Impact of the radial electric field profile to the magnetic topology and comparisons with models of the edge transport in the Large Helical Device

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NINS
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597th Wilhelm and Else Heraeus Seminar Stochasticity in Fusion Plasmas
Physikzentrum Bad Honnef, Germany 10-12 September, 2015

Acknowledgement

K. Ida, M. Yoshinuma, H. Tsuchiya, S. Sakakibara,
K. Y. Watanabe, Y. Narushima, S. Ohdachi, I. Yamada,
R. Yasuhara, K. Tanaka, T. Akiyama, T. Morisaki,
M. Kobayashi, G. Kawamura,
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Y. Feng (IPP-Greifswald, Germany)

We would like to thank all colleagues to do this work!

Outline

1. Introduction
2. Experimental Setup
3. Measurements of E_r in different magnetic field
4. Comparison with modeling
5. Summary

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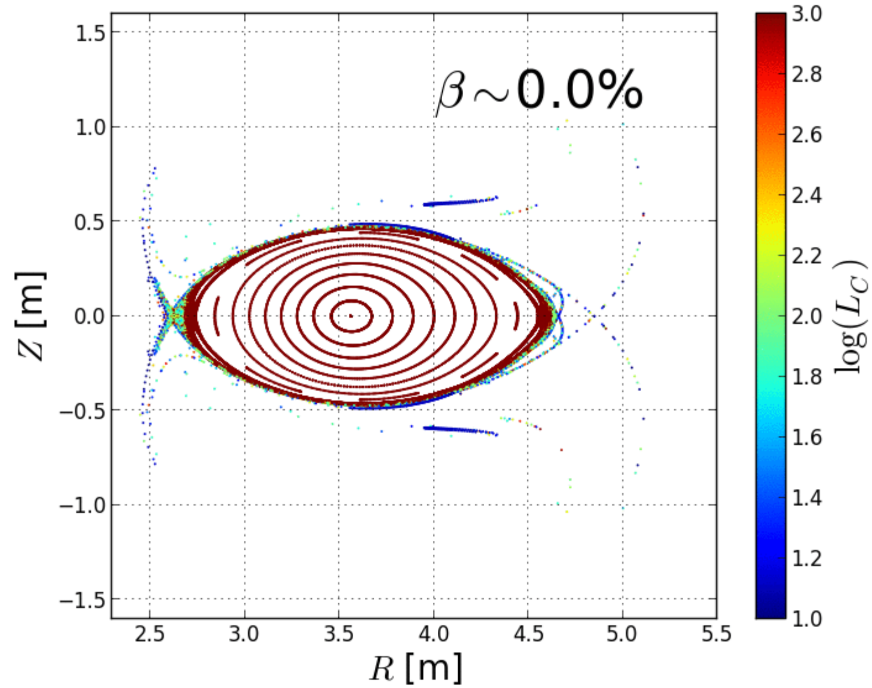
Background

- LHD is an L/M=2/10 Heliotron configuration. The stochastization of magnetic field lines naturally appears because of no symmetry.
- In addition, 3D MHD equilibrium analyses predict the stochastization by the "***nonlinear 3D equilibrium response***". That is, magnetic field lines are further stochastized by pressure-induced perturbed field driven by currents along rippled field lines.

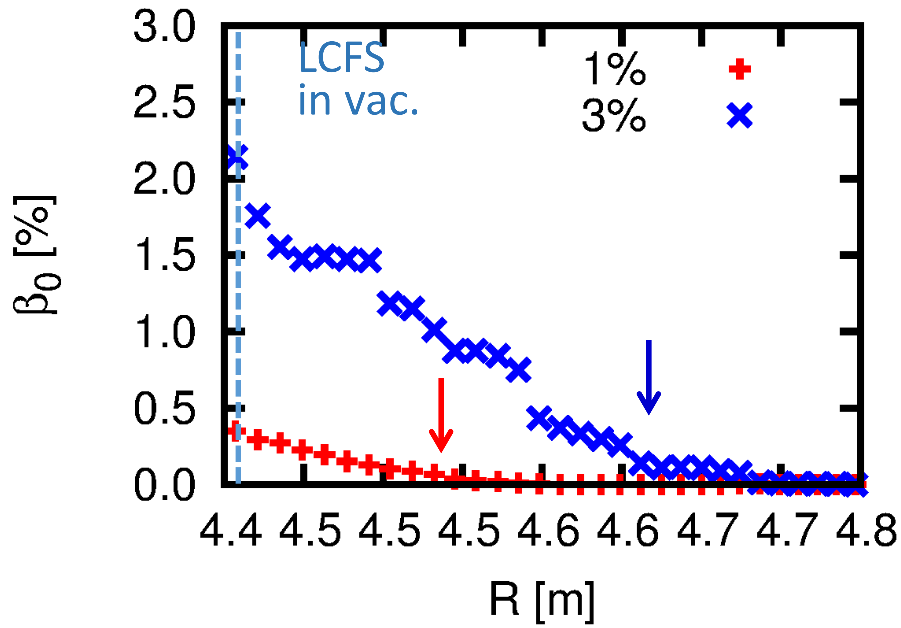
3D MHD modeling by HINT



Background

- LHD is an L/M=2/10 Heliotron configuration. The stochastization of magnetic field lines naturally appears because of no symmetry.
- In addition, 3D MHD equilibrium analyses predict the stochastization by the "***nonlinear 3D equilibrium response***". That is, magnetic field lines are further stochastized by pressure-induced perturbed field driven by currents along rippled field lines.
- In experiments, changing the boundary of plasma pressure is observed. Increasing β, the boundary shifts to the outward of the torus.

Pressure profiles with different β

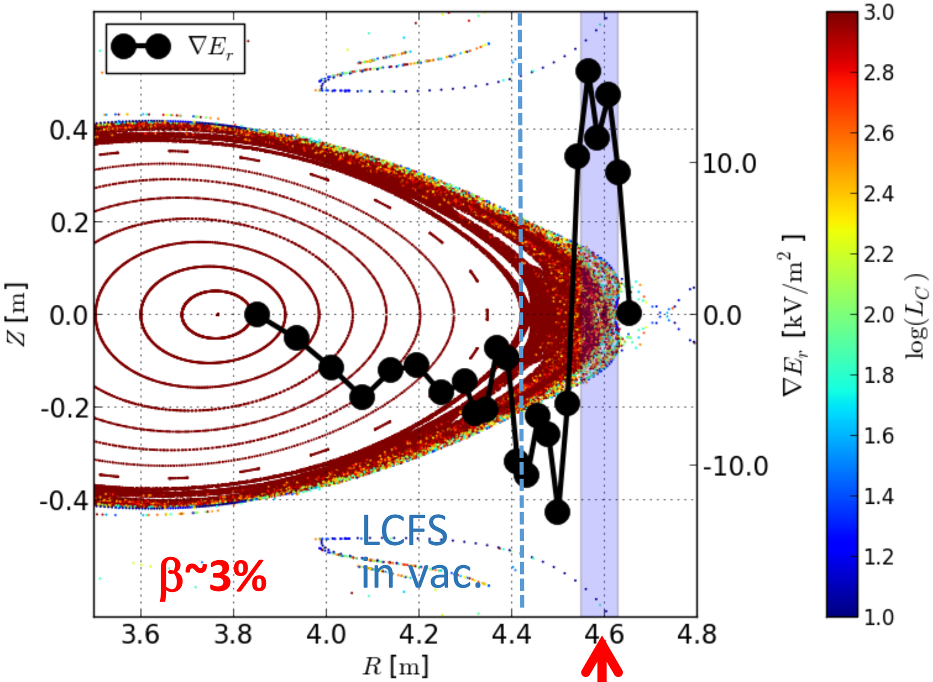


Previous studies

To study where the 'effective' boundary, the radial electric field, E_r, was studied in the edge.

Hypothesis:
Lost of electrons along opened field lines produces positive electric field.
=> Positive electric field in the peripheral region reflects the magnetic field structure!

Comparison with HINT2 modeling



strong E_r shear appears in stochastic region

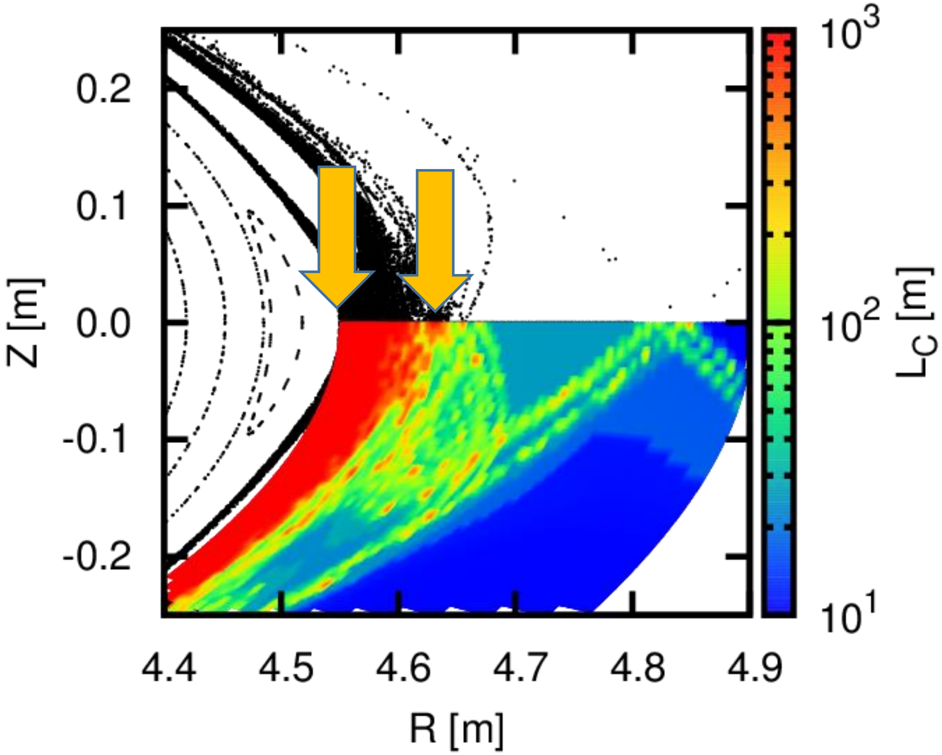
- In previous studies, E_r profiles are studied for high-β plasmas.
- With increased β, Positions of strong E_r shear shift to the outward of the torus.
- This suggests the magnetic field structure was changed.

