ISOTOPE SCALING OF HEATING AND CONFINEMENT IN MULTIPLE REGIMES OF TFTR*

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Abstract

ISOTOPE SCALING OF HEATING AND CONFINEMENT IN MULTIPLE REGIMES OF TFTR.

The isotope effect on confinement has been studied in a variety of TFTR plasma regimes comparing deuterium to deuterium–tritium performance. The strongly favorable isotope effect observed previously in the peaked-density supershot regime ($\tau_E \propto \langle A \rangle^{0.85}$) has been observed also in the high ℓ_i regime, with comparable strong increases in core ion energy confinement. In high-power beam-heated L-mode plasmas with broad density profiles, conditions which are more prototypical of ITER plasmas, deuterium–tritium plasmas attain 12–25% more thermal energy than comparable deuterium plasmas, corresponding to $\tau_E^{th} \propto \langle A \rangle^{0.5}$. ICRF-heated L-mode plasmas with 4 MW of heating show an 8–11% increase in total stored energy in deuterium–tritium plasmas, consistent with $\tau_E \propto \langle A \rangle^{0.35-0.5}$. In both the L-mode and supershot regimes, 30% more heating power is required to sustain the same temperature in the deuterium plasma than in tritium, which implies a transport scaling ($\chi \propto \chi_{Bohm} \rho_*^{-2}$) that differs qualitatively from the scaling inferred from B-field scans with fixed isotope. A model for the isotope effect is proposed based on shear-flow effects that explains most of the observed increase in temperature in the L-mode beam-heating experiments. No isotope effect on global τ_E is observed in ohmic plasmas, reverse shear discharges, or enhanced reverse shear discharges. More heating power is required for obtaining an ERS transition in tritium than in deuterium, which may provide a useful test of proposed models of ERS transition physics.

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1. Introduction

Previous experiments in supershot plasmas [1,2] identified a strongly favorable isotope effect on energy confinement between deuterium and tritium. Despite achieving only modest tritium concentrations (~50%), supershots heated with tritium beams achieved 25% higher stored energy than comparable plasmas heated with deuterium beams, consistent with $\tau_E \propto \langle A \rangle^{0.85}$ at high power. The isotope effect was especially pronounced in the central ion thermal diffusivity, with $\chi_i \propto \langle A \rangle^{-1.8}$ at fixed ion temperature. A favorable isotope effect on τ_E between deuterium and DT has also been observed in peaked-density limiter H-mode plasmas[3,4]. Further isotope-scaling experiments have now been carried out on TFTR in DT plasmas to document the isotope effect in a variety of regimes, including broad-density L-mode regimes with $T_i \approx T_e$, regimes with significant electron heating (ICRF heating)[5], and ohmic heating. The observed energy confinement in broad-density plasmas with auxiliary heating is higher in tritium than in deuterium, and the improvement is consistent with $\tau_E \propto \langle A \rangle^{\sim 0.5}$.

From the ensemble of supershot and L-mode discharges it is possible to construct scans in which plasma beta and collisionality are held fixed while the normalized ion gyro-radius $\rho_* = \rho/a$ is changed through the isotope concentrations. These scans confirm that transport improves with increasing ion mass despite larger ρ_*, a trend that is contrary to the observed scaling of transport with ρ_* in magnetic-field scans. A theoretical model of the isotope effect is proposed based on shear-flow effects that reconciles these observations, and which explains most of the observed increase in temperature in the L-mode beam-heating experiments. Implications of this model for projecting the isotope effect to ITER will be discussed.

Finally, isotope effects have been studied in advanced-tokamak regimes with modified current profiles: high-ℓ_i[6], reverse shear (RS),and enhanced reverse shear (ERS)[7,8]. In high ℓ_i plasmas a robust isotope effect is observed similar to that in supershots. By contrast, little or no isotope effect on confinement is observed in reverse-shear or enhanced-reverse shear plasmas despite densities, temperatures, and heating profiles which are quite similar to those obtained in supershots. More heating power is required in tritium than in deuterium to generate an ERS transition, which may provide an interesting challenge to proposed theories of transition dynamics.

2. L-mode Regime with Neutral Beam Heating

To study the isotope effect in L-mode plasmas, we performed a beam power scan at constant $\overline{n}_e$ in deuterium ($D^o \rightarrow D^+$) and tritium ($T^o \rightarrow D^+ +$

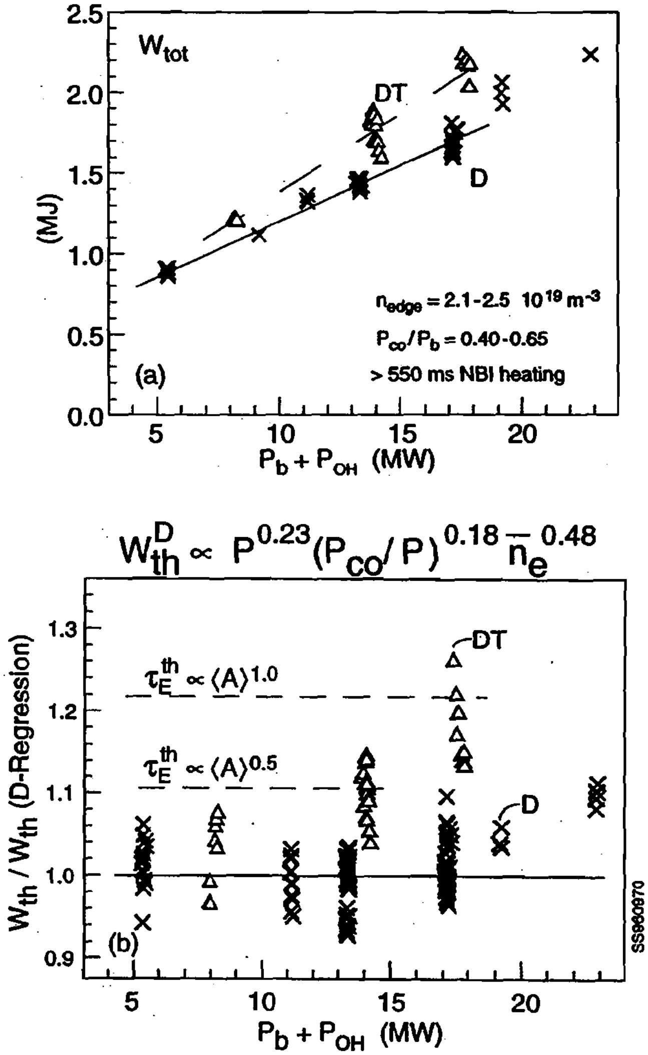

FIG. 1. (a) Total plasma energy as a function of heating power in L-mode plasmas heated with D-NBI versus T-NBI. Plasma conditions were R = 2.52 m, a = 0.87 m, $\bar{n}_{e19}$ = 4–5.5, T_{eo} = 3–7 keV and T_{io} = 3–12 keV. Data points represent measurements at top of sawteeth ≥550 ms after start of beam injection. (b) Ratio of thermal stored energy to power-law regression fit to the deuterium data.

