Magnetic Shear Effects on Plasma Transport and Turbulence at High Electron to Ion Temperature Ratio in DIII-D and JT-60U Plasmas

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Negative magnetic shear has been demonstrated to mitigate the confinement degradation typically observed with increasing the electron to ion temperature ratio (T_e/T_i), and the mechanisms are now understood in terms of fluctuation measurements and gyrokinetic (GK) simulations in DIII-D steady-state plasmas. The impact of T_e/T_i on plasma transport and confinement is a critical issue for ITER and DEMO, where electron heating by alpha particles will be dominant. In the new experiments in DIII-D negative magnetic shear (NS) discharges, the T_i profile was maintained as T_e/T_i increased through electron cyclotron range of frequency (ECRF) heating, while in positive magnetic shear (PS) plasmas, a large reduction in T_i was observed at increased T_e/T_i. The different transport behaviour has been explained by the turbulence measurements and GK simulations; the increase in T_e/T_i had less impact on broadband turbulent fluctuations in the NS plasmas compared with that in the PS plasmas. The difference reflects changes in thermal energy confinement; the ion thermal diffusivity remained constant in the NS plasma but increased in the PS plasma when ECRF was applied. The reduced confinement degradation at high T_e/T_i with NS has been commonly observed in DIII-D and JT-60U.

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Magnetic shear effects on plasma transport and turbulence at high electron to ion temperature ratio in DIII-D and JT-60U plasmas

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Abstract. Negative magnetic shear has been demonstrated in DIII-D and JT-60U to mitigate the confinement degradation typically observed with increasing the electron to ion temperature ratio (T_e/T_i). In recent experiments in DIII-D negative magnetic shear (NS) discharges, the thermal transport in the internal transport barrier in the negative shear region remained constant and modestly increased in the outer region compared to the positive shear (PS) case, when T_e/T_i increased through electron cyclotron heating (ECH). The reduced confinement degradation at high T_e/T_i with NS plasmas was commonly observed in DIII-D and JT-60U. The mechanism of the different transport responses between the PS and NS plasmas has been assessed in terms of fluctuation measurements and gyrokinetic simulations in DIII-D; NS gave a smaller rise in the low-wavenumber broadband turbulent fluctuations with the increase in T_e/T_i compared with the PS case. It is consistent with gyrokinetic simulations; a smaller rise in the growth rates of the ion temperature gradient mode in the NS plasmas, with increasing T_e/T_i. The increase in the thermal transport in the outer region, where the magnetic shear was positive was correlated with an increase in higher-wavenumber fluctuations and the growth rates of the trapped electron mode when T_e/T_i increased from about 0.8 to 1.1.

1. Introduction

Impact of the electron to ion temperature ratio (T_e/T_i) on plasma transport and confinement is a critical issue for ITER and DEMO, where electron heating by alpha particles will be dominant. Confinement degradation has been observed as T_e/T_i approaches unity with application of ECH to neutral beam heated discharges ($T_i>T_e$) in several tokamaks with positive shear (PS) operation [1-6]. Ion temperature internal transport barriers (T_i-ITBs) were degraded by ECH in JT-60U PS plasmas, and the degradation increases with increasing ECH power [3, 5] and decreasing the plasma current [3]. The reduction in the core ion temperature was reported in DIII-D and explained by a decline in the critical gradient for the ion temperature gradient (ITG) mode [1, 4, 6]. In ASDEX Upgrade, a strong ITB was compatible with predominant electron heating and T_e/T_i~1 in negative shear plasmas by stabilizing double tearing modes with current profile control with ECH [7]. In the last IAEA FEC, JT-60U experimental results showed that the negative magnetic shear (NS) prevented the increase in thermal and particle transport as T_e/T_i approached unity even without current profile modification [5]. However a physics understanding of the underlying mechanisms was not identified due to the lack of fluctuation measurements.

