Magnetic shear effect on plasma transport at $T_e/T_i \sim 1$ through electron cyclotron heating in DIII-D plasmas

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Received 30 June 2020, revised 22 September 2020
Accepted for publication 9 October 2020
Published 23 November 2020

Abstract
The effect of magnetic shear on plasma transport for an electron to ion temperature ratio ($T_e/T_i$) near unity has been explored in DIII-D utilizing electron cyclotron heating (ECH). Previous reports showed that significant confinement degradation occurred at $T_e/T_i \sim 1$ in positive shear (PS) plasmas in DIII-D, whereas reduced confinement degradation was observed in negative central shear (NCS) plasmas. In this study, plasma transport in weak magnetic shear (WS) plasmas with ECH is investigated and compared with that in NCS and PS plasmas. Here the magnetic shears ($\hat{s}$) are $\hat{s} > 0.5$, $\sim 0$ and $< -0.1$ in the core region ($\rho \sim 0.3$–0.4) of PS, WS and NCS plasmas, respectively, and flat or negative inside $\rho \sim 0.4$ in the WS and NCS plasmas. Weak magnetic shear is found to be effective in minimizing degradation of ion thermal confinement as $T_e/T_i$ increases through ECH application, and an improved confinement factor of $H98\gamma2 \sim 1.2$ is maintained, similar to NCS plasmas. At $T_e/T_i \sim 1$, the ion thermal diffusivity around an internal transport barrier decreases when changing the magnetic shear from positive to weak or negative shear. Also, reduced local particle and momentum transport was indicated by steeper density and toroidal rotation profiles in the weak and negative shear regimes. Linear gyrokinetic simulations predict little change in growth rates of low-$k$ turbulence with ECH application in the WS and NCS plasmas, which is consistent with the transport and profile analyses.

Keywords: plasma transport, magnetic shear, rotation shear, electron heating

(Some figures may appear in colour only in the online journal)
1. Introduction

Magnetic shear and the safety factor profile are essential issues for developing ITER-Hybrid and steady-state DEMO operations where the ratio of electron to ion temperature ($T_e/T_i$) will be around unity with dominant electron heating. The impact of $T_e/T_i$ or electron heating on plasma transport and confinement have been studied in several tokamaks, Alcator C-Mod, DIII-D, JT-60U, ASDEX Upgrade, KSTAR [1–13]. Ion thermal transport increased as $T_e/T_i$ approaches unity with application of electron cyclotron heating (ECH) to neutral beam heated discharges ($T_e > T_i$) in DIII-D, ASDEX Upgrade, and JT-60U H-mode plasmas [1–3, 7, 8]. A flattening of the density profile was observed with ICRH minority electron heating in Alcator C-Mod [6, 7], and with ECH in DIII-D H-mode plasmas [7, 8] and ASDEX Upgrade L and H-mode plasmas [9, 11]. The mechanisms were investigated with gas-puff modulation experiments [10] and gyrokinetic simulations [6–9].

Tungsten accumulation was reduced with a central ECH in ASDEX Upgrade and JT-60U H-mode plasmas [11, 12] and Molybendum accumulation was arrested with on-axis minority ICRH electron heating in Alcator C-Mod [6, 7]. A reduction in the core Ar was observed with core ECH in KSTAR L-mode plasmas [13]. The intrinsic rotation changes in the co- or counter-current direction with electron heating [14–16]. These were mostly studied in PS plasmas, although the studies in weak or negative shear plasmas could be very important for ITER-Hybrid and DEMO scenario development. It has been predicted based on gyrokinetic simulations [6–8] that weak or negative magnetic shear would avoid the observed core degradation with electron heating. The impact of ECH, here through $T_e/T_i$, on thermal transport was examined in negative and positive magnetic shear plasmas on DIII-D and JT-60U, with negative shear operation found to mitigate thermal transport as $T_e/T_i$ increased compared to PS operation [17, 18]. However, the effectiveness of WS at mitigating confinement reduction with increased $T_e/T_i \sim 1$ has been an open question. Some regimes show no core degradation and actually improve with ECH [19], even with monotonic magnetic shear.