T^+) plasmas with high-recycling limiters. This generated sawtoothing discharges with broad density profiles ($F_{ne} = n_e(0)/\langle n_e\rangle = 1.4 - 1.8$), $T_i/T_e = 1.0 - 1.4$, and values of τ_E within 20% of the L-mode scaling values in deuterium. In order to achieve L-mode plasmas, the limiter was saturated with either deuterium or tritium gas. Only partial saturation of the limiter with tritium was accomplished due to the reservior of deuterium in the carbon tiles, yielding a tritium concentration of 32-40% in the hydrogenic influx from the limiter during beam injection. The core tritium concentration was larger (~45%) due to tritium beam fuelling.

The total plasma stored energy (Fig. 1) was larger in DT plasmas than in comparable deuterium plasmas. Using a power-law regression fit to the deuterium data, $W^D_{tot} \propto P^{0.61}_{inj}(P_{co}/P_{inj})^{0.1}n^{-0.17}_{edge}$, we see that global energy confinement in tritium increased 8-11% at low power (8 MW) and 10-25% at high power (13-18 MW). There was some tendency for the improvement ratio to decrease with time during the heating phase, with the lower range of 10-15% being obtained near the end of the 1.2-second T-NBI pulse. The plasma behavior in the first several hundred milliseconds of beam injection showed some indications of sliding into the supershot regime (with $T_i/T_e > 2$), so we consider the data late in the beam-heating phase to be most respresentative of the true effect in L-mode plasmas. The observed increase there was roughly consistent with the increase of 11% that would be expected from $\tau_E \propto \langle A\rangle^{0.5}$ scaling, given the modest increase in $\langle A\rangle$ from 1.9 to 2.4 in these plasmas.

DT L-mode plasmas attain $\sim$ 30% higher central temperatures and thermal energy densities than D plasmas with comparable density profiles and heating power (16-17 MW). This occurs despite somewhat broader power deposition by tritium beams, which deliver ~12% less power on-axis per incident MW than the deuterium beams. Due to preferential heating of the thermal ions, the volume-integrated beam heating power to ions $P_{bi}(r = a/2)$ remains about constant between deuterium and tritium, while P_{be} decreases ~24% in T-NBI. Thermal stored energy in the deuterium discharges can be well represented by the power-law expression $W^D_{th} \propto P^{0.23}_{inj}\overline{n}_e{}^{0.48}(P_{co}/P_{inj})^{0.18}$, similar to previous thermal scaling in TFTR L-mode plasmas[9]. Normalized to this scaling (Fig. 1b) the tritium discharges show increases in W_{th} of $-2\% \rightarrow +7\%$ at 8 MW, 4%-14% at 14 MW, and 12%-25% at 18 MW. Kinetic analysis indicates that, at high power, electron energy confinement $\tau_{Ee}(a/2)$ increases 10-20% in tritium, and ion energy confinement $\tau_{Ei}(a/2)$ increases 20-40%. Our confidence in this conclusion is weakened by an unresolved systematic discrepancy ($\leq$ 25%) in the ratio of kinetic to magnetic stored energy in these plasmas (comparable in size for D and DT). Momentum confinement during pure co-injection is approximately 15% better in tritium at high power, suggesting an improvement in the ion channel, if, as is typical, $\tau_\phi \approx \tau_{Ei}$.

3. Isotope and ρ_* Scaling

By varying the magnetic field and simultaneously adjusting the plasma density and heating power, gyro-radius scaling experiments can observe [10–13] the variation of heat transport with normalized ion gyro-radius, $\rho_* \equiv \rho/a$. In the L-mode regime, the *single-fluid* thermal diffusivity generally follows a simple Bohm-like scaling, $\chi_{fluid} \propto \chi_B\rho_*^{\sim 0}$ where $\chi_B = cT/eB$. Experiments on DIII-D have identified different gyro-radius scalings for the ions and electrons separately[11,12], with electrons having a gyroBohm scaling $\chi_e \propto \chi_B\rho_*^{1.1\pm0.3}$, and the ions having a Goldston-like

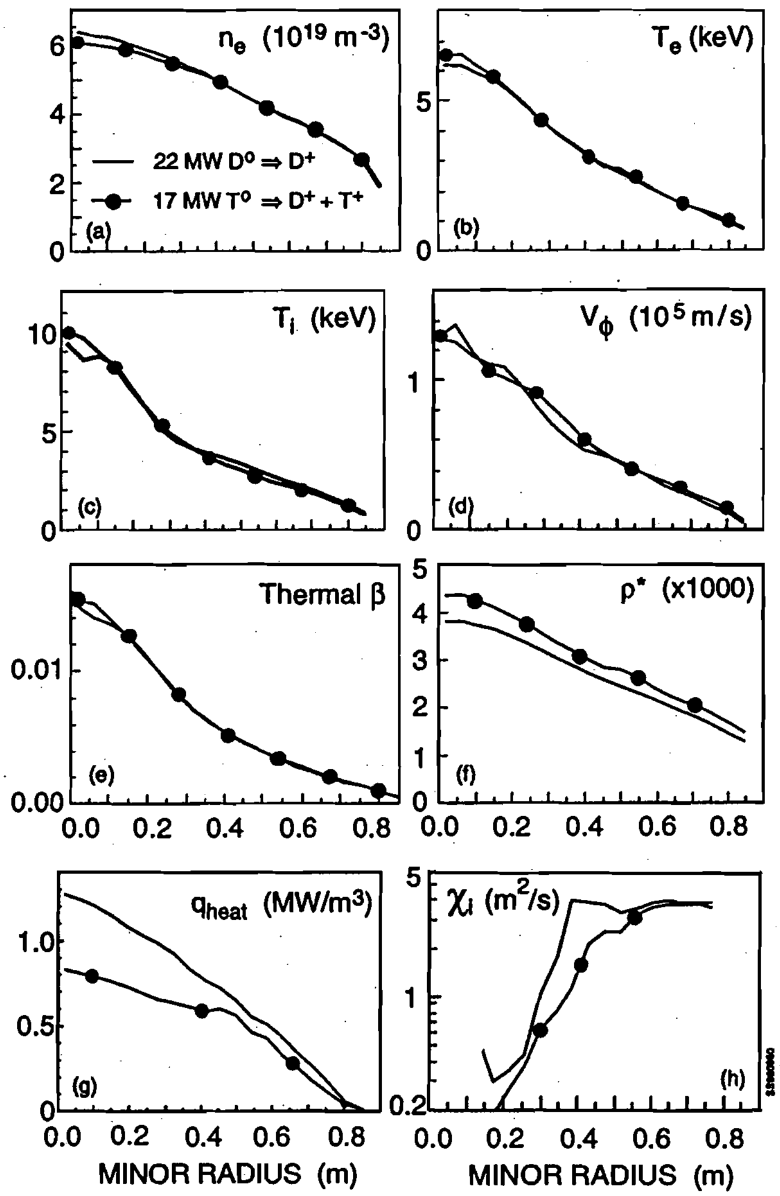

FIG. 2. Kinetic profiles in D and DT L-mode 'isotope ρ_*-scaling' plasmas matched in density, temperature, beta, ν^*, B_t, I_p, Z_{eff}, and ν_{*e}. Contrary to gyroBohm expectations, the D plasma with smaller ρ_* requires ~30% more heating power to sustain the temperature.