In this paper, the negative magnetic shear effect on plasma transport as T_e/T_i~1 has been demonstrated in DIII-D steady-state scenario plasmas [8] as well as JT-60U plasmas to mitigate confinement degradation, and the physics mechanisms has been assessed using a set of fluctuation measurements and gyrokinetic (GK) simulations in DIII-D. New experiments in DIII-D steady-state scenario plasmas enable a systematic comparison of core turbulence and transport at high T_e/T_i with different magnetic shears, allowing for a better physics understanding of the transport processes.

2. Experimental Conditions in DIII-D

DIII-D has several capabilities to clarify the physics mechanisms of magnetic shear effects on plasma transport at high T_e/T_i by means of various fluctuation measurements, high time and spatial resolution profile measurements, high power ECH and off-axis NBI to control the magnetic shear and the value of T_e/T_i. Magnetic shear effects on thermal and particle transport at increased T_e/T_i toward ~1 were investigated in steady state operation with an ELMy H-mode edge. Changes in transport and turbulence with variations in T_e/T_i were examined in negative and positive shear plasmas. In the series of discharges (without ECH in NS, with ECH in NS, without ECH in PS and with ECH in PS), the plasma current (I_P=1.2 MA), toroidal magnetic field (B_T=-1.9 T), neutral beam power (P_{NB}≈6.2 MW), ECH power (P_{EC}≈3.2 MW) and the plasma shape were kept constant with q_{95}=4.6. Normalized β varied from 2.0 to 2.7, and the line average density was ~4-5×10^{19} m^{-3}. The target q-profile with q_{min}~2.2 was developed by early beam heating for an early L-H transition with a fast I_P ramp-up rate. Obliquely launched ECH of ≈2.2 MW and radially launched ECH of ≈1.0 MW were applied at the same location of ρ=0.3-0.5 in the NB heated plasmas, and T_e/T_i was increased from ~0.7 to ~1.1 across the profile with P_{EC}≈3.2 MW of ECH power.

Density fluctuation measurements were obtained with beam emission spectroscopy (BES) (low-k density fluctuations) [9], Doppler backscattering (DBS) (intermediate-k density fluctuations) [10], and phase contrast imaging (PCI) (medium- to high-k density fluctuations) [11] to obtain multiscale fluctuation measurements over the wavenumber ranges for expected instabilities that drive thermal transport. Low-k Electron temperature fluctuations were observed with correlation electron cyclotron emission (CECE) [12].

3. Magnetic Shear Effect on Transport in DIII-D and JT-60U

The effects of negative magnetic shear on the thermal transport at high T_e/T_i was observed in both DIII-D and JT-60U using ECH. Figure 1 illustrates the response of the ion temperature profiles to ECH in PS and NS operations on DIII-D and JT-60U [5]. The ratio of T_e/T_i was increased from ~0.8 to ~1.1 across the profile in DIII-D, when ECH was applied. A significant reduction in T_i was observed as T_e/T_i increased in the PS DIII-D and JT-60U plasmas as shown in figure 1(a) and 1(c). In the DIII-D PS plasmas, the core-T_e increased about 10%, the electron density (n_e) decreased about 20%, and the toroidal rotation velocity (V_ϕ) decreased about 30% as T_e/T_i increased. On the other hand, a modest or strong internal transport barrier (ITB) in T_i was maintained in NS plasmas on DIII-D and JT-60U as T_e/T_i increased (figure 1(b) and 1(d)). In the DIII-D NS plasmas, the increase in T_e was about 20%, larger than the increase in the PS case. The reduction in n_e and V_ϕ were about 10% and less than 5%, respectively, as T_e/T_i increased, smaller reductions than in the corresponding PS case. Thus, less impact of higher T_e/T_i on thermal transport in the NS plasmas compared with that in the PS plasmas was commonly observed in DIII-D and JT-60U.

