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Impact of Local Magnetic Shear and T_e/T_i ratio on Confinement Properties in Toroidal Confinement Systems

T. Fukuda[1), N. Tamura[2), K. Ida[2), K. Tanaka[2), M. Yoshinuma[2), T. Kobuchi[4), K. Y. Watanabe[2), H. Funaba[2), H. Igami[2), K. Itoh[2), T. Ido[2), S. Inagaki[5), T. Oishi[2), T. Kato[2), S. Kado[6), S. Kubo[2), M. Goto[2), R. Sakamoto[2), S. Satake[2), A. Shimizu[2), T. Shimozuma[2), C. Suzuki[2), S. Sudo[2), Y. Takeiri[2), K. Toi[2), T. Tokuzawa[2), H. Nakano[2), K. Narihara[2), S. Nishimura[2), T. Notake[2), S. Muto[2), S. Morita[2), Y. Liu[2), H. Yamada[2), I. Yamada[2), M. Yokoyama[2), K. Kawahata[2), A. Komori[2) the LHD experimental group[2)

1) Graduate School of Engineering, Osaka University, Suita, Japan
2) National Institute for Fusion Science, Toki, Japan
3) Budker Institute of Nuclear Physics, Novosibirsk, Russia
4) Graduate School of Engineering, Tohoku University, Sendai, Japan
5) Research Institute for Applied Mechanics, Kyushu University, Kasuga, Japan
6) High Temperature Plasma Center, The University of Tokyo, Kashiwa, Japan

Abstract. As a result of a series of deliberate experiments in a helical device and detailed comparative analysis against the tokamak database, aimed at resolving the role of local magnetic shear and T_e/T_i ratio on confinement, it was found that (1) the pronounced effect of magnetic shear, which has hitherto been considered to be ubiquitous and strongly impacts the core transport in the tokamak experiments, is not quite obvious in a helical device without a transport barrier, and (2) the influence of T_e/T_i ratio strongly prevails commonly in both the toroidal confinement systems in the improved confinement mode. It is thereby suggested that not only the magnetic shear but also the T_e/T_i ratio may carry significance only in plasmas with an already-established improved mode of confinement.

1. Introduction

For the comprehensive understandings of transport phenomena in toroidal confinement systems and improvement of the predictive capability of burning plasmas in ITER, the impact of magnetic shear and T_e/T_i ratio has been extensively investigated in the Large Helical Device (LHD) for comparison with the results of tokamak experiments [1], such as in JET and JT-60U[2], using the international database described in Ref. [3]. The intrinsic advantage of magnetic shear for the transport reduction has been often obscure partly due to the interplay of MHD but occasionally highlighted out of the shadow in tokamaks, such as the high li mode in DIII-D, namely $\beta_N \sim 4l_i$ as well as the scaling of the pedestal pressure written as $W_{ped} \sim I_p^2 l_i$. In particular, spontaneous ITB formation in the T_e profile has been pervasively recognized in tokamaks under the negative shear. In addition, conventional linear models proposed to date considers that the magnetic shear influences the growth rate of turbulence and accordingly the anomalous transport, as expressed in a form: $\gamma_L = k_\theta \rho_s (c_s/a)(a/R)^{1/2} f(s) a^{1/2} (L_n^{-1/2} + L_T^{-1/2})(T_i/T_e)^{1/2}$ for the ITG turbulence, using the commonly accepted notations [4]. On the other hand, Ref. 5 suggests a combination of three different stabilizing mechanisms, namely the density peaking, **E**×**B** shear and magnetic shear, based on the drift wave stability calculations. In order to extract the magnetic shear contribution out of various parametric dependences, a series of dedicated experiments has been designed and performed in LHD, where inherently negative shear is modified solely by the tangentially injected beam driven current.

The direction of tangential nNB (negative-ion based NB) injection was thereby switched from co to ctr and vice versa at different densities and T_i/T_e values under the sustained heating power in the experiment. The influence of the modification in the local magnetic shear, evaluated using the MSE diagnostic, has been extensively investigated in terms of the changes in the kinetic profiles. In addition, the perpendicular pNB (positive-ion based NB) has also been applied at various densities for the ion heating to elucidate the involvement of T_i/T_e ratio. Furthermore, besides the pellet injection, modulated ECH was applied at 29 Hz across the nNB switch for the perturbative transport analysis. This paper addresses the result and implications of the magnetic shear and T_i/T_e for the transport reduction, aiming at comprehensive understandings of transport appertaining to the toroidal confinement systems in common.

