3D simulations of edge impurity flow obtained by the vacuum ultraviolet emission diagnostics in Large Helical Device with EMC3-EIRENE

Shuyu Dai [1], M. Kobayashi [2], G. Kawamura [2], T. Oishi [2], S. Morita [2], Y. Feng [3], D. Z. Wang [1]

[1] Key Laboratory of Materials Modification by Laser, Ion and Electron Beams (Ministry of Education), School of Physics, Dalian University of Technology, Dalian 116024, PR China

[2] National Institute for Fusion Science, Toki 509-5292, Japan

[3] Max-Planck-Institute für Plasmaphysik, D-17491 Greifswald, Germany

1. Introduction

2. VUV spectrometer system

3. Codes implementation on LHD

4. Modelling of impurity flow velocity in the stochastic layer of LHD

5. Simulations of impurity flow velocity with different scenarios

6. Summary

1. Introduction

2. VUV spectrometer system

3. Codes implementation on LHD

4. Modelling of impurity flow velocity in the stochastic layer of LHD

5. Simulations of impurity flow velocity with different scenarios

6. Summary

Introduction

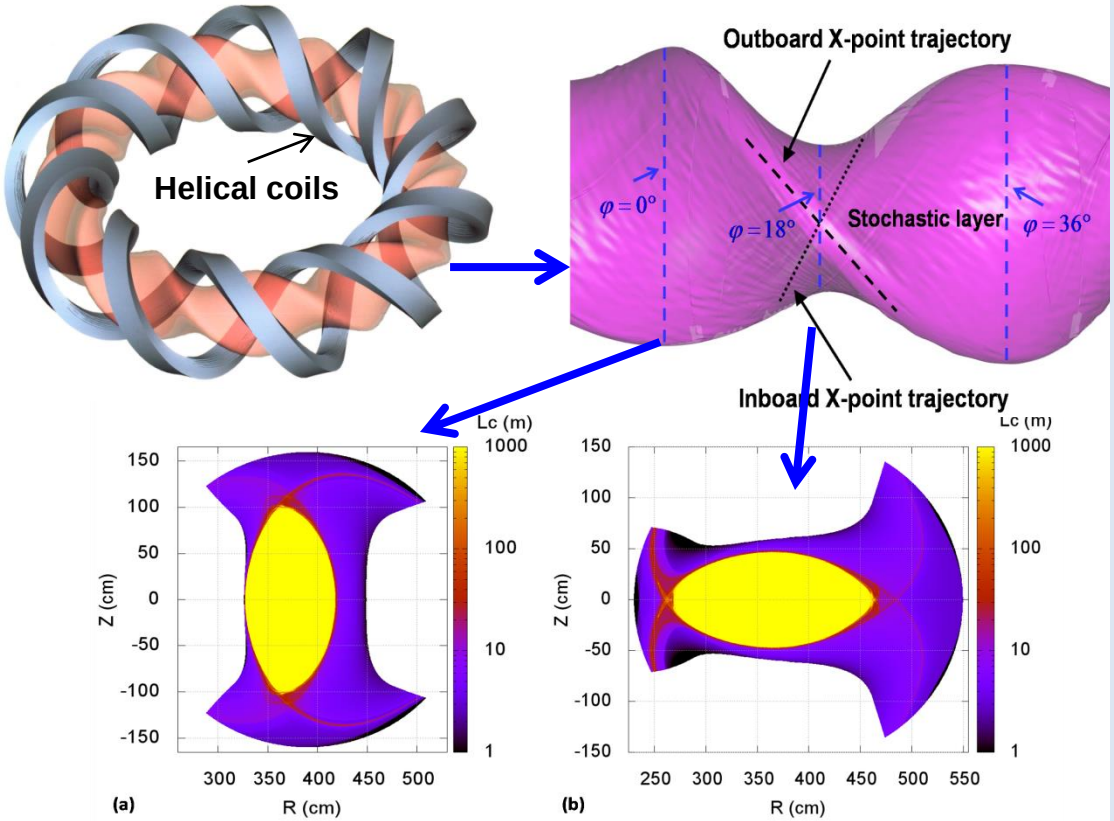
大连理工大学 DALIAN UNIVERSITY OF TECHNOLOGY

Control of the impurity transport in the edge plasma of fusion devices is critical to sustaining high-performance plasma and to mitigating the divertor heat flux.

The 3D magnetic field structure in the stochastic layer of LHD (∥and ⊥transport dominant) bring us a totally different edge transport compared with that in tokamaks with 2D magnetic field structure (∥transport dominant) [1-2].

[1] M. Kobayashi, et al., Nucl. Fusion, 53, 033011 (2013).

[2] Shuyu Dai, et al., Nucl. Fusion, 56, 066005 (2016).



Recent experiments in LHD achieve the measurement of the impurity flow at the edge plasma by VUV spectrometer [3], which provides a straightforward way to validate the impurity momentum transport model commonly used in the studies of edge impurity transport. In this study, the 3D edge transport code EMC3-EIRENE is used to study the impurity transport behavior in the stochastic layer of LHD.

[3] T.Oishi. et al 2014 Appl. Optics 53, 6900-6912.

1. Introduction

2. VUV spectrometer system

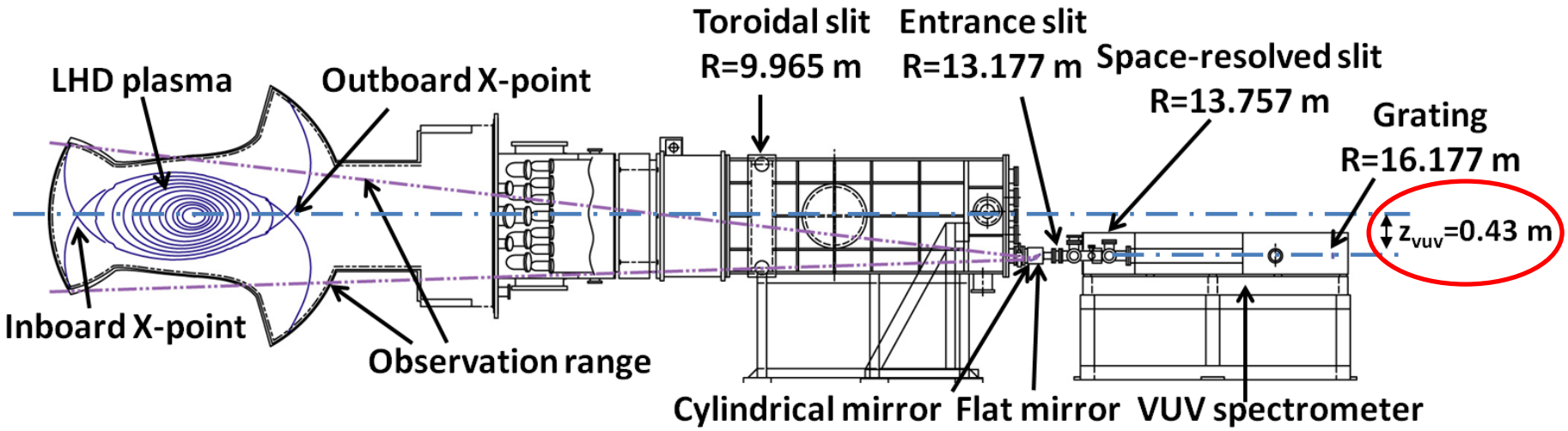
3. Codes implementation on LHD

4. Modelling of impurity flow velocity in the stochastic layer of LHD

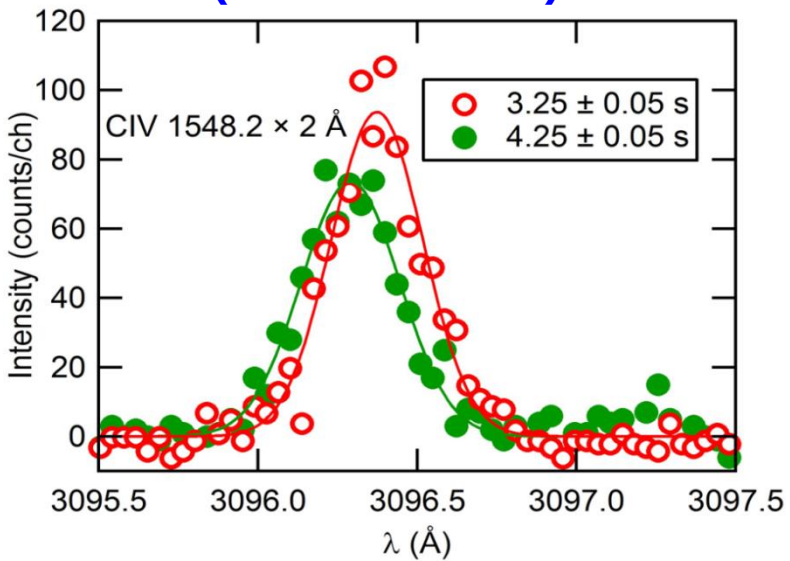
5. Simulations of impurity flow velocity with different scenarios

6. Summary

VUV spectroscopic system



Profile of the spectra of CIV (1548.20 × 2 Å) obtained at different times of *t* = 3.25 s (open circles) and *t* = 4.25 s (closed circles).



