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ION THERMAL CONFINEMENT IN THE TFTR ENHANCED CONFINEMENT REGIME

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Abstract

Measurements of the plasma ion temperature and toroidal rotation speed profiles have allowed the study of ion thermal transport in the TFTR hot ion enhanced confinement regime. Central ion temperatures up to 30 keV and rotation speeds up to 8×10^5 m/sec have been confirmed with new diagnostic measurements, and the ion thermal diffusivity is found to be non-neoclassical and comparable to the anomalous electron thermal diffusivity. The dominant effects of strong rotation are the down-shifting of the neutral beam energies in the plasma frame, which results in reduced ion and electron heating on axis, and the presence of off-axis ion heating from viscous damping of the plasma rotation.

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Since the discovery of the enhanced confinement energetic ion regime on the TFTR tokamak,¹ considerable efforts have been made to perform detailed measurements of the ion energy confinement in order to improve our understanding of this regime. In addition to its intrinsic interest, an understanding of this regime is necessary in order to further pursue the goal of scientific breakeven for fusion power production in TFTR. To that end, we have performed a series of measurements of the radial profiles of the thermal ion temperature and ion toroidal rotation speeds. In addition to verifying the attainment of extremely high ion temperatures of 25-30 keV in a tokamak plasma, these measurements have allowed us to examine the ion thermal transport in these plasmas and study the effects of plasma rotation on the plasma performance. The influence of plasma rotation on the plasma heating is a topic of intense interest since the neutron production and energy confinement in TFTR plasmas have been found to depend strongly on the degree to which the neutral beam injection is balanced with respect to the torque applied to the plasma.^{1,2}

Central ion temperature measurements on early smaller tokamaks and the lack of good profile information led to a common assumption that the plasma ion thermal transport was reasonably described by a thermal diffusivity, χ_i , whose magnitude was typically up to a few times that predicted by neoclassical theory coupled with a convective power flux $= 5/2 n_i T_i v_{\perp}$. As a consequence, ion thermal energy transport was not considered to be a dominant loss channel in neutral-beam-heated plasmas.³⁻⁶ With the development of the charge-exchange recombination spectroscopy technique to provide reliable measurements of the ion temperature profile, that interpretation has come into question. The important results of Groebner et al.⁷ on the D-III tokamak indicated that the χ_i in high density H-mode plasmas was comparable to the electron thermal diffusivity χ_e in magnitude and radial dependence, and in disagreement with neoclassical predictions. Similar measurements on the PBX tokamak yielded less conclusive results because the neoclassical χ_i was comparable to both the measured values and the electron thermal diffusivity in the $r = a/2$ region, and because electron-ion coupling and convective losses were dominant in

the ion power balance.⁸ Thus, it is interesting to study the ion thermal diffusivity and power balance in the present generation of large, high-temperature tokamak experiments. The TFTR enhanced confinement regime offers an especially attractive environment for such ion power balance studies since the high electron temperatures and modest densities attained here result in almost negligible ion-electron coupling, and ion thermal conduction is the dominant ion energy loss mechanism over most of the plasma cross section.

The high-temperature enhanced confinement ("supershot") regime is attained in TFTR by neutral beam injection into a low recycling target plasma. The discharges studied here had a major radius of 2.45 m and a minor radius of 0.79 m. Deuterium plasmas were heated by up to 20 MW of deuterium neutral beam injection, with about 6 MW counter-tangential to the plasma current, and the remaining power co-tangential. The highest values of stored energy, central ion temperature, and neutron emission were obtained with near-balanced injection. With the availability of up to ≈ 12 MW of balanced beam power, maximum temperatures and neutron output were attained at discharge currents of 0.8 to 1.0 MA. The ion temperature profiles were highly peaked for the balanced injection cases, while they were broader for the lower confinement, purely co-injection cases with high toroidal rotation speeds, as was also the case for the measured electron density profiles.

A multispatial and multispectral imaging charge-exchange recombination spectroscopy diagnostic (CHERS) was installed on TFTR to provide radially resolved measurements of the ion temperature, $T_i(R,t)$, and toroidal rotation speed, $v_\phi(R,t)$, for a wide range of discharge parameters. The fast doping neutrals needed for the charge-exchange excitation of visible lines from impurity ions were provided by either the heating neutral beams or a dedicated diagnostic neutral beam. Up to 12 positions in the plasma could be measured simultaneously, with a 10-cm spatial separation of the viewing sightlines for a single shot, but this could be reduced to 5 cm by changing the field of view between shots. The spatial resolution of the measurements was typically 3 cm. For most of the measurements reported here, the CVI 5292 Å ($n = 8-7$) transition was used, with estimated corrections

applied to the measured line width and shift to account for the variation of the charge-exchange-recombination rates with center-of-mass frame energy across the line profile.⁹ The central values of T_i and v_ϕ in the enhanced confinement regime measured by the CHERS diagnostic and by X-ray Doppler broadening measurements of the Ni XXVII K-alpha line are in agreement within their respective error bars.^{2,10}

The measured profiles have been analyzed with the SNAP (1D, equilibrium) and TRANSP (1-1/2D, time-dependent) kinetic analysis codes, with an emphasis on deriving the ion thermal diffusivities and elucidating the effects of rotation on the thermal ion power balance. These codes use, among other parameters, the measured profiles of ion and electron temperature, electron density, and plasma toroidal rotation speed to derive the power balance for each plasma species. Both codes can be used in either an analysis mode, in which the measured $T_i(r)$ profiles are used as input to derive a value of $\chi_i(r)$ from the data, or in a predictive mode, in which a given model is chosen for $\chi_i(r)$ and the resulting calculated $T_i(r)$ profile is compared to the measurements. In these kinetic analyses, we assume classical electron-ion coupling and a spatially uniform Z_{eff} profile.