Y. Suzuki, et al., Nucl. Fusion 53 (2013) 073045
Y. Suzuki, et al., Plasma Phys. Control. Fusion 55 (2013) 124042

However:
This hypothesis completely ignored the perpendicular transport.

Motivation

The radial electric field, E_r, can be considered as an index of the plasma boundary.



However,

The magnetic field of the LHD consists of 3 regions

1. **Nested flux surfaces**
2. **Stochastic layer**
3. **Scrape-Off layer**

Where is the boundary decided by the E_r?

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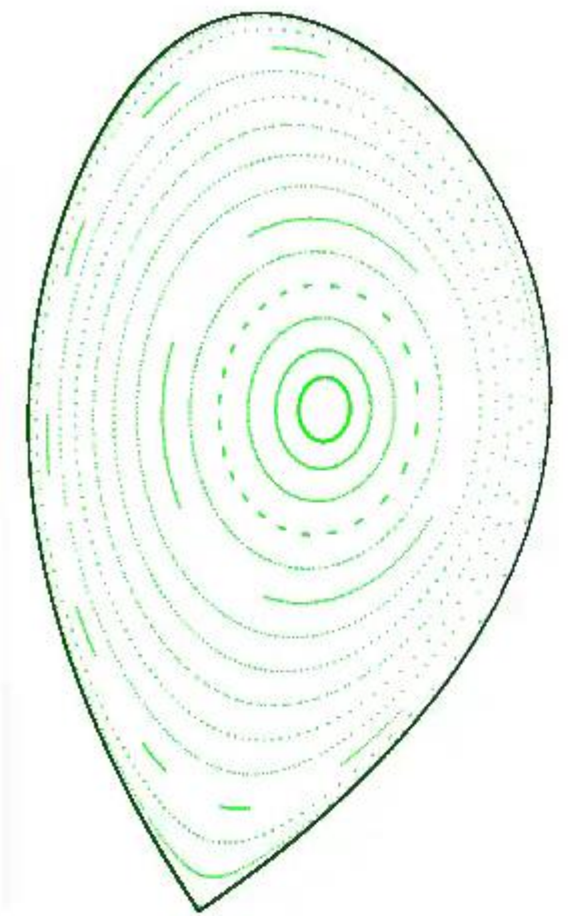

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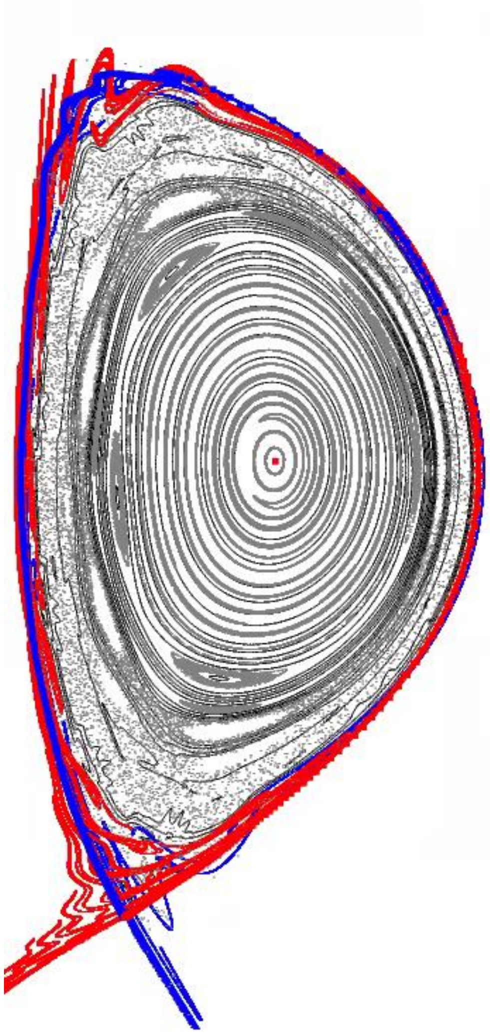

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↓

Where is the boundary decided by the E_r?

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This is an important issue of RMP experiments in tokamaks!

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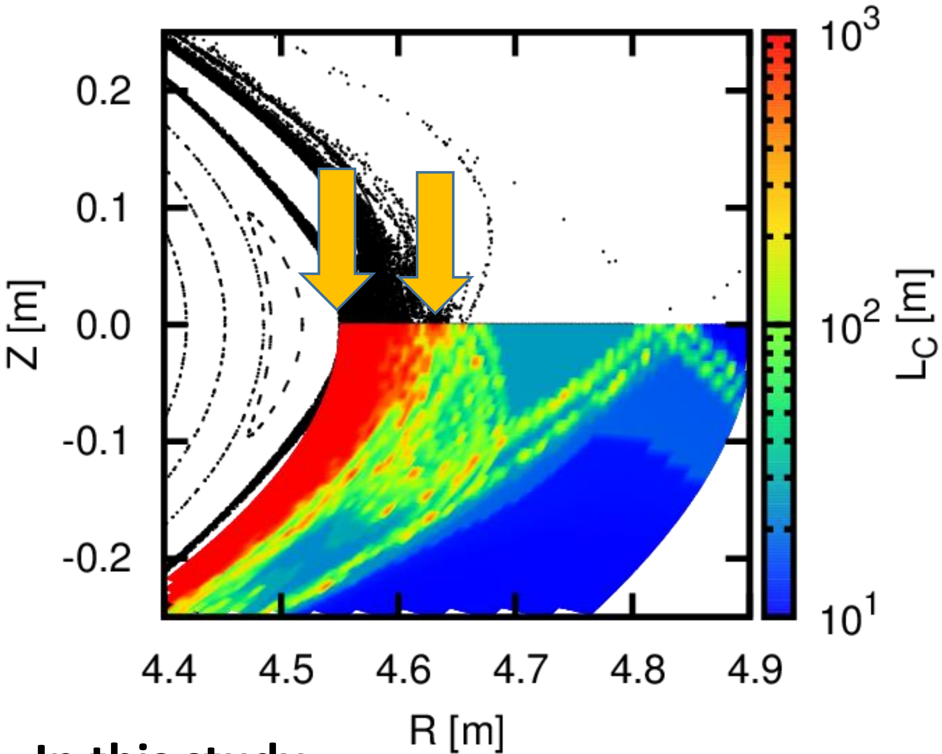

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The magnetic field of the LHD consists of 3 regions

1. **Nested flux surfaces**
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Where is the boundary decided by the E_r?

This is an important issue of RMP experiments in tokamaks!

In this study,

1. **The radial electric field on the stochastic layer is studied in the LHD.**
2. **Two magnetic configurations with different width of stochastic layers are studied in low-β. In such a case, the vacuum model can be used.**
3. **Impacts of perpendicular diffusion of stochastic field lines are studied.**

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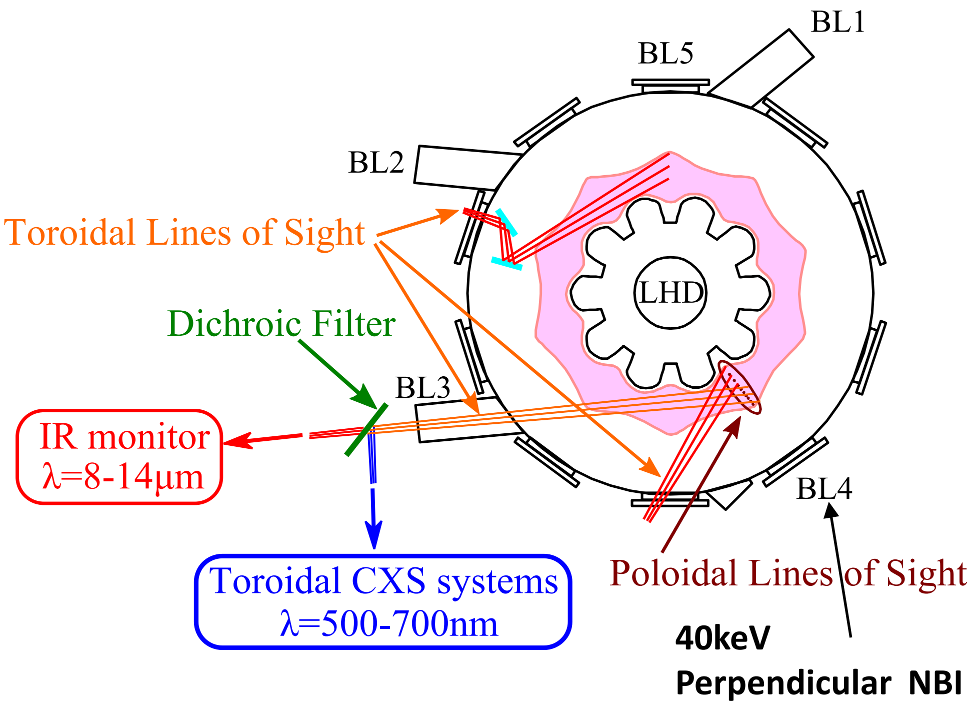
Radial Electric Field Measurement by CXRS

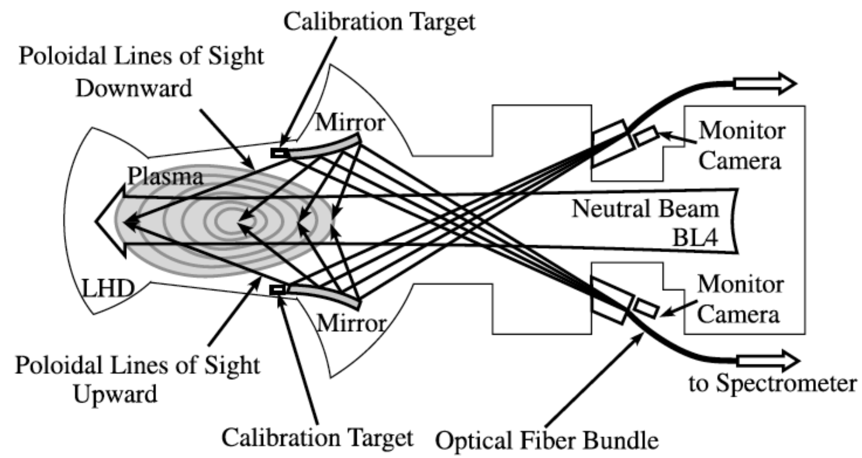
The Charge Exchange Recombination Spectroscopy in LHD measures velocities of carbon impurity ions (C^{6+}).

