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Properties of internal diffusion barrier in high density plasmas on Large Helical Device

LHD Project,
National Institute for Fusion Science

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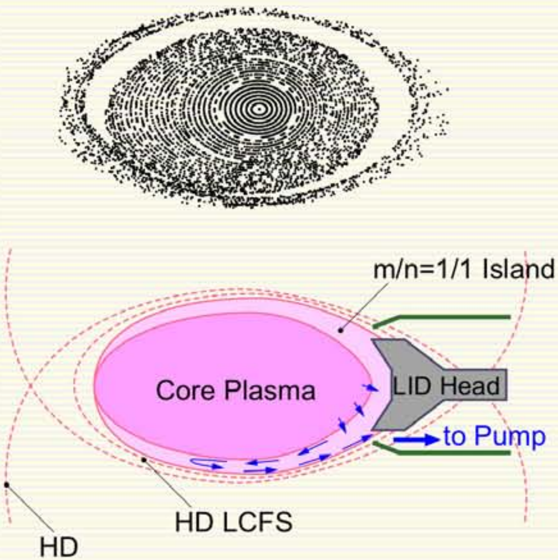
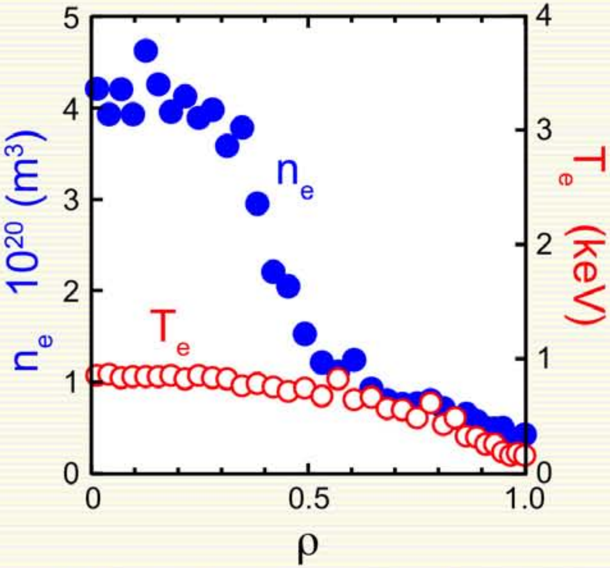
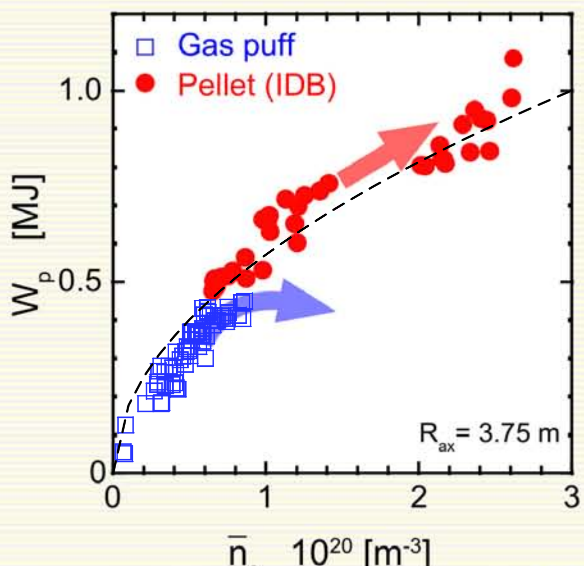
Motivation

- **Internal diffusion barrier (IDB)**
  - ✓ pellet fueled high density discharges
  - ✓ active pumped local island divertor (LID) configuration
- **LID configuration**
  - ✓ efficient pumping property due to the localized installation (η_{pump}~ 40 %)
  - ✓ struggle with high heat flux
- **IDB formation in intrinsic helical divertor configuration (HD)**

An experimental study has been performed in order to explore the operational space of the IDB discharge with the intrinsic HD configuration.

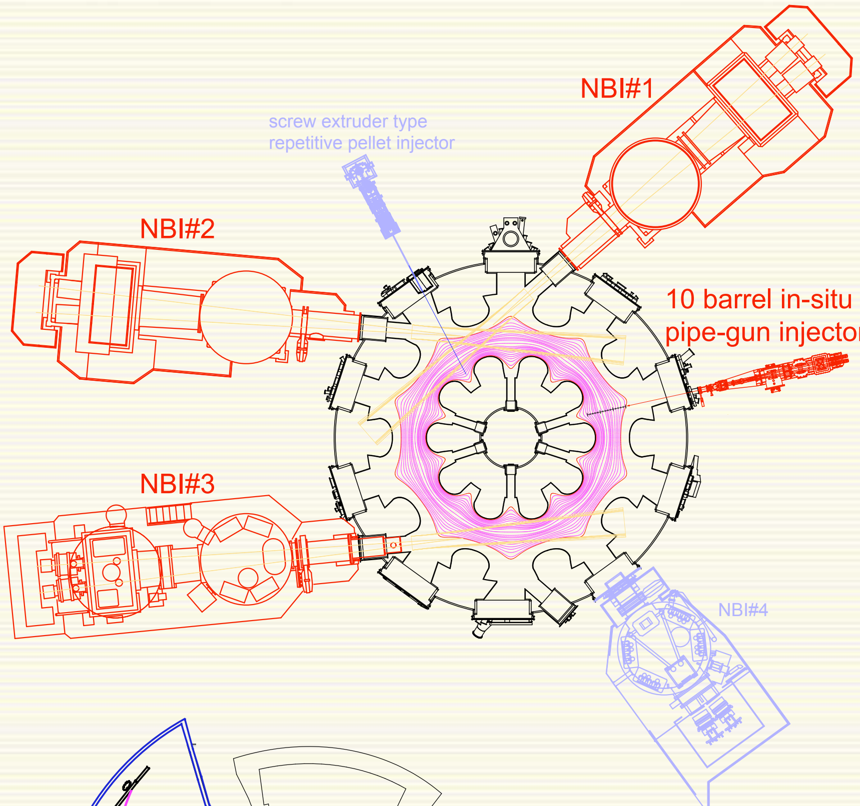


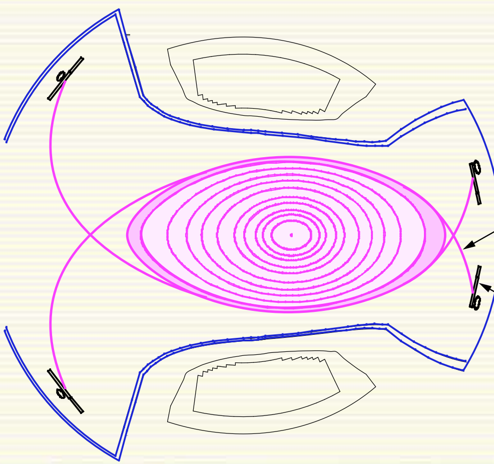




Experimental Setup

- **Large Helical Device**
  - ✓ heliotron type device with NbTi super-conducting coils
  - ✓ high energy NBI heating (~ 12 MW)
- **Helical Divertor**
  - ✓ intrinsic divertor configuration in heliotron type device
  - ✓ open divertor configuration with forced water cooled carbon target plate
  - ✓ no active pumping capacity
  - ✓ larger heat receiving area than LID
- **Pellet Injector**
  - ✓ 10 barrel in-situ pipe-gun injector
  - ✓ pellet size: 3.4 - 3.8 mm (1.5 - 2.0×10^{21} atoms/pellet)
  - ✓ pellet velocity: 1,000-1,200 m/s

