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

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- Summary

Introduction

Stochastization of the edge magnetic field has been extensively studied in the researches of magnetically-confined torus plasmas.

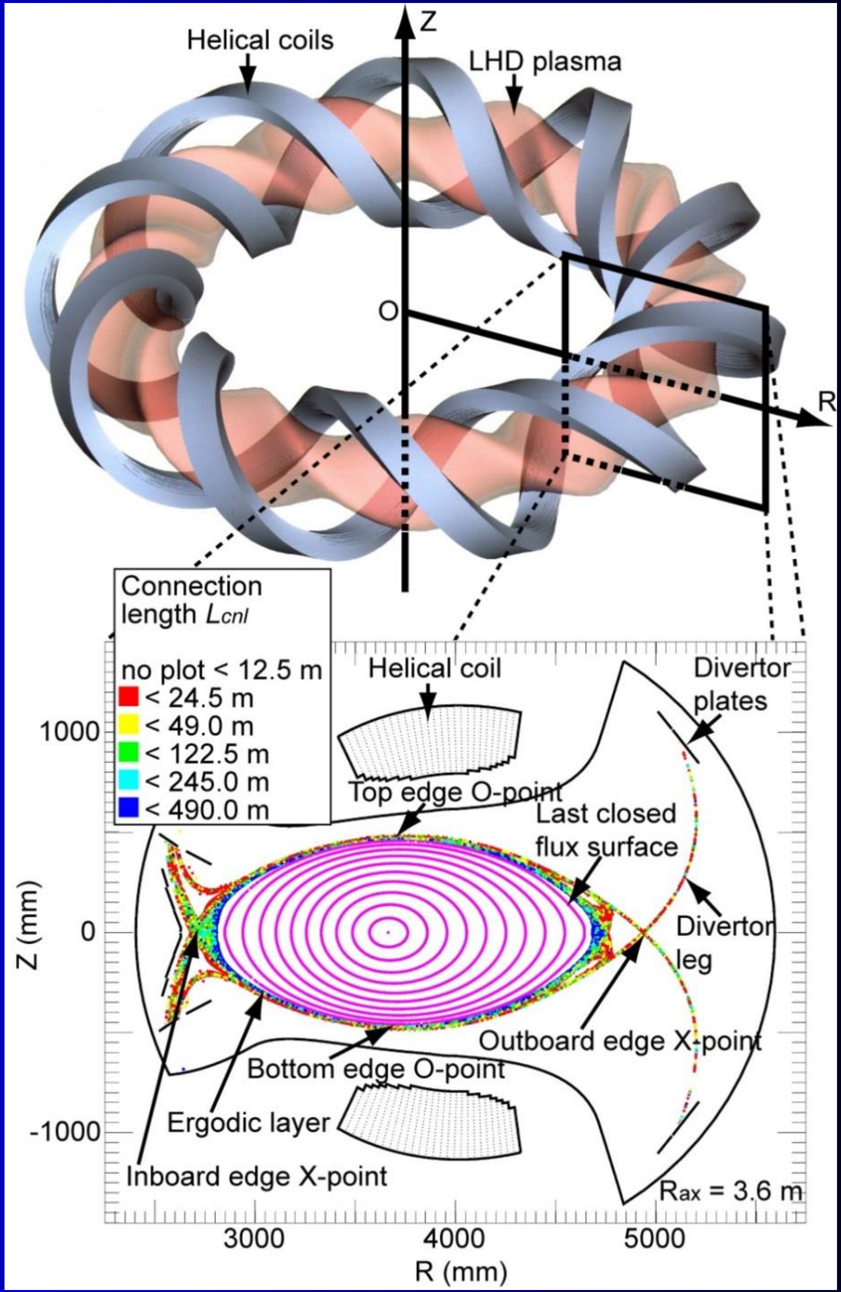
- Roles of edge stochastic magnetic fields
  - Tokamaks:

    ELM mitigation by imposing RMP, ergodic divertor
  - Helicals:

    Intrinsic edge stochastization
- Large Helical Device (LHD)

  R = 3.6 m, $<a>$ = 0.64 m,

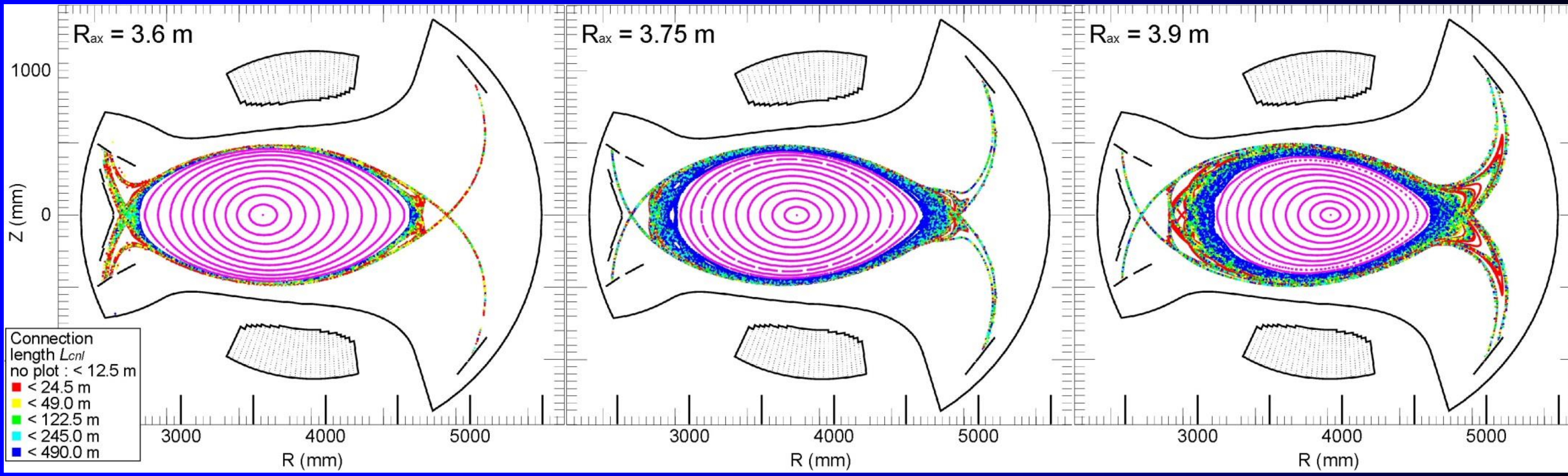
  B_t < 3 T, m/l = 10/2
- A thick stochastic magnetic field layer called "ergodic layer" is located outside the core plasma.



Ergodic layer in the Large Helical Device

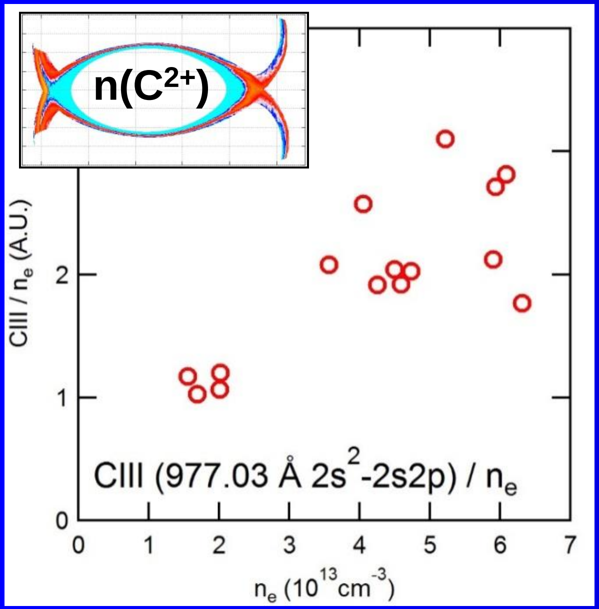
- The ergodic layer consists of stochastic magnetic field lines with connection lengths from 10 to 2000 m. (0.5~100 toroidal turns in LHD)
- Thick ergodic layer with the outward-shifted magnetic axis
- T_e = 10~500 eV -> Impurity lines emit significantly in the VUV wavelength range.
- Transport phenomena due to the existing of the ergodic layer
  - Impurity screening
  - Divertor detachment without impurity seeding
  - Asymmetrical profiles of impurity ions

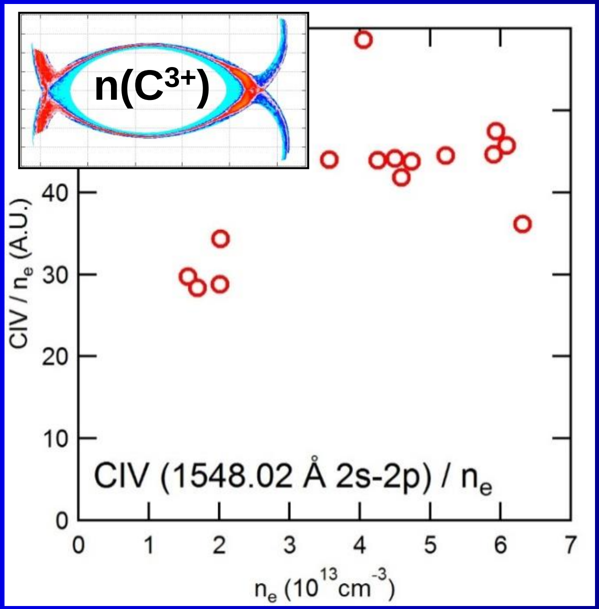
Impurity line emissions released from the ergodic layer of LHD are investigated by the spectroscopic methods.



