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Parametric Variations of Ion Transport in TFTR

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1. Introduction

This paper is divided into three roughly independent sections. The first is a historical review of the twenty year history of experimental ion heat transport measurements from many tokamaks. The second is a study of ion heat transport in Ohmic TFTR plasmas which shows that $\chi_i \sim \chi_e \approx 15\chi_i^{\text{neo}}$. Thus, ion heat transport is demonstrated to be strongly anomalous even in the absence of auxiliary heating. The third section describes the variation of χ_i with local ion temperature in TFTR during auxiliary heating, with emphasis on characterizing the differences between transport in the L-mode and supershot regimes. The results are consistent with the conjecture that improved ion energy confinement in supershot plasmas is caused by a high ratio of T_i/T_e .

2. Review of χ_i measurements

We begin with a review of measurements of ion heat transport in Ohmic and beam-heated plasmas. Our objective here is principally to provide an annotated bibliography of various experimental χ_i studies, rather than a complete review of the literature. Mostly for historical perspective, the early χ_i measurements will be compared to the predictions of then-current neoclassical theory. This approach does not provide a time-independent benchmark because the neoclassical theory itself evolved during the 1970's and early 1980's. Also, it is slightly deficient in that χ_i is found to be so large a 'multiple' of χ_i^{neo} in current, large tokamaks that the relevance of neoclassical theory to ion heat transport is questionable. But it remains the most convenient approach because the original measurements themselves were typically compared to neoclassical theory. More recent χ_i measurements will be considered also in comparison to χ_e and to qualitative predictions of ITGDT theory.

Interestingly, transport studies in about a dozen different tokamaks worldwide found χ_i to be roughly consistent with neoclassical theory in both Ohmic and auxiliary-heated plasmas for more than ten years, from 1970 to the early to mid-1980's. Due to limited diagnostic capability and strong ion-electron coupling, initial studies of ion transport in small tokamaks (T-3, TM-3, T-4) could establish only that χ_i was roughly the correct order of magnitude as expected from neoclassical theory (Table 1). Subsequent Ohmic studies in JFT, ALC, TFR, Alcator, T10, PLT, and ISX-A, including some analyses based on ion temperature profile measurements, claimed more quantitative agreement, implying $\chi_i \leq 2\chi_i^{\text{neo}}$. These observations naturally led to a prolonged focus on electron transport as the dominant anomalous loss mechanism in tokamak plasmas. Since the mechanisms underlying ion versus electron heat transport were thought to be different, only a few of the early studies compared the relative magnitude of χ_i to χ_e . TFR reported that the scaling of *central* temperature could be reproduced by assuming that the $\tau_i = \tau_{Ei}[1]$, while profiles of $T_i(r)$ measured by charge-exchange could be adequately modelled using $\chi_i \leq 2\chi_i^{\text{neo}}[2]$. Measurements in T-4, although roughly consistent with neoclassical χ_i , were also comparable to the

where $\beta_{\perp} \approx 3\tau_E$ was observed in some regimes in Ohmic PLT, however here the electrons were dominated by radiation.

One early experimental anomaly was the failure of τ_E to follow its linear scaling with $\bar{n}_e$ at high density in Ohmic ISX-A plasmas. Murakami[4] observed that ion heat transport could dominate the total power flow even if $\chi_i \approx \chi_i^{\text{neo}}$, which explained the high-density saturation of τ_E without the need to postulate an additional deterioration of χ_i . Global τ_E measurements at high density in ISX-A and Alcator were found to be consistent with ion heat transport at roughly the neoclassical level. This provided further support for the supposition that ion heat transport could be adequately understood in a neoclassical framework, with no need to invoke anomalous ion losses driven by microturbulence or MHD.

Of course, inferences of χ_i in Ohmic plasmas required accurate temperature measurements, since the power flow to the ions depends on $T_e - T_i$. Most of the Ohmic studies relied on neutron emission or analysis of the energy spectrum of escaping neutrals to measure the ion temperature[5]. Global neutron emission provides a reasonably accurate measurement of $T_i(0)$, provided that the deuterium depletion (Z_{eff}) is measured with modest accuracy. However, analysis of χ_i in Ohmic plasmas based only on $T_i(0)$ is relatively insensitive to the magnitude of ion transport beyond $r = a/2$, and so agreement with neoclassical predictions of $T_i(0)$ does not provide much assurance that χ_i is close to neoclassical throughout the confinement region. Multi-chord neutral particle analysis (NPA) can measure a $T_i(r)$ profile; however, without a doping neutral beam the signal is chord-integrated. The measurement requires numerical modelling of the neutral density profile, whose accuracy is difficult to evaluate, to deduce the $T_i(r)$ profile.

Therefore it was with some relief that early studies of beam-heated plasmas in the late 1970's, some extending into the 1980's, also found $\chi_i \approx \chi_i^{\text{neo}}$. TFR roughly doubled $T_i(0)$ to 1.9 keV with 650 kW of neutral injection[6] in 1976. True, the inferred χ_i was independent of collision frequency, contrary to the neoclassical prediction; hence the "multiplier" on χ_i^{neo} was ~ 1 at $\nu/\epsilon^{\frac{3}{2}} > 4$ and $\sim 3-4$ for $\nu/\epsilon^{\frac{3}{2}} < 1$. However, given diagnostic and modelling uncertainties of the power source, they could not conclude that the ion transport was more than a factor two greater than χ_i^{neo} . The magnitude of χ_i^{neo} was still evolving as the neoclassical theory was refined, so a factor of two discrepancy with experiment was regarded as corroborative evidence for the basic neoclassical mechanism of ion heat transport. ORMAK[7] also concluded that χ_i was neoclassical during beam injection, based mostly on comparisons of measured and calculated $T_i(0)$. Interestingly, their published data shows that neoclassical theory overestimated the $T_i(0)$ outside the error bars both at high power and low density. Furthermore, the χ_i inferred from some $T_i(r)$ measurements agreed with χ_i^{neo} in the plasma center, but $\chi_i/\chi_i^{\text{neo}}$ increased to a factor ~ 3 at $r = a/2$, and to a factor ~ 7 close to the edge.

Collisionality was pushed down to $\nu^* \leq 0.01$ and $T_i(0)$ up to 7 keV in the first high-power heating experiments in PLT[8,9], where trapped-particle modes were used to enhance energy transport. Due to the keen interest in documenting the high temperatures and the non-existence of catastrophic transport driven by

the trapped-particle modes, the central ion temperature was measured with three independent diagnostics (see Table 2). It was found to be in good agreement with the temperature predicted from χ_i^{neo} . However, the authors were careful to point out that the temperature measurements could not exclude enhancements of χ_i over χ_i^{neo} by as much as a factor 3-5. Also, the toroidal rotation speed induced by the beam torque was much less than expected from neoclassical momentum transport. Subsequently, neutral-beam heating studies in mostly L-mode plasmas extending through 1984 on ISX-B, T-11, ASDEX, and PDX all found χ_i to be described by χ_i^{neo} to within a factor of three.

The earliest claims of anomalous ion heat transport originated from studies of high density Ohmic plasmas. Unlike the linear increase of τ_E with $\bar{n}_e$ observed in Alcator-A, τ_E started to saturate above $\bar{n}_{e19} = 25$ in Alcator-C. Due to the strong ion-electron coupling at high density, it was not possible to unambiguously attribute the τ_E saturation to anomalous ion transport. In 1980, Fairfax *et al.* could demonstrate only that χ_i^{neo} would have to be multiplied by 2-4 to reproduce the observed τ_E if ions alone were blamed for the entire transport[10]. In 1982, Blackwell *et al.* [11] reported that local transport analysis in Alcator C implied a neoclassical multiplier of 2-4 in the core (which dominates the neutron emission), but they could not unambiguously exclude the alternate possibility of increased core electron transport. The discovery that $\tau_E \propto \bar{n}_e$ was recovered at high density if pellets were injected[12], thereby forming a peaked density profile, stimulated further experiments and analysis. Global energy confinement times with pellets were up to 70% higher than gas-fuelled shots at the highest densities. Subsequent studies of transport in moderate-density Ohmic plasmas led to a firmer conclusion that χ_i was several times the neoclassical value in broad-density, gas-fuelled plasmas, which was reduced to roughly the neoclassical value in pellet-fuelled plasmas with peaked density profiles[13-16]. The Alcator group observed that the correlation of improved χ_i with peaked density profiles suggested a possible role for ion-temperature-gradient driven turbulence in driving "anomalous" ion transport in broad-density, gas-fuelled plasmas[13]. This work motivated a number of studies in other tokamaks of confinement differences between peaked-density versus broad-density plasmas, with peaked density profiles created by pellet injection or other means.

