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Scaling of Confinement with Isotopic Content in Deuterium and Tritium Plasmas

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The scaling of the electron thermal diffusivity, χ_e, with relative gyro radius, ρ_*, has been measured on TFTR by comparing nearly identical ICRF-heated discharges which differ only in hydrogenic isotopic content. Contrary to the gyro-Bohm scaling ($\chi_e \sim \chi_B \rho_*$, where χ_B is the Bohm diffusivity) observed on DIII-D when ρ_* was varied through a scan of magnetic field strength, χ_e is found to scale inversely with ρ_*. Hence, global energy confinement is 8-11% higher in deuterium-tritium plasmas than in deuterium only plasmas, with the higher stored energy attributed almost entirely to the electrons.

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One of the most critical issues in fusion energy research is the development of a theoretical understanding of the anomalous cross-field energy transport in magnetically confined plasmas. A particularly important consideration regarding the performance of future reactor grade plasmas composed primarily of deuterium (D) and tritium (T) is the dependence of this transport on the hydrogenic isotope mass. Based on the fundamental assumption that transport depends only on local quantities and is driven by micro-instabilities arising from local density and temperature gradients, Kadomtsev [1] proposed that the cross-field diffusivity in tokamaks should increase in plasmas composed of heavier ions, based on the premise that the diffusive step-size of the turbulent transport scales like the gyro radius, ρ. This widely accepted paradigm, referred to as "gyro-Bohm scaling" [2], suggests that $\chi \sim \chi_B \rho_*$, where $\chi_B = cT_e/eB$, $\rho_* = \rho / a$, a is the plasma minor radius, T_e is the electron temperature and B is the magnetic field strength. If this scaling is correct, then global energy confinement, which is inversely proportional to the average local diffusivity, should decrease as isotopic mass increases. Though direct measurements of the electron diffusivity in dimensionally similar plasmas on DIII-D are consistent with the gyro-Bohm model [3,4], measurements on JET [5] and TFTR[2] indicate that the effective total thermal diffusivity is Bohm-like, i.e., independent of ρ_*. Previous experiments comparing global energy confinement in hydrogen and deuterium plasmas, heated either ohmically or with auxiliary heating such as neutral beam injection (NBI) or electromagnetic wave - particle interactions, in general display an increase in the global energy confinement with increasing isotopic mass, though the magnitude depends on operating regime and device [6]. However, isotope scaling experiments utilizing NBI are subject to uncertainties arising from differences in the beam stored energy content and related power deposition profiles, both of which depend on the beam and background ion species [7,8]. In a similar vein, the analysis of previous isotope scaling experiments in hydrogen and deuterium plasmas heated with electromagnetic waves is subject to large uncertainties because the chosen heating scenario, and, therefore, the power deposition characteristics, differ significantly depending on the majority isotope under consideration [6]. More recently, experiments comparing global and local energy confinement in D and mixed D-T plasmas in the hot ion NBI-driven supershot regime in the Tokamak Fusion Test Reactor (TFTR) [7] have also shown a strong enhancement of confinement with increasing isotopic mass.

In this Letter we report the results of isotope scaling experiments on TFTR in D and D-T gas-fueled plasmas with nearly identical target plasma parameters and with nearly identical auxiliary heating provided with ICRF waves in the minority-hydrogen

(H) cyclotron absorption regime [9]. We note that the minority-H regime is unchanged for practical purposes in switching from D majority to D-T majority plasmas. In addition, momentum input to the plasma by the ICRF waves is known to be insignificant in this regime [10], particularly in comparison to the momentum input in plasmas driven with unbalanced NBI. The resulting TFTR discharges feature broad density and temperature profiles with roughly equal ion and electron temperatures, and hence are relevant to plasmas predicted for the next generation of fusion devices such as the International Thermonuclear Experimental Reactor (ITER). An enhancement in the energy confinement time in the range of 8-11% has been observed in D-T plasmas relative to the D plasmas. The corresponding increase in the plasma stored energy occurs almost exclusively in the electron channel. Because the plasmas are otherwise nearly identical, the confinement enhancement can be unambiguously ascribed to the change in the isotopic mass, or equivalently, to changes in ρ_* . These experiments indicate that χ_e scales inversely with ρ_*, in contrast with the scaling inferred from measurements in dimensional similar discharges on DIII-D [3,4] with fixed isotopic content.