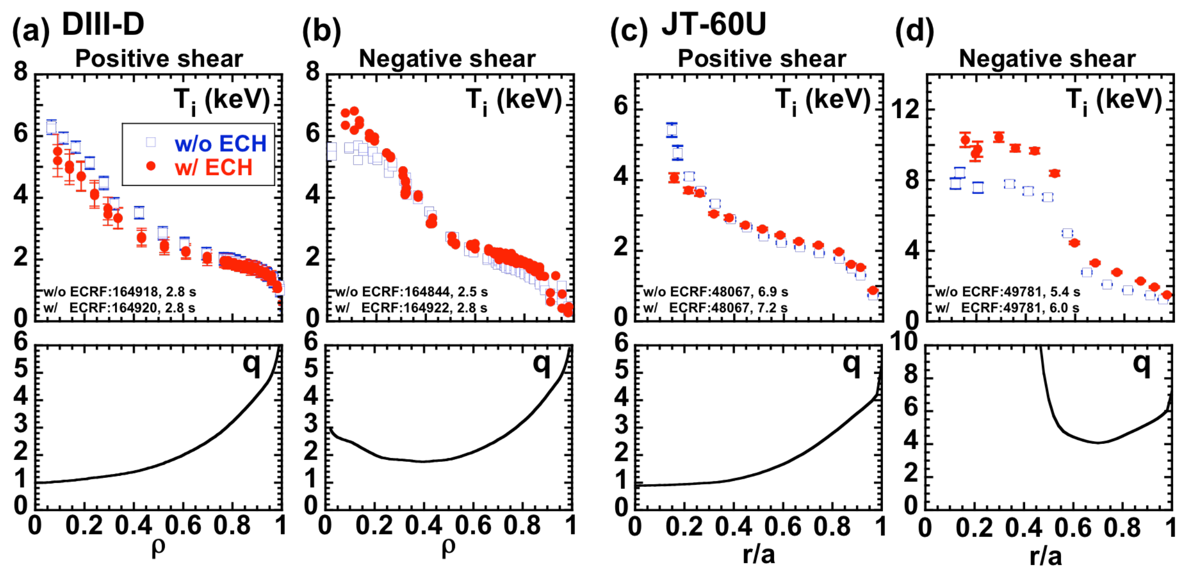

FIG. 1. Responses of the ion temperature (T_i) profiles to ECH in a positive magnetic shear (PS) plasma and a negative magnetic shear (NS) plasma on DIII-D and JT-60U (PS: I_P=1.0 MA, B_T=1.9 T, P_{NB}=7.9 MW, P_{EC}=2.5 MW, NS: I_P=1.2 MA, B_T=3.7 T, P_{NB}=9.3 MW, P_{EC}=2.9 MW).

Figure 2 shows radial profiles of the ion heat diffusivity (χ_i) at low and high T_e/T_i in the DIII-D PS and NS plasmas for the same discharges in figure 1. The ion heat diffusivity significantly increased over the entire radii in the PS plasma with increased electron heating. On the other hand, in the NS plasma, the increase in χ_i (by going from low T_e/T_i to high T_e/T_i) was smaller not only inside q_{min} (or ITB) but also outside q_{min}. The global mitigation of the thermal confinement degradation stems from the lower magnetic shear in NS across the profile relative to PS as shown in Figure 1. The electron heat diffusivity (χ_e) in the NS plasma also increased less with increasing T_e/T_i compared to that of the PS plasma. Global energy confinement degradation exhibits similar scalings (e.g. an L-mode scaling $\propto P^{-0.73}$ and the IPB98(y,2) scaling $\propto P^{-0.69}$), therefore adding 3.2 MW of ECH power in addition to 6.2 MW of NBI power would lead to a thermal energy confinement reduction of ~25%. Using IPB98(y,2) gyroBohm type normalization for H-mode, the confinement factor H_{98y2} reduction was <10% in the NS plasma (from H_{98y2} = 1.23 to 1.19), while the reduction in the PS case was 30% (from H_{98y2} = 1.31 to 1.07). The transport dependence on DIII-D is consistent with that observed on JT-60U [5]. The ion thermal diffusivity remained roughly constant in the negative shear region but increased in the positive shear region with increased T_e/T_i through ECH heating as shown in figure 3. Here the change in χ_i with ECH in the ITB regions is plotted as a function of the magnetic shear in DIII-D and JT-60U. Closed circles, triangles and squares denote the new data from PS and NS operations on DIII-D, respectively. Open symbols denote the data from previous JT-60U results [5]. In the three JT-60U NS plasmas marked by thin arrows, the $E\times B$ flow shearing rates ($\gamma_{E\times B}$) were much smaller than

