Isotopic Scaling of Transport in Deuterium-Tritium Plasmas

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Abstract

Both global and thermal energy confinement improve in high-temperature supershot plasmas in the Tokamak Fusion Test Reactor (TFTR) when deuterium beam heating is partially or wholly replaced by tritium beam heating. For the same heating power, the tritium-rich plasmas obtain up to 22% higher total energy, 30% higher thermal ion energy, and 20-25% higher central ion temperature. Kinetic analysis of the temperature and density profiles indicates a favorable isotopic scaling of ion heat transport and electron particle transport, with $\tau_{Ei}(a/2) \propto \langle A \rangle^{0.7-0.8}$ and $\tau_{pe}(a) \propto \langle A \rangle^{0.8}$.

1. Introduction

The variation of energy confinement with isotopic composition has been studied in many tokamaks over the past two decades, primarily by comparing hydrogen, deuterium, and helium plasmas. In this paper we compare heat and particle transport in high temperature beam-fueled deuterium TFTR plasmas to those with mixed deuterium-tritium or pure tritium beam fueling. For the same heating power, the total plasma energy (W_{tot}) as measured by magnetic diagnostics is up to 22% higher in plasmas fueled with tritium beams relative to comparable deuterium plasmas. Some of this increase can be attributed to simple classical effects such as energy stored in the unthermalized fusion alpha component and the increased energy stored in unthermalized beam ions during tritium beam injection. Up to 60% of the total increase in W_{tot} arises from additional energy stored in the thermal ions and electrons, indicating a favorable dependence of τ_E on isotopic composition in these plasmas. In particular, the most tritium-rich plasmas experience a 20-25% increase in central ion temperature, a 30% increase in energy stored in the thermal ions, and a 35% reduction in ion thermal diffusivity. Electron particle transport is improved by a comparable factor, while the change in electron temperature and electron thermal diffusivity appear to be smaller.

The range of isotopic mass explored in these experiments is rather limited due to deuterium influx from the limiter [$\langle A \rangle \equiv (n_h + 2n_d + 3n_t)/(n_h + n_d + n_t) \approx 1.9 \rightarrow 2.6$]. The observed confinement improvement between deuterium and nominally tritium plasmas therefore implies a rather strong isotopic dependence, with τ_E (magnetic) varying as $\langle A \rangle^{2/3}$ and $\tau_{Ei}(a/2)$ varying as $\langle A \rangle^{0.7-0.8}$.

2. Discharge conditions

These experiments were conducted in TFTR supershot plasmas, which are characterized by high ion temperatures (~ 30 keV), peaked electron density profiles, and relatively low influx of hydrogenic neutrals from the limiter[1]. The plasmas were members of three experimental DT campaigns, designated here as A, B, and C, which span a modest range in heating power and limiter conditioning. A mixture of deuterium and tritium neutral beams with energies 90-107 keV were injected to both heat and fuel the discharge. The 12 beam sources were aimed in toroidally opposed directions to yield little net toroidal momentum input to the plasma. A major consideration in the design of these experiments was to obtain matched scans of deuterium (DD) and deuterium-tritium (DT) plasmas whose conditions were as similar as possible with the exception of tritium concentration. Table 1 summarizes the plasma conditions in these scans and the variation in limiter conditioning between DD and DT plasmas. Generally this variation was limited to less than 5% in carbon influx (only a $\pm 1\%$ variation for scan C1), which corresponds to less than a 2% uncontrolled variation in τ_E .

The scan members were selected to have similar low m,n MHD between DD and DT plasmas. However, there remains some variability in the time evolution of the MHD in these plasmas, particularly in scans A1 and A2. Based on correlations of low m/n MHD amplitude with τ_E in previous supershot experiments[2], the observed MHD in the DD and DT plasmas of Table 1 was responsible for a reduction in W_{tot} of less than $\sim 3\%$ at 3.45 sec, and less than $\sim 5\%$ at 3.60 sec. To ensure that the inferred isotopic scaling of heat transport is not affected by MHD, we focus on analysis early in the beam heating pulse (450-600 ms), before the MHD grows to sufficient amplitude to significantly affect the transport. This also avoids possible deterioration of confinement associated with the enhanced deuterium influx in the DT plasmas, which could be responsible for a 9% reduction in τ_E , based on previously observed correlations of τ_E and limiter recycling in supershots.