The experiment consisted of two series of similar discharges, the first in D and the second in D-T plasmas in which the applied ICRF power was varied up to the maximum available of about 5 MW. Prior to each series, the limiter was saturated with either D or T, depending on the desired isotopic content. For these plasmas, the major radius, R_0, was 2.62 m, the minor radius, a, was 0.95m, and the plasma current, I_p, was 1.8 MA. In the chosen minority-H heating scenario, the ICRF waves are directly absorbed by the dilute hydrogen species present in roughly the same amount in both plasmas due to wall recycling processes. With a toroidal magnetic field, B_{T0}, at R_0 approximately equal to 4.5 T, the ICRF waves at 63.6 MHz were resonant with H near the Shafranov-shifted magnetic axis of the discharges. As a result of the high power wave absorption by the dilute H population, the minority-H ions are accelerated to energies well in excess of the critical energy, E_c, at which the fast ions would lose energy equally to bulk ions and electrons via collisions. Since E_c is only weakly dependent on the mass of the bulk ions ($E_c \leq 65$ keV / 50 keV for the D / DT plasmas with $T_{e0} \leq 7$ keV), the energetic H-tail ions slow down primarily on electrons, leading to negligible differences in the net power deposition and in the volume-integrated tail ion energy content between the D and D-T plasmas. It is well-known that MHD activity, such as sawtooth oscillations [10] and toroidal Alfven eigenmodes (TAE) [11,12] can significantly affect ICRF power deposition. To avoid these complications, the data set was chosen with the ICRF power sufficiently high, $P_{RF} \geq 3$ MW, to suppress sawtooth oscillations. At the highest ICRF powers used, $P_{RF} \leq 4.8$ MW, the TAE modes were only marginally excited. As an aside, we note that there was no significant difference in the power required for onset of the TAE between the D and the D-T plasmas, but that sawtooth stabilization was somewhat more difficult to achieve in the D-T plasmas.

Gas feedback was used to obtain a set of discharges with central electron densities, $n_e(0)$, of about 5.8×10^{13} cm^{-3}, within approximately ±3%. According to visible bremsstrahlung measurements, the effective ionic charge, Z_{eff}, in these plasmas varied between 1.7 and 1.9, with a carbon impurity content of 2 - 3% relative to n_e. Based on spectroscopic measurements of the H_α, D_α, and T_α emission lines [13], the H concentration, relative to the total density of hydrogenic ions, was approximately 12% ± 3% in the D plasmas and 7% ± 3% in the D-T plasmas. By combining the Z_{eff} values with the measured relative hydrogenic ratios in the kinetic calculations discussed later in this paper, the absolute hydrogen concentration relative to the electron density was inferred to be about 8% in the D only shots and 5% in the DT shots. It is interesting to note that the ratio of H_α to D_α emission remained nearly constant at ~12% over the entire set of discharges. Reasons for the relative constancy of this ratio in both D and DT plasmas are being explored and will be discussed elsewhere. The T concentrations, measured by the same methods, were less than 2% in the D discharges and were in the range of 45% ± 5% in the D-T discharges.

A reproducible increase in the plasma stored energy in the range of 8-11% was observed between matched pairs of D and D-T discharges, as shown in Fig. 1 for plasmas heated with 3.1 and 4.5 MW of ICRF power. [The transient drops in the stored energy for the 4.5 MW D-only discharge at t ≈3.3 and 3.9 s were due to brief interruptions in the applied ICRF power.] Within either the set of D only or DT discharges, the shot to shot variability in the total stored energy for a given ICRF power level was about 3-4 % or less. Comparison of the time evolution of the total measured plasma stored energy, W_{tot}, and the total electron stored energy, W_e, calculated with the TRANSP code [14] from the volume integrated product of the measured electron density and temperature profiles, demonstrates clearly that the increase in the stored energy occurs almost exclusively in the electron channel, as shown in Fig. 2. We note that in previous isotope scaling experiments in beam-heated discharges, the enhanced energy content of the plasma was observed primarily in the ion channel [7,8] as opposed to the electron channel. The enhanced energy confinement is maintained throughout the ICRF heating pulse, which extended over more than 4 energy confinement times. Time independent kinetic analysis of these discharges, assuming that the ion thermal diffusivity, χ_i, is equal to χ_e was performed at t = 3.8 s using the SNAP analysis code [15] in order to check the data for self-consistency. The calculated total stored energy exceeded the measurement by between