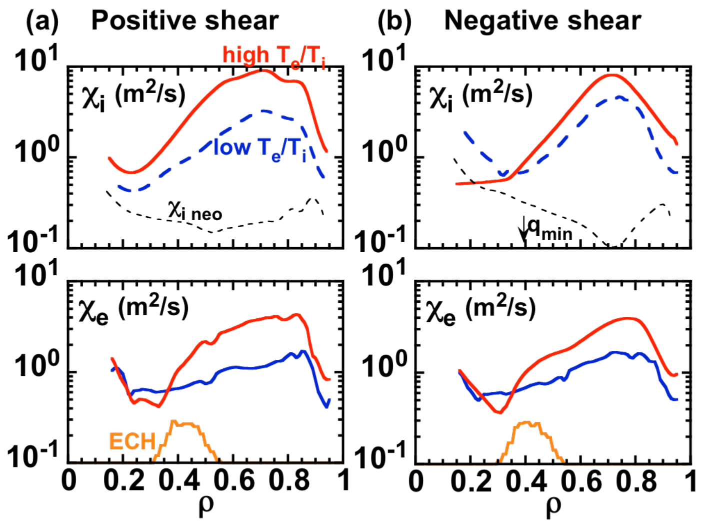

FIG. 2. Radial profiles of the ion heat diffusivity (χ_i), the electron heat diffusivity (χ_e) in DIII-D PS and NS plasmas. Ion neoclassical transport diffusivities ($\chi_{i\ neo}$) and ECH deposition regions are illustrated.

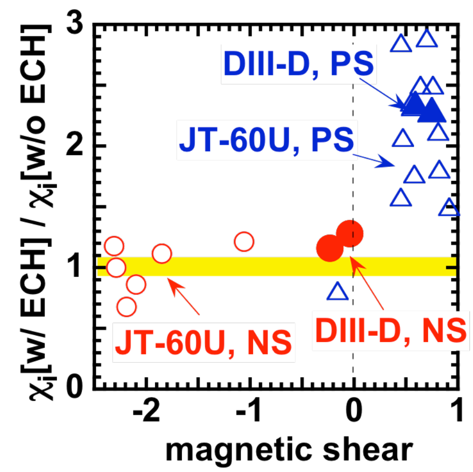

FIG. 3. Change in χ_i with ECH versus magnetic shear around ITB regions. Open circles and triangles show data in JT-60U PS and NS discharges, respectively.

those in other JT-60U and DIII-D NS discharges. The ion thermal confinement remained nearly constant in the NS plasmas with a certain rotation shear. Thus, confinement optimization with NS at higher T_e/T_i has been verified by common observations in DIII-D and JT-60U.

4. Fluctuation Measurements in DIII-D

Fluctuation measurements in the NS plasmas as well as PS plasmas using the suite of fluctuation diagnostics showed a consistency with the transport responses discussed in the previous session. A comparison of the changes in the low-wavenumber ($k_\perp \rho_s < 1$) density fluctuation spectra from BES between the PS and the NS plasmas is shown in figure 4. In the ITB region (ρ~0.46), the increase in frequency-integrated fluctuations at higher T_e/T_i was about 28% in the NS case, which was smaller than the increase in the PS case (~43%). Low-k fluctuations typically reflect ITG modes and trapped electron modes (TEMs) (discussed later). The shift of the fluctuations to lower frequency is attributed to the change in toroidal rotation and/or a change in the mode frequencies. The modest increase in the low-k turbulent fluctuations in the NS plasmas is observed in other radial positions, for example at ρ~0.58 (Figs. 4 c) and d)). The systematic fluctuation measurements in these PS and NS plasmas have identified that the increase in broadband turbulent fluctuations with increased T_e/T_i in the NS plasma was smaller than that in the PS plasmas.

