16th IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems – Theory of Plasma Instabilities

Electrostatic potentials generated by NBI fast ions in tokamak and helical plasmas

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PLASMA SIMULATOR

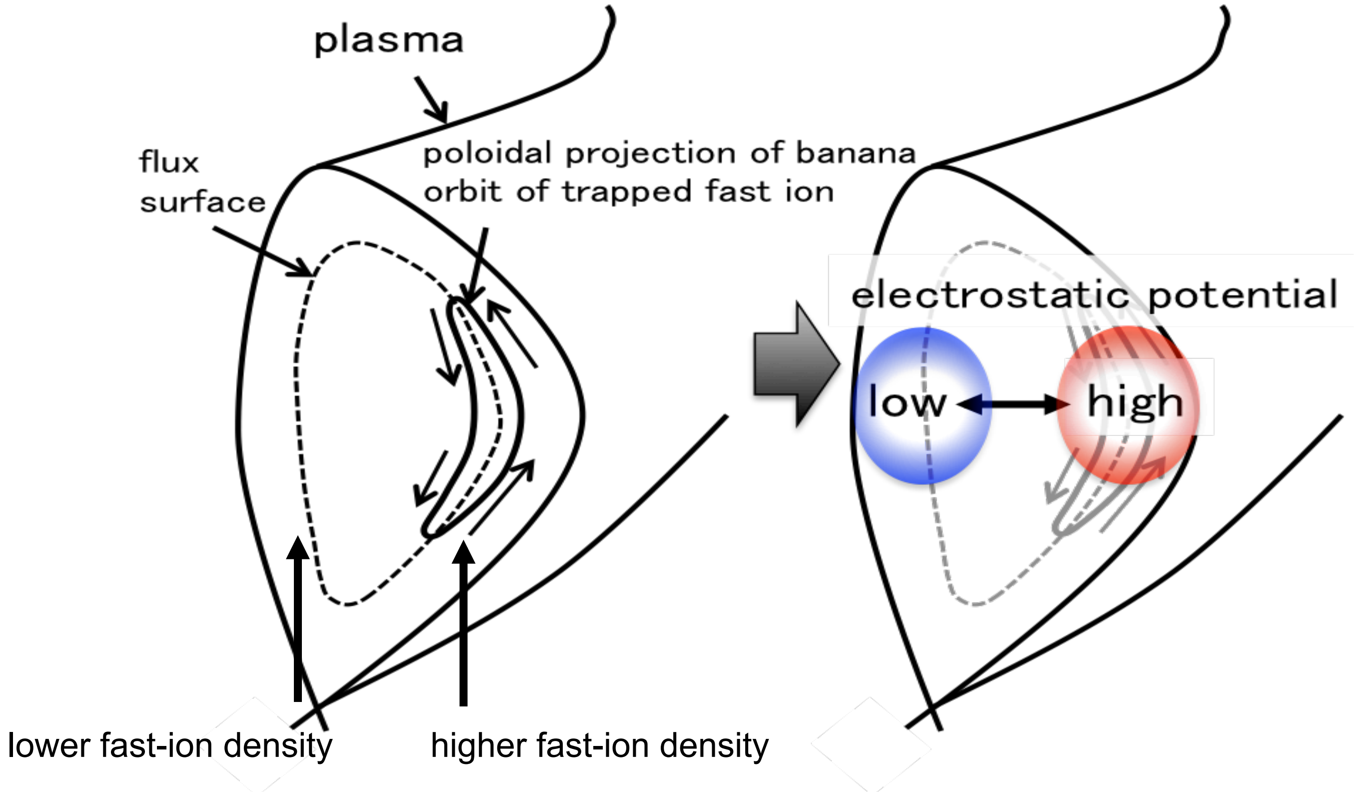
Background

- Understanding of impurity-ion transport in the core plasma of fusion reactor is an important issue.
- Numerical study has shown that **electrostatic potential varying on flux surface** (~0.01T_i) has significant effect on neoclassical flux of high-*Z* impurity ions in stellarators[1].
- The ratio between magnetic mirror force to parallel electrostatic force depends on the charge number *Z*：

Parallel electrostatic force	$-Ze\nabla_{\parallel}\Phi$	$\propto Z$
Mirror force	$-\mu\nabla_{\parallel}B$	$\propto$ kinetic energy

➔High-Z impurity ions are more sensitive to $\nabla_{\parallel}\Phi$.

