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


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  - Experimental setup
  - Helical divertor (HD) configuration

- **Internal Diffusion Barrier (IDB) Formation in HD**
  - Fueling (particle deposition)
  - Magnetic Configuration (position of magnetic axis)

- **Properties of IDB Plasmas**
  - Change of profile
  - Particle transport
  - Potential model of IDB plasma
  - Sustainability of IDB plasma
  - Core density collapse event in IDB plasma
  - Impurity behavior in IDB plasma

- **Summary**
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- **Summary**
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 ($\eta_{pump} \approx 40\%$)
- 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 $\Rightarrow$ \textit{STABLE}
  - inward shift $\Rightarrow$ \textit{GOOD}

- **Orbit of high energetic particles**
  - inward shift $\Rightarrow$ \textit{GOOD}

- **Global confinement property**
  - $R_{ax} = 3.6 - 3.65$ m $\Rightarrow$ \textit{OPTIMAL}

- **Divertor function**
  - inward shift $\Rightarrow$ \textit{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 $\beta$ become high (> 5%) even at high magnetic field ($B_t > 2.54$ T)
  - Very large Shafranov shift ($\Delta/a_{\text{eff}} \approx 1/2$)

![Graph showing density, temperature, and pressure profiles for gas-puff and pellet injection fueling in LHD plasma.]

- $R_{\text{ax}} = 3.75$ m, $P_{\text{NBI}} = 11$ MW

- IDB (Pellet), #68996, 1.466s
- Normal (Gas Puff), #63555, 1.236s

- Flux coordinate
- Real-space

- Plasmas become high even at high magnetic field ($B_t > 2.54$ T)
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
    - $2.7 \times 10^{20}$ m$^{-3}$ at $R_{ax} = 3.65$ m
    - $5.0 \times 10^{20}$ m$^{-3}$ at $R_{ax} = 3.75$ m
    - $>7.4 \times 10^{20}$ m$^{-3}$ at $R_{ax} = 3.85$ m
  - Pressure rise is abruptly terminated by a core density collapse (CDC) event

- **Graph Details**
  - $P_{NBI} = 11$ MW, $B_t = 2.54$ T
  - 9 Pellet Injection
  - Pressure rise
  - Central electron density ($n_e$)
  - Temperature ($T_e$)
  - Time ($t$)

- **Tables**
  - $R_{ax} = 3.85$ m (#69268)
  - $R_{ax} = 3.75$ m (#68996)
  - $R_{ax} = 3.65$ m (#68956)
**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.

![Graphical representation of IDB formation](image_url)
High Density Operation with Confinement Improvement

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

![Graph showing IDB formation regime and pressure, density, and temperature profiles at various $R_{ax}$ values.](image)
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Change of IDB Profile from Moment to Moment

- **Operational regime:** plateau
  - $1 \leq n_b^* \leq 10$, $n_p^* \leq 1$ 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?

![Graphs showing changes in profile from moment to moment](image)
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

\[
\begin{align*}
X &= -\frac{1}{n_e} \frac{\partial n_e}{\partial \rho} \\
Y &= \frac{\Gamma_e}{n_e} = \frac{\int (S_e - \frac{\partial n_e}{\partial t})dV}{n_e A}
\end{align*}
\]
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 \( \rho = 0.8 \) deteriorates during IDB phase

- **Thermal transport coefficient unaffected by particle transport change**
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

![Graph showing times and ne, He_a]
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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- **Potential solution: Suppression of Shafranov shift**
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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

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**Equation:**

$$R_0 = (A - R_{ax}) \left( 1 - e^{-B \beta_0} \right) + R_{ax}$$

- $R_0$: Vertical elongation
- $A$: 4.22 m
- $R_{ax}$: 3.85 m
- $B$: 2.00 T
- $P_{NBI} \approx 12$ MW

**Graph:**

- $\beta(0)$ vs. $K_{eff}$
- $\Delta_{Shift}$ vs. $\beta(0)$ for CDC and CDC free conditions
**Impurity Behavior in IDB Plasma**

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

![Graph showing ion density and temperature profiles over time](image)
**Impurity Behavior in IDB Plasma**

- **EMC3-EIRENE calculation**
  - Impurity shielding potential in ergodic layer
    - Outward friction force dominates impurity behavior in high-density regime

\[
V_{Z\parallel} = V_{i\parallel} + 2.2 \frac{\tau Z_i}{m_Z} Z^2 \frac{\partial T_i}{\partial s}
\]

- Thermal force
- Friction force

**Carbon density distribution** (EMC3-EIRENE)

- Thermal force dominant
  - \(n_{LCFS} = 2 \times 10^{19} \text{ m}^{-3}\)
  - \(n_{LCFS} = 3 \times 10^{19} \text{ m}^{-3}\)
  - \(n_{LCFS} = 4 \times 10^{19} \text{ m}^{-3}\)

**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 $1 \times 10^{21} \, \text{m}^{-3}$ at $R_{ax} \geq 3.9 \, \text{m}$ 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 Shafranov shift with ellipticity control can mitigate CDC event and the central $\beta$ is increase up to 120 % of standard configuration.

❖ Harmful impurity accumulation has not been observed in IDB plasma.