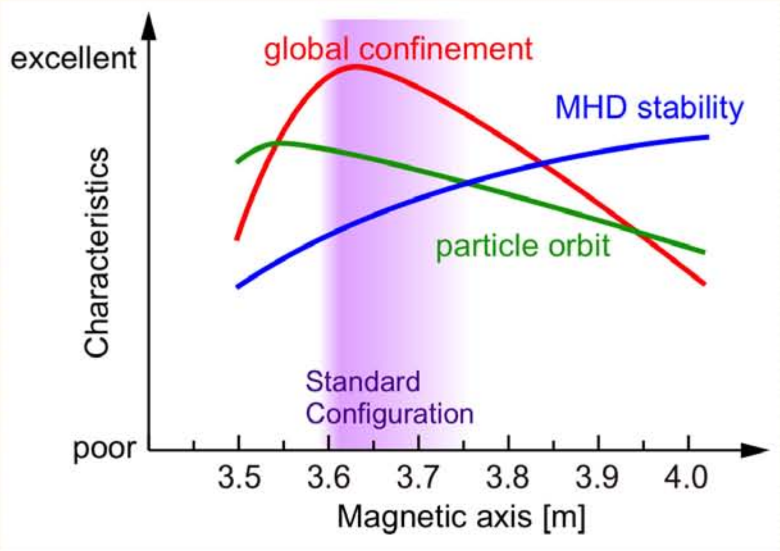


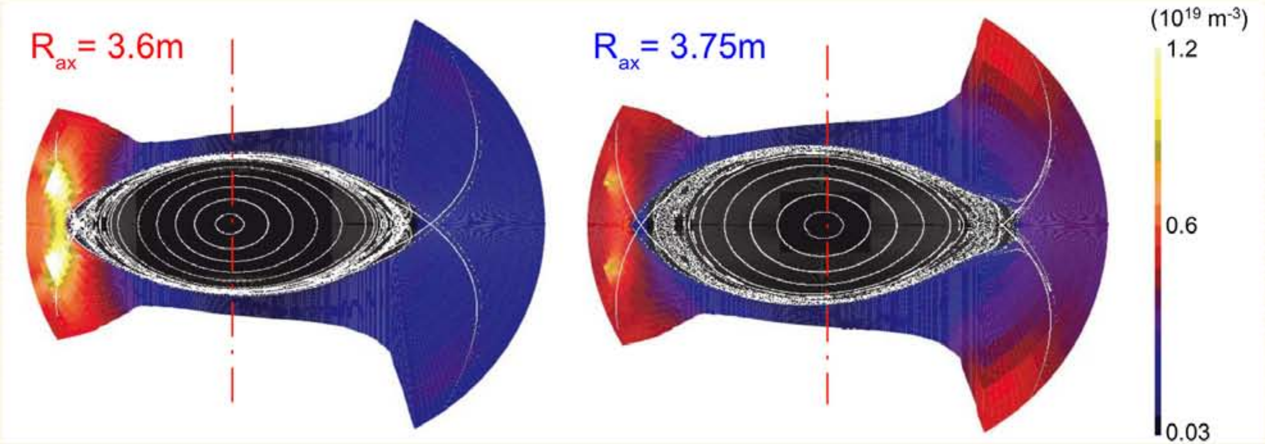


Position of Magnetic Axis: R_{ax}

A key operational parameter characterizing configuration effect in LHD

- **MHD stability**
  - ✓ outward shift ⇒ ***STABLE***
- **Orbit of high energetic particles**
  - ✓ inward shift ⇒ ***GOOD***
- **Global confinement property**
  - ✓ Rax= 3.6-3.65 m ⇒ ***OPTIMAL***
- **Divertor function**
  - ✓ inward shift ⇒ ***heavy neutrals concentration in inboard side***





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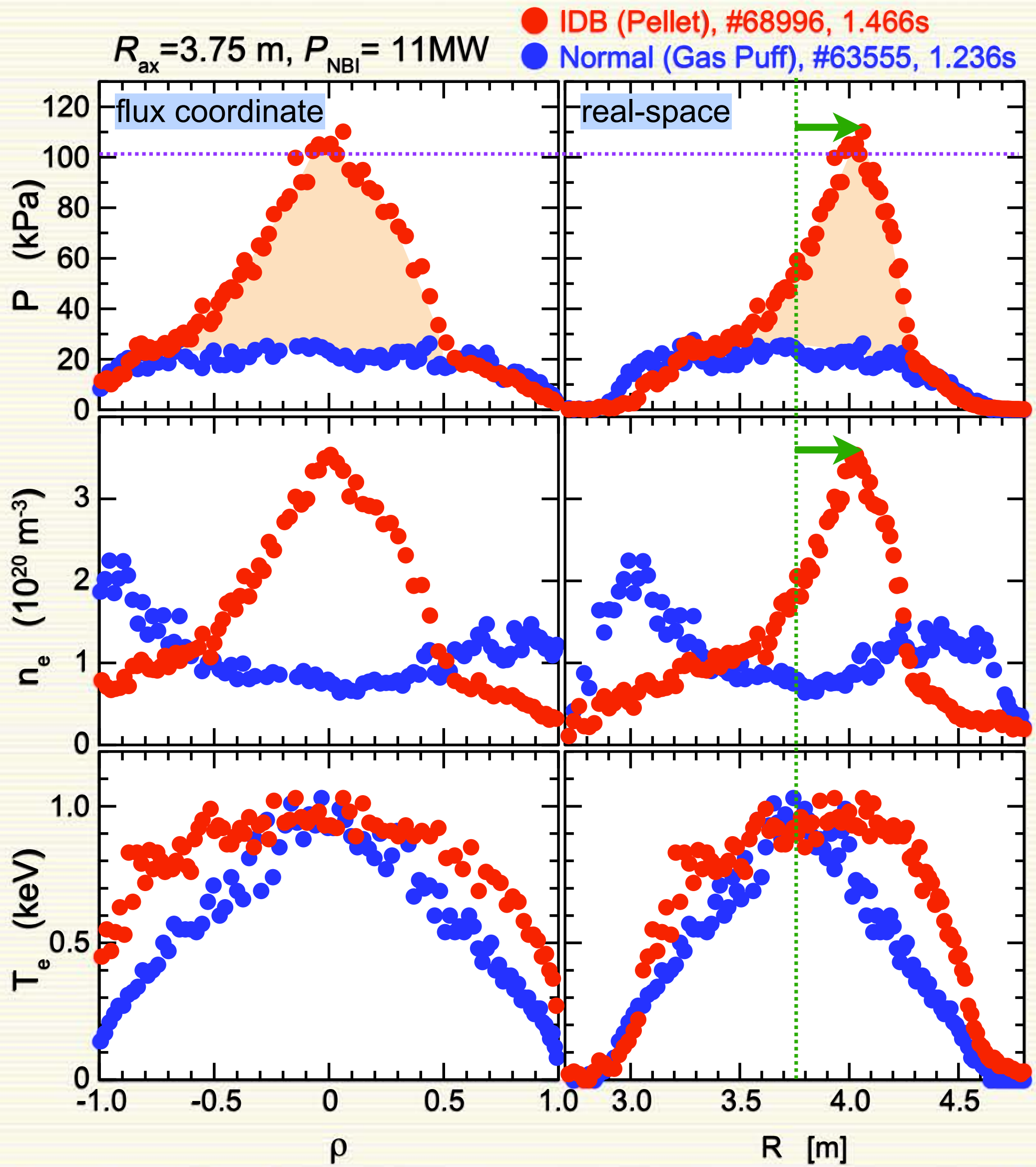
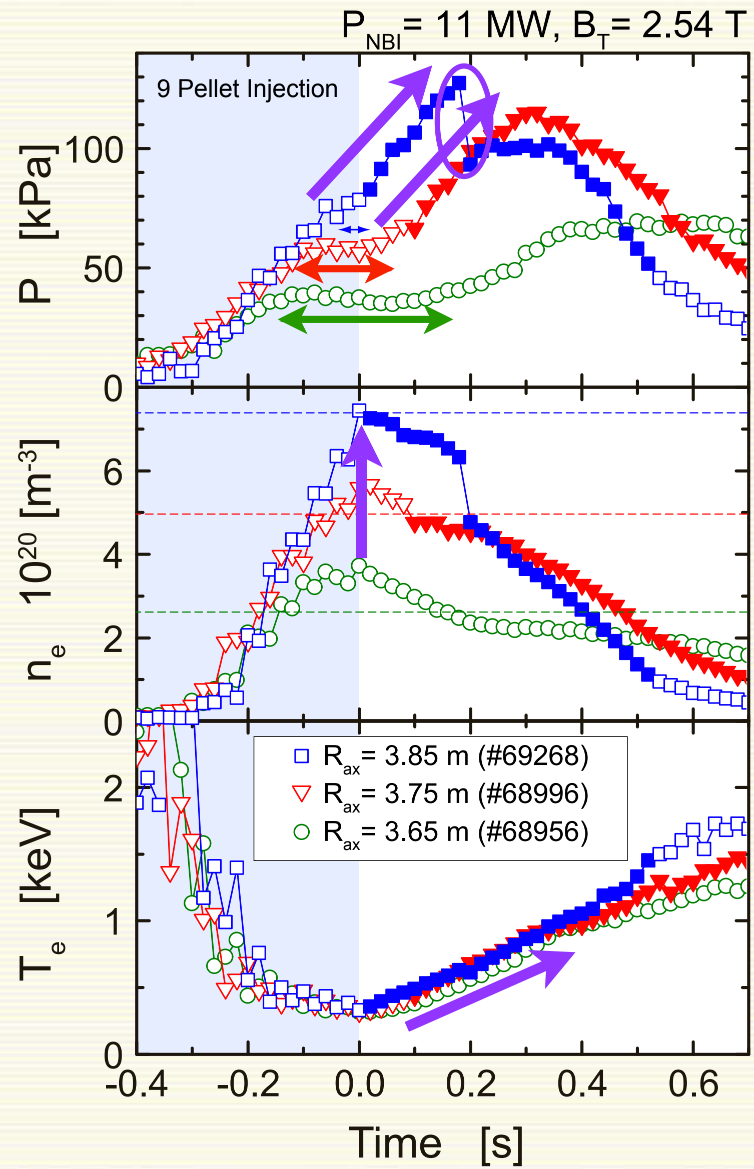
Effects of Particle Deposition (Fueling)