Scan	Sym	I_p	Pulse	P_b	P_t/P_b	B_{co}	Ohmic target conditions			$\Delta W/W$	Tr	
		(MA)		(MW)			Li	ΔC_{II}	ΔH_α	$\Delta \bar{n}_e$		
A1	●	1.98	<u>73265</u>	29.7	0.00	-0.02	2	—	—	—	-0.07	✓
			73255	29.2	0.48	0.10	2	-0.04	0.00	-0.03	—	✓
			73268	29.6	0.66	0.08	2	0.03	0.01	0.02	-0.10	✓
A2	◇	1.98	<u>73262</u>	27.5	0.00	0.07	1	—	—	—	-0.06	✓
			73254	26.7	0.44	0.00	2	-0.04	-0.05	-0.05	-0.08	✓
			73258	26.8	0.53	0.04	1	-0.01	0.01	-0.02	-0.07	✓
B1	△	1.78	<u>73459</u>	22.7	0.00	0.33	0	—	—	—	-0.05	✓
			73446	22.1	0.67	0.23	0	0.02	-0.03	0.01	-0.08	✓
			73450	23.0	1.00	0.24	0	-0.03	0.00	0.02	-0.14	—
B2	□	1.78	<u>73449</u>	20.5	0.00	0.26	0	—	—	—	-0.03	✓
			73452	20.2	0.74	0.15	0	0.00	0.07	0.00	-0.03	✓
			73447	20.9	1.00	0.15	0	-0.04	-0.01	-0.02	-0.03	✓
C1	○	1.97	<u>75925</u>	26.6	0.00	0.06	0	—	—	—	—	✓
			75926	28.5	0.56	0.05	0	0.01	-0.03	0.01	—	✓
			75932	29.0	0.55	0.04	0	0.00	-0.04	0.01	—	✓
			75941	28.9	0.47	0.06	0	0.01	0.01	0.03	—	✓

Table 1: Scans of tritium beam fueling in otherwise similar plasma discharges. All plasmas have $R = 2.52$ m, $a = 0.87$ m, $B_t = 4.98$ Tesla. Underlined shot numbers represent the deuterium “reference” discharges which best match conditions in the deuterium-tritium discharges. ‘Sym’ indicates the symbol type used to identify scan members in the figures. $B_{co} = (\Gamma_{co} - \Gamma_{ctr})/(\Gamma_{co} + \Gamma_{ctr})$ defines the beam torque fraction [-1=counter, 0 = balanced, 1=pure co-injection]. ‘Li’ indicates the number of lithium pellets injected into previous discharge. Columns under the “Ohmic target conditions” show the fractional difference between each discharge and the reference deuterium discharge in carbon influx, hydrogenic influx, and line-averaged electron density just prior to start of beam injection. $\Delta W/W$ is the fractional change in total stored energy between the peak and the end of beam heating. A check (✓) in the last column identifies plasmas whose results are included in the regression analysis.

3. Typical DD and DT Performance

Fig. 1 illustrates the time evolution of DD plasma 73265 versus DT plasma 73268 of scan A1 for which tritium neutral beams delivered 66% of the total beam power. The most striking difference is the 22% increase in total plasma stored energy in the DT plasma. There is a substantial, sustained increase in the central ion temperature and a somewhat smaller increase in central electron temperature, as measured by an ECE diagnostic, which is delayed in time relative to the increase in T_{i0} . The deuterium discharge 73265 had no significant coherent MHD activity, while the DT discharge suffered from a growing $m/n = 4/3$ mode starting at 3.4 seconds, which could be responsible for a 10% loss of W_{tot} by the end of the heating pulse. The DD and DT plasmas have very nearly the same evolution of the central electron density and chord-integrated visible bremsstrahlung emission, implying similar Z_{eff} . Deuterium neutral influx from the limiter, as indicated by the edge $H\alpha$ light emission, is very similar for the two plasmas for the first 450 ms of beam heating. Beyond that time the DT plasma suffers from as much as 18% more hydrogenic influx, which may also contribute to the deteriorating energy confinement.

Measured profiles of temperature and density for these plasmas are shown in Fig. 2. This figure illustrates several features that are common to most of the DD/DT plasma comparisons. First, the central ion temperature is significantly larger in the DT plasma, and T_i remains visibly larger across much of the plasma cross-section. The electron density profiles are similar, with comparable values of the central electron density, and slightly larger edge densities in the DT plasma. The electron temperature profile measured by ECE is also higher in the DT plasma, although this trend is consistently less pronounced in the $T_e(R)$ profiles measured by Thomson scattering.

Table 2 summarizes the results of transport analysis for several pairs of DD and DT plasmas, including the discharges shown in Fig. 1 and 2. About 40-45% of the total energy increase observed between DD and DT plasmas can be attributed directly to changes in the beam-ion and alpha population. The remaining 55-60% arises from an increase in the integrated energy density of thermal ions and electrons. Since the total alpha heating in these plasmas is at most ~ 1 MW or $\sim 4\%$ of the total beam power, the increased energy stored in the thermal plasma suggests that thermal energy confinement is higher in DT plasmas.