scaling, $\chi_i \propto \chi_B \rho_*^{-0.5\pm0.3}$. Alternately, ρ_* can be varied at constant beta and collisionality simply by comparing D and DT discharges matched in temperature and density (rather than at constant heating power). Such a comparison in supershot plasmas[14] showed that 25% less power was required to sustain the same temperature and density profiles in DT as compared to DD, while ρ_* was about 15% *larger* in DT due to tritium's larger mass.

A similar result is obtained in L-mode plasmas: the T-NBI discharge shown in Fig. 2 with $\sim$12% larger ρ_* required 23% less total heating power (about 35% less power deposited on-axis) to sustain the temperature profile against thermal losses. A simple interpretation of these 'isotope ρ_* scaling' comparisons is that transport decreases with increased ρ_*, and viewed this way they imply $\chi_i \propto \chi_B \rho_*^{-2}$. However this result is incompatible with the Bohm-like ρ_* scaling inferred by varying the magnetic field with a single isotope. The isotope effect on χ_i is in the same direction as, but stronger than, the Goldston-like ρ_* scaling observed in DIII-D L-mode plasmas. In H-mode plasmas the apparent discrepancy is greater: the isotope τ_E scaling observed in the H-mode regime[15] implies a ρ_* scaling which is in the opposite direction to the observed gyroBohm scaling of both ions and electrons in that regime[12]. An alternate interpretation is that increased ion mass has an intrinsic and pronounced effect on transport whose full strength is obscured to some extent by the increased ρ_*.

4. Proposed Mechanism of the Isotope Effect

Figure 3 compares the measured T_i profiles for a pair of D and DT L-mode plamas at fixed heating power to the predictions of the original IFS-PPPL ITG-based transport model[16], and to predictions based on an extended model that includes sheared-flow effects:

$$\chi = \chi_{\text{IFS-PPPL}} \times (1 - \gamma_{ExB}/\gamma_{lin}) \tag{1}$$

where $\gamma_{E\times B}$ is the $E \times B$ shearing rate including general geometry effects[17] and neoclassical corrections to the impurity rotation measure-

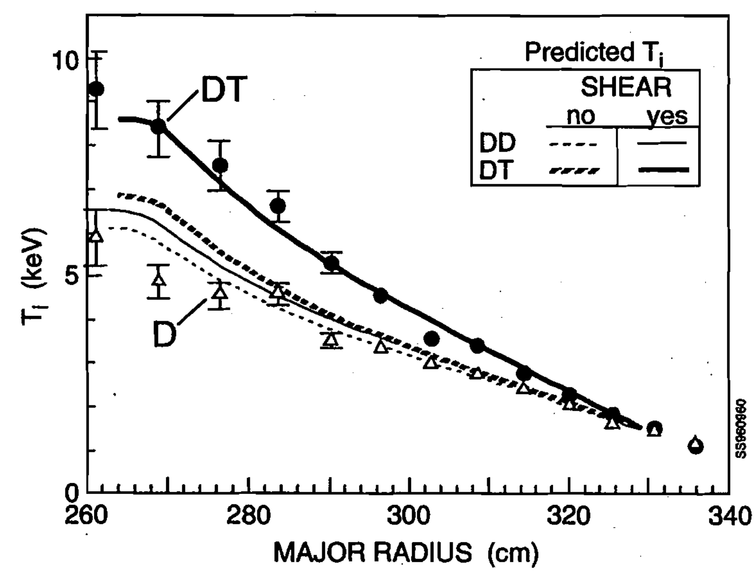

FIG. 3. Measured ion temperature in L-mode plasmas heated with comparable heating power (16.4 MW for D, 17.0 MW for DT) compared with predictions of the IFS–PPPL transport model with and without sheared-flow effects.

ments[18,19]. Here γ_{lin} is an approximate parameterization of the linear ITG growth rate maximized over k_θ. The basic mechanism underlying this shear-flow stabilization model was proposed by Biglari, Diamond, and Terry[20] for H-modes. The prescription of comparing $\gamma_{E\times B}$ with the linear growth rate is suggested by nonlinear ITG simulations[21,22]. As Waltz *et al.* have pointed out, this modified χ formula is of the form $\chi = \chi_{Bohm}\rho_*(1-\alpha\rho_*)$, and thus one can get different ρ_* scalings in various regimes. Formally, the original IFS-PPPL transport model had a pure gyroBohm scaling which would give an unfavorable isotope scaling. This behavior is partially offset by marginal-stability features of the model which yield a fairly strong dependence on the boundary conditions (e.g. for these conditions, $T_i(0) \propto T^{0.4}_{i,r=0.85a}$).

The simulations use the measured density profile and calculated convective loss terms. Measured temperatures at r/a=0.85 were used as boundary conditions. Discrepancies between the predicted and measured temperature near the axis ($r/a \leq 0.15$) may be due to the lack of a sawtooth model in the present simulations. Figure 3 shows that much of the observed isotope effect on T_i can be modelled by the sheared-flow extension of the IFS-PPPL transport model. E_r shear has more stabilizing influence in the tritium shot than in the deuterium shot partly because γ_{lin} scales as v_{ti}/R, so a fixed amount of shearing will be more effective in tritium - because of its slower growth rate - than in deuterium. In this pair of discharges, another contributing factor is a slight mismatch in the net beam torque, with $P_{co}/P_{inj} = 0.50$ for deuterium versus 0.61 for tritium. A more powerful test of the shear-flow physics in the modified IFS-PPPL model is comparison against experimental heating results in TFTR toroidal rotation scans at fixed heating power. Preliminary analysis shows a level of consistency with theory similar to that shown in Fig. 3. Over a wider range of TFTR L-mode plasmas, variations between the transport model and measured temperatures of order 20% are typically obtained, indicating that further refinements are still needed. One known limitation is that the magnitude of $\gamma_{E\times B}/\gamma_{lin}$ needed for stabilization varies by a factor of two in some nonlinear simulations, depending on parallel shear flow destabilization[21] and on other parameters[22] in a way which has not yet been parameterized.