- **Gas-puff fueling**
  - ✓ flat or hollow density profile due to peripheral fueling
- **Pellet injection fueling**
  - ✓ highly peaked density profile
  - ✓ high central pressure (exceeds atmospheric pressure)
  - ✓ plasma β become high (> 5 %) even at high magnetic field ($B_t > 2.54$ T)
  - ✓ very large Shafranov shift ($\Delta/a_{eff} \approx 1/2$)



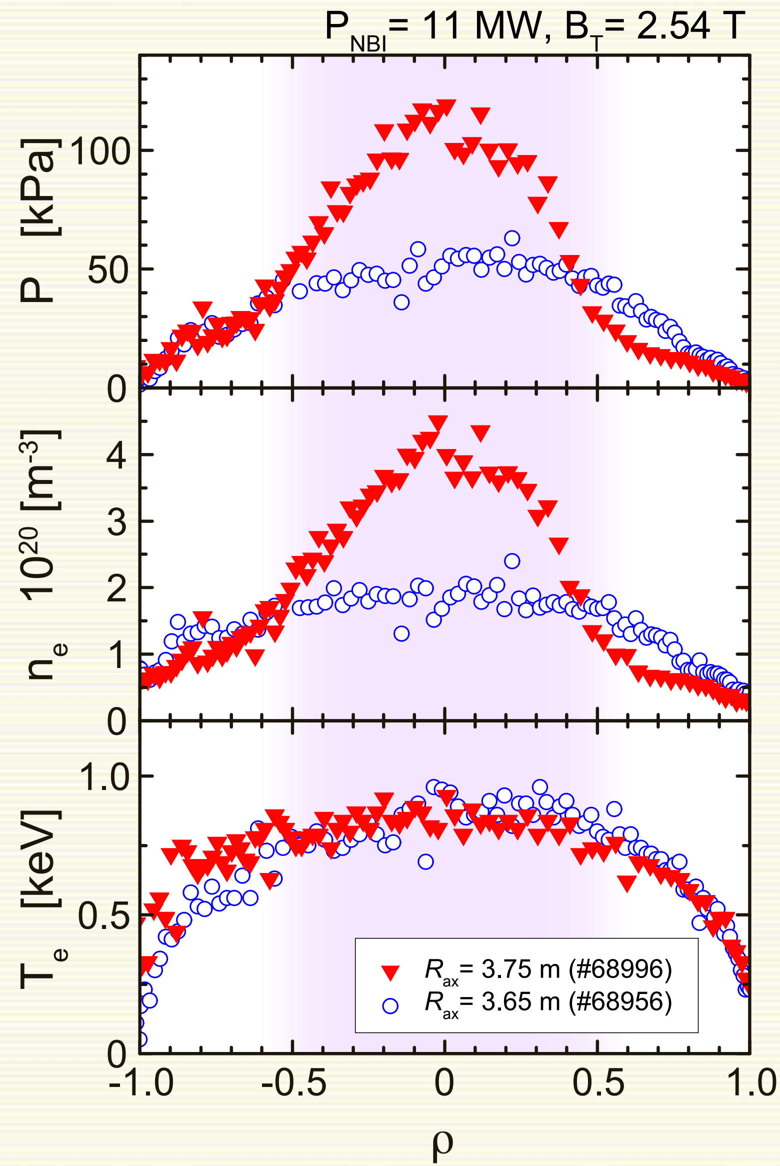
Effects of Magnetic Configuration (R_{ax})

- **Achievement of high-density/high-pressure operation**
  - ✓ attainable central plasma density becomes higher as the magnetic axis shifts outward
    - IDB formation
  - ✓ central temperature follow quite a similar course after pellet injection
  - ✓ IDB formation and central pressure rapidly increase at $R_{ax} \geq 3.75$ m
  - ✓ Plateau of pressure rise at high density regime
    - 2.7×10^{20} m^{-3} at R_{ax}= 3.65 m
    - 5.0×10^{20} m^{-3} at R_{ax}= 3.75 m
    - $>7.4\times10^{20}$ m^{-3} at R_{ax}= 3.85 m
  - ✓ Pressure rise is abruptly terminated by a core density collapse (CDC) event



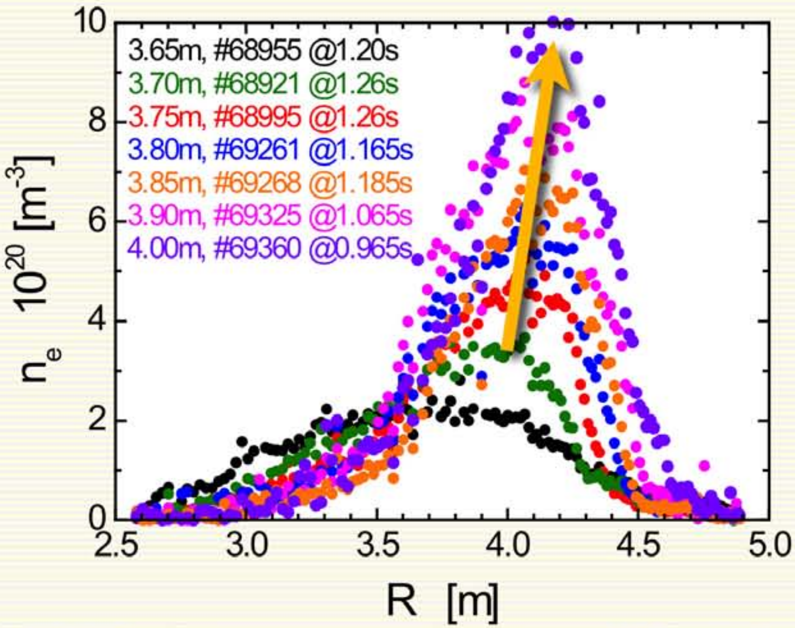
Effects of Magnetic Configuration (R_{ax})

