Bifurcated particle transport states driven by regulatory energetic ions in LHD plasmas

M. Nishiura[1,2], S. Satake[1], M. Nunami[1], A. Shimizu[1], T. Ido[3], M. Yoshinuma[1], H. Yamaguchi[1], H. Nuga[1], R. Yanai[1], K. Fujita[4], M. Salewski[5]

[1] *National Institute for Fusion Science, Toki, 509-5292, Japan*

[2] *Graduate School of Frontier Sciences, The University of Tokyo, Chiba 277-8561, Japan*

[3] *Kyushu University, Kasuga, 816-8580, Japan*

[4] *Nagoya University, Nagoya, 464-8601, Japan*

[5] *Technical University of Denmark, Lyngby, 2800 Kgs., Denmark*

e-mail address: nishiura@nifs.ac.jp

We have experimentally demonstrated that the electron density profile can bifurcate into two steady states, either peaked or flattened, following a carbon pellet injection. This bifurcation is regulated by the anisotropy of energetic ions produced from neutral beams. In the two steady states, the gyrokinetic theory indicates that the ion temperature gradient (ITG) instability was excited, affecting turbulent transport. To investigate further the impact of the regulatory energetic ions, we conducted additional experiments without pellet injection to separate the pellet effect. We found that after energetic beams perpendicular to the magnetic field—where the perpendicular and parallel ratio of the energetic ion stored energy $En_{\perp}/En_{\|} = \infty$ —the hollowed electron density profile transits into the peaked one, which was accompanied by the accumulation of impurity carbon. This characteristic is consistent with the behavior observed during pellet injections.

Many studies on thermal particle transport have been reported because it affects the performance of fusion reactors [1]. Recently, positive effects of energetic ions on confinement conditions have been reported. Mazzi et al. reported that in JET, ions in the MeV region excite Alfvénic instabilities and improve confinement by suppressing turbulence [2]. In KSTAR, a 100 million K plasma is sustained for 20 s to suppress the buildup of edge instabilities and impurities due to the high fraction of fast ions [3]. Most thermal particle transport studies, which determine the performance of fusion plasmas, have focused on the transport of thermalized electrons and ions in high-temperature plasmas due to turbulence suppression. On the other hand, in a recent study [4], we found that the anisotropic nature of the energetic beam for heating can be exploited to induce spontaneous particle transport phenomena that significantly affect the confinement performance of high-temperature plasmas.

We have recently found that the energetic ions drive the particle transport in the plasma core of LHD. The features are summarized in Table 1. The electron-density profile decayed into two steady states after a carbon pellet injection when we regulated the energetic ion anisotropy by changing the power ratio of perpendicular and tangential neutral beams $P_{\perp}/P_{\|}$. The Fokker Planck simulation evaluated the ratio of the perpendicular and parallel energetic ion stored energy $En_{\perp}/En_{\|}$. For $En_{\perp}/En_{\|} < 0.35$, n_e has a flat profile and n_c has a hollow profile, the so-called "impurity hole" state; for $En_{\perp}/En_{\|} \sim 0.4$, dn_e/dr and dn_c/dr change steeply to peaked profiles. In contrast, $En_{\perp}/En_{\|} > 0.47$ can access an

Table 1. Heating conditions and observed density states with a carbon pellet injection.

shot	**$P_{\perp}$ [MW]**	**$P_{\|}$ [MW]**	**$P_{\perp}$ / $P_{\|}$**	**$En_{\perp}/En_{\|}$**	**n_e profile**	**n_{c0}/n_{e0}**	**Pellet**
#182745	9.9	8.2	1.2	0.35	Flatten	0.015	Yes
#182744	14.0	5.4	2.6	0.77	Peaked	0.039	Yes
#182736	14.0	8.1	1.7	0.47	Peaked	0.039	Yes
#188832	0-11	0-4	0-∞	0-∞	Hollowed/flattened/peaked	0.006-0.013	No

inward flux state to form peaked density profiles. The change in the ratio of n_{c0}/n_{e0} at the plasma center is considered to reflect the changes in the transport state. Controlling the energetic ion anisotropy leads to a novel concept of particle control in the burning plasmas of nuclear fusion reactors.

