Bifurcated particle transport states driven by regulatory energetic ions in LHD

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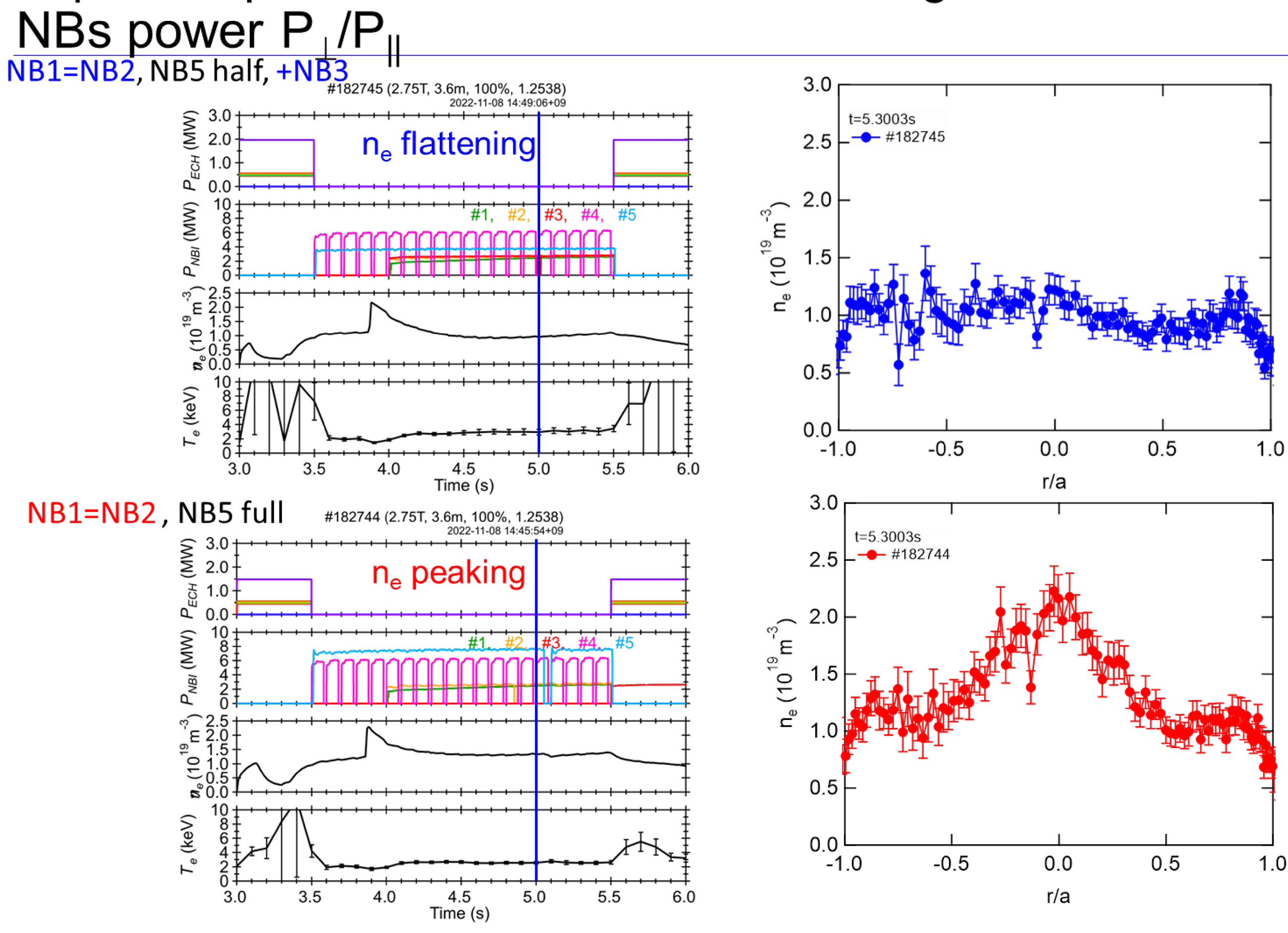
ABSTRACT

Understanding particle transport in fusion plasmas is a critical issue that determines core performance. As a new transport mechanism, the anisotropy of energetic ions has been reported to cause a reversal of radial particle transport. It is experimentally demonstrated that, following carbon pellet injection, the electron density profile bifurcates into two steady states, either peaked or flattened. In both steady states after pellet injection, gyrokinetic theory suggests that ion temperature gradient (ITG) instabilities are excited, thereby influencing turbulent transport. To further clarify the role of regulatory energetic ions, additional experiments were conducted without pellet injection to eliminate pellet effects. During discharges, the anisotropy of energetic neutral beams, expressed experimentally as $P_\perp/P_\parallel$ (equivalent to the stored energy ratio of energetic ions, $En_\perp/En_\parallel$) , was varied between 0 and ∞. The electron density profile was found to be hollow for $P_\perp/P_\parallel$ = 0-1.2, peaked for $P_\perp/P_\parallel = \infty$, and flattened for $P_\perp/P_\parallel$ = 0. The spatial profile of carbon impurities exhibited a similar profile. This behavior was consistent with that observed under pellet injection. Analysis indicates that particle fueling from perpendicular neutral beam injection does not affect the peaked electron density profile, and that carbon impurities originate exclusively from the wall. These results imply that the effect of velocity anisotropy is attributed to a driving mechanism other than neutral beam fueling. The findings suggest that the velocity anisotropy of energetic ions may serve as a new transport knob for controlling particle transport in burning plasmas.

