Unifying Role of Radial Electric Field Shear in the Confinement Trends of TFTR Supershot Plasmas

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A model is presented to explain the favorable ion thermal confinement trends of supershot plasmas in the Tokamak Fusion Test Reactor (TFTR). Turbulence suppression by radial electric field shear is important to reproduce the measured temperatures. Supershot confinement scalings are reproduced in more than sixty discharges, including favorable core power scaling and variation with isotopic mass, density peakedness, edge recycling, and toroidal rotation. The results connect the transitionless supershot regime with improved confinement regimes which are attained through sharp confinement transitions in the core or edge. [S0031-9007(98)07088-4]

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The large size and cost of many proposed fusion reactors derives partly from empirical scalings in which confinement degrades with heating power, and improves strongly with major radius and plasma current [1]. It is therefore desirable to extend predictive models to regimes of operation having more favorable confinement scalings. Enhanced confinement regimes, such as the H-mode (high confinement mode) [2], supershot [3], VH-mode (very high confinement mode) [4], ERS or NCS mode (enhanced reversed or negative central magnetic shear) [5,6] and high-β_P mode [7], show promise in this regard. The complete suppression of turbulence by strongly sheared flows, associated with the radial electric field E_r, has been proposed to explain the sharp and localized transitions in the H-mode, VH-mode, and reverse magnetic shear regimes, as reviewed in Ref. [8]. The supershot regime, by contrast, is attained without a sharp transition by gradually reducing the edge particle influx from the plasma facing surfaces. The core ion thermal diffusivity is more than 10 times lower than in high-recycling (L-mode) plasmas. Both the particle and ion thermal energy confinement of the supershot core improve, rather than degrade, with central fueling and heating [9], similar to more recently discovered regimes with internal transport barriers [8].

In this work, we develop and test a model for ion thermal transport that reproduces the favorable confinement scalings of supershot plasmas. We propose that this *transitionless* improved confinement results from strong but incomplete turbulence suppression by sheared flows. Including this effect doubles the simulated ion temperature to reach agreement with measured values.

The model presented [10] involves ion thermal diffusion from toroidal ion temperature gradient (ITG) driven modes [11], suppressed by radial electric field shear in the plasma core. The neoclassical radial electric field and ion temperature are calculated self-consistently (using the measured toroidal impurity velocity). A self-consistent calculation is necessary because the plasma core is not far from marginal stability to toroidal ITG modes in the absence of sheared flows. The thermal hydrogenic density is inferred from the measured electron density, measured carbon impurity density, and TRANSP Monte Carlo calculations of the beam ion density [12].

Two distinct approaches are taken, demonstrating that the conclusions for the inner half-radius are independent of the model for the ion thermal diffusivity χ_i. The first approach reproduces temperature profiles from an analytic criterion describing turbulence suppression by E_r shear in the inner half-radius, while the second extends the model of Ref. [13] to include the effect of a self-consistent neoclassical radial electric field E_r, covering 85% of the plasma cross section. Large nonmonotonic features in the measured toroidal velocity profiles of impurity ions are consistently explained by the same neoclassical calculation which provides E_r [10,14].

Equation for the ion temperature profile.—The confinement trends are first described through an expedient criterion taking the E_r shearing rate $\omega_{E\times B}$ [15,16] and maximum linear growth rate of the toroidal ITG mode $\gamma_{\rm lin}^{\rm max}$ approximately equal in the core [10]. This corresponds, within a factor of 2, to nearly complete turbulence suppression on the basis of toroidal gyrofluid calculations [17]. The maximum linear growth rate near marginal stability, in the absence of sheared flows, is derived from the results of a comprehensive linear gyrokinetic code for the flat density gradient limit of the toroidal ITG mode [13],

$$\gamma_{\rm lin}^{\rm max} \simeq -\frac{T_e}{4T_i}\left(\frac{T_i}{m_i}\right)^{1/2}\frac{1}{T_i}\frac{dT_i}{dr} - \frac{(T_e/m_i)^{1/2}}{4L_T^{\rm crit}(T_e = T_i)}, \qquad (1)$$

where T_i and T_e are, respectively, the ion and electron temperatures, m_i is the ion mass, r is the local minor

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radius, and $L_T^{\mathrm{crit}} \propto (T_e/T_i)^{0.52}$ is the critical temperature gradient scale length.

A simplified expression for the neoclassical shearing rate $\omega_{E\times B}$ can be derived [10,14],

$$\omega_{E\times B} = \frac{RB_\theta}{B}\frac{d}{dr}\left(\frac{E_r}{RB_\theta}\right) \simeq \frac{T_i}{Br_n}\frac{d\ln(RB_\theta)}{dr} + \frac{1}{B}\frac{d(V_{\varphi i}B_\theta)}{dr} - \frac{1}{B}\frac{d}{dr}\left(\frac{T_i}{r_n}\right), \quad (2)$$

where $r_n^{-1} = -d\ln n_i/dr$, n_i is the thermal hydrogenic density, B and B_θ are, respectively, the total and poloidal magnetic fields, and $V_{\varphi i}$ is the hydrogenic toroidal velocity.

