Observation of Carbon Impurity Flow in the Edge Stochastic Magnetic Field Layer of Large Helical Device and its Impact on the Edge Impurity Control

T. Oishi\textsuperscript{1,2}, S. Morita\textsuperscript{1,2}, S. Y. Dai\textsuperscript{1,3}, M. Kobayashi\textsuperscript{1,2}, G. Kawamura\textsuperscript{1}, X. L. Huang\textsuperscript{1}, H. M. Zhang\textsuperscript{2}, Y. Liu\textsuperscript{2}, M. Goto\textsuperscript{1,2}, and the LHD Experiment Group\textsuperscript{1}

\textsuperscript{1} National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan
\textsuperscript{2} Department of Fusion Science, Graduate University for Advanced Studies, 322-6 Oroshi-cho, Toki 509-5292, Japan
\textsuperscript{3} School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian 116024, PR China

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- Experimental results: Flow profiles of carbon impurity flows in the ergodic layer and comparison with simulations
- Summary
Roles of edge stochastic magnetic fields
- **Tokamaks:**
  - ELM mitigation by imposing RMP, ergodic divertor
- **Helicals:**
  - Intrinsic edge stochastization

**Large Helical Device (LHD)**
- $R = 3.6$ m, $<a> = 0.64$ m,
- $B_t < 3$ T, $m/l = 10/2$
- A thick stochastic magnetic field layer called “ergodic layer” is located outside the core plasma.

Stochasticization of the edge magnetic field has been extensively studied in the researches of magnetically-confined torus plasmas.
The ergodic layer consists of stochastic magnetic field lines with connection lengths from 10 to 2000 m. (0.5~100 toroidal turns in LHD)

- Thick ergodic layer with the outward-shifted magnetic axis
- $T_e = 10$~500 eV -> Impurity lines emit significantly in the VUV wavelength range.

Transport phenomena due to the existing of the ergodic layer
- Impurity screening
- Divertor detachment without impurity seeding
- Asymmetrical profiles of impurity ions

Impurity line emissions released from the ergodic layer of LHD are investigated by the spectroscopic methods.
Spectroscopic observation of impurity screening

- Ionization potentials $E_i$ for each charge state:

<table>
<thead>
<tr>
<th>Charge state</th>
<th>$E_i$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C^{2+}$</td>
<td>48</td>
</tr>
<tr>
<td>$C^{3+}$</td>
<td>65</td>
</tr>
<tr>
<td>$C^{4+}$</td>
<td>392</td>
</tr>
<tr>
<td>$C^{5+}$</td>
<td>490</td>
</tr>
</tbody>
</table>

- Carbon lines emitted from outer region of the ergodic layer (CIII, CIV) increase while those from inner region (CV, CVI) decrease in higher $n_e$ discharges…
  - Indicates enhancement of the impurity screening.
Impurity transport model in the ergodic layer

Parallel momentum balance on impurity ions

Impurity ion pressure gradient  Parallel electric field

Impurity flow in edge magnetic fields

Flow is a key mechanism to determine impurity distribution

Electron thermal force

Ion thermal force

- $\nabla n_i \uparrow \rightarrow$ Friction force $\uparrow \rightarrow$ Impurity flow toward divertor plates (screening)
- $\nabla T_i \uparrow \rightarrow$ Ion thermal force $\uparrow \rightarrow$ Impurity flow toward core plasmas (accumulation)

Friction force

$m_z \frac{\partial V_z^\parallel}{\partial t} = -\frac{1}{n_z} \frac{\partial T_z n_z}{\partial s} + Z e E^\parallel + m_z \frac{V_i^\parallel - V_{Z^\parallel}^{imp}}{\tau_s} + 0.71 Z^2 \frac{\partial T_e}{\partial s} + 2.6 Z^2 \frac{\partial T_i}{\partial s}$
Impurity screening in the ergodic layer

- The impurity screening/accumulation is determined by the balance between the friction force and the thermal force working on impurity ions.
- The impurity flow driven by the force balance is a measurable quantity.

Simulation of carbon impurity transport in the ergodic layer of LHD by EMC3-EIRENE code. M. Kobayashi et al., Nucl. Fusion 53, 033011 (2013)

Flow measurement by impurity spectroscopy
Vertical profile of VUV lines are measured.

- Wavelength range: 300 - 3200 Å,
- Spectral resolution: $d\lambda/dx = 0.037 \text{ Å/pixel}$
- $\Delta t$: 20 ms (full-binning) / 100 ms (space-resolved)
- The vertical observation range can be switched between the edge profile measurement and the full profile measurement.

Spectrum analysis for CIV ($C^3+$, $E_i = 65$ eV) $1548.2 \times 2 \text{ Å} (1s^22s-1s^22p)$

1. Intensity -> impurity density
   \[ I(\text{CIV}) \propto n(C^3+) \ n_e \]
2. Dopplar broadning -> $T_i$
   \[ T_i = 1.68 \times 10^8 M_i \ \left( \Delta_{FWHM} / \lambda_0 \right)^2 \]
3. Dopplar shift -> plasma flow
   \[ \Delta \nu = c \ \left( \Delta \lambda / \lambda \right) \]

The flow is in a relative value taking a peak of a spectrum measured in a certain experiment condition as a reference.
Profiles of CIV emission intensity and $T_i$

$R_{ax} = 3.6 \text{ m}, \quad B = 2.75 \text{ T}, \quad \text{H discharge}$

$n_e$ scan in $2.0 \sim 6.0 \times 10^{13} \text{ cm}^{-3}$

The peaks of the intensity profile are results of line integration in a long path along the sightline through the ergodic layer where $C^{3+}$ ions are located.