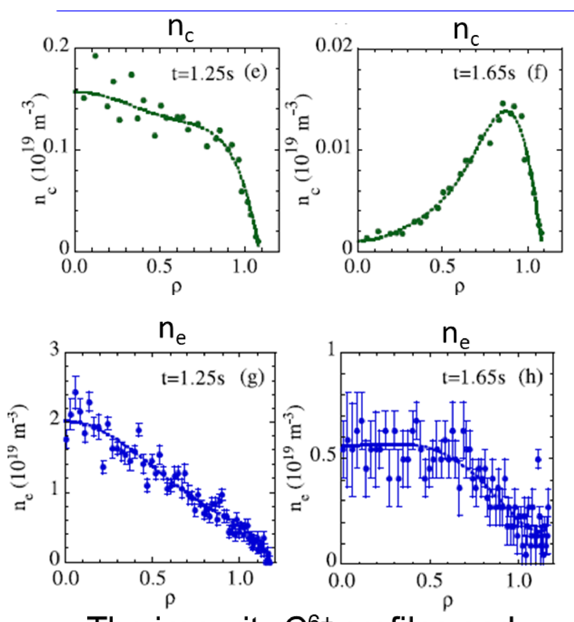
Improved particle confinement with energetic ion anisotropy controlled by NBs power $P_\perp/P_\parallel$



NBs sustain D plasmas with an impurity accumulation or a hole state.

shot	$P_\wedge$ [MW]	$P_{||}$ [MW]	$P_\perp / P_{||}$	$En_\wedge/En_{||}$	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

Bulk and impurity ion transport in LHD



The impurity C^{6+} profiles and electron density profiles in an impurity hole case[4].

From a radial density profile in LHD, transport analysis of bulk and impurity ions has been performed [5].

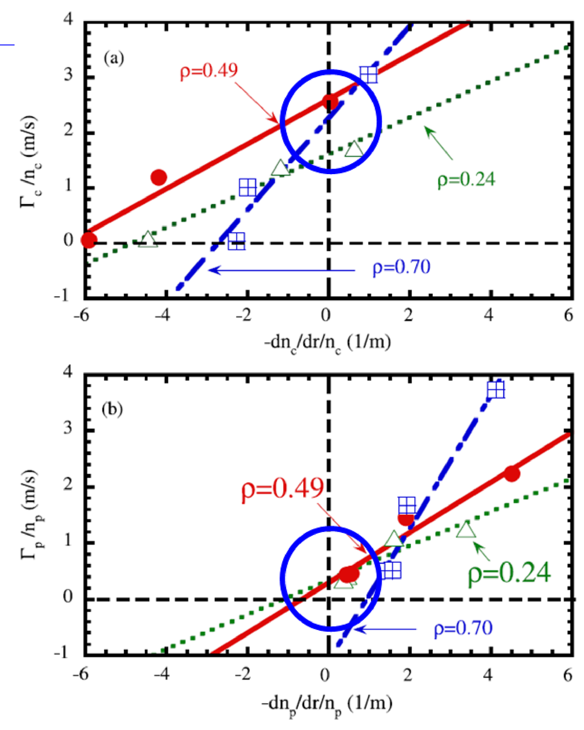
The radial particle flux normalized by the density reads

$$\frac{\Gamma}{n} = -D\frac{\nabla n}{n} + V$$

The outward convection(positive V) exists in the impurity hole state.

The neoclassical prediction is negative V. Therefore, they in [3] conclude that the ion gradient drives the outward convection.

This case focused on the exhaust of impurity ions from the core plasma.
They considered that the turbulence induces the radial transport.