2. Impact of Local Magnetic Shear on Confinement

As one of the major experimental difficulties in extracting the magnetic shear contribution out of the transport characteristics is to waive the MHD effect, we have adjusted the position of magnetic axis R_{ax} in a preparatory experiment, aiming at relocating the malign rational surface out of the core region. As shown in Fig. 1, an abrupt reduction in $dT_e/d\rho$ was observed when $\iota = 0.5$ surface resides in the low shear region for the case R_{ax}=3.6m when nNB was switched from co- to ctr-direction. For discharges with larger R_{ax} of 3.75m, which is less vulnerable to MHDs, due to the extended magnetic well structure over half the minor radius, no sign of apparent MHD was observed in the magnetic probe signals. Fig.1 (left column) depicts that $dT_e/d\rho$ remains around 1.5 and the responses of T_e gradient and thermal diffusivity to the magnetic shear are quite subtle, although the magnetic shear at the $\iota = 0.5$ surface is decreased monotonically under the nearly constant heating power of 3.8 MW. Indeed, in weak shear plasmas, MHD characteristics are largely modified by the magnetic shear predominantly at rational surfaces, and local flattening of the T_e profile has been observed in the case of R_{ax} = 3.6 m due to the island formation, which advertently obscures the influence of local

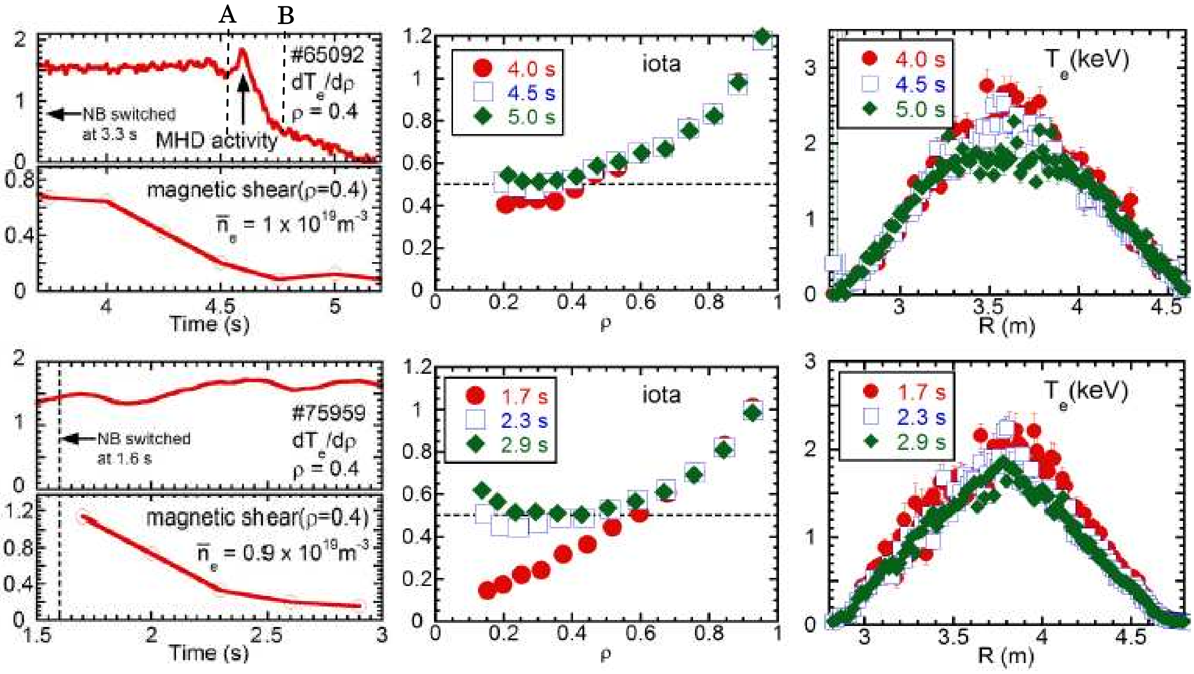

Fig. 1. Changes in $dTe/d\rho$ and magnetic shear (left), iota profile (middle) and T_e profile (right) are compared between the R_{ax}=3.60 m (upper row) and R_{ax}=3.75 m (lower row).

