Characteristics of Impurity Hole in LHD

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Introduction

Simultaneous achievement of improved energy confinement and low impurity confinement is one of the crucial issue 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.

Although, 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.

Introduction

In neoclassical transport theory, a temperature screening effect due to an ion temperature gradient is expected in tokamaks.

In the non-axisymmetric system, the temperature screening effect is over-canceled by the inward convection due to the negative electric field, witch is driven by the ion temperature gradient.

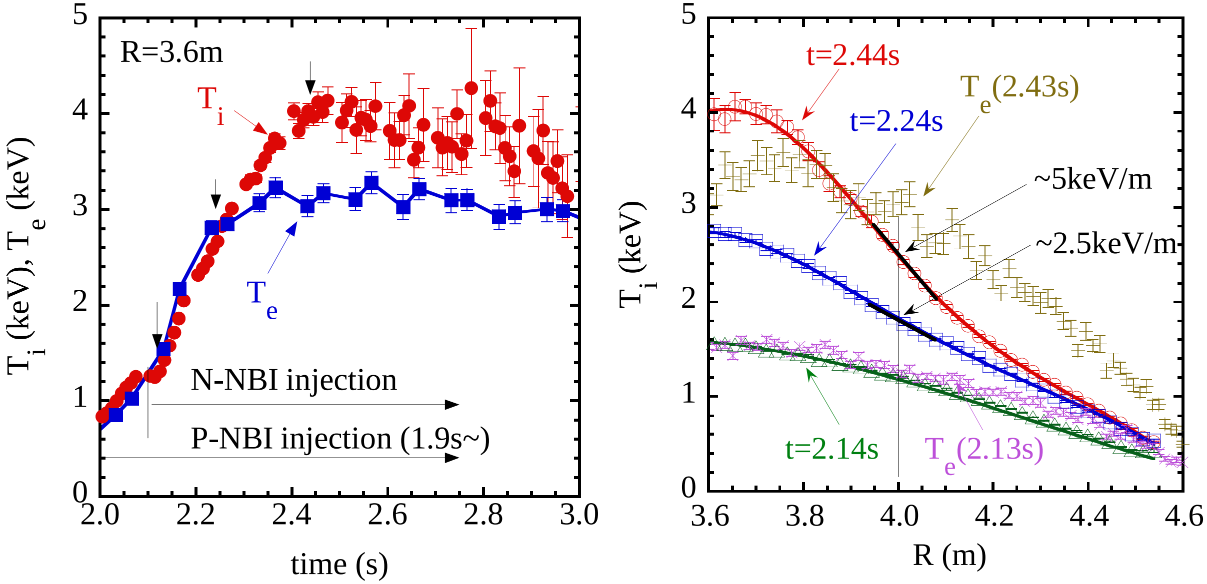
And the impurity convection can be outward and the impurity density can be hollow due to the positive radial electric field in the electron-ITB plasmas, where the electron temperature is much higher than the ion temperature.

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.

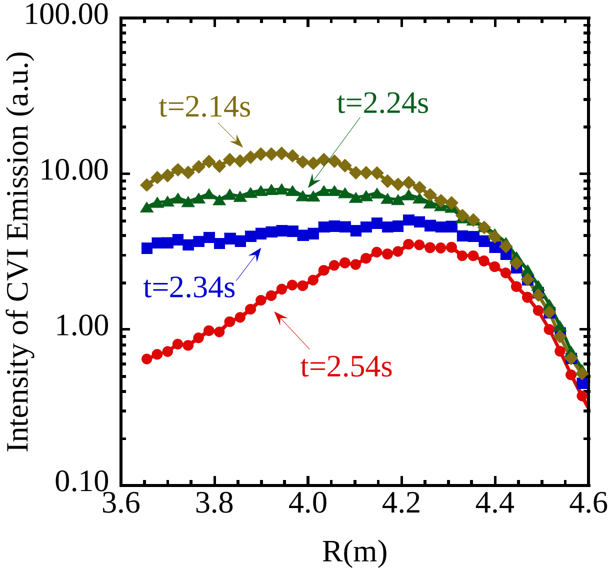
Extremely hollow impurity profiles due to an outward convection is observed in the plasma with a steep gradient of ion temperature is observed in LHD.

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.