5. L-mode Regime with ICRF Heating

Isotope scaling experiments were also conducted using ICRF heating in the minority hydrogen (H) regime[23] with majority D or DT L-mode plasmas. The minority-H heating regime was chosen because its wave propagation, absorption, and fast-ion physics should remain similar in deuterium or deuterium-tritium plasmas and should provide comparable

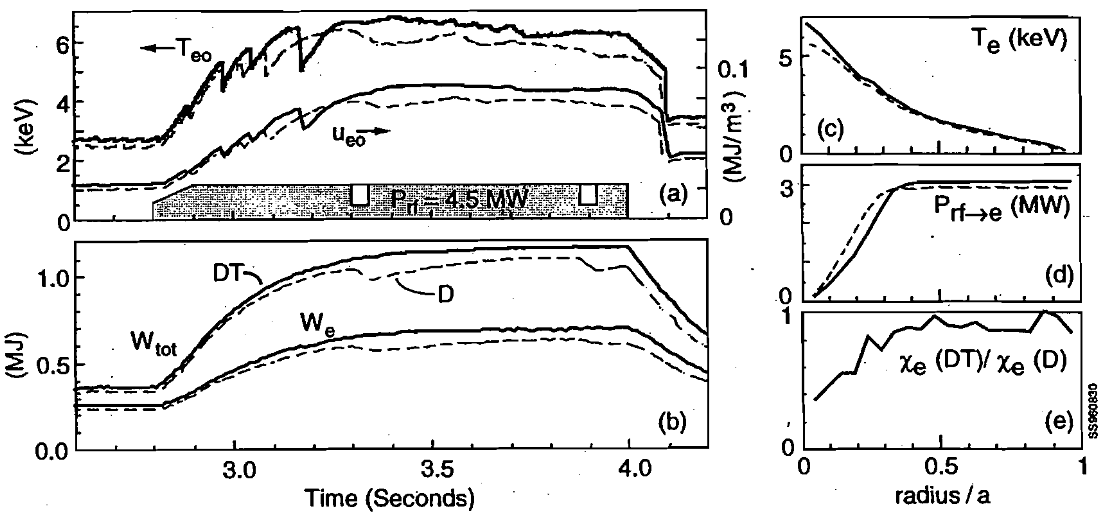

FIG. 4. (a) Central electron temperature measured by ECE and central electron pressure in matched D and DT plasmas with matched density profiles (n_{eo} = 5.9 × 10^{19} m^{-3}) with RF heating. (b) Total plasma energy and total electron energy. (c–e) Electron temperature profile, RF power deposition profile, and ratio of χ_e in the DT discharge to that in the DD discharge.

heating profiles for the two isotopes. These experiments complement the L-mode NBI experiments by avoiding possible effects associated with the isotopic mass of the energetic ion species. For these discharges the limiter was saturated with deuterium or tritium gas in ohmic plasmas similar to the sequence used for the L-mode NBI experiment. The experiments were conducted in moderate density ($\overline{n}_{e19} \approx 4$), broad-profile ($F_{ne}$=1.8) plasmas having roughly equal ion and electron temperatures.

The DT plasma attains 8-12% higher T_{eo}, 2-3% higher n_{eo}, and 10-15% higher central electron pressure (Fig.4). The volume-integrated increase in total electron energy content equals the increase in total plasma energy, suggesting little change in total ion energy content. This result provides clear evidence of a favorable isotope effect on χ_e in L-mode plasmas, which was difficult to demonstrate conclusively in the beam-heating experiments. Direct measurements of the RF-driven energetic H minority ions using a pellet charge-exchange diagnostic indicate that the peak tail temperatures are nearly identical for the D and D-T plasmas at a given RF power level. The tail temperatures are proportional to the RF power input, consistent with the Stix model[23]. Power deposition calculations indicate that virtually all of the RF power is absorbed within $r/a \leq 0.3$ (Fig. 4c) for both isotopes. In the region $r/a \geq 0.3a$, where the power input to the electrons is accurately known, χ_e is 10% lower in the DT plasmas. The kinetic analysis indicates a stronger isotopic effect on χ_e in the core ($r/a \leq 0.3$), although in this region the power deposition profile is more uncertain due to uncertainties in the minority hydrogen density and assumed antenna spectra.

The overall increase in W_{tot} in DT plasmas was 11% for $P_{rf} \leq 3.8$ MW and 8% at 4.5 MW, corresponding to $\tau_E \propto \langle A \rangle^{0.5}$ and $\tau_E \propto \langle A \rangle^{0.35}$ respectively.

6. Ohmic Confinement Scaling

In preparation for the L-mode beam-heating experiments, the inner bumper limiter was saturated with deuterium or tritium gas using a sequence of 3-6 ohmic plasmas with strong gas puffing. Two gas-up sequences were conducted in deuterium (19 ohmic discharges), followed by four sequences in tritium (30 discharges) and a partial change-over to tritium was achieved. Tritium concentration in the limiter influx measured by a Fabry-Perot interferometer [24] was typically ~30% at $\overline{n}_{e19}$=1.8, increasing to 40-45% at $\overline{n}_{e19}$=3.5. Thus these scans varied the plasma isotopic composition from H:D:T = 10:89:1 in the "deuterium" plasmas to 10:45:45 in the higher-density "tritium" plasmas, corresponding to increasing the average plasma mass $\langle A \rangle$ from 1.91 to 2.35.

The electron density profile measured just before sawteeth remained relatively broad throughout the scan, with F_{ne} varying over the range 1.3-1.7 and reaching a local maximum at about $\overline{n}_{e19}$=2.5. Similar trends

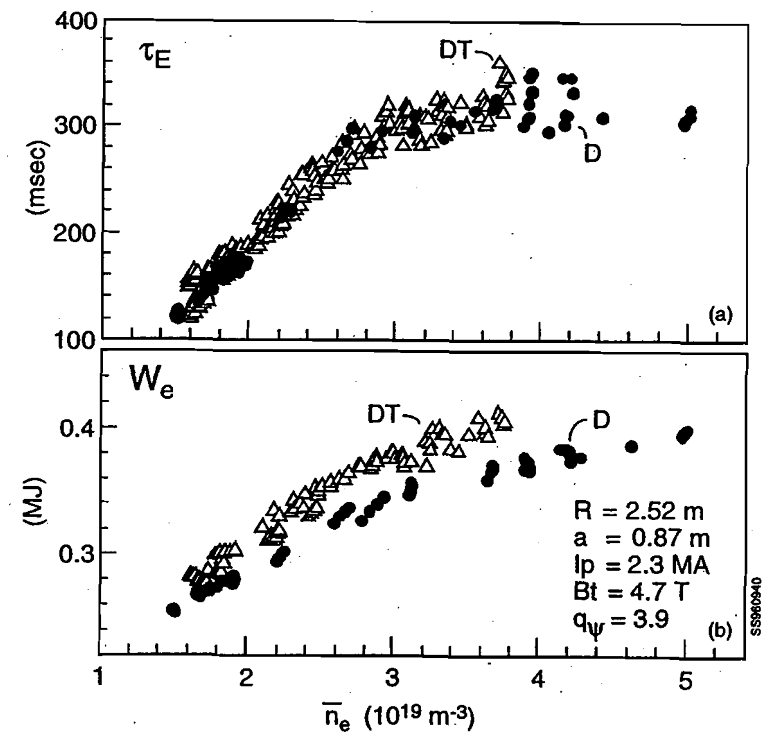

FIG. 5. (a) Global energy confinement time in ohmic D versus DT plasmas measured by magnetic diagnostics. (b) Total electron energy content from ECE T_e and interferometer n_e diagnostics.

in the density profile shape were observed previously in ohmic experiments comparing hydrogen to deuterium [25]. Z_{eff} inferred from visible bremsstrahlung decreased from 3.0 at low density to 1.3 at high density in deuterium. Central parameters ranged from $n_{eo} = 2 - 5 \times 10^{19}$ m^{-3}; $T_{eo} = 2.2 - 4.5$ keV; and $T_{io} \approx 2$ keV, independent of density, was inferred from neutron emission.