How fast ions generate Φ varying on flux surface



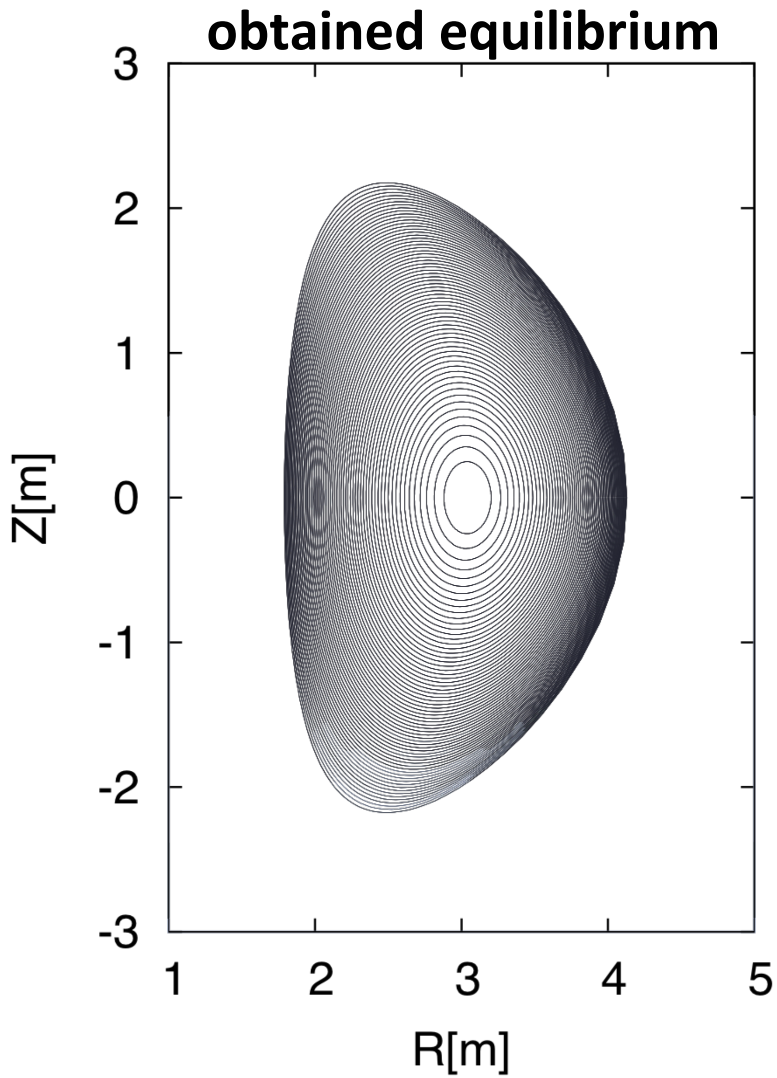
- Poloidal electrostatic field by perpendicular neutral beam injection (NBI) [2]
- **Fast-ion density is generally not uniform on flux surface**.
- Charge-neutrality condition ➔ parallel gradients in $n_{e,i}$
- Parallel pressure gradients are balanced by $E_{||}=-q\nabla_{||}\Phi$

Objectives

- Previously, we performed numerical estimation of Φ generated by fast ions of perpendicular neutral beam injection (NBI): Φ_{NBI} in tokamak and helical plasmas[3,4].
- In order to estimate Φ_{NBI} in the condition closer to plasma experiments in real devices, we study two additional cases:
  - **JT60-SA[5]-like tokamak**
  - **Tangential NBI in the Large Helical Device[6] configuration**
- Neoclassical diffusion coefficient of tungsten ion, W^{45+}, in the core plasma of JT60-SA-like tokamak is studied using Monte Carlo method taking into account Φ_{NBI}.

JT60-SA-like tokamak configuration

- MHD equilibrium is calculated using VMEC[7] in fixed-boundary mode (up-down symmetry is assumed).



Boundary-shape parameters

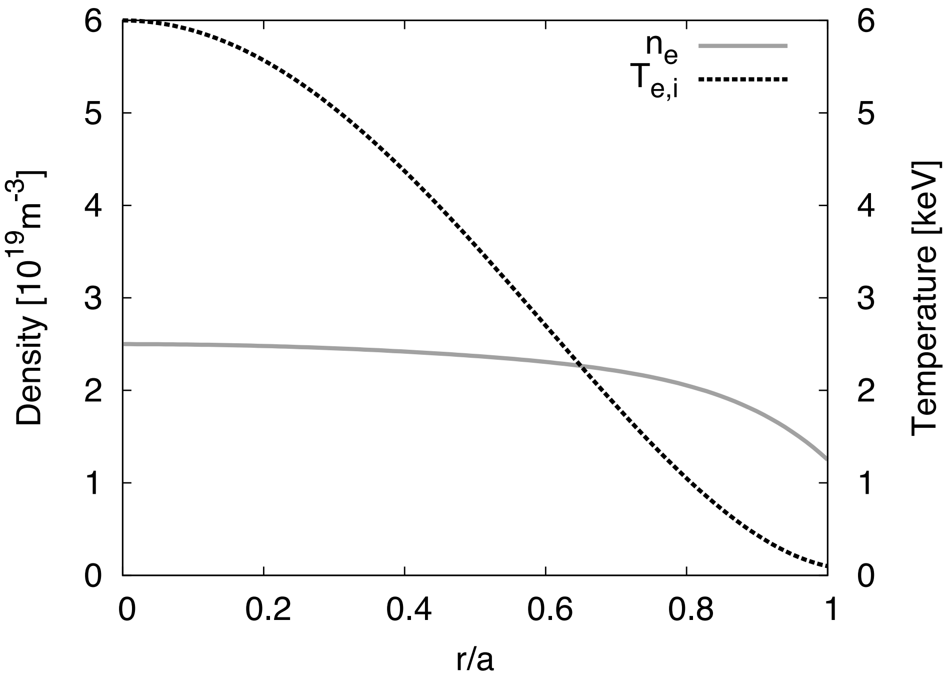
Major rad.	2.96 m
Minor rad.	1.17 m
Ellipticity	1.86
Triangularity	0.4

