in broad-density L-mode plasmas. These results are consistent with the conjecture that electrostatic turbulence is the dominant transport mechanism in the tokamak fusion test reactor tokamak (TFTR) [Phys. Rev. Lett. **58**, 1004 (1987)], and are inconsistent with predictions both from test-particle models of strong magnetic turbulence and from ripple transport. Toroidal rotation speed measurements in peaked-density TFTR "supershots" with partially unbalanced beam injection indicate that momentum transport decreases as the density profile becomes more peaked. In high-temperature, peaked-density plasmas the observed gradient scale length parameter $\eta_i^{\rm tot} = d \ln T_i / d \ln n_e$ correlates reasonably well with predictions of the threshold for exciting ion-temperature-gradient-driven turbulence (ITGDT), as would be expected for plasmas at marginal stability with respect to this strong transport mechanism. In L-mode plasmas where ITGDT is expected to be too weak to enforce marginal stability, $\eta_i^{\rm tot}$ exceeds this threshold considerably. However, preliminary experiments have failed to observe a significant increase in ion heat transport when $\eta_i^{\rm tot}$ was rapidly forced above η_c (the threshold for exciting ITGDT) using a perturbative particle source, as would have been expected for a plasma at marginal stability.

I. INTRODUCTION

The discovery of a peaked-density plasma regime (the so-called "supershot" regime) offering improved energy confinement and ion heating in the tokamak fusion test reactor (TFTR)[1,2] has sparked considerable experimental effort to characterize and understand the effect of density profile shape on radial energy transport. The peakedness of the electron density profile $F_{ne} = n_e(0)/\langle n_e \rangle$ in neutral-beam heated TFTR plasmas spans a continuum of values from ~ 1.6 in typical L-mode discharges to ~ 3.0 in the best supershots. There is a corresponding continuous variation of global energy confinement time τ_E, ranging from 0.9 to $3.2 \times \tau_E^{\rm L\ mode}$.[3] The study of a large database of TFTR beam-heated discharges[4,5] has identified a strong correlation between τ_E and F_{ne} throughout these regimes. This correlation reflects marked reduction in local heat transport coefficients with increasing density peakedness, particularly in ion thermal diffusivity, rather than improvements in the penetration depth of neutral beams.[6,7] Indeed, near the center of many supershots the radial ion energy flux is dominated by convective losses associated with ion convection, making a precise determination of the conducted power difficult.[8]

Several features of the observed local transport in these regimes are consistent with those expected from ion-temperature-gradient-driven turbulence (ITGDT). In supershots, the total ion density (including beam ions and assum-

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ing that $Z_{\rm eff}$ is radially uniform) gradient scale length, $L_{n_i^{\rm tot}}$, is correlated with the gradient scale length for ion temperature, L_{T_i}.[7] This is also observed in low-recycling discharges heated by unidirectional beam injection, which attain density peakedness and energy confinement intermediate between the L-mode and balanced-injection supershot regimes.[9] In addition, simultaneous measurements of the local transport or momentum and heat in these discharges (the "hot-ion" mode) show a striking correlation among the thermal diffusivities χ_e, χ_i, and χ_ϕ as would be expected from $\widetilde{E} \times B$ turbulence. Similar correlations between χ_e and χ_i were observed previously in the DIII tokamak[10] and in TFTR supershots.[11]

Studies of local transport of both heat and momentum have now been extended to the L-mode regime, which differs from the supershot and hot-ion mode regimes in several parameters that are expected to influence the behavior of ITGD turbulence. In particular, the ratio of T_i/T_e drops to ~ 1 in the L mode from ~ 3 in the supershot and hot-ion regimes, and the role of fast ions is reduced considerably relative to that in the hot-ion regime.