In this paper, plasma transport in WS plasmas as $T_e/T_i$ approaches unity with ECH application has been measured and compared with that in negative central magnetic shear (NCS) and positive magnetic shear (PS) plasmas on the DIII-D tokamak. Moreover, a magnetic shear dependence on the thermal transport and plasma profiles at $T_e/T_i \sim 1$ with dominant electron heating with ECH has been investigated by using a systematic scan of the magnetic shear in order to contribute to the exploration of operational scenarios for ITER and DEMO.

The experimental observations are compared with gyrokinetic modeling to discuss the underlying physics of the plasma responses to ECH.

This paper is arranged as follows: In section 2, the experiments in DIII-D are introduced. The response of global energy confinement and thermal transport to ECH in weak shear plasmas is studied in section 3. The effect of magnetic shear on plasma transport at $T_e/T_i \sim 1$ through ECH are assessed in section 4. After a discussion in section 5 by means of gyrokinetic simulations, a summary is given in section 6.

Figure 1. Radial profiles of the safety factor ($q$) in the positive magnetic shear (PS), weak magnetic shear (WS), and negative magnetic shear (NCS) plasmas on DIII-D. The $q$-profile scan was conducted at $T_e/T_i \sim 1$ in the core region through ECH application.

2. Experimental conditions in DIII-D

Magnetic shear effects on plasma transport at $T_e/T_i \sim 1$ were investigated in ELMy H-mode plasmas with a modest internal transport barrier in the ion temperature profile. The same series of discharges in [18] was used for this study. The plasma current ($I_p = 1.2$ MA), toroidal magnetic field ($B_T = 1.9$ T), edge safety factor ($q_{95} = 4.6$), and the plasma shape (elongation $\kappa_e = 1.8$, upper triangularity $\delta_{up} = 0.38$, lower triangularity $\delta_{bot} = 0.60$) were kept constant. Controlled power scan was made; neutral beam power and ECH power ranged from $P_{NB} \approx 5.7–6.6$ MW and $P_{ECH} \approx 1.1–3.3$ MW, respectively. Normalized $\beta$ varied from $\beta_N = 2.0$ to 2.7, and the line average density was $n_e \sim 3.5–5.7 \times 10^{19}$ m$^{-3}$. The safety factor ($q$) profile was scanned as shown in figure 1 by changing the early beam heating power, the obliquely launched ECH (i.e. electron cyclotron current drive (ECCD)) power and the ECH deposition. The minimum safety factor from motional Stark effect (MSE) measurements was located at $\rho \sim 0.4$ in NCS plasmas. This experiment sought to minimize core MHD activity to assess the magnetic shear effect on plasma transport. Data with $n = 1$ tearing modes are excluded in this study since the $n = 1$ tearing mode can significantly affect confinement and turbulence properties. Although a weak $n = 2$ mode (typically $m = 5$) appeared around $\rho = 0.6$ in some discharges, the weak $n = 2$ mode had little impact on plasma profiles inside of $\rho = 0.6$, which were the focus of this study. The impact of the $5/2$ mode on the thermal confinement time was less than 10%.

Figures 2(a), (b) and (c) illustrates the response of radial profiles of ion and electron temperatures ($T_i$ and $T_e$), electron density ($n_e$) and toroidal rotation velocity ($V_{\phi}$) to ECH in PS, WS an NCS plasmas. The open squares (blue) correspond to profiles without ECH, and the closed circles (red) indicate profiles with ECH. A modest internal transport barrier in $T_i$ ($T_{i-ITB}$) was formed at $\rho \sim 0.4$ without ECH in all three...
magnetic shear scenarios, as evidenced by the sharp change in $T_i$ gradient at this radius. Electron cyclotron heating was applied in the radial range of $\rho = 0.3$–0.5 in NB heated plasmas with similar power and deposition, as illustrated in the second row. The core ion temperature decreased with ECH in the PS plasmas, showing the degradation of the $T_i$-ITB. On the other hand, the $T_i$-ITBs were maintained and the central ion temperature rather increased with ECH in the WS and NCS plasmas. The core electron temperature slightly increased with ECH in the PS plasmas while the core electron temperature increased more significantly in the WS and NCS plasmas, relative to the PS case. The response of these profiles to ECH indicates better thermal confinement in the WS and NCS plasmas compared to the PS plasmas (discussed later). In contrast to the temperature profiles, the electron density decreased in all shear conditions by about 15%–20% over the plasma radius. No density feedback was applied for these plasmas. The reduction in the electron density with ECH was reported previously \cite{8, 10, 20} and will be discussed in section 3 of this paper. The toroidal rotation velocity was reduced by about 20%–30% with ECH in the PS plasmas, especially in the central region. The toroidal rotation profile did not change much with ECH in the WS and NCS plasmas. These data suggest that WS is as effective as NCS in minimizing changes in thermal and momentum transport when $T_e/T_i$ increases through ECH injection \cite{8}. The ratio of $T_e/T_i$ was increased with ECH in the core region, for instance, from $\sim0.8$ to $\sim1$ at $\rho \sim 0.35$. In some shots with WS and NCS, the toroidal rotation velocity decreased around the ECH deposition radius as illustrated in figure 2(b). It can be interpreted as an increase of momentum transport with increasing