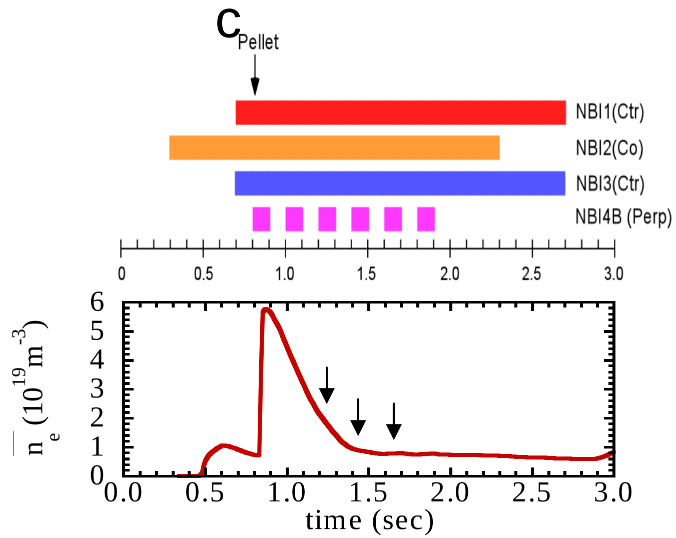
The ion temperature become higher than the electron temperature at the plasma core with a steep gradient of ion temperature near the mid-radius of the plasma.

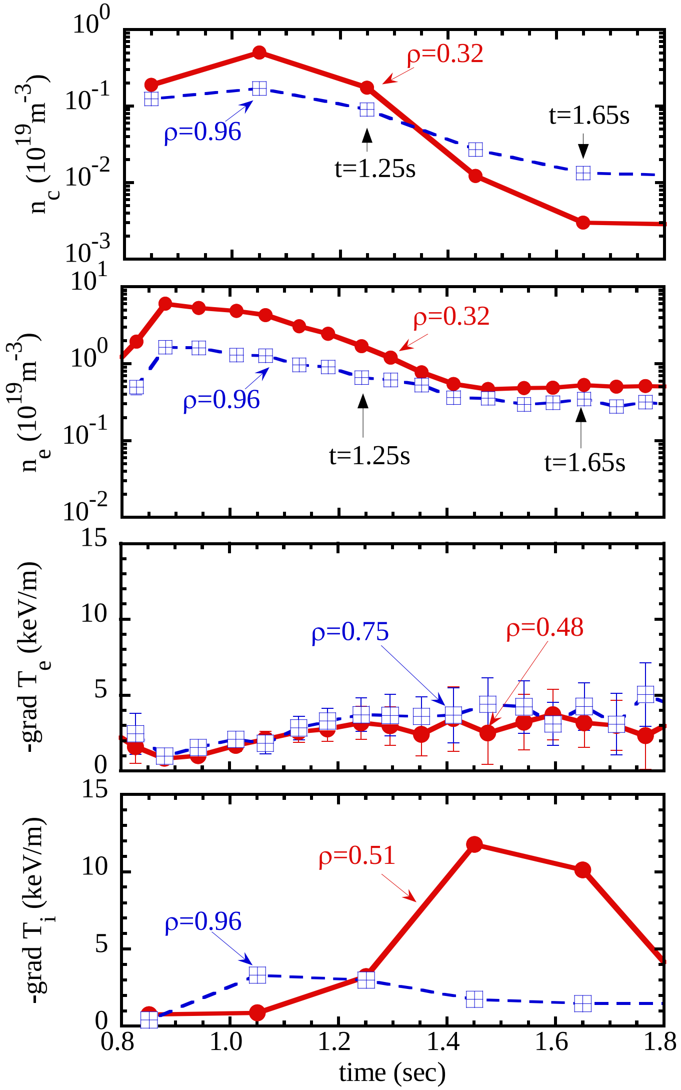
Intensity near the center of the plasma decreases faster than that at the plasma edge.

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.

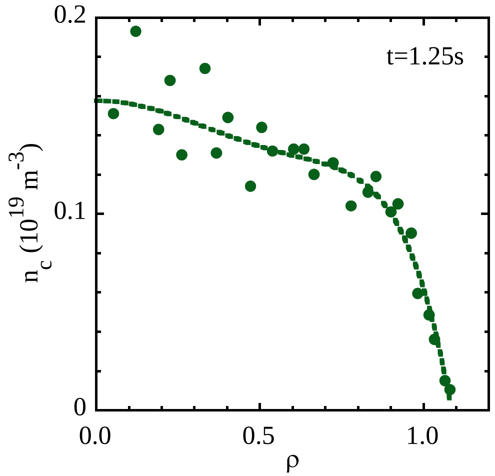
Density profiles before and after the formation of the Impurity Hole