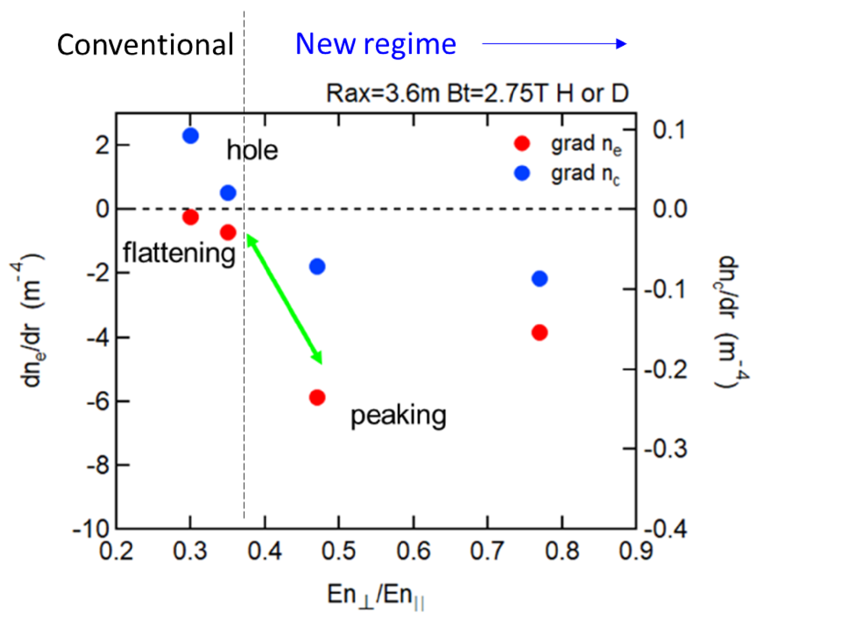
Transport analysis for bulk and impurity ions in an impurity hole case[4]. The condition is similar to shot#182745.

Dependence of density gradient on energetic ion anisotropy

The energetic ion anisotropy is varied.

- Increasing the $En_\perp/En_\parallel$ forms the peaked density profiles.
- The low $En_\perp/En_\parallel$ exhausts the impurity carbon ion in the core plasma at r/a < 0.5.

The particle transport is controlled by the energetic ion anisotropy $En_\perp/En_\parallel$.



Dependence of density gradients for bulk (red circles) and impurity ions (blue circles) on the $En_\perp/En_\parallel$.

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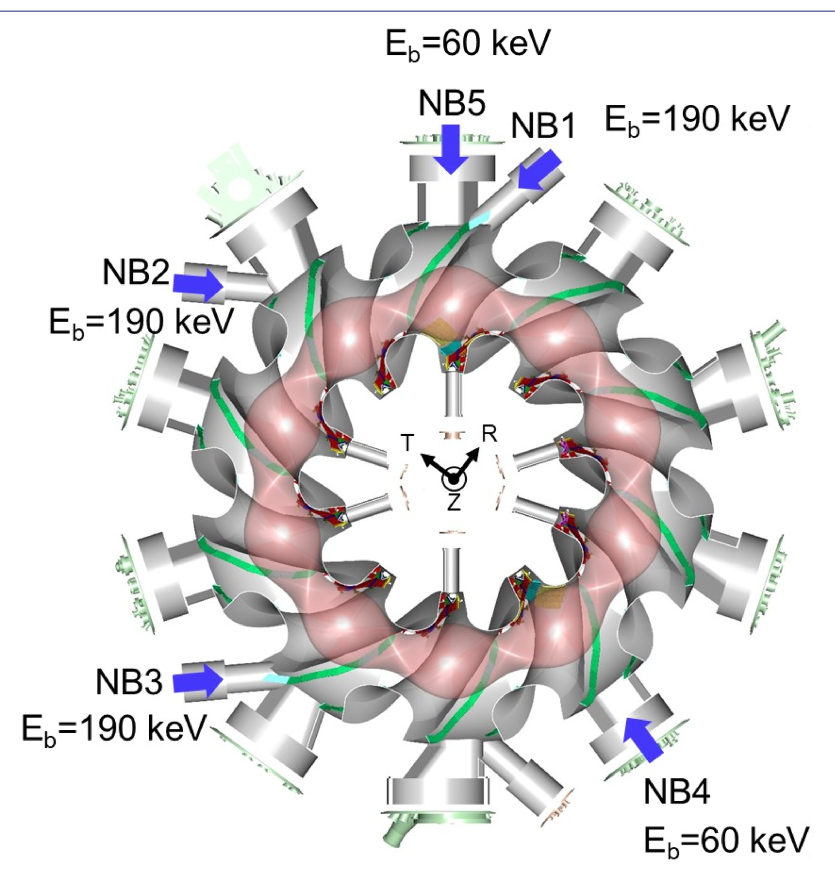
Energetic ions as a control knob of transport in LHD

The neutral beams (NBs) for plasma heating are available at the LHD with the tangential beam power $P_\parallel$ for Ctr-NB#1, Co-NB#2, and Ctr-NB#3 and the perpendicular beam power $P_\perp$ for NB#4 and #5.

The beam energies for the perpendicular and the tangential NBs are fixed at 60 keV and 190 keV, respectively.