M. Yoshinuma, et al., Fusion Science and Technology, **58** (2010) 375.

Toroidal system



Poloidal system



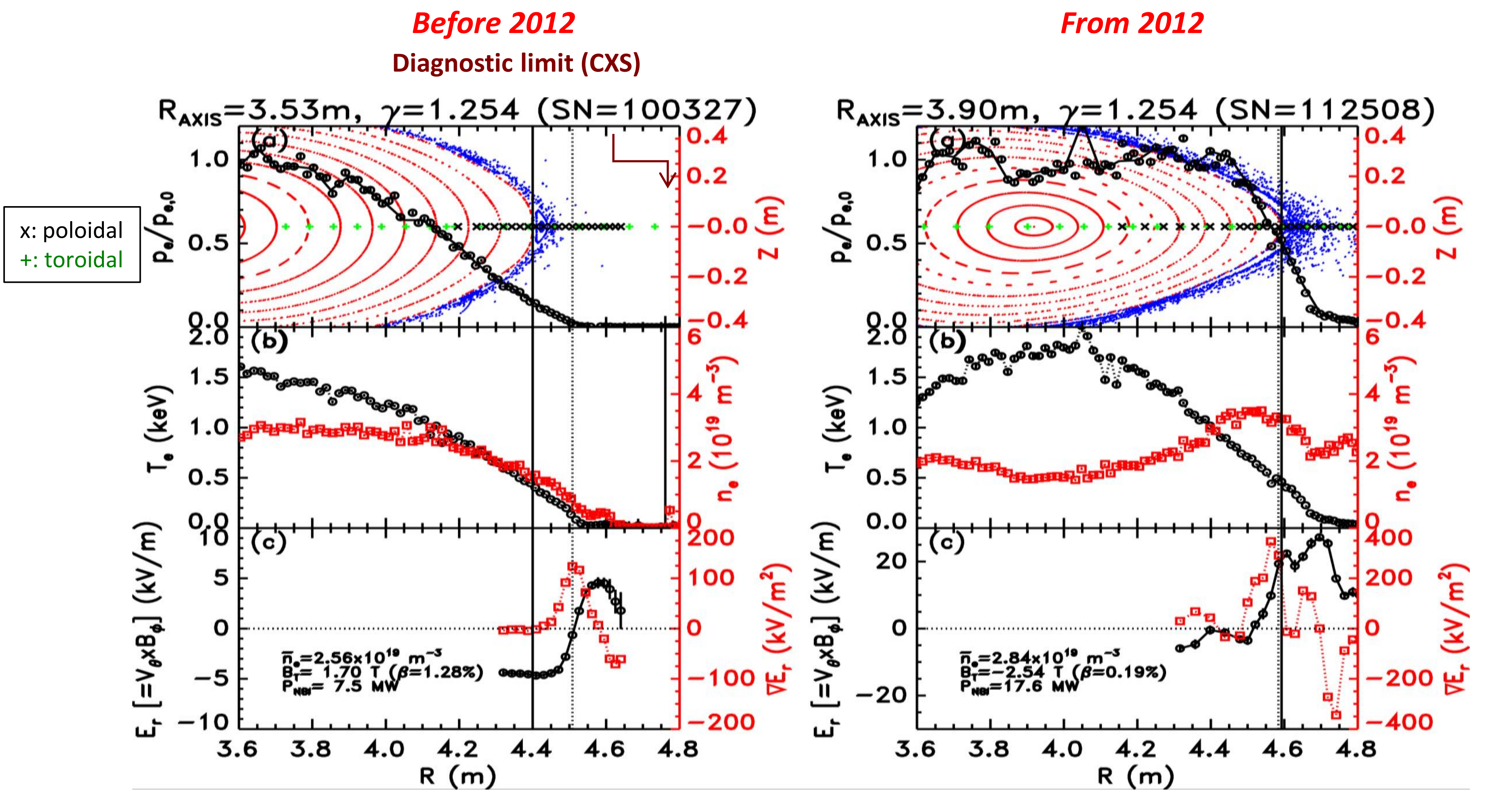
The radial electric field E_r is defined by a following radial force balance equation,

$$E_r = (Z_j e n_j)^{-1} \nabla p_j - V_{\theta,j} B_\phi + V_{\phi,j} B_\theta$$

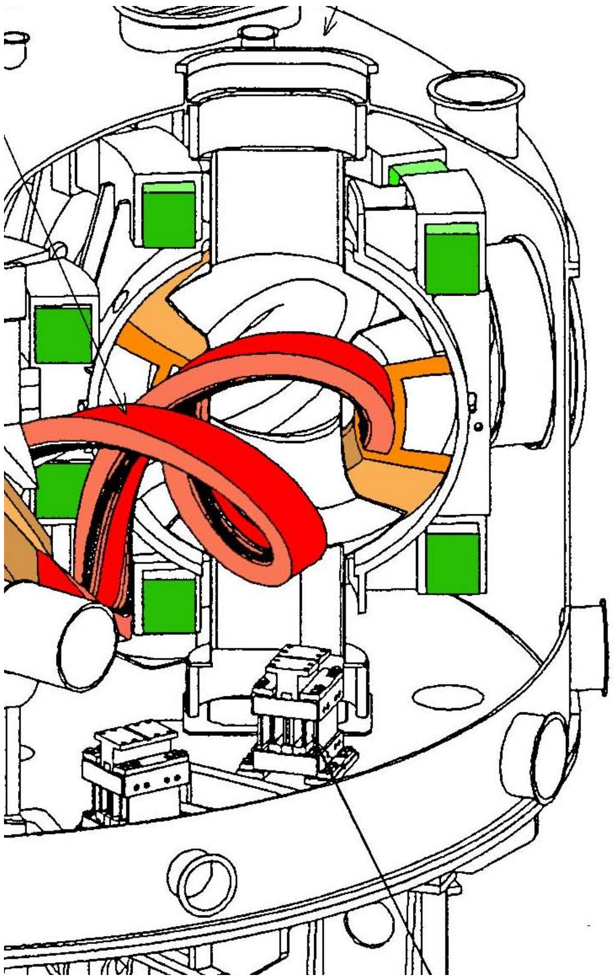
In this study, the magnetic field in the outward of the torus is studied at horizontally elongated cross section.

Upgraded CXRS to cover SOL region

- Changed the angle of mirror system, poloidal sight was extended to the outward of torus. (light fibers of toroidal sight was also increased.)
- All configurations can be covered.



Magnetic configuration of LHD



The LHD is an L/M=2/10 Heliotron.

Superconducting coils:

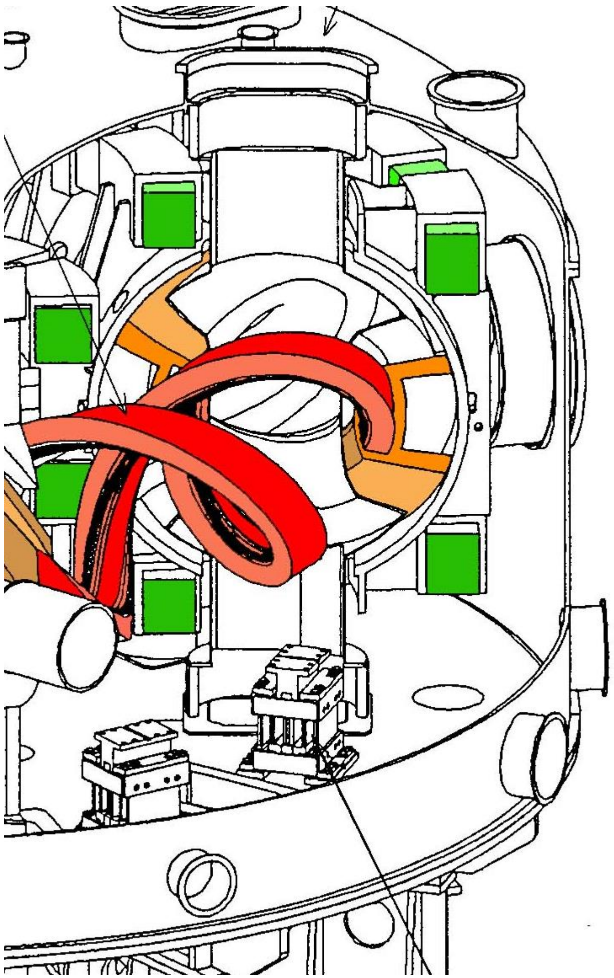
- 1 pair of Helical Coils
- 3 pair of Poloidal Field Coils

Changing coil currents:

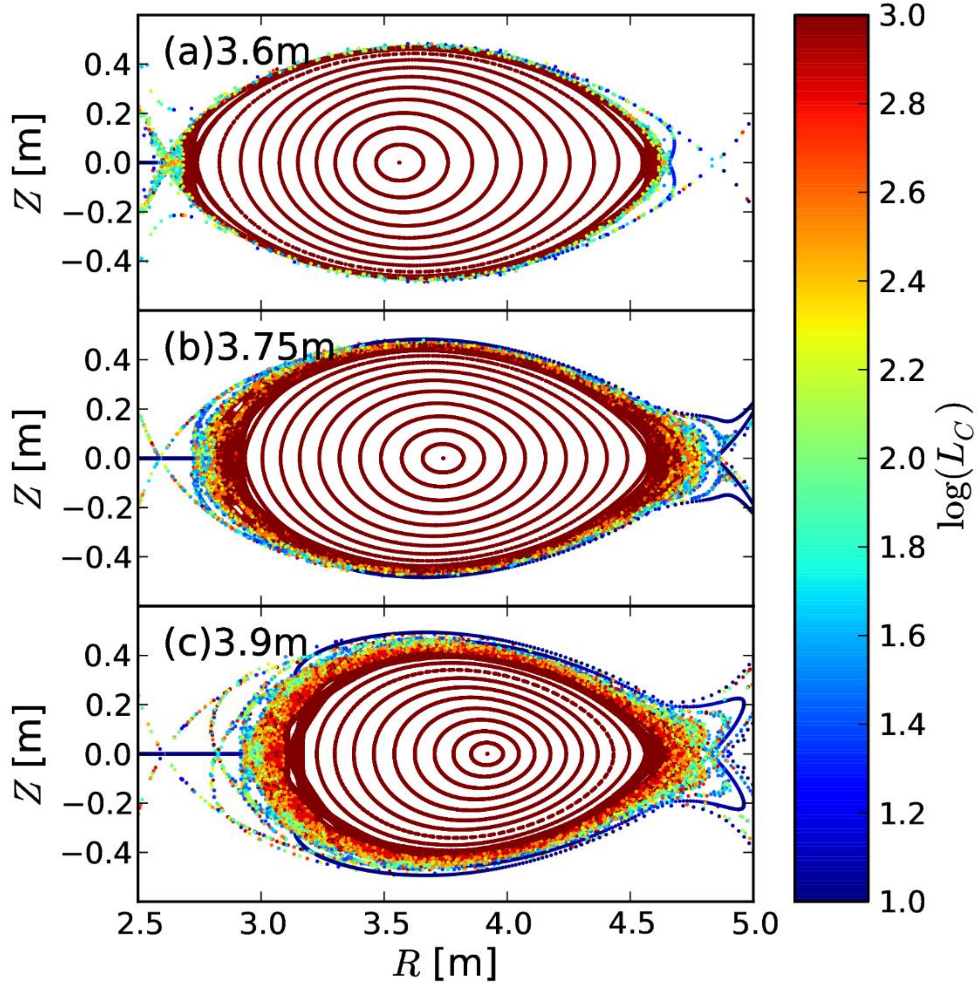
- Rotational transform
- Magnetic well/hill
- Plasma volume
- Elongation

can be controlled.