Parameters of assumed equilibrium

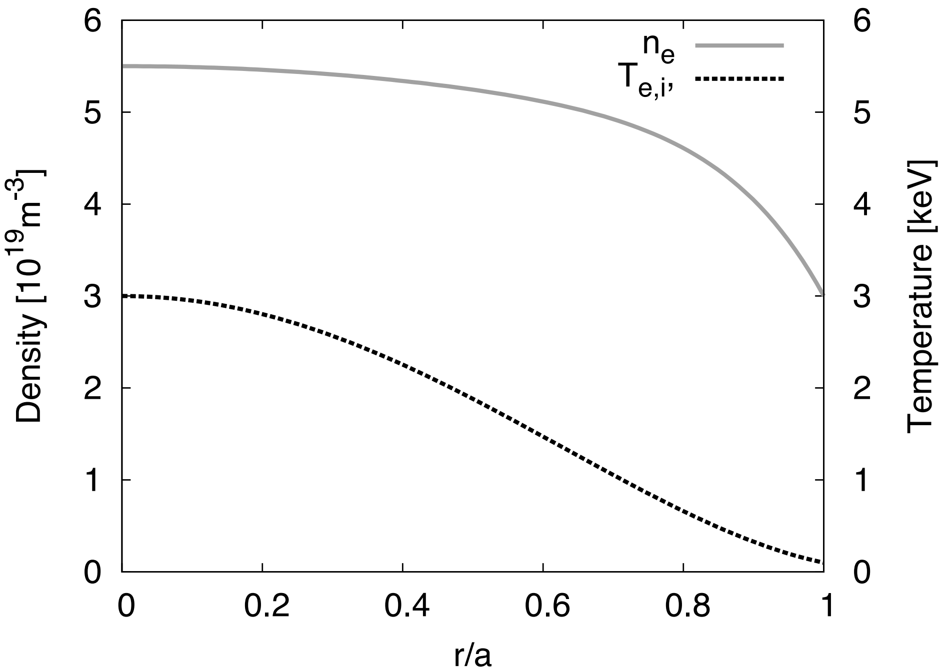
B at axis	2.4T
Toroidal current	~ 5 MA
Volume-averaged beta (total)	3%
safety factor	1.02-3.63

Assumed plasma profiles for JT60-SA-like case

Low density case	
n_e	$2.5\text{x}10^{19}$ m^{-3}
$T_e(=T_i)$	6keV



High density case	
n_e	$5.5\text{x}10^{19}$ m^{-3}
$T_e(=T_i)$	3keV

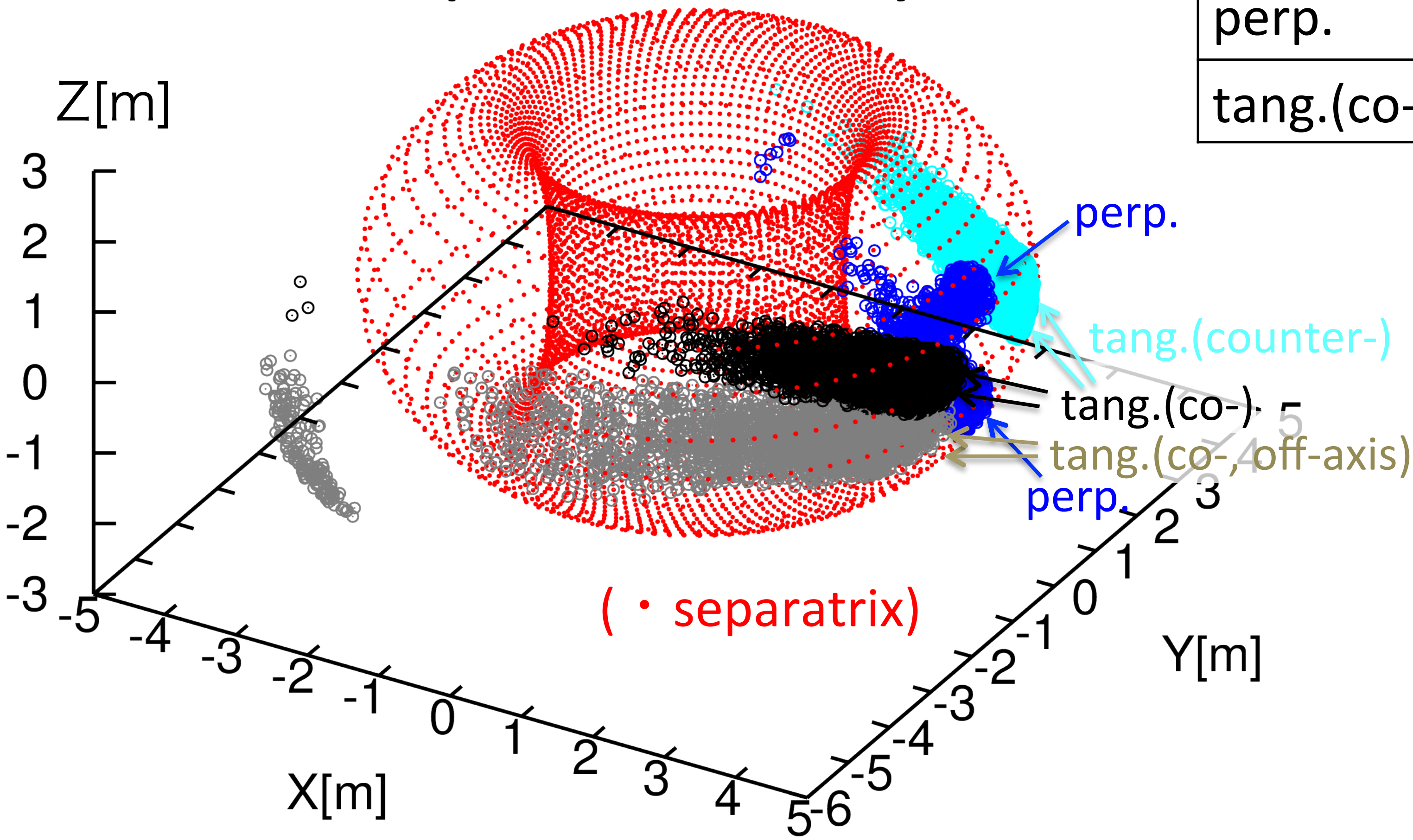


Note: MHD equilibrium is fixed to the one in the previous slide for both profiles.