It is clearly seen that this is a Doppler shift between the two CIV spectral profiles (emitted by C^{3+}), which is analyzed with Gaussian profile fitting.

$$\Delta v = c(\Delta\lambda / \lambda)$$

where *c* is the light speed, is the Doppler-shift, and is the wavelength of the line emission.

1. Introduction

2. VUV spectrometer system

3. Codes implementation on LHD

4. Modelling of impurity flow velocity in the stochastic layer of LHD

5. Simulations of impurity flow velocity with different scenarios

6. Summary

EMC3 - Fluid model for impurities

大连理工大学 DALIAN UNIVERSITY OF TECHNOLOGY

Particle:

$$\nabla\cdot\left(n_I^z V_{I\|}^z \boldsymbol{b} - D_I^z \nabla_\perp n_I^z\right) = S_{z-1\to z} - S_{z\to z+1} + R_{z+1\to z} - R_{z\to z-1}$$

Momentum:

$$U_{Ii}^z\left(V_{I\|}^z - V_{i\|}\right) = -\boldsymbol{b}\cdot\nabla n_I^z T_I^z + n_I^z ZeE_\| + n_I^z Z^2 C_e \boldsymbol{b}\cdot\nabla T_e + n_I^z Z^2 C_i \boldsymbol{b}\cdot\nabla T_i$$

$$\boldsymbol{b}\cdot\nabla n_e T_e + n_e eE_\| + n_e C_e \boldsymbol{b}\cdot\nabla T_e = 0$$

Energy:

$$T_I^z = T_i$$

Transport parameters:

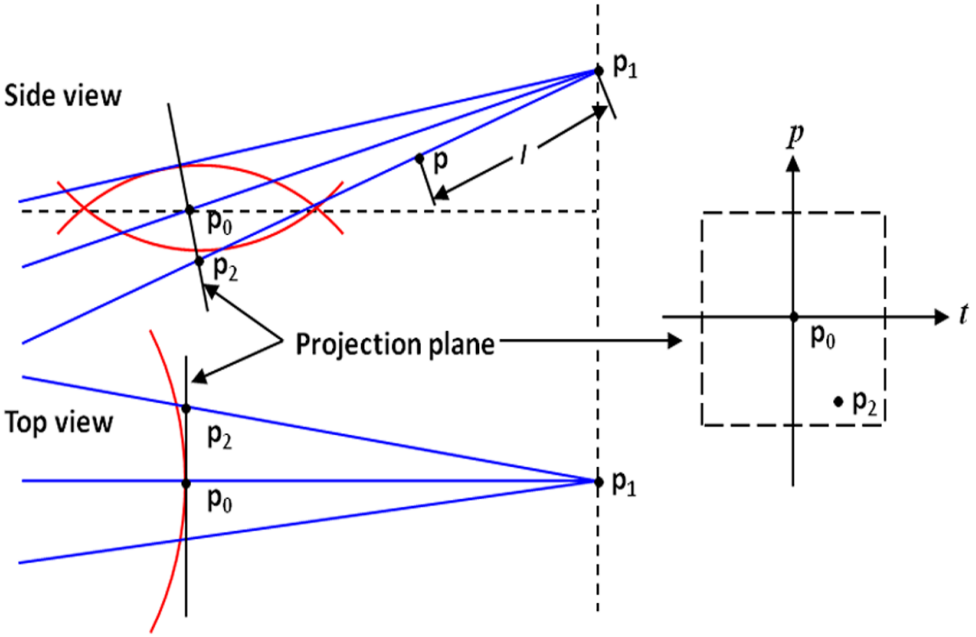
Parallel transport coefficients : *determined by the force balance*

Cross-field transport coefficients : — ***free input parameter*** D_I^z

Friction force **Ion thermal force**

$$m_z \frac{dV_{z\|}}{dt} = -\frac{1}{n_z}\frac{dp_z}{ds} + ZeE_\| + m_z \frac{V_\| - V_{z\|}}{\tau_s} + 0.71Z^2\frac{dT_e}{ds} + 2.6Z^2\frac{dT_i}{ds}$$

Calculation of the chord-integrated velocity of impurity flow



A sophisticated post-processing program for calculating the volumetric emissivity has been developed (by Dr. G. Kawamura and Shuyu Dai), which can trace the lines of sight for each observation chord of the VUV spectrometer through the 3D emission distribution obtained from the EMC3-EIRENE code.

The chord-integrated velocity of impurity flow can be expressed by the below equation:

$$V^{z}_{chord} = \frac{\int V^{z}_{chord\,(loc)} I^{z}_{(loc)} dl}{\int I^{z}_{(loc)} dl}$$

$$I^{z}(T_e, n_e) = n_e \cdot n^{z}_{imp} \cdot L^{z}(T_e)$$

This emission intensity weighted method can make an effective suppression of the numerical noise for the post-processing data according to the test simulations.