This paper presents an analysis of local transport in L-mode plasmas, its relationship to local transport in other regimes, and its interpretation within the framework of ITGDT theory. Particular attention is given to studies of momentum transport during unbalanced beam injection, which represents a useful tool for exploring transport in the ion channel because ion–electron coupling is unimportant in the momentum balance. In Sec. IV, we discuss transport measurements in supershots whose peaked density profiles were transiently flattened by a particle source (gas puff or pellet). A large increase in ion heat transport that was expected from ITGDT when the plasma exceeded the threshold for exciting these modes was not observed, suggesting that the supershot profiles are *not* marginally stable with respect to a strong transport mechanism.

II. LOCAL TRANSPORT MEASUREMENTS IN L-MODE PLASMAS

Over a wide range of plasma currents and beam powers, the behavior of TFTR discharges is similar to the L-mode regime observed on other tokamaks whenever the surface layers of the graphite inner bumper limiter is loaded with deuterium gas so that particles recycle with high efficiency. In the high-recycling discharges discussed here, the global energy confinement time τ_E was in the range 1.0–$1.3\times\tau_E^{\rm L\,mode}$ as the plasma current was varied from 0.9–1.8 MA, and as the beam power was increased to ~ 20 MW. In Table I we list the plasma conditions for typical L-mode, hot-ion-mode, and supershot plasmas of comparable plasma currents and beam powers, along with the parameters of a higher-current supershot. For a given beam power and plasma current, the lowest density is obtained in coinjection hot-ion-mode plasmas, which are therefore strongly beam dominated, as shown by the ratio of parallel to perpendicular pressure. Supershot plasmas at higher plasma current and higher central density generate beam-ion populations more similar to those observed in L-mode plasmas. Significantly higher ion temperatures and rotation speeds, and modestly higher electron temperatures occur in hot-ion-mode discharges compared to L-mode discharges.

Local transport coefficients in these plasmas have been determined by solving the power and momentum balance using a one-dimensional (1-D) steady-state transport analysis code SNAP[8] based on the measured density, velocity, and temperature profiles. Here $T_e(R)$ was measured by first harmonic ECE radiometry and by Thomson scattering, $T_i(R)$ and $v_\phi(R)$ by charge-exchange recombination spectroscopy, $n_e(R)$ by Thomson scattering and by a ten channel infrared interferometer, and $Z_{\rm eff}$ by tangential visible bremsstrahlung emission. Edge hydrogenic-neutral influx was inferred from D_α emission measurements by a poloidal array of five absolutely calibrated detectors.[12] All measured profiles were smoothed using a triangular weighting function with full width at half-maximum (FWHM) = 10%–15% of the minor radius. For this paper the local thermal diffusivities for radial transport of heat and momentum are defined by

$$Q_i = -\chi_i(\Sigma_j n_j)\nabla T_i + \tfrac{3}{2}\Gamma_i T_i,$$

$$Q_c = -\chi_e n_e \nabla T_e + \tfrac{3}{2}\Gamma_e T_e,$$

$$\gamma = -\chi_\phi(\Sigma_j n_j m_j)R\nabla v_\phi + \Gamma_i\langle m_h\rangle R v_\phi,$$

where Q_i and Q_e are the total ion and electron heat flux, γ is the radial flux of toroidal momentum, Γ_i is the radial ion flux determined from the calculated particle sources at steady state (Γ_i is assumed hydrogenic with average mass $\langle m_h\rangle$), and Σ_j represents a sum over all ion species including impurities. The convective heat flows $Q_{\rm conv}$ have been set to $\frac{3}{2}\Gamma T$ for consistency with previous transport analysis of supershot and hot-ion mode plasmas, for which the power balance yields unphysical *negative* χ_i and χ_e near the plasma center if $Q_{\rm conv}$ is taken as $\frac{5}{2}\Gamma T$.[6,11] Convection remains an important term in the electron and ion power near the plas-

TABLE I. Plasma conditions for typical L-mode and hot-ion mode plasmas utilizing cotangential injection, and typical supershot plasmas utilizing balanced injection. The pressure ratio is determined from equilibrium field and diamagnetic measurements. The beam ion density and total energy are computed from classical beam deposition and slowing down calculations including the effects of rotation.