4. Global Confinement Scaling

As a starting point for understanding the isotopic scaling of local heat transport, it is useful to assess the scaling of global τ_E as determined from the magnetic diagnostics alone. Figure 3 plots the ratio of τ_E in each discharge after 540 ms of beam heating to τ_E in the corresponding DD reference discharge, as a function of the fraction of beam power which was tritium and also as a function of the average hydrogenic mass. There is some variability in DT performance, e.g. the DT discharges with nominally equal levels of D^0 and T^0 beam injection experience increases in τ_E ranging from 6% to 17% compared to the reference DD plasmas. Nevertheless, τ_E determined from magnetic analysis correlates roughly with the tritium beam fraction, and the maximum increase of 26% was realized during pure tritium beam injection. Collectively, the data are fit by $\tau_E/\tau_E^{dd} = 1.0 + 0.21 P_t/P_b$, which corresponds to a dependence $\tau_E \propto \langle A \rangle^{0.67 \pm 0.06}$. The isotopic scaling changes only slightly ($\tau_E \propto \langle A \rangle^{0.60}$) if the d/dt correction to τ_E is neglected (by defining $\tau_E \equiv W_{tot}/(P_b + P_{OH})$) because these plasmas are close to equilibrium at 3.5 sec, with $\dot{W}_{tot}$ typically being less than 6% of the heating power. Including alpha heating as a power source term decreases the isotopic scaling of τ_E only modestly, from $\propto \langle A \rangle^{0.67}$ to $\propto \langle A \rangle^{0.54}$. If, in addition, the alpha stored energy is

Figure 1: Time evolution of DD versus DT supershot plasmas 73265 and 73268. Arrows indicate the times of steady-state transport analysis.

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Figure 2: Measured ion and electron temperature profiles in DD versus DT supershot plasmas 73265 and 73268 after 450 ms of beam heating

Parameter	Units	Scan A1			Scan C1				
		DD	DT	Δ	DD	DT	Δ	DT	Δ
R	m	2.52	2.52		2.52	2.52		2.52	
a	m	0.87	0.87		0.87	0.87		0.87	
B_t	Tesla	4.95	4.95		4.98	4.98		4.98	
I_p	MA	1.98	1.98		1.97	1.97		1.97	
q_ψ		4.70	4.98		4.69	4.77		4.77	
P_b (total)	MW	29.7	29.6		26.6	28.4		28.9	
P_t	MW	0	19.5		0	16.0		13.5	
n_{eo}	10^{19} m^{-3}	7.65	7.57		7.26	7.46		7.46	
n_{h+d+t}	10^{19} m^{-3}	5.30	5.27		4.64	4.83		4.89	
$Z_{\text{eff}}(0)$		2.06	2.04		2.22	2.24		2.16	
T_{io}	keV	31.2	35.6		21.6	25.2		24.6	
T_{eo}	keV	9.7	10.6		9.0	10.0		10.0	
W_i	MJ	1.33	1.63	0.30	1.04	1.23	0.19	1.36	0.32
W_e	MJ	1.05	1.21	0.16	0.94	1.10	0.16	1.16	0.22
W_{beam}	MJ	1.97	2.21	0.24	1.67	1.83	0.16	1.89	0.22
W_α	MJ	0.	0.14	0.14	0	0.12	0.12	0.13	0.13
W_{kin}	MJ	4.36	5.20	0.84	3.65	4.28	0.63	4.55	0.90
W_{mag}	MJ	4.20	4.96	0.76	3.70	4.24	0.54	4.52	0.82
$P_{dt-fusion}$	MW	-	6.17		-	4.71		5.23	
Pulse		73265	73268		75925	75926		75941	

Table 2: DD and DT reference shots.

subtracted from the total stored energy, the isotopic scaling is reduced further, to $\tau_E \propto \langle A \rangle^{0.43}$.

5. Kinetic Measurements and Analysis

Diagnostics

The electron temperature profiles in these experiments were measured by two diagnostics: a 20-channel grating polychromator normalized to an absolutely calibrated Michelson interferometer, and a 76-channel Thomson scattering diagnostic. The electron density profile was measured by a 10-chord interferometer viewing the plasma vertically. The ion temperature and toroidal rotation profiles were measured by a charge-exchange recombination spectroscopy (CXRS) with viewing sightlines every 6 cm. $Z_{\text{eff}}(R)$ profiles were obtained by measuring the chord-integrated visible bremsstrahlung emission with a 16-channel visible spectrometer array viewing tangentially in the horizontal midplane ($R_{\text{tan}} = 1.70 - 3.42$ m).

SNAP Transport Model

Local heat and particle transport coefficients are inferred from the measured profiles using the equilibrium transport code SNAP[3]. The beam-ion distribution function is calculated from a solution of the Fokker-Planck equation in the rotating plasma frame. The energy transport is analyzed assuming that the radial transport mechanisms are cross field diffusion, represented

Figure 3: (a) Ratio of global energy confinement time measured by a diamagnetic loop and equilibrium magnetic diagnostics in DT plasmas to that in reference DD plasmas as a function of tritium-beam power fraction. (b) Same ratio plotted as a function of the average thermal hydrogenic mass. The symbols represent plasmas in different scans as defined in Table 1.

by anomalous diffusivities D_e , χ_i , and χ_e :

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

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, $\sum_j$ represents a sum over all ion species including impurities, and χ_i^{tot} and χ_e^{tot} are “total” diffusivities which include both the convective and conductive fluxes.