1. Introduction

2. VUV spectrometer system

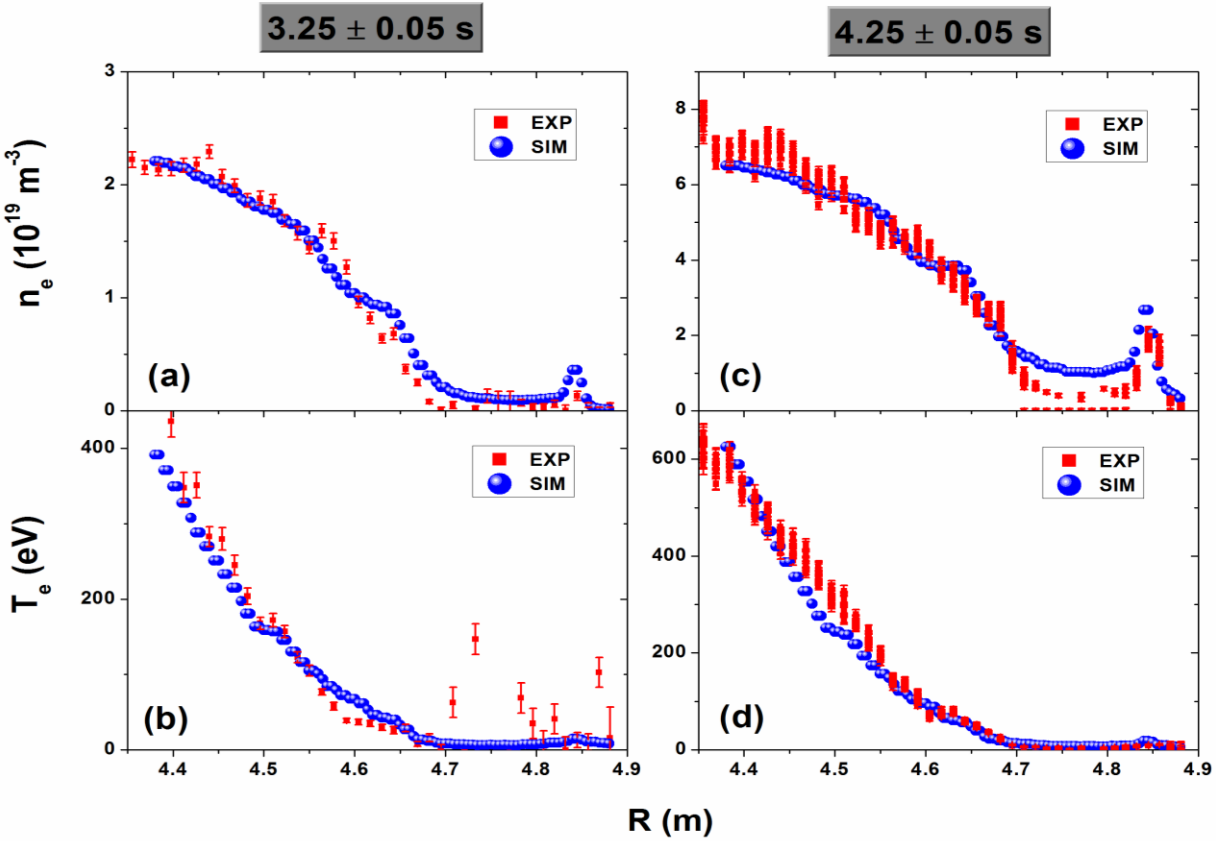
3. Codes implementation on LHD

4. Modelling of impurity flow velocity in the stochastic layer of LHD

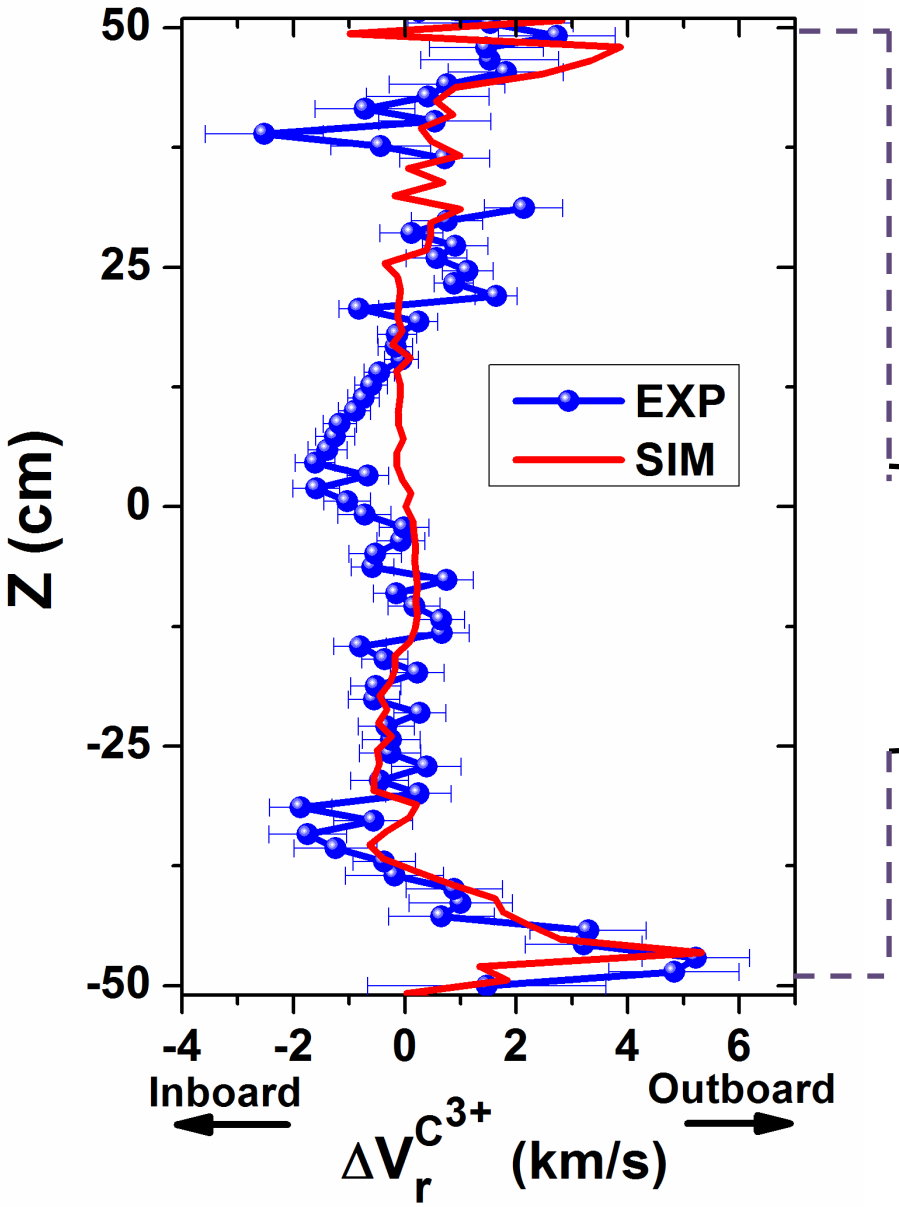
5. Simulations of impurity flow velocity with different scenarios

6. Summary

Horizontal profiles of the plasma temperature (a) and density (b) in the experiments and simulations at the outboard midplane of LHD; (a), (b) for *t* = 3.25 s and (c), (d) for *t* = 4.25 s.

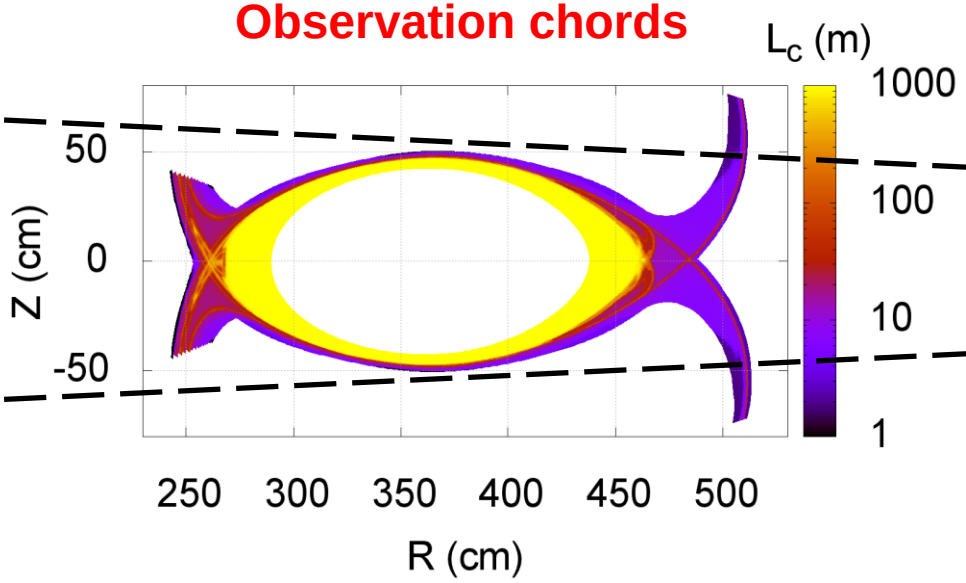


	P	n_{LCFS}	$D_\perp$	$X_\perp$
t=4.25 s	10 MW	6.5×10^{19} m^{-3}	0.4 m^2s^{-1}	0.4 m^2s^{-1}
t= 3.25 s	2 MW	2.2×10^{19} m^{-3}	0.3 m^2s^{-1}	0.4 m^2s^{-1}