Regime	I_p MA	P_b MW	B_ϕ T	$\bar{n}_e$ 10^{19} m^{-3}	F_{ne}	$Z_{\rm eff}$	$\tau_E^{\rm dia}$ msec	τ_E/τ_E^{LM}	$P_\parallel/P_\perp$	$W_b/W_{\rm tot}$	n_{e0} 10^{19} m^{-3}	n_{b0}/n_{e0}	T_{e0} keV	T_{i0} keV	$v_{\phi 0}$ 10^5 m/sec
L mode	1.2	12.0	3.8	3.4	1.7	2.2	83	1.3	1.15	0.36	5.0	0.10	4.1	4.6	1.7
Hot-ion mode	1.1	11.6	4.8	2.0	1.9	3.1	106	2.0	1.42	0.60	3.0	0.20	6.6	22	5.5
Supershot	1.2	14.5	4.8	2.4	2.5	3.5	138	2.4	1.24	0.65	4.3	0.40	7.4	19	0.6
Supershot	1.4	22.0	4.7	3.9	3.0	2.4	176	3.1	1.13	0.41	8.1	0.13	8.0	26	···

ma center even with the assumption that $Q_{conv} = \frac{3}{2}\Gamma T$, but it never dominates the momentum balance,[8,9] because the toroidal velocities remain much less than the beam velocity and because a unity multiplier is assumed for torque convection. By contrast, convection is only a modest term in the power balance of L-mode plasmas (owing to the lower temperatures), for which $Q_{conv,i}/Q_i \leqslant 0.13$ and $Q_{conv,e}/Q_e \leqslant 0.25$ in the region $r/a \geqslant 0.2$. Electron–ion coupling is considerably larger in L-mode plasmas than in hot-ion-mode plasmas (for fixed $\Delta T = T_i - T_e$) because $n_e^2 Z_{eff}/T_e^{3/2}$ is larger for the L-mode parameters. At $r/a = 0.5$, the integrated electron–ion power transfer represents up to 25% of Q_i (typically $<15\%$) but up to 70% of Q_e, despite the relatively modest temperature differences $[\Delta T(r=0) \leqslant 2\,\text{keV}]$. Thus the experimental measurements of χ_e in L-mode discharges are sensitive to relatively small uncertainties in the temperature measurements.

Figure 1 illustrates the radial dependence of the thermal diffusivities for a typical coinjected L-mode discharge $I_p = 1.2\,\text{MA}$. The error bar represents the estimated uncertainty in local χ as determined from an ensemble of transport analyses using the measured profiles $[v_\phi(R), T_i(R), T_e(R), n_e(R)]$ and other input data (Z_{eff}, P_b, etc.) simultaneously varied within their ranges of uncertainty by Monte Carlo sampling a Gaussian distribution for both statistical and systematic errors. Similar to the behavior observed during unidirectional injection into hot-ion-mode plasmas,[9,13] the diffusivities increase strongly with minor radius and are comparable in magnitude, generally ordered $\chi_\phi \gtrsim \chi_i > \chi_e$. Also shown are several theoretical estimates of transport expected from ITGDT.[14–17] Note that the theoretical χ_i profiles do not reproduce the observed strong increase of $\chi_i(r)$ with minor radius, rather they tend to decrease. The χ_i from Guo *et al.*[14] shows the flattest variation with minor radius because it has a q dependence relative to the other theoretical formulas. Although each of the theoretical expressions for χ_i agrees with the measured value at some radius in Fig. 1