Magnetic configuration of LHD

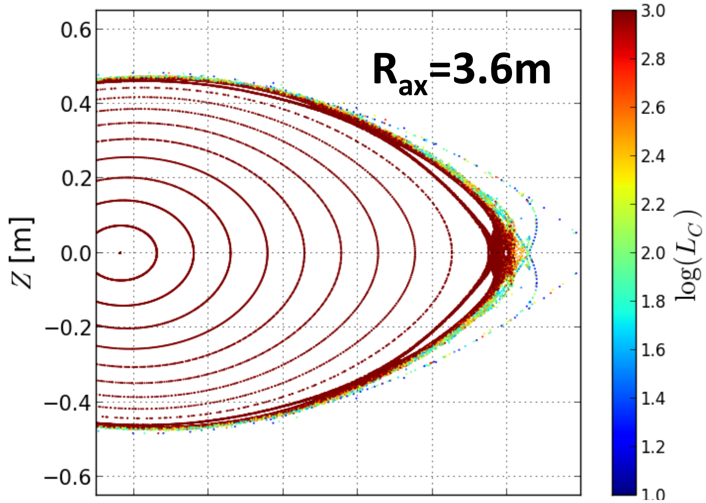


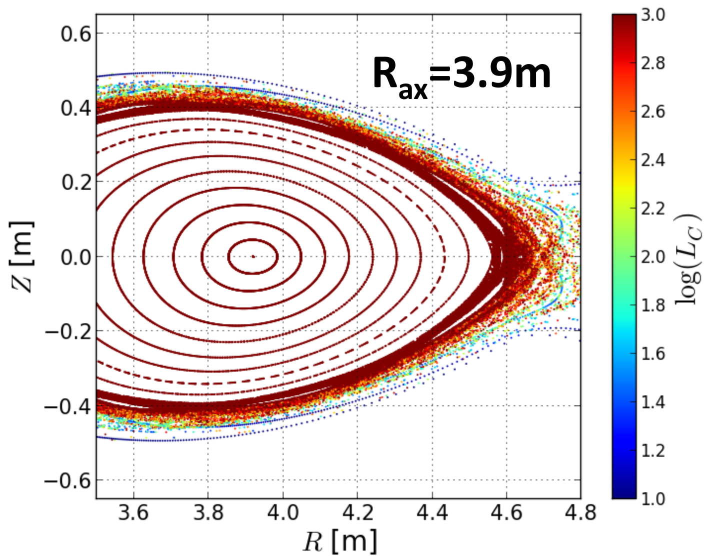
Vacuum model



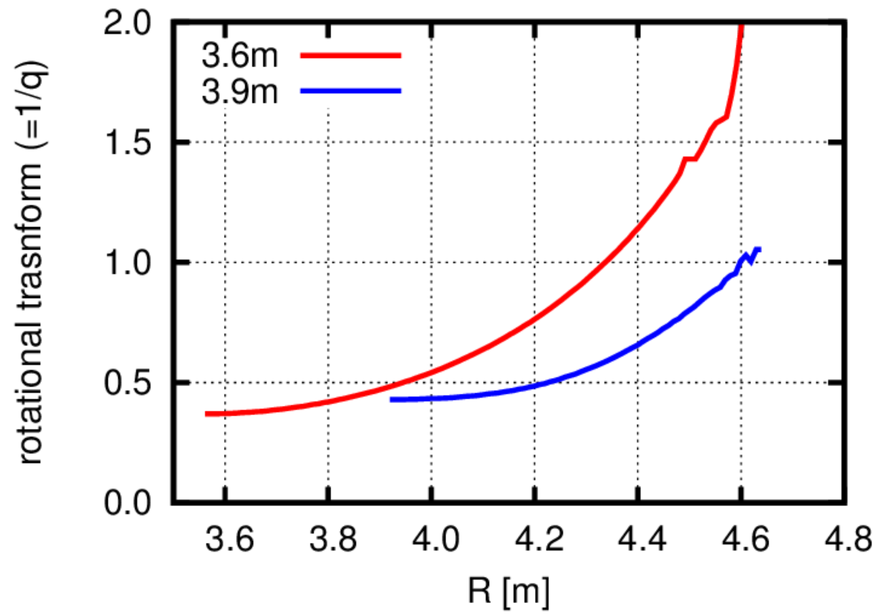
Magnetic configuration with different R_{ax}

Vacuum model



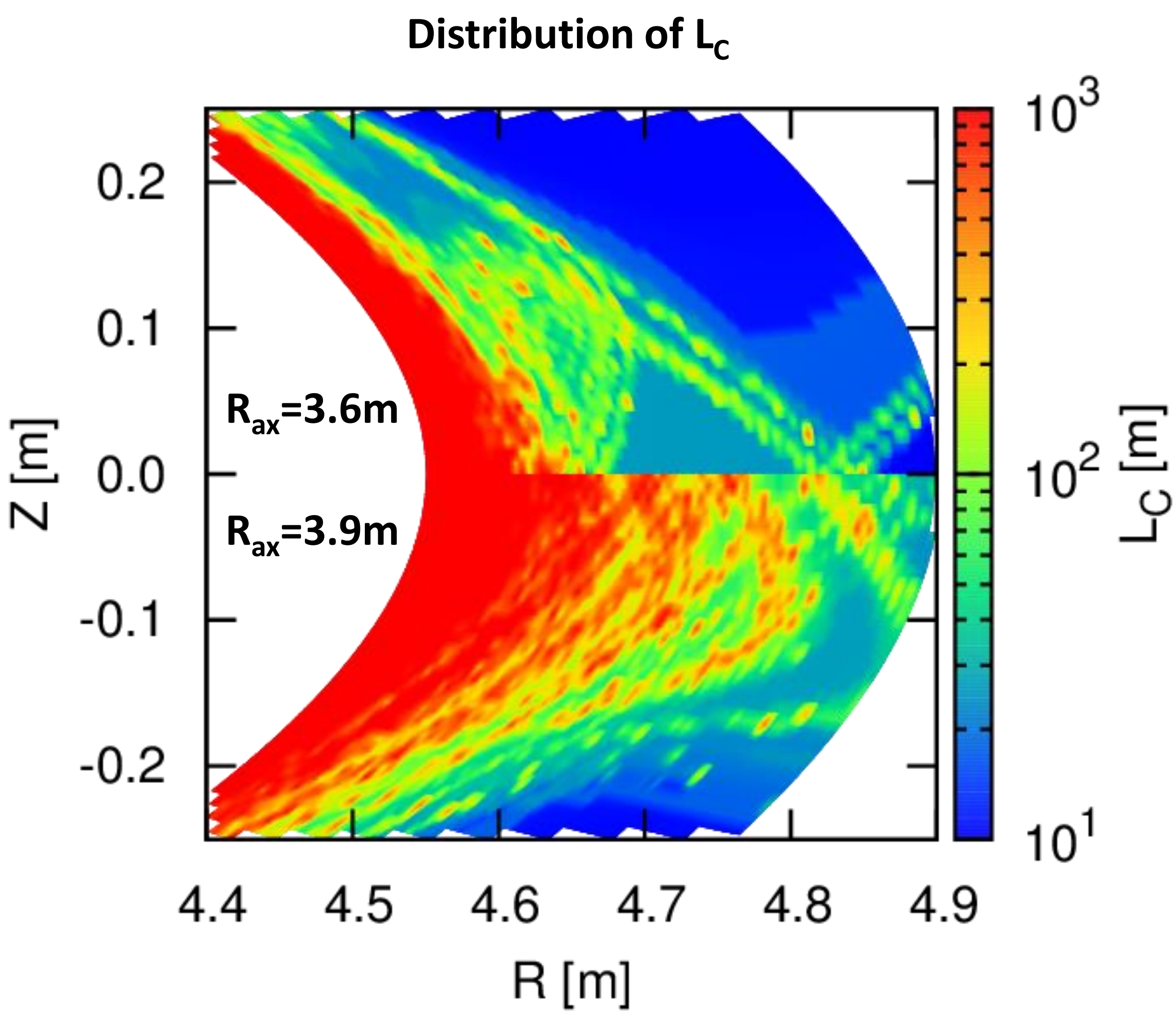


Rotational transform with different R_{ax}



- **Controlling the preset vacuum magnetic axis R_{ax}, the rotational transform on the axis and edge can be changed.**
- **Changing the magnetic shear, the stochastic layer in the peripheral region can be also changed!**

Stochastic layer with different R_{ax}



- The vacuum LCFS are almost same in inward and outward shifted configurations.
- Stochastic layers appear in both configurations.
- Laminar zones appear near the SOL.
- Stochastic field lines might be intersected in long and short L_C.