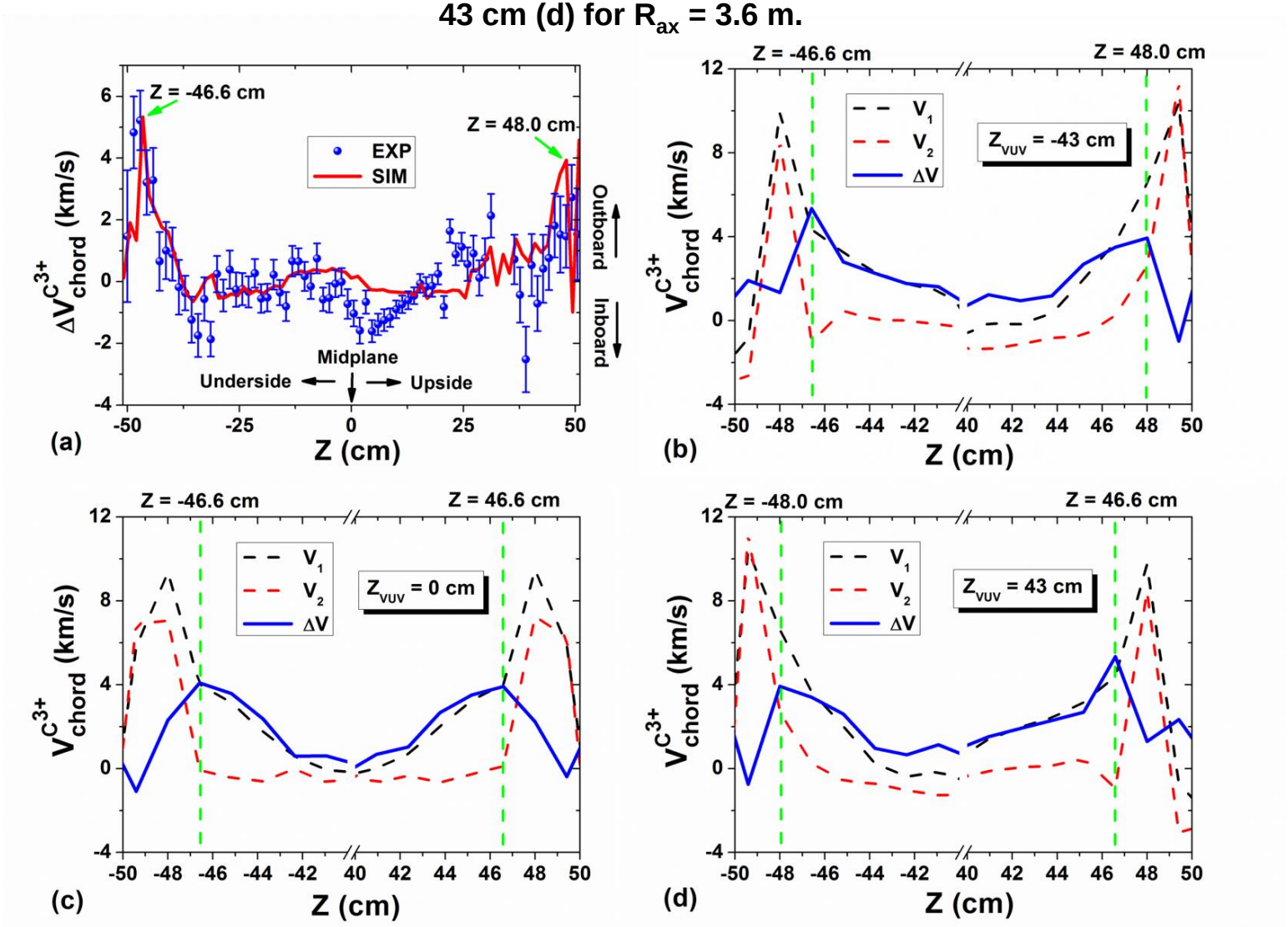


Profile of the vertical distributions of the relative chord-integrated velocity of C^{3+} impurity flow measured by the VUV spectrometer and modelled by EMC3-EIRENE.

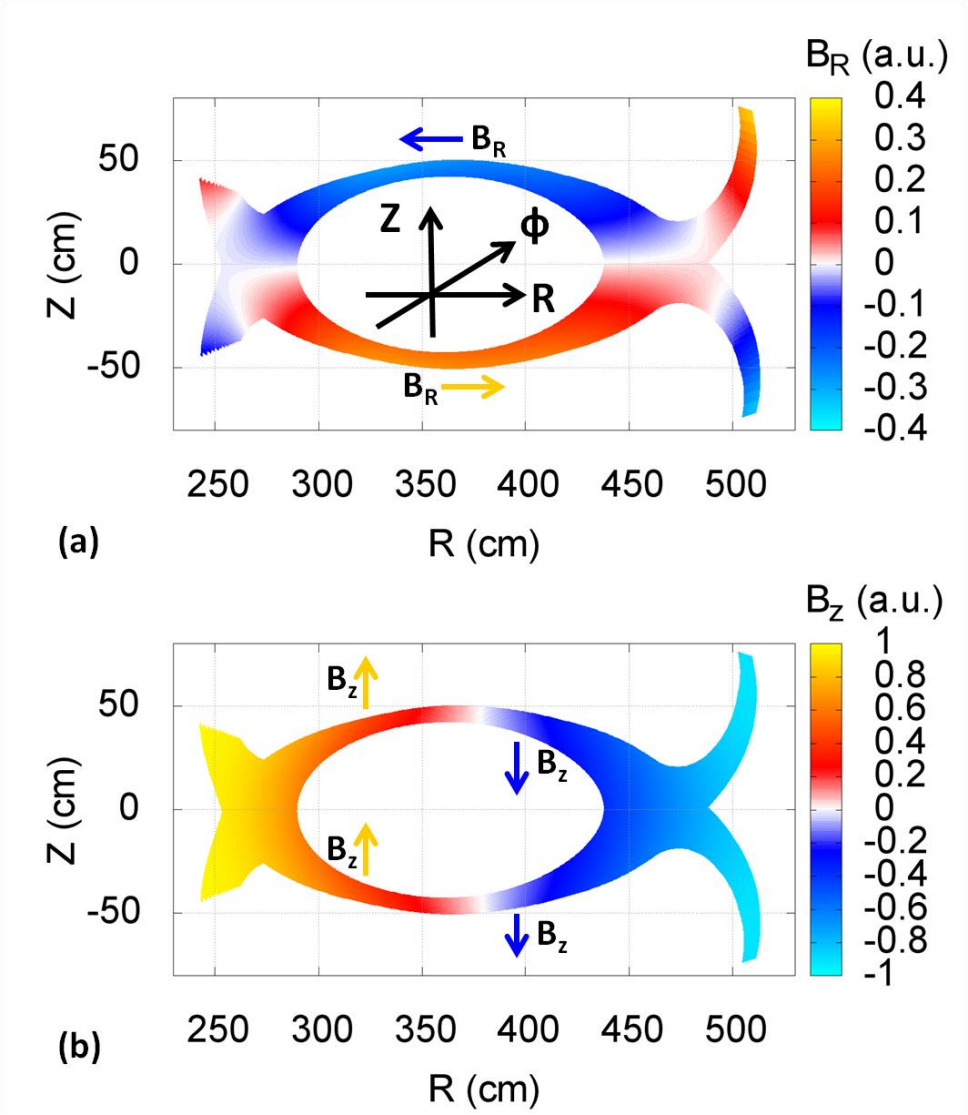
Observation chords



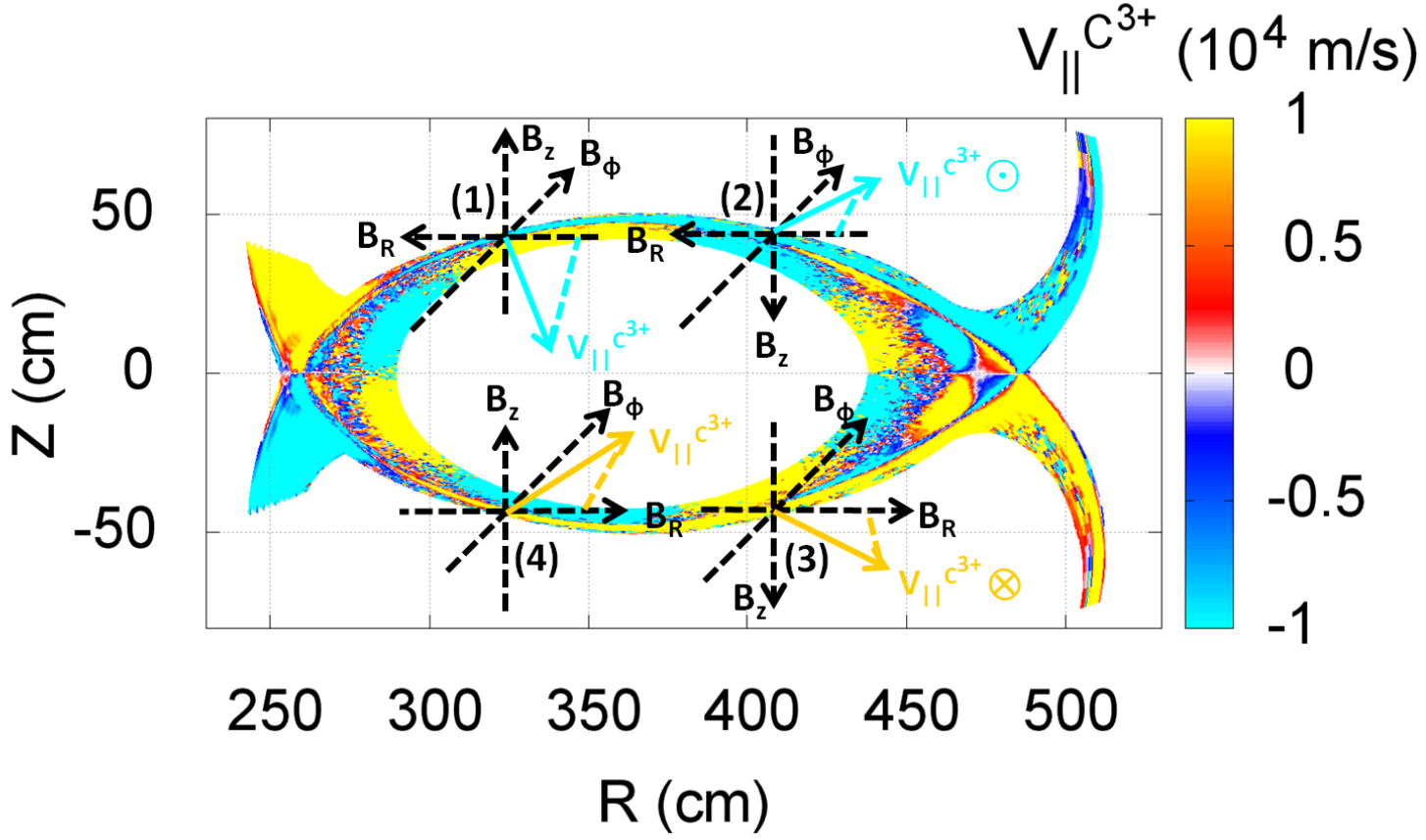
Profile of the vertical distributions of the relative chord-integrated velocity of C^{3+} impurity flow measured by the VUV spectrometer and modelled by EMC3-EIRENE (a), Zoom-in profiles of the vertical distributions of the absolute (V_1 (t=4.25 s) and V_2 (t=3.25s)) and relative ($\triangle V = V_1 - V_2$) horizontal velocities of C^{3+} impurity flow for different vertical positions of the VUV spectrometer located at Z_{vuv} = -43 cm (b), 0 cm (c), 43 cm (d) for R_{ax} = 3.6 m.