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**Figure 2.** Radial profiles of the ion temperature ($T_i$), the electron temperature ($T_e$), the electron density ($n_e$) and the toroidal rotation velocity ($V_\phi$) with and without ECH in (a) PS, (b) WS, and (c) NCS plasmas ($I_p = 1.2$ MA, $B_T = 1.9$ T). Closed circles indicate the profiles with ECH, and open squares mean the profiles without ECH. 3.2 MW of ECH was injected into the core region as illustrated in the second row of figures from the top.
remained nearly constant at the ITB region in the WS plasmas as well as in NCS plasmas with increased $T_e/T_i$ through the ECH application. The increase in $\chi_i$ with increased $T_e/T_i$ is observed in the PS plasmas. As the previous studies reported that $E \times B$ flow shear could mitigate the confinement degradation at $T_e/T_i \sim 1$ [17, 19], a toroidal rotation gradient ($V_{\phi}$-grad) dependence which is a proxy for the $E \times B$ flow shear was examined as shown in figure 4(d). The thermal transport is low with large toroidal rotation gradient similar to the results in the previous studies. Figure 4(d) also illustrates a significant variation in $\chi_i$ near at almost constant rotation shear as pointed by the labels (A), (B) and (C). The three points labeled (A), (B) and (C) indicate the NCS, WS and PS plasmas in figures 4(c). This variation appears to stem from the difference in magnetic shear rather than $E \times B$ flow shear, as the variation in the $E \times B$ shearing rate in the plasmas of (A), (B), and (C) is only about 10%. Moreover, the $E \times B$ shearing rates are lower than the linear growth rates of turbulent instabilities in the three discharges (discussed in section 5). Thus, mitigation of confinement degradation in the WS plasmas, compared to PS plasmas, with stronger electron heating or $T_e/T_i \sim 1$ has been demonstrated.

Electron density decreased across the radius with the ECH application at all magnetic shear scenarios, dissimilar to the response of the other kinetic profiles. The WS and NCS plasmas have steeper density gradients ($n_e$-gradient) in the central region compared the PS plasmas at lower $T_e/T_i$, but the reduction with increased $T_e/T_i$ was significant as shown in figure 5(a). The density reduction profile was already observed in the previous studies in PS H-mode plasmas and explained by an increase in the particle diffusivity and a decrease in the inward particle pinch [8, 10]. Gyrokinetic simulations showed an increase in the particle flux as the trapped electron modes (TEM) instability threshold decreased with the increasing $T_e/T_i$ [8]. In reference [10], the dominant instability switches from the ion temperature gradient (ITG) modes to TEM with ECH was predicted by gyrokinetic simulations. In the plasmas analyzed in this paper, the dominant instability in the outer region of $\rho \sim 0.6$ tends to change from ITG to TEM at all magnetic shears (discussed in Appendix). This is consistent with the observations in the paper [10], the reduction in the edge density could affect the reduction in the core density profile due to a change in the turbulence transport. Changes in the edge density were controlled in reference [8] to separate core and pedestal effects.

The toroidal rotation gradient remained constant or increased in the WS and NCS plasmas as $T_e/T_i$ was increased while the toroidal rotation gradient was reduced in the PS plasmas, as shown in figure 5(b). The central toroidal rotation velocity remained constant or slightly increased with ECH in the NCS and WS plasmas. In some weak shear and negative shear discharges, the toroidal rotation around the ECH deposition reduced or changed to the counter direction as illustrated in figure 2(b). The change in the toroidal rotation velocity around the ECH deposition could be associated with a change in the momentum diffusivity, momentum pinch and/or intrinsic torque [15, 21, 22]. In order to answer this question, further experiments using perturbation techniques will

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**Figure 3.** The improved confinement factor $H_{98y2}$ as a function of electron heating ratio, $P_{ECH}/P_{TOTAL}$, in the PS, WS and NCS plasmas.