$Z (R=3.6 \text{ m})$

$C^{3+}$ density profile calculated with EMC3-EIRENE code

Vertical 102CH -> to spectrometer

Near X-point chords

Edge chords

$T_i \text{ (eV)}$
Profile of the edge impurity flow

$R_{ax} = 3.6 \, \text{m}, \, B = 2.75 \, \text{T}, \, n_e = 6.0 \times 10^{13} \, \text{cm}^{-3}$

- Full vertical profile of $\text{C}^{3+}$ impurity flow are evaluated from Doppler shift of CIV line emission $(1548.20 \times 2 \, \text{Å})$.

- Carbon impurity flows in the outboard direction observed at both top and bottom edges.

The measured flow velocity is projection of the flow along the observation chord.

$\Rightarrow$ Approximately considered to be the direction of the plasma major radius.

CIV spectrum measured in the plasma termination phase is used as a flow reference.
Parallel flow profile of $\mathrm{C}^3+$ ions in the ergodic layer calculated with the EMC3-EIRENE code

- $R_{\text{ax}} = 3.6 \text{ m}$, $B_t = 2.75 \text{ T}$, $n_{e_{\text{LCFS}}} = 6 \times 10^{13}\text{ cm}^{-3}$

- Flow components in the major radius direction are directed to the outboard side at both top and bottom edges of the ergodic layer.

... agrees with the experiment.
To obtain a synthetic vertical profile of the carbon flow, $V_{\text{syn}}(Z)$, local value of the calculated flow, $V_{\text{loc}}(R,Z)$ is line-integrated weighted by emission intensity along each observation chord.

$$V_{\text{syn}} = \frac{\int V_{\text{loc}} \varepsilon n_{C^{3+}} n_e \, dl}{\int \varepsilon n_{C^{3+}} n_e \, dl}$$
Profile of the edge impurity flow

- The synthetic profile of the simulated flow agrees with the experimental result excellently.

- The parallel impurity flow can be mainly determined by the momentum balance along the magnetic field line.

- Enhancement of impurity screening due to the impurity flow driven by the friction force has been predicted theoretically at higher electron density range.

- The density dependence of the flow was also certificated experimentally.
Variation of magnetic field line structures in the ergodic layer

- Magnetic field lines in the ergodic layer are concentrated in the inboard side on the horizontally-elongated cross section and outboard side on the vertically-elongated cross section in the inward-shifted configuration.

- Positions of “active” divertor legs switch between inward- and outward-shifted magnetic configurations.
Flow components in the major radius direction are directed to the inboard side at the bottom ... agrees with the simulation.

- $R_{ax} = 3.9$ m, $B_t = 2.539$ T, $n_{e_{LCFS}} = 4 \times 10^{13}$ cm$^{-3}$

- Edge profile measurement
The Parallel flow of carbon impurity in a thick stochastic magnetic field layer called “ergodic layer” located at the edge plasma of LHD was studied with a space-resolved VUV spectroscopy.

1. The carbon flow at the top and bottom edges in the ergodic layer had the same direction toward outboard side along the major radius direction in the inward-shifted magnetic field configurations in LHD.

2. The carbon flow at the bottom edge in the ergodic layer had a direction toward inboard side along the major radius direction in the outward-shifted configuration.

3. The observed flow quantitatively agreed with simulation result calculated by a three-dimensional simulation code EMC3-EIRINE. It experimentally verified the validity of edge parallel flow mechanism driving the impurity screening.
Simulation of parallel impurity flows in the ergodic layer

- $R_{ax} = 3.9$ m, $B_t = 2.539$ T, $n_{e_{LCFS}} = 4 \times 10^{13}$ cm$^{-3}$

- Flow components in the major radius direction are directed to the inboard side at both top and bottom edges of the outermost region of the ergodic layer.

Top Edge

Bottom Edge
Interpretation of CIV emission intensity profiles

- 2-D (toroidal-vertical) EUV spectroscopy for CIV line ($\lambda = 384$ Å, 2p-3d, $E_i = 65$ eV).
- $R_{ax} = 3.6$ m, $n_e \sim 6 \times 10^{19}$ m$^{-3}$
- Emission around $Z = 0$ mm is superposition of inboard and outboard X-points.
- Emission around $Z = \pm 460$ mm is from the ergodic layer.
- Understandable relatively straightforward
- Preferable for flow measurement
Simulation of parallel impurity flows in the ergodic layer

- Parallel flow profile of C$^{3+}$ ions in the ergodic layer calculated with the EMC3-EIRENE code.
- $R_{ax} = 3.6$ m
- $n_{e_{LCFS}} = 6 \times 10^{13}$ cm$^{-3}$
- Friction Force is dominant in high-density regime.

Friction Force

Ion Thermal Force