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Integrated discharge scenario for high-temperature helical plasma on LHD

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Outline

1. Introduction
2. Discharge Scenario of ion ITB
   - Ion ITB plasma in LHD
   - Wall conditioning effects
3. Integration of ion ITB and electron ITB
   - Transport characteristics
   - Profile control
4. Summary

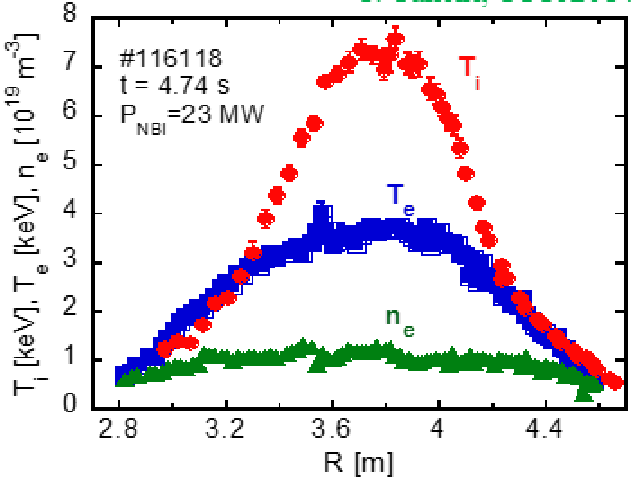
Introduction

–Background and Motivation-

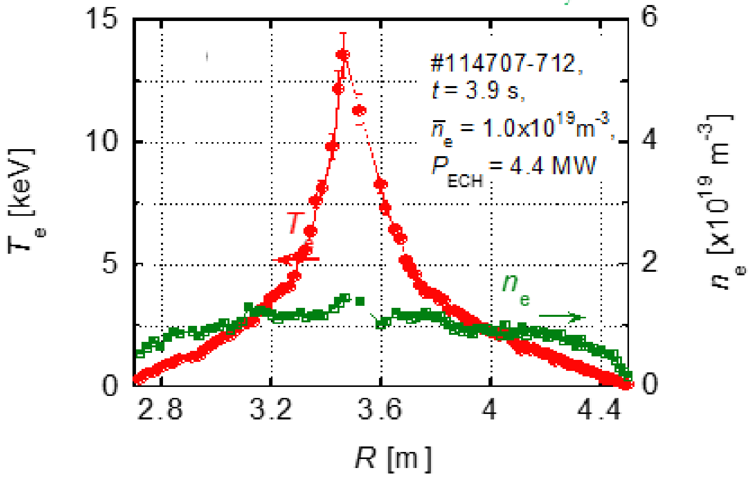
Background

1) Helical plasmas have good performance in high density regime and an advantage in steady state operation ➔ **Discharge scenario of high temperature helical plasmas**
2) High T_i plasma and high T_e plasma have been investigated separately, so far ➔ **Integration**

Y. Takeiri, PFR 2014



H. Takahashi, PoP 2014



High Ti plasma (ion ITB)

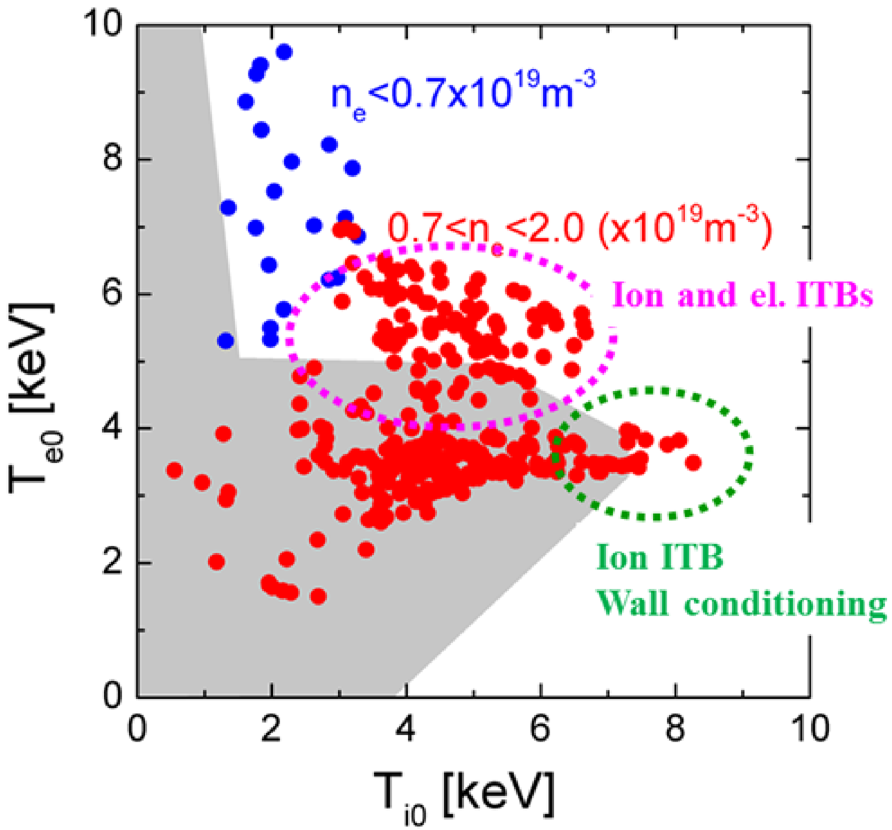
1) Improved heat transport with a factor of 3-5, and χ_i becomes to NC level
2) Reduction of momentum transport and reversal of intrinsic rotation
3) Impurity hole formation

High Te plasma (electron ITB/ CERC)

1) Improved heat transport with positive Er
2) Er shear caused by a bifurcation of Er
3) Impurity hole formation

Introduction

-Extension of temperature regime-



- Recently, the temperature regime of LHD plasma has been significantly extended.
- The central ion temperature of **8.1keV has been achieved** in low Z_{eff} plasma with intense helium wall conditioning.
- $T_e \sim T_i$ regime has been also extended by **integration of ion ITB and electron ITB**.

- Improved factor of global confinement with respect to normal confinement is **1.5 for ion ITB** and **1.7 for ion and electron ITBs** are achieved based on ISS04 scaling.