Spectroscopic observation of impurity screening

CIII and CIV in VUV emission

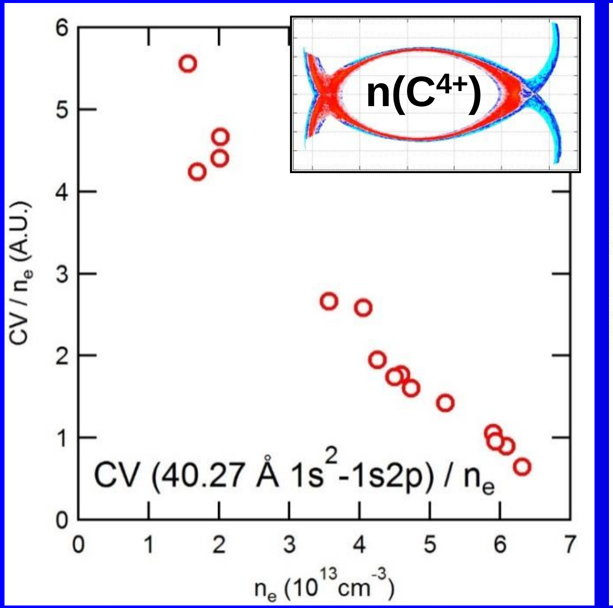


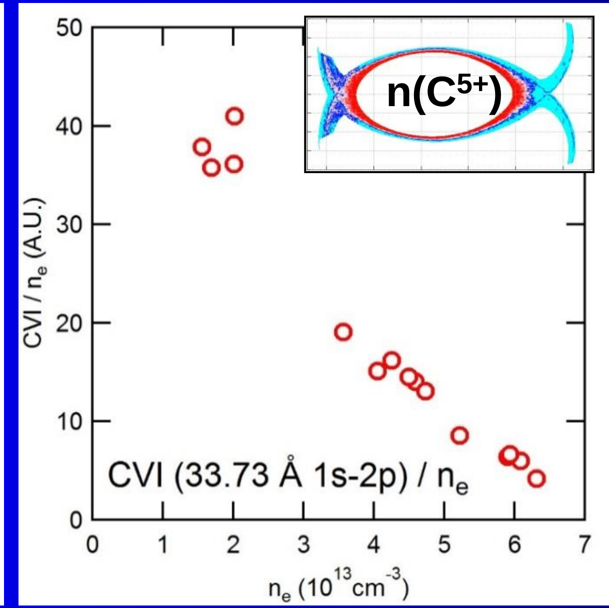


- Ionization potentials E_i for each charge state:

Charge state	Ei (eV)
C^{2+}	48
C^{3+}	65
C^{4+}	392
C^{5+}	490

CV and CVI in EUV emission





- 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 dischages…
  - <u>Indicates enhancement of the impurity screening.</u>

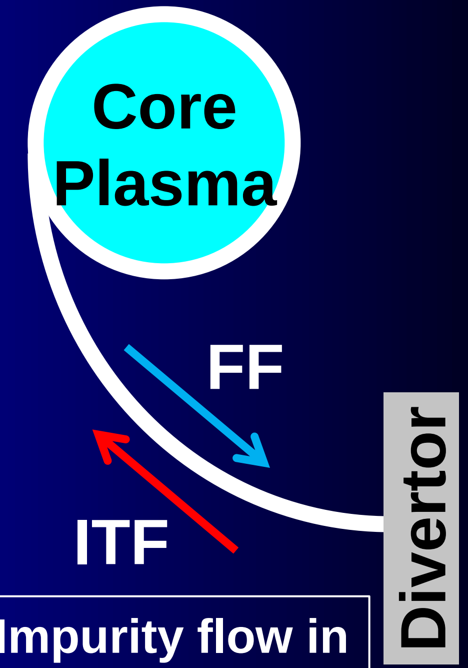
Impurity transport model in the ergodic layer

parallel momentum balance on impurity ions

Impurity ion pressure gradient | Parallel electric field | **Friction force**

$$m_z \frac{\partial V_{z\|}}{\partial t} = -\frac{1}{n_z}\frac{\partial T_z n_z}{\partial s} + ZeE_{\|} + m_z \frac{V_{i\|} - V_{Z\|}^{imp}}{\tau_s}$$
$$+0.71Z^2\frac{\partial T_e}{\partial s} + 2.6Z^2\frac{\partial T_i}{\partial s},$$

Electron thermal force | **Ion thermal force**



Impurity flow in edge magnetic fields

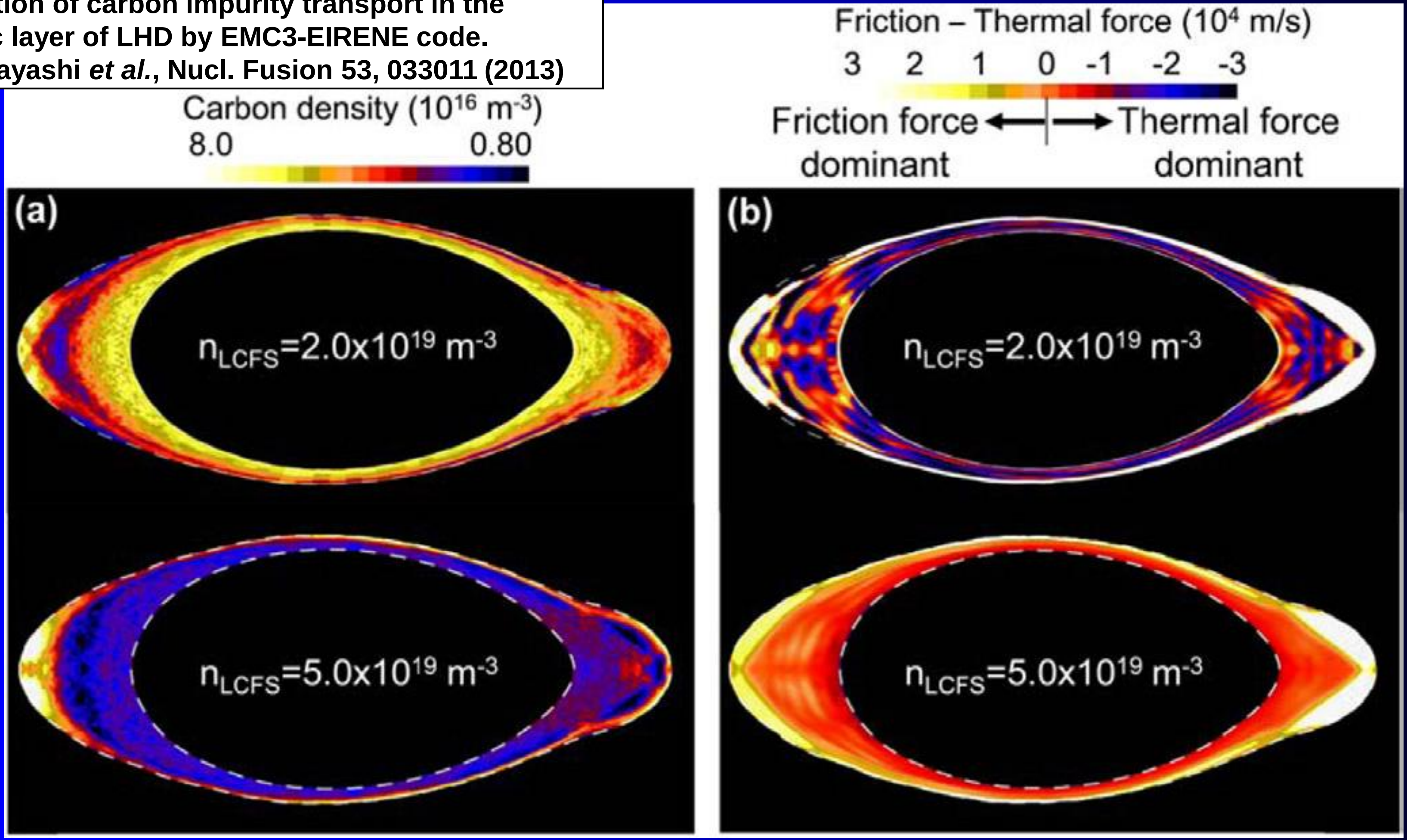
- ∇n_i↑ →Friction force↑ →Impurity flow toward divertor plates（screening）
- ∇T_i↑ →Ion thermal force↑ →Impurity flow toward core plasmas（accumulation）