2D distributions of the normalized magnetic field components B_r (a) and B_z (b) at the poloidal cross section of 18°. The arrows show the directions of the toroidal, horizontal and vertical magnetic field components.



2D distribution of the parallel velocity of C^{3+} impurity flow at the poloidal cross section of 18°. The directions of the magnetic field lines and the parallel velocity of impurity flow are shown for the positions (1)-(4).



The parallel velocity of C^{3+} impurity flow has a reversed toroidal direction at the top and bottom edges of the stochastic layer. All the horizontal components of C^{3+} impurity flow for P1-P4 have the same direction towards the outboard side of the torus.

1. Introduction

2. VUV spectrometer system

3. Codes implementation on LHD

4. Modelling of impurity flow velocity in the stochastic layer of LHD

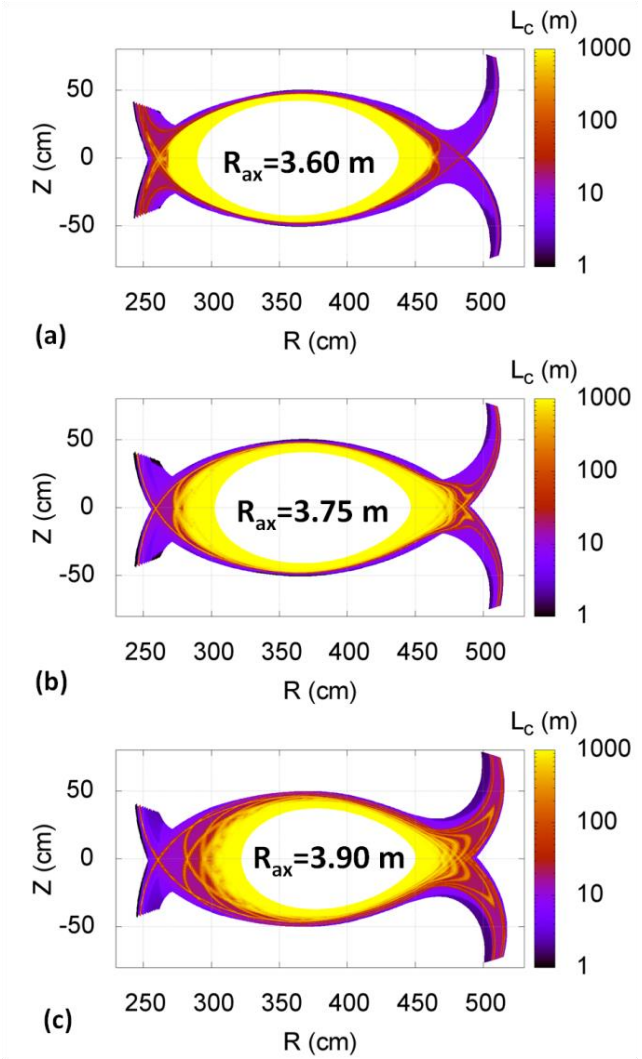
5. Simulations of impurity flow velocity with different scenarios

6. Summary

The effect of magnetic configuration

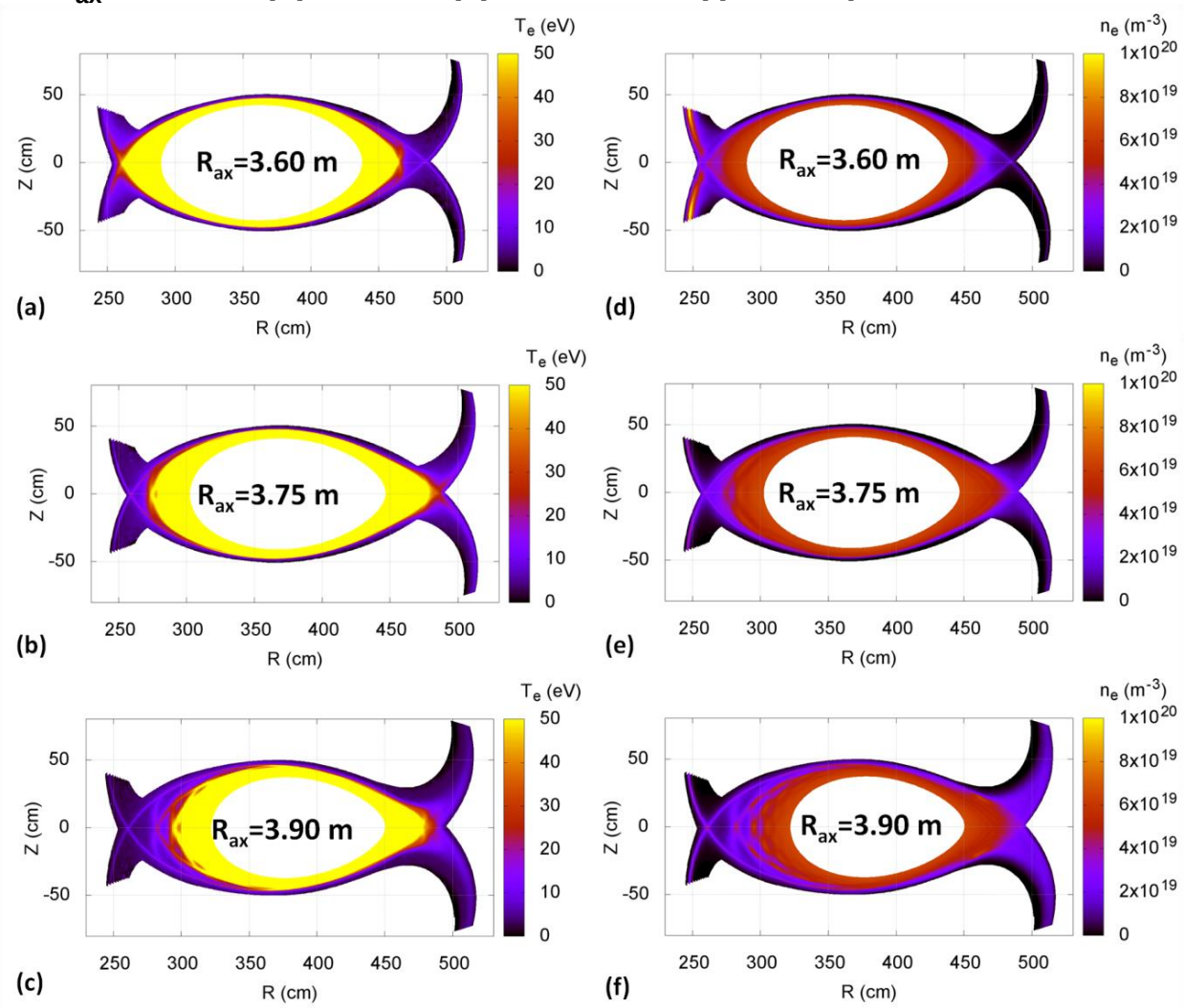
大连理工大学 DALIAN UNIVERSITY OF TECHNOLOGY

2D distributions of the connection length for R_{ax} = 3.60 m (a), 3.75 m (b) and 3.90 m (c) at the poloidal cross section of 18 ° .