The models of alpha particle heating and thermalization implemented in SNAP are similar to those used in its calculation of beam-ion physics. The raw alpha particle source rate is calculated as a function of minor radius from the DT fusion rate. Losses due to unconfined orbits and banana-trapped alpha particles whose banana tips lie in the stochastic ripple region are regarded as prompt-lost. The resulting confined, orbit-averaged alpha source rate is assumed to thermalize classically. This model agrees well ($\Delta P_\alpha \leq 0.1$ MW, $\Delta W_\alpha \leq 0.03$ MJ) with more comprehensive TRANSP calculations which follow the guiding-center collisional orbits of an ensemble of thermalizing alpha particles.

Plasma Composition

The hydrogenic thermal ion density is determined in SNAP by subtracting the electron density associated with impurities and beam ions from the local measured electron density. The relative concentration of deuterium and tritium is determined by a simple model that is calibrated to give agreement with the measured DT neutron emission during injection of pure T^0 neutral beams. The model assumes fixed ratios of n_h , n_d , and n_t across the entire plasma.

To assess the magnitude of the central deuterium concentration, the expected DT neutron emission was calculated as a function of deuterium concentration for discharges with trace tritium beam injection (11%), ~50%, and 100% tritium beam injection. The relative deuterium and tritium concentrations are specified by the adjustable parameter Υ_t , where $\frac{n_t}{n_t+n_d} \equiv \Upsilon_t \frac{P_t}{P_t+P_d}$ and P_t and P_d are the total tritium and deuterium beam power, respectively. As shown in Fig. 4, the calculated DT neutron emission approaches zero as Υ_t approaches 1.0 in plasmas with pure T^0 injection, since in this limit there is no deuterium in the plasma with which to fuse. For these discharges, the calculated neutron emission agrees with the measured emission for Υ_t values in the range 0.65-0.75. As discussed below, the accuracy of the calculated neutron emission in these plasmas is approximately 10%, which corresponds to an uncertainty in the inferred value of Υ_t of order ± 0.1 . For consistency, the relative tritium and deuterium concentrations for all plasmas in this experiment with mixed DT beam injection were determined using $\Upsilon_t \approx 0.65$.

As shown in Fig. 4, for plasmas with nominally equal amounts of tritium and deuterium beam power a variation of ± 0.1 about the nominal value $\Upsilon_t = 0.65$ should change the calculated neutron emission by only a few percent. For the DT discharge 73268 with 66% tritium beam fueling, calculations by the SNAP code indicate that varying Υ_t by ± 0.1 changes the DT fusion power and unthermalized alpha energy by about 0.7%, total stored plasma energy by less than 0.25%, and χ_e^{tot} and χ_i^{tot} by less than 2% and 1%, respectively, across the entire plasma cross section. Thus, uncertainties in the relative concentration of deuterium to tritium in these plasmas contribute only negligibly to the total uncertainty in the inferred local transport coefficients, largely because the alpha heating power is small relative to beam heating, and because in nominally 50:50 D:T plasmas the fusion rate is insensitive to variations in the relative deuterium to tritium concentration.

Figure 4: Ratio of DT neutron emission computed by SNAP to the measured neutron emission as a function of assumed Y_t for plasmas with pure T^o -NBI, nominally equal T^o -NBI and D^o -NBI power, and trace (11%) T^o -NBI beam injection.

Power Deposition

Because both the density profile and beam energy were very similar for the DD and DT plasmas, to first order the heating profiles are reasonably similar also. Figure 5 compares the calculated heating profiles of DD discharge 73265 to DT discharge 73268. There is negligible difference in the beam power deposition profile to ions, because the poorer penetration of the tritium beam neutrals is partially compensated by the increased fraction of tritium beam power which is collisionally coupled to ions. By contrast, beam power deposition to electrons is reduced significantly in the plasma center, because both of these effects reduce beam power deposition to core electrons. However, this is offset by core heating of electrons by alpha particles and increased ion-electron coupling in the DT plasma. Overall, there are only small differences in the net heating profile between these DD and DT plasmas. Consequently, observed differences in temperature between them reflect differences in local transport properties.

Conduction is the dominant loss channel at the half radius for both ions and electrons. As is typically observed in supershot plasmas, the conducted losses become small near the plasma center, and particle convection becomes the dominant loss process, particularly for ions. Radiation is a significant loss channel for electrons only in the outer 15 cm of the plasma.