Flow is a key mechanism to determine impurity distribution

Impurity screening in the ergodic layer

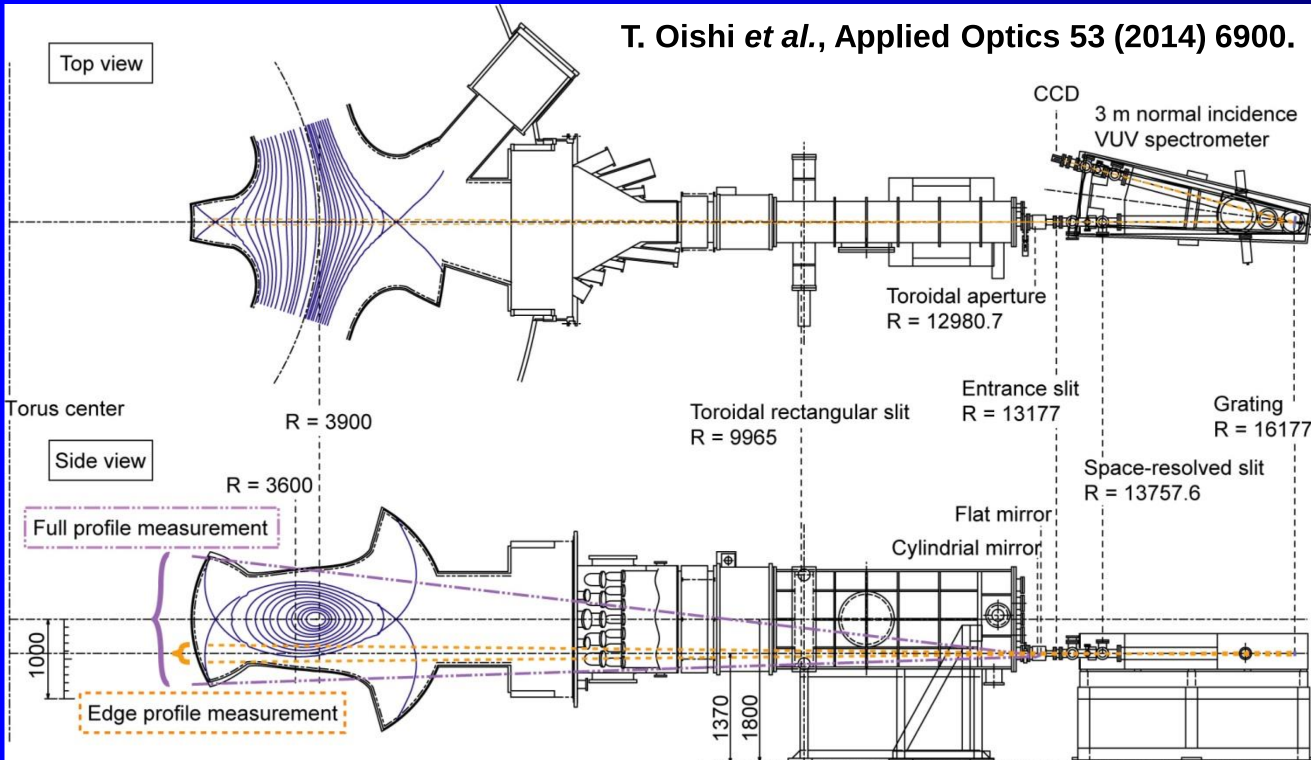
- The impurity screening/accumulation is determined by the balance between the friction force and the thermal force working on impurity ions.
- The impurity flow driven by the force balance is a measureable quantity.

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

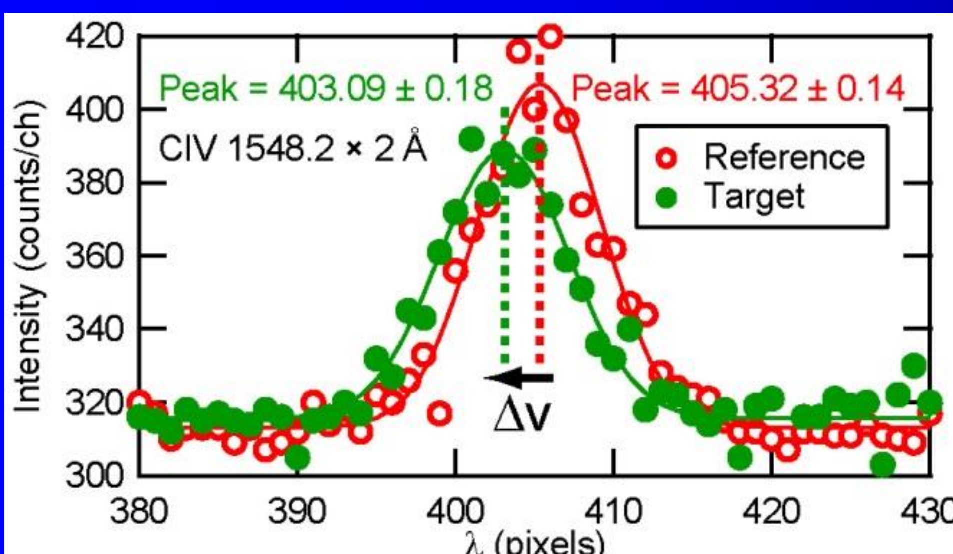


Flow measurement by impurity spectroscopy

3 m Normal Incidence VUV Spectrometer for Impurity Diagnostics



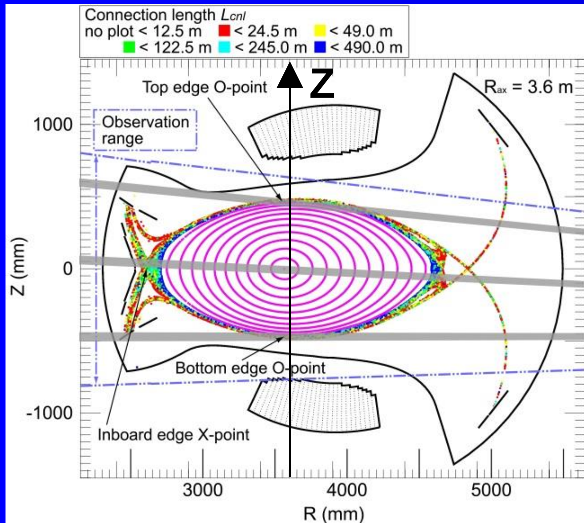
- Vertical profile of VUV lines are measured.
- Wavelength range : **300 - 3200 Å**,
- Spectral resolution : $d\lambda/dx$ = 0.037 Å /pixel
- Δt : 20 ms (full-binning) / 100 ms (space-resolved)
- The vertical observation range can be switched between the <u>edge profile measurement</u> and the <u>full profile measurement</u>.



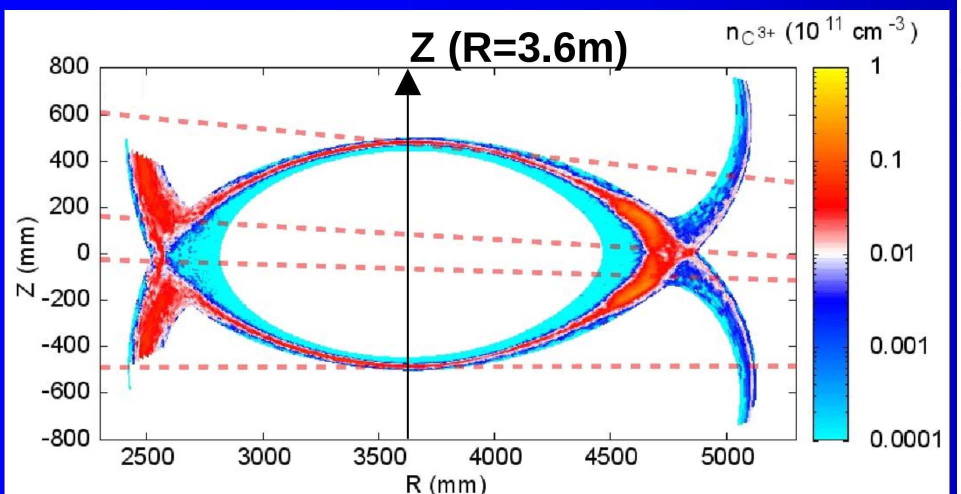
- Spectrum analysis for CIV (C^{3+}, E_i = 65 eV) 1548.2 × 2 Å ($1s^2 2s$-$1s^2 2p$)
  (1) Intensity -> impurity density
  $I(\mathrm{CIV}) \propto n(C^{3+})\, n_e$
  (2) Dopplar broadning -> T_i
  $T_i = 1.68 \times 10^8 M_i (\Delta_{FWHM} / \lambda_0)^2$
  (3) Dopplar shift -> plasma flow
  $\Delta v = c\,(\Delta\lambda / \lambda)$
- 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

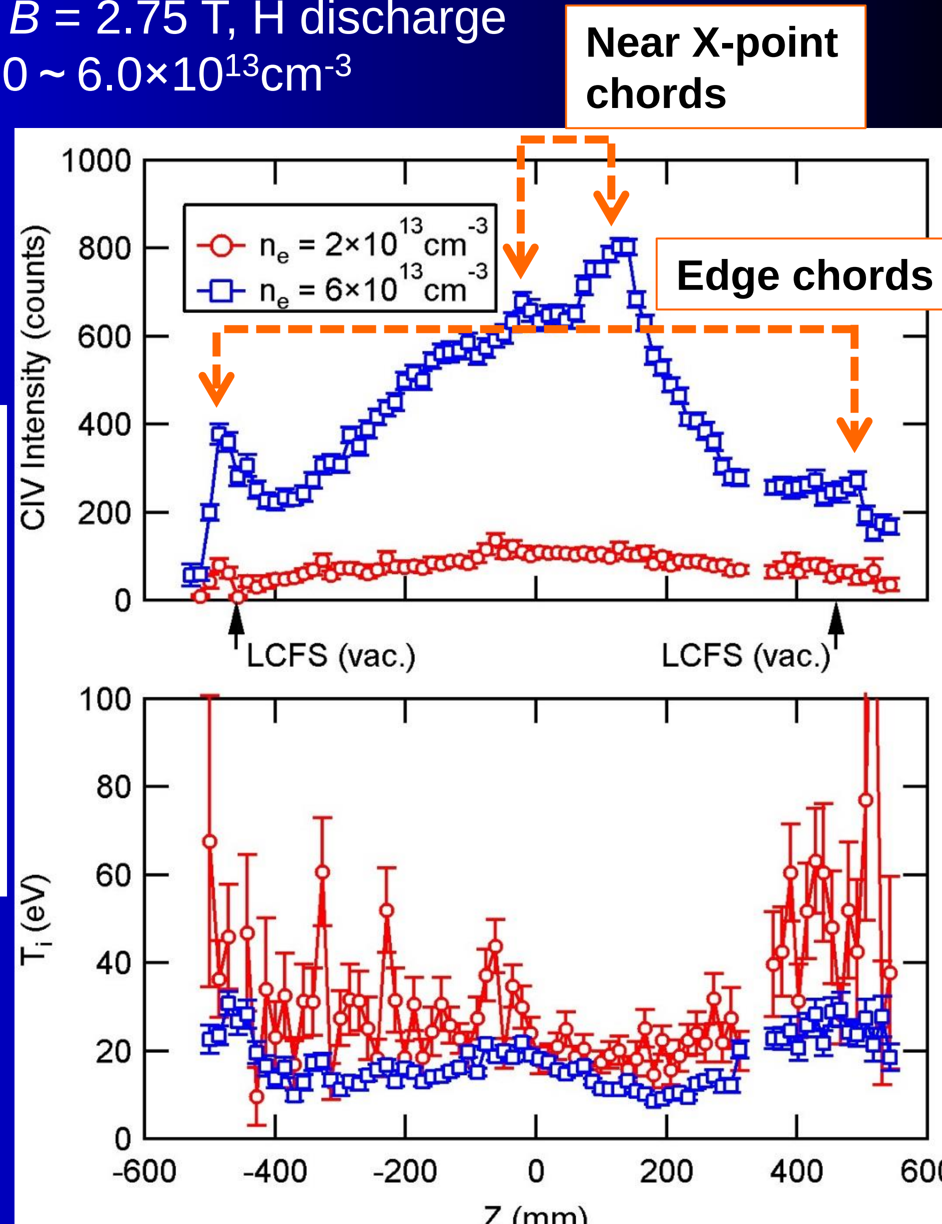
R_{ax} = 3.6 m, B = 2.75 T, H discharge
n_e scan in 2.0 ~ 6.0×10^{13}cm^{-3}