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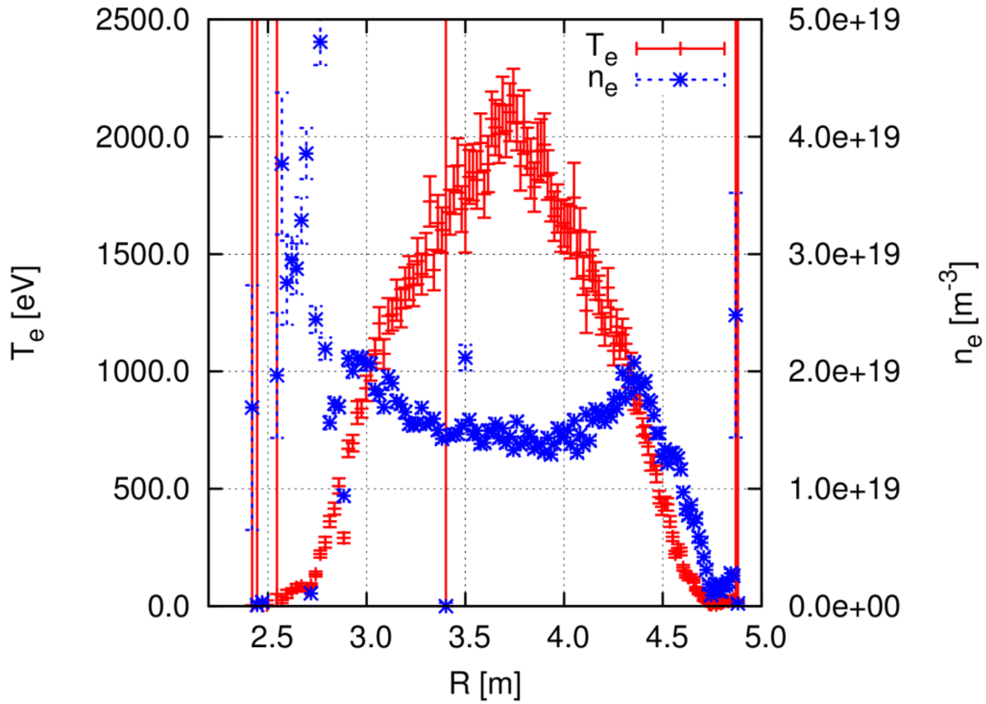
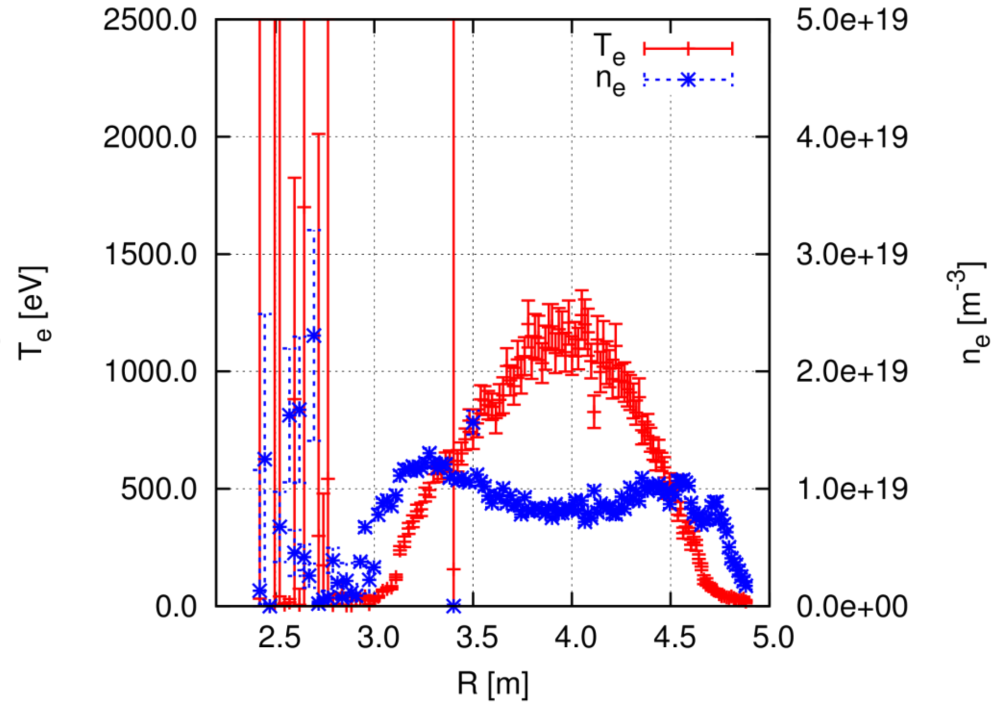
Comparison of T_e and n_e profiles for R_{ax}=3.6 and 3.9m

R_{ax}=3.6m
B=1.6T



R_{ax}=3.9m
B=1.6T



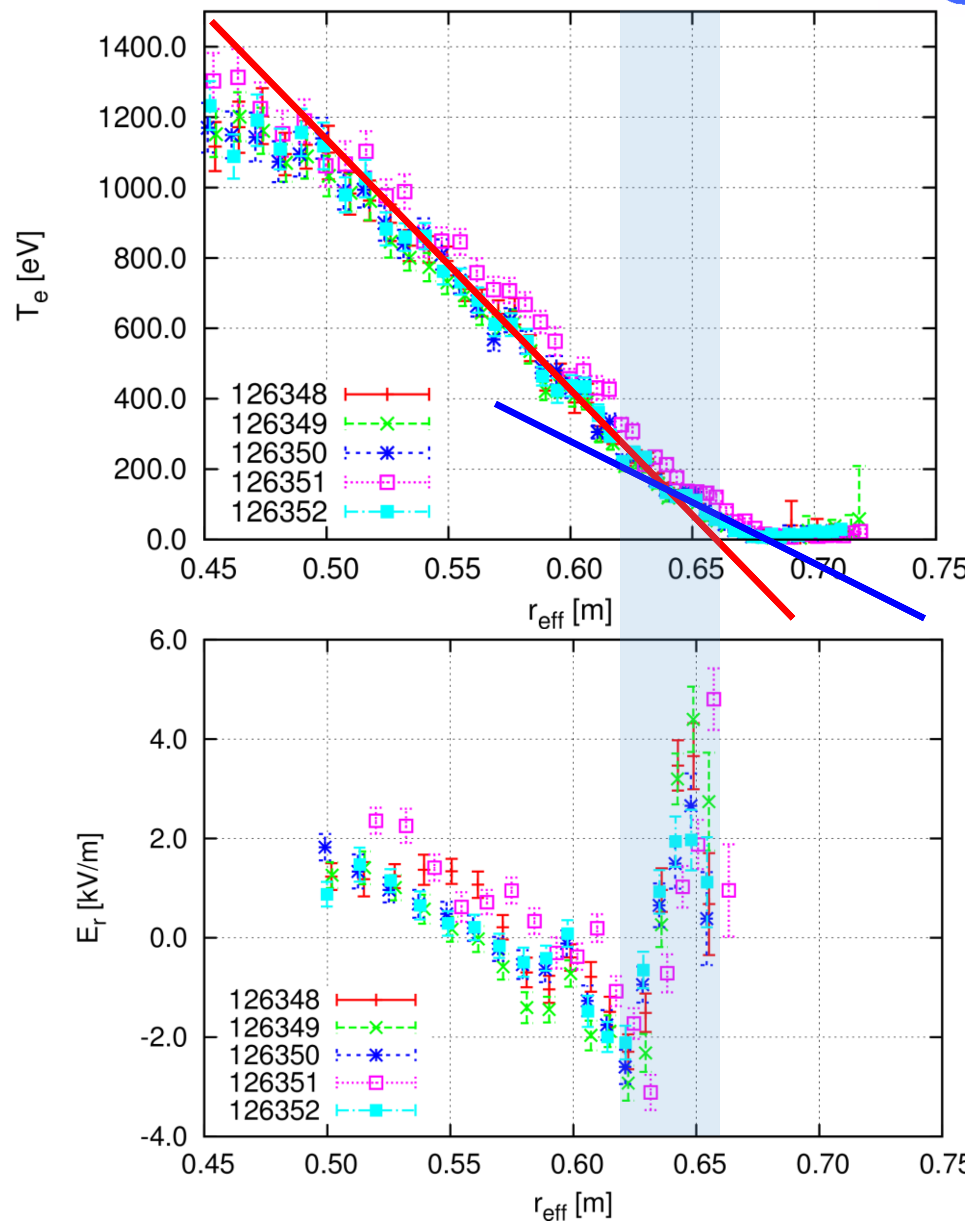
- **We studied low-β plasma (< 1%) because for high-β (> 1%) magnetic fluctuations driven by the resistive interchange mode will be strong.**
- **T_{e0} (n_{e0}) of R_{ax}=3.6m is higher (lower) than that of R_{ax}=3.9m.**
- **This reflects the transport property.**
- **But, electron pressure and mean free path are almost comparable in edge region.**

T_e and E_r profiles in Edge

- E_r shear from negative to positive appear at r_{eff} ~ 0.63m.
- In the strong E_r shear region, T_e gradients become sufficiently small.

Is the hypothesis of the parallel electron dynamics OK?