Increased global τ_E was observed in peaked-density, pellet-fuelled TFTR Ohmic plasmas compared to gas-fuelled plasmas at the same $\bar{n}_e$ [17]. However, it was not possible to disentangle the ion and electron power flows at the plasma center and thus to determine whether χ_i dropped to χ_i^{neo} following pellet injection. The total heat flow (ions+electrons) following pellet injection was $\sim 2-3$ times the value expected from χ_i^{neo} alone, but the comparable multiplier before pellet injection was not evaluated. Similarly, ASDEX observed a reduction of χ_i down to neoclassical levels in a variety of Ohmic regimes that involve peaked density profiles, including pellet fuelling[18], the Improved Ohmic Confinement regime (IOC) obtained by reducing gas flow[19], and the sawtooth-free Ohmic regime [20]. The enhanced core χ_i in the SOC regime was comparable to that expected simply from sawteeth, making a comparison with HGBF theory problematic. As with most Ohmic studies, these conclusions derived

from relatively small differences in measured $T_e - T_i$, but the latter two papers were based on profiles of $T_i(r)$ from neutral-particle analysis with an active doping beam which improved the spatial localization of the measurement.

Year	Tok		$\lambda_i/\lambda_i^{\text{neo}}$	λ_i/λ_e	a	I_p	$\bar{n}_{e19}$	$T_i^m(0)$	Diag	neo	Reference
70	T-3	-	~ 1	-	0.15	0.06-0.11	1.5-3.8	0.5	cx	$T_i(0)$ gs	Artsimovich[21]
70	TM-3	-	~ 1	-	0.08	0.02-0.04	1.0-3.0	0.2	cx	$T_i(0)$ gs	Artsimovich[21]
73	T-4	-	~ 1	-	0.20?	~ 0.15		0.6	cx,n	$T_i(0)$ -	Gorbunov[22]
74	JFT	-	~ 1	-	0.25	0.08	0.5-1.0	0.2	cx	$T_i(0)$ -	Fujisawa[23]
74	ORMAK	-	~ 1	-	0.23	0.06-0.16	0.5-2.5	0.4	cx	$T_i(0)$ hr	Berry[24,25]
75	ATC	-	~ 1	-	0.17	0.08	0.6-2.0	0.2	cx	$T_i(0)$ hh	Stott[26]
76	TFR	-	≤ 2	-	0.20	0.30	4.5	1.0	cx	$T_i(r)$ hr	TFR[2.1]
78	T-11	-	~ 1	~ 1	0.20	0.1	0.5-5.0	0.3	cx	$T_i(0)$ -	Vlasenkov[3]
78	ALC	-	~ 1	-	0.10	0.13-0.24	10-30	0.6	cx,n	$T_i(0)$ hh	Gondhalekar[27]
78	ALC	-	≤ 1.5	-	0.10	0.13-0.24	60	0.6	e	e hh	Gondhalekar[27] [28]
78	T10	-	~ 1	-	0.35	4-56	3-7	1.1	cx,n	$T_i(0)$ -	Bagdasarov[29]
78	PLT	-	~ 1	-	0.40	0.4	$\sim 2-4$	1.2	cx,K α ,n	$T_i(r)$ hr	Brusati[30]
79	ISX-A	-	1-2	-	0.26	0.12	1-5.5	0.5	cx	$T_i(0)$ hh	Murakami[4]
80	ALC-C	-	2-4	-	0.16	0.25-0.54	20-60	-	cx,n	e -	Fairfax[10]
82	ALC-C	-	2-4	-	0.16	0.10-0.75	20-70	1.0	cx,n	$T_i(0)$ hh	Blackwell[11]
82	DIII	-	2-7	-	0.44	0.46	2.0-4.3	0.7	cx	$T_i(0)$ hh	Ejima[31]
84	TFTR	-	1-3	>1	0.41	0.9-3.2	1-3	-	n	$T_i(0)$ ch1	Efthimion[32]
84	TFTR	-	0-8	-	0.83	0.6-1.4	2.7	-	cx,n,K α	$T_i(0)$ ch1	Efthimion[32]
84	JET	-	$\sim 1-3$	-	1.1	1.2-3.5	0.7-3.4	-	cx	$T_i(0)$ ch1	Cordey[33]
88	JET	-	$\sim 4-8$	-	0.8-1.2	1.0-4.0	~ 1	~ 3	cx,n,ns	$T_i(0)$ ch2	Bartlett[34]
88	JET	-	$\sim 1-3$	-	0.8-1.2	1.0-4.0	~ 3	~ 2.5	cx,n,ns	$T_i(0)$ ch2	Bartlett[34]
92	TFTR	-	15	1-2	0.80	2.0	2.4	2.4	cxrs	$T_i(r)$ ch2	Figure 1
84	ALC-C	PEL	5-1	-	0.60	0.4-0.8	30-60	1.5	n	$T_i(0)$ ch1	Greenwald[13]
86	TFTR	PEL	≤ 3	-	0.70	1.6	≤ 14	-	n	$T_i(0)$ -	Schmidt[17]
86	ALC-C	PEL	5-1	-	0.16	0.25-0.55	10-30	1.5	n	$T_i(0)$ ch1	Wolfe[15][14,16]
88	ASDEX	PEL	1-1	-	0.40	0.38	5	~ 0.5	cx,n	$T_i(0)$ ch2	Gruber[18]
89	ASDEX	IOC	20-1	-	0.4	0.38	2.5-4.7	1.0	acx	$T_i(r)$ ch2	Stroth[19] ($q < 1$)
91	ASDEX	SFO	~ 1	-	0.40	0.25-0.32	4-6	0.8	acx	$T_i(r)$ ch2	Stroth[20]

Table 1: Historical Survey of λ_i measurements in tokamaks. Diagnostics: cx=passive neutral-particle analysis of charge-exchange efflux; acx = active neutral-particle analysis with diagnostic beam; n=total neutron emission; ns = neutron spectroscopy; e=total energy content; K α = measurement of Doppler-broadened x-ray radiation; cxrs=charge-exchange recombination spectroscopy. Neoclassical models: gs = Galeev-Sagdeev[35]; hr = Hinton-Rosenbluth[36]; hh = Hinton-Hazeltine[37,38]; ch1 = Chang-Hinton[39]; ch2 = Chang-Hinton[40]. Regimes: PEL=peaked-density following pellet injection; IOC=peaked density improved-Ohmic regime; SFO=peaked-density sawtooth-free Ohmic. $T_i^m(0)$ = maximum central ion temperature in dataset.