Vertical
102CH
->to spectrometer



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

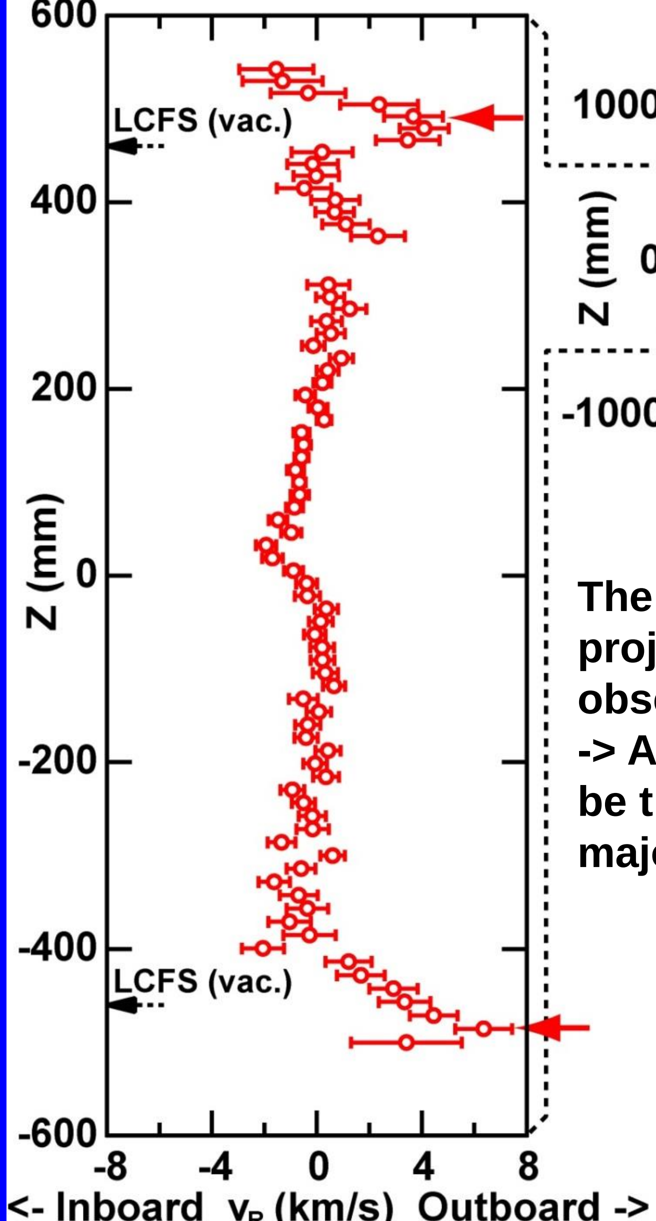


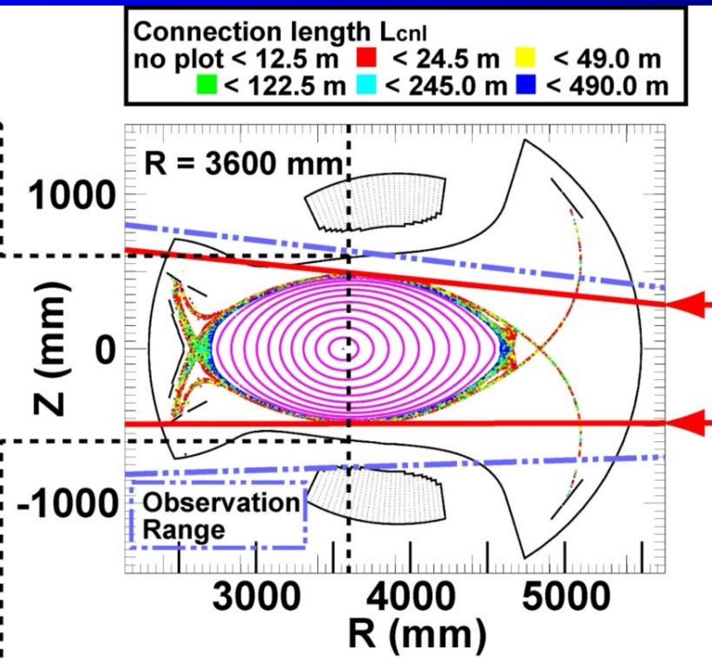
- The peaks of the intensity profile are results of line integration in a long path along the sightline through the ergodic layer where C^{3+} ions are located.

Profile of the edge impurity flow

R_{ax} = 3.6 m, B = 2.75 T, n_e = 6.0 × 10^{13} cm^{-3}

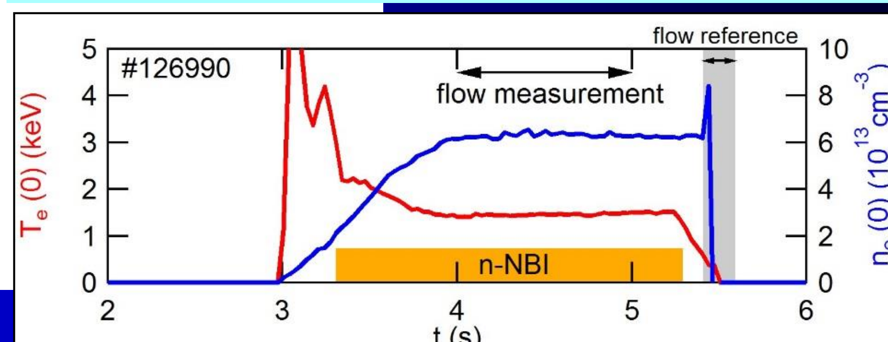
- Full vertical profile of C^{3+} impurity flow are evaluated from Doppler shift of CIV line emission (1548.20 × 2 Å).
- Carbon impurity flows in the outboard direction observed at both top and bottom edges.





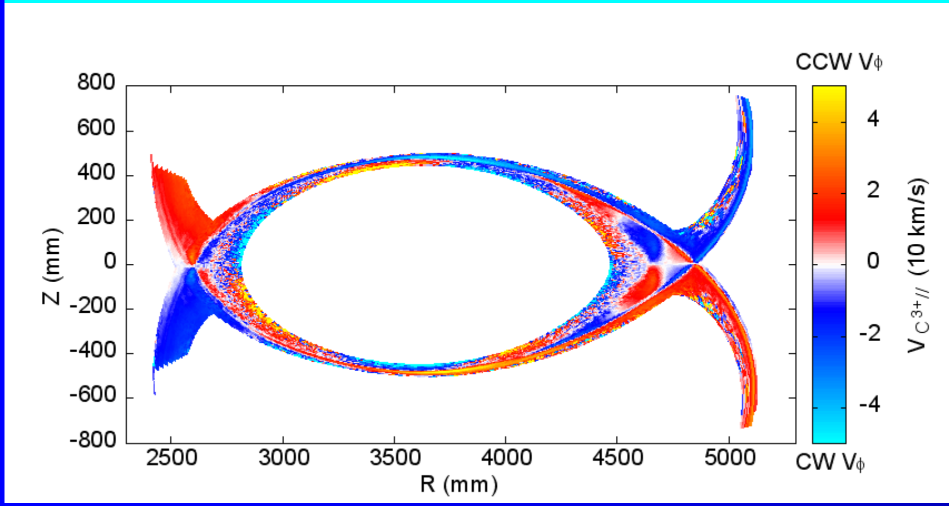
The measured flow velocity is projection of the flow along the observation chord.
-> Approximately considered to be the direction of the plasma major radius.