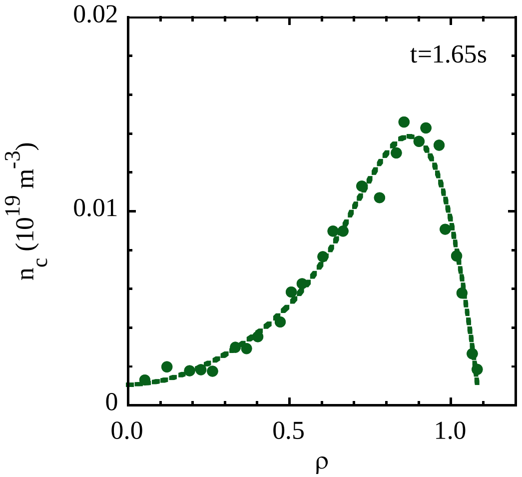
Before

After

Carbon

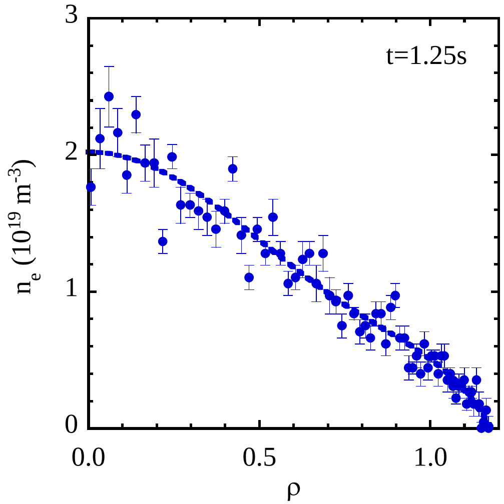
Extremely hollowed profile is produced.

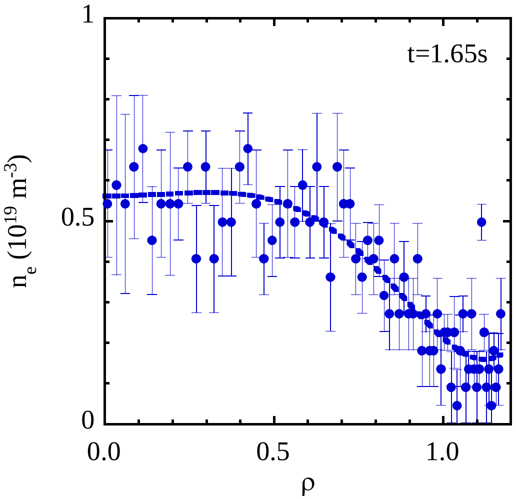




Electron

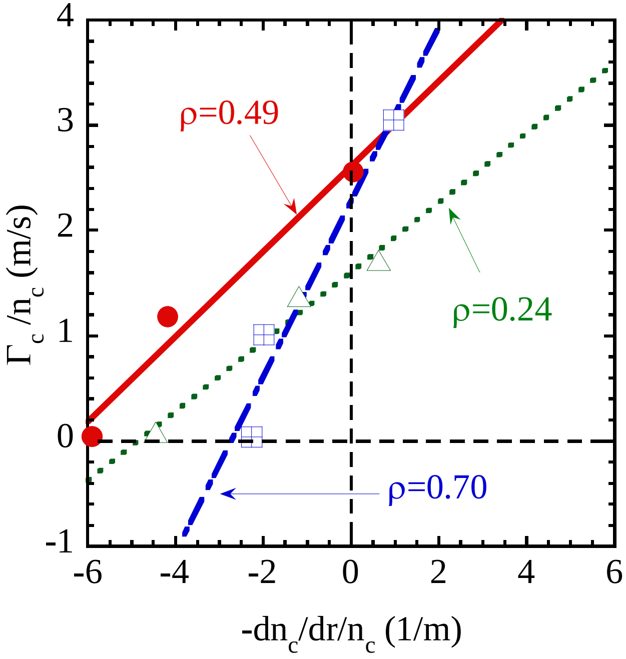
Peaked profile is kept after the impurity hole.



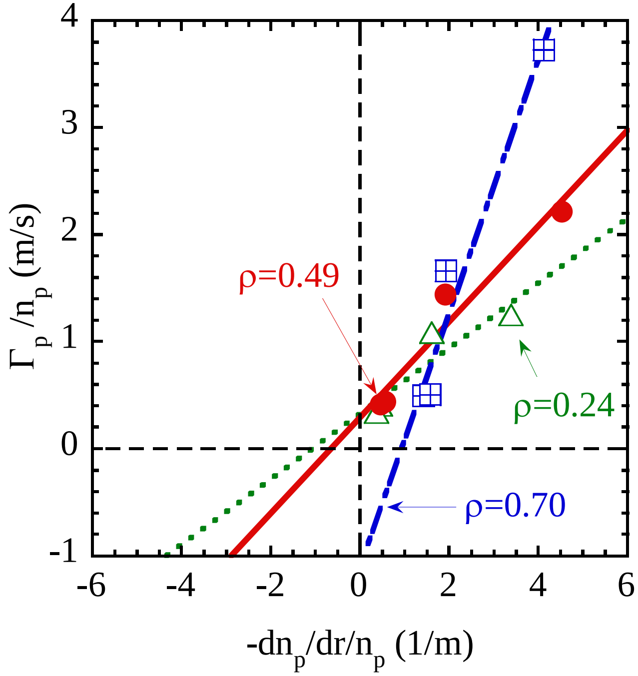


$n_c/(n_c+n_p) \sim 0.03$ after the formation of the impurity hole.