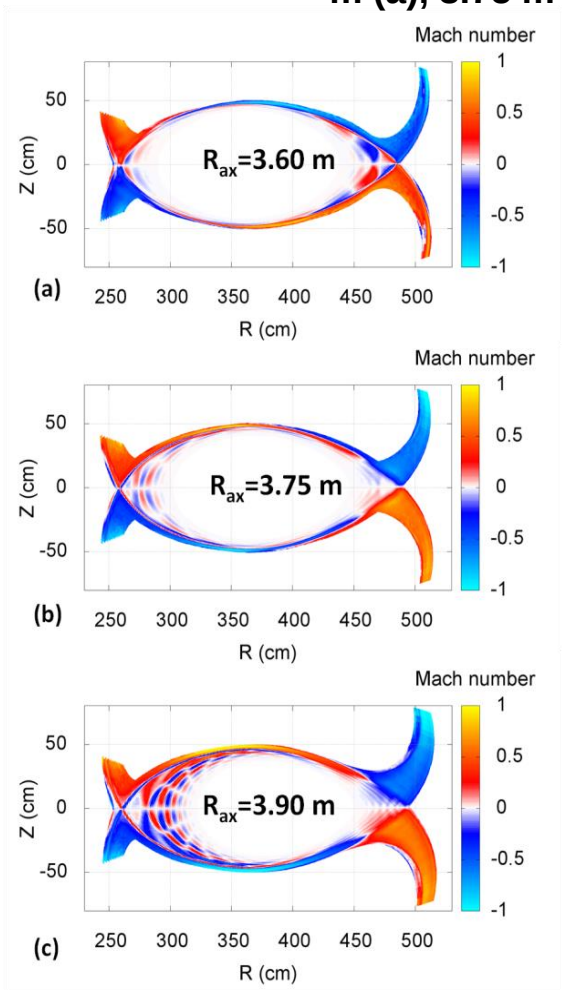
In the outermost region of the stochastic layer, the L_c of the open field lines are very short (L_c < 10 m) for all three magnetic configurations. The stochastic magnetic field lines surrounded by the short field lines (L_c < 10 m) have a variety of L_c (10 < L_c < 2000 m), which corresponds to 0.5-100 toroidal turns of the LHD torus.

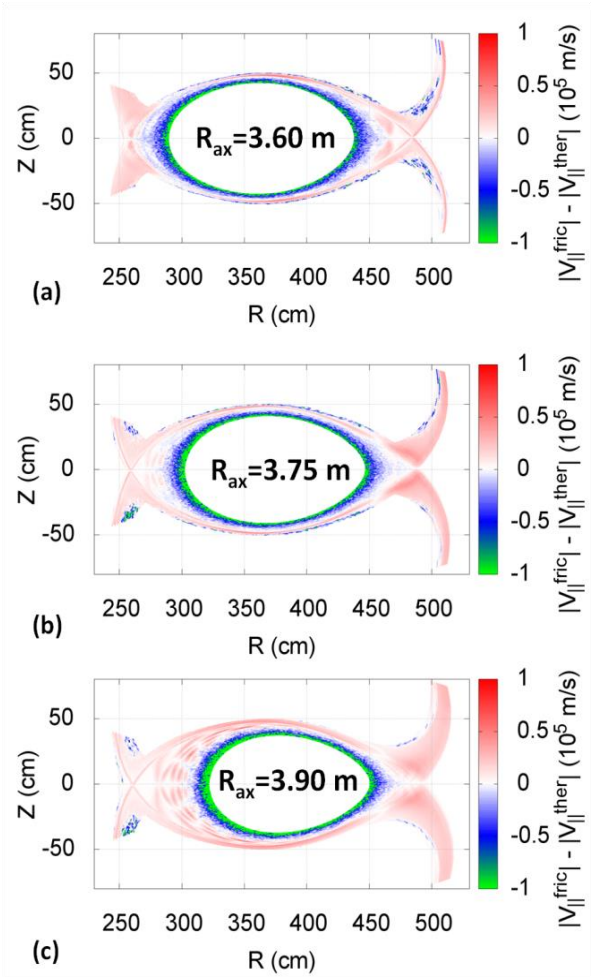
2D distributions of the plasma temperature for R_{ax} = 3.60 m (a), 3.75 m (b) and 3.90 m (c) and the plasma density for R_{ax} = 3.60 m (d), 3.75 m (e) and 3.90 m (f) at the poloidal cross section of 18 ° .

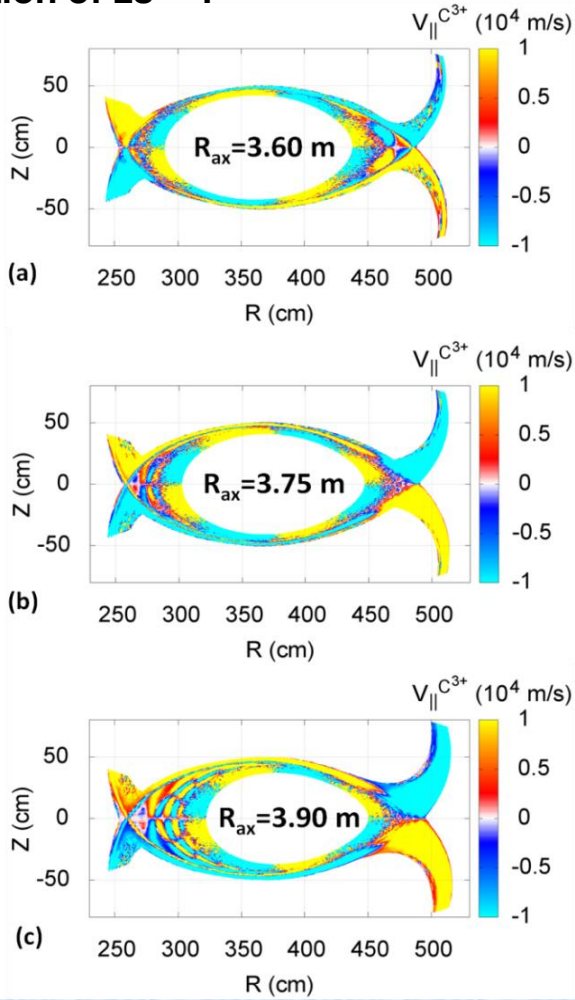


The plasma temperature and density at the inboard X-point region reduce gradually when the R_{ax} moves from 3.60 to 3.90 m. Accordingly, an increase of the plasma temperature and density is obtained at the outboard X-point region.

2D distributions of the Mach number , force balance and parallel velocity of C^{3+} impurity flow for R_{ax} = 3.60 m (a), 3.75 m (b) and 3.90 m (c) at the poloidal cross section of 18 ° .

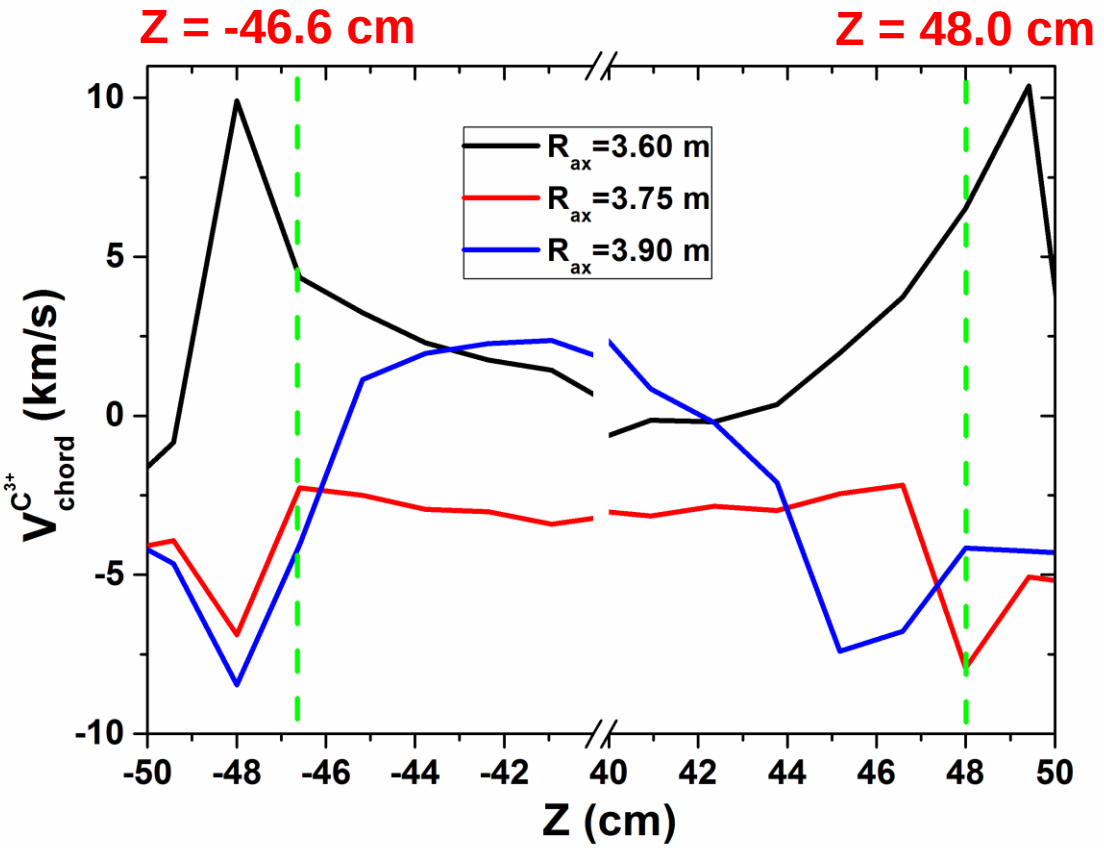






- The directions of the plasma flow **at the top and bottom edges** of the stochastic layer are **opposite** for all three magnetic configurations.
- The plasma edge regions are **in the friction force dominant regime** for all three magnetic configurations.
- The distributions of the parallel C^{3+} impurity flow in the stochastic layer show the **same phase as the plasma flow profiles**. This is because the plasma edge regions are dominated by the friction force for all three magnetic configurations.