160 - 200 kJ in all of the analyzed discharges, where the uncertainty in the measurement is about ±130kJ. Nevertheless, the relative difference in the calculated stored energy content between the D and D-T discharges is similar to the measured difference for all of the discharges considered. The calculated neutron yields on the DT discharges agreed with the measurements to within the ±16% experimental uncertainty. Deuterium neutral beam pulses lasting for about 100 ms were applied at the end of the ICRF pulse (t ~ 3.9 s) on selected discharges to measure the ion temperature profiles. For $r/a \geq 0.2$, there was no discernible change in the measured T_i profiles between the D and DT plasmas, within the error bars of ± 200 eV. Within $r/a \leq 0.2$, however, the data is less certain but is consistent with model estimates for $T_i(0)$ of about 3.5 keV for these discharges. Kinetic analysis of these discharges using the measured Ti profiles also indicates that χ_e is reduced in the discharges with the larger effective isotopic mass.

In order to verify experimentally that there were no significant changes in the ICRF power deposition which could distort any observed isotope effect, the total H-tail stored energy was monitored with the magnetic diagnostics. In addition, the peak H-tail temperature was measured on selected pairs of shots by injecting a lithium pellet and measuring the charge-exchange spectra with the Pellet Charge Exchange (PCX) diagnostic [16]. As shown in Fig. 3, for the same discharges treated in Fig. 1, the excess perpendicular stored energy associated with the presence of the H-tail ions is unchanged at a given ICRF power level between the D and D-T discharges. The H-tail stored energies calculated in the kinetic analysis discussed above are well within the ±50kJ uncertainty range of the measurement, which is derived from the difference between the total (parallel plus transverse) stored energy and the total transverse stored energy. According to the PCX data, for the 4.5 MW pair of shots, the H-tail temperature was about 205 keV ± 10% in the D discharge and about 195 keV ± 10% in the DT discharge. The H-tail temperatures inferred from ICRF models in the kinetic analyses discussed previously were 186 keV and 195 keV, respectively, for these two discharges. A measurement of the H- tail temperature is not available for the D-only shot at 3.1 MW. However, the measured H-tail temperature of 132 keV ± 10% in the 3.1 MW D-T discharge agrees well with the kinetically inferred value of 142 keV. For comparison, the calculated H-tail temperature in the companion D-only shot was 143 keV. Changes in the calculated ICRF power deposition profile to the electrons were minimal between the D and D-T discharges, to within the accuracy of the models, as shown in Fig. 4. The small differences shown are on the same order as variations in the inferred deposition profiles that can arise from uncertainties in the H concentration or in the assumed antenna spectrum, for example. The observed differences in the core region, if real, would imply an even more favorable isotope effect on electron transport than is inferred elsewhere in this paper.

The isotopic scaling of global τ_E decreases with ICRF power, ranging from $\tau_E^{0.5}$ to $\tau_E^{0.35}$ as the ICRF power is raised from 3.1 to 4.5 MW, respectively, as shown in Fig. 5 for the entire set of discharges. The source of the apparent decrease in the enhancement with A at the higher power levels can not be ascertained from this limited data set.