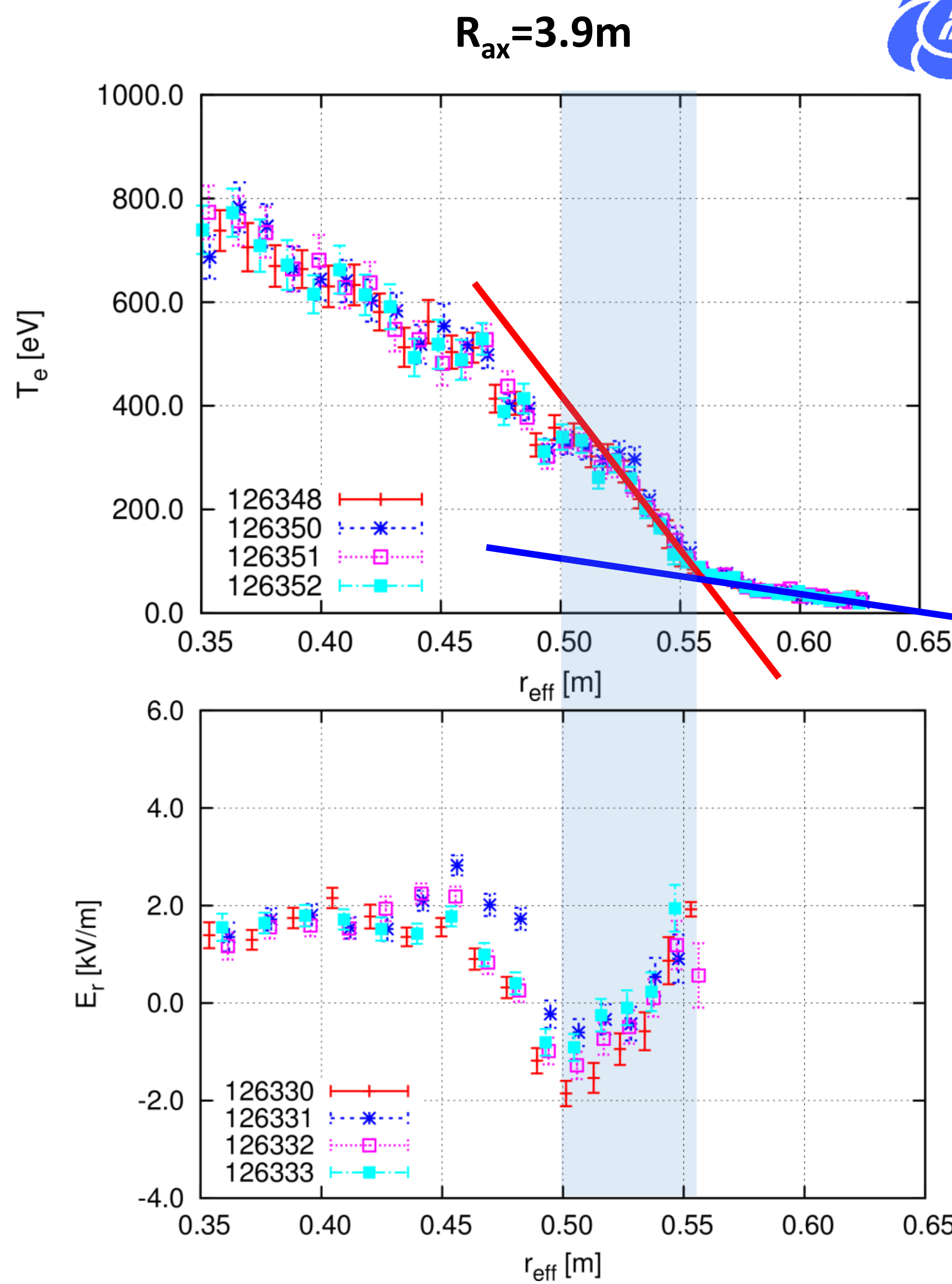
R_{ax}=3.6m



T_e and E_r profiles in Edge

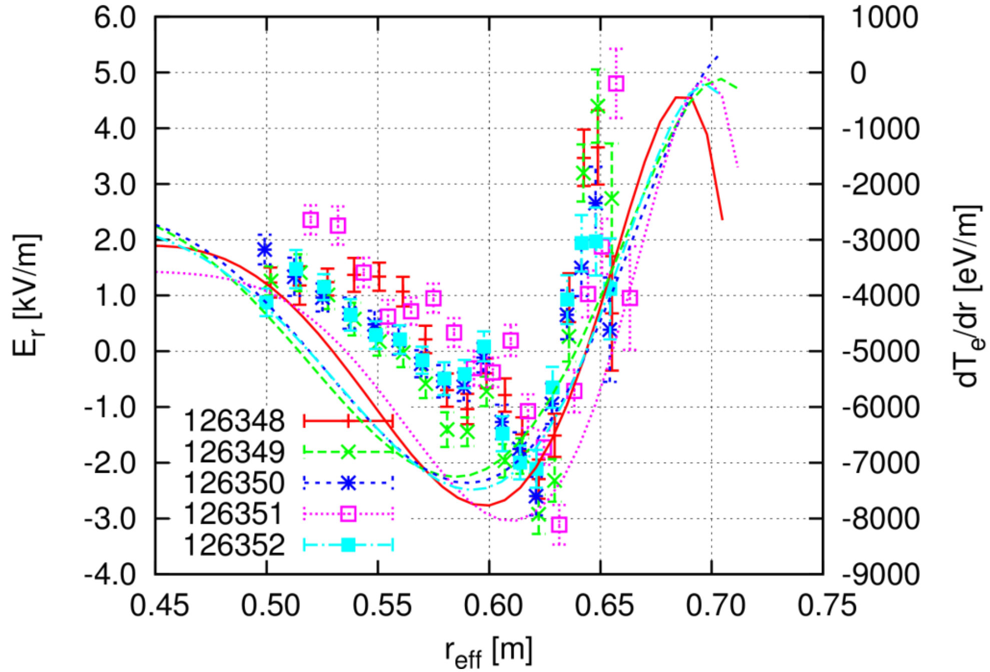
- E_r shear from negative to positive appear at r_{eff} ~ 0.5m.
- E_r shear is not strong.
- In the strong E_r shear layer, steep T_e gradients still exist.
- In the outside of strong E_r shear layer, Te gradients become low.
- E_r shear layer is wider.

Is this the difference of the magnetic configuration?

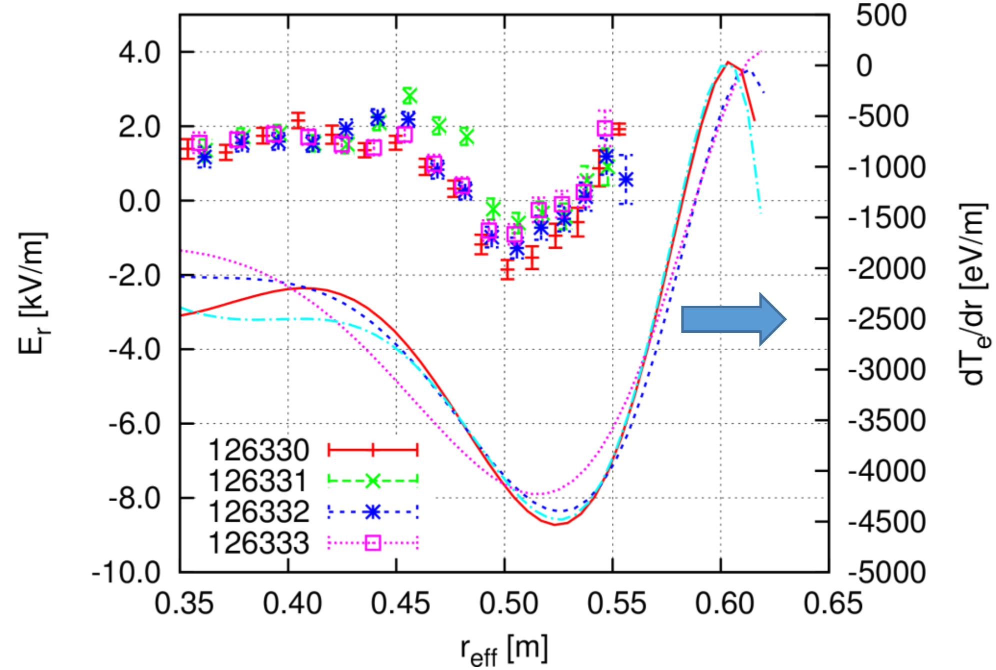


grad-T_e and E_r profiles in Edge

R_{ax}=3.6m



R_{ax}=3.9m



- **For R_{ax}=3.6m, E_r and grad-T_e correlate well.**
- **For R_{ax}=3.9m, E_r and grad-T_e correlate but steep grad-T_e exists in positive E_r shear layer.**

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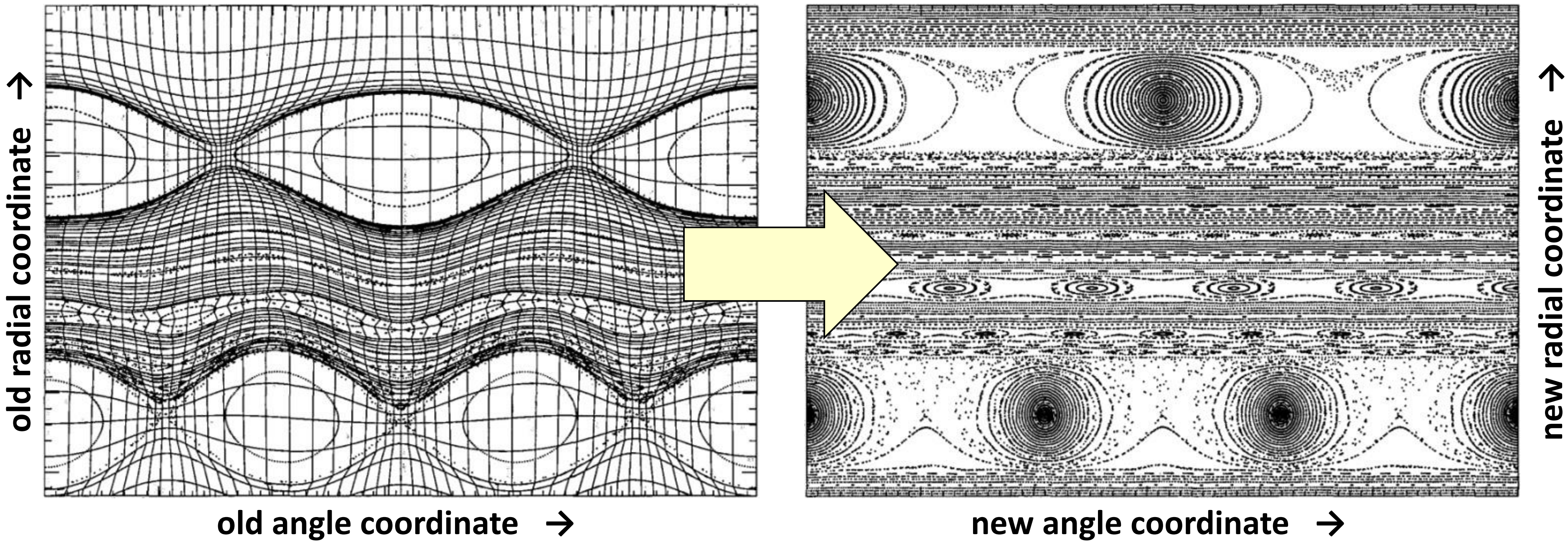
Chaotic coordinate in stochastic field

Poincaré plot of chaotic field
(in **action-angle** coordinates of **unperturbed** field)

Poincaré plot of chaotic field
in chaotic coordinates



phase-space is partitioned into (1) regular ("irrational") regions with "good flux surfaces", temperature gradients
and (2) irregular (" rational") regions with islands and chaos, flat profiles