The radiated power fraction in deuterium followed the usual trend in ohmic plasmas, increasing from 30% at low density to 50% at high density. Both visible-bremsstrahlung emission and radiated power fraction were consistently higher in the tritium plasmas compared to deuterium plasmas at the same $\overline{n}_e$, with VB emission being about 11% higher, and the radiated power fraction about 15% higher (i.e. 58% vs 50% at high density). Total hydrogenic influx was about 25% less in the DT ohmic plasmas compared to D plasmas at the same $\overline{n}_e$ or edge density. A similar isotopic effect on radiated power and edge influx was also observed in previous TFTR ohmic experiments comparing ohmic hydrogen to deuterium[25] and in ASDEX[26].

Figure 5 shows the variation of global energy confinement time with $\overline{n}_e$ for deuterium and tritium. There is no observable difference in global τ_E between the two isotopes in ohmic plasmas. Statistical analysis indicates a ratio of τ_E^T/τ_E^D of 1.01 ± 0.05 at the low-density end ($\overline{n}_{e19}$=2.0-3.5), and a ratio of 1.02 ± 0.07 at the high-density end ($\overline{n}_{e19}$=3.5-5.0). A similar analysis of the total plasma energy also shows no isotope effect, with $W_{tot}^T/W_{tot}^D = 0.98 \pm 0.04$. The 1σ variation in deuterium τ_E for fixed density in this dataset is only 4%, so if the scaling $\tau_E \propto \langle A \rangle^{0.5}$ had been obeyed in this experiment, it should have been possible to resolve the "expected" increase of $\sqrt{1.23} = 11\%$. A less than 1% isotope effect on τ_E and W_{tot} was observed in the ohmic phase preceding the start of beam injection in the L-mode studies ($\overline{n}_{e19}$=1.6-3.3), which had a 1σ variation of about 4% for each species at fixed density. Previous studies of ohmic confinement in TFTR found $\leq 10\%$ higher τ_E in deuterium compared to hydrogen in the high-density saturated regime[25], however this difference was less than the variability in performance among various deuterium density scans.

Despite the absence of an isotope effect on global τ_E, there does appear to be a clear improvement in *electron energy* confinement. The core electron pressure is $10 \pm 4\%$ higher in the tritium plasmas for the same $\overline{n}_e$. As shown in Fig. 5b, the total stored electron energy, W_e, is $11 \pm 2\%$ larger in tritium at high density ($\overline{n}_{e19} \geq 2.5$), and the ratio of W_e to ohmic heating power is $17 \pm 6\%$ larger. The constancy of W_{tot} measured by the magnetic diagnostics in DT versus D plasmas, coupled with the increased W_e measured kinetically, implies that total ion energy must have decreased in tritium. Part of this decrease may be attributed to increased dilution in the tritium plasmas; Z_{eff} is 0.2 higher in tritium at high density and 0.1-0.7 higher at low density, corresponding to a change in dilution ($\Delta n_i/n_e$) of

8% at low density and 4% at high density. Lacking measured T_i profile measurements in the ohmic plasmas, we cannot determine whether local χ_i changed between D and DT ohmic plasmas.

7. High ℓ_i Regime

The "high-ℓ_i" plasma regime is created by a special plasma growth technique in the ohmic phase to increase the central current density followed by strong beam injection[6], and has density and temperature profile