CIV spectrum measured in the plasma termination phase is used as a flow reference



Simulation of parallel impurity flows in the ergodic layer

$V_{//}$ (C^{3+}) (R_{ax} = 3.6 m, inward-shifted)



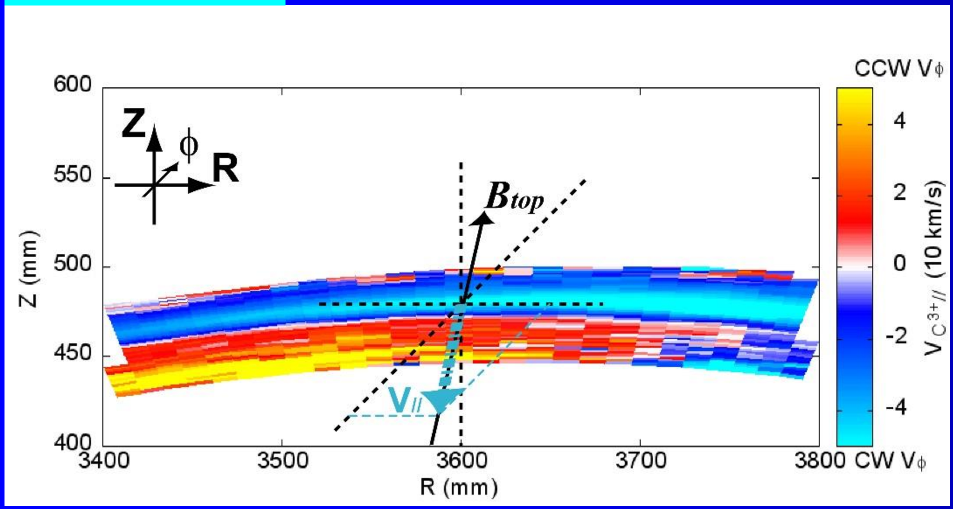
- Parallel flow profile of C^{3+} ions in the ergodic layer calculated with the EMC3-EIRENE code
- R_{ax} = 3.6 m, , B_t = 2.75 T,

$n_{e\_LCFS} = 6 \times 10^{13} cm^{-3}$

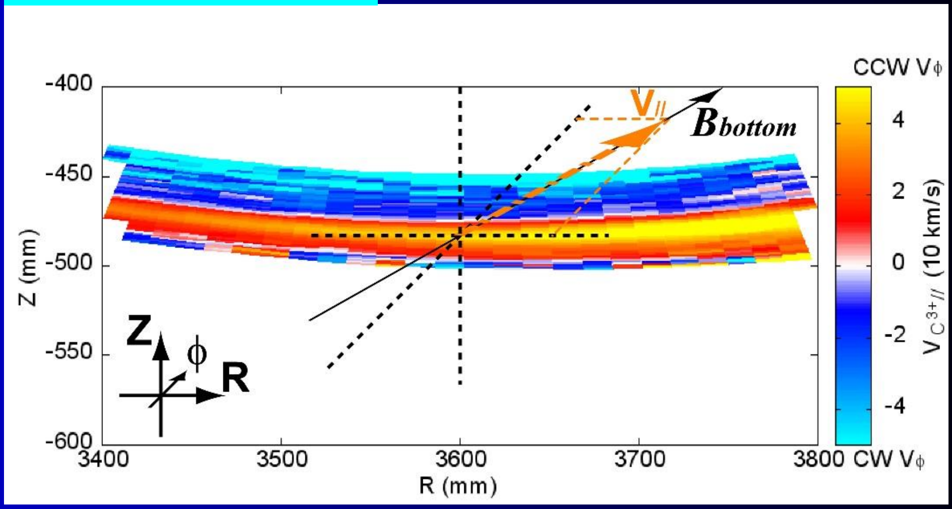
- Flow components in the major radius direction are directed to the outboard side at both top and bottom edges of the ergodic layer.

… agrees with the experiment.

Top Edge

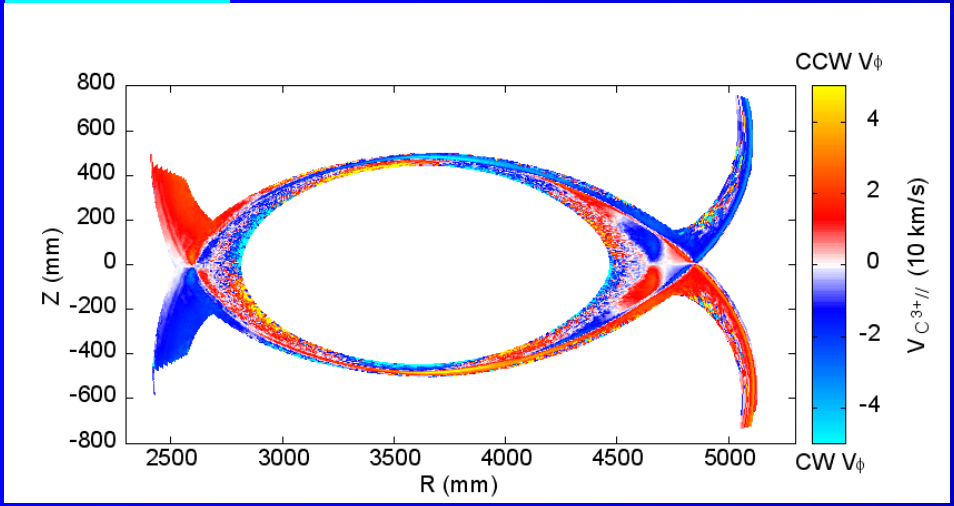


Bottom Edge



Synthetic carbon flow profile

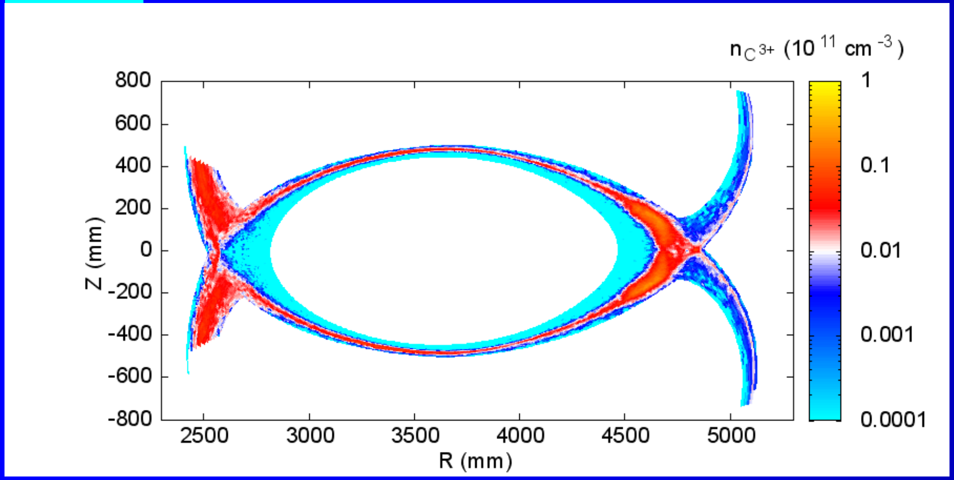
$V_{//}$ (C^{3+})



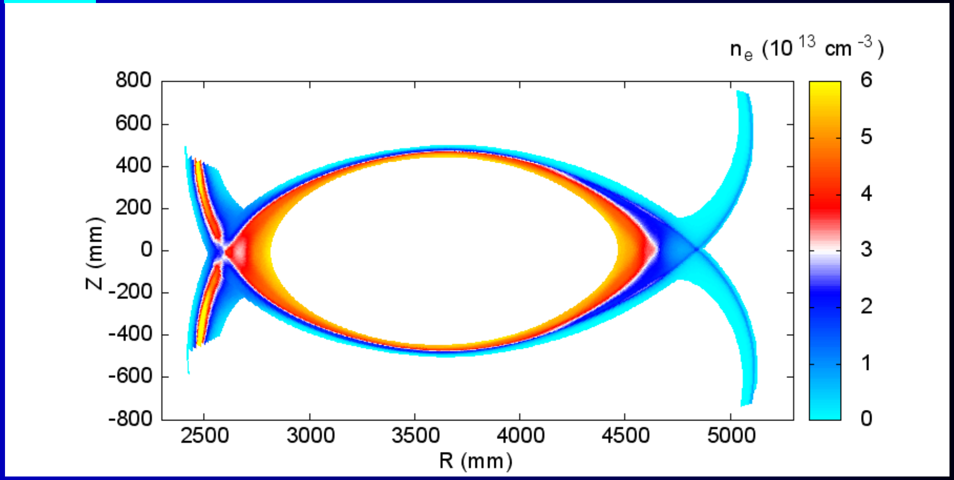
- To obtain a synthetic vertical profile of the carbon flow, V_{syn} (Z), local value of the calculated flow, V_{loc} (R,Z) is line-integrated weighted by emission intensity along each observation chord.