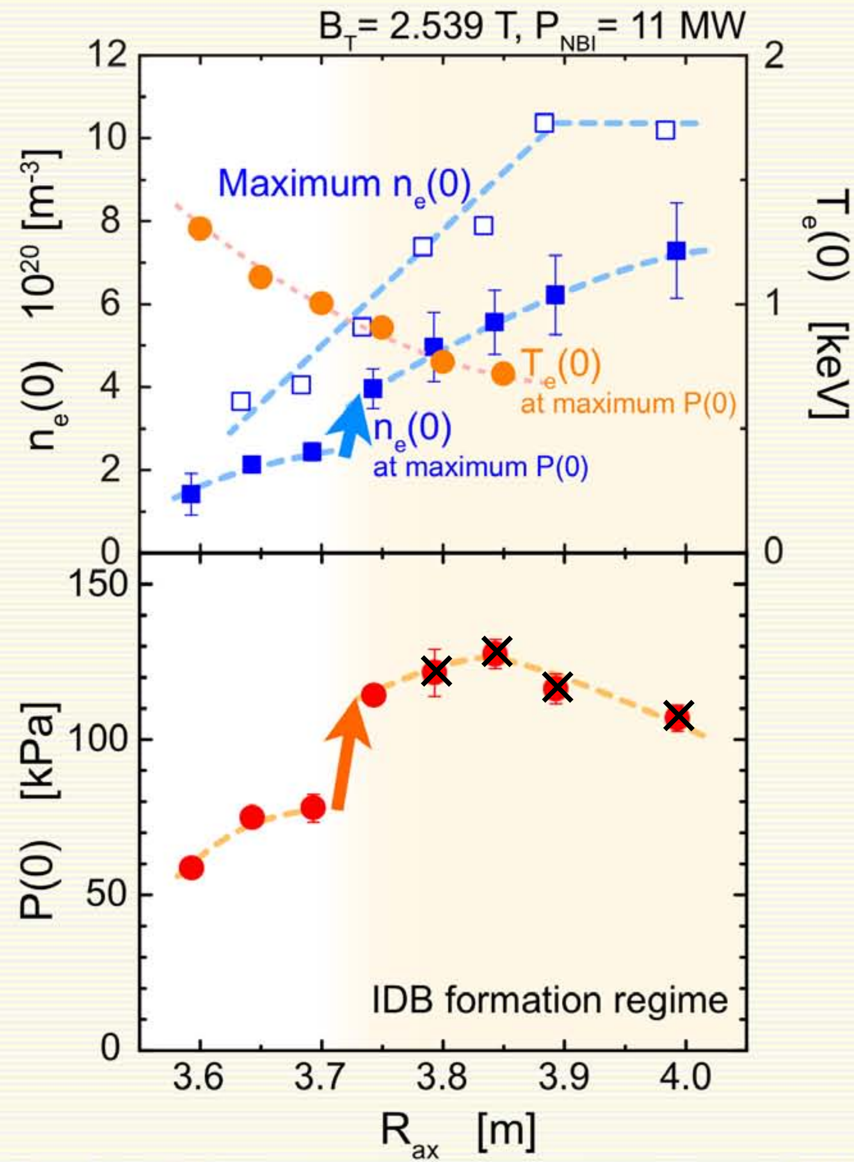
- **IDB formation in the outward shifted magnetic configuration (R_{ax}= 3.75 m)**
  - ✓ sharp bend in the density profile around $\rho = 0.55$
    - low density mantle and high density core
  - ✓ Achievement of double density without fall of temperature
  - ✓ Magnetic configuration (outward shift) is another factor of the IDB formation in addition to pellet core fueling.



High Density Operation with Confinement Improvement

- Maximum central density reaches 1×10^{21} m^{-3} at $R_{ax} > 3.9$ m.
- A jump of the central pressure is observed around $R_{ax} = 3.7$ m
- Central pressure reach its largest value (130 kPa) at $R_{ax} = 3.85$ m.
- Suppression of pressure rise due to CDC event





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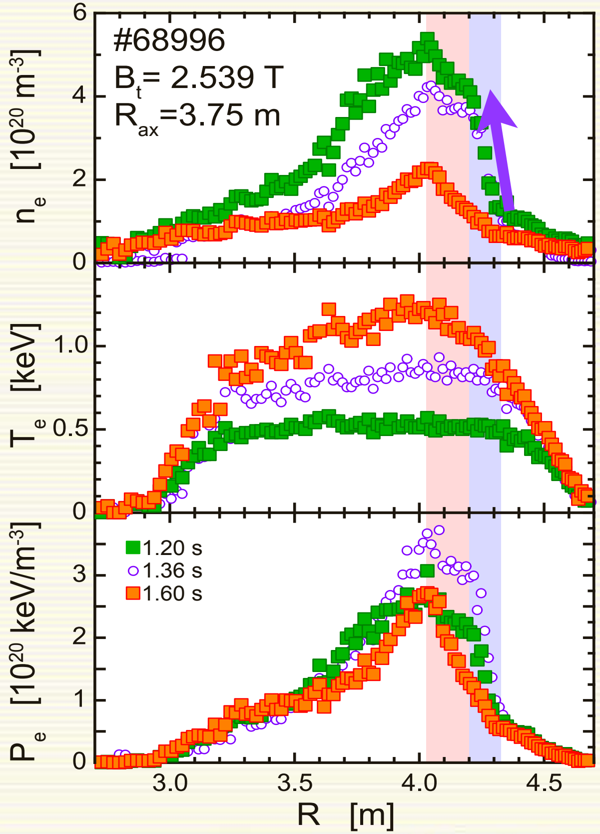
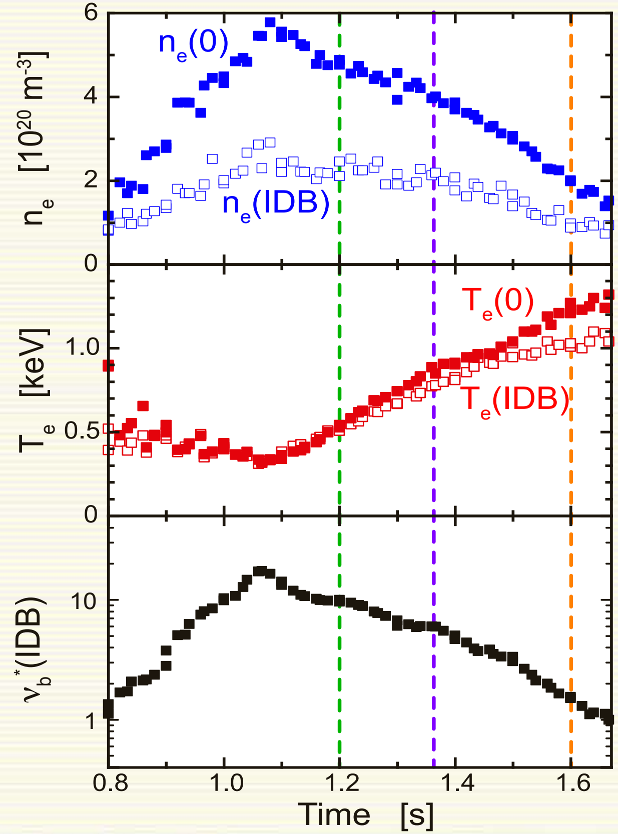
Change of IDB Profile from Moment to Moment

- **Operational regime: *plateau***
  - ✓ $1 \le \nu_b^* \le 10$, $\nu_p^* \le 1$ at $\rho = 0.5$
- **IDB gradient gradually decrease and spread into core region**
  - ✓ box-profile into linear-profile
  - ✓ due to lack of particle source inside IDB? or confinement degradation?