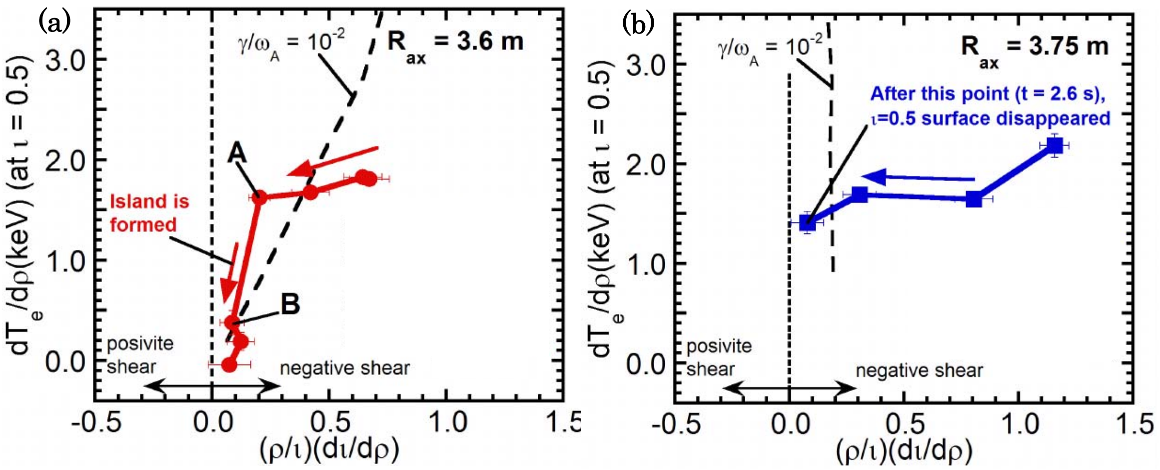

Fig. 2 The dynamic evolutions of $dT_e/d\rho$ and magnetic shear, shown together with the result of low-n ideal interchange mode stability analysis for (a)R_{ax}=3.6m and (b)R_{ax}=3.75m.

magnetic shear on the transport properties [6]. Fig. 2 indicates the result of low-n ideal interchange mode stability analysis. In the case of R_{ax}=3.6m, $dT_e/d\rho$ abruptly decreases as the normalized growth rate crosses the critical value of 10^{-2} under reducing magnetic shear, whereas the reduction of the shear results in the disappearance of the ι= 0.5 surface in the R_{ax}=3.75m case. Here, A and B refer to the times indicated in Fig. 1. Accordingly, R_{ax} =3.75m was chosen throughout the rest of the campaign, and extended experiment has been performed, enhancing the range of magnetic shear with the long pulse nNB injection. The typical discharge waveforms and corresponding iota profiles are respectively shown in Fig. 3. As seen in the top subpanel, the tangential nNB was switched from co- to ctr-direction at 4.3 s, sustaining the total heating power approximately the same at n_e~$6\times10^{18}$$m^{-3}$. Here, B_t=1.3T, and diagnostic beams for the MSE and CXS measurements have been injected for 5s from 0.3s and 2.3s from 3s in the bursting manner, respectively. Ne gas puff at 0.8s was intended to enhance the NB deposition power, and the introduction of Ar at 1.5s was aimed at performing the simultaneous T_i measurement with the crystal spectrometer. A large amount of nNB driven current that reached I_p/B_t~90kA/T has been observed in the Rogowski signal, as depicted in the 4th row. Here, the flattening of iota profiles was observed, similar to the tokamak experiments. The iota value is substantially changed from 0.18 to 0.84 in the core region at ρ = 0.28.