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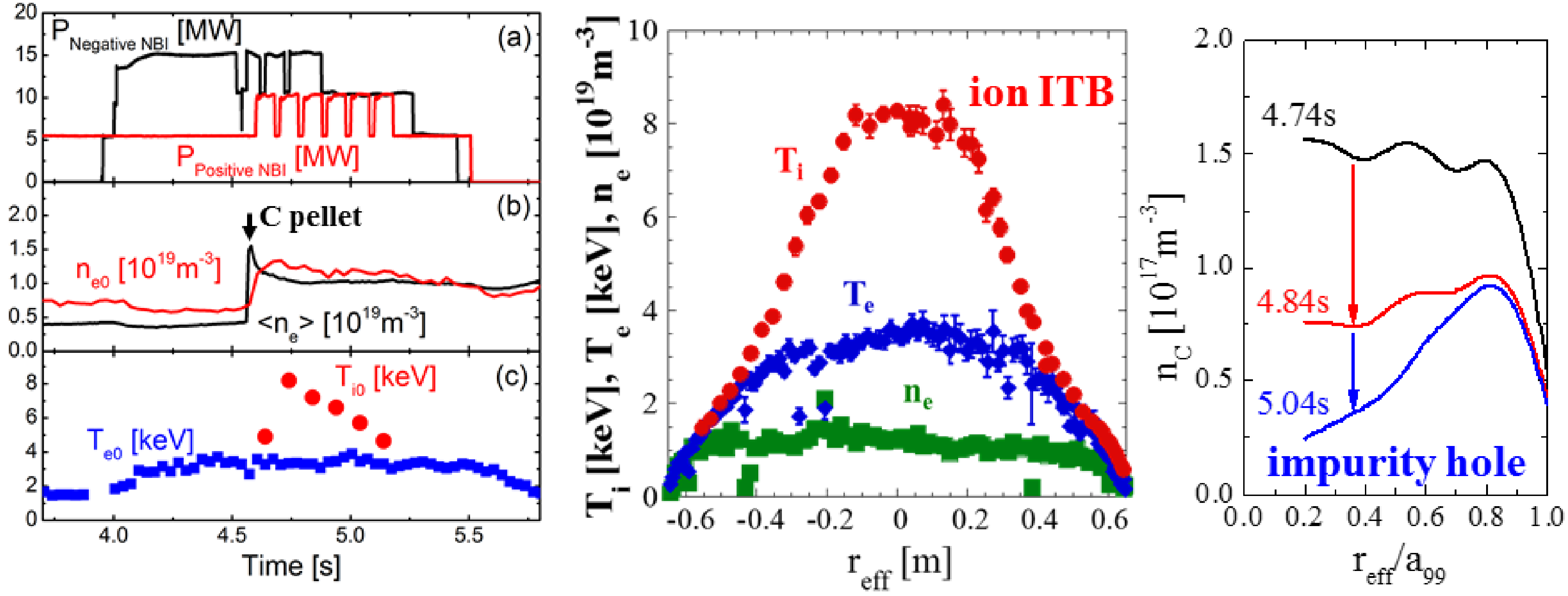
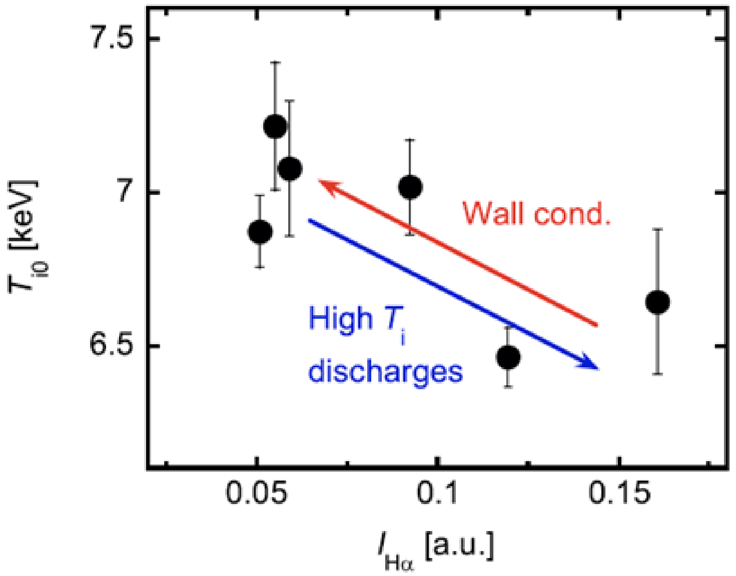
Ion ITB plasma in LHD

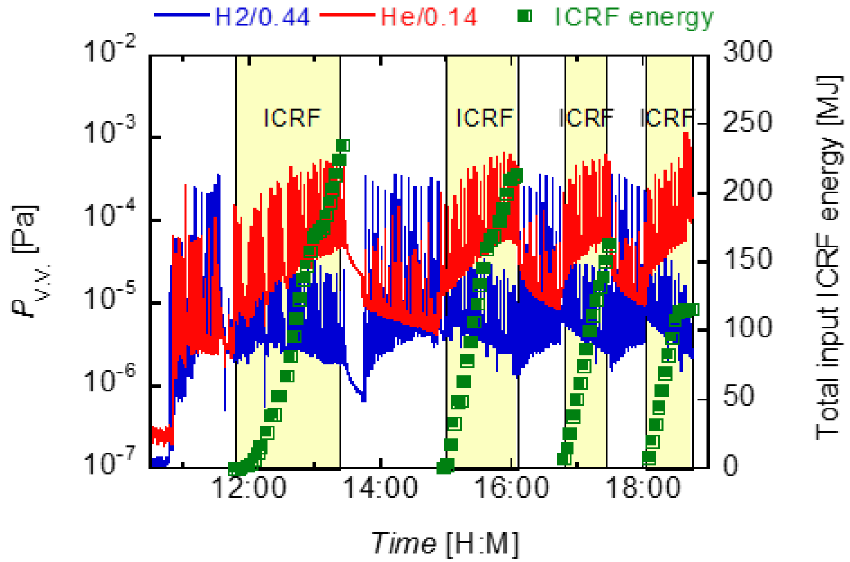


- Carbon pellet was injected, then positive NBI was added.
- The central Ti increased in the density decay phase.
- The peaked Ti profile with steep gradient (**ion ITB**) formed, and no ITB was observed in the electron temperature and density profiles.
- Carbon impurity was expelled from the core (**Impurity hole formation**)

Low recycling condition is preferable to increase T_i

H. Takahashi, PFR 2014

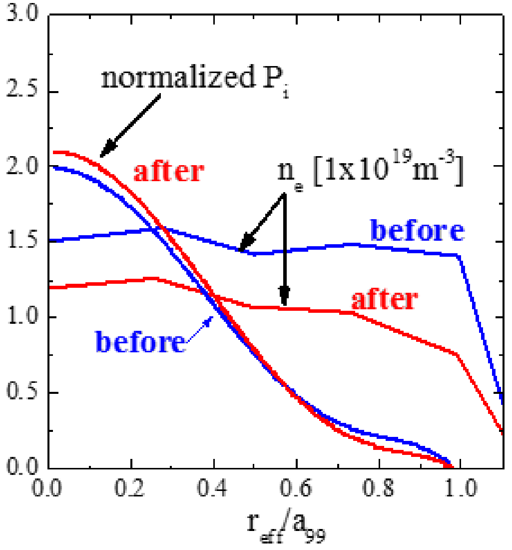




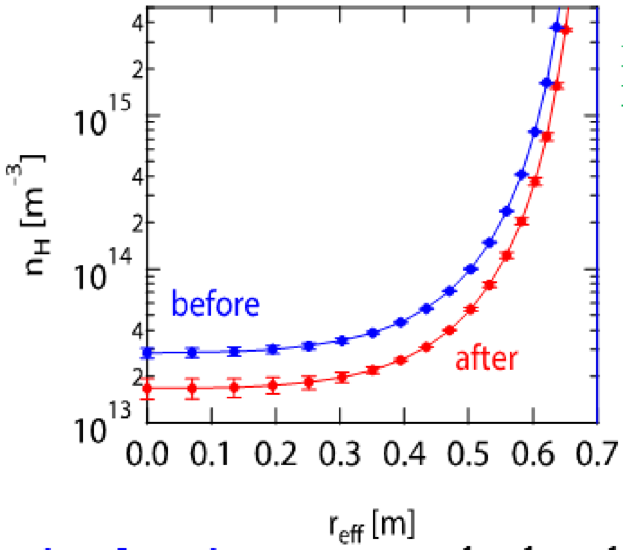
- **Central ion temperature increases with the decrease of Hα** intensity, indicating the low wall recycling is preferable to extend Ti regime
- **Repetitive helium main discharges** with ion cyclotron range of frequency (**ICRF**) heating **is performed to reduce wall recycling**.
- The hydrogen pressure decreases with injected energy of ICRF and ECH, and the low recycling condition is realized after repetitive conditioning discharges.