Data Consistency

To assess the data consistency among diagnostics in the high-neutron environment of DT experiments, we compare the results of kinetic analysis to direct diagnostic measurements of total stored energy and neutron emission. The overall stored-energy agreement is excellent, generally within 10%, although the ratio W_{kin}/W_{mag} does tend to increase systematically with P_t/P_b , with the best fit to the data having a slope of 0.059. Equivalent analysis performed

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Figure 5: Comparison of calculated heating profiles in deuterium and deuterium-tritium plasmas. Here $q_i^{TOTAL} \equiv q_{bi} + q_{ai} - q_{ie} + q_{viscous}$; $q_e^{TOTAL} \equiv q_{be} + q_{OH} + q_{ae} + q_{ie}$, and q_{bi} includes both beam collisional and thermalization power.

for the ratio of the kinetic diamagnetic energy to that measured by a diamagnetic loop shows a weaker systematic bias of only 1.4%. The measured 2.45 MeV neutron emission from DD plasmas was 10-15% greater than that calculated by SNAP using the measured density and temperature profiles, while it was about 10% less than calculated in the DT discharges[4]. In both cases the discrepancy is comparable to the combined uncertainties of the kinetic prediction (10-13%, based on estimated uncertainties in T_i , T_e , n_e , Z_{eff} , beam power, etc.) and the neutron measurement ($\pm 13\%$ for 2.45 MEV neutron flux, and $\pm 7\%$ for 14 MeV neutron flux).

6. Transport Analysis

The results of the local transport analysis for these experiments is summarized in Figs. 6 and 7. Figure 6 plots the profile of the local *ratio* of χ_i^{tot} and D_e in the DT plasma to reference DD plasma for three representative scans. In these plots, the reference DD data is represented by a horizontal line at $y = 1$. The range of variation in similarly-prepared DD plasmas is represented by a shaded region. Over most of the plasma cross-section, χ_i^{tot} is lower in DT plasmas than in the reference DD plasma, and the difference is larger than the usual shot-to-shot variation observed among similar DD discharges. The error bars shown in Fig. 6 represent the 1- σ relative uncertainty in the diffusivity ratios arising from measurement error. Over most of the plasma cross-section, χ_i^{tot} in DT is more than 1- σ below its value in the reference DD plasma, but typically not more than 2- σ less.

Averaged over the plasma cross-section, χ_e^{tot} is also slightly smaller ($\sim 15\%$ in the DT plasma of scan A1) compared to the reference DD plasma. This is consistent with TRANSP analysis of the same discharges[5], which showed that the measured $T_e(r, t)$ of the DT discharge is higher than the predicted values using the calculated heating profiles for that discharge (including the alpha heating), and assuming that $\chi_e(r, t)$ was held constant at the value obtained in the DD plasma. However, a consistent trend toward improved χ_e^{tot} in DT plasmas does not appear in the other scans. While the reduction in χ_e^{tot} in scan C1 is larger than the estimated experimental precision, the change is not larger than the observed shot-to-shot variation. In addition, the Thomson scattering $T_e(R)$ profile measurement shows a consistently smaller increase in T_{eo} between DD and DT plasmas than is measured by ECE. By contrast, D_e is consistently reduced over most of the plasma cross section by an amount comparable to the difference in χ_i^{tot} .

These trends are summarized in Fig. 7, which plots the ratio of χ_i^{tot} and D_e to the corresponding value in the reference DD plasma at the plasma half-radius. The left-hand column of graphs have as the x-axis the fraction of tritium beam power. The right-hand graphs illustrate the power-law fit to the mass scaling of the diffusivities. A favorable dependence of χ_i^{tot} and D_e on $\langle A \rangle$ is obtained, $\chi_i^{\text{tot}} \propto \langle A \rangle^{-1.4}$ and $D_e \propto \langle A \rangle^{-1.0}$.

Similar regression analysis was carried out for other local plasma parameters, transport coefficients, and confinement times at a variety of minor radii. Tables 3 and 4 present the results of this study. In all cases, the regression includes data only from scans A1, A2, B1, B2, and C1 at 3.45-3.60 seconds. The regressions confirm improved core ion heating (15-19%), core electron heating (5-10%), increased thermal ion stored energy (23%), electron stored energy (12%), edge electron density (13%), and negligible change in core electron density and Z_{eff} with increasing tritium beam fraction. By construction, there was little correlation of total beam power ($\Delta P_b \approx 2\%$) with the tritium beam power fraction. There was virtually no increase in the edge ion temperature ($r/a = 0.92$) with tritium concentration. Thus, the improved ion performance in DT plasmas cannot be attributed to changes in edge T_i , which has been previously identified as a parameter which correlates well with core ion energy

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Figure 6: χ_i^{tot} and D_e as a function of minor radius, normalized to their profile values in reference DD plasmas. The shaded regions show the 1- σ variation of the transport coefficients in deuterium plasmas. The error bars for scan C1 represent the estimated precision of the transport coefficient ratios between DD and DT plasmas. Each DT shot number is followed by its fraction of tritium beam power in parentheses.

confinement[6,7].

