17th International Stellarator / Heliotron Workshop
12-16 October 2009 Prinston, New Jersey, USA

Observations of Impurity Hole on LHD

M.Yoshinuma, K.Ida, M.Yokoyama, C.Suzuki, M.Osakabe, H.Funaba, K.Nagaoka, S.Morita, M.Goto, N.Tamura, S.Yoshimura, Y.Takeiri, K.Ikeda, K.Tsumori, H.Nakano, O.Kaneko, and LHD Experiment Group

National Institute for Fusion Science (NIFS), Toki, Japan

Contents

Introduction

Simultaneous achievement of improved energy confinement and low impurity confinement is one of the crucial issues to realize the plasma relevant to nuclear fusion because impurities cause reduction of the fusion power density by enhancing the cooling of the plasma with radiation and also by diluting the hydrogen fuel.

Impurities tend to accumulate in the plasma with an improved confinement mode such as H-mode and internal transport barriers (ITB) in tokamaks.

To avoid impurity accumulation

Impurity accumulation can be avoided in the ELMy H-mode discharges.

⇒ Impurity accumulation is **still a problem** in the discharges of the **ELM-free H-mode** and the discharges with an **internal transport barrier**.

Temperature screening effect due to an ion temperature gradient is expected in tokamaks and the outward convection of impurities was confirmed in an improved confinement plasma with a weak density gradient and a strong ion temperature gradient on DIII-D [M. R. Wade et al., Phys. Rev. Lett. **84** (2000) 282].

Introduction

In non-axisymmetric system

High energy and low impurity confinement times are demonstrated in high density H-mode (HDH) plasma in the Wendelstein 7-AS stellarator by **density profile control** with an intensive gas puff [K. McCormick et al., Phys. Rev. Lett. **89** (2002) 015001].

Radial electric field is strongly affected to the impurity transport.

The **impurity convection can be outward** and the impurity density can be hollow due to the **positive radial electric field** in the **electron-ITB** plasmas, where the electron temperature is much higher than the ion temperature.

Inward convection of impurities is expected from neoclassical theory in the plasma with a **high ion temperature gradient** because of the **negative radial electric field**.

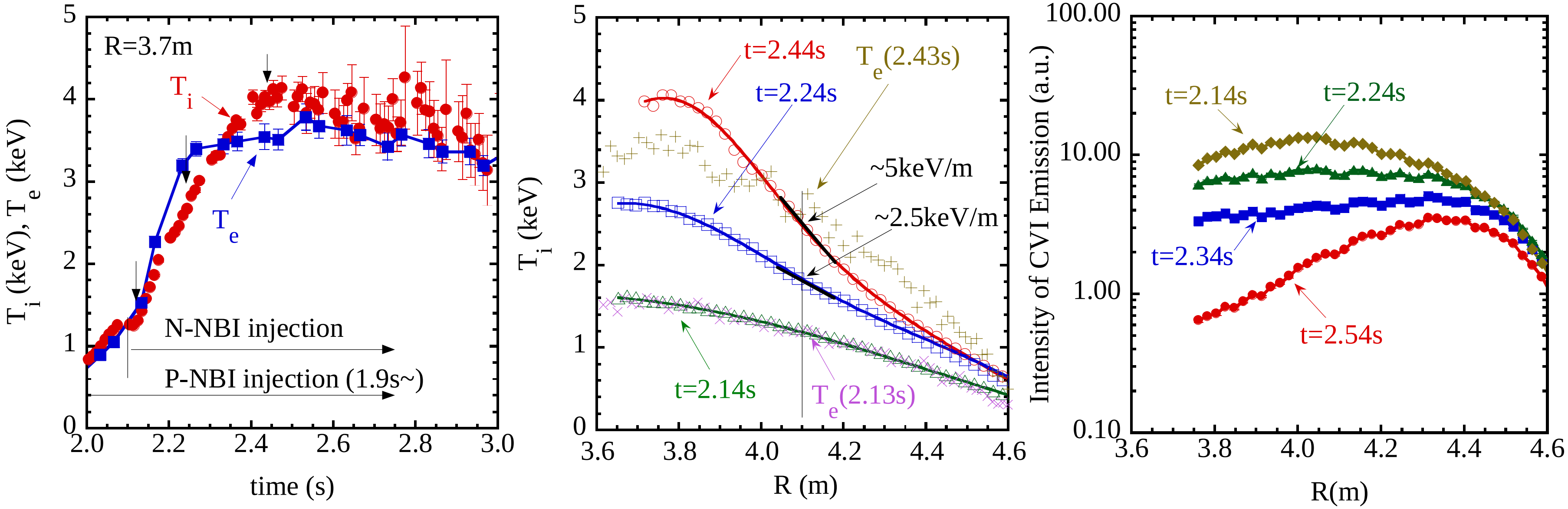
⇕

Extremely hollow impurity profiles due to an **outward convection** is observed in the plasma with **a steep gradient of ion temperature** is observed in LHD.