Assumed NBI systems for JT60-SA case

- NBI systems of JT60-SA shown in [4] are mocked using the NBI module, FIT3D[8].

beam ion birth points calculated by FIT3D



Summary of assumed NBI systems

beam	E_{beam}	P_{NB}
tang.(co-,ctr-)	85keV	4MW
perp.		16MW
tang.(co-,off axis)	500keV	10MW

GNET code[9]

- Solves the drift-kinetic equation for fast ions using Monte Carlo method in five-dimensional phase space:

$$\frac{\partial f_{\mathrm{f}}}{\partial t} + (\boldsymbol{v}_{||} + \boldsymbol{v}_{\mathrm{D}}) \cdot \nabla f_{\mathrm{f}} + \dot{\boldsymbol{v}} \cdot \nabla_{v} f_{\mathrm{f}} = C(f_{\mathrm{f}}) + L^{\mathrm{particle}}(f_{\mathrm{f}}) + S_{\mathrm{beam}}$$

$f_{\mathrm{f}} = f_{\mathrm{f}}(r,\vartheta,\zeta,v_{||},v_{\perp})$: 5-D fast ion distribution function

$\boldsymbol{v}_{||}$: parallel velocity, $\boldsymbol{v}_{\mathrm{D}}$: drift velocity,

C : linear Coulomb collision operator (pitch-angle and eng.)

L^{particle} : particle loss term (charge exchange and orbit losses)

S_{beam} : particle source term by NBI (from FIT3D)

Calculation model for Φ_{NBI}

Fast-ion density

$$n_\mathrm{f} = \langle n_\mathrm{f} \rangle(\psi) + \tilde{n}_\mathrm{f}(\psi, \theta, \zeta)$$

Charge-neutrality conditions

$$n_e - n_i - Z n_Z - n_\mathrm{f} = 0$$

$$\langle n_e \rangle - \langle n_i \rangle - Z\langle n_Z \rangle - \langle n_\mathrm{f} \rangle = 0$$

Boltzmann relations on flux surface

$$n_\mathrm{e} = \langle n_\mathrm{e} \rangle \exp\left(\frac{\Phi_{NBI}}{T_e}\right)$$

$$n_\mathrm{i} = \langle n_\mathrm{i} \rangle \exp\left(-\frac{\Phi_{NBI}}{T_i}\right)$$

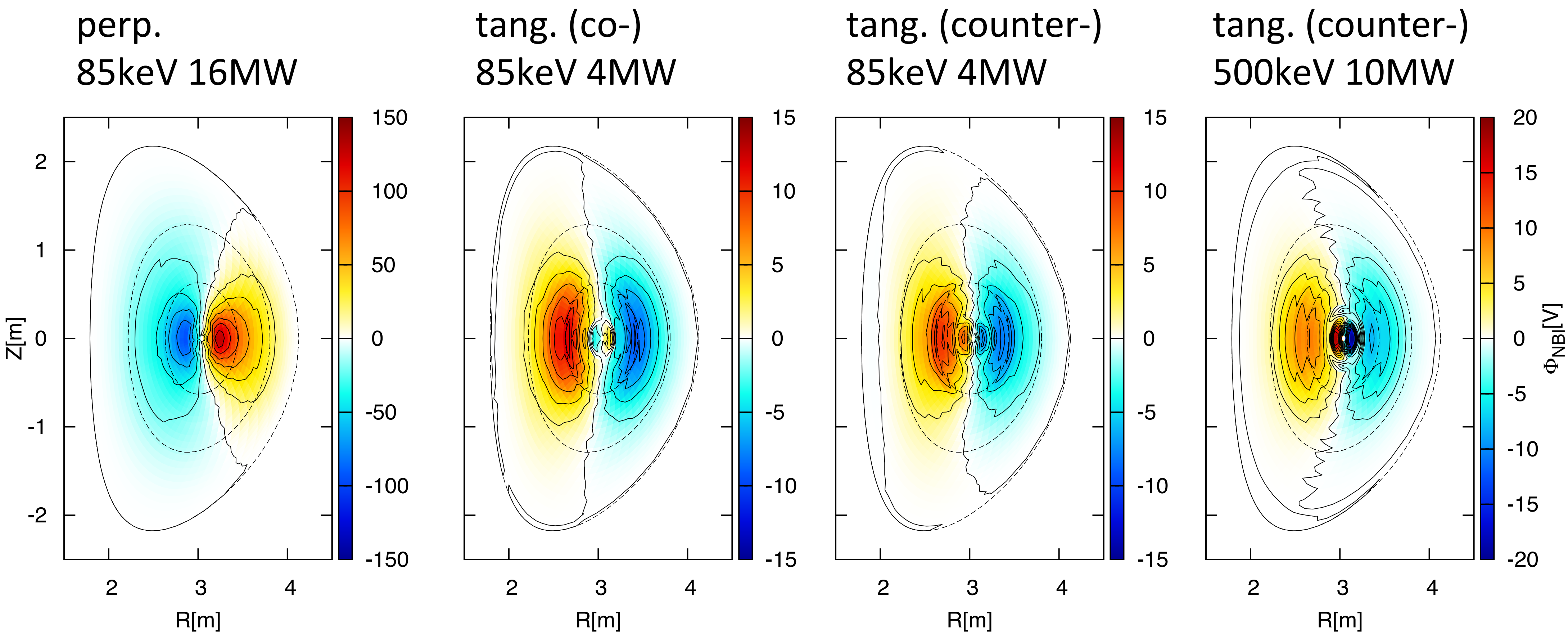
$$n_Z = \langle n_Z \rangle \exp\left(-Z\frac{\Phi_{NBI}}{T_i}\right)$$

$$\Phi_{\mathrm{NBI}} = \tilde{n}_\mathrm{f}\left(\frac{\langle n_\mathrm{e} \rangle}{T_\mathrm{e}} + \frac{\langle n_\mathrm{i} \rangle}{T_\mathrm{i}} + Z^2\frac{\langle n_Z \rangle}{T_Z}\right)^{-1}$$