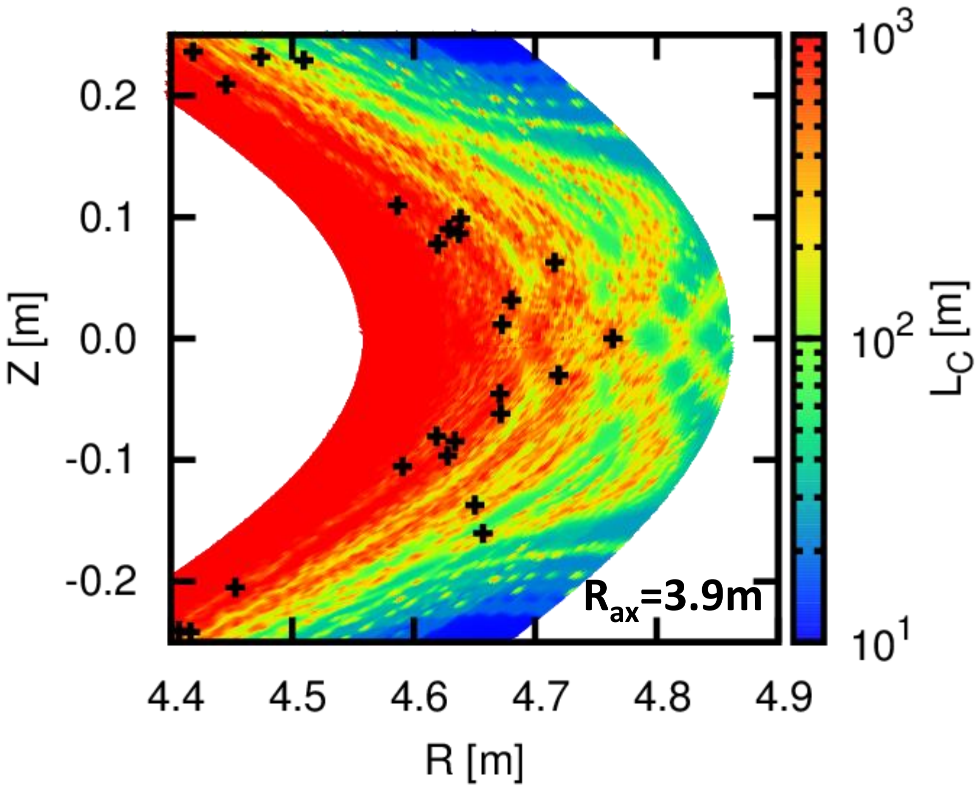
S. Hudson and Y. Suzuki, Phys. Plasmas 21, 102505 (2014)

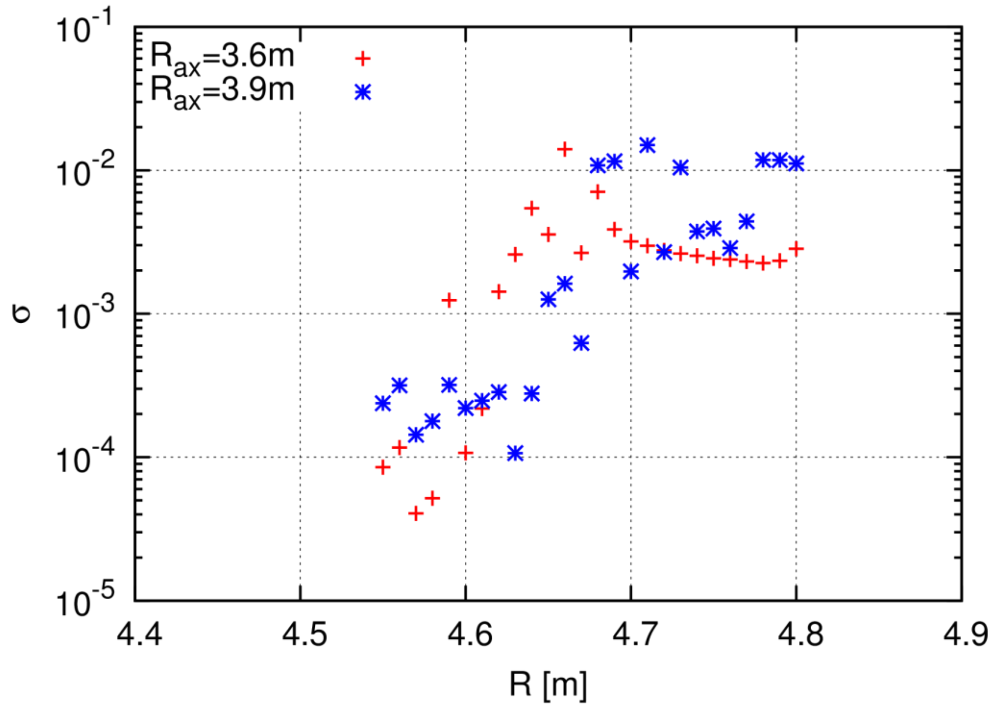
The Chaotic coordinate can allow the statistical analysis of the stochastic field line.

‘Variance’ of magnetic field lines

Ex: A field line started from R=4.764m.
It intersects the region in long and short L_C.

$$\sigma = \frac{1}{m}\sum_{i=1}^{m}\left(X_i - \langle X_i \rangle\right)^2$$



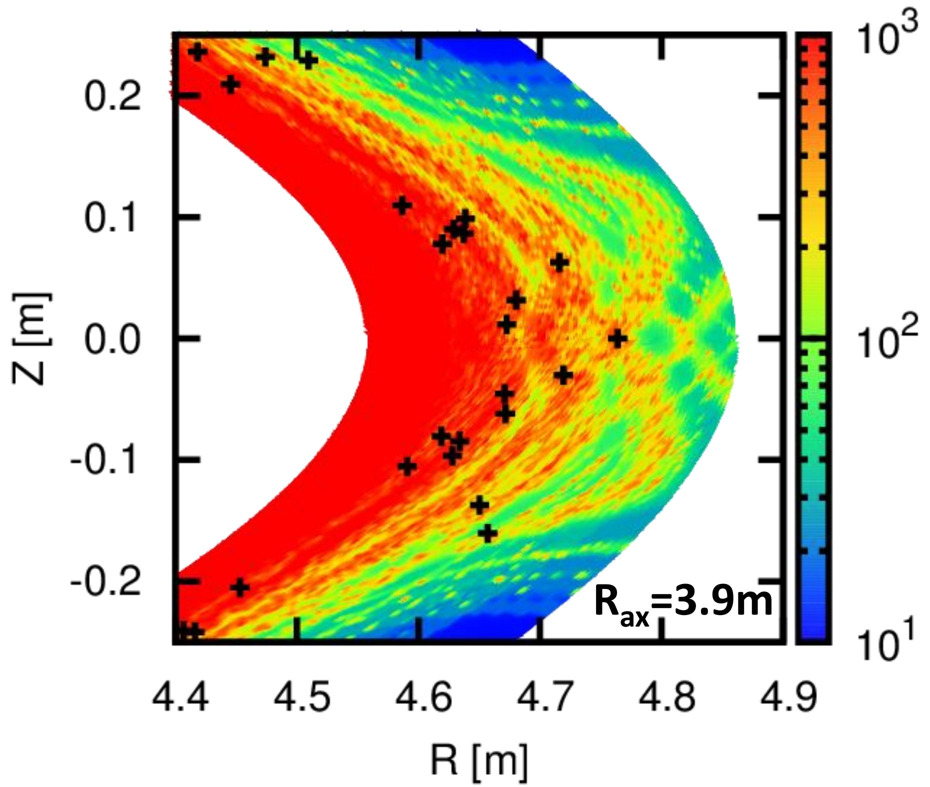


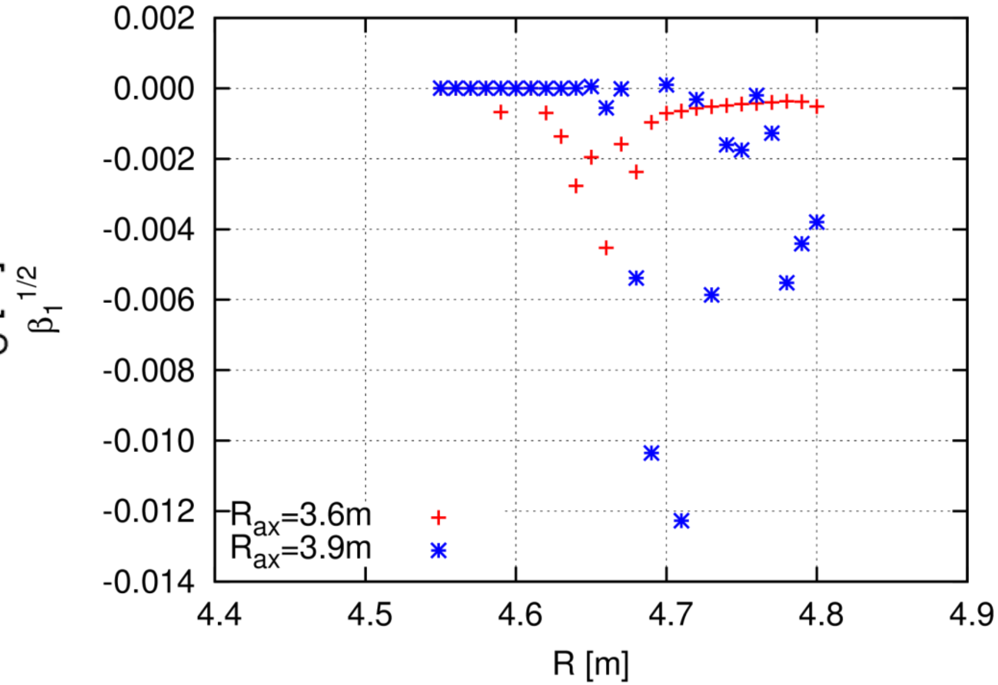
- **The variance increases in the stochastic layer.**
- **No significant differences for R_{ax}=3.6m and 3.9m**

'Skewness' of magnetic field lines

Ex: A field line started from R=4.764m.
It intersects the region in long and short L_C.