High ion temperature plasma on LHD

Ion and Electron Temperature

Intensity of CVI



Higher ion temperature plasma is produced by injection of N-NBI into the plasma sustained by the P-NBI.

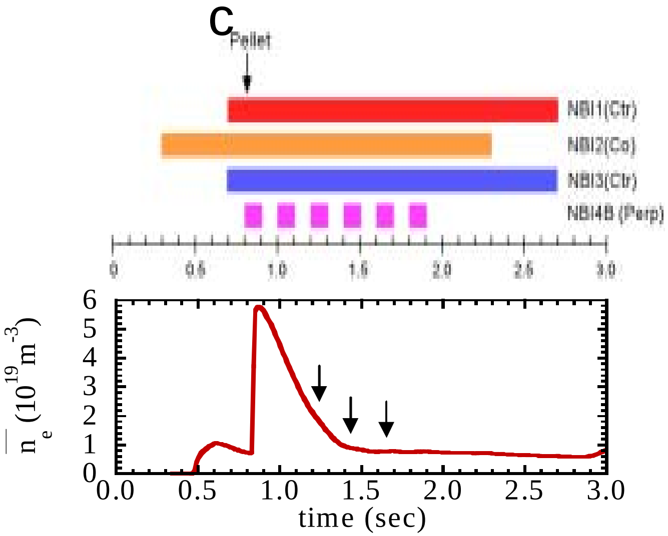
The ion temperature become higher than the electron temperature at the plasma core with a steep gradient of ion temperature near the mid-radius of the plasma.

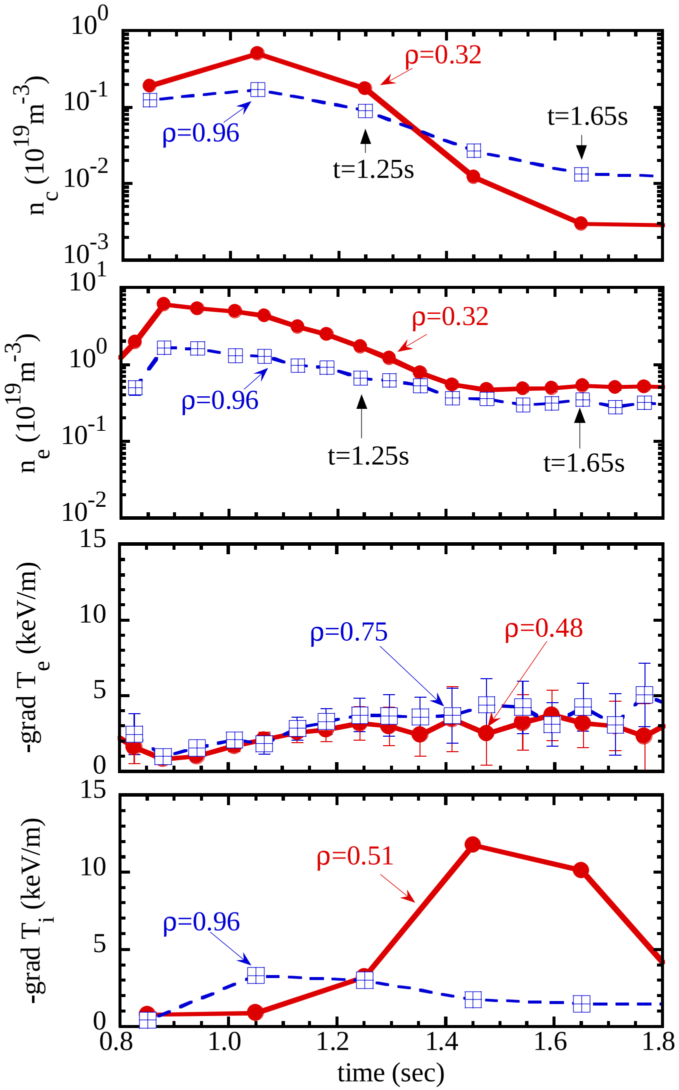
Intensity near the center of the plasma decreases faster than that at the plasma edge.

Outward flow of Impurity → **Impurity Hole**

Experiment of Impurity Hole

A Carbon Pellet is injected at t=0.8s





Decay speed of carbon at the edge is similar to that of electron density.

The carbon density near the plasma core decreases faster than that at the edge.

There is no significant change in the gradient of T_e.

The gradient of T_i increased during the decay phase of the density.