Wall conditioning increases ion heating power in the core

Profile change



Charge exchange loss



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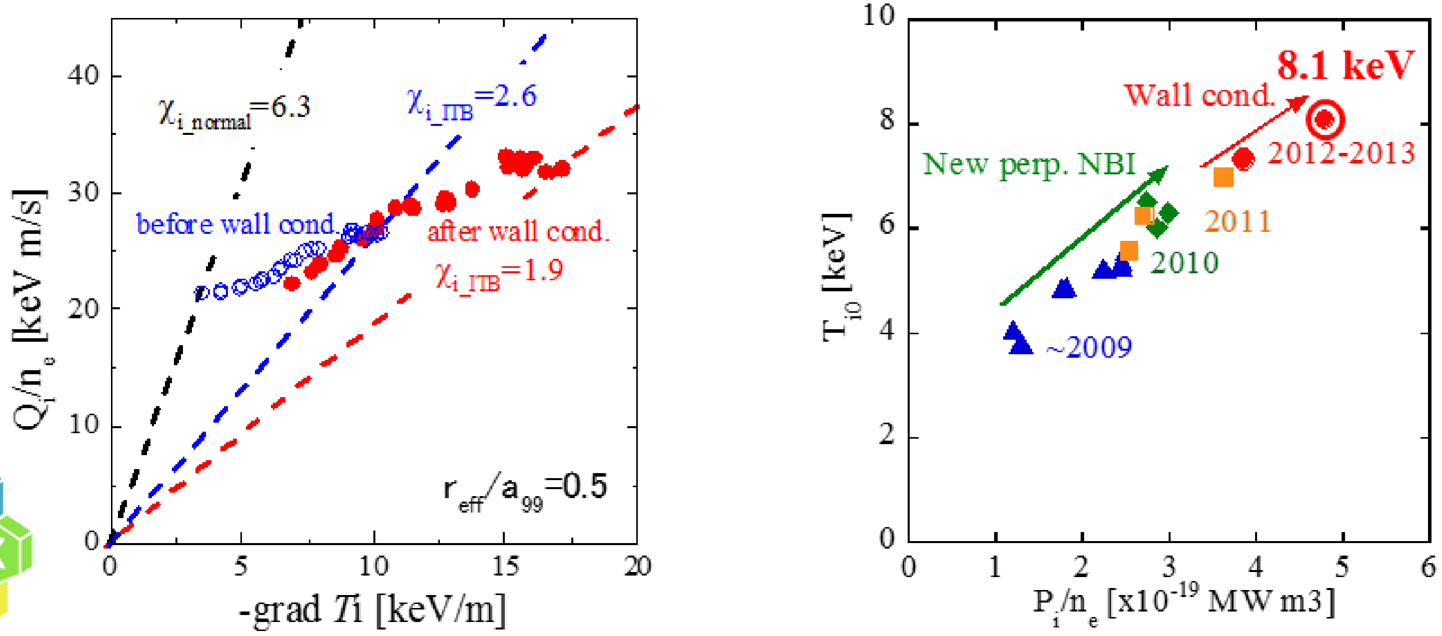
- The edge density become lower. **The ion heating power** calculated by FIT-3D code became **peaked profile** after helium conditioning discharges.
- **The peaking factor of ion heating power ($P_i(r_{eff}/a_{99}<0.5)/P_{i\_total}$) increases from 0.48 to 0.55** after helium conditioning discharges.
- **The neutral density profile** was experimentally measured with a high-dynamic range of Balmer-α spectroscopy.
- **The loss of energetic ions reduced from 14% to 7%** in the core region.

Further improvement is realized by wall conditioning



- **Increase of ion heating power** due to the wall conditioning **is not so much**, however, **the ion heat transport improves further**.
- Therefore **the wall conditioning becomes more effective to increase T_{i0}**.
- **The central ion temperature of 8.1keV was achieved with intense conditioning discharges**.

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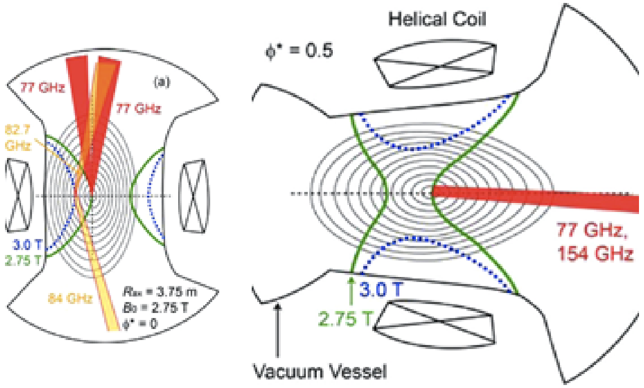
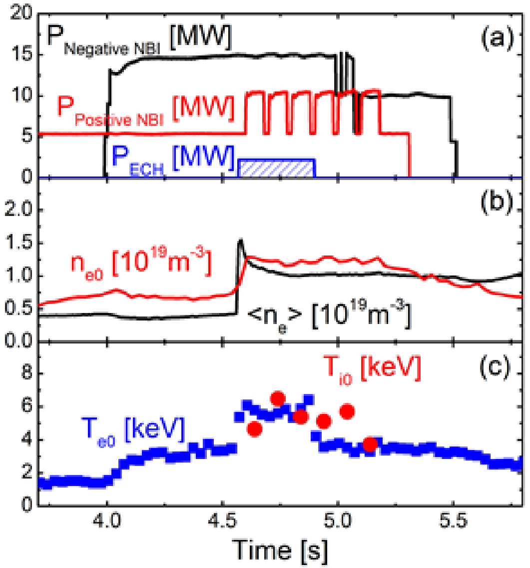
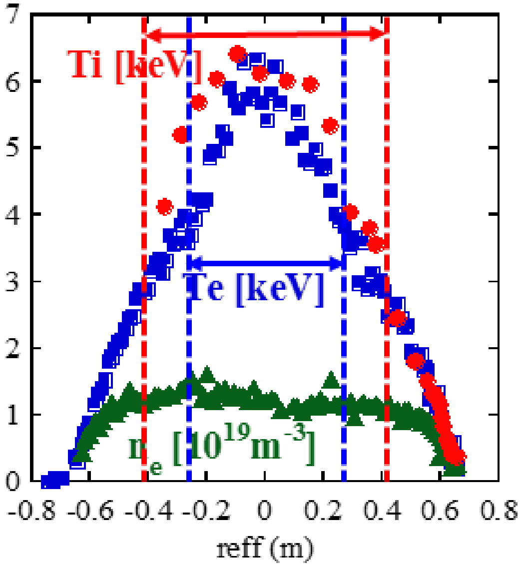
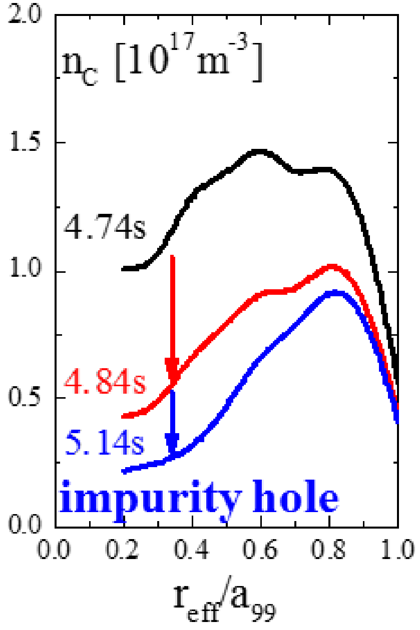
Simultaneous formation of ion ITB and electron ITB