The diffusivities for radial transport of ion thermal energy and toroidal momentum are nearly equal [18] (as expected from quasilinear theory), while the profile shapes of T_i and inferred $V_{\varphi i}$ are very similar [10,14]. Then $dV_{\varphi i}/dr \simeq \xi_V dT_i/dr$, where ξ_V is a constant approximately equal to the ratio of net torque to net heating power absorbed by the ions.

The criterion becomes $\omega_{E\times B} = f(B,\ldots)\gamma_{\mathrm{lin}}^{\mathrm{max}}$, where in general $f \sim 1$ accounts for additional parametric dependences, e.g., anisotropy in the turbulent wave number spectrum. This can be written as a first order differential equation, $dT_i/dr + T_i/r_T^E = 0$, where

$$1/r_T^E = \frac{\frac{T_i}{B}\frac{d}{dr}\left(\frac{1}{r_n}\right) - \frac{T_i}{Br_n}\frac{d\ln(RB_\theta)}{dr} - \frac{(T_e/m_i)^{1/2}f}{4L_T^{\mathrm{crit}}(T_i=T_e)}}{\frac{T_i}{Br_n} - \frac{B_\theta}{B}\xi_V T_i + \frac{T_e}{4T_i}\left(\frac{T_i}{m_i}\right)^{1/2} f}. \quad (3)$$

This reduces to the condition for marginal stability of the odd-parity toroidal ITG mode when $\omega_{E\times B} \to 0$, corresponding to the core of L-mode plasmas. The calculated ion heat flux retains a relatively sharp increase above the toroidal ITG threshold despite finite contributions below the threshold from trapped-electron destabilization of the even-parity mode [11,13]. Suppression by E_r shear allows the ion temperature gradient to steepen beyond that which is marginally stable in the absence of sheared flows. The mutually reinforcing character of supershot trends is driven by the strong nonlinearity in T_i and the coupling of particle and thermal energy transport by E_r shear (first term in numerator). The effect of varying $f \sim 1$ in Eq. (3) is weakened by its large coefficients.

Figure 1 compares the calculated and measured T_i profiles. Outside the half-radius, where the local confinement trends are characteristically L-mode, the shearing rate falls progressively short of the growth rate as the radius increases. Equation (3) can be shown to reproduce the core T_i profiles of the set of 45 discharges shown later in Fig. 7.

Nonlinear simulations.—The nonlinear simulations, carried out using the TRV code [10] cover 85% of the plasma cross section and give T_i profiles in the inner half-radius nearly identical with those from the criterion $\omega_{E\times B} \simeq \gamma_{\mathrm{lin}}^{\mathrm{max}}$. In the outer half-radius, an estimate of the turbulent χ_i is required to find the progressive deviation from toroidal ITG marginal stability. Here we use the model of Ref. [13] for the ion thermal diffusivity χ_{i0} and include the effect of E_r shear by taking a simple parametrization of the results of Ref. [17], neglecting destabilization by the gradient of the parallel velocity, $\chi_i = \chi_{i0}(1 - |\omega_{E\times B}|/\gamma_{\mathrm{lin}}^{\mathrm{max}})H(1 - |\omega_{E\times B}|/\gamma_{\mathrm{lin}}^{\mathrm{max}})$, where H is the unit step function. The neoclassical E_r is calculated from an analytical form more complete than Eq. (2), reproducing numerical results [10,14] obtained using a full viscosity matrix.

The nonlinear simulations, shown in Fig. 2, reproduce the expansion of the enhanced confinement zone with heating power. The hydrogenic temperature profiles obtained using the χ_i inferred from measured data with TRANSP,

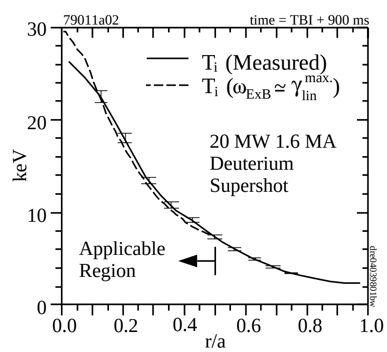

FIG. 1. Supershot ion temperature profile in inner half-radius can be recovered from the criterion $\omega_{E\times B} \simeq \gamma_{\mathrm{lin}}^{\mathrm{max}}$.