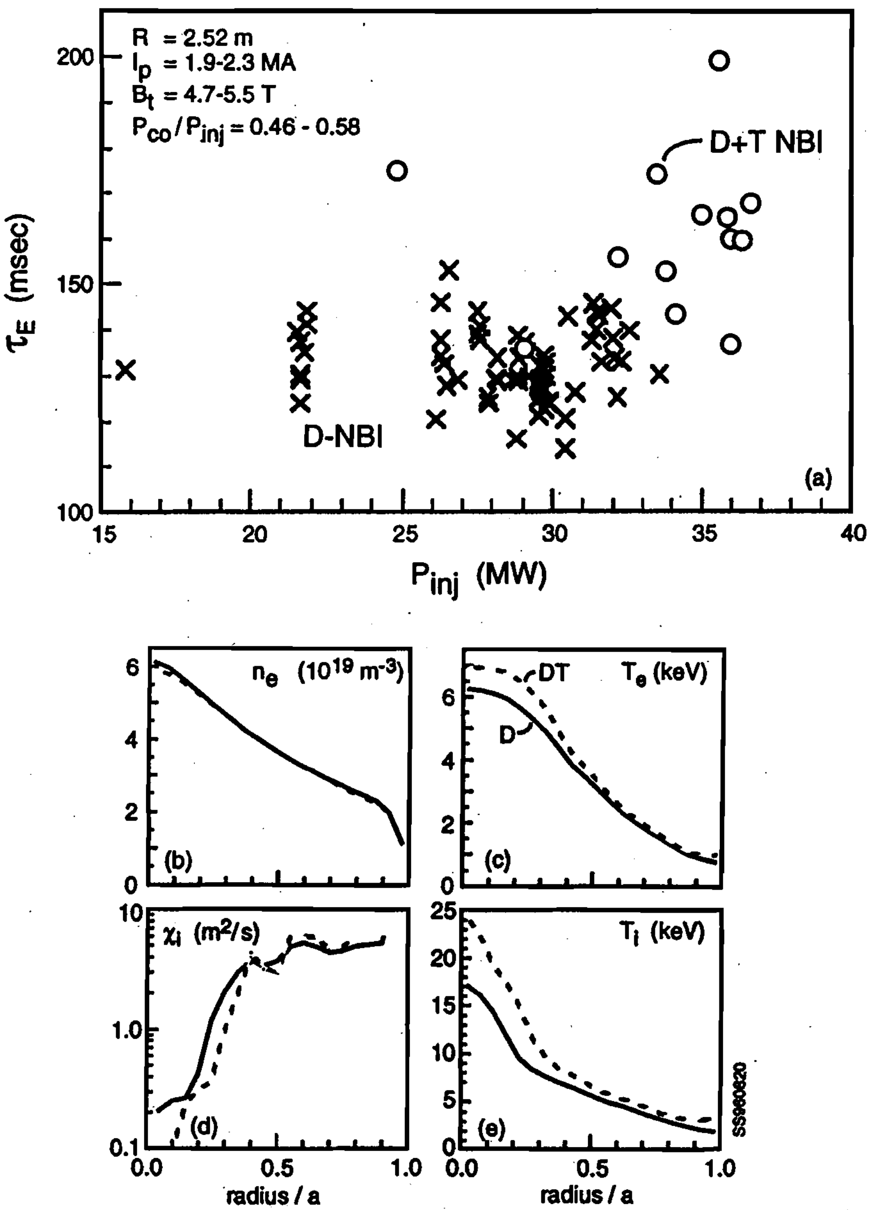

FIG. 6. (a) Energy confinement time at time of peak stored energy in the high-ℓ_i regime. Plasma conditions were $R = 2.52$ m, $I_p = 2.25$ MA, $B_t = 5.1$ T, $q_\psi = 4.3$, and $P_{co}/P_{inj} = 0.48$. (b–e) Measured density and temperature profiles and inferred χ_i for matched D and DT plasmas with $P_{inj} = 26$–29 MW.

shapes similar to supershots. A strong isotope effect has been observed in the high-ℓ_i regime: it occurs in high ℓ_i plasmas as a 20% increase in global τ_E, a 15% increase in central T_e, and a 40% increase in central T_i. For the comparison shown in Fig. 6, the density profiles are almost identical while the central ion temperature increases from 17 to 24 keV in the DT discharge, indicating significantly improved core ion confinement. Kinetic transport analysis by the TRANSP code indicates that χ_i is reduced 30-50% in the DT plasma over the core region $r/a \leq 0.35$. These features are similar to the isotope effect observed in supershot plasmas.

8. Reverse-Shear Regime

By contrast, there appears to be little or no isotope effect on confinement in plasmas with a reverse-shear q-profile (RS), at least as measured by global stored energy and τ_E. This is surprising, since the plasma conditions prevalent in RS plasmas are qualitatively similar to supershot plasmas: the density profile is peaked ($F_{ne} > 2$), and the central temperatures are high with $T_{io} > 20$ keV and $T_i/T_e \approx 3$.

Figure 7 plots the total stored energy as a function of heating power for RS plasmas heated with either pure D-NBI or mostly T-NBI. The 'NBI

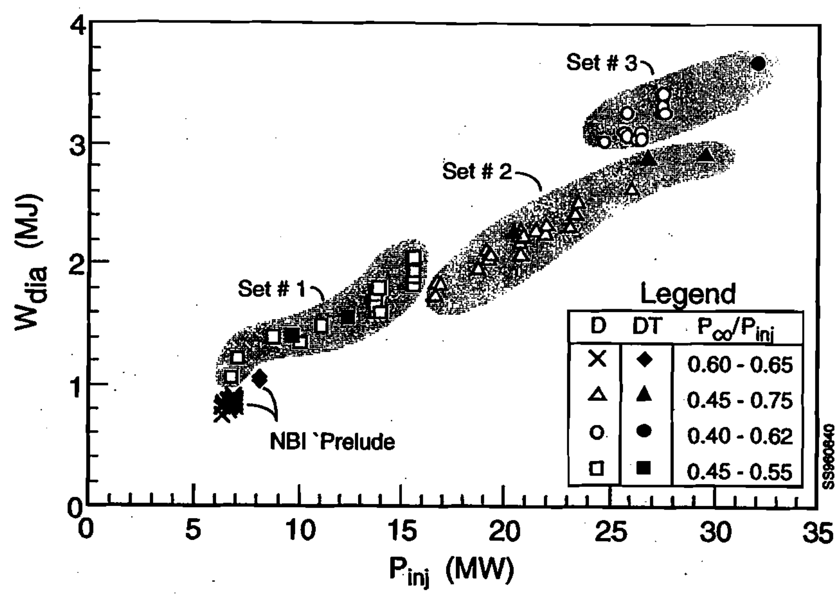

FIG. 7. Diamagnetic stored energy as a function of heating power in reverse-shear plasmas without an ERS transport barrier. All shots have $I_p = 1.6$ MA, $B_t = 4.6$ T, $R = 2.59$ m, with identical plasma growth and neutral beam 'prelude' [7] prior to the start of high-power beam heating. For the DT plasmas, the fraction of beam power in tritium is 100% for the 'NBI-prelude' discharges, 50–70% for Set 1, 60–100% for Set 2, and 55% for Set 3.

prelude' data points represent performance at the end of the beam prelude, when plasma conditions have reached thermal equilibrium. Set 1 comprises measurements taken 375 ms after the *end* of the high-power heating phase, during a 'postlude' of lower beam power. At this time, the plasma conditions are also nearly stationary. The higher-power data sets #2 and #3 represent measurements 275 ms and 325 ms, respectively, after the start of high-power injection, when the plasma conditions are still evolving rapidly but before any ERS transitions have occurred. There is no evidence for a significant isotope effect on confinement at *any* power in Fig. 7. Small increases in the total plasma energy during the first 100-200 ms of high-power beam heating in RS plasmas have been observed between D-NBI and T-NBI (see Fig. 9), but the plasma is strongly dominated by beam ions at that time, with $W_{beam}/W_{tot} \approx 0.7$.

The absence of an isotope effect on τ_E for RS plasmas is interesting primarily because it represents a challenge to proposed mechanisms of isotope effect in L-mode and supershot plasmas. It suggests that the q-profile or magnetic shear may be involved in the physics underlying the isotope effect.

9. Enhanced Reverse-Shear Regime

The absence of an isotope effect on confinement in reverse-shear plasmas appears to persist in plasmas which experience a transition to the enhanced reverse shear regime[7]. Figure 8 compares three identically prepared plasmas with reverse-shear q-profiles. Two of the shots had pure D-NBI throughout the discharge. The third had T-NBI+D-NBI in the ratio 3:1 during the high-power phase, then pure T-NBI during the reduced-power 'postlude' phase, when the plasma reached transport equilibrium. All three of the discharges experience an ERS transition early in the period of high-power beam injection, at about ~1.6 seconds, which persisted throughout the entire postlude phase. There is some difference in the total stored energy during the high-power phase owing to differences in heating power and onset time of the ERS transition. However in the postlude where all the plasmas have the same heating power (14.2 ± 0.1 MW), total stored energy is very similar and τ_E measured by magnetic diagnostics is virtually identical between the D and DT plasmas. The core tritium concentration in the T-NBI plasma calculated by TRANSP using particle transport models developed for supershot plasmas is approximately 40%. This tritium concentration would overpredict the measured DT neutron emission. A tritium concentration of $\geq$70% is implied by the measured DT neutron emission in the postlude.