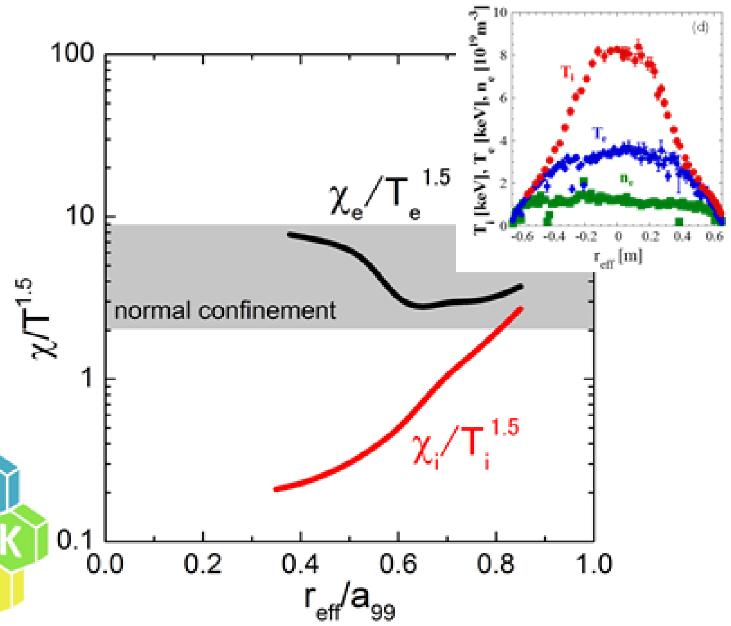


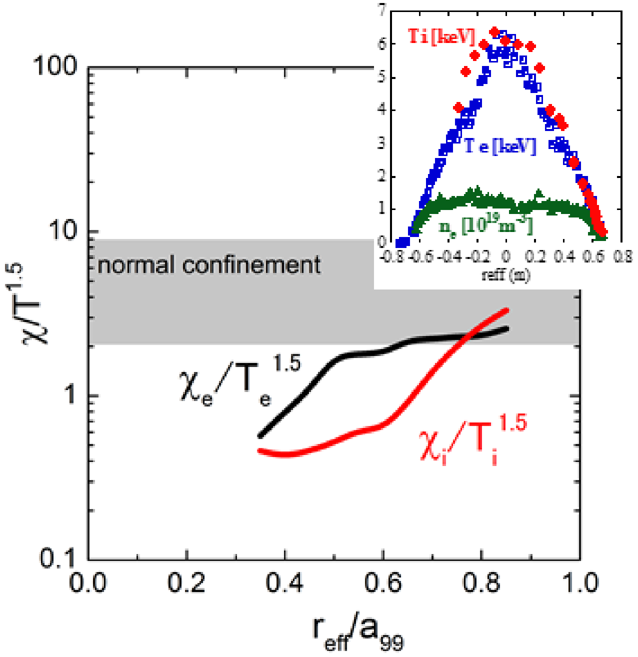




- ECH with horizontal injection can **finely control the power deposition profile**, and applied to ion ITB plasma. The electron temperature increases to the same level with ion temperature **$T_e \sim T_i \sim 6$ keV**.
- **The width of ITBs are different (wider ion ITB & narrower electron ITB)**
- **"Impurity hole"** was also intensively formed.

Simultaneous improvement of ion and electron heat transport

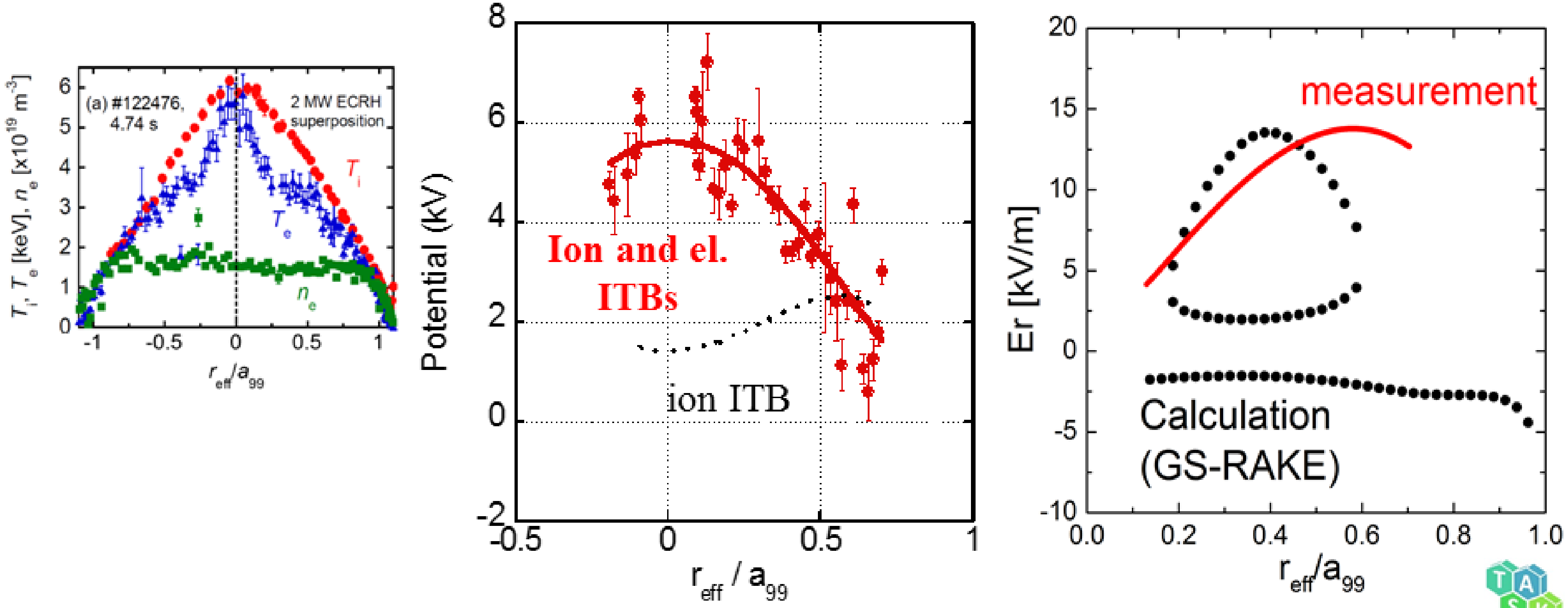




- The normal confinement in LHD shows **gyro Bohm dependence**, $\chi \sim T^{1.5}$.