$T_e/T_i$ and/or an increase in the counter current intrinsic rotation [15, 21, 22] (to be discussed later).

**3. Global confinement and plasma transport response to ECH in weak shear plasmas**

The advantage of WS on the plasma confinement and transport under dominant electron heating (or $T_e/T_i \sim 1$) were validated in these DIII-D experiments. Figure 3 describes the improved confinement factor ($H_{98y2}$) as a function of electron heating ratio in the core region. Here $H_{98y2}$ is defined as the energy confinement time normalized by the IPB98(y,2) scaling $\propto P^{-0.69}$ [23]. The electron heating ratio (heating power to electrons over the total power) increased from 35% to 60% with the ECH application in NB injected H-mode plasmas while other experimental conditions, such as NBI power and configuration, were kept almost constant. The ratio of $T_e/T_i$ varied from 0.8 to 1 in the core region with ECH. Higher confinement was maintained in WS plasmas as well as NCS plasmas even when the electron heating ratio or $T_e/T_i$ increased. On the other hand, the reduction in the confinement factor with ECH was about 18% in PS plasmas as the electron heating ratio increased from 0.35 to 0.6.

Figures 4(a) and (b) show radial profiles of the power balance ion heat diffusivity ($\chi_i$) and electron heat diffusivity ($\chi_e$) with and without ECH in the WS plasmas calculated by the TRANSP code [24] through the OMFIT workflow manager [25, 26]. The ion heat diffusivity remained almost constant with increased $T_e/T_i$ inside the $T_i$-ITB at $\rho \sim 0.4$. The electron heat diffusivity ($\chi_e$) also increased less with increasing $T_e/T_i$ compared to that of the PS plasma. Accordingly, a higher improved global confinement factor was achieved in the WS plasma at $T_e/T_i \sim 1$. The response of thermal transport to ECH in the WS plasmas is similar to that in the NCS plasmas [18]. Figure 4(c) describes the change in $\chi_i$ with ECH in the ITB regions as a function of the magnetic shear. Closed circles, triangles, and squares denote the data from PS, WS and NCS plasmas, respectively. The ion thermal diffusivity
be needed. On the other hand, the perturbation experiment would be more challenging in the quasi-steady-state operation with better confinement since a small perturbation could significantly disturb the plasma performance.

4. Magnetic shear effect on plasma transport during electron heating

Section 3 and the previous study [17, 18] reported the responses of plasma profile and transport to ECH in PS, WS and NCS plasmas by comparing these values with and without ECH. Magnetic shear dependence at $T_e/T_i \sim 1$ or dominant electron heating would be more informative for ITER and DEMO predictions. This section focuses on the profile and transport characteristics at $T_e/T_i \sim 1$ using data from the ECH injected plasmas. Figures 6(a) and (b) show the magnetic shear ($\tilde{s}$) dependence of the ion and electron thermal diffusivities at the ITB region during ECH, respectively. Here the symbols shown in figure 4 are used. The thermal diffusivities are calculated by the power balance equation in the TRANSP code. The ion thermal diffusivity was clearly reduced when the magnetic shear was varied from positive to near zero. On the other hand, the ion thermal diffusivity was not sensitive to the depth of the negative shear in the range of $-1 < \tilde{s} < 0$. The advantage of lower magnetic shear was also observed in the outer region of $\rho = 0.6$ where the magnetic shear in all PS, WS and NCS plasmas are positive (see Appendix). The results could indicate that a wider region of low magnetic shear would be beneficial for higher confinement during dominant electron heating (or $T_e/T_i \sim 1$). Strong negative shear may not be required necessarily to avoid confinement degradation by electron heating [8], although it can realize better confinement. Little magnetic shear dependence was observed in the electron thermal diffusivity at $\rho$-ITB region in the range of $-1 < \tilde{s} < 0.5$. The region of $\rho = 0.35 - 0.4$ was selected for the electron thermal diffusivity as the region of $\rho < 0.35$ is inside of the ECH deposition (located between $\rho \approx 0.35 - 0.5$). The heat pinch term, which was not evaluated in this study, might dominate the electron thermal transport inside the ECH deposition. Characteristics of the electron heat pinch and its role in the electron temperature profile are described in detail in the recent paper [19].