Figure 8(c-e) shows the kinetic profiles obtained late in the postlude period. No significant differences are apparent in either the density or

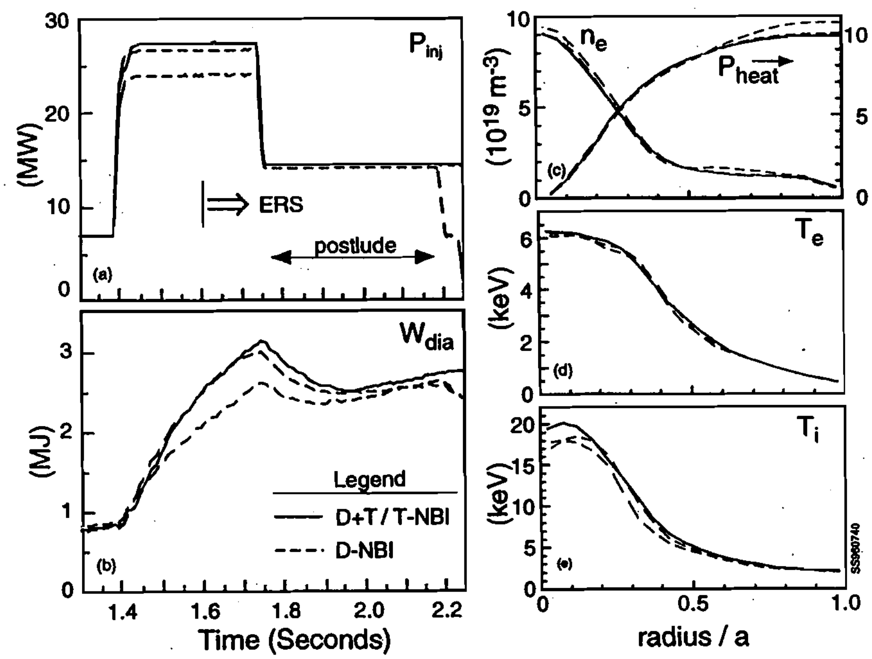

FIG. 8. (a, b) Time history of heating power and plasma energy in ERS plasmas heated with D-NBI versus T-NBI. ERS transition occurs at ~1.6 s and is sustained throughout the low-power postlude. (c–e) Profile measurements and heat deposition profile for the discharges at 2.15 s, when plasmas are nearly stationary.

temperature profiles. Since the heating profiles were also similar for these discharges, we infer that local transport is not materially changed by isotope in these plasmas. As is typical of the ERS regime, core ion energy confinement is very good in these plasmas, and it might be difficult to observe a further improvement due to isotope. The profiles do clearly indicate that the location of the transport barrier is the same between deuterium and tritium.

10. Isotope Scaling of the ERS Transition

In contrast to the negligible effect of isotope on energy confinement in ERS plasmas, there does appear to be a systematic trend in the conditions required to trigger an ERS transition. Under otherwise comparable conditions ERS transitions are reliably obtained at lower power in D-NBI than in T-NBI. Figure 9 plots the total plasma energy at 175 ms into the period of high-power heating and identifies plasmas which experience an ERS transition as a function of heating power with D-NBI versus T-NBI. The ensemble of plasmas illustrated in Fig. 9 was prepared with identical plasma-growth waveforms to produce a reverse-shear q-profile,

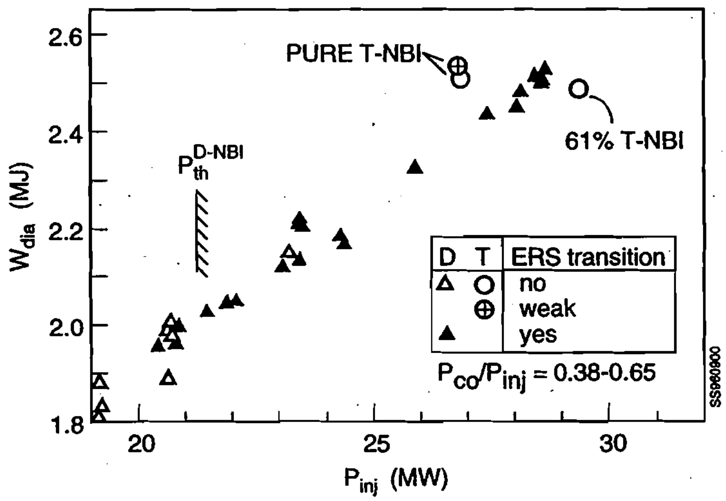

FIG. 9. Plasma stored energy as a function of beam power 175 ms after start of high power NBI in plasmas with a reverse-shear q-profile, shortly before transitions to ERS in the D-NBI plasmas. P_{th} is the threshold power for reliably obtaining an ERS transition.

near-balanced injection, similar limiter conditions, and the same timing of 'prelude' and high power neutral beams. ERS transitions were infrequent below 21 MW with D-NBI under these conditions but were reliably obtained above 23 MW. By comparison, a plasma with pure T-NBI at 27 MW had no ERS transition, another at the same power experienced a transition to ERS that was sustained for less than 200 ms. A third attempt with mixed 39%D-NBI and 61%T-NBI at a power level of 29 MW also failed to experience an ERS transition. The T-NBI plasmas fail to experience a transition despite having stored energy comparable to their companion D-NBI plasmas which do go into ERS. This behavior differs from the behavior in TFTR limiter H-modes, for which the H-mode threshold power appears insensitive to isotope[3].

By commencing high-power beam heating somewhat earlier in the plasma-growth startup, at 1.4 seconds versus the 1.7 seconds for the dataset considered above, robust and sustained ERS transitions were obtained with tritium beam concentrations up to 50-70% at power levels of 26-27 MW. Under these conditions the ERS power threshold with D-NBI was about 19 MW. Partial tritium injection with total power below 25 MW was not attempted.