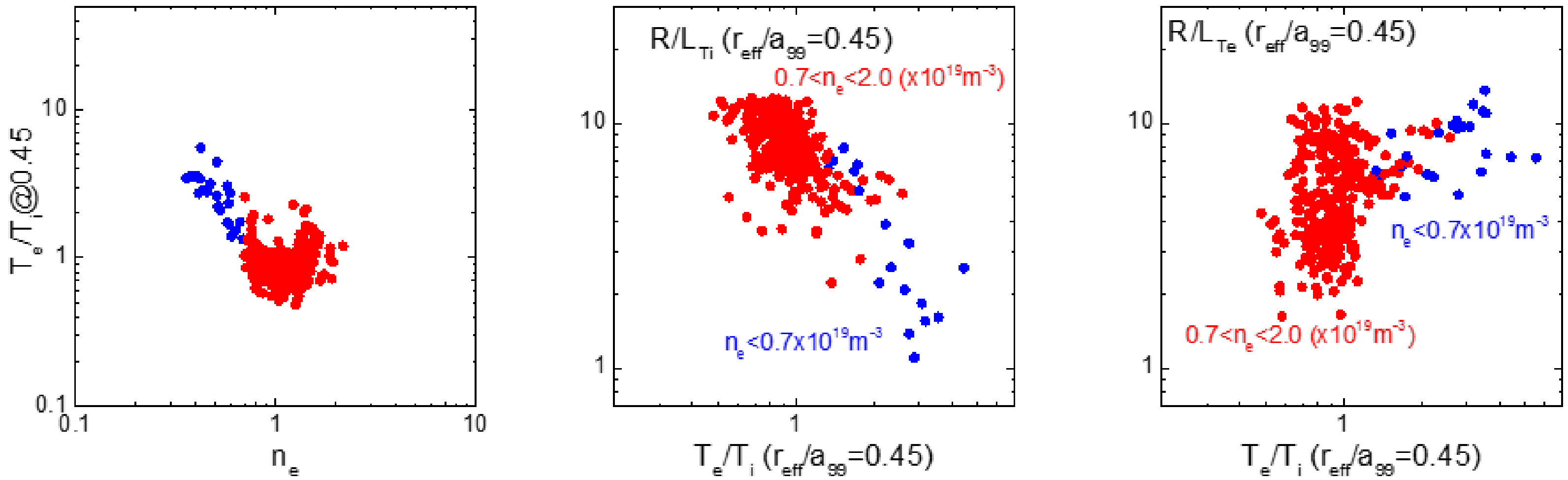
- The ion heat transport improved in the ion ITB core region.
- **The improvement of ion and electron heat transport** were confirmed in the $T_e \sim T_i$ plasma. Therefore, **ion ITB and electron ITB are formed simultaneously**.

Improvement with **Positive Er**



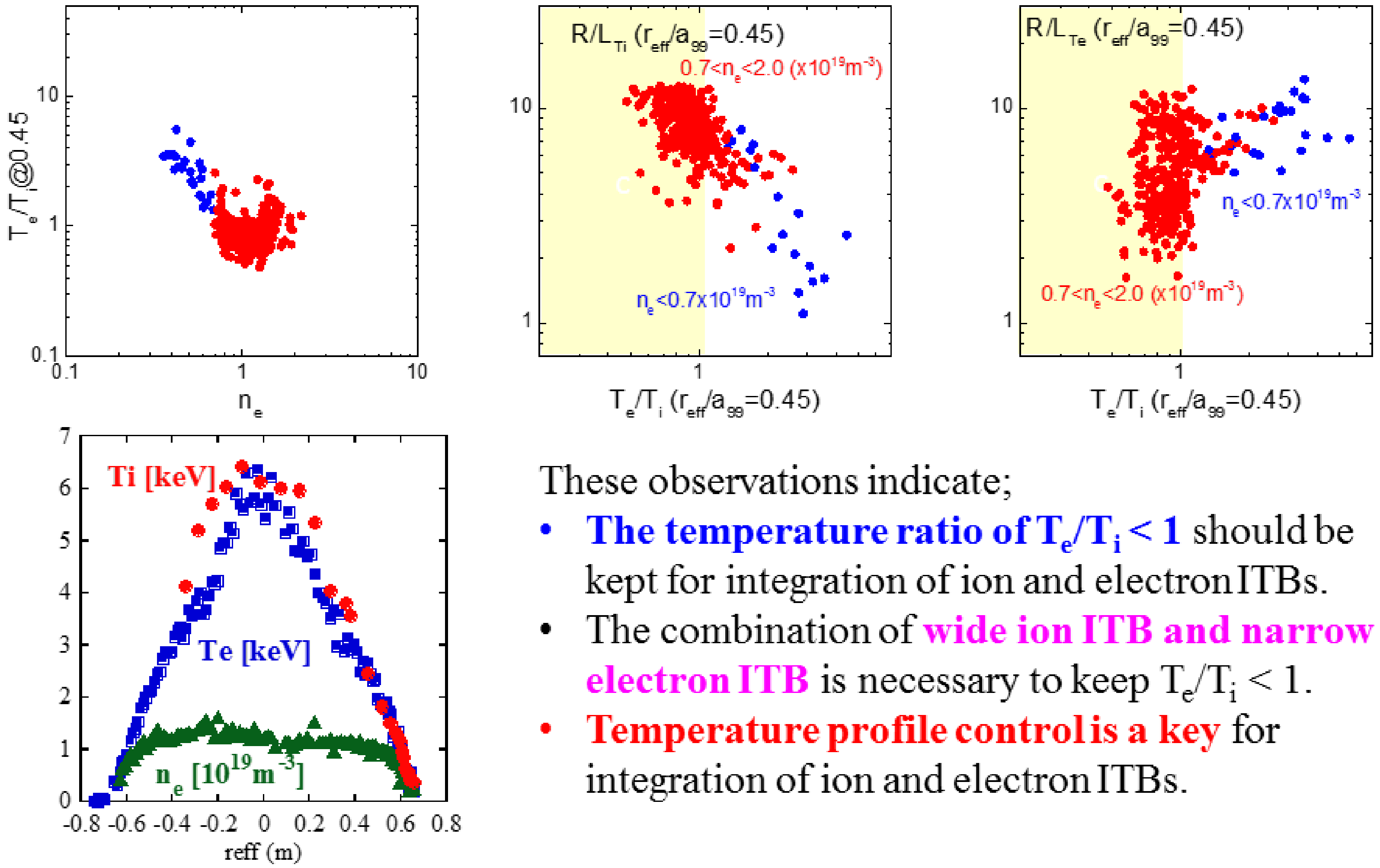
- The electrostatic potential of ion and electron ITBs was measured by a heavy ion beam probe, and the **positive E_r was observed in the core region**, while the negative E_r was observed in the ion ITB plasma.
- The NC ambipolar E_r is calculated by GSRAKE code and is consistent with experimental observation.
- It is noted **that ion heat transport also improved with positive E_r**.