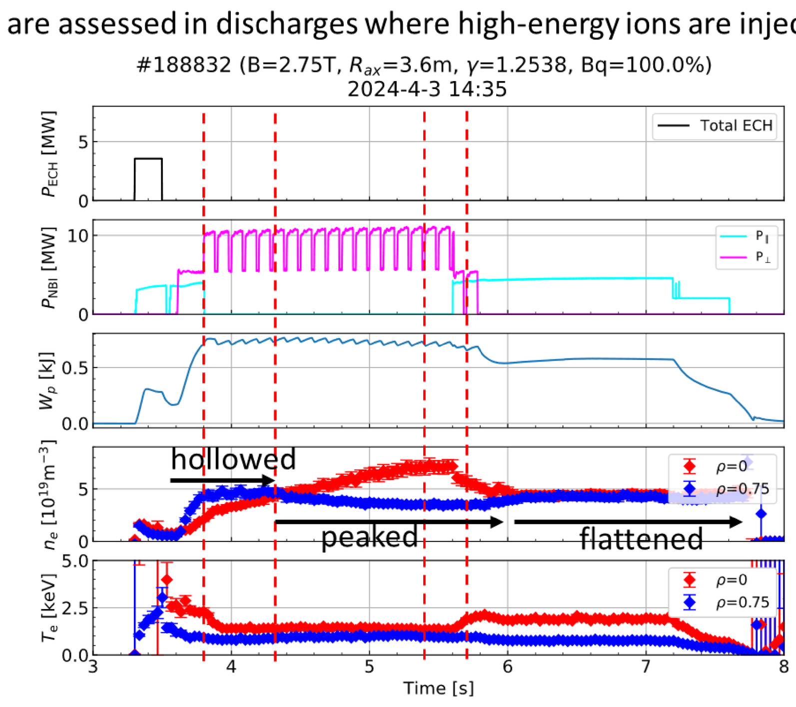
The beam currents of ion sources are changed to control $P_\perp$ and $P_\parallel$ in the experiments.

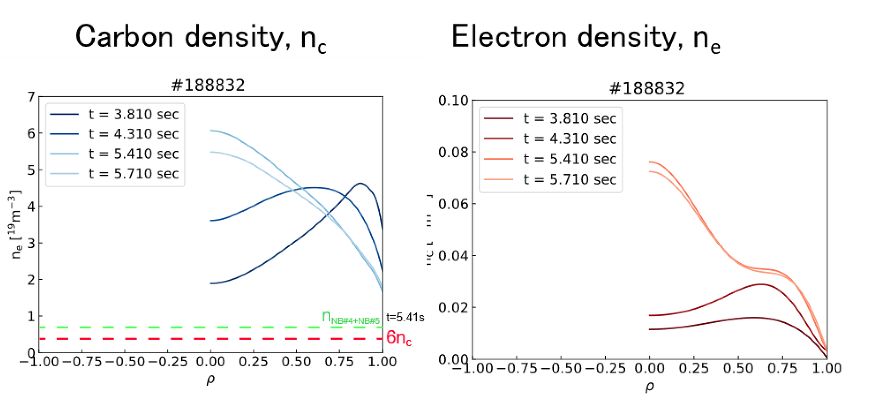


Impurity C^{6+} ions flow inward and outward associated with electrons.
Source of C^{6+} ions from the plasma edge should be small. However, flow direction changes by $P_\perp / P_{||}$.
Therefore, the transport dominates the diffusion and convection rather than a fueling effect.

Reversal of radial particle transport driven by regulatory energetic ions

To exclude the rapid density changes and impurity influence from pellets, radial transport and the resultant density profile are assessed in discharges where high-energy ions are injected perpendicular to the magnetic field without pellets.





- $P_\perp/P_\parallel$ changes from 0 to ∞
  follow profile → peak profile → flatten profile
  Outward flux Inward flux Outward flux
- Without C pellet, the density profile shows the same characteristics.
- Impurity Carbon and NB fueling is one order of magnitude lower than the electron density.

Control of the particle profile during a single discharge is achievable through the velocity anisotropy of energetic ions, and this has been demonstrated up to an electron density of $n_e = 6 \times 10^{19}\ \mathrm{m}^{-3}$.

Summary

We have identified a novel particle confinement state in which applied energetic ion anisotropy changes the core density profiles with peaking and flattening in the LHD experiments.

- Without pellet injection, the reversal of radial particle flux has been observed by a reduced anisotropy of stored energy for energetic ion $En_\perp/En_\parallel$, resulting in an electron density peaking in the core plasma of the LHD.
- The density peaking evolves up to $6\times10^{19}\ \mathrm{m}^{-3}$ which perp. NB stops injecting.
- Analysis of the E_r effects induced by perpendicular NB suggests a possible improvement in the confinement of trapped particles. However, the relation between high-energy-ion–driven E_r formation, turbulence excitation, and the resulting transport requires further investigation.

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