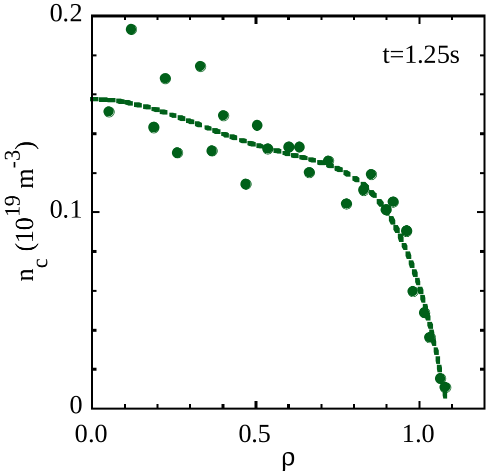
B_0=2.676T, R_{ax}=3.6m, γ=1.254, Bq=100%

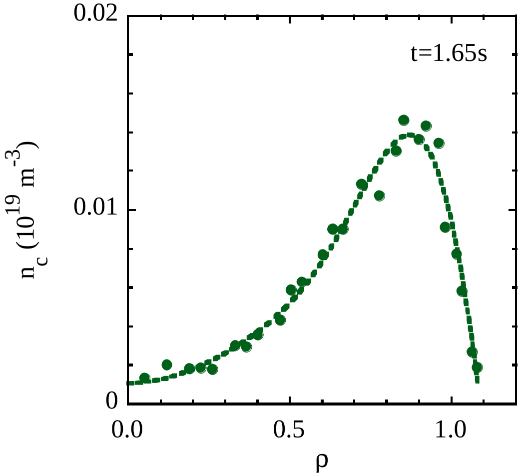
Density profiles before and after the formation of the Impurity Hole

Before **After**

Carbon

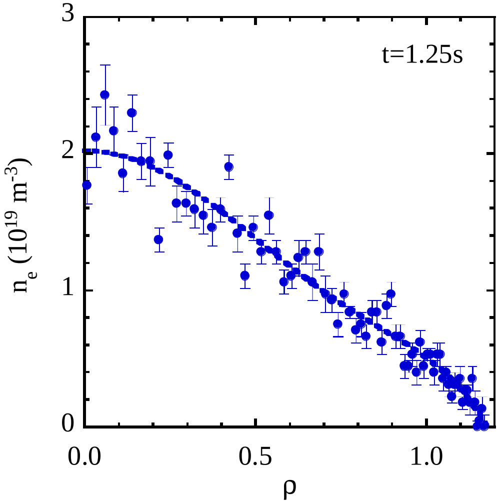
Extremely hollowed profile is produced.