The comparison between ion and electron thermal diffusivities at $T_e/T_i \sim 1$ are shown by closed symbols in figure 6(c). Open symbols are references of data without ECH where the ratio of ion thermal diffusivity to electron thermal diffusivity ($\chi_i/\chi_e$) was around unity in all magnetic shear operations. The ratio of $\chi_i/\chi_e$ remained around unity in the WS

Figure 4. Radial profiles (a) the ion heat diffusivity ($\chi_i$) and (b) the electron heat diffusivity ($\chi_e$) with ECH and without ECH in WS plasmas. (c) Change in $\chi_i$ with ECH around the internal transport barrier region as a function of magnetic shear. (d) Change in $\chi_i$ with ECH as a function of the toroidal rotation gradient ($V_\phi$-grad). The variation in magnetic shear denoted by (A), (B) and (C) in figure 4(c) was obtained at nearly the same $V_\phi$-grad value.
and NCS plasmas while $\chi_i/\chi_e$ tends to increase in the PS plasmas. Ion thermal transport exhibited a larger relative improvement compared to electron thermal transport as $T_e/T_i$ increases going from PS to WS plasmas. The experimental observations will be discussed with gyrokinetic simulations in the next section.

Weak or negative shear is also favorable for particle and momentum transport even during ECH. The particle and momentum transport were discussed using profile analysis since perturbative experiments were not conducted in this study. Figure 7(a) shows the density gradient around $n_e=0.35$ at $T_e/T_i \sim 1$ with the ECH application. Both density and density gradient decreased across radius with ECH for all magnetic shear cases, as shown in figure 2. The NCS and WS plasmas, however, still have a slightly steeper density gradient at $T_e/T_i \sim 1$ compared to the PS plasmas, indicating better particle confinement or larger inward pinch at weak or negative shear. The toroidal rotation gradient also became steeper when varying the magnetic shear from positive to near zero or negative, as shown in figure 7(b). The effective momentum diffusivity ($\chi_\phi^{\text{eff}}$), which is calculated by the angular momentum balance equation in the TRANSP code, reflects the gradient of the toroidal rotation velocity since the external momentum input was almost constant in this experiment. The effective momentum diffusivity was reduced by changing the magnetic shear from positive to near zero and negative, similar to the ion thermal diffusivity, as shown in figure 8. The correlation between $\chi_i$ and $\chi_\phi^{\text{eff}}$ indicates that the ion channel was especially sensitive to the magnetic shear. The ratio of the effective momentum diffusivity to the ion thermal diffusivity (referred to as the Prandtl number) is lower than unity and does not change with ECH. Recently, the Prandtl number has been evaluated by separating the momentum diffusivity from the momentum pinch term via a transient transport analysis: $m_i \nabla n_e V_e/\partial t = -\nabla \{-m_i \chi_e \nabla n_e V_e/\partial r + m_i V_{\text{pinch}} n_e V_e\} + S$ [27]. Here $n_i$, $m_i$, $\chi_\phi$, $V_{\text{pinch}}$ and $S$ are the ion density, ion mass, momentum diffusion, momentum pinch velocity, and toroidal momentum source, respectively. The momentum pinch is usually negative (inward direction in the plasma radius) in H-mode plasmas as observed in several tokamaks [28]. If the momentum pinch is negative in these plasmas, then the pure momentum diffusivity ($\chi_\phi$) evaluated by the transient analysis will be larger than the effective momentum diffusivity [27], making $\chi_\phi/\chi_i$ closer to or above unity. In JT-60U PS plasmas, the ratio of pure momentum diffusivity to the ion thermal diffusivity ($\chi_\phi/\chi_i$), where $\chi_\phi$ was evaluated by modulation experiments, was around unity and did not change significantly with ECH (see appendix). The results in DIII-D are consistent with these previous observations in JT-60U.