Particle flux v.s. Density gradient



Carbon



Proton

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.

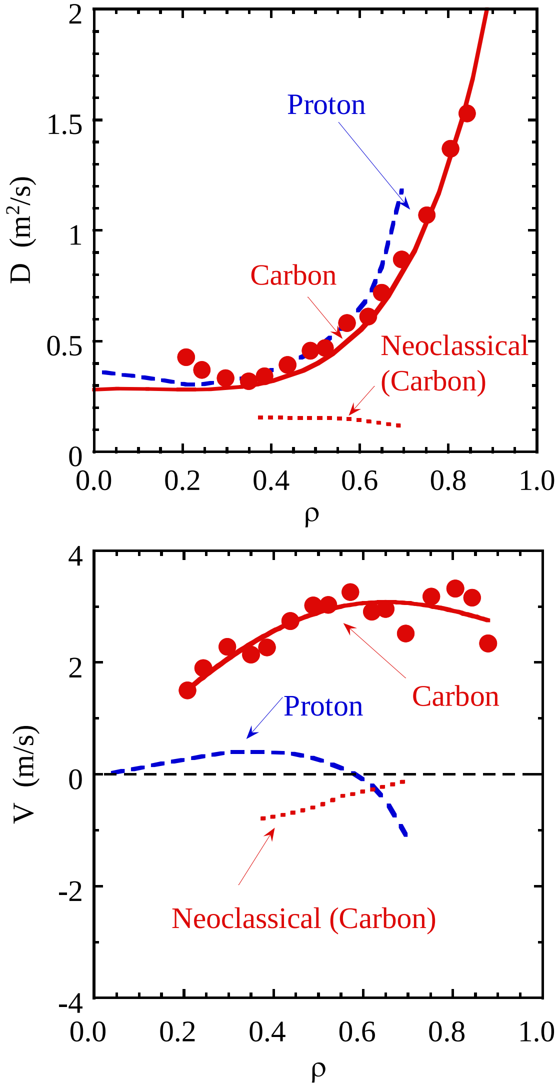
The **convection velocity of carbon impurity is large and positive**, while the convection velocity of **proton is close to zero** in the plasma core and negative near the edge.

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 of convection velocity on ion temperature gradient

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.

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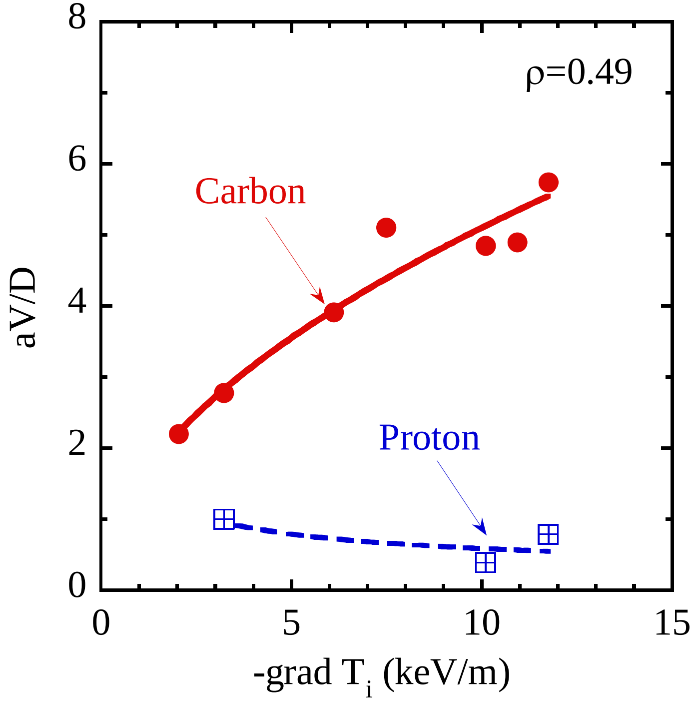
Ion temperature gradient is the most possible candidate for driving the outward convection.

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

V normalized by D



averaged minor radius a=0.65

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) This result supports the simultaneous achievement of the good energy confinement and low impurity confinement in non-axisymmetric systems.