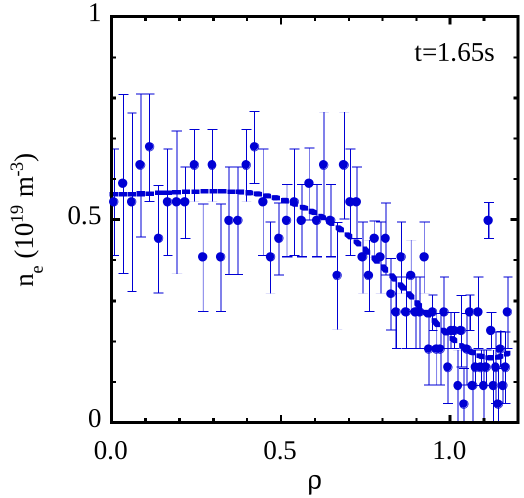




Electron

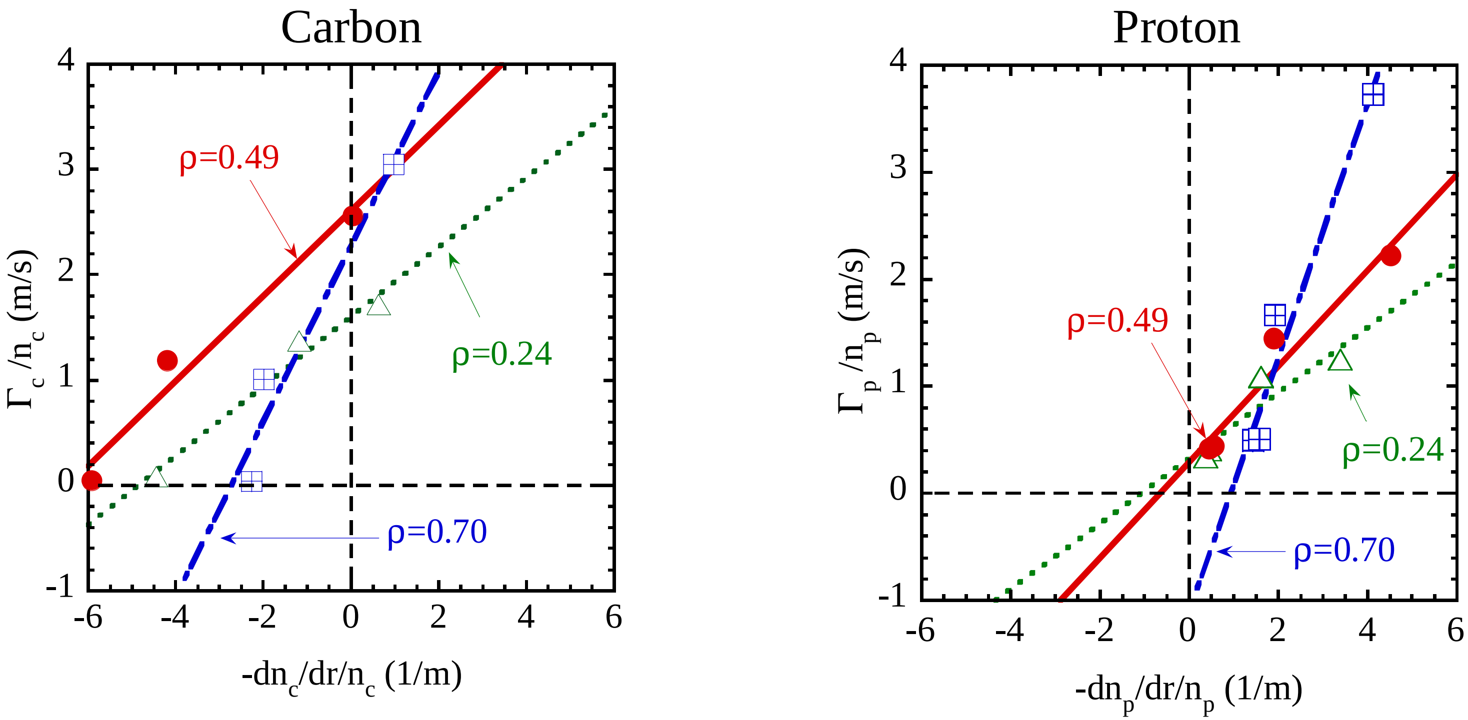
Peaked profile is kept after the impurity hole.





$n_c/(n_c+n_p) \sim 0.03$ after the formation of the impurity hole.

Particle flux v.s. Density gradient



Particle flux normalized by the density.

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

Both the diffusion coefficients of impurity and bulk ions show similar trends, where the diffusion coefficient becomes large near the plasma edge.

There are clear differences in convection velocity between the carbon impurity and bulk ions.

Diffusion Coefficient and Convection Velocity

The **diffusion coefficient** of carbon impurity **increases towards the edge,** while the profile of the diffusion coefficient of **protons is quite similar** to that of carbon impurity.

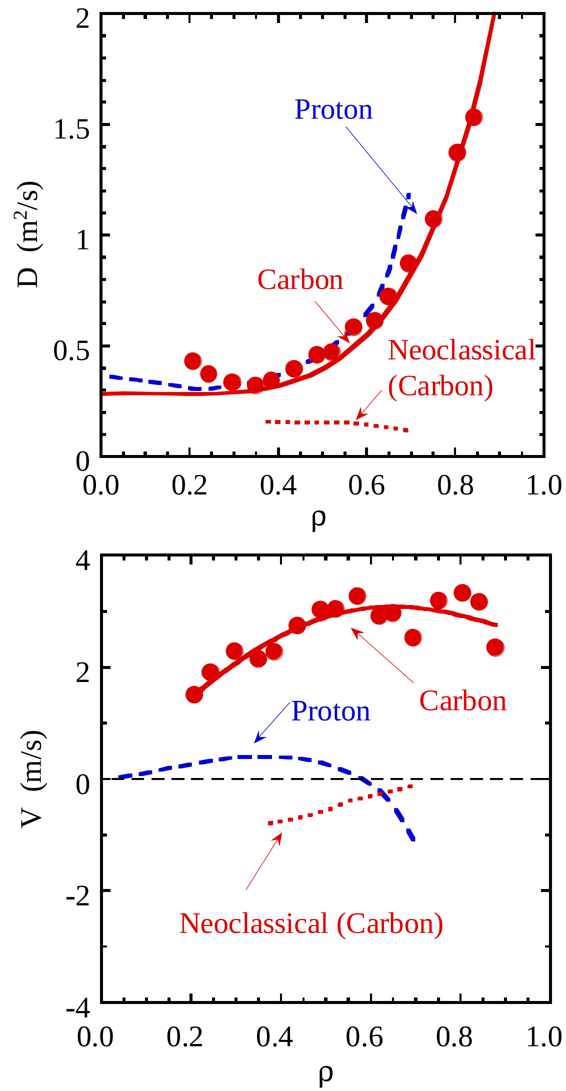
The **convection velocity of carbon impurity is large and positive**, while the convection velocity of **proton is close to zero** in the plasma core and negative near the edge.

The **extremely hollow profile of carbon** is attributed to the **large positive convection velocity and small diffusion coefficient** in the plasma core region.