Through the 1980's, additional studies in gas-fuelled Ohmic plasmas were conducted in larger tokamaks then coming on line (DIII, TFTR, JET). Fairly large anomaly factors ($\lambda_i/\lambda_i^{\text{neo}} = 2-7$) were reported as early as 1982 by DIII[31]. Ejima *et al.* noted that their results were not qualitatively different from previous comparisons with neoclassical theory (which obtained smaller anomaly factors) because the expressions for λ_i^{neo} were also evolving. For example, they pointed out that the TFR

Year	Tok	Regime	$\lambda_i/\lambda_i^{\text{neo}}$	λ_i/λ_e	a	I_p	$\bar{n}_{e19}$	P_b	$T_i^m(0)$	Diag	Prof	neo	ref
75	ATC		~ 1	-	0.17	0.08	0.6-2.0	0.1	0.3	cx	$T_i(0)$	hh	Stott[26]
76	TFTR		$\sim 1 (\nu^* > 4)$	-	0.20	0.2-0.4	3.5-7.5	0.65	1.9	cx	$T_i(r)$	hh	TFTR[6,1]
76	TFTR		$3-4 (\nu^* < 1)$	-									
76	ORMAK		~ 1	-	0.23	0.16-0.18	2-6	0.4	1.8	cx,n	$T_i(0)$	hr, hh	Berry[7]
79	PLT		$\sim 1 (\leq 5)$	-	0.40	0.43	3.0	2.9	6.3	cx,n, $K\alpha$	$T_i(0)$	-	Eubank[8][9]
81	ISX-B	lmode	1-3	-	0.26	1-2	3-7	2.5	1.3	cx,n	$T_i(0)$	hh	Swain[41]
82	T-11		~ 1	-	0.20	0.1	5-6	0.6	0.5	cx	$T_i(0)$	-	Barsukov[42]
82	ASDEX	lmode	1-3	-	0.40	0.3-0.4	1.5-6.5	2.2	4.0	cx	$T_i(r)$	hh	Becker[43,44]
84	ISX-B	lmode	~ 1	-	0.26	0.14	-	2.5	1.1	cx	$T_i(0)$	ch1	Murakami[45]
84	PDX	lmode	0.5-3.0	-	0.4	0.2-0.5	2.5-4.2	7.2	6.5	cx, $K\alpha$	$T_i(0)$	ch1	Kaye[46]
86	DIH	lmode	$5-15(a/2)$	2-5	0.40	0.35-0.9	3.7-7.9	6.1	3.8	cxrs	$T_i(r)$	ch1	Groebner[47]
86	DIH	lmode	$\sim 1(r=0)$	> 1									
86	PBX	hmode	~ 1	~ 1	0.30	0.38	-	2.1	2.5	cxrs	$T_i(r)$	ch1	Okabayashi[48]
88	TFTR	super	$\sim 25(a/2)$	1-2	0.80	1.4	3.9	22	27	cxrs	$T_i(r)$	ch2	Zarnstorff[49]
88	TFTR	super	$\sim 1(r=0)$	-									
88	TFTR	lmode	$\gg 1$	~ 4	0.80	1.4	3.9	22	4	cxrs	$T_i(r)$	ch2	Zarnstorff[49]
89	TFTR	super	$\sim 10(a/2)$	~ 2	0.8	0.9	2.5	20	30	cxrs	$T_i(r)$	ch1	Fonck[50]
90	TFTR	lmode	$\gg 1$	1.3-5	0.9	0.9-1.8	2.9-4.4	12	6	cxrs	$T_i(r)$	ch2	Scott[51]
92	JT60	lmode	10-50	3-6	0.6-0.9	1.0-2.7	1.2-6.5	17	6	cxrs	$T_i(r)$	ch2	Hirayama[52]
92	JET	lmode	$\sim 15-30(a/2)$	5-10	1.15	3.1	2.4-3.1	18	10	cxrs	$T_i(r)$	ch2	Balet[53,54]
92	JET	lmode	$\sim 2-6(r=.1)$	1-2									
92	JET	hihm	$\sim 10(a/2)$	~ 1	1.08	4.0	~ 4	18	22	cxrs	$T_i(r)$	ch2	Balet[53]
92	JET	hihm	$\sim 1(r=0.2)$	~ 0.15						cxrs	$T_i(r)$	ch2	Balet[53]

Table 2: Historical Survey of λ_i measurements in tokamaks in beam-heated plasmas. Regimes: super=supershot, hihm = hot-ion H-mode.

results would require a multiplier of 5 on the Hazeltine-Hinton expression for λ_i^{neo} . They also presented some indirect evidence from scans at $a = 23, 32$, and 44 cm. based not on T_i measurements but on the assumption that $n_e \lambda_e$ remained constant, that the neoclassical anomaly factor increases with a or a/R . This trend was confirmed by later size-scaling studies in TFTR[32] which found roughly neoclassical transport ($\lambda_i/\lambda_i^{\text{neo}} \leq 3$) in small plasmas ($a = 0.41$ m), but anomaly factors up to 8 in larger plasmas ($a = 0.80$ m).

Early analysis (1984) of JET Ohmic ion transport by Cordey[33] obtained $\lambda_i = 1-3\lambda_i^{\text{neo}}$. A later study with improved diagnostics based on $T_i(0)$ measurements from charge-exchange, supplemented by neutron emission and neutron spectroscopy[34], implied neoclassical multipliers of 4-8 at low density ($\bar{n}_{e19} \approx 1$), decreasing to 1-3 at moderate density ($\bar{n}_{e19} \approx 3$). However, Bartlett *et al.* concluded that although the JET data suggested a large anomaly over λ_i^{neo} , they could not exclude the possibility that $\lambda_i \approx \lambda_i^{\text{neo}}$ without measurements of the $T_i(r)$ profile. A prior JET study[55] using four NPA diagnostics to measure a coarse $T_i(r)$ profile concluded that $\lambda_i \approx 5\lambda_i^{\text{neo}}$.

Charge-exchange recombination spectroscopy (CXRS) was developed and implemented on several tokamaks in the 1980's, and represented a major advance in the study of ion heat and momentum transport. Its advantages over prior techniques are that it is a local measurement, fairly accurate, and straightforward to construct as a diagnostic to measure the full radial $T_i(r)$ profile. Groebner *et al.* used CXRS in

their pioneering work on DIII to demonstrate clearly that during neutral injection $\chi_i(r)$ had a radial profile quite different from that of χ_i^{neo} , with the ratio $\chi_i/\chi_i^{\text{neo}}$ increasing strongly with radius[47]. The observed χ_i was within error bars of χ_i^{neo} near the plasma center, but increased to 5-15 times χ_i^{neo} at the half-radius. Ion heat transport, rather than electron heat transport, was found to be the dominant heat loss mechanism in auxiliary-heated plasmas, at least in the usual case of the neutral beam injection energy not being significantly higher than the critical energy determined primarily by the electron energy. This conclusion was subsequently confirmed by CXRS measurements in TFTR, JET, and JT60 L-mode plasmas (see Table 2), for which the ratio $\chi_i/\chi_i^{\text{neo}}$ was as high as 50 at the half-radius and was rarely less than 10. Even in enhanced-confinement regimes, such as the H-mode and supershot, χ_i was more than a factor 10 larger than χ_i^{neo} at the half-radius. Only near the center of the supershot and hot-ion H-mode plasmas (characterized by peaked density profiles, $T_i > 10$ and $T_i > T_e$), where heat transport due to particle convection becomes a significant or dominant term in the ion power balance, could χ_i still be within error bars of the neoclassical prediction.

Tokamaks comparable in size to DIII but which used NPA diagnostics to measure ion temperature, including PDX[46] and ASDEX[43,56], reported smaller anomaly factors relative to χ_i^{neo} during auxiliary heating. For example, Becker[43] found χ_i to be within a factor of three of neoclassical over a wide range of ASDEX L-mode co-injected plasmas, including ion temperatures of 0.5–3.9 keV and electron densities 1.5–6.5. Subsequently, Gruber[56] observed that χ_i was reduced to neoclassical levels during counter injection (with peaked density) on the basis that the total plasma energy would be underestimated if the neoclassical multiplier observed during co-injection (3-4) was used, even in the limit of no heat transport by electrons.