Comparisons of the measured $T_i(r)$ profiles with model transport calculations from SNAP in the predictive mode show that the ion thermal diffusion is strongly non-neoclassical. For example, Fig. 1(a) shows the measured $T_i(r)$ profile for a 0.9-MA discharge with 13.6 MW of balanced neutral injection, $\bar{n}_e = 2.5 \times 10^{19} \text{ m}^{-3}$, and $n_e(0) = 5.0 \times 10^{19} \text{ m}^{-3}$. The solid points in the plot indicate measurements on the outboard side of the plasma center where the beam-neutral density is higher and where the CHERS signals are most reliable. The open symbols indicate data from points inboard of the plasma center. The solid lines indicate the smoothed and fitted curves for $T_i(r)$ and $T_e(r)$ used for the transport calculations in the analysis mode. Also shown in Fig. 1(a) are comparisons of the measured $T_i(r)$ profile with the values calculated from the SNAP code under the assumptions that $\chi_i = 3 \times \chi_i^{\text{NC}}$, where χ_i^{NC} is the Chang-Hinton neoclassical ion thermal diffusivity,¹¹ and $\chi_i(r) = 2 \times \chi_e(r)$, where $\chi_e(r)$ is the electron thermal diffusivity derived from the measured $T_e(r)$ profiles. The measured $T_i(r)$ profile is clearly much narrower than

that expected from neoclassical theory, while $\chi_i \approx 2 \times \chi_e$ produces a much closer approximation to the measured values. Indeed, a survey of several discharges using the SNAP code in the analysis mode to derive a $\chi_i(R)$ profile indicates that $\chi_i \approx (1-3) \chi_e$ at $r/a \approx 0.5-0.7$, with similar radial profiles except in the innermost central region. More detailed modelling with the TRANSP code, which included the additional effects of beam-ion energy diffusion and beam-neutral charge exchange with unthermalized beam ions, indicates that $\chi_i \approx \chi_e$ is often a reasonable approximation for most of the plasma cross section.

While ion thermal convection is usually negligible over most of the minor radius, it is significant in the central plasma region ($r/a < 0.2$). Depending on the discharge conditions, a convective ion power flow given by $Q_{i, \text{conv}} = (1.5)T_i\Gamma_i$ (where Γ_i is the ion particle flux) is required to give good agreement with the measured profiles and to avoid unphysical negative χ_i 's in the central plasma region. The deviation of the convective multiplier from the often-used 5/2 value presumably reflects the nature of the assumed turbulence underlying this convective transport.¹² For consistency, we use a value of 3/2 in the analyses presented here.

High toroidal rotation speeds have a direct influence on the plasma performance in this hot ion regime, and measurements of the T_i and v_ϕ radial profiles help to quantify the effects of rotation on the plasma behavior. The overall neutron yield is lowered by the reduced relative energy between the fast ions and the rotating bulk plasma ions, and rotation has a strong effect on the plasma power deposition.¹³ The reduced relative speeds between the plasma and neutral beam particles result in reduced beam energy deposited in the plasma in its rotating frame, and reduced beam penetration to the plasma core. This, in turn, results in a power deposition profile with less central ion and electron heating than in the non-rotating case. The viscous damping of the plasma rotation is assumed to provide an additional source of heating power to the ions which, since it is strongest where the $v_\phi(r)$ gradient is largest, peaks off axis.

These combined effects of rotation lead to the broader $T_i(r)$ profiles observed in unbalanced injection cases, and, in extreme cases, have resulted in flat or hollow $T_i(r)$ profiles. For example, Fig. 1(b) shows the measured and calculated ion temperature profiles for an unbalanced injection case. Here full co-injection of 11 MW gives rise to a peaked $v_\phi(r)$ profile (i.e., Gaussian in shape with a half-width-at-half-maximum ≈ 0.34 m) with $v_\phi(0) \approx 8 \times 10^5$ m/sec for a standard 0.9-MA discharge of $\bar{n}_e = 1.7 \times 10^{19} \text{ m}^{-3}$ and $n_e(0) = 3.1 \times 10^{19} \text{ m}^{-3}$. As with the balanced injection case, the ion thermal diffusivity χ_i is strongly non-neoclassical, and $\chi_i \sim \chi_e$ plus the effects of ion viscous heating reasonably reproduces the measured $T_i(r)$ profile. The analysis of the momentum transport in these plasmas will be reported in a separate paper.¹⁴