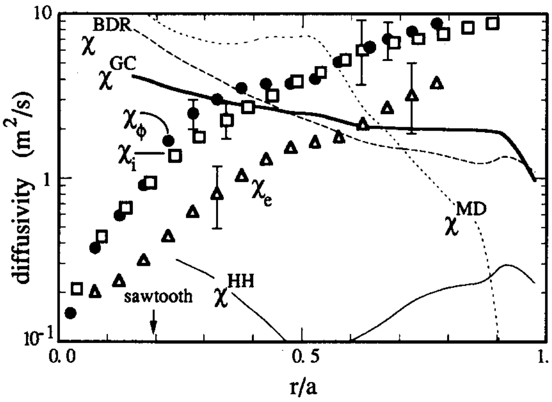

FIG. 1. Local thermal heat and thermal diffusivities for the L-mode discharge listed in Table I. Also shown are theoretical calculations of χ_i from ITGD turbulence by Guo *et al.*[14] (χ_i^{GC}), Mattor and Diamond[15] (χ_i^{MD}), Hamaguchi and Horton[16] (χ_i^{HH}), and Biglari, Diamond, and Rosenbluth[17] $[\chi_i^{BDR} = \omega_{*e}\rho_s^2 q(1+\eta_i)/(\tau\bar{s})]$, using Romanelli's estimate of η_c in the fluid kinetic limit $[(1+1/\tau)2\epsilon_n]$, and using η_i^{tot} rather than η_i in the formulas. Over the region $r/a > 0.15$, the inferred η_i (assuming flat Z_{eff}) is $\sim$0.5–1.5 units greater than η_i^{tot}. Fully developed nonlinear turbulence is expected because $\eta_i^{tot} \geqslant \eta_c + \Delta$, where Δ, the width of the transition region, is evaluated from $\Delta = (1+1/\tau)L_{n_i^{tot}}/L_s$.[23]

(with the exception of the Hamaguchi and Horton expression), there is wide variability (factor ~ 10) in the ratio of χ_i^{theory}/χ_i even at fixed radius, as the plasma current and beam power are varied. In Fig. 2 we compare the measured transport coefficients in L-mode and hot-ion-mode plasmas at similar I_p and P_b. The shaded regions in Fig. 2 illustrate the range of values obtained in three L-mode and two hot-ion-mode discharges and thus indicate the discharge-to-discharge reproducibility of the inferred χ, while the error bars represent the uncertainty in χ at $r/a \sim 0.5$ determined from the Monte Carlo analysis. Despite the relatively large differences in plasma conditions between the L-mode and hot-ion-mode regimes (cf. Table I), the inferred transport differs by typically less than a factor of 2 with χ being lower in the hot-ion regime.

Plasma current scans in the L-mode regime show that the ion momentum and heat diffusivities, and to a lesser extent the electron heat diffusivity, decrease with I_p (Fig. 3) yielding a global τ_E that improves with current in accord with the usual L-mode scaling ($\tau_E^{\text{L mode}} \propto I_p$.) The observed decrease of χ_e with plasma current is only comparable to the measurement accuracy, because of uncertainties in electron–ion power coupling. The correlation of χ_ϕ, χ_e, and χ_i in the "confinement zone" (outside the sawtooth radius but inside $r/a \leqslant 0.8$) is illustrated in Fig. 4 for coinjected L-mode discharges in a plasma current scan (0.9, 1.2, 1.5, 1.8 MA) at $P_b = 10$–12 MW and a beam power scan (2–12 MW) at $I_p = 1.2$ MA. The ratios of local diffusivities are roughly bounded by $0.7 \leqslant \chi_\phi/\chi_i \leqslant 1.4$ and $0.2 \leqslant \chi_e/\chi_i \leqslant 0.7$, similar to the ratios obtained in the hot-ion mode[9] and in the supershot regime (for χ_e/χ_i).[6] We remark that ratios of order 1 would be expected from $\widetilde{E} \times B$ turbulence but the ratio of χ_e to χ_i would be of order $\sqrt{m_i/m_e}$ for strong $v_\parallel \widetilde{B}$ turbulent transport.