The observed large anomaly of χ_i over neoclassical at the half-radius discredited the use of χ_i^{neo} as a benchmark for reporting χ_i measurements, and it became more common to compare the magnitude of χ_i with χ_e or with the predictions of ITG theory. There is consistent evidence from the larger tokamaks that $\chi_i > \chi_e$ in L-mode plasmas, outside the error bars, at $r \approx a/2$; ratios ranging from 1.3 to 10 have been published from TFTR, JET, and JT60, with values of 3-4 being typical. The ratio χ_i/χ_e at $r = a/2$ decreases to 1-2 in the supershot and hot-ion H-mode, reflecting the general trend that ion transport improves more strongly than electron transport in these regimes. One issue that remains unclear from an experimental perspective is the relationship between χ_i and χ_s : TFTR consistently observes $\chi_i \sim \chi_s$ across the confinement region in L-mode and supershot plasmas[51,57], whereas JET observes that χ_i/χ_s ranges up to 10 at the half-radius in L-mode plasmas. Furthermore JET and DIII-D[58] find that in the hot-ion H-mode regime (whose core resembles the TFTR supershot regime), the radial profile of χ_s more closely resembles that of χ_e rather than χ_i .

3. Diagnostics

This section describes the TFTR diagnostic set that was used for the transport studies described in Sections 5 and 6. The ion temperature and toroidal rotation profiles were measured by a charge-exchange recombination spectroscopic (CXRS) diagnostic[59] with viewing sightlines every 5-10 cm. The electron density profile was measured by a 10-chord interferometer[60,61]. Four electron temperature diagnostics were used: Thompson scattering[62], an absolutely calibrated Michelson interferometer[63], an absolutely calibrated ECE radiometer[64-67], and a grating polychromator[68] normalized to Thomson scattering. Table 3 lists the T_e diagnostic used for particular scans. Total neutron emission was measured with a calibrated set of fission detectors[69-71] with an uncertainty of $\pm 15\%$ [72]. The neutron emission profile is also measured by 10 detectors in a multi-channel neutron collimator[73-75]. Being a line-integrated measurement, the measured profile does not put strong constraints on the ion temperature profile. Preliminary results from using the neutron collimator are consistent with the results of this paper. The total stored plasma energy is determined from magnetic analysis of the diamagnetic flux and equilibrium magnetic field[76,77], with an estimated uncertainty of 70 kJ. The plasma Z_{eff} , assumed radially constant, was deduced from a single-channel visible Bremsstrahlung measurement in the horizontal midplane[78]. In Ohmic plasmas this measurement was checked against pulse-height analysis (PHA) of the soft x-ray spectrum[79] and from the surface voltage, assuming neoclassical resistivity[80]. The magnitude of neutral sources due to deuterium efflux recycled on the inner bumper limiter was inferred from measurements of the $H\alpha$ emission along five poloidal viewing sightlines[81,82]. The profile of flux-surface-averaged radiated power density was deduced by Abel-inverting[83] measurements of two bolometer arrays[84,85] which viewed the plasma poloidally.

4. Transport Analysis

Local heat and momentum transport coefficients are inferred from the measured profiles using the equilibrium transport code SNAP[86-88]. The measured profiles are first smoothed with a triangular weighting function with a full width at half-maximum of approximately 7-10 cm. The calculated beam deposition in the SNAP code includes ionization and charge-exchange processes by thermal ions and electrons, as well as by the slowing-down beam ion population. The beam-ion slowing down population is simulated as a separate species not subject to anomalous transport. The beam-ion distribution function is calculated from a solution of the Fokker-Planck equation in the rotating plasma frame[89], neglecting radial diffusion. Beam ions are treated as joining the background thermal ion species when their energy falls below $\frac{2}{3}T_i$. Electron-ion energy exchange is assumed to be classical. The particle, momentum and energy transport is analyzed assuming that the radial transport mechanisms are cross field diffusion, represented by anomalous diffusivities D_e , χ_ϕ , χ_i , and χ_e , radial convection due to particle flows, and charge-exchange losses, which are important for

the ion power balance near the edge:

$$\begin{aligned} Q_i &\equiv -\chi_i(\sum_j n_j)\nabla T_i + \frac{3}{2}\Gamma_i T_i &\equiv -\chi_i^{\text{tot}}(\sum_j n_j)\nabla T_i \\ Q_e &\equiv -\chi_e n_e \nabla T_e + \frac{3}{2}\Gamma_e T_e &\equiv -\chi_e^{\text{tot}} n_e \nabla T_e \end{aligned} \quad (1)$$

where Q_i and Q_e are the total ion and electron heat flux, Γ_i and Γ_e are the ion and electron particle flux (Γ_i is assumed hydrogenic with average mass $\langle m_h \rangle$), $\sum_j$ represents a sum over all ion species including impurities, Γ is the radial flux of toroidal momentum, and χ_i^{tot} and χ_e^{tot} are “total” diffusivities which include both the convective and conductive fluxes. Use of such total diffusivities remove the uncertainty involved in the choice of 3/2 or 5/2 as the convective multiplier[90,91]. Since steady-state is assumed, the particle fluxes Γ_i and Γ_e are simply the integrated volumetric particle source terms (wall and beam) and divided by the flux-surface area. This analysis neglects pinch effects and off-diagonal terms, as well as local damping due to toroidal field ripple. SNAP also calculates the total stored energy from the kinetic measurements (including the beam stored energy) and the total neutron emission (including beam-beam interactions), which provide consistency checks when compared to the corresponding measured quantities[72].

5. Ion Transport in Ohmic Plasmas

This section discusses measurements of χ_i in Ohmic TFTR plasmas using two techniques: active measurements of the ion temperature by charge exchange recombination spectroscopy, and measurements of the neutron emission. The $T_i(R)$ measurement was performed during the first 20 ms of beam injection, before the ions could receive significant heating power from the beam ion population. Both ion temperature techniques indicate that χ_i is of order $\sim 10 - 20$ times larger than neoclassical theory. The plasma for the study utilizing CXRS measurements of $T_i(R)$ was a 2.0 MA deuterium Ohmic discharge with other parameters as described in Scan OH1 in Table 3. Sawteeth with period ~ 75 ms and inversion radius $r_{\text{inv}} = 0.23$ m modulated the central electron temperature by $\Delta T_e = 0.5$ keV. Carbon was the dominant impurity ($Z_{\text{eff}}^{\text{metals}} = 0.03$). Other data including the profile measurements of $n_e(R)$ and $T_e(R)$ were averaged over a period of 100 ms and thus represent sawtooth averages. There was good agreement amongst the measurements of Z_{eff} : $Z_{\text{eff}}^{\text{VB}} = 2.4$, $Z_{\text{eff}}^{\text{PHA}} = 2.0$, and, from a measurement of the surface voltage, $Z_{\text{eff}}^{\text{neo}} = 1.7 - 1.8$. The kinetic measurements reproduced the diamagnetic stored energy to within 35 kJ (8%). The neutron emission calculated from the measured $T_i(r)$ and $n_e(r)$ profiles, using the $Z_{\text{eff}}^{\text{VB}}$ for ion depletion, is only about 30% lower than the measured value. Since σ_{nn} increases as E^2 for $E > 2$ MeV, the neutron emission would imply a central ion temperature about 10% higher than CXRS, assuming the same profile shape.