$\langle\ \rangle$: flux-surface average

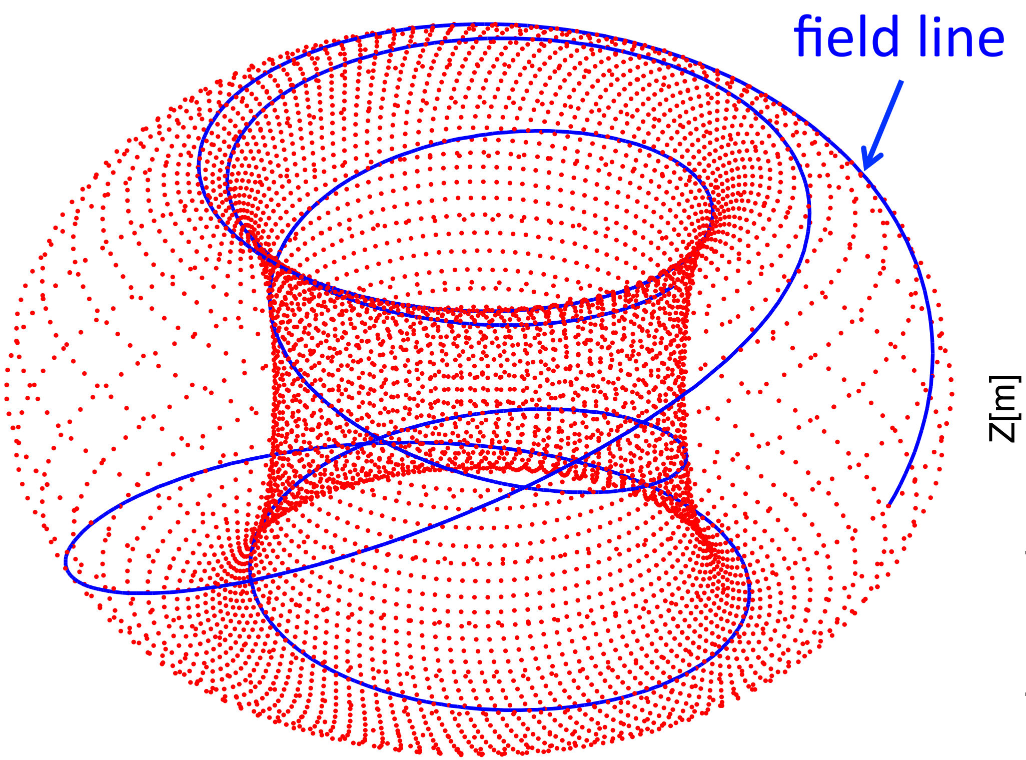
- This model for Φ_{NBI} does **not** describe the radial electrostatic field determined by cross-field radial momentum balance.