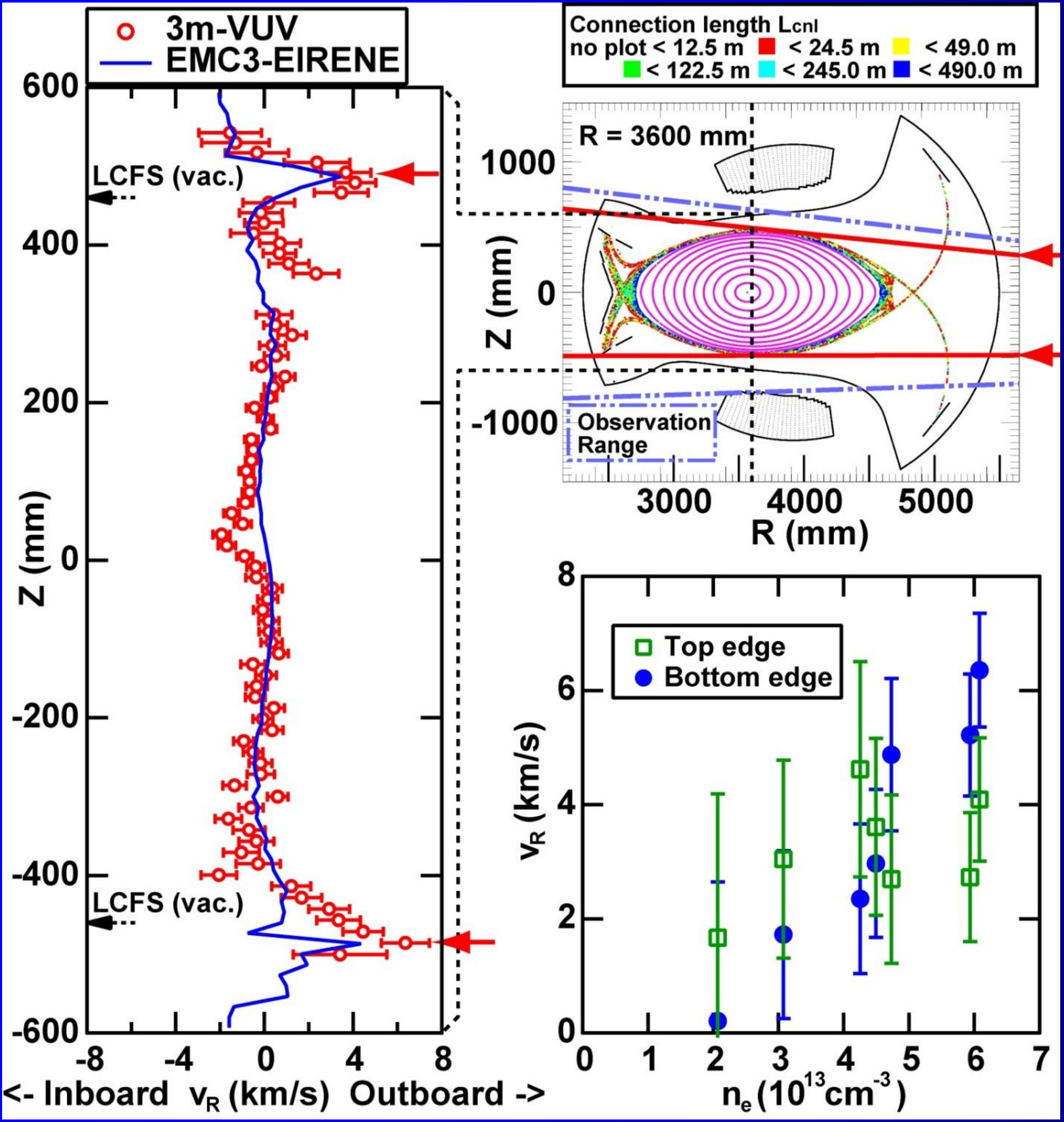
$$V_{syn} = \int V_{loc}\, \varepsilon\, n_C^{3+} n_e\, dl \Big/ \int \varepsilon\, n_C^{3+} n_e\, dl$$

n_C^{3+}



n_e





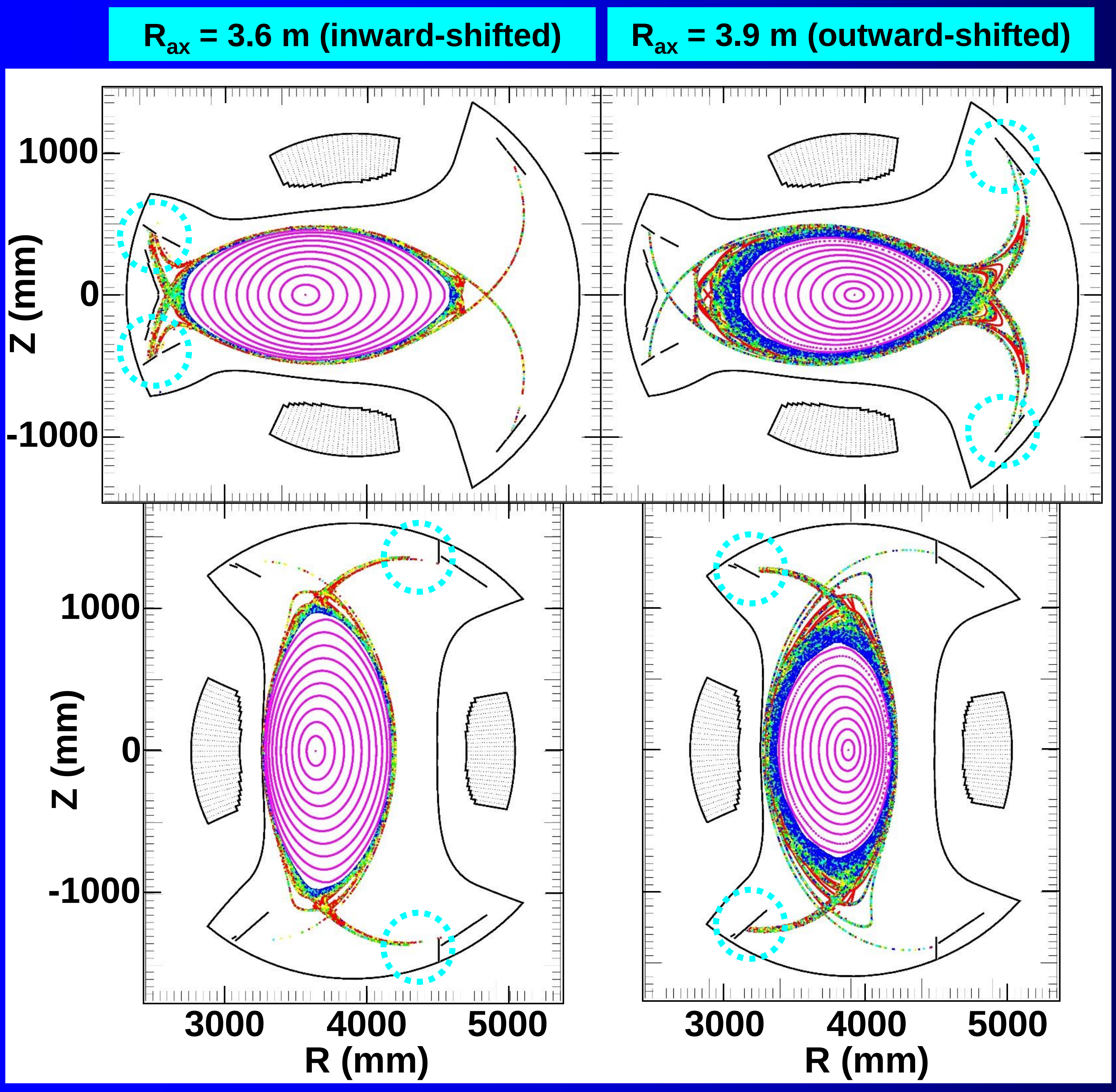
Profile of the edge impurity flow

- 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.

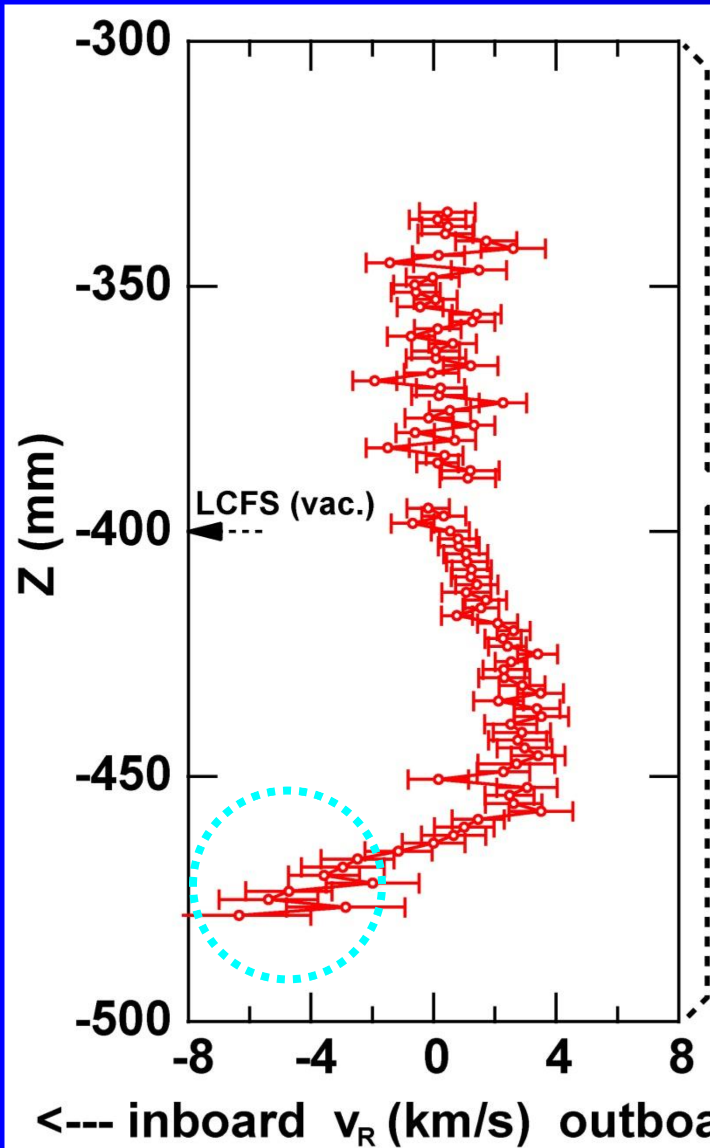


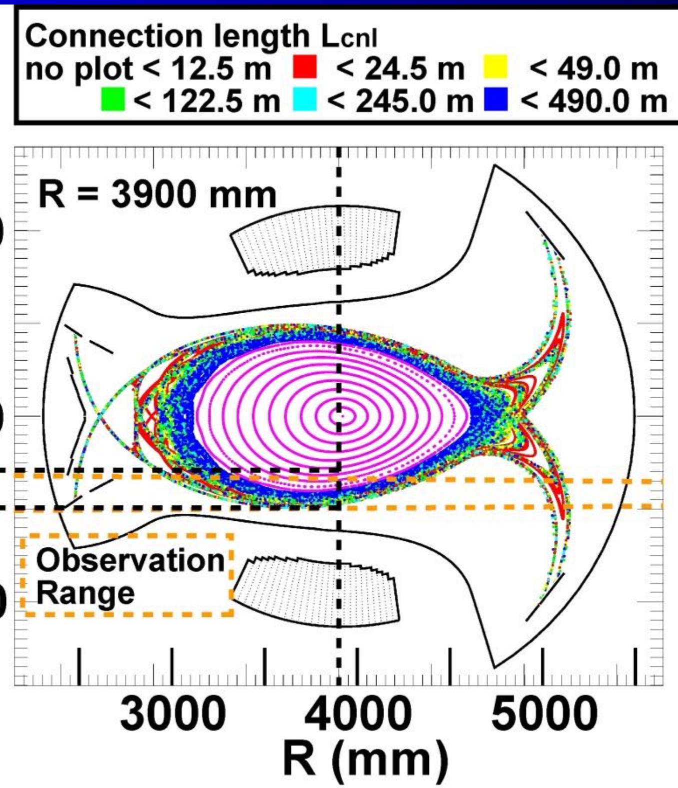
Variation of magnetic field line structures in the ergodic layer

- 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.