In summary, a positive enhancement in the total plasma stored energy has been observed in ICRF- heated D and D-T plasmas with broad density profiles, with $T_i \sim T_e$, and with negligible toroidal rotation that can be unambiguously ascribed to differences in the average isotopic mass content of the discharges. The increase in the plasma stored energy occurs almost exclusively in the electron channel, indicating a decrease in electron transport with an increase in the effective isotopic mass of the plasma. This observation is at variance with the predictions of gyro-Bohm transport models and with previous measurements of χ_e on the DIII-D [3,4] in which a gyro-Bohm-like scaling $[\chi_e \sim \chi_B \rho_*]$ for electrons was observed. The data presented here is consistent with $\chi_e \sim \rho_*^{-1} \sim A^{-0.5}$. Theoretical models based on micro turbulence use the ansatz that $\chi \sim \gamma \Delta_r^2$ where γ is the growth rate of the dominant micro instability and Δ_r is the relevant radial correlation length of the turbulence [1,2]. Recent studies [17,18,19] of multi-ion plasmas find growth rates for ion temperature gradient modes (ITG modes) which decrease as the effective isotopic mass in the plasma increases. By arguing that Δ_r is independent of ρ [19], one can derive an electron diffusivity which scales like $A^{-0.5}$. However, experimental measurements of the dependence of Δ_r on the isotopic mass of the plasma in L-mode plasmas have yet to be conducted, and those in the supershot regime are not yet conclusive [20,21]. In order to resolve the discrepancy between the results for χ_e scaling obtained in dimensionally similar plasmas and in plasmas which differ only in their isotopic mass content, detailed experimental diagnosis of the relationship between plasma transport and the properties of the micro turbulence present in the plasma should be conducted. Such measurements, when combined with further extensions of the theoretical models, may lead to a better understanding of the fundamental properties of energy transport in magnetically confined plasmas.

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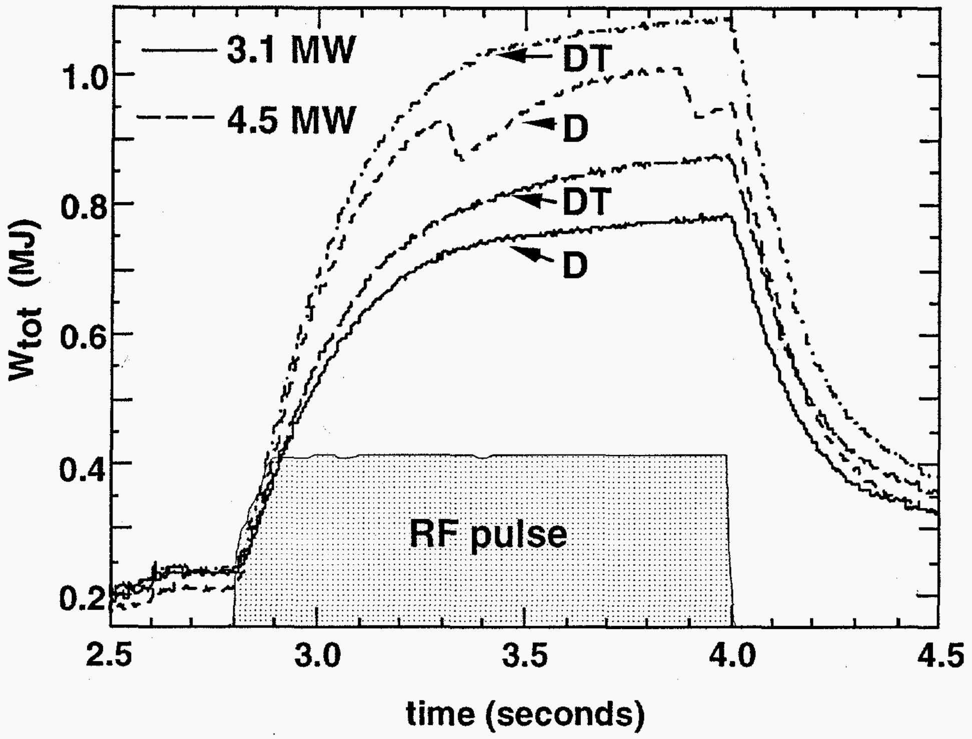

Fig. 1. Total plasma stored energy for D and DT plasmas heated with 3.1 and 4.5 MW of ICRF power. The transient drops in W_{tot} at t ≈ 3.3 and 3.9 s are due to momentary interruptions in the applied ICRF power.