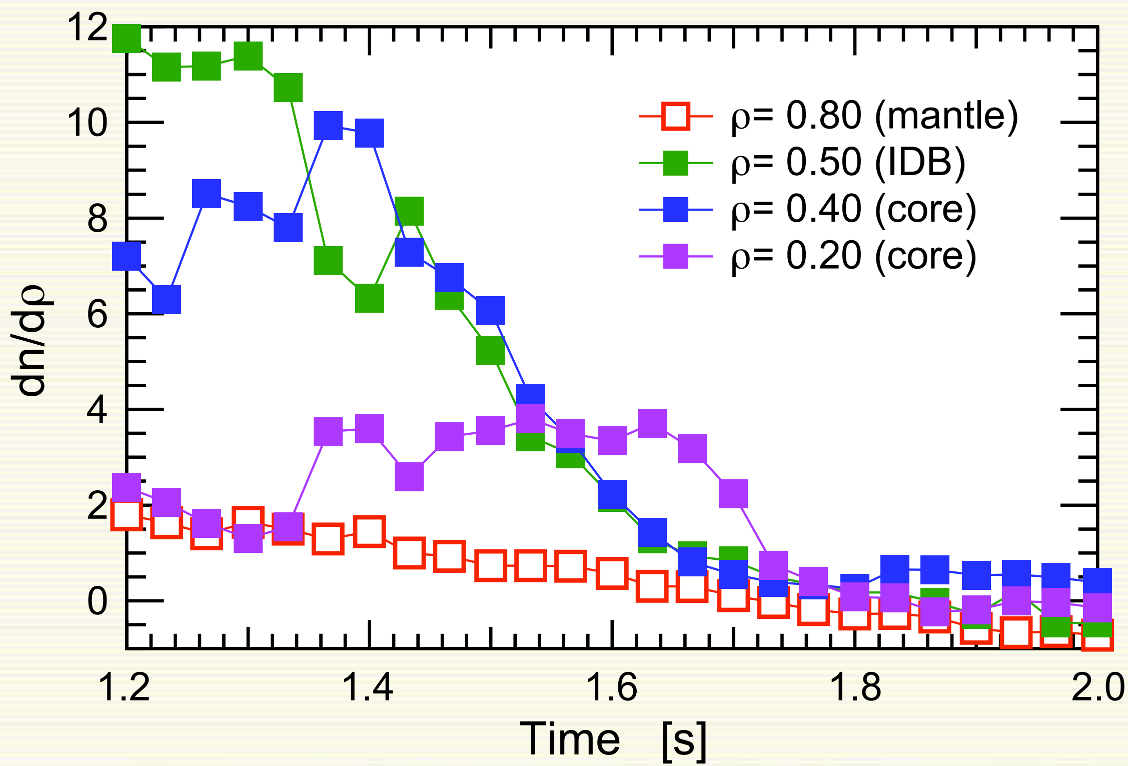


Temporal Change in Density Gradient

- Particle transport coefficient of IDB plasma is estimated from time evolution and gradient of density profile.

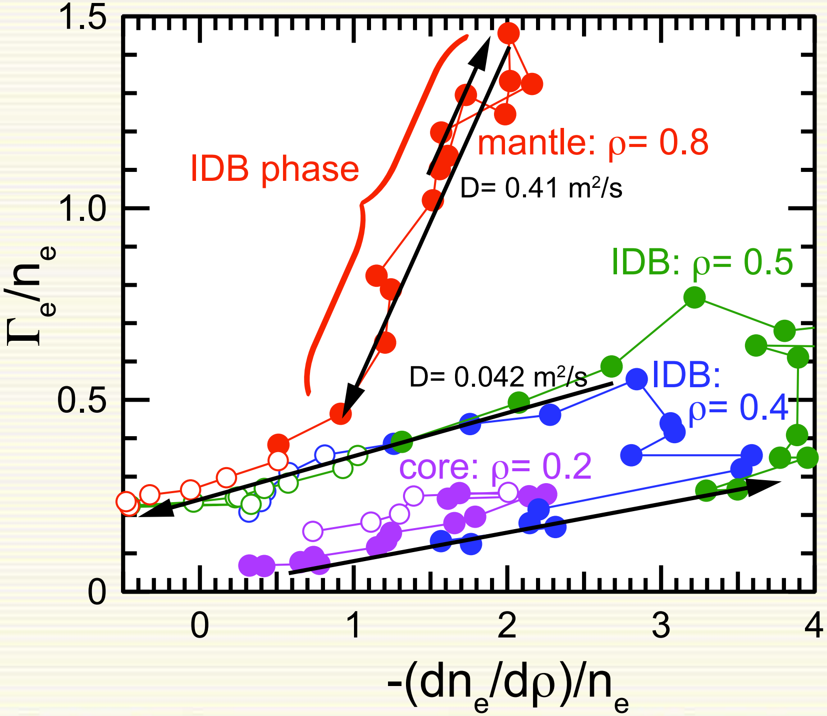
$$\Gamma_e = -D_e \frac{\partial n_e}{\partial \rho} + n_e v_e$$
$$Y = D_e X + v_e$$

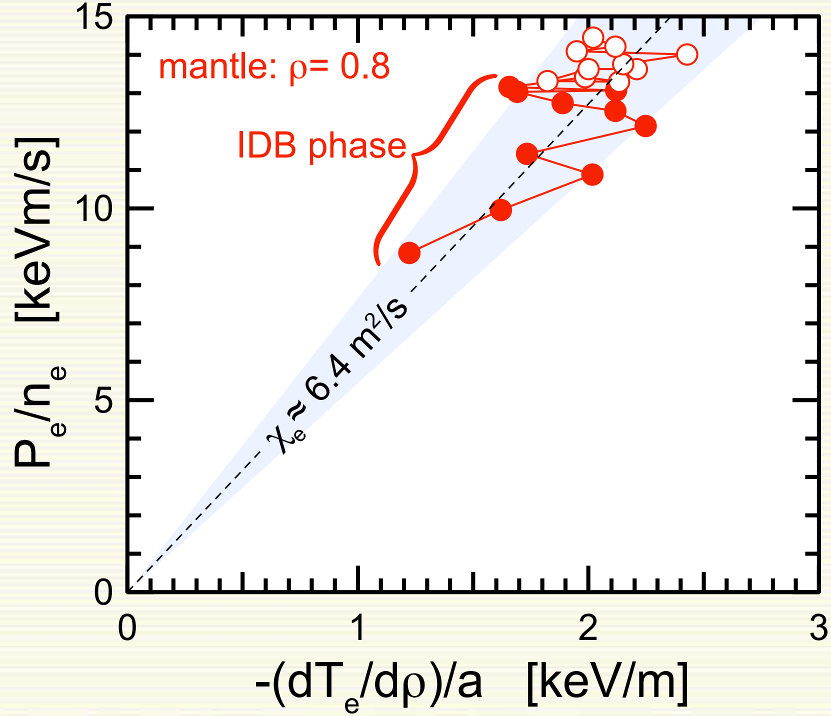
where
$$\begin{cases} X = -\dfrac{1}{n_e}\dfrac{\partial n_e}{\partial \rho} \\ Y = \dfrac{\Gamma_e}{n_e} = \dfrac{\int (S_e - \frac{\partial n_e}{\partial t}) dV}{n_e A} \end{cases}$$



Particle Transport of IDB Plasmas

- **Core diffusivity is kept at low level even high density gradient.**
  - ✓ profile change (Box-like into linear profile) is explained by lack of particle source inside IDB
  - ✓ not sensitive to collisionality
- **Diffusivity of mantle (ρ= 0.8) deteriorates during IDB phase**
- **Thermal transport coefficient unaffected by particle transport change**





Possible Model of IDB Plasma

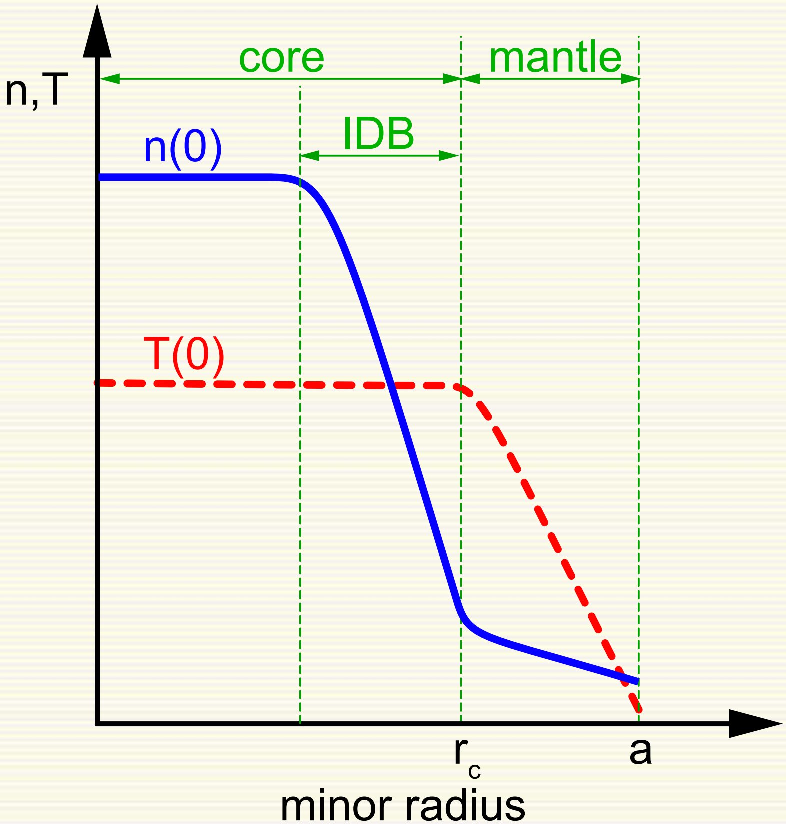
- Confinement region is separated into low density mantle and high density core. This lead to high-density/high-pressure IDB plasma without radiation problem.