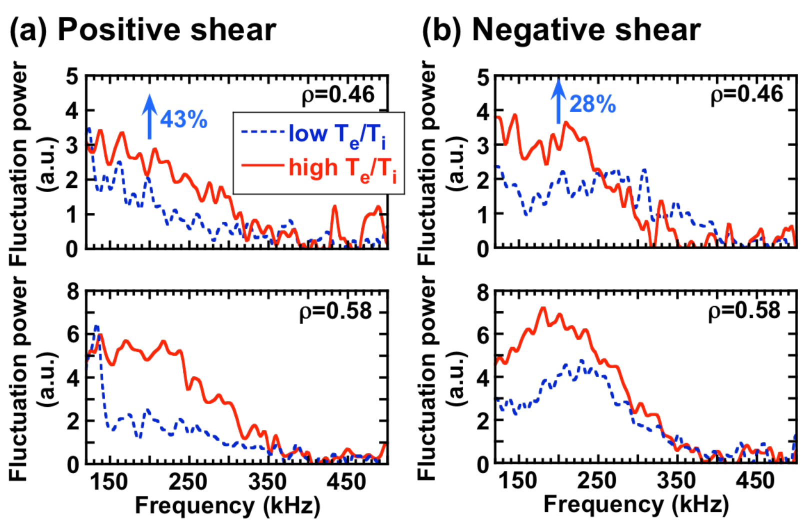

FIG. 4. Density fluctuation spectra of broadband turbulence at low and high T_e/T_i in the PS and the NS plasmas around the ITB region of ρ=0.46 and the out side of the ITB region of ρ=0.58.

Since a phase difference between electric potential (or density) and electron temperature fluctuations can yield plasma transport, the electron temperature fluctuations were examined using CECE. Clear broadband T_e fluctuations were not observed in the negative shear region, whereas a small quasi-coherent mode (~200 kHz) was excited at higher T_e/T_i in the outer region as shown in figure 5. The observations support the idea that increased low-k fluctuations enhanced the thermal transport with increasing T_e/T_i in the outer region.

Intermediate-k fluctuations were examined to consider TEM behaviors which tend to be destabilized by increasing T_e/T_i. Medium to high-k ($k_\perp\rho_s$~0.3 – 5) density fluctuations from PCI, which measures the spatially integrated fluctuations along a vertical chord located at R=1.98 m (ρ>0.4), showed that the peak fluctuation power moved to a higher-k at higher frequencies of f~500-1500 kHz in the high T_e/T_i plasma, as shown in figure 6. That may indicate TEM and/or the electron temperature gradient (ETG) modes can be destabilized with increasing T_e/T_i (discussed later). The fluctuation power at lower frequencies of f<500 kHz increased as T_e/T_i increased, consistent with the BES signals.

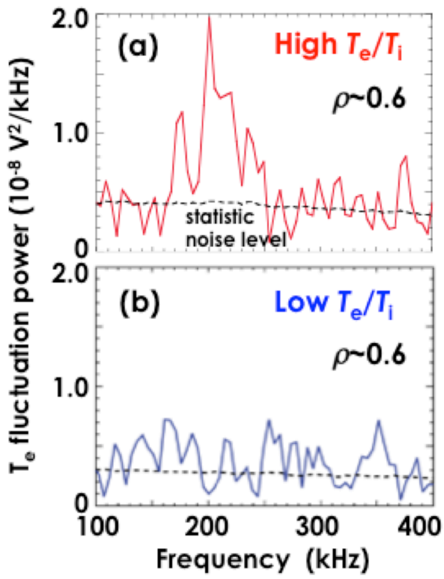

FIG. 5. Electron temperature fluctuation power as a function of the mode frequencies from CECE at (a) high T_e/T_i and *(b) low* T_e/T_i *at* ρ*~0.6 in the NS plasmas.*