The **direction** of the convection velocity **is opposite** to the **neoclassical prediction**.

➡ Turbulence driven outward convection

Diffusion Coefficient D and Convection Velocity V



Dependence on ion temperature gradient of convection velocity

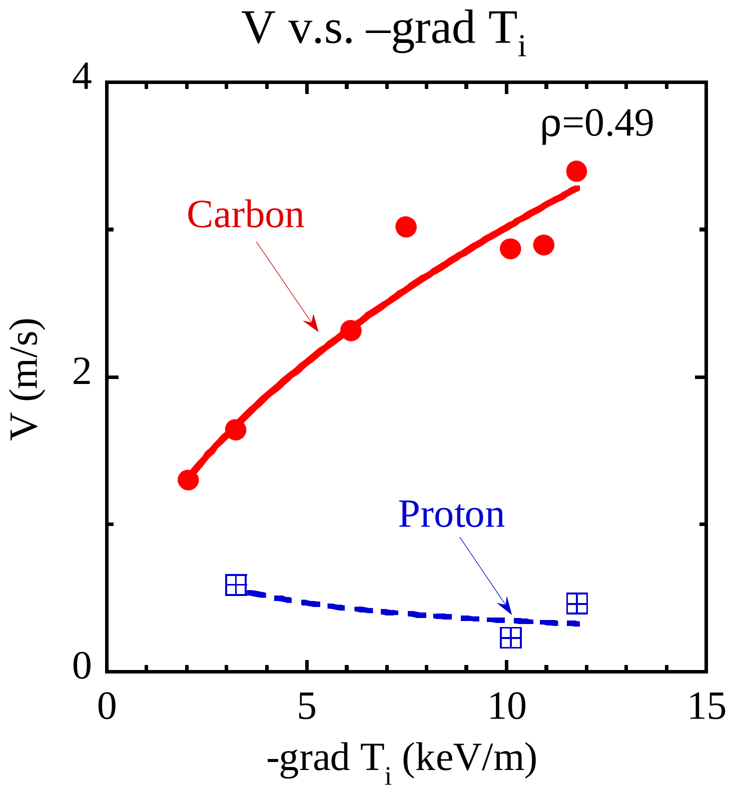
A convection velocity is driven by the gradient of other parameters as off-diagonal terms.

Ion temperature gradient rather than the electron temperature gradient starts to increase at the beginning of the formation of the impurity hole.

↓

Ion temperature gradient is the most possible candidate for driving the outward convection.

The magnitude of convection velocity increases as the ion temperature gradient is increased.



Dependence on magnetic axis position in helical system

Position of magnetic axis is one of control parameters which changes helical ripples, and it affects radial electric field and confinement.

Radial electric field [K. Ida et al., Nucl. Fusion **45** (2005) 391.]

Helical ripple sharply increases at the plasma edge and the electron root region is localized near the plasma edge in the inward shift case.

Helical ripple gradually increases towards the plasma edge and the electron root regime extends to plasma core.

Density profile [K. Tanaka et al., Plasma Fusion Res. **3** (2008) S1069.]

Density peaking factor depends on the position of the plasma, and it decreases with increases of the magnetic axes shift.

Zornal-flow [T.-H. Watanabe et al., Phys. Rev. Lett. **100** (2008) 195002.]

Turbulent transport is reduced with enhancing zonal-flow generation in the plasma with inward shifted configuration.

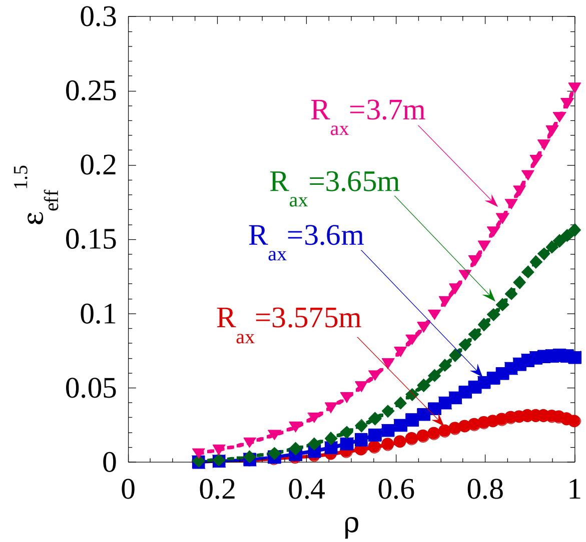
The change of the magnetic axis or helical ripples affects not only the neoclassical transport but also the anomalous transport.