Zoom-in profile of the vertical distributions of the horizontal velocity of C^{3+} impurity flow for R_{ax} = 3.60, 3.75 and 3.90 m.

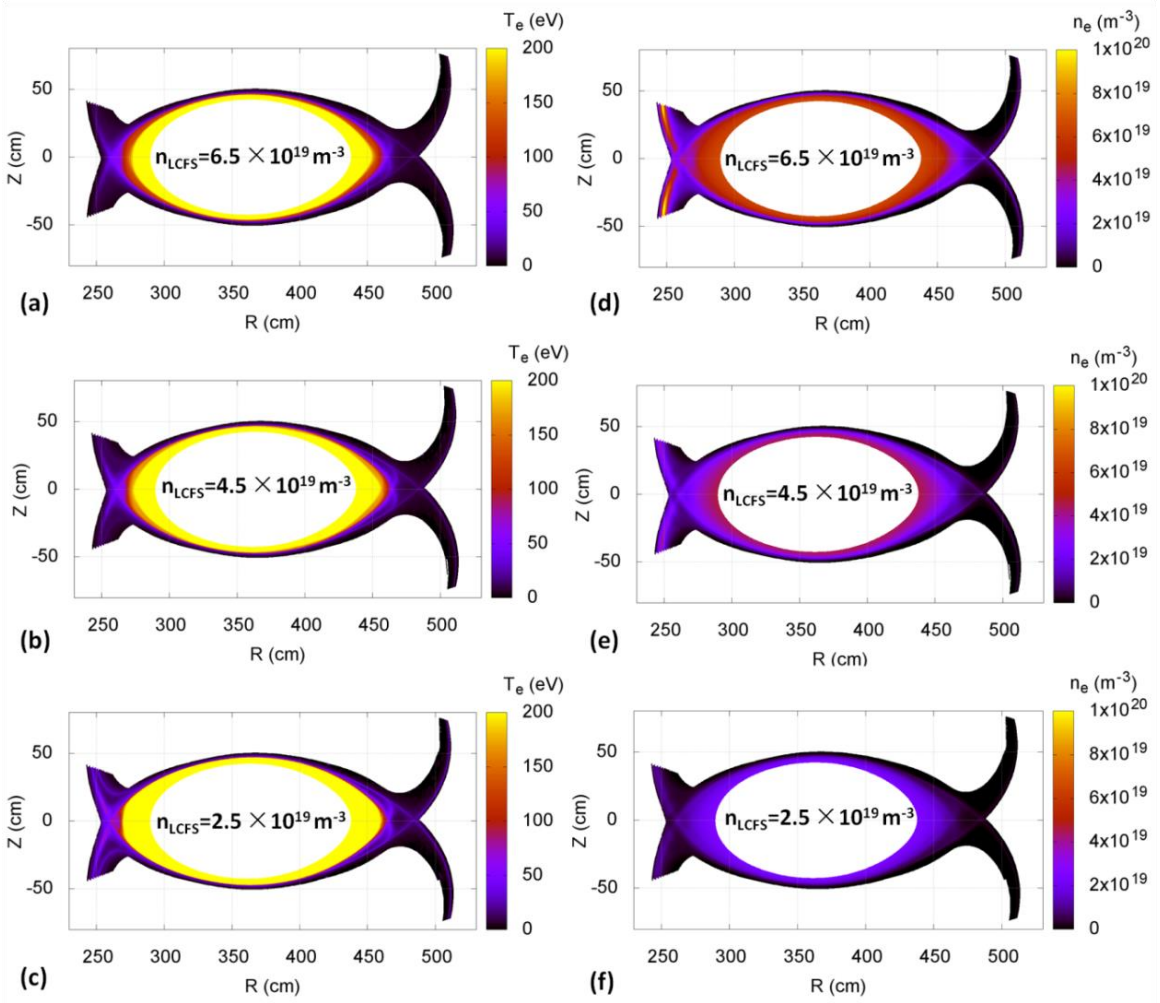


The distributions of the magnetic field components B_R and B_z for R_{ax} = 3.75 and 3.90 m are similar to that for R_{ax} = 3.60 m. Hence, the directions of the horizontal C^{3+} impurity flow are determined by the parallel C^{3+} impurity flow directions. This leads to a reversed direction of the horizontal impurity flow for R_{ax} = 3.75 and 3.90 m compared to that for R_{ax} = 3.60 m at the top and bottom edges of the stochastic layer.

The effect of plasma condition

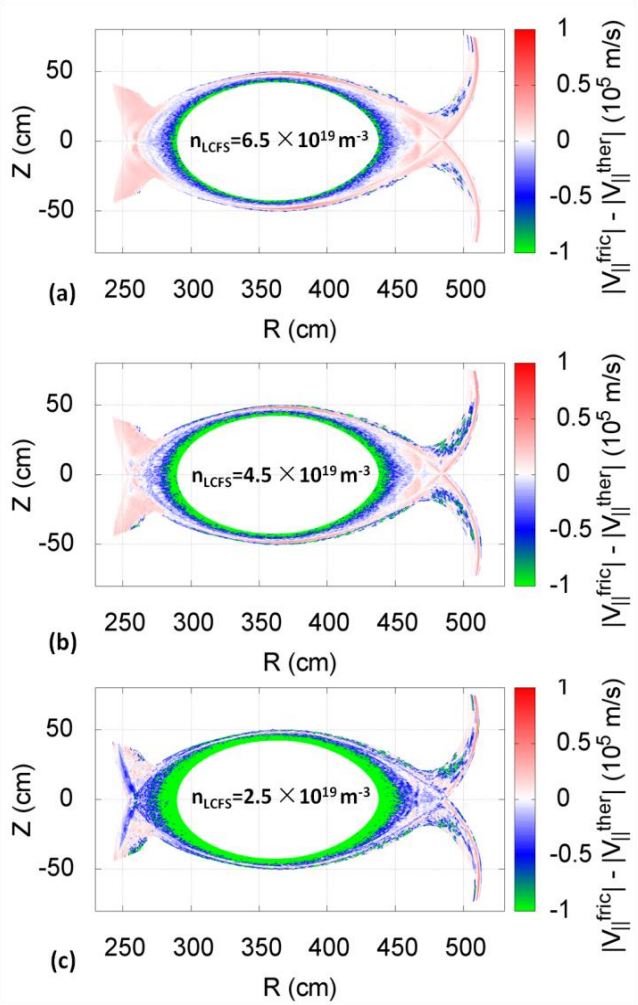
大连理工大学 DALIAN UNIVERSITY OF TECHNOLOGY

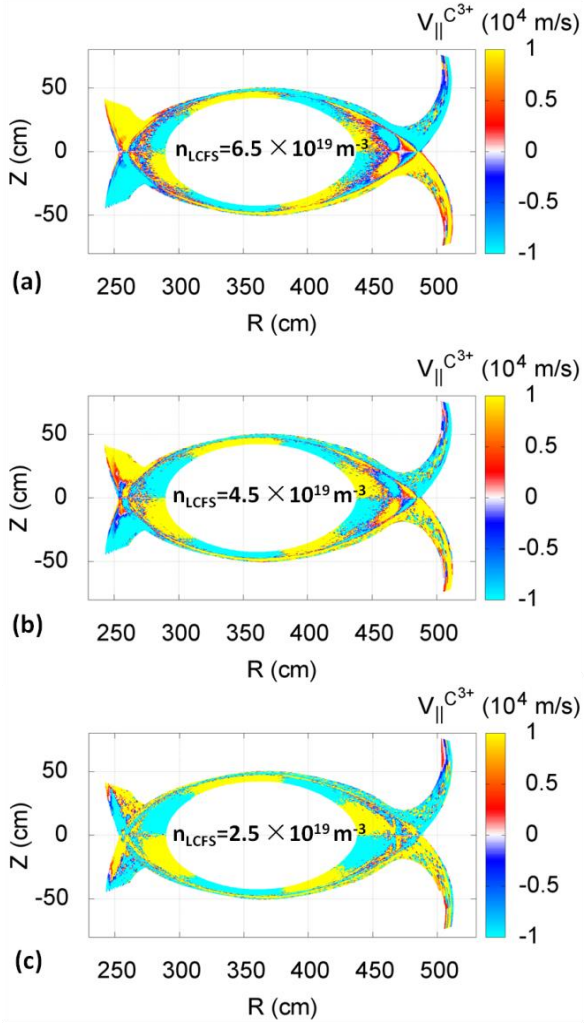
2D distributions of the plasma temperature for n_{LCFS} = 6.5×10^{19} m^{-3} (a), 4.5×10^{19} m^{-3} (b) and 2.5×10^{19} m^{-3} (c) and the plasma density for n_{LCFS} = 6.5×10^{19} m^{-3} (d), 4.5×10^{19} m^{-3} (e) and 2.5×10^{19} m^{-3} (f) at the poloidal cross section of 18 ° .