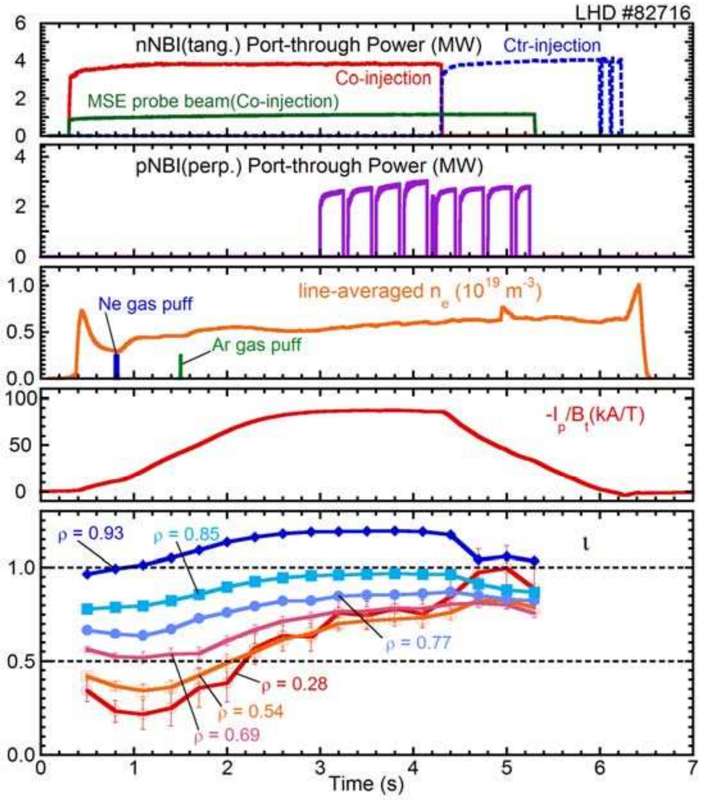

Fig. 3. Typical discharge waveforms for the magnetic shear and T_e/T_i modification experiment performed at R_{ax}=3.75m

However, the T_e and T_i profiles indicate subtle changes, in spite of the substantial modifications in the rotational transform profile. The T_e/T_i ratio remained at around 2, since the absorption power of nNB would be larger than that of pNB in this density regime. This may possibly be one of the reasons why noticeable reduction in the core transport was not observed. The moderately increasing density in the core region, due to the NB fuelling, turns to decrease after the beam is switched from co- to ctr-direction, as a result of the changes in the deposition profile. However, the gas puffing efficiently supplies particles in the outer region, and the profile shape itself in the core region does not vary substantially as a whole without the apparent changes in the n_e gradient. Indeed, not only the equilibrium but also L_n, L_T and T_e/T_i are sustained at nearly constant values within a few percent during the magnetic shear modification. Therefore, it may be conjectured that dynamic changes in the magnetic shear do not simply modify the growth rate of the turbulence that influences the anomalous transport. It was confirmed that the electron thermal diffusivity stays around (5-10)m^2/s and remains roughly the same during the magnetic shear modulation, which is consistent with the subtle changes in the profile shape. In regard to the turbulent fluctuations, vigorous dynamics have occasionally been observed under the magnetic shear modulation, which somehow respond in much faster time scale than the characteristic time scale for either the magnetic diffusion time or the profile evolution. In regard to the perturbative analysis, transient reduction in the local diffusivity was observed when the magnetic shear was reduced.

3. Impact of Local T_e/T_i on Confinement

On the other hand, the influence of T_e/T_i ratio seems to prevail commonly in toroidal devices. Fig. 4 depicts the values of R/L_T against T_e/T_i. The LHD data indicates that R/L_T monotonically decreases against T_e/T_i, regardless of the magnetic shear in the core region. The JET H-mode results are roughly on the extrapolated line for LHD, and the JT-60 ITB database resides above JET in a similar T_e/T_i regime. It was thereby concluded that T_e/T_i may not be significant, though it might exist, and its role is enhanced in the improved mode of confinement. However, the response of R/L_n was obscure, as the neoclassical transport in the core region is generally enhanced in a low collisionality regime in helical devices, and the density profiles were often hollow, which makes the contribution of T_e/T_i on anomalous transport inarticulate.

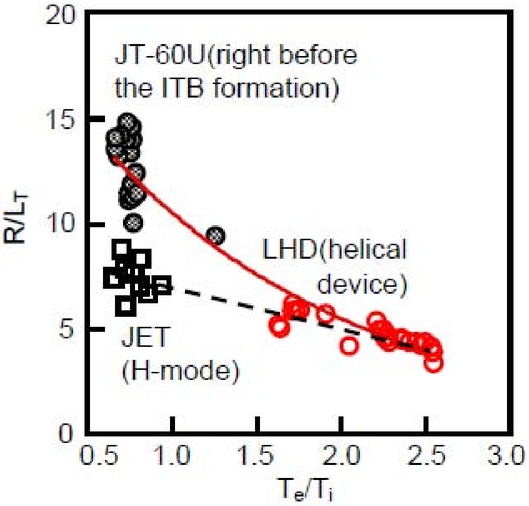

Fig. 4 Values of R/L_T against T_e/T_i at the local maximum of the T_i or T_e profiles in LHD, JT-60U and JET

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