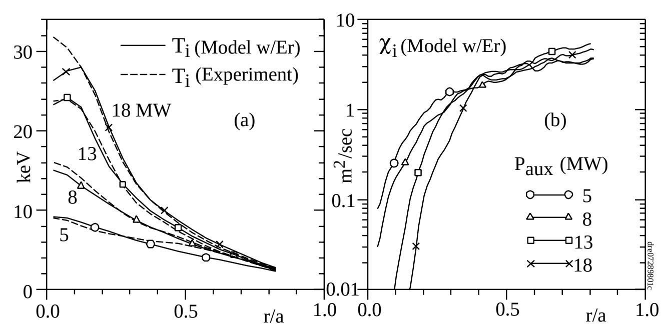

FIG. 2. Model reproduces expansion of core enhanced confinement zone as auxiliary heating power increases from 5 to 18 MW. (a) Comparison of hydrogenic temperature profiles from model and experiment. (b) Ion thermal diffusivity χ_i.

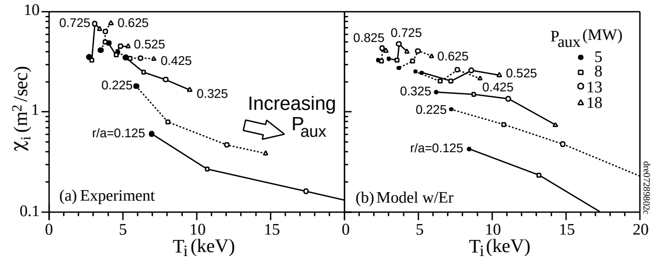

FIG. 3. Ion thermal diffusivities at various normalized radii as a function of T_i. (a) Inferred from TRANSP (experiment). (b) Simulated (model w/E_r).

in place of the model χ_i, are shown for comparison. When this expansion was considered at fixed minor radius (e.g., the one-third radius), an apparent rough scaling $\chi_i \propto 1/T_i$ was inferred [9]. Figure 3(a) shows the diffusivity inferred from TRANSP. In the inner half-radius, the scaling with T_i is favorable, while in the outer half-radius, χ_i increases with T_i as in L-mode plasmas. Figure 3(b) shows that this qualitative behavior is recovered in the nonlinear simulations.

Lithium pellets, injected into the Ohmic phase, subsequently reduce the edge recycling to strongly improve performance. Small amounts of helium, by contrast, increase recycling and spoil performance. The model reproduces this strong sensitivity, both in lithium pellet experiments, shown in Fig. 4 for the scan of Ref. [19], and in helium spoiling experiments [10]. Coupling of particle and energy transport through E_r shear results in pronounced sensitivity to edge conditions.

In reactor-relevant mixtures of deuterium and tritium [20], local core particle and ion thermal energy confinement are strongly improved relative to deuterium plasmas [20–22]. The supershot isotope effect $\tau_E \propto A_i^{0.80-0.89}$ is much stronger than in deuterium-tritium L-mode plasmas, for which $\tau_E \propto A_i^{0.5}$ [23], where A_i is the volume average thermal hydrogenic atomic number. In the model presented, E_r shear plays an essential role in this trend, resulting in a heightened nonlinear sensitivity of the core temperature to that in the outer regions. A weaker "intrinsic" isotope effect, with strength similar to the L-mode regime, may result from E_r shear itself, as demonstrated for an L-mode D-T case in Ref. [23] (constant shearing rate with $\gamma_{\text{lin}}^{\text{max}} \propto A_i^{-1/2}$), or another mechanism [24]. This weaker intrinsic effect would be strongly amplified by E_r shear in the inner half-radius, where 75% of the energy in supershots is stored. Figure 5 illustrates the consequences of the criterion $\omega_{E\times B} \simeq \gamma_{\text{lin}}^{\text{max}}$ of Eq. (3) when used to calculate the central T_i as a function of that at the half-radius for a matched pair of disharges. The isotope effect is nonlinearly accentuated by the peaked density profile as described by Eq. (3). No prior theory predicts an effect stronger than $\tau_E \propto A_i^{0.5}$.

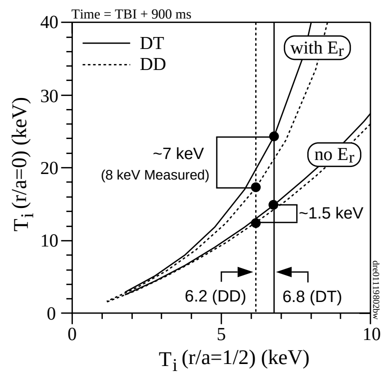

FIG. 5. Heuristic model for the strong isotope effect in supershot plasmas. With E_r shear, the core T_i is a strong nonlinear function of T_i at the half-radius. With $\omega_{E\times B} \simeq \gamma_{\text{lin}}^{\text{max}}$, the measured DD → DT T_i increase at the half-radius projects to an increase of 7 keV at the magnetic axis, relative to 8 keV measured.