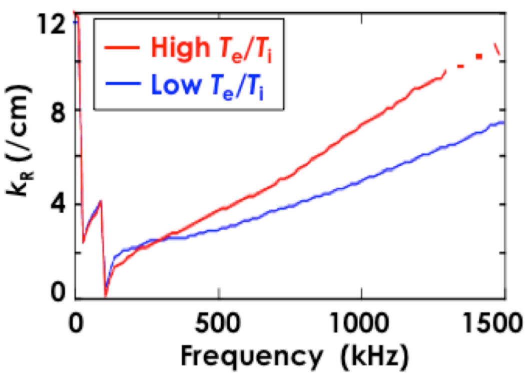

FIG. 6. Radial wavenumber spectra at high T_e/T_i *and low* T_e/T_i *in the NS plasmas from the PCI covering medium to high-k* ($k_\perp\rho_s$~0.3 – 5) *density fluctuations.*

The detailed impact of the intermediate-k fluctuations on transport was examined using the local intermediate-k fluctuations measurement, DBS. The intermediate-k density fluctuations decrease with T_e/T_i in the outer region as shown in figure 7. When we compare the signals at high T_e/T_i condition, no significant difference between the NS and PS

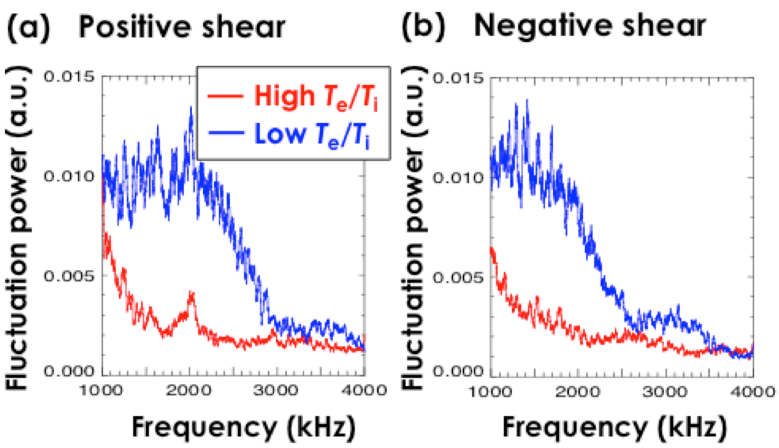

FIG. 7. Intermediate-k density fluctuation power as a function of the frequency from DBS at low and high T_e/T_i *in the PS and the NS plasmas at* ρ*=0.65-0.7.*

was observed. The experimental observations indicate the intermediate-k does not affect transport too much.

5. Gyrokinetic Simulations

Linear and nonlinear gyrokinetic simulations were performed using the GKV electromagnetic gyrokinetic Vlasov code [13] for the DIII-D PS and NS discharges to compare with the transport and fluctuations. The poloidal wavenumber spectra of the linear growth rates (γ) at ρ~0.46 and ρ~0.58 in the PS and NS plasmas are shown in figure 8, respectively. In the ITB region at ρ~0.46, ITG-TEM modes were unstable in PS and ITG modes dominated the turbulence in NS plasmas at low T_e/T_i. As T_e/T_i increased, the linear growth rates in the NS plasma increased more modestly compared to those in the PS plasmas. The thermal transport was still dominated by ITG turbulence in the NS plasma. At the outer region of ρ~0.58, the dominant turbulence changed from ITG to TEM with increased T_e/T_i, and the growth late of higher-k turbulence increased. The calculation strongly correlates with the PCI measurements. Also the smaller increase in the growth rate in the NS plasmas compared with that in the PS plasmas correlates with the thermal transport behavior; the thermal transport increased less in the NS plasmas at increased T_e/T_i.