✓ ***Low density mantle***

- suppress radiation loss ⇒ free from radiative density limit
- secure temperature gradient for high density core

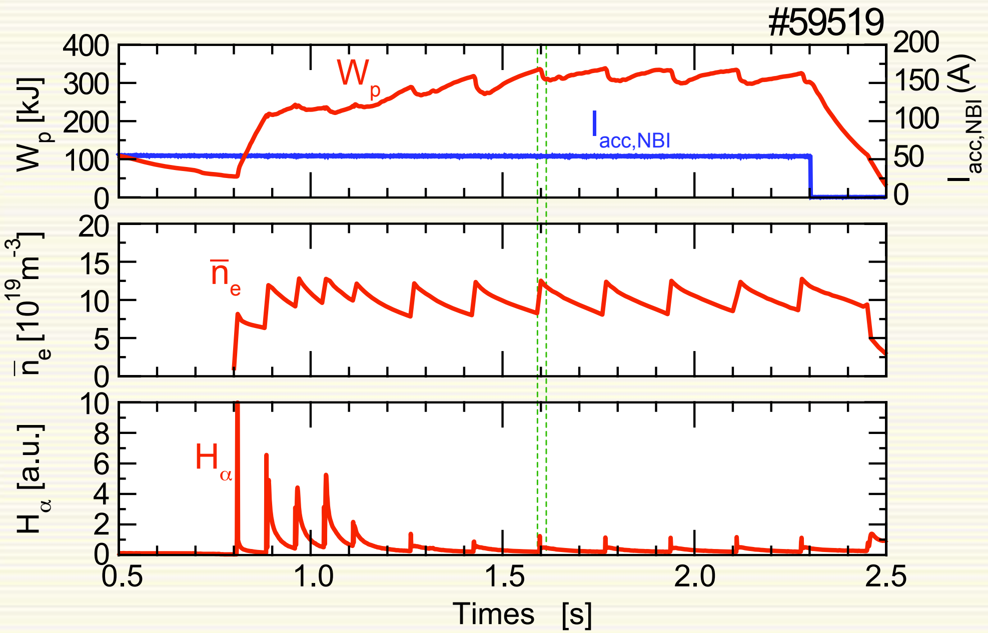
✓ ***High density core***

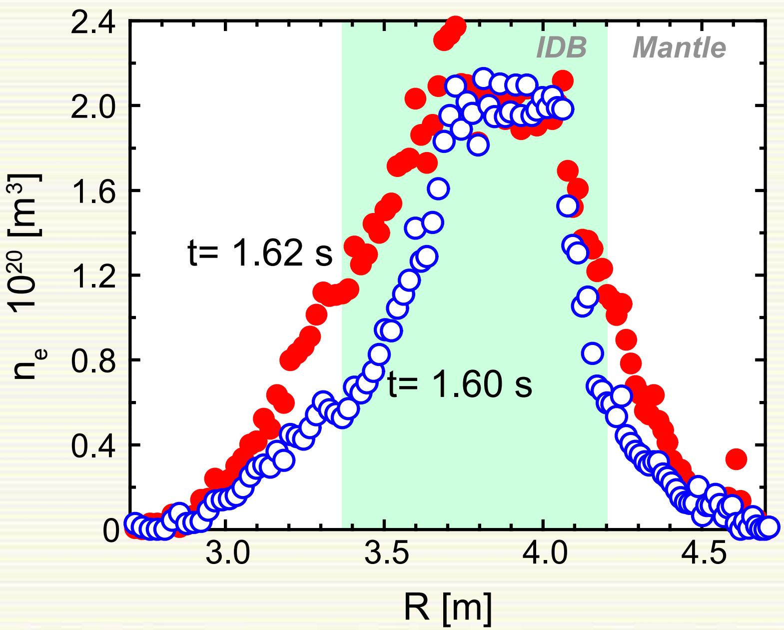
- deep pellet fueling and good particle confinement lead to high pressure core plasma



Sustainability of IDB Plasma

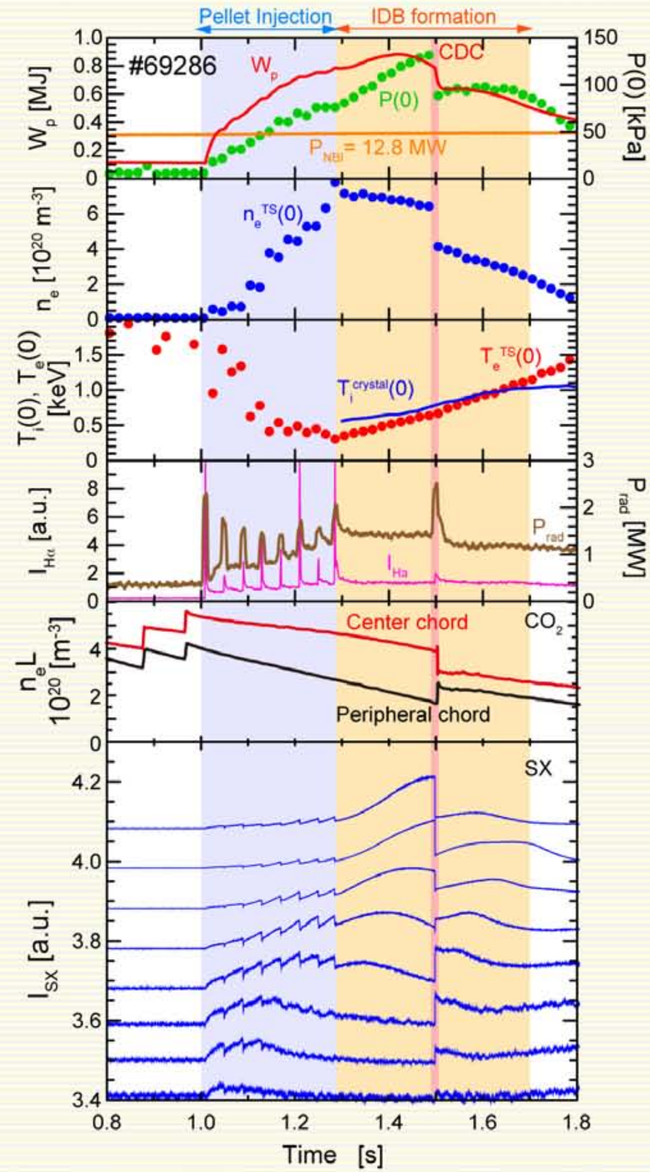
- **IDB plasma can be sustained by using repetitive pellet injection**
  - ✓ Demonstrated in low-B, low-power experiment
- **Core fueling is essential to maintain SDC plasma**
  - ✓ High speed and large pellets are required
  - ✓ High frequency injection is not required





Core Density Collapse Event in IDB Plasma

- **Core density collapse (CDC) event**
  - ✓ Core density is abruptly expelled at high pressure regime
  - ✓ Time scale of CDC is sub-ms
  - ✓ Limit central pressure
  - ✓ Mechanism of CDC
    - MHD stability?
    - Equilibrium limit?
    - Turbulence?
    - ……
- **Potential solution: Suppression of Shafranov shift**
  - ✓ Vertical field control (inward shift)
  - ✓ Suppressing P-S currents
    - Aspect ratio (reduce minor radius)
    - Ellipticity (vertical elongation)