The reduced upstream plasma density (n_{LCFS}) leads to a higher edge plasma temperature and a lower edge plasma density. This results in an increase of the thermal force and a reduction of the friction force in the stochastic layer, which will have an impact on the parallel transport behaviour of C^{3+} impurity flow.

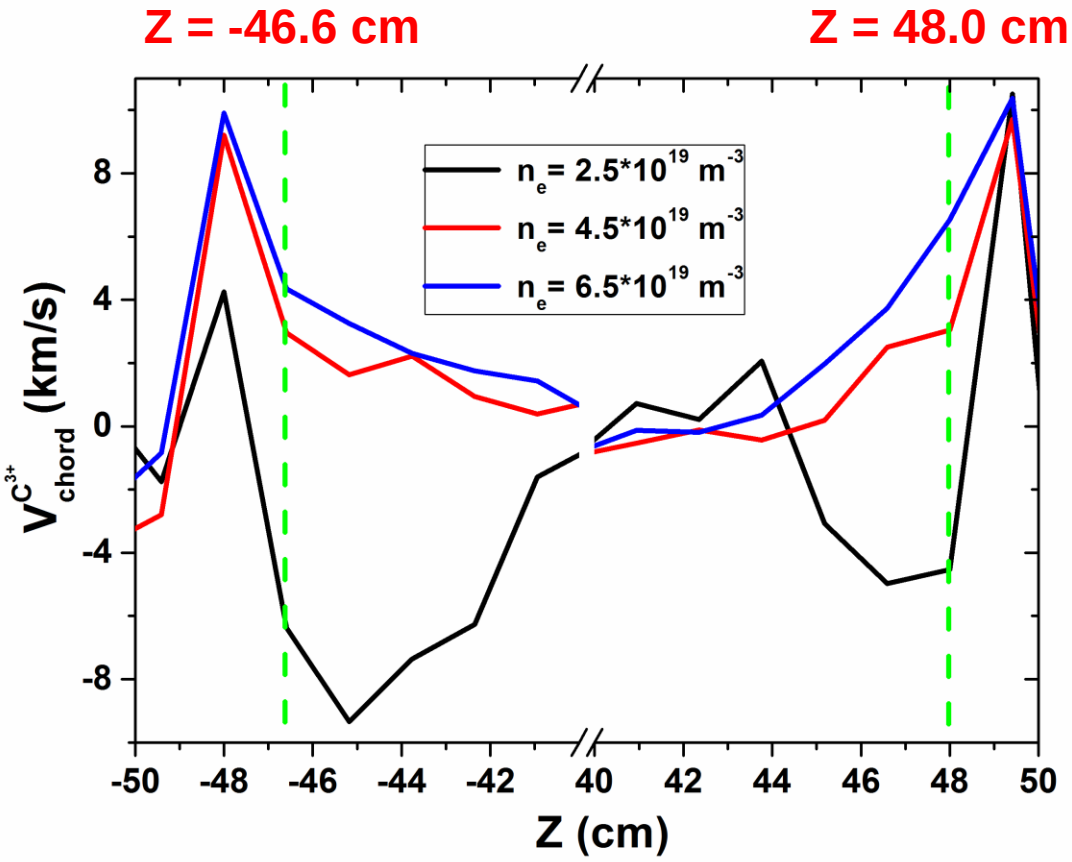
2D distributions of the force balance and parallel velocity of C^{3+} impurity flow for $n_{LCFS} = 6.5\times10^{19}$ m^{-3} (a), 4.5×10^{19} m^{-3} (b) and 2.5×10^{19} m^{-3} (c) at the poloidal cross section of 18 ° .





- **The reduced upstream plasma density results in an expansion of the thermal force dominant regions.**
- **For $n_{LCFS} = 2.5\times10^{19}$ m^{-3}, the distribution of the parallel velocity of C^{3+} impurity flow becomes noisy in the stochastic layer, which is induced by the change of the force balance.**

Zoom-in profile of the vertical distributions of the horizontal velocity of C^{3+} impurity flow for $n_{LCFS} = 6.5\times10^{19}$, 4.5×10^{19} and 2.5×10^{19} m^{-3}.



For $n_{LCFS} = 6.5\times10^{19}$ and 4.5×10^{19} m^{-3}, the positive horizontal C^{3+} impurity velocities at Z = 48.0 and -46.6 cm indicate the outward impurity flows along the major radius direction, while a reversed direction of impurity flow is obtained for $n_{LCFS} = 2.5\times10^{19}$ m^{-3}. This reversal of impurity flow is due to the enhanced thermal force at the inner radii.

1. Introduction

2. VUV spectrometer system

3. Codes implementation on LHD

4. Modelling of impurity flow velocity in the stochastic layer of LHD

5. Simulations of impurity flow velocity with different scenarios

6. Summary

Summary

1. The transport characteristics of the edge impurity flow in the stochastic layer of the LHD have been investigated with the EMC3-EIRENE code. The good agreement between the VUV measurements and the EMC3-EIRENE simulations has been obtained.

2. The investigation of the asymmetric structure of the chord-integrated velocity of C^{3+} impurity flow at the top and bottom edges has been performed by artificially changing the vertical position of the VUV spectrometer.

3. The measured C^{3+} impurity flows at the top and bottom edges of the stochastic layer move towards the outboard side of the torus along the major radius direction, which can be well interpreted by the detailed analysis of the 3D magnetic field structure and the parallel impurity flow direction.

Summary

4. The parallel transport of C^{3+} impurity flow are determined by the plasma flow behaviour in the edge plasma regions, which results in an opposite direction of the horizontal impurity flow for R_{ax} = 3.75 and 3.90 m to that for R_{ax} = 3.60 m at the top and bottom edges of the stochastic layer.

5. The relatively noisy distribution of the parallel velocity of C^{3+} impurity flow for the low upstream plasma density leads to a reversed direction of the horizontal C^{3+} impurity flow compared to the cases of the high upstream plasma density.

Thank you for your attention!

EMC3 - Fluid model for background plasma

大连理工大学 DALIAN UNIVERSITY OF TECHNOLOGY

Particle:

$$\nabla\cdot\left(n_i V_{i\parallel}\boldsymbol{b} - D\nabla_\perp n_i\right) = S_p$$

Momentum balance:

$$\nabla\cdot\left(m_i n_i V_{i\parallel} V_{i\parallel}\boldsymbol{b} - \eta_{\parallel}\nabla_{\parallel} V_{i\parallel} - m_i V_{i\parallel} D\nabla_\perp n_i - \eta_\perp \nabla_\perp V_{i\parallel}\right) = -\nabla_{\parallel} p + S_m$$

Energy transport for electrons and ions:

$$\nabla\cdot\left(\tfrac{5}{2} n_e T_e V_{i\parallel}\boldsymbol{b} - \kappa_e \nabla_{\parallel} T_e - \tfrac{5}{2} T_e D\nabla_\perp n_e - \chi_e n_e \nabla_\perp T_e\right) = -k\left(T_e - T_i\right) + S_{ee} + S_{imp}$$

$$\nabla\cdot\left(\tfrac{5}{2} n_i T_i V_{i\parallel}\boldsymbol{b} - \kappa_i \nabla_{\parallel} T_i - \tfrac{5}{2} T_i D\nabla_\perp n_i - \chi_i n_i \nabla_\perp T_i\right) = +k\left(T_e - T_i\right) + S_{ei}$$

Transport parameters:

Parallel transport coefficients: $\eta_{\parallel}$, κ_e, κ_i

Cross-field transport coefficients : $\eta_\perp = m_i D$, ***D, χ_e, χ_i — free input parameters***

Source terms:

S_m, S_{ee}, S_{ei} *: sources due to plasma-neutral interaction provided by EIRENE code*

S_{imp}*: impurity radiation (a trace impurity model included in EMC3 code)*