Since the DT plasmas experience a substantial increase in central thermal ion energy (24%) without much change in total heating power (1-3%), the core ion energy confinement time is inferred to increase substantially, corresponding to a scaling $\tau_{Ei}(a/2) \propto \langle A \rangle^{0.69}$. The corresponding scaling of $\tau_{Ee}(a/2)$ is considerably weaker, increasing only as $\langle A \rangle^{0.25}$. The overall thermal energy confinement time determined from kinetic analysis has an isotopic dependence $\tau_{ei} \propto \langle A \rangle^{0.52}$, similar to that of the total kinetic energy confinement time (including beam-ion stored energy), $\tau_E^{tot} \propto \langle A \rangle^{0.59}$. The “steady-state” magnetics analysis implies a weaker isotopic scaling ($\propto \langle A \rangle^{0.41}$) than the kinetic analysis ($\propto \langle A \rangle^{0.59}$), reflecting the fact that the increase in W_{tot} observed by magnetic analysis is smaller than that from kinetic analysis.

The uncertainties and correlation coefficients shown in Tables 3 and 4 reflect only the shot-to-shot variability of the parameters listed, and do not include additional uncertainties arising from diagnostic errors. It is not surprising that parameters such as Z_{eff} which correlate weakly with tritium beam power fraction (less than 1% change) have a weak correlation coefficient ($R^2 = 0.09$), since weak correlations are, by definition, easily obscured by small uncontrolled variations in other parameters. However, the quality of fit is also only moderately good for parameters such as central ion temperature, χ_i^{tot} , and total stored ion energy, all of which are inferred to have a stronger dependence ($\Delta=12-35\%$) on plasma composition. This reflects the fairly significant shot-to-shot variation illustrated in Fig. 7, which shows improvements in $\chi_i^{tot}(a/2)$ ranging from almost negligible to 35% for DT plasmas with comparable amounts of D-NBI and T-NBI heating relative to those with pure D-NBI. Straightforward statistical analysis of the dataset yields relatively small uncertainties (typically $\leq \pm 0.15$) for the exponent on $\langle A \rangle$ in the power-law fits of transport parameters shown in Table 4. However, given the limited quality-of-fit and the significant scatter apparent in Fig. 7, we believe that the total uncertainty in the isotopic-mass scaling of transport is larger than that indicated by the statistical analysis. For this reason uncertainties are not quoted for most of the exponents in the power-law fits of Table 4. Future isotope scaling studies will emphasize comparisons of plasmas with pure T-NBI versus pure D-NBI to increase the difference in plasma performance associated with isotopic content relative to the shot-to-shot irreproducibility.

Comparison with Scan C1

A comparable regression analysis was carried out for a dataset consisting solely of plasmas in scan C1, which has T_i measurements uncompromised by differing isotope in the doping beam used by CXRS. The results for energy confinement times at both the half radius and integrated over the plasma as a whole are very similar to those obtained for the combined scans. In particular, the scaling of $\tau_{Ei}(a)$ is virtually identical, while the dataset from scan C1 indicates a slightly stronger improvement at the half-radius, $\tau_{Ei}(a/2) \propto \langle A \rangle^{0.80}$. There are somewhat greater differences in the inferred scaling of local parameters, with scan C1 obtaining $\chi_i^{tot} \propto \langle A \rangle^{-0.6}$ at both the third and half-radius, compared to $\chi_i^{tot} \propto \langle A \rangle^{-1.4}$ at the half-radius for the combined dataset. Determining whether the isotope scaling of local χ_i^{tot} lies closer to the bottom or top end of this range will be the subject of future experiments. Overall, the results from scan C1 confirm that local ion energy transport is improved in DT plasmas relative to DD plasmas, indicating that the effect observed in the other scans is not an artifact of spurious ion temperature profile measurements.

Comparison with Thomson Scattering

The ECE T_e profile measurement is narrower than that measured by Thomson scattering and larger at the center, being 1-1.7 keV higher than the Thomson scattering measurement at the plasma center and ~ 0.8 keV smaller at $R = 3.10$ m. There is only a modest effect on the

Figure 7: Ratio of local transport coefficients in DT and DD plasmas to those in the reference DD plasma at $r = a/2$. (a-b) Ratio as a function of tritium beam power fraction. (c-d) Ratio as a function of average hydrogenic mass.