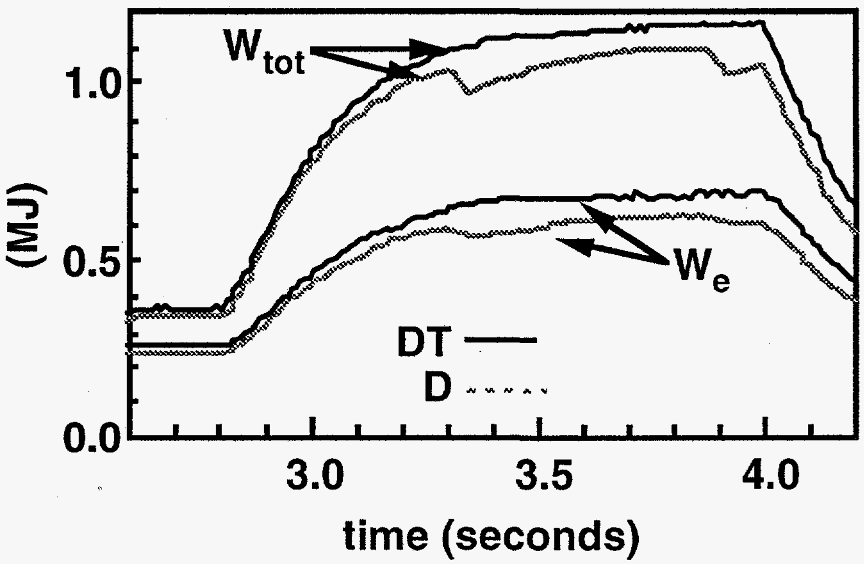

Fig. 2 . Time evolution of the total stored energy and electron stored energy in D and DT plasmas heated with 4.5 MW of ICRF power.

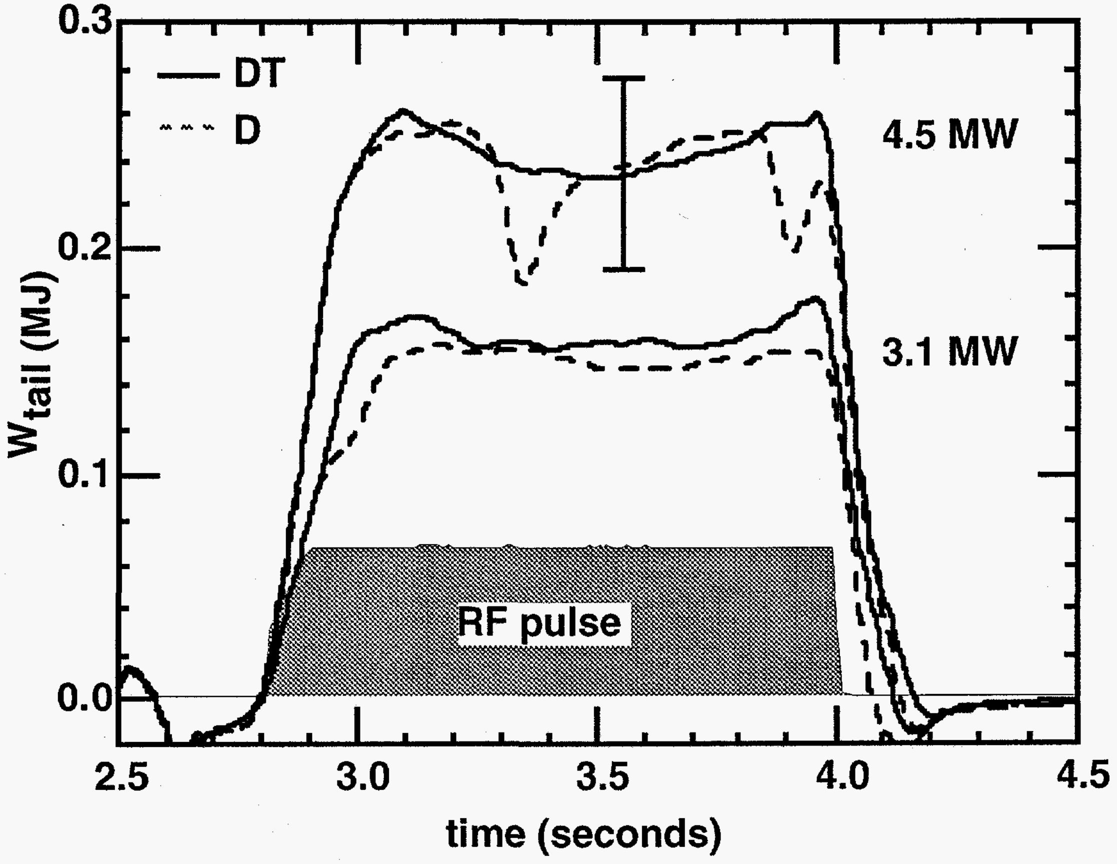

Fig. 3. Time evolution of the hydrogen tail stored energy for 3.1 and 4.5 MW of ICRF power in D and DT plasmas. The error bar represents the uncertainty in the absolute measurement of the tail stored energy.