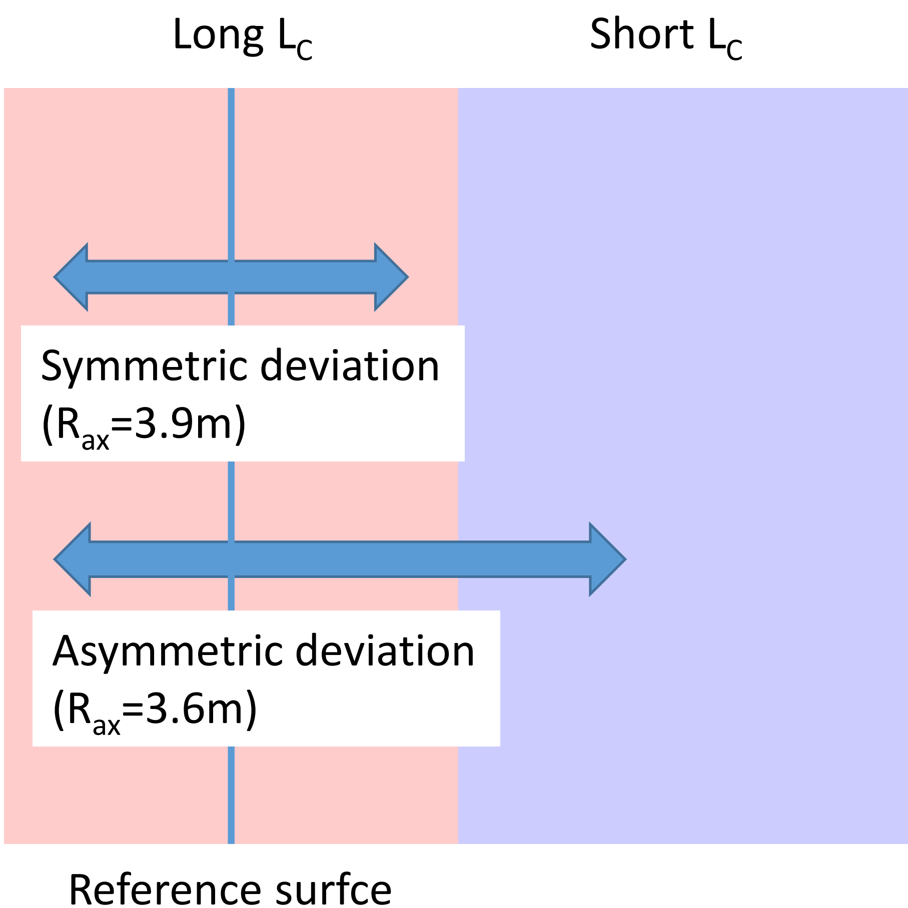
$$\beta_1^{1/2} = \frac{1}{m}\sum_{i=1}^{m}\left(X_i - \langle X_i \rangle\right)^3$$



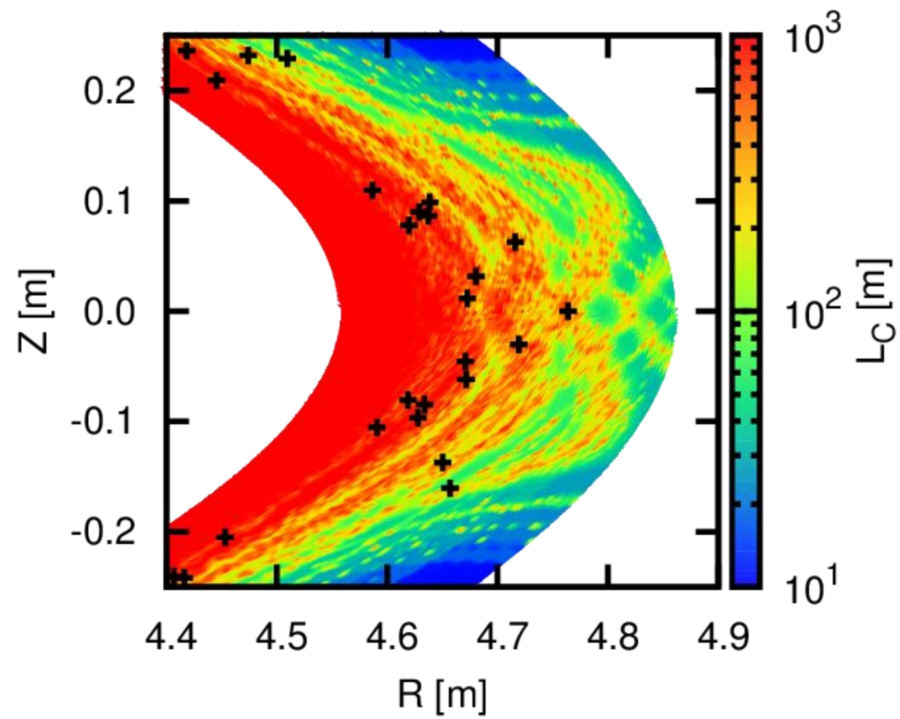


- **Strong asymmetry of the field line distribution appears.**
- **The 'effective' connection length for R_{ax}=3.6m might be short?**

Possible scenario of perpendicular transport



Ex: A field line started from R=4.764m.
It intersects the region in long and short L_C.



- **Stochastic field lines of asymmetric distribution invade the short L_C region.**
- **In the case, the effective L_C might be short.**

Anisotropic heat diffusion

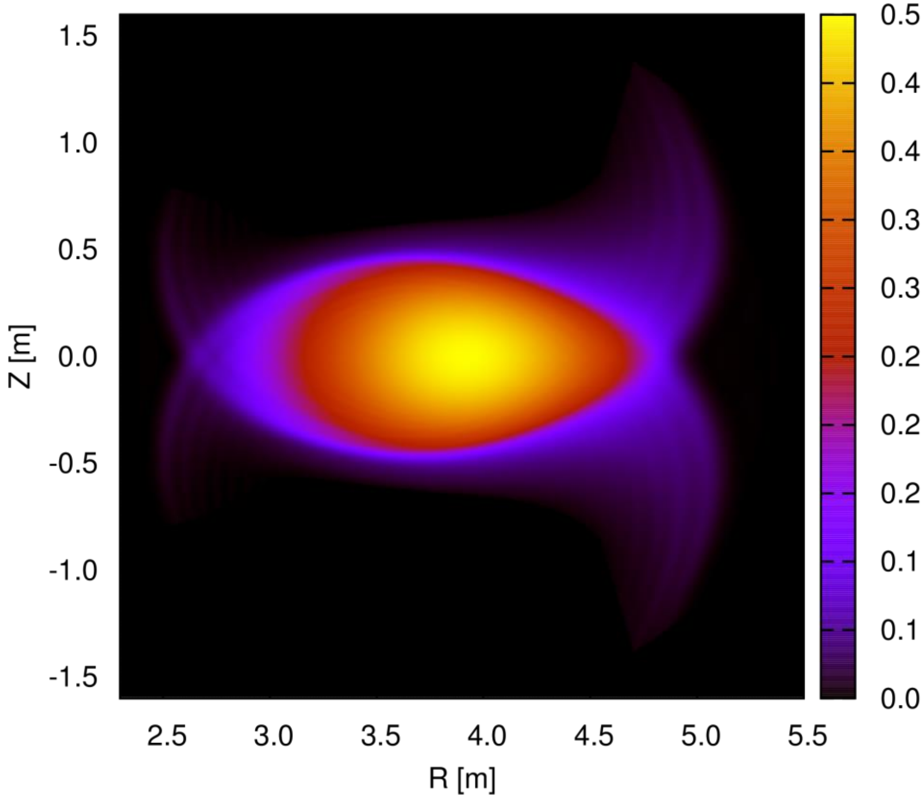
Preliminary!!

Anisotropic heat diffusion is studied in the LHD geometry.

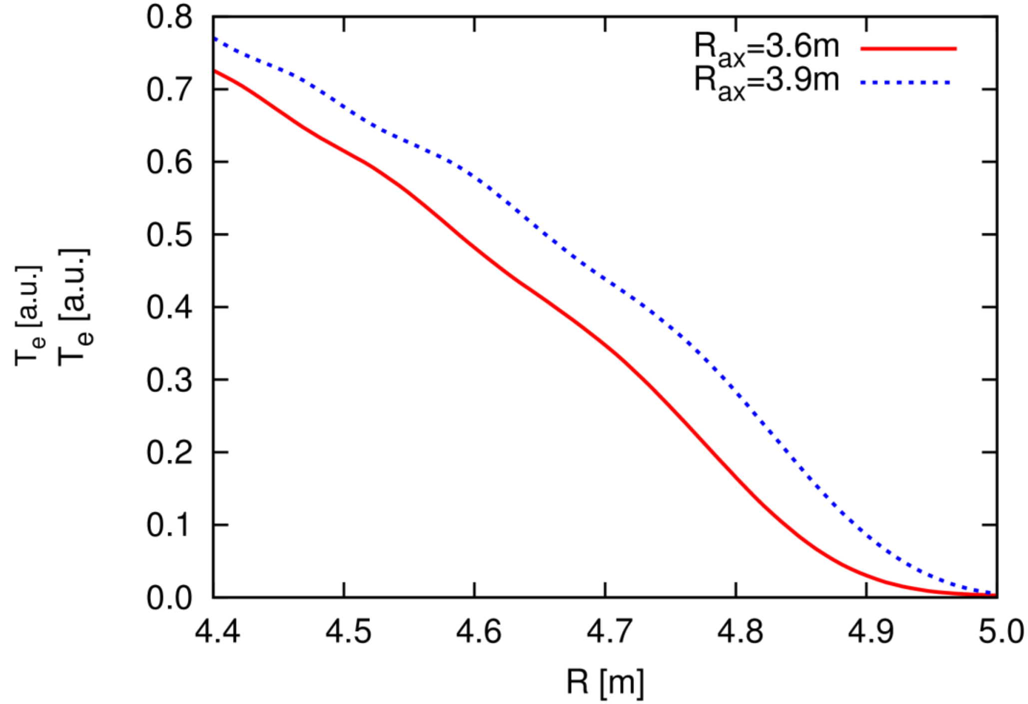
$$\frac{\partial T}{\partial t} = \nabla \cdot \left(\kappa_{\|} \nabla_{\|} T + \kappa_{\perp} \nabla_{\perp} T \right) + S$$

S. Guenter, et al., J. Comput. Phys. 209, 354 (2005).
S. R. Hudson et al., Phys. Rev. Lett. 100, 095001 (2008).

R_{ax}=3.9m



$$\kappa_{\|} / \kappa_{\perp} = 10^8$$



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Summary

- The radial electric field, E_r, is experimentally studied in the LHD configuration.
- E_r profiles are studied for two magnetic configurations with different widths of the stochastic layer. Strong E_r shear from negative to positive appears at the edge of the stochastic layer. This suggests the stochastic region can be considered as a plasma confined region.
- Comparing E_r profiles in different magnetic configuration, correlations of E_r and T_e profiles are found. However, according to the width of the stochastic layer, differences are found.
- Experimental observations are compared with the field line modeling. The ‘skewness’ of stochastic field lines is studied. If the skewness becomes negative, the connection length of electrons in the stochastic layer becomes effectively short.

Outlook

- **The identification of the stochastic layer will be done in next experimental campaign.**
- **The transport modeling should be improved. As a first step, the heat transport in the stochastic field will be studied.**