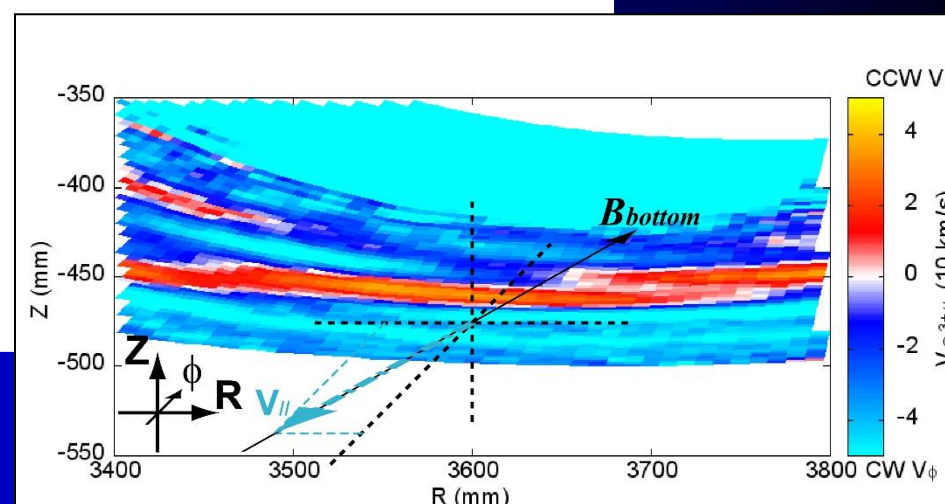
- Positions of “active” divertor legs switch between inward- and outward-shifted magnetic configurations.

Profile of the edge impurity flow





- R_{ax} = 3.9 m, B_t = 2.539 T, n_{e_LCFS} = 4×10^{13}cm^{-3}
- Edge profile measurement

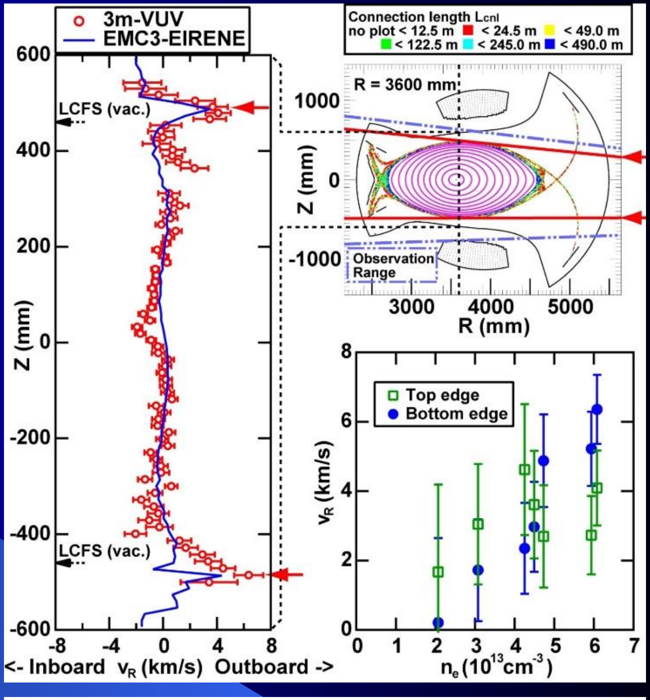


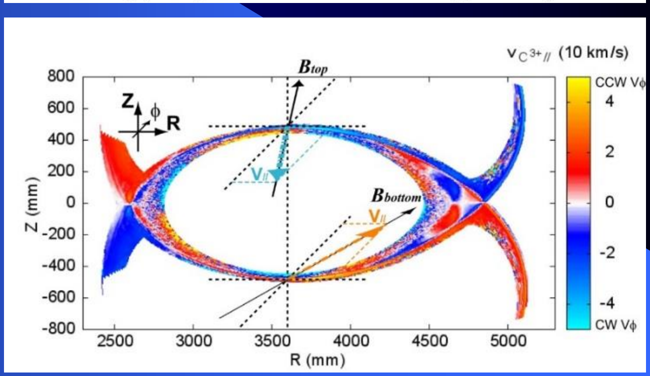
- Flow components in the major radius direction are directed to the inboard side at the bottom …agrees with the simulation.

Summary

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.

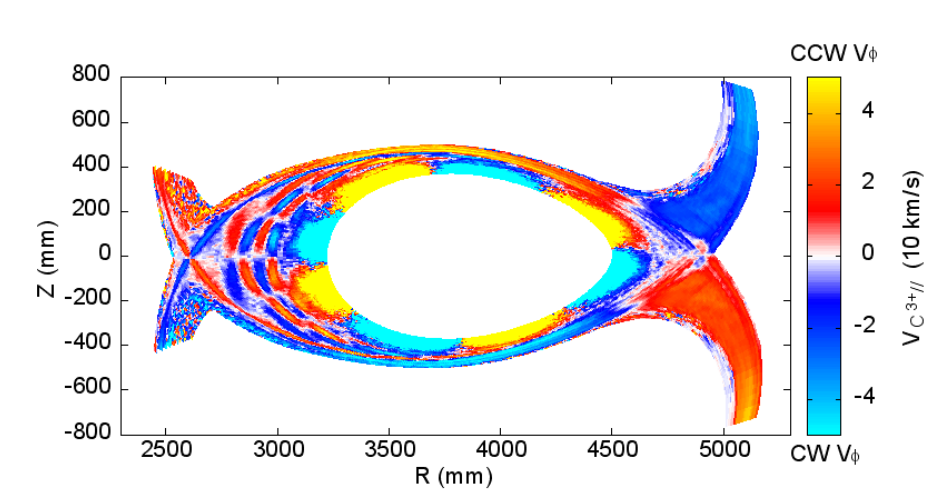
1. The carbon flow at the top and bottom edges in the ergodic layer had the same direction toward outboard side along the major radius direction in the inward-shifted magnetic field configurations in LHD.
2. The carbon flow at the bottom edge in the ergodic layer had a direction toward inboard side along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





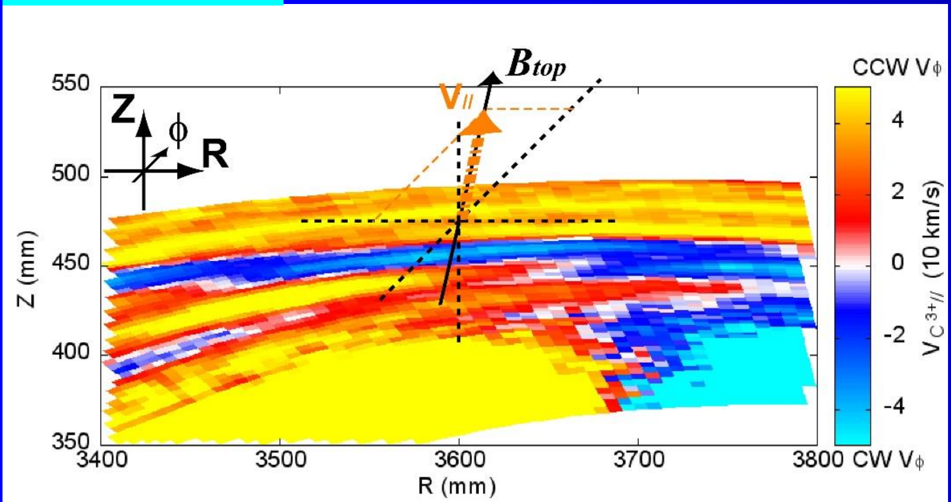
Simulation of parallel impurity flows in the ergodic layer

$V_{//}$ (C^{3+}) (R_{ax} = 3.9 m, outward-shifted)

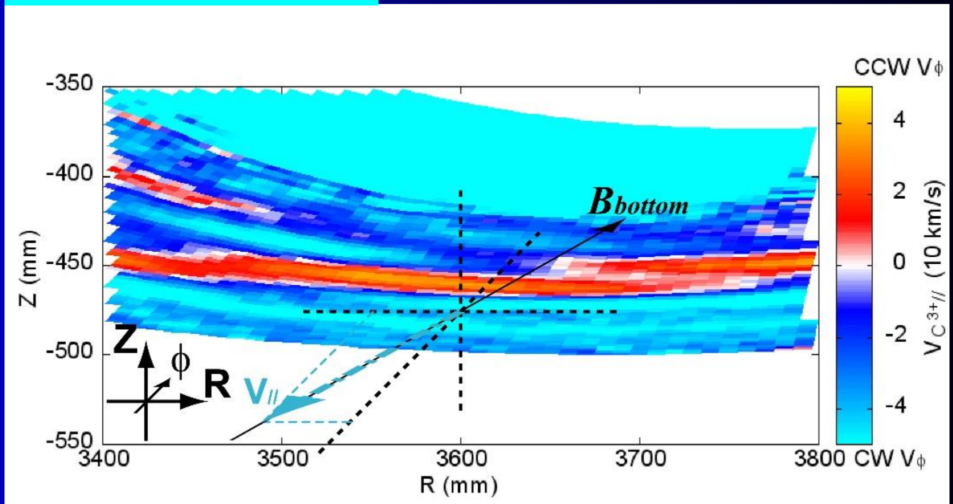


- R_{ax} = 3.9 m, B_t = 2.539 T, $n_{e\_LCFS} = 4 \times 10^{13} cm^{-3}$
- Flow components in the major radius direction are directed to the inboard side at both top and bottom edges of the outermost region of the ergodic layer.