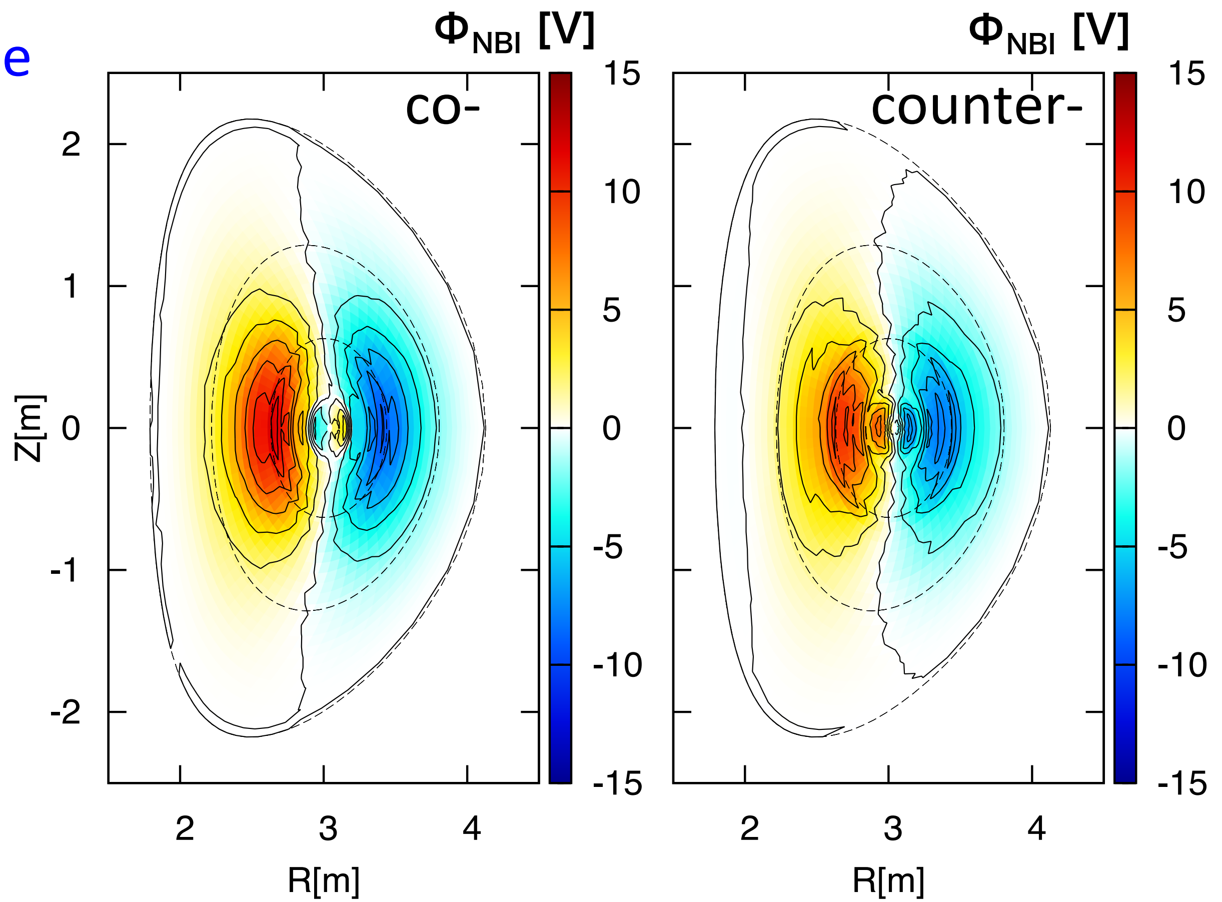
Simulation results for low-density case



- Trapped ions of perp. NBI generate $\Phi_{NBI}(\theta\sim 0) > \Phi_{NBI}(\theta\sim\pi)$, much higher than Φ_{NBI} of tangential NBIs.
- Tangential NBs generate Φ_{NBI} higher at $\theta\sim 0$ in most of plasma volume regardless of direction of injection.

Φ_{NBI} by Tangential injections





- In the assumed configuration, the pitch of field line is lower in the inner side of the torus: ➔passing ions spend longer time ➔ higher fast ion density

Monte Carlo evaluation of diffusion coefficient

- *N* test particles are randomly distributed on the target surface and followed to evaluate two statistical quantities:

$$\langle r \rangle = \frac{1}{N}\sum_{n=1}^{N} r_n \qquad C^{2\mathrm{nd}} = \frac{1}{N}\sum_{n=1}^{N}(r_n - \langle r \rangle)^2$$

r_n: radial position of *n*-th test particle

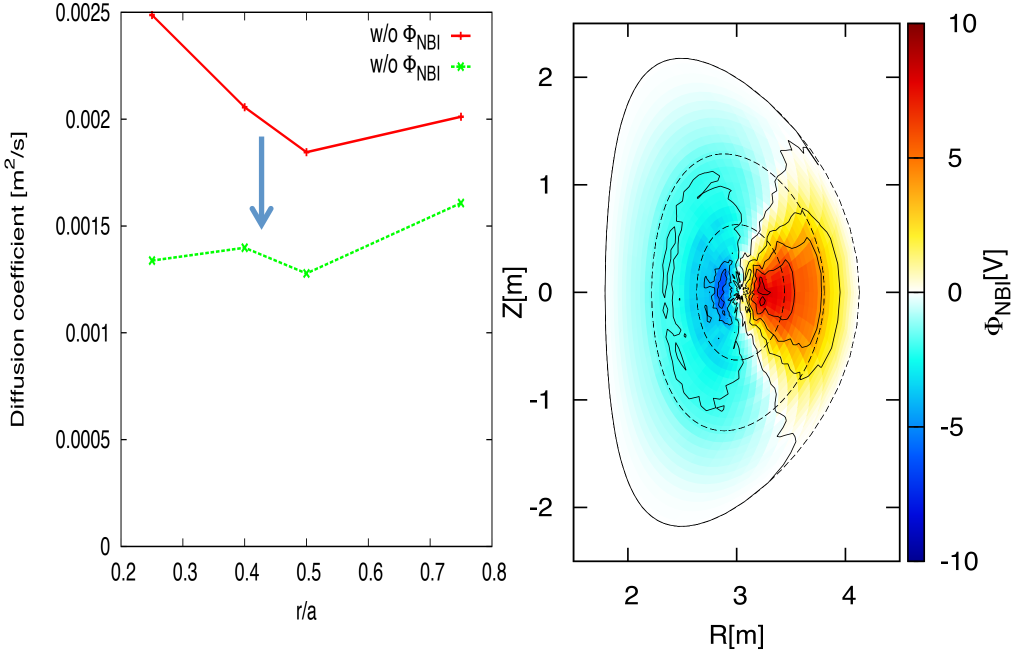
- Diffusion coefficient and radial velocity are calculated as

$$D = \frac{1}{2}\frac{dC^{2\mathrm{nd}}}{dt} \qquad V = \frac{d\langle r \rangle}{dt}$$