Figure 1a and b show the measured profiles mapped to a minor radius grid. The ion-electron temperature difference is large in this plasma, which allows the ion power balance to be evaluated with reasonable accuracy. As shown in Figure 1c, electron heat conduction is the dominant loss channel in the plasma core, but it exceeds the ion loss

Figure 1: (a) Measured temperature profiles for Ohmic pulse 52499. The dashed line represents an ion temperature profile calculated using $\chi_i = 15.3 \chi_i^{neo}$ which matches the neutron emission. (b) Measured electron density profile, and deuterium density inferred from Z_{eff} . (c) Integrated radiated power, and power flows through ions and electrons. The shaded region represents the contribution of convection ($q_{conv} \equiv \frac{3}{2} \Gamma T$) to the power flow. (d) Local heat diffusivities χ_i and χ_e inferred from power balance analysis. The two lines for χ_e represent analysis based on the ECE grating polychromator (normalized to Thomson scattering) and Michelson measurements of T_e .

channel by only $\sim 50\%$ at $r/a = 0.5$. Radiation and convection become the dominant loss channels in the outer 20 cm. The profiles of χ_i and χ_e inferred from the power balance are illustrated in Fig. 1d. Throughout the confinement region we observe that $\chi_i \approx \chi_e \gg \chi_i^{\text{neo}}$. The error bars illustrate the effect of moving the measured $T_i(r)$ profile to the top and bottom of its error bars, or moving the measured $T_e(r)$ profile (by the Michelson interferometer) up and down by 7%. Clearly, χ_i is much greater than χ_i^{neo} throughout the confinement region, well outside the experimental uncertainties. It is interesting to note that the χ_e is relatively “flat” across the minor radius, and does not increase significantly at the outside of the plasma. Such a flat χ_e profile is typical of medium-to-high density TFTR Ohmic plasmas, though the robustness of the result is clouded by the increasing effects of convection and radiation at the outside.

Alternately, a neoclassical model of χ_i can be adopted to *calculate* the ion temperature profile, using an global multiplier adjusted to match the the measured neutron emission. As shown in Fig. 1c, a multiplier of 15.3 is required to reproduce the measured neutron emission. The width of the calculated $T_i(r)$ is slightly broader than the measured $T_i(r)$ profile. The required neoclassical multiplier varies from 13-17 as the T_e profile is varied up or down 7% and from 12-19 as Z_{eff} is varied up or down 15%. Thus, measurements of both the ion temperature profile and the neutron emission indicate that $\chi_i \gg \chi_i^{\text{neo}}$ in this Ohmic plasma.

To determine the behavior of χ_i over a wider parameter range, we consider the 2.0 MA deuterium Ohmic density scan OH2 described in Table 3. For these plasmas, the $T_i(r)$ profile is calculated assuming some multiplier on neoclassical transport from the measured neutron emission. Figure 2 shows the variation of central T_e and T_i with density. Gas fuelling only was used for most plasmas with $\bar{n}_{e19} \leq 4$, while higher densities were achieved only with deuterium pellet fuelling. The pellet data represent measurements 300-1500 ms after pellet injection, when the time rate of change of stored energy was small ($|W/(\partial W/\partial t)| > 1.6$ sec). The gas-only discharges had the customary broad density profiles ($F_{ne} < 2.0$), while quite peaked density profiles ($F_{ne} \leq 4.5$) were obtained with pellet injection. As reported previously in TFTR Ohmic plasmas[32,94], Z_{eff} decreases systematically with increasing $\bar{n}_e$, in this scan dropping from 3.0 to ~ 1 . Figure 3 shows the global energy confinement time in these plasmas, evaluated from the kinetic data. The confinement times for gas-fuelled discharges are similar to those obtained in previous density scans[32], however pellets provided little or no increase in τ_E in contrast to earlier results in slightly smaller plasmas, which obtained $\tau_E = 500$ ms[17]. The reason for the lack of improvement at high density is not understood.

The transport analysis will focus on the lower density plasmas ($\bar{n}_{e19} \leq 3$) where the electron-ion coupling is not too strong. $T(r)$ profiles were calculated for all the gas discharges in Fig. 4, using transport models of the form $\chi_i(r) = c_e \chi_e(r)$ or $\chi_i = c_e \chi_i^{\text{neo}}$ with c_e iteratively chosen to reproduce the global neutron emission. Of course, although the models calculate the radial profile of χ_i as part of the convergence algorithm, analysis based on measurements of the global neutron emission cannot provide any information regarding the radial shape of χ_i because the global neutron

Scan	Sym	Gas	R	a	B _t	I _p	P _b	$\bar{n}_{e19}$	S	P _{ne}	T _{io}	T _{eo}	R _n	R _W
OH1		D	2.45	0.80	4.8	2.0	0.0	2.4	-	1.6	2.4	3.5	0.70	0.92(-33kJ)
OH2		D	2.58	0.93	4.5	2.0	0.0	1.0-3.0	-	2.0-1.8	2.0-2.0	4.0-2.4	$\equiv 1$	$\pm 50\text{kJ}$
L1	▲	D	2.58	0.93	3.8	1.2	2.4-17	3.0-3.6	1.24-1.13	[1.48-1.54]	2.1-4.2	2.6-3.6	0.7-1.3	1.12-1.04
L2	■	D	2.58	0.93	3.8	1.8	2.2-20	[3.0-3.2]	[1.2-1.3]	1.66-1.91	3.3-8.2	2.7-5.0	[0.98-1.24]	1.06-1.01
L3	●	D+He	2.45	0.80	4.0	1.3	4.3-22	3.2-3.6	1.16-1.47	1.95-1.73	3.5-9.5	3.1-5.2	[0.84-0.90]	[1.00-1.04]
S1	△	D	2.45	0.79	4.8	5.1	12-22	2.5-3.9	1.7-2.8	1.8-3.1	14-27	5.7-8.0	[1.00-1.30]	[0.92-1.04]
S2	+	D	2.45	0.80	4.8	1.6	10-24	2.3-3.8	1.5-2.4	1.8-2.9	13-28	6.0-8.6	0.95-0.73	[0.88-1.04]
S3	○	D	2.45	0.80	4.8	1.3	4.3-21	1.6-3.2	1.4-2.5	2.0-2.4	9.6-27	5.8-8.6	[0.66-0.76]	[0.94-1.04]
S4	⊗	D	2.45	0.80	4.8	1.1	2.3-14	1.2-2.6	1.4-2.4	2.08-2.36	8.1-19.4	4.0-6.3	[0.90-1.00]	1.09-1.00†

Scan	τ_E	Z _{off}	V _{oo}	W _b /W	W _i /W	W _e /W	Diag	Year	Shots	Ref
OH1	270	2.4	-	-	0.35	0.65	YG,YM	1990	52499	Figure 1
OH2	200-350	3-1.5	-	-	0.33-0.46	0.67-0.56	YS,TS	1990	45195-46501	Figure 3
L1	170-73	[1.8-2.6]	[-0.4-1.0]	0.12-0.40	0.38-0.23	0.49-0.37	YS,TS	1990	45620-46588	Scott[51]
L2	230-100	1.8-4.0	[-0.3-1.3]	0.09-0.52	0.42-0.16	0.49-0.31	YS,TS	1990	45585-45621	Scott[51]
L3	128-81	[2.2-2.4]	2.4-1.5	0.23-0.55	0.28-0.16	0.48-0.28	YS	1990	51068-51169	Scott[92]
S1	132-166?	3.3-2.9	[-0.2-1.3]	[0.50-0.60]	[0.20-0.26]	[0.21-0.23]	TS,YS	1988	35782-37266	Zarnstorff[49]
S2	[130,160]	[2.3,3.5]	[1.4]	[0.44-0.50]	[0.24-0.32]	[0.22-0.30]	YM	1990	47613-49539	Strachan[93]
S3	163-134	3.9-3.3	[1.6,3.4]	[0.48-0.56]	[0.18-0.26]	[0.22-0.28]	YS	1990	51023-51073	Scott[92]
S4	[139,172]	[2.1-2.5]	[-2.7,2.0]	0.41-0.54	0.33-0.24	0.27-0.22	YG	1992	65684-65703	-