The increased power threshold with T-NBI represents a useful test of proposed theories of the ERS transition mechanism based on shear-flow stabilization of microturbulence[27,28]. As shown in Fig. 10, the temperature and density profiles in the T-NBI shots do not differ markedly from the range of profiles obtained in the D-NBI plasmas, yet the D-NBI plasmas undergo a transition to ERS while the T-NBI plasmas do not. There is a tendency for slightly higher central carbon-ion temperature and higher ∇v_ϕ

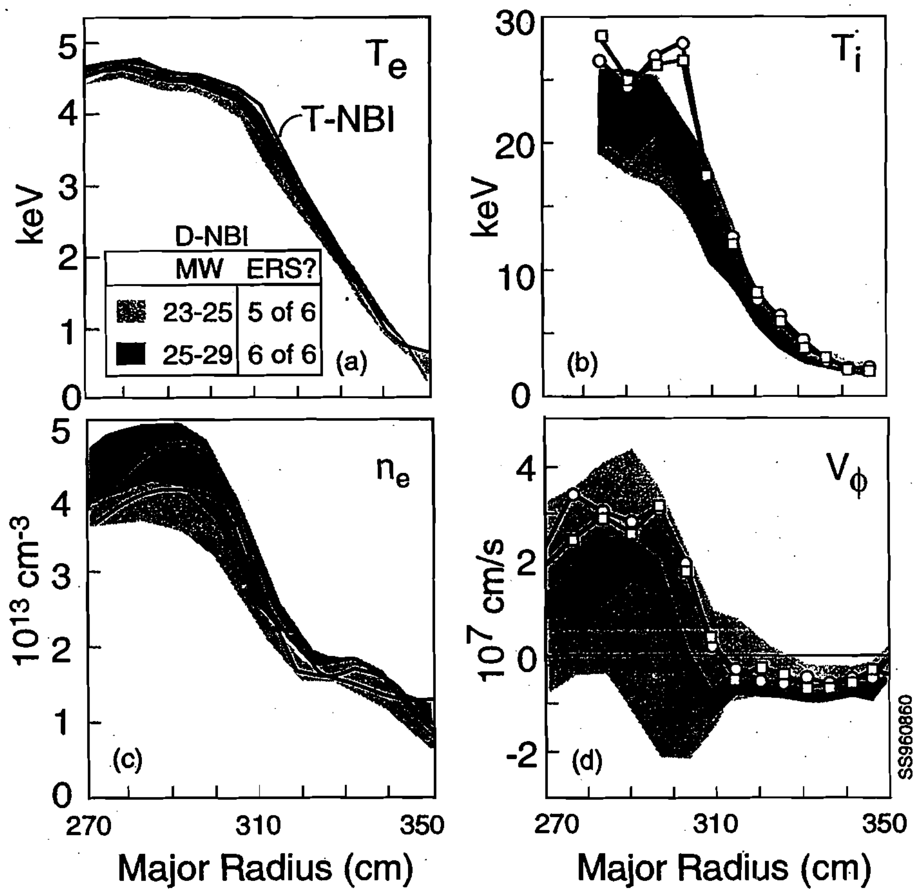

FIG. 10. Kinetic profiles for the discharges in Fig. 9. D-NBI data at 23–25 MW include two co-dominated shots (P_{co}/P_{inj} = 0.65) which experienced an ERS transition. Shaded regions represent range of variability in D-NBI profiles. The T-NBI plasmas with 27 MW experienced no or only weak ERS transitions.

in the T-NBI plasmas. Detailed shear-flow and growth-rate calculations are in progress to assess whether subtle differences in profile shapes could be reducing the E_r shear in the T-NBI discharges and thereby increasing the power threshold as predicted by theory.

11. Discussion

The TFTR experiments reported here comparing performance in deuterium versus deuterium-tritium operation have confirmed a favorable isotope effect on τ_E in a variety of plasma regimes, including regimes which at least superficially resemble proposed ITER plasmas: broad density profiles having $T_i \approx T_e$ with significant electron heating. On a purely empirical basis, these experiments provide experimental support for the ITER design assumption that τ_E will be larger in DT than D plasmas by a factor of order $\tau_E \propto \langle A \rangle^{0.5}$. Projections of the isotope effect to ITER would be less favorable if isotope scaling is indeed caused by sheared-flow effects, which get weaker in a large plasma. It is intriguing - and perhaps suggestive - that in both the L-mode and supershot regimes the isotope effect appears to be strongest at high heating power and high temperature. In this regard it is interesting to note that the maximum τ_E attained in quasi-stationary conditions (at the time of peak stored energy) in *any* deuterium plasma in TFTR is about 220 ms, whereas a confinement time of 330 ms, an increase of 50%, has been obtained with pure tritium-beam injection in a supershot plasma with a limiter well-conditioned with lithium pellets which attained a central ion temperature in excess of 40 keV.

But the TFTR experience has also confirmed the perplexing variability of the isotope effect that has been reported previously in other tokamaks: its strength appears to be sensitive to plasma conditions. The complete absence of an isotope effect on global τ_E in ohmic D versus DT plasmas is particularly surprising, in view of extensive studies on many other tokamaks which clearly demonstrate improved confinement in deuterium compared to hydrogen. The apparent absence of an isotope effect in reverse shear plasmas is also puzzling, given the overall similarity of the temperature and density profiles to supershot and high-ℓ_i plasmas, for which a strong isotope effect is observed. This trend suggests that the isotope effect is affected by the shape of the current profile, and represents a challenge for theoretical models of the isotope effect. Similarly, the larger heating power required to initiate an ERS transition in reverse-shear plasmas when heating with tritium beams should provide a potentially useful test of proposed models of the transition dynamics.

Identifying ρ_* scans from the L-mode and supershot isotope-scaling experiments which match all conditions except ρ_*, by varying the plasma isotope and heating power, clearly indicate improved confinement in the plasmas with larger ρ_*. This result fundamentally contradicts the scaling of transport with ρ_* observed by varying the magnetic field. Accepting the validity of the underlying Bohm or gyroBohm character of ρ_* scaling - since among other reasons it is roughly consistent with observed global τ_E scaling - one is led to conclude that the isotope effect must be governed by a fairly powerful, non-gyroBohm mechanism that leads to reduced transport for heavier isotopes *despite* their larger gyroradius. The proposed theoretical model of shear-flow modifications to ion-temperature-gradient turbulence, as embodied in the IFS-PPPL transport code, embodies such an intrinsic isotope effect through the ratio of linear growth rate to E_r shearing rate. Quantitatively, it reproduces the observed isotope effect in L-mode plasmas reasonably well. Interestingly, the model suggests that E_r-shear may affect transport scaling even in the L-mode regime, extending well beyond its previously appreciated role in controlling transport in enhanced confinement regimes such as H-modes, VH-modes and ERS plasmas.

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DISCUSSION

K. LACKNER: How does your experience with hydrogen plasmas fit into your observations with deuterium and tritium?

S.D. SCOTT: Confinement scaling has been studied in NBI heated hydrogen versus deuterium L mode plasmas using deuterium beam injection of up to 6 MW (see Ref. [25]). Compared with the hydrogen plasmas, the deuterium plasmas achieve 20% higher total stored energy and 10% higher thermal energy, with most of the difference arising in the electron energy content. This represents a somewhat stronger isotope effect than observed in deuterium versus tritium L mode plasmas at comparable heating power.

G. BATEMAN: One of the explanations for the decrease of χ_i with increasing isotope mass has to do with the effect of impurities on ITG modes. Was there any change in the impurity profile in reversed shear discharges as the hydrogen isotope was changed?

S.D. SCOTT: The average Z_{eff} deduced from single-chord bremsstrahlung measurements is similar in deuterium and tritium reversed shear plasmas. Analysis of the radial profile of the impurity content is in progress.