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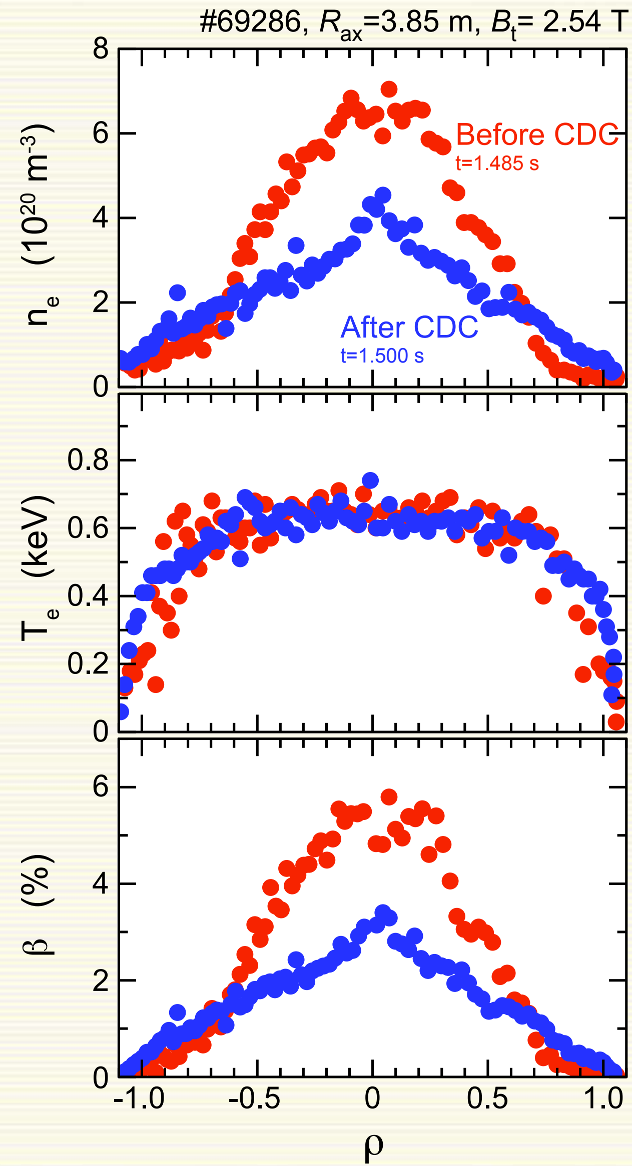
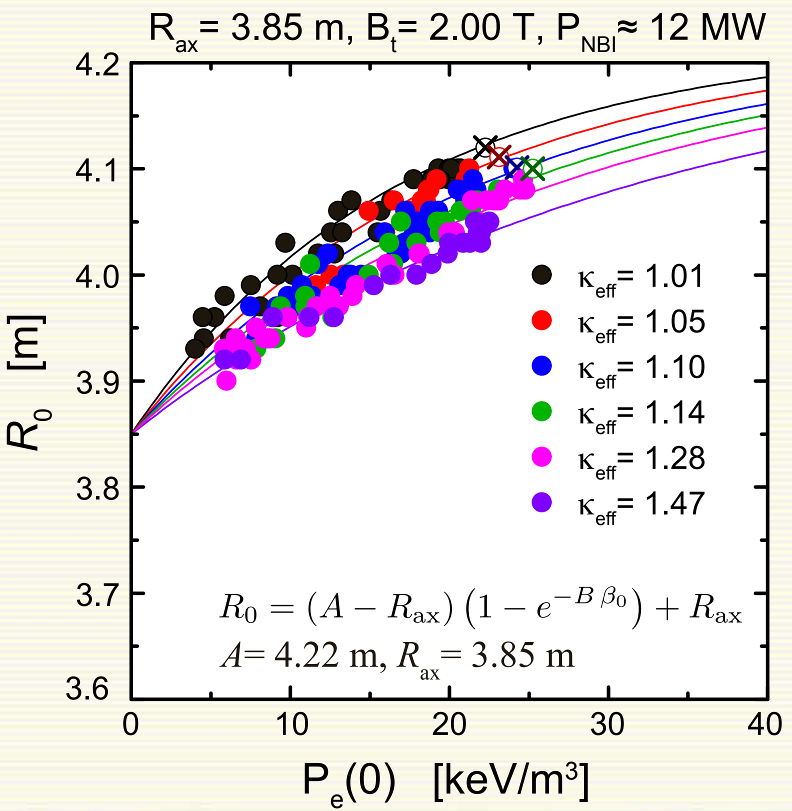
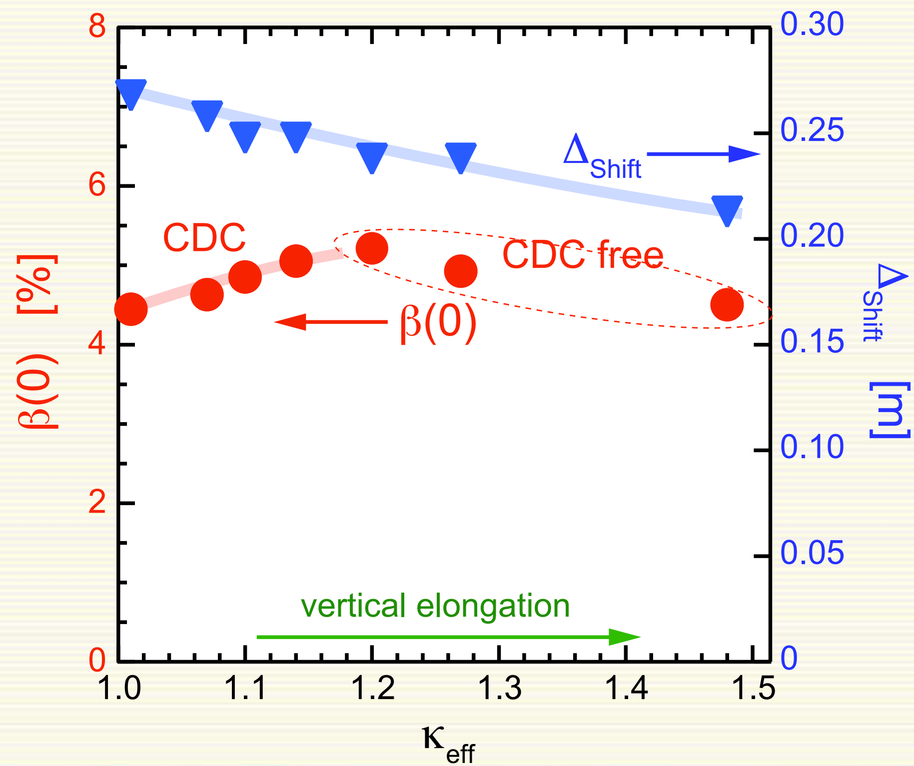


Suppression of Shafranov Shift by Vertical Elongation

- **Vertical elongation is effective to suppress the Shafranov shift**
  - ✓ CDC limits central pressure for $\kappa < 1.2$
  - ✓ CDC disappears when $\kappa > 1.2$
  - ✓ Higher central beta 6.6 % has been achieved under CDC free condition

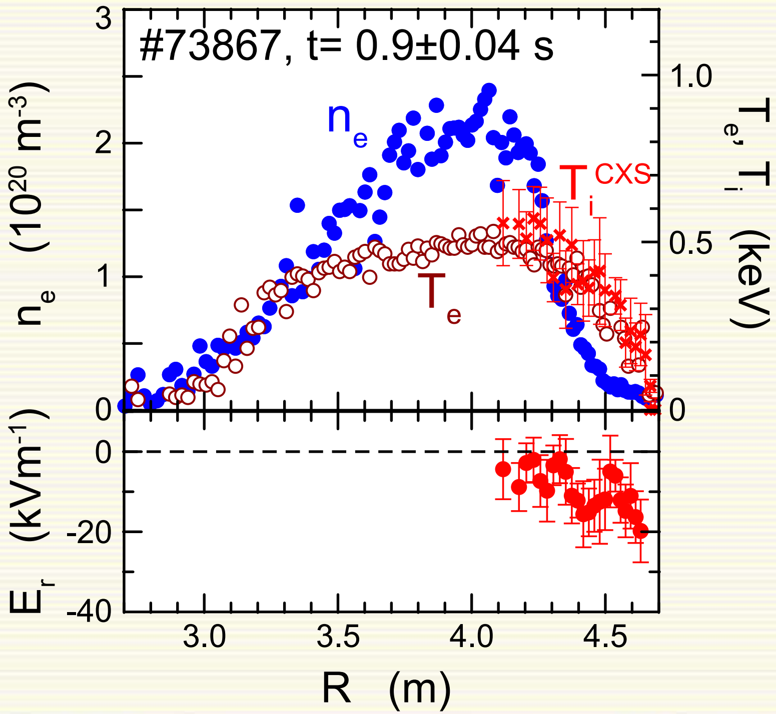
related poster at P1-051: Ohdachi and P1-087: Miyazawa