Characteristics of heat transport
-temperature ratio dependence-



- The temperature ratio (T_e/T_i) in the low density region decreases with density.
- **The scale length ion temperature gradient is observed to decreases with the temperature ratio**.
- However, **the achievable scale length of electron temperature gradient is unchanged with temperature ratio**.

Profile control is a key for integration of ion and electron ITBs



These observations indicate;

- **The temperature ratio of $T_e/T_i < 1$** should be kept for integration of ion and electron ITBs.
- The combination of **wide ion ITB and narrow electron ITB** is necessary to keep $T_e/T_i < 1$.
- **Temperature profile control is a key** for integration of ion and electron ITBs.

Summary

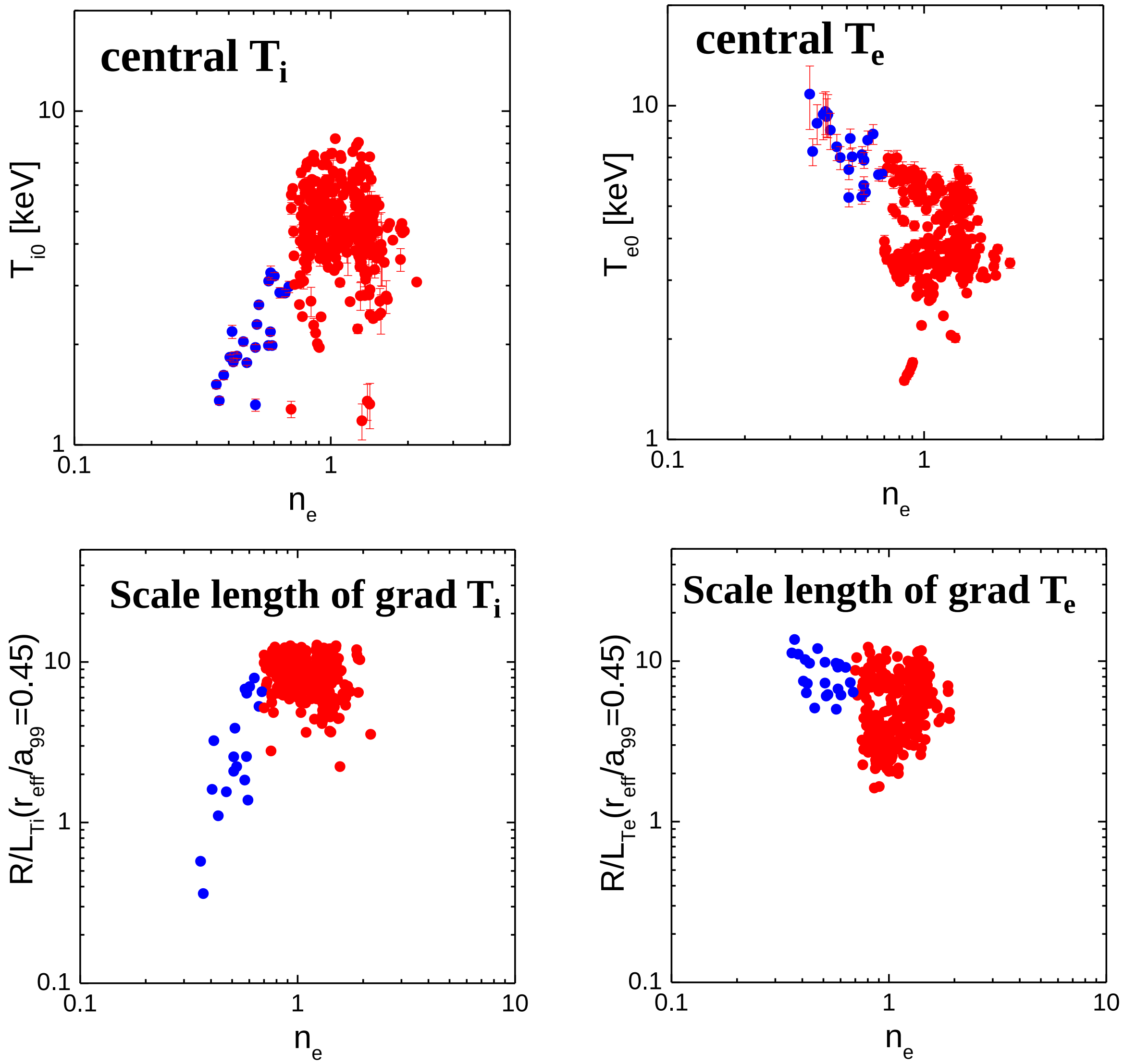
High T_i scenario development;

- The **wall conditioning effects (change of density profile** and **reduction of charge exchange loss of energetic ions)** are discussed.
- **The high T_i regime was significantly extended** by the wall conditioning due to **further improvement** of heat transport.
- **T_{i0} = 8.1 keV was achieved in LHD**.

Integration of high T_i scenario and high T_e scenario;

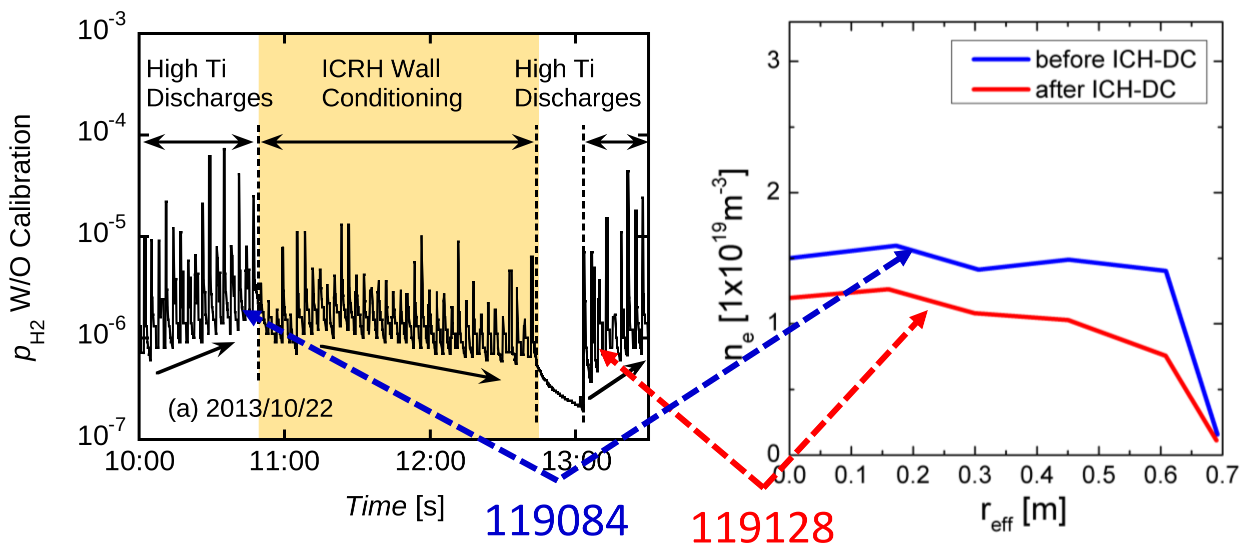
- **The ion ITB and electron ITB was integrated** with application of strongly focused ECH to the ion ITB plasma
- **$T_{i0} \sim T_{e0} \sim$ 6 keV was achieved** associated with **impurity hole**.
- **The ion heat transport is also improved with positive E_r** and **degrades with increase of T_e/T_i**, indicating **the importance of temperature profile control** to integrate ion and electron ITBs.