Figures 2(a) through (d) show the calculated heating power density profiles and the integrated power balance profiles for both the balanced injection and the fully co-injected discharges discussed above. To ease comparison between these different cases, we plot here the power densities divided by the volume-averaged total input heating power from the neutral beams (i.e., the absorbed beam power minus direct charge-exchange ion losses). Likewise, the ion power balance curves from SNAP shown in Figs. 2(c) and (d) give the volume-integrated power losses normalized to the total heating power. In the balanced injection case, the high relative beam energies lead to substantial direct ion and electron heating in the plasma center and strong central absorption of the neutral beams in these low recycling, low edge density discharges. In contrast, the down-shifted relative beam energies in the rotating plasma case lead to reduced central heating of the ions and electrons and a somewhat broadened beam deposition profile. In addition, there is substantial off-axis heating of the ions due to viscous rotation damping.

The ion power balance for the balanced injection case confirms that the ion power losses are strongly dominated by thermal conduction (given by $n_i \chi_i \nabla T_i$) over most of the plasma cross section, except for the central $r/a \leq 0.2$ region, where conductive and convective losses are of equal magnitude. In some contrast, the ion power balance analysis

of the rotating plasma [Fig. 4(d)] indicates that convection dominates the core power flow for $r/a \leq 0.3$, and it remains non-negligible (along with electron-ion coupling) beyond $r/a = 0.6$. The volume-integrated power input to the ions from viscous damping of the plasma rotation becomes a significant fraction of the overall input power to the ions for $r > 0.4$ m. In both cases, the consequence of $\chi_i(r) = \chi_{\perp}(r)$ is that the ion loss channels are much more important in the overall power balances than for the case of neoclassical transport.

Given the strong role of balanced injection in the production of high stored energies and neutron fluxes, it is of interest to ask whether the above-mentioned effects of rotation on the beam deposition are sufficient to produce the observed differences in overall confinement between balanced and unbalanced injection cases. To that end, Fig. 3 shows the comparisons of the inferred $\chi_i(r)$ and $\chi_e(r)$ for four balanced ($\tau_E = 0.14$ sec) and two unbalanced ($\tau_E = 0.10$ sec) injection cases. These shots had 0.9 MA with $P_{\text{INJ}} = 11$ MW for the co-injection cases, and 12-14 MW for the balanced cases. The results are plotted in Fig. 3 as a range of values of χ at each radius, with the range indicating the spread of values obtained from the similar discharges. The uncertainties in the values of $\chi_i(r)$ and $\chi_e(r)$ from a single discharge, estimated from the uncertainties in the $T_i(r)$, $T_e(r)$, Z_{eff} , and other parameters from a single shot, are 1 to 2 times larger than the ranges indicated in Fig. 3 for $r/a \geq 0.5$. At small radii, near the plasma center, large uncertainties in χ_i and χ_e arise from uncertainties in the respective convective multipliers. As seen in Fig. 3, $\chi_i(r)$ has a magnitude and radial dependence comparable to that of $\chi_e(r)$, which agrees with the results from the T_i simulations shown in Fig. 1. For comparison, the range of the values of χ_i^{NC} derived from neoclassical theory is also shown in Fig. 3(a), and is seen to deviate strongly from the range of values deduced from the kinetic measurements.

The thermal diffusivities themselves are not significantly different between cases of balanced and unbalanced injection. The observed differences in the ion temperature profiles are adequately explained by taking into account the down-shift of beam energies in the rotating plasma frame, a mild broadening of the beam deposition profile, and the occurrence of off-axis ion heating due to viscous rotational damping.

In summary, new measurements of the ion temperature profile in TFTR indicate that the ion thermal transport is found to be very non-neoclassical in these large high-temperature plasmas. The anomalous ion thermal diffusivity is similar in magnitude and profile to the anomalous electron thermal diffusivity. Analysis of the transport near the plasma axis indicates that the convective power flow is lower than used in earlier analyses of smaller experiments. The presence of strong toroidal rotation is manifested mainly by broadened temperature profiles due to down-shifting of the beam ion speeds in the plasma frame and the presence of off-axis heating due to viscous rotational damping.

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Figure Captions

Figure 1. (a) Measured and simulated ion temperature profiles for a balanced injection discharge. Closed symbols: measurements for $R \geq R_{pl}$; open symbols: $R < R_{pl}$, where R_{pl} is the major radius of the plasma axis. The smoothed T_e profile is also shown. (b) Same as (a) but for full cc-injection with $v_\phi(0) = 8 \times 10^5$ m/sec.

Figure 2. Comparison of input power densities and volume-integrated ion power balance for a nonrotating and strongly rotating discharge. For the balanced case (a,c), $P_{inj} = 13.6$ MW and $P_{absorbed} = 12.8$ MW, while $P_{inj} = 11.0$ MW and $P_{absorbed} = 10.4$ MW for the co-injection case (b,d).

Figure 3. Ion (a) and electron (b) thermal diffusivities for nonrotating and rotating discharges. The neoclassical ion diffusivity range includes both types of discharges.

Fig. 1

Fig. 2

FIG. 3