Figure 6 compares matched deuterium and tritium supershot plasmas. Without E_r shear, the model of Ref. [13] often falls 35%–50% below experiment in supershots, without resolving the isotope effect. This is consistent with the simulation of a supershot in Ref. [13] which neglected E_r shear [revised T_i measurements (1996) show T_{i0} to be 10 keV higher than quoted for this discharge

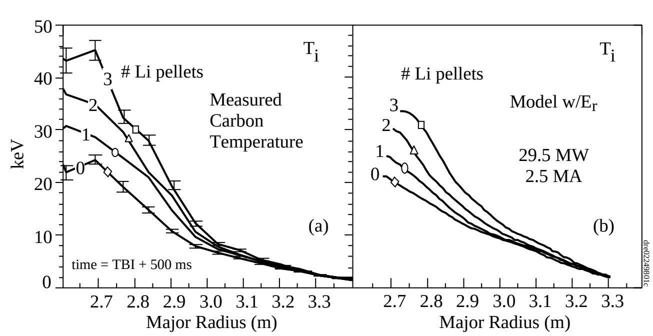

FIG. 4. Nonlinear simulations of lithium pellet scan at 29.5 MW heating power and 2.5 MA plasma current: carbon temperature profiles. (a) measured (b) simulated.

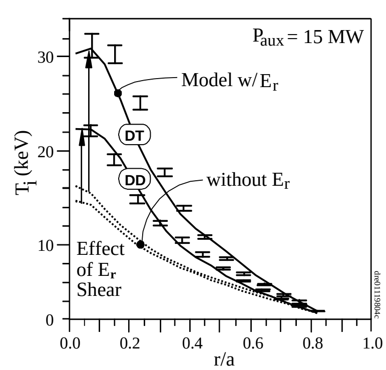

FIG. 6. Comparison of simulated hydrogenic T_i with experiment for a matched pair of discharges, one fueled by tritium beams (DT), the other by deuterium (DD).

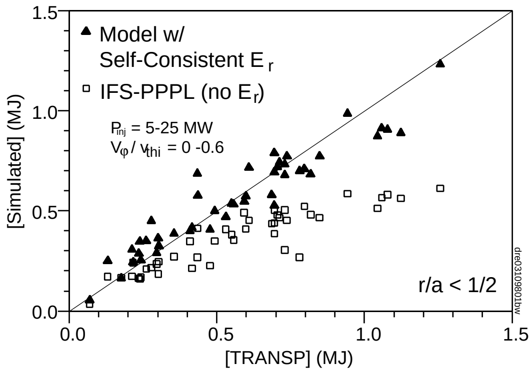

FIG. 7. Energy stored in the thermal ions in the inner half-radius $\int_0^{a/2}(3/2)n_i T_i 4\pi^2 Rr\,dr$, comparing models with and without E_r shear to TRANSP (experiment). 45 TFTR discharges are shown.

(1992) [13], revealing a 35% discrepancy [10]]. The extended model, with self-consistent neoclassical E_r, brings the simulated temperatures to agreement with data and recovers known confinement scalings.

Figure 7 compares the thermal ion kinetic energies in the inner half-radius for 45 supershot discharges [21,22] with plasma current 1.6 MA, major/minor radius 2.52/0.87 m, toroidal magnetic field 4.8 T, heating power 5–23 MW, isotopic mass $1.9 < A_i < 2.6$, and varying toroidal rotation. Without E_r shear, the discrepancy between experiment and simulation increases with stored energy; E_r shear is more important at higher ion temperatures.

In summary, the model presented reproduces distinguishing trends of the TFTR supershot regime while retaining validity in L-mode plasmas. The nonlinear simulations assume radial convective transport $c_i \Gamma_i T_i$, where Γ_i is the radial ion flux density, and $c_i = 3/2$. The results are relatively insensitive to c_i, as confirmed by the approach taking $\omega_{E\times B} \simeq \gamma_{\rm lin}^{\rm max}$, independent of c_i. Simulations of particle transport have not been carried out but are essential for *ab initio* predictions.

Finally, comparisons with recent spectroscopic measurements of E_r in TFTR are underway. A significant nonuniform offset of the measured carbon poloidal velocity, in the ion diamagnetic direction relative to neoclassical, is observed [25]. The offset is qualitatively consistent with turbulence-generated equilibrium flows seen in global codes [26], which are (i) stronger with more peaked profiles, (ii) in the ion diamagnetic direction giving $E_r > 0$, and (iii) radially extended. Nevertheless, the positive measured E_r is strongly correlated with the energy confinement time. Our nonlinear simulations using measured E_r also reproduce supershot T_i profiles, preserving the criterion $\omega_{E\times B} \simeq \gamma_{\rm lin}^{\rm max}$ in the core to within a factor of 2.

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