Carbon density profiles in high T_i discharges

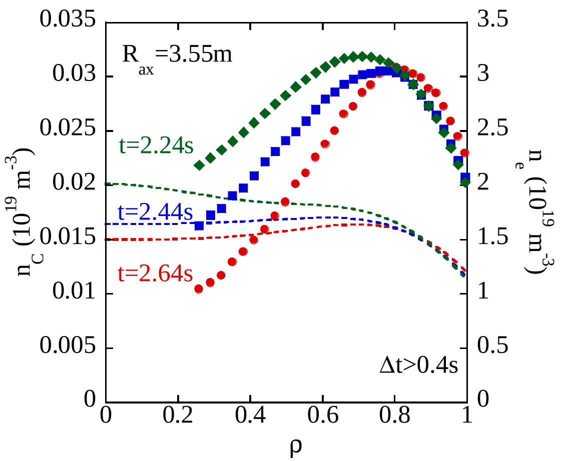
We have observed the difference of the carbon density profiles depend on the position of the magnetic axis.

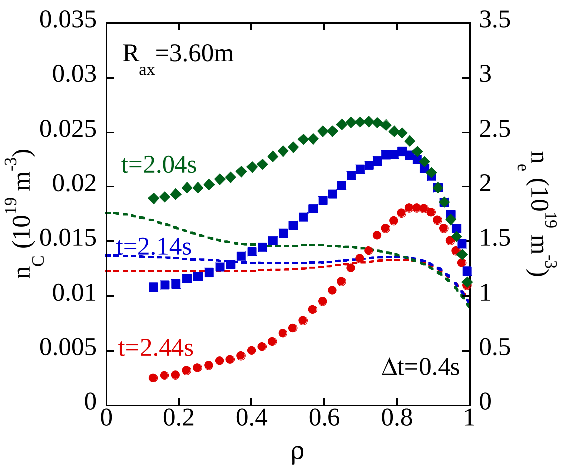
The carbon density decreases after the tangential NBI injection (t=1.9s).

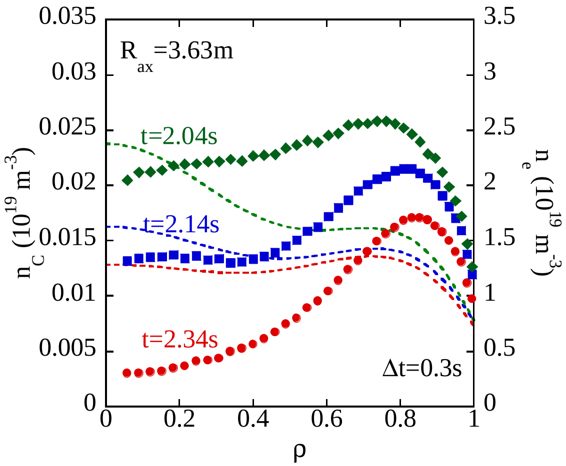
The decay speed of the carbon density in the outward shifted configuration is faster than that in the inward shifted configuration.



Inward shifted ← → **Outward shifted**





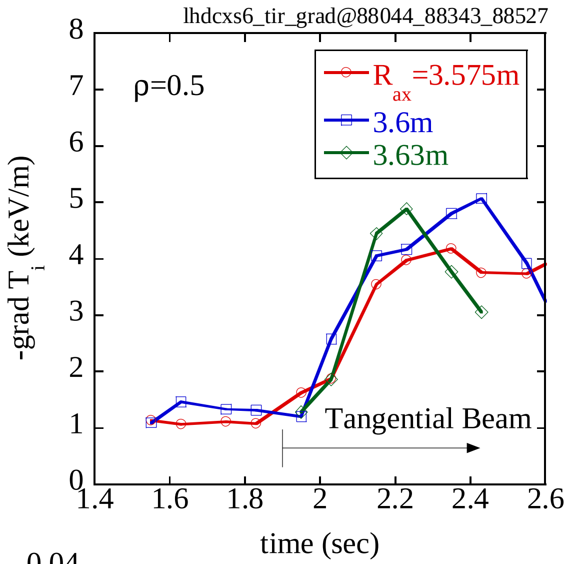


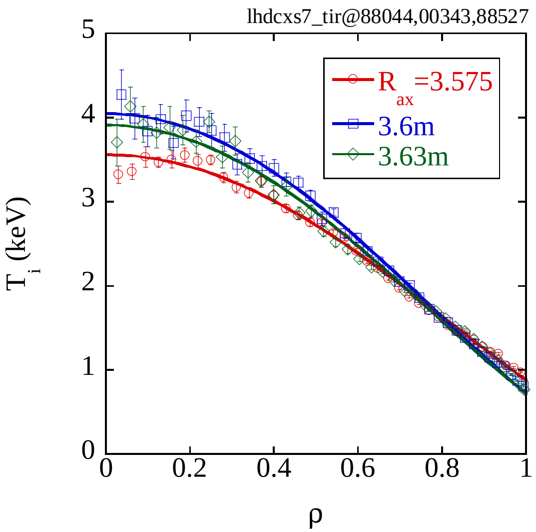
Impurity Hole in the plasmas with different position of magnetic axis