According to the experimental results, neoclassical E_r produced by thermal bulk ions and anisotropic energetic ions were evaluated by the GNET code and its module DGN/LHD. The simulation shows that E_r = -10 kV/m at normalized small radii ρ = 0.3 - 0.5 in #182744 and #182745, which is comparable to the E_r measured by a heavy ion beam probe diagnostic, suggesting that an electric field of that magnitude cannot significantly alter the bulk electron and ion transport. Since the ion temperature gradient is almost unchanged at t = 5.01 s for both states, we cannot conclude that turbulence excited by the ion temperature gradient drives the particle transport as in [7]. We analyzed the linear ITG instability using the GKV code and plasma parameters from #182744 and #182745 to investigate how turbulence affects plasma transport. In Fig. 1, the ITG mode is unstable for ρ = 0.2 (or 0.18) and 0.5 in peaked and flattened density profile cases. The ITG mode for the peaked density profile has a higher growth rate γ at the core region, while the real frequency ω exists in almost the same range. This result implies the possibility of the particle transport driven by turbulence in both cases. The fueling effects are unlikely to explain the phenomena from the source profile of NBs and impurity density profiles.

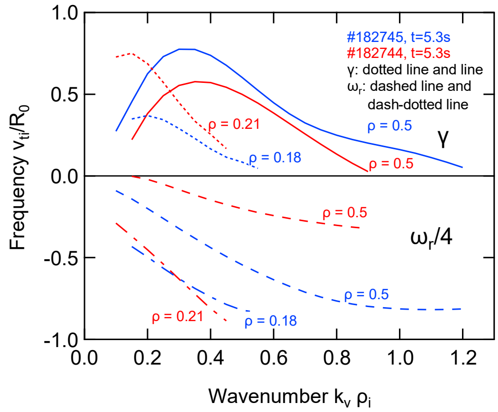

Fig. 1 Comparison of the growth rate γ and real frequency ω spectra at the core and the foot of the density peaking for micro instabilities after the carbon pellet injection of LHD shots #182744 (peaked density profile) and #182745 (flattened density profile) by regulatory energetic ions.

To validate separately the pellet effect, we demonstrated the hydrogen gas puffing discharge with hydrogen neutral beams for shot # 188832 in Fig. 2. The electron densities at ρ = 0 and 0.75 are plotted to monitor the profile shape. At t = 3.3 s, the plasma starts up by ECH and tangential NB#1. When the anisotropy of parallel energetic ions is switched to perpendicular ones by perpendicular NB#4 at t = 3.6 s and slightly delayed perpendicular NB#5 at t = 3.8 s, the density peaking occurred and reached 7 $\times 10^{19}$ m^{-3} at the plasma center. A gradual impurity accumulation was also observed up to ~ 1$\times$ 10^{18} m^{-3} at the center during the peaked density. From t = 5.8 s, the parallel energetic ions start sustaining the discharge. The peaked density profile transits to the flattened one. The experimental results indicate that the regulatory energetic ions promote inward and outward transport in confined plasma and burning areas. This new finding holds promise for a control knob of nuclear fusion reactors to enhance fusion power output.

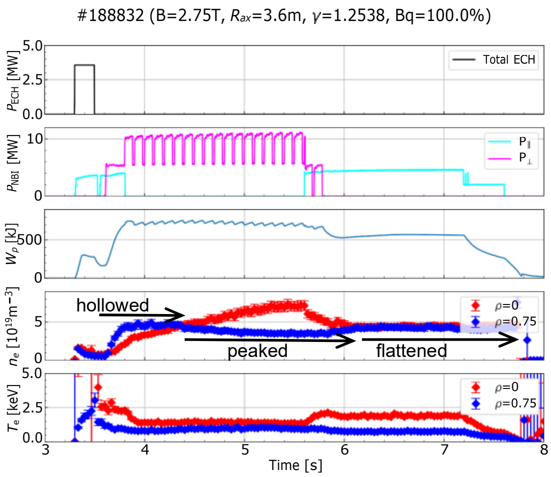

Fig. 2 LHD shot#188832 for heating powers of ECH and parallel and perpendicular NBIs, diamagnetic energy, and electron densities and temperatures at ρ = 0 and 0.75. Bifurcated transport states start at t = 3.6 s from a hollowed profile to a peaked electron density profile.

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