Table 3: Summary of TFTR density and power scans. Units and definitions: Sym = symbol identifying scan shots in Figures 6-9; R(m); a(m); B_t(Tesla); I_p(MA); $\bar{n}_{e19}$ (10¹⁹m⁻³); P_b(MW); S(W_{tot}/W_{L-mode}); F_{ne} = n_e(0)/⟨n_e⟩; T_{io}, T_{eo}(keV); R_n=Neutron emission[kinetic]/Neutron emission[measured]; R_W=W_{tot}^{kin}/W_{tot}^{dia}; τ_E = global τ_E including beam-ion contribution; V_{oo} is the central toroidal rotation speed (10⁵m/s); W_b/W, W_i/W, and W_e/W are the ratios of beam, thermal ion, and electron energy to total energy. Where a range of values is quoted it represents a systematic variation with increasing density or beam power. Values in brackets [] indicates that the parameter's value varied during the scan over the indicated, but without a systematic trend with power. Electron temperature diagnostics: TS (Thompson scattering); YG (ECE grating polychromator normalized to TS); YS (absolutely calibrated ECE radiometer); YM (absolutely calibrated Michelson interferometer). The supershot values exclude one exceptional shot (35782) in scan S1 with Z_{off} = 2.5, W_b/W = 0.39, W_i/W = 0.38, W_e/W = 0.23, and one exceptional shot (49426) in scan S2 at P_b = 22.6 MW which attained P_{ne} = 3.29 and T_{eo} = 9.8. † Kinetic measurements of W_{tot} agree with diamagnetic measurements within 0.07 MJ across the entire scan. The ratio R_W is 1.18 at P_b = 2.3 MW because the total stored energy is small (0.35 MJ).

Figure 2: Variation of central temperatures in the Ohmic density scan. $T_i^{\min}$ is the minimum possible central ion temperature consistent with ion-electron power coupling, assuming no radial transport of heat by electrons.

emission is mostly determined by the central plasma conditions. SNAP calculates that more than 70% of the neutron emission originates from within $r/a < 0.33$. Thus, the "multiplier" on χ_e or χ_i^{neo} required to match the global neutron emission represents a complicated radial average (somewhat centrally weighted because $T_i \approx T_e$ is enforced at the edge by strong ion-electron equilibration, irrespective of $\chi_i/\chi_i^{\text{neo}}$) of the local ratio of χ_i to χ_i^{neo} or χ_e .

The dominant errors which affect our inferences of χ_i in these Ohmic plasmas are the measurement uncertainties in T_e , n_e , Z_{eff} , and neutron emission. Since the metallic contribution to Z_{eff} is small ($Z_{\text{eff}}^{\text{metal}} \leq 0.3$, implying $n_m Z_m/n_e \leq 0.01$), it is adequate to consider a single impurity, carbon. Then the deuterium concentration is simply related to Z_{eff} by $n_d/n_e = (6 - Z_{\text{eff}})/5$. Redundant measurements of Z_{eff} by PHA, by resistive loop voltage measurements (assuming neoclassical resistivity), and by a radially-viewing VB monitor complement the standard Z_{eff} measurement by the tangential VB monitor. These measurements agree within ± 0.5 units and correspond to an uncertainty in central T_e of 7%. The calibration uncertainty in neutron emission ($\pm 15\%$) corresponds to an error in T_i of 3.5%. The uncertainty in density becomes significant only in highly peaked density profiles following pellet injection, when the density scale length becomes less than the spacing between interferometer chords (10-

Figure 3: Global energy confinement time as a function of line-average density in the Ohmic density scan. τ_E^{ss} is the steady-state global energy confinement time evaluated from the kinetic data. τ_E is the same quantity but corrected for the time-dependence of stored energy, $\tau_E \equiv \tau_E^{ss}/(1 - W/\dot{W})$, and is shown only where the correction exceeds 10%.

20 cm). However, it is difficult to deduce a meaningful χ_i in high density Ohmic plasmas anyway, due to strong ion-electron coupling.

The local ion-electron heat transfer is given by $q_{ei} = c_{ei}(T_e - T_i)Z_{eff}n_e^2/T_e^{3/2}$ where c_{ei} is a constant. Thus in regions of high electron density and/or low electron temperature, small ion-electron temperature differences drive large power flows between the two species. A lower bound on T_i can be calculated by assuming no radial transport of heat by electrons, i.e. that all of the Ohmic input power q_{OH} is *locally* transferred to the ions. This yields

$$T_i^{min} \equiv T_i - \frac{q_{OH} T_e^{3/2}}{c_{ei} Z_{eff} n_e^2}. \quad (2)$$

At high density, the T_i is constrained to be very close to T_e irrespective of the magnitude of χ_i , i.e. $T_i^{min} \approx T_e$. Thus measurements of ion temperature can provide meaningful inferences of χ_i only when T_i^{min} is considerably less than T_e .

Figure 4 plots the inferred neoclassical multiplier as a function of $\bar{n}_e$. Throughout the density range where the temperature difference is large enough to permit accurate

Figure 1: Multiplier on neoclassical χ_i required to match the neutron emission in the Ohmic density scan. Error bars represent the variation of χ_i as the T_e profile measured by ECE is increased or decreased 7%.

inferences of χ_i , the neoclassical multiplier is approximately 15, with no apparent trend with density. A fixed neoclassical multiplier of 3 in the analysis yields T_i profiles whose neutron emission exceeds the measured emission by a factor 2 - 3.5 for $\bar{n}_{e19} \leq 3$, which is enormously outside the error bars. The multiplier on χ_e required to match the neutron emission increases from 0.8-2.0 over the density range $\bar{n}_{e19} = 1 - 3$. Analysis of transport in reduced-bore Ohmic plasmas ($a = 0.50$ and 0.61 m) indicates considerably smaller neoclassical multipliers, $\chi_i = 3 - 6\chi_i^{\text{neo}}$, which is consistent with the observations in DIII size-scaling experiments[31].

The pellet-fuelled, high-density shots in Fig. 4 are potentially interesting because η_i at the mid-radius is decreased from its value of $\sim 1.5 - 2.5$ at moderate density ($\bar{n}_{e19} = 2 - 3$) to ~ 0.5 at $\bar{n}_{e19} = 7.5$ and to ~ 0.2 at $\bar{n}_{e19} = 8.6$ ($F_{ne} = 4.1$). Thus if HCD mechanisms control the ion heat transport, one might expect to observe improved χ_i in these plasmas. Due to the strong ion-electron power exchange, it is not possible to deduce an accurate χ_i in these plasmas from neutron emission and measured T_e , but one might expect to observe an improved global τ_E to the extent that ion heat transport is a significant loss mechanism. In contrast to Ohmic pellet-fuelling experiments conducted in slightly smaller plasmas ($a = 0.7$) in 1986, which produced a higher τ_E with pellets [17], there is no indication of improved energy confinement with peaked density in this data set. Both the gas-fuelled and pellet-

fuelled τ_E saturate at approximately 300 ms. Unfortunately, for $\bar{n}_{e19} \geq 6$ the energy balance is complicated by a large fraction of core radiated power, which ranges from 80% to 150% of the Ohmic input power (with considerable uncertainty) at $r/a = 0.4$ at these high densities. Correspondingly, the $T_e(r)$ profile is flat or inverted inside this radius at high density. We will not discuss the highest-density plasmas further except to note that if radiation is neglected, and all heat transport is attributed to the ions, the implied χ_i is again more than ten times larger than neoclassical at the half radius.

In the intermediate density region ($\bar{n}_{e19} = 5$, $F_{ne} = 2.6$) where core radiation is small (30% at $r = a/2$, 50% at $r = a$) and where the $T_e(r)$ profile remains peaked, there is tantalizing evidence that χ_i is indeed reduced. The multiplier on neoclassical χ_i required to match the neutron emission for one discharge (45271) is less than two even when the $T_e(r)$ profile measured by ECE or Thomson scattering is taken at the top of the $1 - \sigma$ error bars. However a detailed transport and error analysis of this discharge has not been completed.