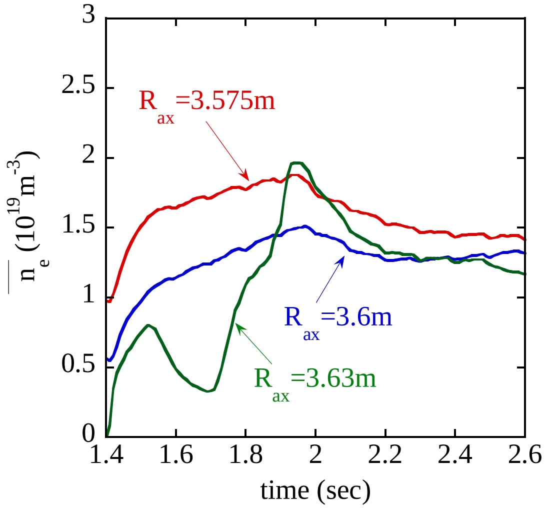
Compare three discharges with different magnetic axis configurations.

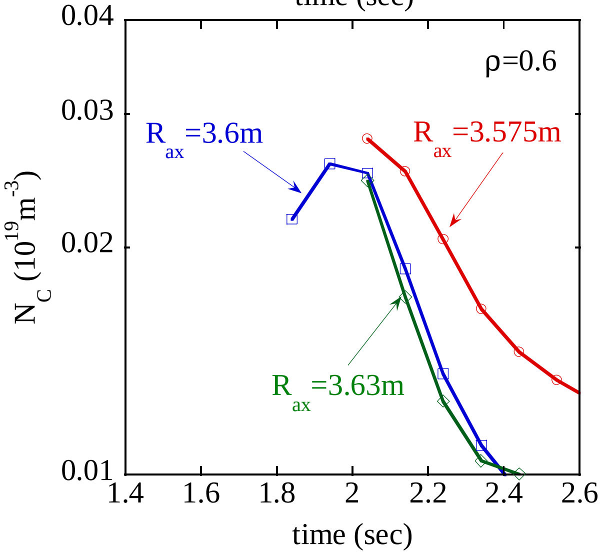
Gradient of ion temperature increases after the injection of tangential NBI heating.

Ion temperature gradient is achieved 4keV/m at ρ=0.5 after the NBI injection, while the gradient is 1keV/m before the NBI injection.