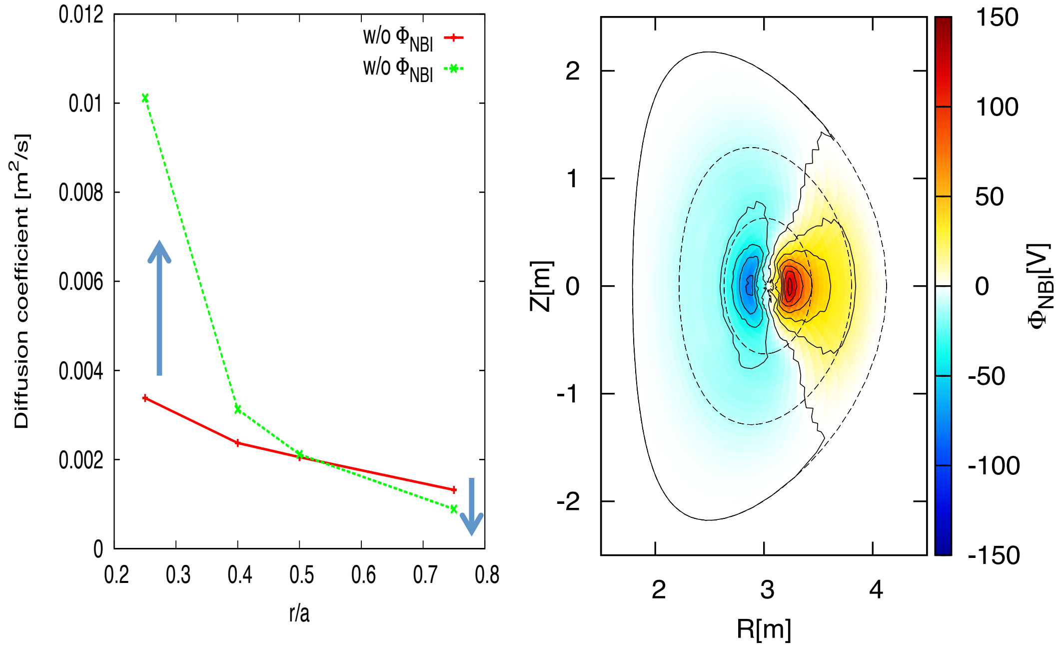
- We assume **tungsten impurity ion with *A*=184, *Z*=45 (W^{45+})** as the test particles.

Diffusion coefficient of W^{45+} (E_r=0)

High-density case



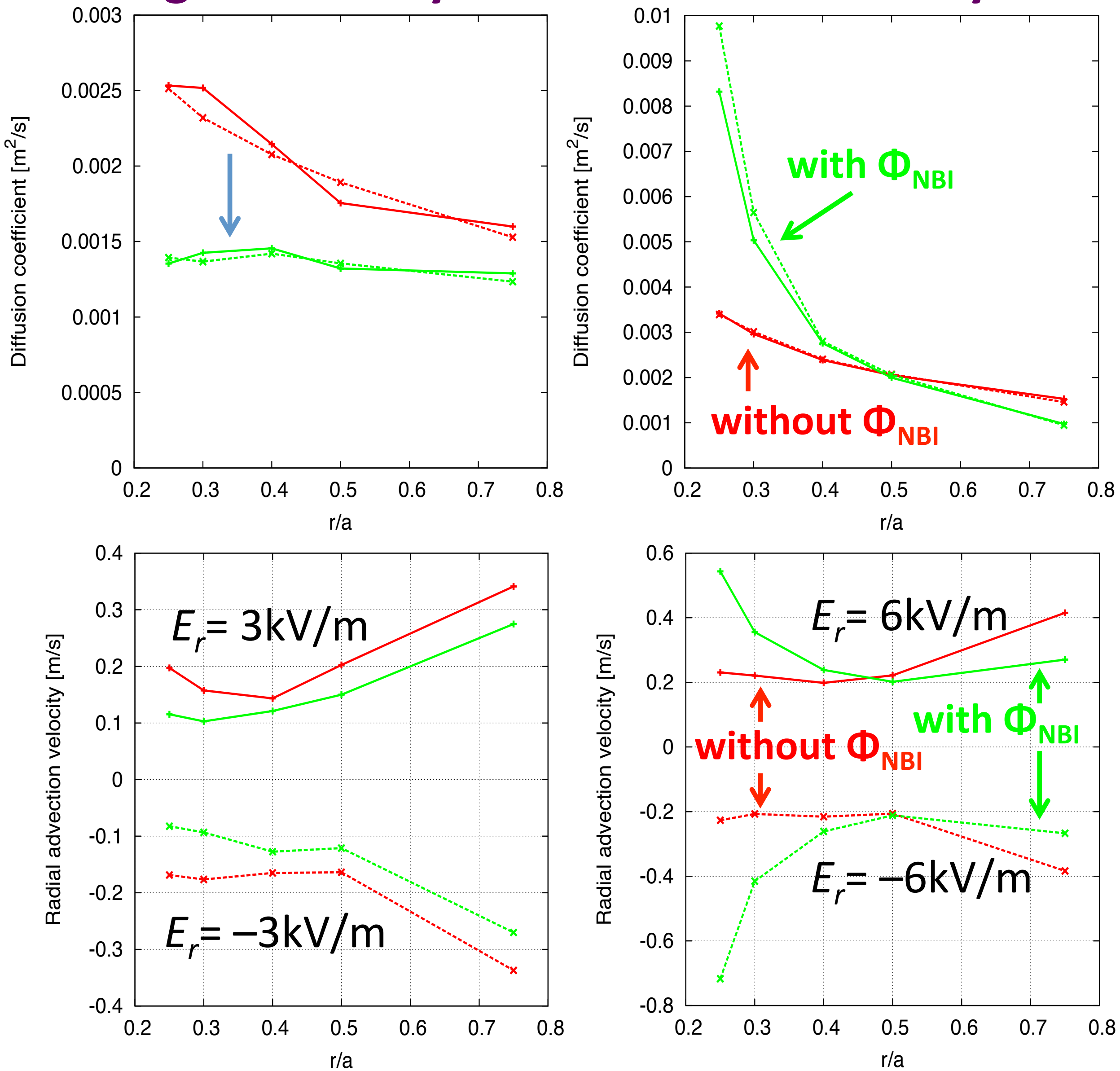
Low-density case



- In low density case, Φ_{NBI} is an order higher than high density case.
- Diffusion coefficient is reduced by Φ_{NBI} except in the region r/a<0.5 of low density case (Φ_{NBI} > ~25V).
- *Moderate poloidal electric field decreases trapped particle fraction ε_t, while strong one causes* ***electrostatic trapping*** [10] *of W^{45+}, which starts to compete with decrease in ε_t.*