6. Variation of χ_i with temperature

The variation of heat transport coefficients with temperature in tokamaks is not well understood. Theoretical models based on ITGDT turbulence are gyroBohm in character and so have an intrinsic temperature dependence $\chi \propto T_i^\alpha T_e^\beta / B^2$ with $\alpha + \beta = \frac{3}{2}$, although this is sometimes modified by the temperature dependence implicit in other dimensionless factors which enter the theoretical expressions for χ . The relative exponents on T_i and T_e vary considerably from theory to theory (see Connor *et al.*[95]). Experimentally, both regression analysis of τ_E across a wide database and analysis of dedicated heating power scans find that the global energy confinement time τ_E decreases with increasing power in L-mode plasmas. This behavior is often interpreted as a consequence of χ_i and χ_e increasing with local temperature.

By adjusting the gas puff rate or recycling state of the limiter, it is possible to maintain constant density as the power is increased. Measurements of local transport in such constant-density power scans on TFTR found that both particle transport (measured with perturbative techniques) and heat transport increase as $\propto T^m$ with $m = 1.5 - 2.5$ across the plasma radius [96]. Preliminary analysis of complementary experiments which vary the density at constant temperature suggest there is little change in χ as the density increases by a factor ~ 2 (Fig. 5). The lack of increase in χ in the density scan at constant temperature would imply that the increased χ observed in the temperature scan is really associated with temperature rather than pressure.

However, it is well known that several features of the TFTR transport measurements are contrary to the behavior expected from ITGDT theory, which has stimulated further study both theoretically and experimentally. First, as observed on most tokamaks, the measured χ_i increases with minor radius, despite the monotonically decreasing temperature. Second, nondimensional scans which vary $\rho^* = \rho_s/a$ at

Figure 5: Variation of single-fluid thermal diffusivity at $r = a/2$ with density in L-mode scans at constant T_e . Conditions: (a) $I_p = 1.2$ MA, $B_t = 3.8$ T, $R = 2.58$ m, $T_{eo} = 3.5$ keV; (b) $I_p = 1.5$ MA, $B_t = 3.8$ T, $R = 2.58$ m, $T_{eo} = 3.4$ keV; (c) (squares) $I_p = 1.8$ MA, $B_t = 3.8$ T, $R = 2.58$ m, $T_{eo} = 4.0$ keV; (d) (open circles) [97] $I_p = 1.8$ MA, $B_t = 4.8$ T, $R = 2.45$ m, $T_{eo} = 5.0$ keV.

approximately constant β and ν^* find that the heat flux is better described by Bohm rather than gyroBohm scaling[98]. Finally, in supershot plasmas the central ion temperature increases by a factor 3-5 compared to L-mode plasmas with comparable density and heating power, driven by a *reduction* of χ_i of about the same magnitude. Within experimental error, the supershot temperature and density profiles yield values of η_i that are close to or below the threshold for exciting ITG turbulence[99,57,100], which in principle could reduce the ion heat transport dramatically. However, no increase in local χ_i was observed when a supershot density profile was perturbed with gas puffing or pellets to drive $\eta_i \gg \eta_i$ [101,100], indicating that the supershot profiles are *not* marginally stable with respect to a virulent transport mechanism. These studies are described more fully in chapter 222 of these proceedings (Kotschenruther).

The energy confinement realized in supershot plasmas correlates with a number of parameters including edge ion temperature[102], $F_{e0} = n_{e0}/(n_e)$, T_e , T_i/T_e , and ν_{99} . Empirically, the strongest correlation of τ_E in supershots is with low rates of hydrogenic and carbon recycling at the limiter, but it remains unclear how edge recycling affects χ_i in the plasma interior. This section focusses on the role played by T_e/T_i , which is ~ 1 in L-mode plasmas, and ≥ 2 in supershots across most of the plasma. Our fundamental observation is that the reduction of χ_i between L-mode

and supershot plasmas correlates more closely with T_i/T_e than it does with η_i . This trend is clearest in the region $r \geq a/2$ and in low-power supershots, where the density scale lengths in L-mode and supershot plasmas are more similar than they are at high power near the plasma center.

This study used the set of 7 beam power scans described in Table 3, comprising 4 scans with low-recycling limiters (yielding supershots) and 3 scans with high-recycling limiters (yielding L-mode). All scans were conducted with the plasma resting on the carbon-carbon composite inner bumper limiter. Each scan was conducted at fixed R , B_t , and I_p . As shown in Table 3, there is good agreement between the total stored energy and neutron emission evaluated from kinetic measurements, and direct measurements by magnetic and neutron diagnostics. The ratio of kinetic values (neutrons, W_{tot}) to measured values changes only slightly across each scan, indicating no systematic bias of the kinetic measurements with heating power or temperature. Scans L1 and L2 are standard L-mode beam power scans at $I_p = 1.2$ and 1.8 MA, obtained with the limiter saturated with deuterium. Gas puffing and limiter conditioning were adjusted to maintain the density approximately constant as the power was increased. Scan L3 (4.21 MW) was taken with a low-recycling limiter, however helium gas puffing in the Ohmic target plasma provided high-recycling edge conditions. Its performance can be compared directly with supershot scan S3, which was taken under the same conditions but without the helium. Scans L3 and S3 have corresponding symbols (closed and open circles) to facilitate comparison in the figures. Beam injection was partially unbalanced in scans L3 and S3 (2 or 3 more beam sources directed co- than counter-) to permit accurate measurements of momentum transport. The other scans had nominally balanced injection.

Scans S1 and S2 are standard supershot power scans which span a more limited range in beam power (10-24 MW). At the high-power end, these scans include some of the best supershots obtained in TFTR to date. These scans exhibit the customary supershot correlation among beam power, density peakedness, and energy confinement. By contrast, the density profile peakedness in the lower-power supershot scans (S3 and S4) increases only weakly with power and at high power is only marginally greater than in the L-mode. These scans provide an opportunity to evaluate the possible role of parameters other than the density gradient scale length in reducing transport from L-mode to supershot values. As shown in Table 3, unthermalized beam ions represent about 50% of the total plasma energy at high power for *both* L-mode and supershot plasmas. The beam-ion density in the center of high-power discharges $\sim 30\%$ of n_e in supershots and $\sim 20\%$ in L-modes.

Figure 6 plots several measures of plasma performance as a function of heating power for these scans. The supershot plasmas attain a factor ~ 3 higher central T_e and modestly higher n_e than comparable L-modes at high power, yielding an overall improvement of 4-5 in the central product $n_e T_e$ and 2.5 in volume-integrated thermal ion energy. The beam heating profile is slightly more peaked in supershot scans owing to the increased peakedness of the electron density profile, but the heating effectiveness parameter defined by Callen and coworkers [103] is almost the same. Thus the changes in the heat deposition profile are responsible for only a small fraction of the improved

Figure 6. Heating parameters vs. beam power scans in low and high-recycling plasmas. For graphical clarity, data points from three exceptional supershot plasmas (with $n_i \leq 5.0 \times 10^{19} \text{ m}^{-3}$, $n_i T_i \leq 100 \text{ keV } 10^{19} \text{ m}^{-3}$, and $W_i \leq 1.3 \text{ MJ}$) have been omitted. (a) Central ion temperature. (b) Central thermal ion density. (c) Product of central $n_i T_i$. (d) Total thermal ion energy. (e) Peakedness of beam power deposition profile ($h(0) \equiv P_{\text{peak}}/P_{\text{ave}} = 0.63 P_{\text{peak}}^{\text{vol}}/\text{Volume}$). (f) Calculated heating effectiveness parameter, assuming a fixed radial profile shape for $\chi_{\text{eff}} \approx 0.16$, *etc.* Symbols defined in Table 3.

Figure 7: Measured χ_i^{tot} versus heating power at fixed radius. (a,b) χ_i^{tot} versus beam power at $r/a = 0.32$ and $r/a = 0.72$. (c,d) χ_i^{tot} normalized to a gyroBohm scaling ($T_i^{1.5}/B^2$). Symbols defined in Table 3.

central ion heating in supershots, as was reported previously[99]; the dominant cause is a reduction in local heat transport coefficients.