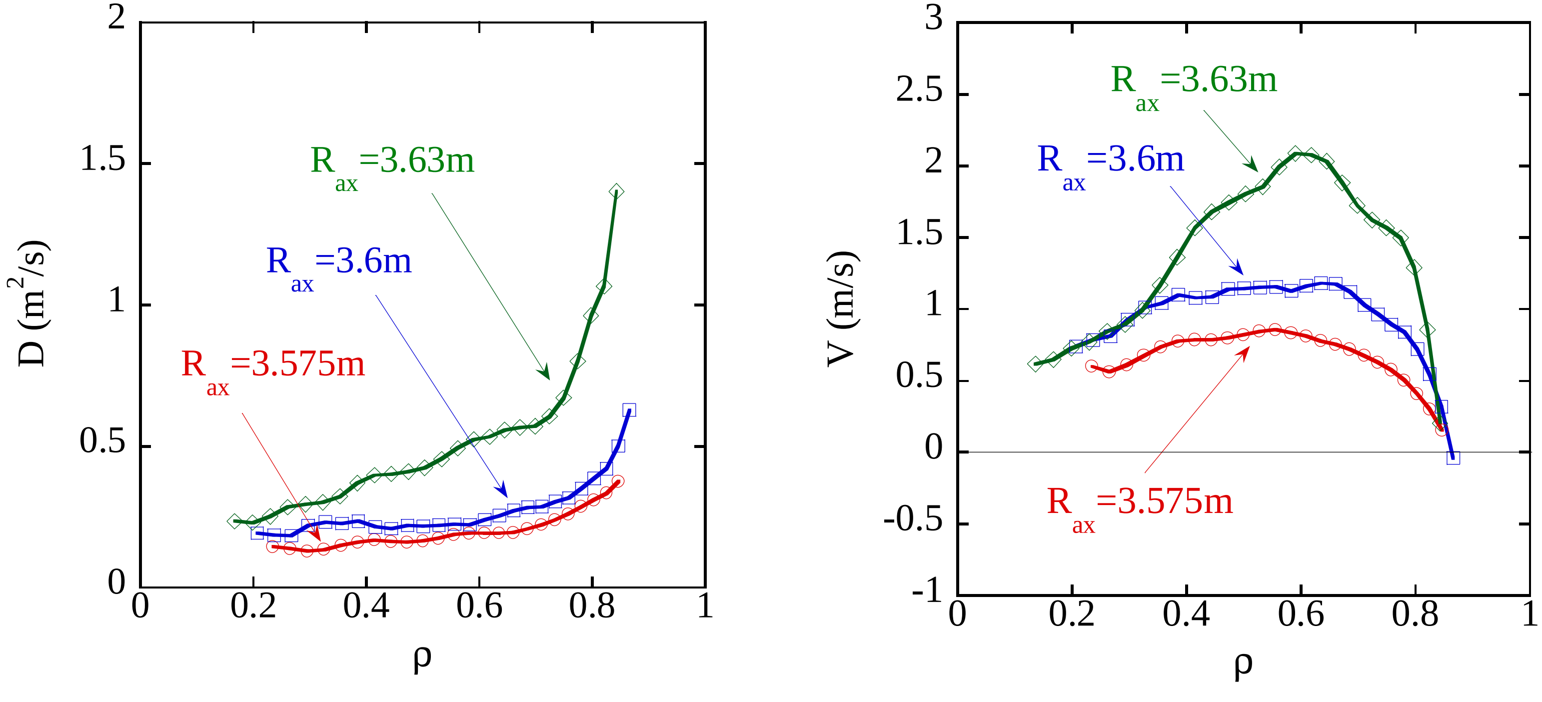


Diffusion coefficient and convection velocity of carbon impurity in impurity hole

The diffusion coefficient and convection velocity are evaluated during the decay phase of carbon density.

The diffusion coefficient is increases sharply towards the plasma edge.

The outward convection velocity becomes large as the magnetic axis is shifted outward.

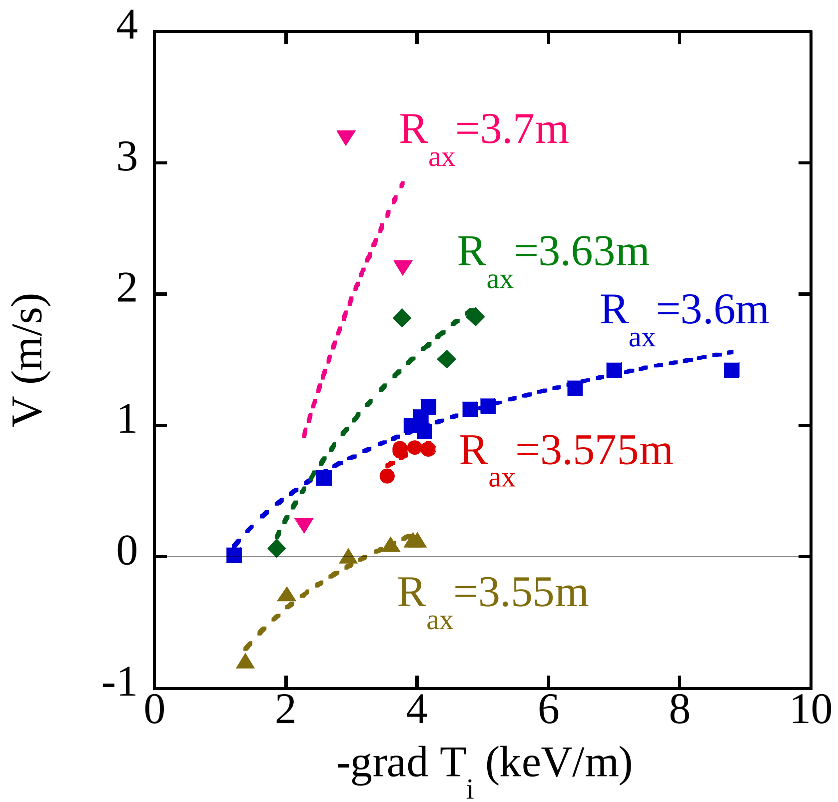


Dependence of convection velocity on ion temperature gradient

The magnitude of convection velocity increases as the ion temperature gradient is increased.

The change of the convection velocity is more sensitive to the change of the ion temperature gradient in the plasma with outward shifted configuration than in the plasma with inward shifted configuration.

Dependence of convection velocity on the magnetic axis position is clearly observed.



Summary

(1) Extremely hollow profile of carbon impurity is observed in the plasma with the steep gradient of the ion temperature.

(2) Transport analysis shows low diffusion coefficients of both carbon and bulk ions in the plasma core, and small positive convection of bulk ions and much larger positive convection of the carbon impurity.

(3) The outward flow of carbon impurity is considered to be due to the ion temperature gradient and driven by the turbulence because the sign of the convection velocity is opposite to the neoclassical prediction.

(4) Dependence of convection velocity on the magnetic axis position is clearly observed in the plasma with ion temperature gradient.

(5) It is suggested that the impurity hole becomes strong as the magnetic axis is shifted outward.