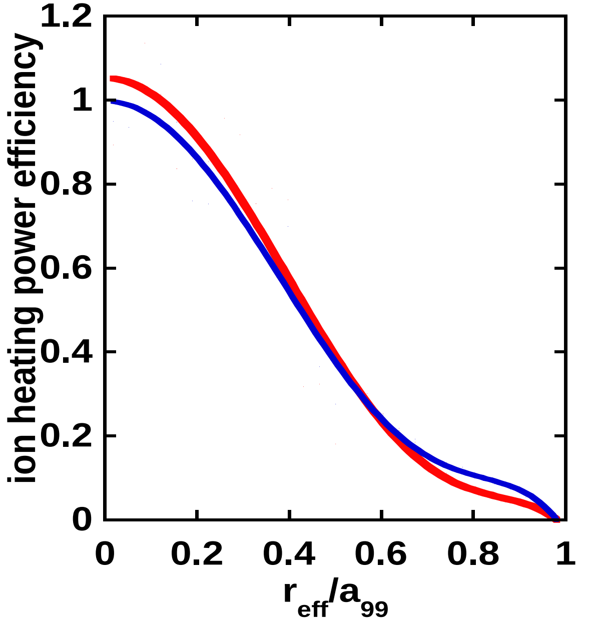
Characteristics of heat transport
-density dependence-



- **The density dependence of achievable temperature is different** in low density regime.
- The ion temperature decreases with the decrease of density, while electron temperature increases in low density.
- **The scale length of ion temperature gradient also decreases with the decrease of density**, while the maximum of scale length of electron temperature gradient is unchanged with the density.

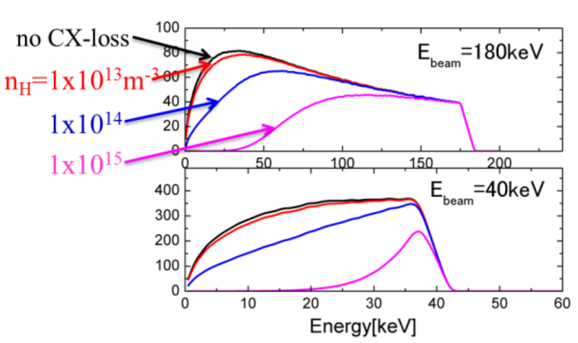
Effect of density profile change

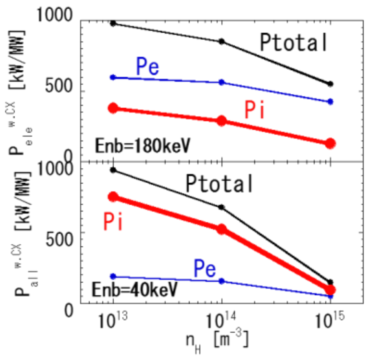




- **The helium wall conditioning** decreases the hydrogen recycling and **changes the change of density profile more peaked**.
- **The ion heating power** was calculated by FIT-3D code and became **peaked profile** after helium conditioning discharges.
- **The peaking factor of ion heating power ($P_i(r_{eff}/a_{99}<0.5)/P_{i\_total}$) increases from 0.48 to 0.55** after helium conditioning discharges.

Effect of charge exchange loss of energetic ions





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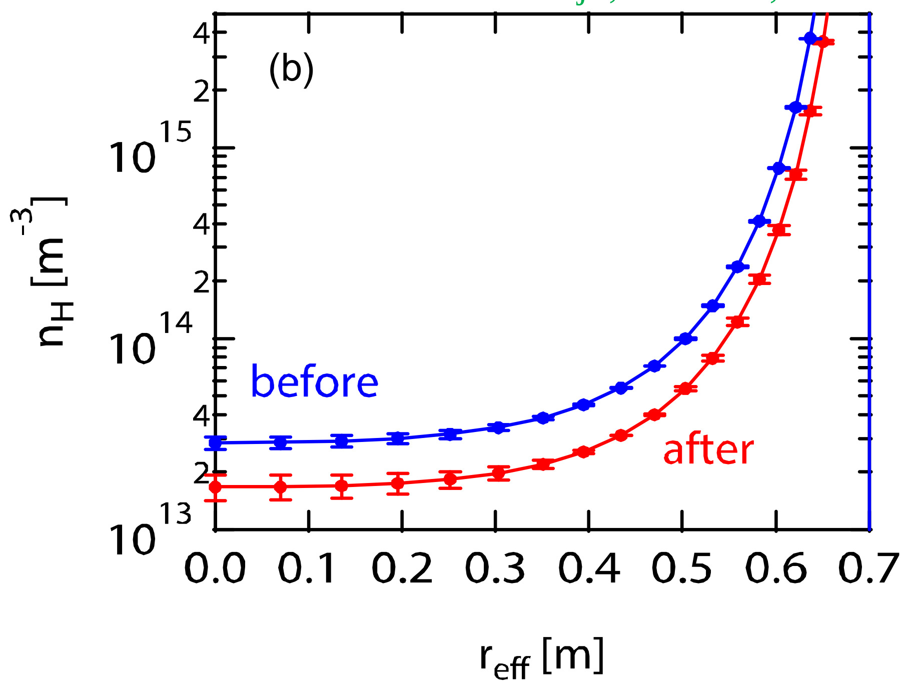
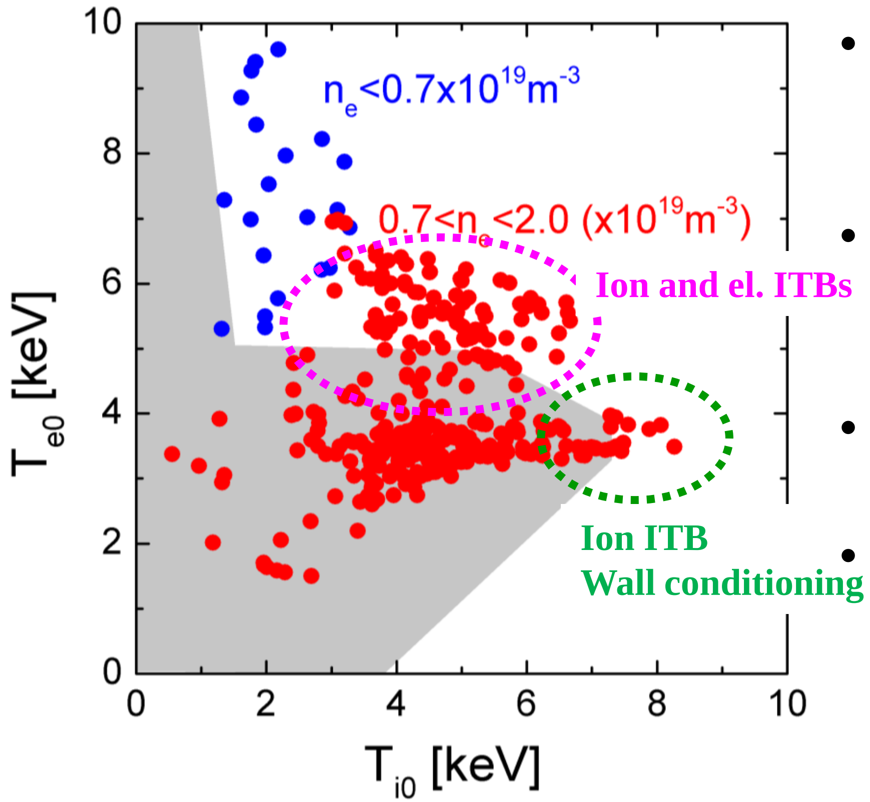