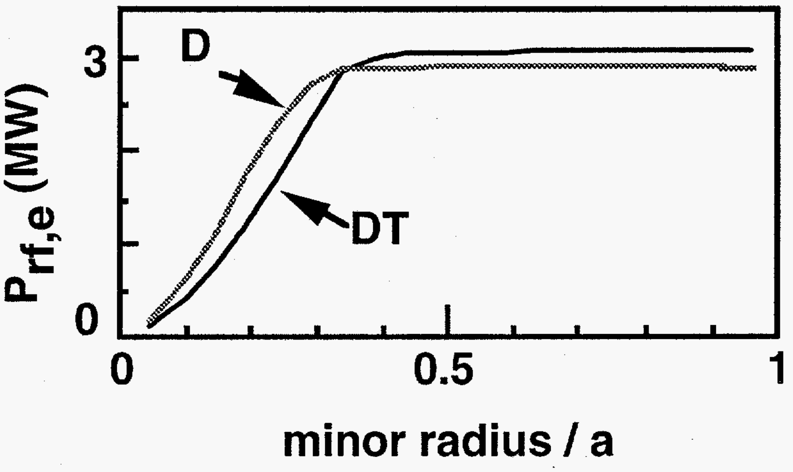

Fig. 4 . Volume integral of the ICRF power absorbed by electrons within each radius in D and DT plasmas with 4.5 MW of applied power.

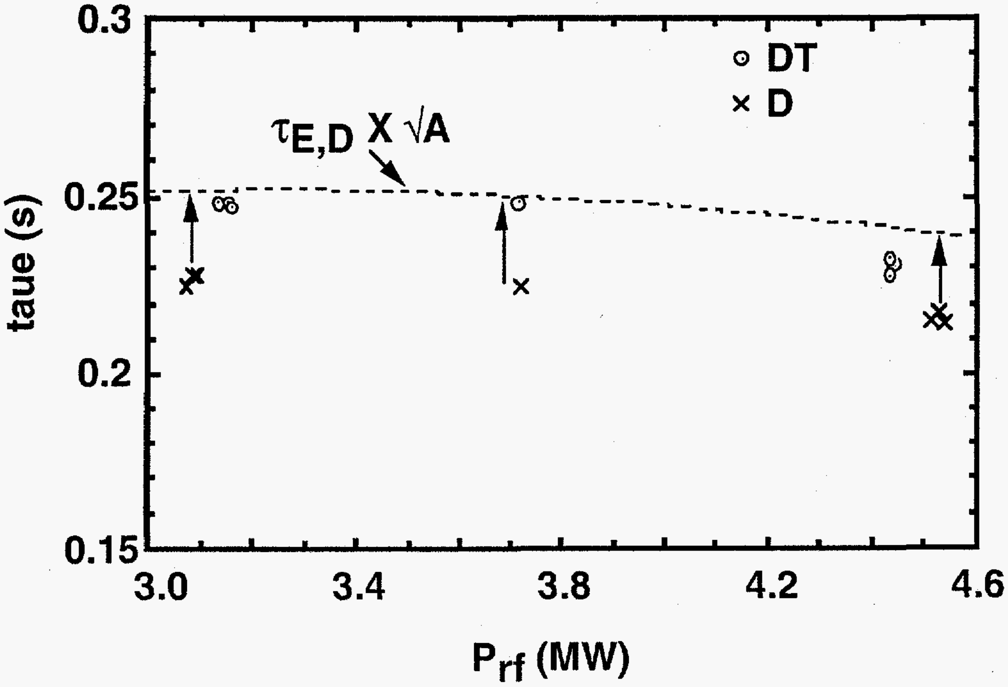

Fig. 5. The measured energy confinement time as a function of applied RF power for D and DT plasmas. The dashed line was computed by multiplying the D confinement data by the square root of the isotopic mass ratio between the D and DT plasmas