Quantity		Variation with Power Fraction	R^2
P_b	1.00 <i>a</i>	$1.00 + 0.02(01)P_t/P_b$	0.03
Z_{eff}		$1.01 - 0.01(01)P_t/P_b$	0.09
F_{ne}		$0.99 - 0.08(01)P_t/P_b$	0.37
T_i	0	$1.00 + 0.12(03)P_t/P_b$	0.30
	0.32 <i>a</i>	$0.99 + 0.19(03)P_t/P_b$	0.46
	0.52 <i>a</i>	$1.00 + 0.15(03)P_t/P_b$	0.62
	0.92 <i>a</i>	$1.01 - 0.02(01)P_t/P_b$	0.04
T_e	0	$1.00 + 0.10(02)P_t/P_b$	0.40
	0.52 <i>a</i>	$1.00 + 0.05(02)P_t/P_b$	0.18
	0.82 <i>a</i>	$1.01 + 0.06(02)P_T/P_b$	0.14
n_e	0	$1.00 - 0.002(016)P_t/P_b$	0.00
	0.52 <i>a</i>	$1.01 + 0.08(02)P_t/P_b$	0.35
	0.92 <i>a</i>	$1.00 + 0.13(02)P_t/P_b$	0.54
W_i	0.52 <i>a</i>	$1.00 + 0.24(04)P_t/P_b$	0.41
	1.00 <i>a</i>	$1.00 + 0.23(04)P_t/P_b$	0.44
W_e	0.52 <i>a</i>	$1.02 + 0.11(02)P_t/P_b$	0.33
	1.00 <i>a</i>	$1.01 + 0.12(02)P_t/P_b$	0.36
W_{beam}	0.52 <i>a</i>	$1.00 + 0.16(01)P_t/P_b$	0.77
	1.00 <i>a</i>	$1.00 + 0.19(01)P_t/P_b$	0.85

Table 3: Scaling of plasma heating and confinement with fraction of tritium beam power. Expressions show the scaling of each quantity normalized to its value in reference deuterium-only comparison plasmas from Scans A1, A2, B1, B2, C1 at 3.44 - 3.62 sec.

Quantity		Variation with Power Fraction	Variation with $\langle A \rangle$	R^2
$W_{\text{tot}}^{\text{mag}}/(P_b + P_{OH})$	1.00 <i>a</i>	$1.00 + 0.16(01)P_t/P_b$	$0.71 \langle A \rangle^{0.54 \pm .04}$	0.75
$W_{\text{tot}}^{\text{mag}}/(P_b + P_{OH} + P_\alpha)$	1.00 <i>a</i>	$1.00 + 0.12(01)P_t/P_b$	$0.77 \langle A \rangle^{0.41 \pm .04}$	0.67
τ_E^{tot} (kinetic)	1.00 <i>a</i>	$1.00 + 0.18(01)P_t/P_b$	$0.68 \langle A \rangle^{0.59 \pm .04}$	0.83
τ_E^{th} (kinetic)	0.52 <i>a</i>	$1.00 + 0.16(02)P_t/P_b$	$0.72 \langle A \rangle^{0.51}$	0.46
	1.00 <i>a</i>	$1.00 + 0.16(02)P_t/P_b$	$0.71 \langle A \rangle^{0.52}$	0.53
τ_{Ei}	0.52 <i>a</i>	$0.99 + 0.22(04)P_t/P_b$	$0.63 \langle A \rangle^{0.69}$	0.40
	1.00 <i>a</i>	$0.99 + 0.17(03)P_t/P_b$	$0.70 \langle A \rangle^{0.54}$	0.35
τ_{Ee}	0.52 <i>a</i>	$1.02 + 0.08(02)P_t/P_b$	$0.86 \langle A \rangle^{0.25}$	0.29
	1.00 <i>a</i>	$1.00 + 0.14(02)P_t/P_b$	$0.75 \langle A \rangle^{0.46}$	0.46
τ_{pe}	0.52 <i>a</i>	$1.01 + 0.34(01)P_t/P_b$	$0.50 \langle A \rangle^{1.07 \pm .03}$	0.96
	1.00 <i>a</i>	$1.00 + 0.25(01)P_t/P_b$	$0.59 \langle A \rangle^{0.80 \pm .04}$	0.90
χ_i^{tot}	0.52 <i>a</i>	$1.04 - 0.35(05)P_t/P_b$	$2.65 \langle A \rangle^{-1.43}$	0.61
χ_e^{tot}	0.52 <i>a</i>	$0.98 - 0.09(03)P_t/P_b$	$1.23 \langle A \rangle^{-0.35}$	0.15
D_e	0.52 <i>a</i>	$0.96 - 0.25(03)P_t/P_b$	$1.89 \langle A \rangle^{-1.04}$	0.55

Table 4: Scaling of local diffusivities with fraction of tritium beam power and with average thermal hydrogenic mass, based on ECE measurements of T_e in scans A1, A2, B1, B2, and C1 (3.44-3.62 sec). Expressions show the scaling of each quantity normalized to its value in reference deuterium-only comparison plasmas.

inferred χ_i^{tot} , because changes in T_e only affect the ion analysis through the ion-electron power coupling, which is a relatively small term in the ion power balance. Transport analysis based on the Thomson scattering measurements of $T_e(R)$ imply a somewhat stronger favorable scaling of χ_i^{tot} with $\langle A \rangle$ than do the ECE measurements, while χ_e^{tot} is inferred to have an *unfavorable* isotopic dependence. Thus with the data currently available it is difficult to reach a definitive conclusion regarding the isotopic scaling of electron heat transport in supershot plasmas.