Previous profile measurements in the supershot and hot-ion regimes found the gradient scale lengths to cluster roughly about $\eta_i^{tot} \sim \eta_c \sim 1$–4,[7,9] where η_c, the critical value of L_T/L_{n_i} required to turn on the ITG mode, has been calculated by several theories.[18–25] Here $\eta_i^{tot} = L_{n_i^{tot}}/L_{T_i}$ (also equal to L_{n_e}/L_{T_i} if Z_{eff} is assumed flat) includes beam ions in the ion density gradient. This is not the situation in L-mode plasmas, which are observed to exceed η_c by a considerable margin (Fig. 5) throughout the confinement zone. The apparent ability of L-mode plasmas to exceed η_c is not inconsistent with the large, but not catastrophic, ion heat transport expected from fully developed ITGDT for the L-

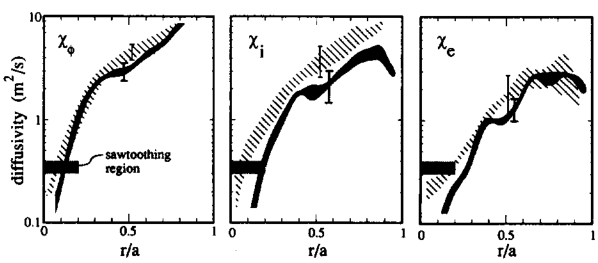

FIG. 2. Measured local diffusivities in L-mode (hatched; $I_p = 1.2$ MA, $B_T = 3.8$ T, $a = 0.92$ m, $\bar{n}_e = 3.4 \times 10^{19}\,\text{m}^{-3}$) and hot-ion mode (solid; $I_p = 1.1$ MA, $B_T = 4.8$ T, $a = 0.79$ m, $\bar{n}_e = 1.9 \times 10^{19}\,\text{m}^{-3}$) plasmas for coinjection at $P_b = 9.3$–12.2 MW.

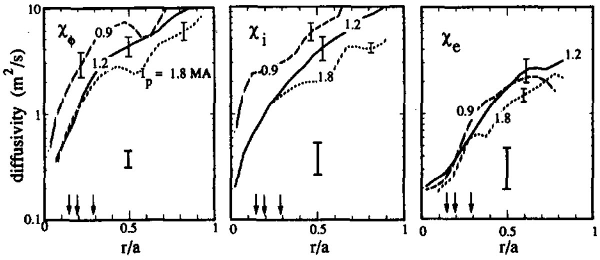

FIG. 3. Local diffusivities in co-injected L-mode discharges at $P_b = 10$–12.5 MW, $R = 2.57$ m, $a = 0.92$ m, and $B_T = 3.8$ T. The line-averaged electron densities are 2.9, 3.4, and $4.4 \times 10^{19}\,\mathrm{m}^{-3}$ at $I_p = 0.9$, 1.2, and 1.8 MA, respectively. Error bars on the individual curves in the figure represent the variation in χ measured in similar discharges, while the boldfaced error bars represent the uncertainty in χ at $r/a \sim 0.5$ for a single discharge as determined from Monte Carlo transport analysis of errors in the primary measurements. Arrows indicate the approximate locations of the sawtooth inversion radius for each of the three plasma currents.

mode plasma parameters. The ITGDT χ_i from Guo *et al.*,[14] for example, generally lies within a factor 0.2–2.0 of the measured χ_i for the data points shown in Fig. 5. By contrast, in the hot-ion and supershot regimes χ_i^{GC} exceeds the measured transport by factors of ~ 10 or more, thus η_i^{tot} can exceed η_c only marginally before ITGDT carries away all the heating power.