- Energy spectra of NBI ions were calculated with / without **charge exchange loss**.
- The CX loss becomes significant in low energy regime, **indicating reduction of ion heating power**.
- **The neutral density profile was evaluated** from a high-dynamic range of Balmer-α spectroscopy measurement.
- It was identified that **the reduction of ion heating power from 14% to 7%** in total ion heating power due to **the reduction of CX loss of energetic ions**.

Introduction

-Extension of temperature regime-



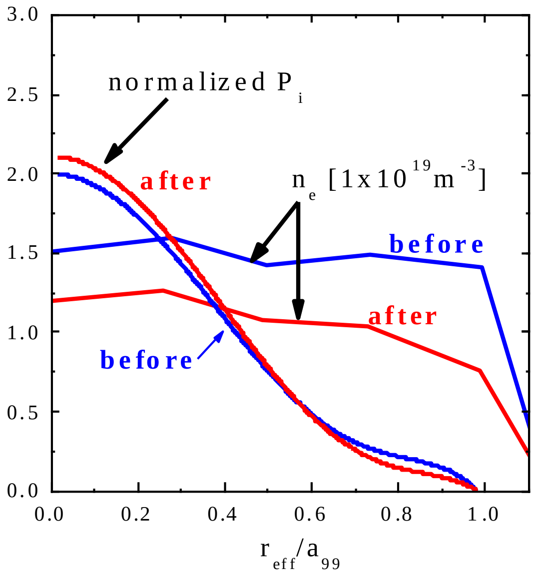
- Recently, the temperature regime of helical plasma has been significantly extended in LHD.
- The central ion temperature of **8.1keV has been achieved** in low Z_{eff} plasma with intense helium wall conditioning.
- $T_e \sim T_i$ regime has been also extended by **integration of ion ITB and electron ITB**.
- Improved factor of global confinement with respect to normal confinement is **1.5 for ion ITB** and **1.7 for ion and electron ITBs** are achieved based on ISS04 scaling.

In this talk, **discharge scenario of high T_i plasma** is presented and effects of **wall conditioning** is discussed. Then **the integration of discharge scenarios of ion and electron ITBs** are presented

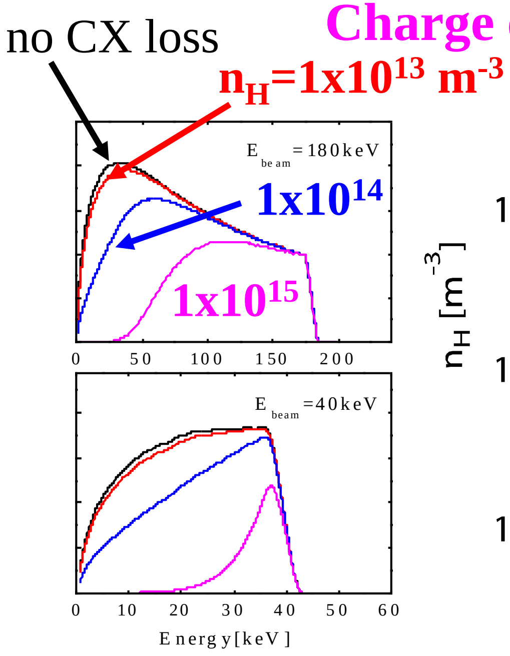
. **The characteristics of heat transport in high temperature regime** are discussed.

Wall conditioning effects on the core plasma

Profile change



Charge exchange loss



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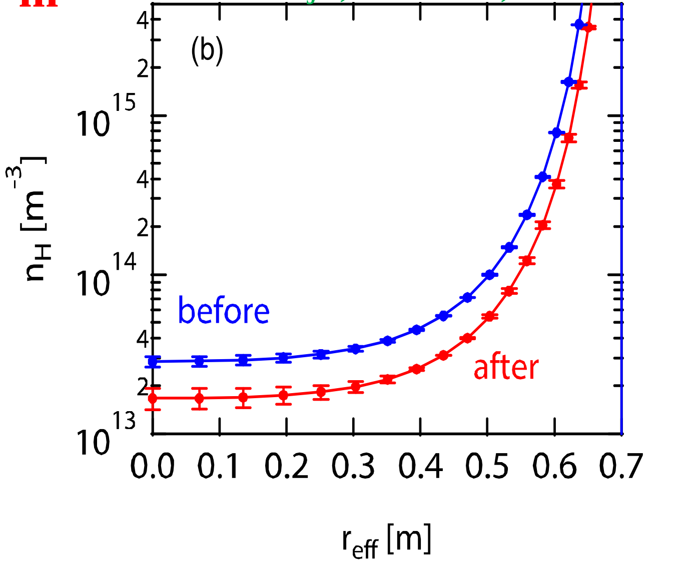

- The edge density become lower. **The ion heating power** calculated by FIT-3D code became **peaked profile** after helium conditioning discharges.
- **The peaking factor of ion heating power ($P_i(r_{eff}/a_{99}<0.5)/P_{i\_total}$) increases from 0.48 to 0.55** after helium conditioning discharges.
- **The charge exchange loss of energetic ions** was calculated and **neutral density profile** was measured with a high-dynamic range of Balmer-α spectroscopy.
- **The loss of energetic ions reduced from 14% to 7% in ion heating power** is identified in this comparison.