7. Discussion

The regression analysis reported here simply correlates various measures of energy confinement (τ_E , χ_i^{tot} , etc.) with tritium concentration. Because the DT plasmas had better confinement than the DD plasmas, their parameters are not exactly matched, in particular the DT plasmas have higher T_i . A favorable *causal* dependence of χ_i^{tot} on T_i (or correlated parameters such as T_i/T_e or β) in supershot plasmas would amplify any intrinsic isotopic scaling, and might give rise to the observed “strength” of the isotope effect in the ion channel in DD/DT comparisons at constant heating power, even if the intrinsic dependence were weak. We have previously observed a favorable scaling of χ_i^{tot} with T_i [8,7] in DD supershot plasmas, with χ_i^{tot} falling roughly as $1/T_i$ at the $r = a/3$ in scans of heating power at constant I_p . The DT scans discussed here span a modest range in heating power, collectively ranging from 20-30 MW. Although there is some overlap between the ion temperatures in the lower-power DT plasmas and the higher-power DD plasmas, we have not unambiguously isolated the isotope dependence of χ_i^{tot} and τ_{Ei} from additional dependences on local T_i or T_i/T_e .

Previous L-mode heating experiments[9] compared deuterium beam injection into deuterium and hydrogen target plasmas at heating power up to 7 MW, spanning about the same range of isotope mix as explored in these DT experiments (the nominally hydrogen plasmas were typically not more than $\sim 65\%$ hydrogen). These plasmas had $T_i \approx T_e$. The deuterium plasmas achieved 8-10% more thermal stored energy than comparable hydrogen plasmas at the same heating power, which implied a relatively weak isotopic scaling $\tau_E^{\text{th}} \propto \langle A \rangle^{0.24}$ [10]. In contrast to the supershot results, the L-mode plasmas experienced a larger isotopic effect on *electron* stored energy than on ion stored energy between hydrogen and deuterium plasmas. No differences in the central momentum density were observed during unidirectional beam injection into hydrogen and deuterium L-mode plasmas, suggesting a negligible or weak isotopic effect on χ_ϕ in that regime.

8. Conclusion

A series of controlled heating experiments on the TFTR tokamak has demonstrated improved energy confinement in plasmas heated and fueled by tritium neutral beams compared to deuterium neutral beams. The maximum increase in total plasma stored energy measured by magnetic diagnostics was 22% for comparable plasma conditions. Regression analysis of a number of controlled scans which varied the fraction of tritium beam power obtained a best-fit increase of 21% in τ_E^{tot} (magnetic) between pure deuterium and pure tritium beam injection. This corresponds to an isotopic scaling $\tau_E^{\text{tot}} \propto \langle A \rangle^{0.67}$, or $\tau_E^{\text{tot}} \propto \langle A \rangle^{0.54}$ if the additional heating by alpha particles is included.

The kinetic analysis indicates that up to 60% of the increase in W_{tot} was due to higher stored energy in the thermal ions and electrons, particularly the ions. The thermal ions experienced a 20-25% increase in central temperature and a comparable increase in stored energy between plasmas heated with pure deuterium versus pure tritium beams. Because

changes in the beam power deposition profile to ions were small, the larger energy ion thermal energy implies improved ion energy confinement in the DT plasmas, $\tau_{Ei}(a/2) \propto \langle A \rangle^{0.69}$. These experiments have not tested whether a favorable dependence of τ_{Ei} on T_i in supershot plasmas amplifies a weaker, intrinsic isotope dependence.

Local electron particle transport was also inferred to be 20-30% smaller in the most tritium-rich plasmas compared to reference DD plasmas. Although reduced χ_e^{tot} was obtained in some DT versus DD shot-pair comparisons, the magnitude of the reduction in χ_e^{tot} was only comparable to the shot-to-shot variation obtained in nominally identical DD plasmas, and it was not consistently observed. In addition, electron temperature profile measurements by Thomson scattering showed a smaller T_e increase than did measurements by ECE diagnostics.

Additional studies to improve our understanding of isotopic scaling of local transport will be pursued during the remainder of the DT campaign on TFTR. These include (a) beam power scans, to distinguish isotope effects from temperature scaling of χ_i^{tot} ; (b) uni-directional beam heating, to determine the isotopic scaling of χ_ϕ ; (c) operation in regimes having $T_i \approx T_e$; and (d) measurements of density fluctuations in DD and DT plasmas by beam emission spectroscopy and correlation reflectometry.

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