III. MOMENTUM TRANSPORT IN SUPERSHOTS

Previous studies of the variation of local heat transport between supershot and L-mode plasmas demonstrated a strong reduction of χ_i as the density profile became more peaked.[6] Since ITGD turbulence is expected to drive comparable levels of momentum and heat transport[15] ($\chi_\phi = \chi_i$), we should observe higher toroidal rotation speeds in peaked-density supershot plasmas than in L-mode plasmas for the same applied beam torque per unit plasma mass. This prediction is difficult to validate experimentally, because highly peaked density profiles typically do not develop during unbalanced injection. However, a few supershot discharges have been obtained with unbalanced injection, and these do exhibit higher rotation speeds than corresponding L-mode discharges (Fig. 6). Preliminary transport analysis by the SNAP code indicates a reduction in local χ_ϕ by a factor of ~ 2 across the confinement region in supershots. A more

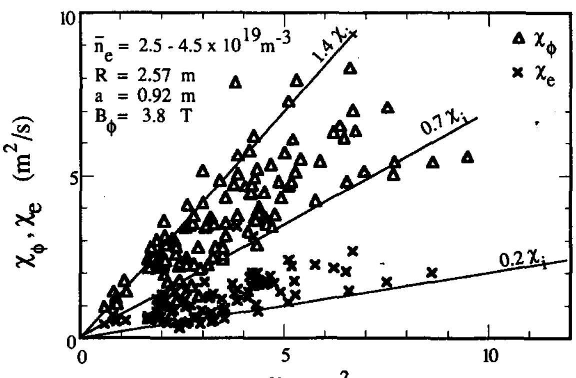

FIG. 4. Measured local diffusivities in L-mode discharges in the confinement zone. Data points are spaced in intervals $\Delta r/a = 0.05$.

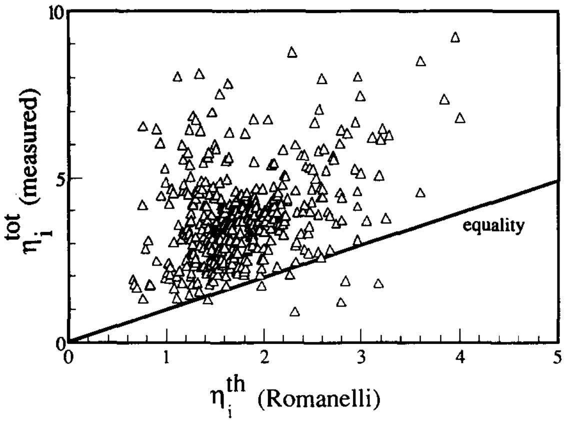

FIG. 5. Comparison of threshold η_c in the local kinetic limit[24] with the measured η_i^{tot} in L-mode plasma scans in the confinement zone ($0.3 < r/a < 0.8$) for $R = 2.57$ m, $a = 0.92$ m, $I_p = 0.9$–1.8 MA, $P_b = 2$–20 MW (co-, counter-, and balanced injection), which have $\bar{n}_e = 2.5$–$4.5 \times 10^{19}\,\mathrm{m}^{-3}$, $T_i(0) < 6$ keV, and $T_e(0) < 4.5$ keV. The data points shown satisfy $n_b/n_e < 0.2$ and $n_i/n_e \geqslant 0.6$. Evaluations of the thermal *ion* density [using the measured $n_e(r)$ and Z_{eff} and the computed beam ion density] yield η_i values marginally greater than η_i^{tot}; $(\eta_i - \eta_i^{\mathrm{tot}}) = 0.2$–$1.0$ for 50% of the data points, and $(\eta_i - \eta_i^{\mathrm{tot}}) \geqslant 1.0$ for 38% of the data points.

detailed analysis of *local* momentum transport in these quasibalanced injection discharges is being undertaken to account for torque delivered through the $J \times B$ force (arising from radial motion of the beam ions), which is different for co- and counterinjection and which is not addressed in the SNAP code.