5. Gyrokinetic simulations

Stability analysis was carried out for the PS, WS and NCS discharges using the GKV code [29, 30]. The poloidal wavenumber spectra of the linear growth rates ($\gamma_{\text{lin}}$) and the real frequencies ($\omega$) with and without ECH are compared in figure 9. Figures 9(a) and (b) show $\gamma_{\text{lin}}$ and $\omega$ in PS, WS and NCS discharges without ECH, respectively. Figures 9(c) and (d) are similar calculations with ECH. The ITB regions are dominated by ITG modes in both plasmas with and without ECH for all magnetic shear operations. The ITG growth rates remain almost constant or slightly decrease with ECH in the WS and NCS plasmas, while destabilization of the ITG modes is predicted by significantly increased growth rates with ECH in the PS plasmas.

The results of the stability analysis can be compared to the experimental observations in sections 3 and 4 to discuss the physics of the plasma responses to ECH. The slight increase or even a decrease in the ITG growth rates with the ECH application in the WS and NCS plasmas at $\rho \sim 0.35$ qualitatively agrees with the response of the ion thermal transport. The ion thermal diffusivity increased less in the WS and NCS plasmas at increased $T_e/T_i \sim 1$ through ECH (figures 4(a) and 6(a)). The $E \times B$ shearing rate is about $\sim 0.07$ 1/s at $\rho = 0.35$ for all magnetic shear cases. As the value is less than the maximum of the linear growth rates of 0.4 or 0.9 1/s in figure 9, the confinement improvement appears due to the variation of the magnetic shear. The dominance of ITG modes over TEM at $\rho \sim 0.35$ may explain why the impact of magnetic shear on electron thermal diffusivity is smaller than that on ion thermal
diffusivity (figure 6(b)). That could demonstrate the different magnetic shear responses of ion and electron thermal diffusivities to \( T_e/T_i \) (figure 6(c)). The puzzle would be the reduction in the density gradient (figure 5(a)), that is, if it was monitored only in the core region. The calculated dominant instability changes from ITG to TEM with ECH in the outer radial region (see Appendix). The reduction in the density in the peripheral region by a possible TEM driven outward particle flux could reduce the core density. The increase in the toroidal rotation velocity gradient could be also explained by considering the change in the dominant microinstability in the outer region. The little increase in the ITG growth rates could explain why the toroidal rotation velocity stays relatively constant inside of the ITB region in the WS and NCS plasmas. The destabilization of TEM can enhance a counter current rotation \([22]\), in other words reduce the co-current toroidal rotation velocity as observed in these experiments. As a result, the toroidal rotation

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Figure 6. Magnetic shear dependence of (a) ion thermal diffusivity and (b) electron thermal diffusivity, at \( T_e/T_i \sim 1 \) during ECH. (c) Relation between \( \chi_i \) and \( \chi_e \) during ECH. The data without ECH were plotted with open squares for reference.

Figure 7. Magnetic shear dependence of (a) the electron density gradient and (b) the toroidal rotation velocity gradient around \( \rho = 0.35 \) during ECH.

Figure 8. Relation the effective momentum diffusivity and the ion thermal diffusivity at \( T_e/T_i \sim 1 \) (closed symbols). Data at lower \( T_e/T_i \) (open symbols) included for reference.
velocity gradient would increase around the ITB region (figure 5(b)). One open question is how much the ITG and/or TEM affect the momentum transport diffusivity and pinch velocity. Dedicated perturbation experiments to evaluate the momentum transport coefficients and more detailed simulations are interesting subjects left for future work.

6. Summary

The effect of WS on relative confinement improvement at $T_e/T_i \sim 1$ has been demonstrated through a systematic scan of the magnetic shear while other experimental parameters are kept nearly constant. An ion internal transport barrier is maintained in the WS plasmas as well as the NCS plasmas when $T_e/T_i$ increases with ECH. For a relatively constant $T_e/T_i \sim 1$, the ion thermal diffusivity decreases by changing the magnetic shear from positive to near zero and negative in the range of $0 < s < 1$ while it is not sensitive to the negative shear over the range $-1 < s < 0$. The electron thermal diffusivity shows a smaller but still observable magnetic shear dependence. Although the electron density decreases with increased $T_e/T_i$ in all magnetic shear cases, the WS and NCS plasmas still have modestly steeper density gradient at $T_e/T_i \sim 1$ compared to that in the PS plasmas. The toroidal rotation profile also tends to be steeper in the core region when changing the magnetic shear from positive to near zero and negative. Thus, the thermal, particle and momentum transport have similar dependences on magnetic shear at $T_e/T_i \sim 1$. This results in a relatively high confinement factor of $H_{98y2} \sim 1.2$ in the WS and NCS plasmas even with dominant electron heating condition. Gyrokinetic simulations predict the linear growth rate at the ITB region does not increase with increasing $T_e/T_i$ in the WS and NCS plasmas while increasing in the PS plasmas. This supports the result that there is little impact on turbulent transport at the ITB region in the WS and NCS plasmas as $T_e/T_i$ is increased. The transport and confinement advantages of weak shear operation at $T_e/T_i \sim 1$ supports the development of such scenarios for ITER hybrid operation.