Standard steady-state transport analysis was carried out for each of the discharges in the scans using the models described in Section 4. Figure 7 plots the total ion thermal diffusivity χ_i^{tot} as a function of heating power at $r/a = 0.32$ and $r/a = 0.72$ for each of the scans. In the L-mode, χ_i^{tot} increases strongly with power at both radii. By contrast, χ_i^{tot} increases weakly with power in the supershot at $r/a = 0.72$ and is almost independent of power at $r/a = 0.32$ [104]. At low power χ_i^{tot} is comparable in the L-mode and supershot, but owing to the differing variations with power, at high power χ_i^{tot} is smaller in the supershot by a factor ~ 4 ($r/a = 0.32$) and ~ 2 ($r/a = 0.72$). This improvement is more striking when viewed from the perspective of the expected *increase* in χ_i^{tot} associated with the higher supershot ion temperatures. Figures 7c and 7d normalize the measured χ_i^{tot} by a factor $T_i^{1.5}/B^2$ which represents a simple gyroBohm scaling of local transport. The gyroBohm-normalized transport improves by a factor 4-5 at the edge and by a factor ~ 15 at the plasma center between

Figure 8: Total ion heat diffusivity as a function of local ion temperature in the L-mode and supershot power scans L3 and S3.

the most comparable L-mode and supershot scans, L3 and S3.

Figure 8 addresses the local temperature dependence of χ_i^{tot} directly by plotting it as a function of local T_i , rather than power, at several radii. Power-law fits to the L-mode data are shown for guidance only and should not be regarded as quantitative measurements of the temperature scaling of local χ_i^{tot} . The important conclusion is that χ_i^{tot} increases throughout the entire plasma cross section in L-mode plasmas, roughly as $T_i^{\pm 1}$. The temperature dependence of χ_i^{tot} is also positive in the edge of supershots, becomes flat at about the half-radius, and then *reverses* near the plasma center. A robust theoretical understanding of the reduction in transport between supershot and L-mode plasmas must address these two fundamental observations: (1) that χ_i^{tot} is reduced *throughout* the plasma, not just in the region of steep electron density gradients, and (2) that χ_i^{tot} improves more in the plasma center than in the edge.

Very close to the plasma edge (≈ 10 cm inside the last closed flux surface), the electron temperature scales roughly linearly with total beam power per electron, showing little or no difference between high and low recycling regimes. However, the edge *ion* temperature is strongly correlated with recycling, being almost an order of magnitude higher in supershots than in L-modes (2.0 versus 0.2 keV) for the same power per particle [102]. Initial studies of the edge power balance could not identify a simple atomic physics mechanism, such as charge-exchange, ion-electron energy exchange, or particle convection sufficiently large to account for the low edge ion temperatures in high-recycling plasmas. Nevertheless, some mechanism associated with reduced particle recycling plasmas apparently allows $T_i > T_e$ in the edge of supershot plasmas. Transport may be reduced in regimes where $T_i > T_e$ because ions with finite Larmor radius and drift surface size effectively average the field fluctuations during the course of their gyro- or transit period [105, 106]. Orbit averaging may also reduce the effect of particles on the fluctuations, thereby modifying the stability and spectrum of modes responsible for turbulent transport [107]. The observation

of small rates of fast-ion diffusion [92, 108–111], and decreased χ_i^{tot} and D_e in the core of supershots (where $T_i/T_e = 2 - 3$) is qualitatively consistent with the expected orbit-averaging effects.

It is difficult to ascertain whether high T_i/T_e or some other parameter such as η_i controls the reduction of χ_i^{tot} in high-power supershots, due to the usual correlation amongst the density profile shape, beam power, and T_i/T_e , and χ_i^{tot} . To address this issue, Fig. 9 plots the temperature ratio T_i/T_e , the gradient scale lengths L_{n_e} and L_{T_i} , and $\eta_i^{\text{tot}} \equiv L_{n_e}/L_{T_i}$ as a function of power at $r/a = 0.32$ and $r/a = 0.72$. At both radii, there is a distinct difference in T_i/T_e between the L-mode and supershot scans, with $T_i/T_e = 1.0 - 1.4$ in L-mode and $T_i/T_e \geq 1.8$ in the supershot.¹ As expected, there is a considerable difference in L_{n_e} at the plasma center between supershots and L-modes. However, further out in radius ($r/a = 0.72$) there is little difference between the supershot and L-mode values of L_{n_e} , L_{T_i} , or η_i^{tot} , particularly for the paired scans L3 and S3. Recall that at this radius the gyroBohm-normalized χ_i^{tot} is lower by a factor 4–5 in the supershot compared to the L-mode. Thus, at least beyond $r/a \geq 1/2$, these plasmas exhibit substantially different transport properties despite having similar values of parameters (η_i , L_{T_i}) which are expected to govern ITG turbulence, yet they do differ in the ratio of T_i/T_e .

The crucial variable is not the value of η_i *per se* but its magnitude relative to the threshold value for exciting ITGDT turbulence. Various theoretical expressions for η_c such as the recent work by Guo *et al.* ($\eta_c^{\text{Guo}} = \frac{1}{3}(1 + \frac{T_i}{T_e})(1 + 2\frac{q}{R})\frac{L_n}{R}$) [112] explicitly involve the temperature ratio, which in principle allows the L-mode plasmas to exceed the threshold condition while the supershots do not, despite having comparable values of η_i . Indeed, at $r/a = 0.72$ the supershot discharges in Fig. 9 have $\eta_i \approx \eta_c^{\text{Guo}}$, whereas η_i for the L-mode discharges lie about 0.5–1.0 units above η_c^{Guo} . Ascertaining whether a difference of this magnitude could be sufficient to cause a factor ~ 4 change in the gyroBohm-scaled χ_i^{tot} in these plasmas will require comprehensive kinetic microinstability calculations of the type developed by Rewoldt and Tang [113–115]. Although not implausible, this explanation appears somewhat unlikely, given that the collisionless trapped electron mode is calculated to drive significant transport even when η_i falls below η_c [116], and in view of the experimental results of Zarnstorff *et al.* showing little increase in χ_i^{tot} even when the threshold criterion for exciting ITGDT turbulence is strongly violated.

Finally, we consider the conjecture that the reduced χ_i^{tot} in supershot plasmas is governed *primarily* by the T_i/T_e becoming large, either through an orbit-averaging effect or through some other mechanism. The data presented in Figs. 7–9 represents mostly a consistency check, in that the χ_i^{tot} always appears to be reduced relative to L-mode values when T_i/T_e substantially exceeds unity. It is also true that the improvement in supershot ion heat confinement is greatest at the plasma center, where the T_i/T_e ratio is the largest. Perhaps the most attractive feature of the T_i/T_e conjecture is that provides a natural mechanism for edge recycling to affect χ_i^{tot} across

¹ An exception is the low-power supershot scan S4 at $r/a = 0.72$, which has T_i/T_e only 1.4–1.6. Interestingly, this scan has higher χ_i^{tot} at $r/a = 0.72$ than the other supershot scans (Fig. 7d).

Figure 9. Variation of T/T_0 , L_{ne} , L_{T1} , and η_{het} with heating power at $r/a = 0.32$ and $r/a = 0.72$. Scan S2.1 has been omitted for clarity. Symbols defined in Table 3.

the plasma cross-section, through its effect on the transport boundary condition, i.e. the edge ion temperature and edge T_i/T_e . The conjecture can be tested in TFTR by examining the variation of χ_i^{tot} in supershots heated with a mixture of neutral beams and ICRF power. Since most of the ICRF power is delivered to electrons, it should be possible to vary the T_i/T_e ratio by varying the mix of ICRF and beam power, and observe the consequent variations in χ_i^{tot} .

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