IV. RIPPLE TRANSPORT

For the hot-ion mode discharge shown in Table I, the momentum damping time expected from ripple-plateau ion transport[26,27] and from ripple-trapping ion transport[28] ($\tau_\phi^{\mathrm{rp}} = \rho_\theta^2 / D^{\mathrm{rp}}$,[26] where D^{rp} is the flux-surface-averaged nonambipolar ion diffusivity[27]), is greater than 2 sec for $r/a \leqslant 0.5$, compared to the measured global momentum confinement time $\tau_\phi \lesssim 0.050$ sec. Thus, toroidal-field ripple is not expected to contribute significantly to momentum transport in these plasmas, largely because its magnitude is small (peak-to-average ripple $\leqslant 0.3\%$ at the plasma edge). Trans-

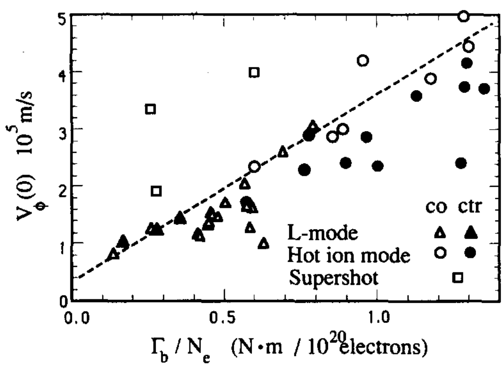

FIG. 6. Measured toroidal rotation speeds at the magnetic axis versus total beam torque incident on the plasma surface normalized to the total electron population. The dashed line represents a rough fit to the highest rotation speeds in L-mode and hot-ion mode plasmas. The supershot at highest v_ϕ had $I_p = 1.0$ MA, $P_{\mathrm{co}} = 9.7$ MW, $P_{\mathrm{ctr}} = 4.9$ MW, $\bar{n}_e = 2.7 \times 10^{19}\,\mathrm{m}^{-3}$, $F_{ne} = 2.8$, and $\tau_E = 165$ msec $= 3.2\ \tau_E^{\mathrm{L\,mode}}$.

port due to ripple-trapped ions is negligible because the ripple wells are absent over most of the plasma cross section. Previous observations of a secular rise in central rotation speed during modulated, edge-weighted beam heating[29] established that local momentum damping of any sort is unimportant compared to diffusive transport.

However, because one can envision various mechanisms (e.g., TF coil misalignment) which could, in principle, increase the ripple far above its calculated value, it is informative to calculate the expected ripple-induced heat flows that would result from assuming that the momentum damping is due entirely to ripple. Under this assumption, one would infer a ripple-induced $\chi_i = 3\rho_\theta^2/\tau_\phi$, where τ_ϕ is the momentum confinement time inferred from the measured $v_\phi(R)$ profiles. For all discharges in the hot-ion regime (where the large T_i makes ripple transport an issue), the ratio of such a χ_i to the $\chi_i(r)$ inferred from the power balance is less than 0.10 at $r/a = 0.40$, decreasing exponentially to a ratio less than 0.015 at $r/a = 0.75$. Thus the measured ratio of momentum to ion heat transport demonstrates that χ_i cannot be attributed to ripple even if the ripple were the dominant mechanism for momentum transport.

V. PERTURBATIVE STUDIES OF MARGINAL STABILITY

An essential requirement of the "marginal stability" interpretation of radial heat balance is that there exist a virulent heat transport mechanism—strong enough to carry away more than the available heating power—that arises rapidly whenever some marginality criterion (e.g., ∇T_i) is exceeded. We have begun perturbative studies of supershots to determine whether this correlation is indeed imposed by a "strong" transport mechanism. These experiments destroy the peaked-density profile of supershots by rapidly introducing a local particle source. Marginal stability is expected to manifest itself by a rapid increase in L_{T_i} such that $\eta_i^{\text{tot}} = L_{T_i}/L_{n_i^{\text{tot}}}$ remains roughly equal to the threshold η_c during the density perturbation. A variety of particle sources, including a small puff of helium (3.5 Torr liter over 16 msec), a deuterium pellet, and a carbon pellet, has been employed to perturb different regions of the plasma and to provide varying sized perturbations to L_{n_i} and L_{n_e}.