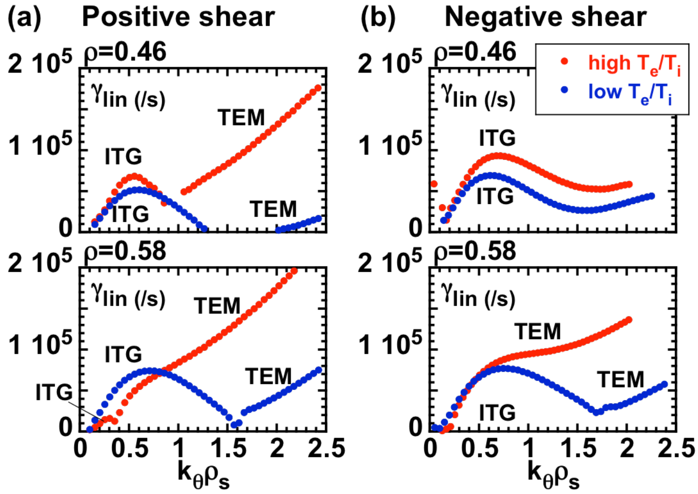

FIG. 8. The poloidal wavenumber spectra of the linear growth rates (γ) at low T_e/T_i (blue) and high T_e/T_i (red) in (a) the PS and (b) RNS DIII-D plasmas.

6. Summary

Confinement optimization with negative shear at higher T_e/T_i has been demonstrated by common observations in both DIII-D and JT-60U. A large reduction in T_i was observed at increased T_e/T_i in the PS DIII-D and JT-60U plasmas, while a modest or strong ITB was maintained in T_i in the NS DIII-D and JT-60U plasmas as T_e/T_i increased. Both the ion and electron thermal transport increased less in the DIII-D NS plasmas, and the reduction of the H_{98y2} factor was less than 10% in the NS plasma, significantly smaller than the 30% reduction in the PS plasmas. The transport dependence observed on DIII-D is consistent with that observed on JT-60U. Systematic comparison of core turbulence and transport at high T_e/T_i

between the PS and NS operations has provided a more comprehensive physics understanding of the transport processes. The low-*k* broadband turbulent fluctuations increase less in the NS plasmas compared to those of the PS plasmas with increased T_e/T_i. The electron heating is correlated with the peak fluctuation power moving to a higher-*k* outside of q_{min} (positive shear region). Gyrokinetic simulations predicted the linear growth rates of ITG or ITG-TEM modes increased less in the NS plasmas compared to those in the PS plasmas, and the dominant mode switched from ITG to TEM in the positive shear region as T_e/T_i increased. From the measurements and theoretical simulations, it can be concluded that the increase in thermal transport at high T_e/T_i can be mitigated by negative magnetic shear operation due to the smaller impact on both the ITG and TEM driven turbulence over the plasma radius, including outside of the radius of minimum safety factor. These results demonstrate a technique to improve confinement with controlled *q*-profile and magnetic shear in ITER and DEMO encouraging to Advanced Tokamak path with a broad current profile.

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References

[1] PETTY C. C. *et al* 1999 *Phys. Rev. Lett.* **83** 3661-3664
[2] ANGIONI C. *et al* 2004 *Nucl. Fusion* **44** 827–845
[3] IDE S. *et al* 2007 *Nucl. Fusion* **47** 1499–1505
[4] MCKEE G. R. *et al 25th IAEA FEC (St Petersburg, 2014)* EX/2-2
[5] YOSHIDA M. *et al* 2015 *Nucl. Fusion* **55** 073014
[6] SCHMITZ L. *et al* 2012 *Nucl. Fusion* **52** 023003
[7] GRUBER O. *et al* 2000 *Nucl. Fusion* **40** 1145-1155
[8] MURAKAMI M. *et al* 2003 *Physical Review Letter* **90** 255001
[9] MCKEE G. R. *et al* 2010 *Rev. Sci. Instrum.* **81** 10D741.
[10] HILLESCHEIM J. C. *et al* 2010 *Rev. Sci. Instrum.* **81** 10D907
[11] DORRIS J. R. *et al* 2009 *Rev. Sci. Instrum.* **80** 023503
[12] SUNG C. *et al* 2016 *Rev. Sci. Instrum.* **87**, 11E123
[13] NAKATA M. *et al* 2016 *Nucl. Fusion* **56** 086010