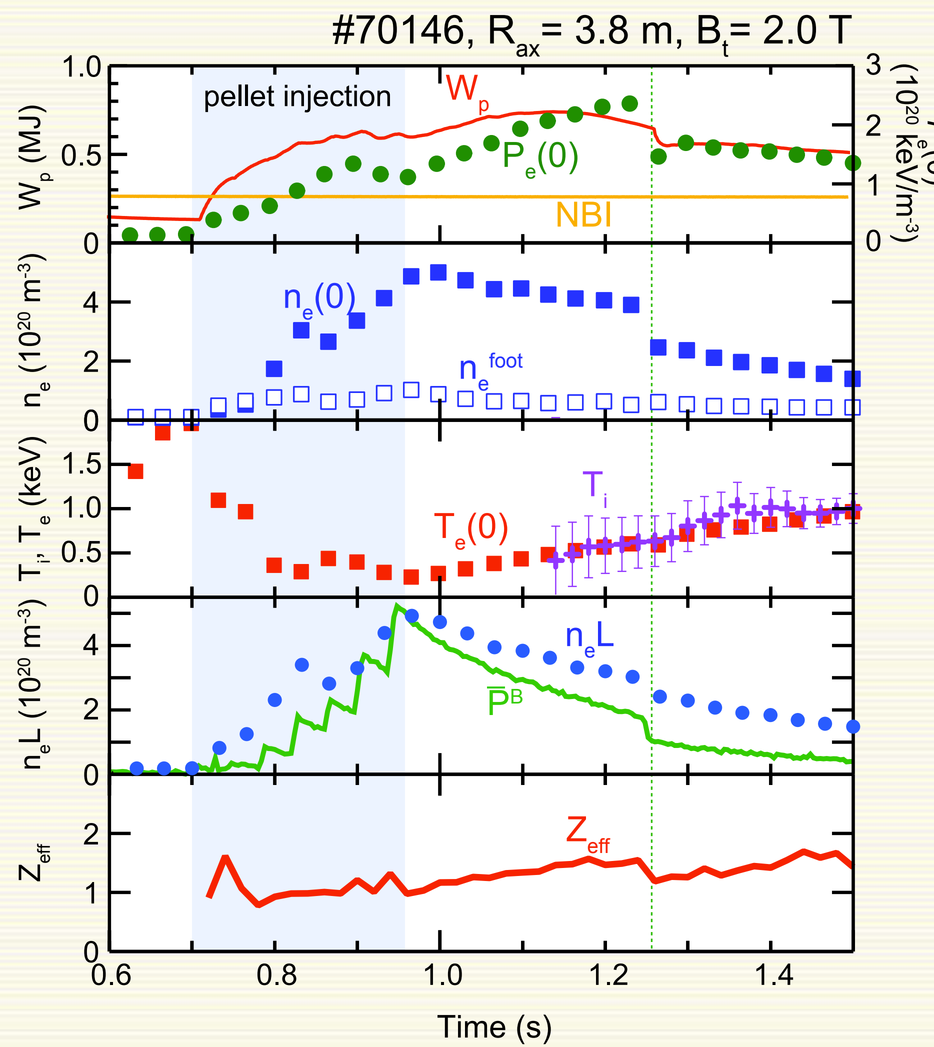




Impurity Behavior in IDB Plasma

- **Neoclassical ambipolar diffusion**
  - ✓ ion root (negative radial electric field)
  - ✓ impurity accumulation?
- **No significant indication of impurity accumulation**





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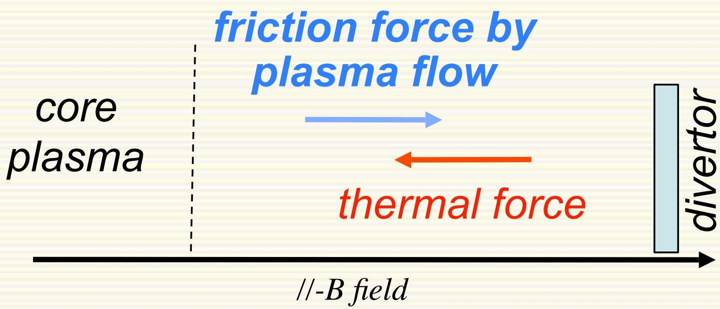


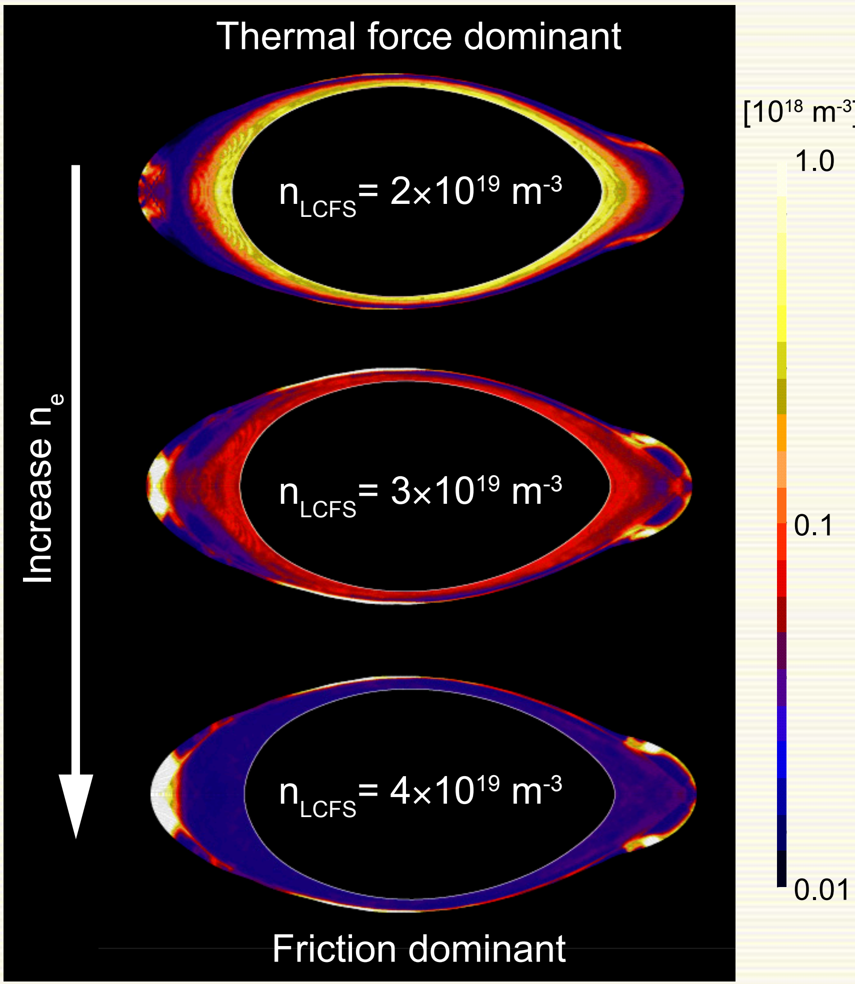
EMC3-EIRENE calculation

- ✓ Impurity shielding potential in ergodic layer
  - – Outward friction force dominate impurity behavior in high-density regime

//-impurity velocity

$$V_{Z\parallel} = \underbrace{V_{i\parallel}}_{\text{Friction force}} + \underbrace{2.2\frac{\tau_{Zi}}{m_Z}Z^2\frac{\partial T_i}{\partial s}}_{\text{Thermal force}}$$

Carbon density distribution (EMC3-EIRENE)



related presentation at I-07: Kobayashi

Summary

- IDB plasma has been reproducibly obtained at the intrinsic helical divertor configuration as in LID configuration by optimizing the pellet fueling and magnetic configuration.
  - ✓ Core fueling by multi-pellet injection is essential.
  - ✓ The IDB easily appears in the outward-shifted magnetic configuration.
- The central density reaches 1×10^{21} m^{-3} at $R_{ax}\geq 3.9$ m and the central pressure has reached 1.3 times atmospheric pressure.
- Confinement region is separated into low density mantle and high density core in IDB plasma. This lead to high pressure core plasma.
  - ✓ Diffusivity is kept at low level even high density gradient in high density core.
  - ✓ Low density mantle suppress radiation loss and secure temperature gradient.
- CDC event, which arise from very large Shavranov shift, limit operational regime.
  - ✓ Suppression of Shafranof shift with ellipticity control can mitigate CDC event and the central β is increase up to 120 % of standard configuration.
- Harmful impurity accumulation has not been observed in IDB plasma.