Initial helium-puff experiments were carried out in supershot plasmas at $I_p = 1.0$ MA with 14 MW of balanced beam injection, which had a density peakedness prior to the helium puff of $F_{ne} = 2.2$ and $\tau_E = 2.5 \times \tau_E^{\text{L mode}}$. As expected, the small helium puff significantly flattened the density profile shape at $r/a = 2/3$, with L_{n_e} increasing from 0.7 to 4.0 m within 20 msec, and remaining above 1.4 m for more than 35 msec after the start of the puff. Surprisingly, the ion temperature scale length L_{T_i} (measured with 10 cm spatial and 10 msec temporal resolution) *decreased* ~35% during this period. Consequently, the measured η_i^{tot} at this radius, which was 2.0–2.5 prior to the puff (in fair agreement with theoretical estimates of the η_c by Hahm and Tang[25] and by Romanelli[24] in the flat density limit) increased beyond 8.0 and remained above 5.0 for more than 25 msec. By contrast, the Hahm–Tang η_c remained below 3.0 throughout the post-puff period and the Romanelli η_c remained below 4.0. The conducted ion heat flux inferred from time-dependent transport analysis using the TRANSP[30] code and the measured $T_i(R)$ increased less than ~25% following the puff. These observations appear to be inconsistent with temperature profiles being marginally stable to strong ITGD turbulence. Initial experiments using deuterium pellet injection to flatten the density profile in supershots yields qualitatively similar results—small reductions to L_{T_i} despite large changes to L_{n_e}.

VI. CONCLUSIONS

Equilibrium measurements of ratios of local transport coefficients in a variety of TFTR plasma regimes lend support to the view that tokamak transport is dominated by $E \times \widetilde{B}$ turbulence rather than transport along destroyed magnetic surfaces or ripple transport. In particular, the observation that $\chi_i \sim \chi_e$ is inconsistent with $v \| \widetilde{B}$ transport being the *limiting* transport mechanism—although it does not rule out the possibility that regions of destroyed magnetic surfaces maybe interspersed with regions of intact surfaces that provide the effective barrier to radial transport. The relationship $\chi_i \sim \chi_\phi$ has been shown to apply to L-mode plasmas which are considerably less dominated by unthermalized beam–ion populations than the hot-ion mode plasmas. There is, in addition, some experimental support from the equilibrium transport measurements for a particular class of $E \times \widetilde{B}$ turbulence, the ion-temperature-gradient-driven turbulence. We observe that the threshold for exciting this mode is only marginally violated when the transport expected from ITGDT is calculated to be strong (hot-ion and supershot regimes), but it can be violated considerably when the calculated transport is roughly equal to the measured transport (L-mode regime). In the hot-ion mode and supershot regimes we do not expect to observe a good correlation between the calculated and measured transport (none is seen), because the large transport calculated for fully developed ITGDT should drive the plasma to marginal stability. However, current ITGDT theories do not reproduce the strong increase of $\chi(r)$ that is observed experimentally in L-mode plasmas, and there is less than satisfactory agreement between the measured and calculated χ_i at fixed radius as plasma conditions are varied. In addition, initial supershot perturbation experiments have failed to reveal a large increase in local ion heat transport during transient increases of η_i^{tot} above η_c which calls into question the conjecture that profiles in these plasmas are determined by marginal stability to a potentially strong transport mechanism.

Note added in proof: The original Hamaguchi–Horton expression for χ_i contains a factor $(\eta_i - \eta_c) \times \exp(-5L_n/L_s)$, which was determined by fitting the shear dependence of their numerical simulations at one value of η_i, implicitly assuming that η_c is independent of shear. However, the Hahm–Tang formula for η_c contains a fairly strong L_s dependence. If we modify the Hamaguchi–Horton χ_i to subsume the shear dependence of η_c, we obtain $\chi_i = 1.5(\rho_s/L_n)(cT_i/eB)(\eta_i - \eta_c)$, which gives values that are typically within a factor of 2 of the Guo–Chen expression for χ_i shown in Fig. 2.

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