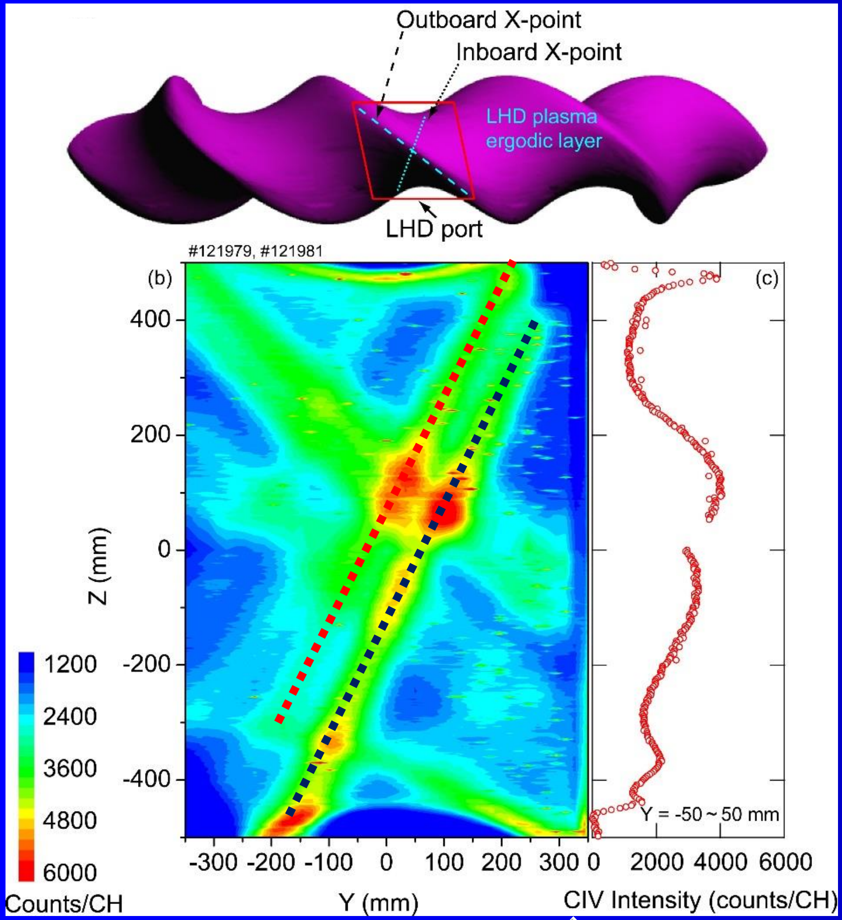
Top Edge



Bottom Edge



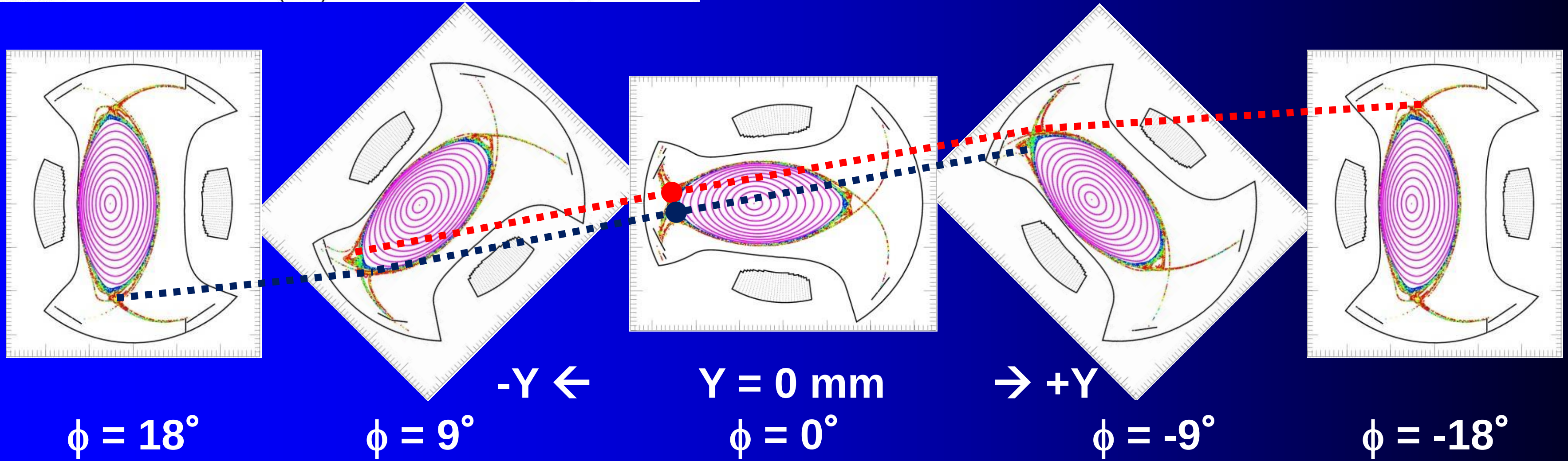
Interpretation of CIV emission intensity profiles



- 2-D (toroidal-vertical) EUV spectroscopy for CIV line (λ = 384 Å, 2p-3d, E_i = 65 eV).
- $\boldsymbol{R_{ax}}$ **= 3.6 m,** $\boldsymbol{n_e \sim 6 \times 10^{19} m^{-3}}$
- Emission around Z = 0 mm is superposition of inboard and outboard X-points.
- **Emission around Z = ±460 mm is from the ergodic layer.**

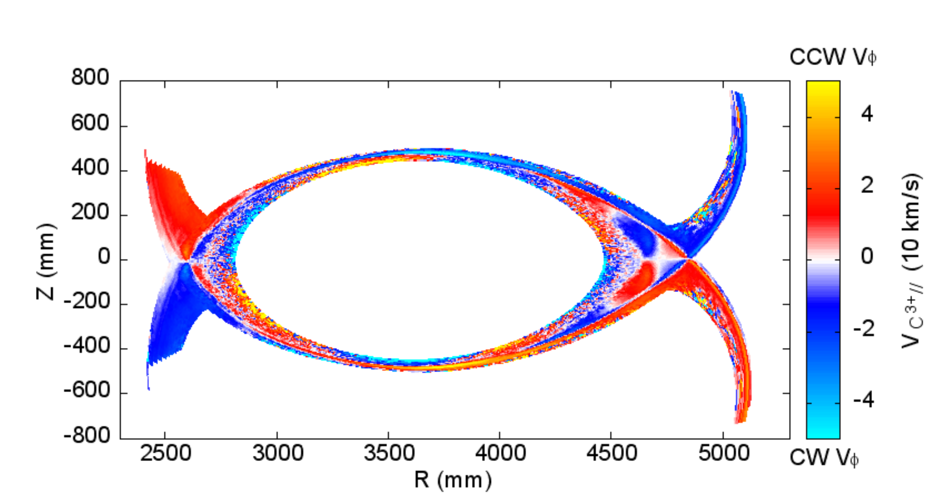
- Understandable relatively straightforward

- Preferable for flow measurement



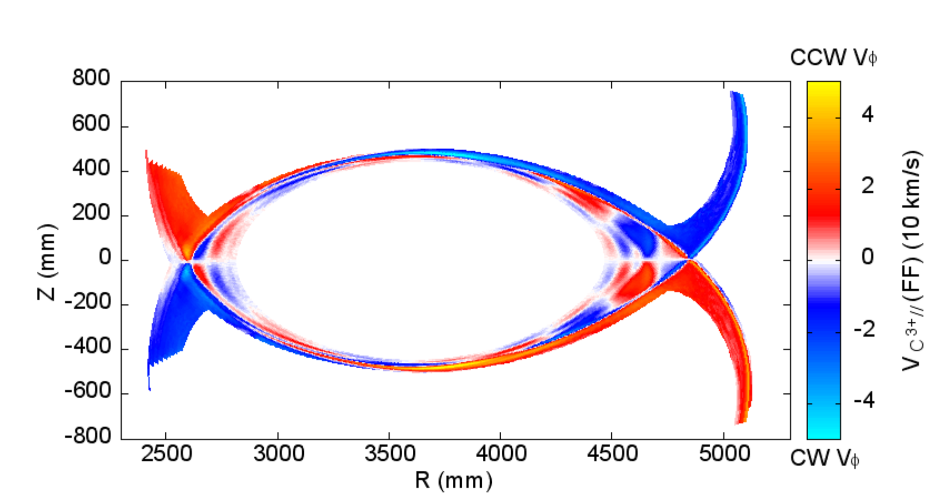
Simulation of parallel impurity flows in the ergodic layer

$V_{//}(C^{3+})$ (R_{ax} = 3.6 m, inward-shifted)



- 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