Acknowledgments

The authors would like to thank R. J. Buttery, M. Murakami, C. Holland, C. Chrystal, S. Mordijck, M. Honda, E. Narita and N. Oyama for their fruitful discussions and suggestions. The authors would also like to thank the DIII-D and JT-60 team for great support for this study. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion facility, a DOE Office of Science user facility, under Awards DE-FC02-04ER54698, DE-FG02-08ER54999, DE-AC02-09CH11466, DE-FG02-08ER54984, DE-SC0016154, Grant-in-Aid for Scientific Research (C) 16K06947, and the MEXT, Grant for Post-K priority issue No. 6: Development of Innovative Clean Energy. DIII-D data shown in this paper can be obtained in digital format by following the links at https://fusion.gat.com/global/D3D_DMP. The experiment analysis was performed with the OMFIT integrated modelling framework [25, 26].
Appendix

This paper has focused on identifying the magnetic shear effect on plasma transport and profile at $T_e/T_i \sim 1$ in the ITB region. On the other hand, the profiles of density and toroidal rotation in the outer region exhibit notable changes. A stability analysis is presented here to discuss the profile changes in the outer region. Figure A1 shows linear growth rates at $\rho \sim 0.35$ (or 0.40), 0.46 and 0.58 in NCS, WS and PS plasmas, without ECH in left column and with ECH in right column. The closed squares, circles and triangles indicate the values at $\rho \sim 0.35$ (or 0.40), 0.46 and 0.58, respectively. The linear growth rates increase with ECH or approaching $T_e/T_i \sim 1$ in the outer regions of $\rho \sim 0.46$ and 0.58 for all magnetic shear cases. They are consistent with the increase in the thermal transport in the outer region. An example of the ion thermal diffusivity at the outer region of $\rho \sim 0.6$ is shown in figure A2. The TEM are significantly enhanced with the ECH application at $\rho \sim 0.58$. This could explain the profile changes in the electron density and toroidal rotation in the outer region as TEM can enhance the outward directed particle pinch [6–8] and counter current intrinsic toroidal rotation [22]. Further studies using non-linear gyrokinetic simulations are needed to discuss the profile changes observed in the experiments.

Figure A1. The poloidal wavenumber spectra of the linear growth rates at $\rho \sim 0.35$ (or 0.40), 0.46 and 0.58, from top to bottom: NCS, WS and PS plasmas, left-hand side: without ECH, right-hand side: with ECH. The most unstable mode is described.

Figure A2. The change in $\chi_i$ with ECH at $\rho \sim 0.6$ as a function of magnetic shear in NCS, WS and PS plasmas.
The ratio of the effective momentum diffusivity over the ion thermal diffusivity ($\chi_{\phi}^{\text{eff}}/\chi_i$) does not change with the ECH application, as discussed in section 5. A similar response was observed in JT-60U. The momentum diffusivity and pinch velocity were evaluated in ELMy H-mode plasmas with and without ECH using perturbative techniques ($I_p = 1.0$ MA, $B_T = 3.8$ T, $P_{NB} = 9.4$ MW, $P_{EC} = 0.6–2.1$ MW). Figure A3(a) illustrates relations between the momentum diffusivity and the thermal diffusivity, and the momentum pinch velocity and the momentum diffusivity in positive magnetic shear plasmas. Here $R$ is the major plasma radius. The ratios of both $\chi_{\phi}/\chi_i$ and $R_{\text{pinch}}/\chi_{\phi}$ did not change significantly with ECH (increased $T_e/T_i$). Here $T_e/T_i$ varied from 0.8 to 1.0 in the core region with ECH application.

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**Figure A3.** (a) The momentum diffusivity and (b) pinch velocity in JT-60U ELMy H-mode evaluated by perturbative techniques.
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