Calculation with E_r to check radial velocity V

Higher-density case **Lower-density case**



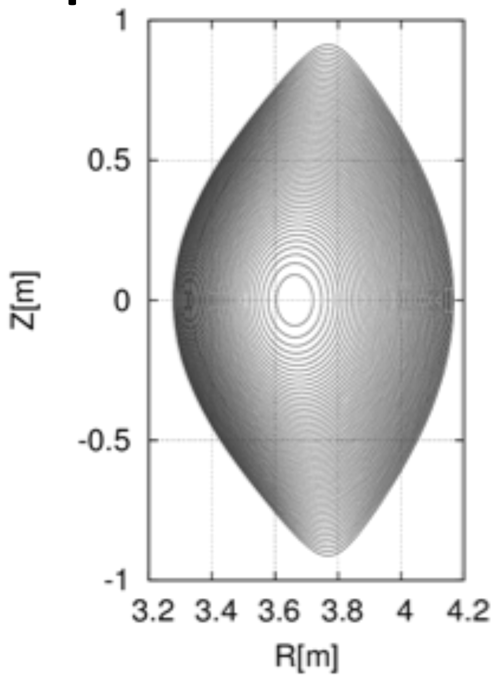
Dashed lines: E_r<0

- In this study, *as a rough estimation,* we assumed a radially-constant electric field, **$E_r \sim T_i/a \sim \pm$6kV/m and ±3kV/m**, which is superimposed onto $\nabla\Phi_{NBI}$ in Monte Carlo calculation.
- E_r does not affect D (w/ exception of r/a=0.75 of high density case) because of axi-symmetry, but it does on V.
- D and V are reduced/enhanced simultaneously.
- **Enhancement of the inward transport or accumulation of W^{45+} may be possible in the region of r/a<0.5 for low density case.**

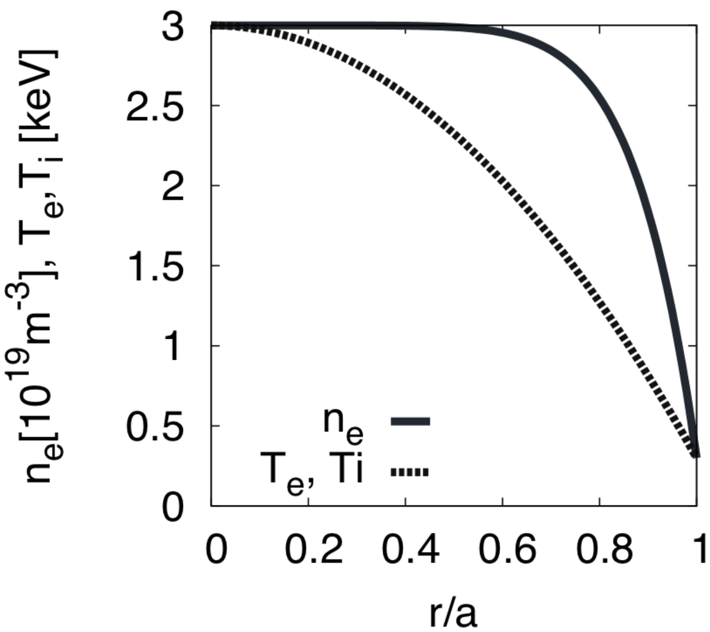
Helical plasma: Large Helical Device

- LHD is a heliotron-type stellarator device[6] with R_0=3.9m.
- Configuration: R_{ax}=3.60 m, a ~ 60cm
- Field strength at axis : 2.75T
- Energy of **tangential NBI : 180keV (5MW)**
  perp. NBI : 40keV (5MW) (done previously)

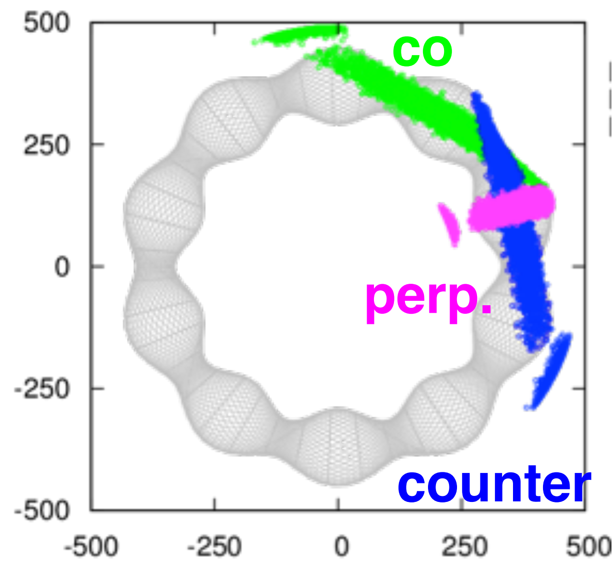
plasma cross section



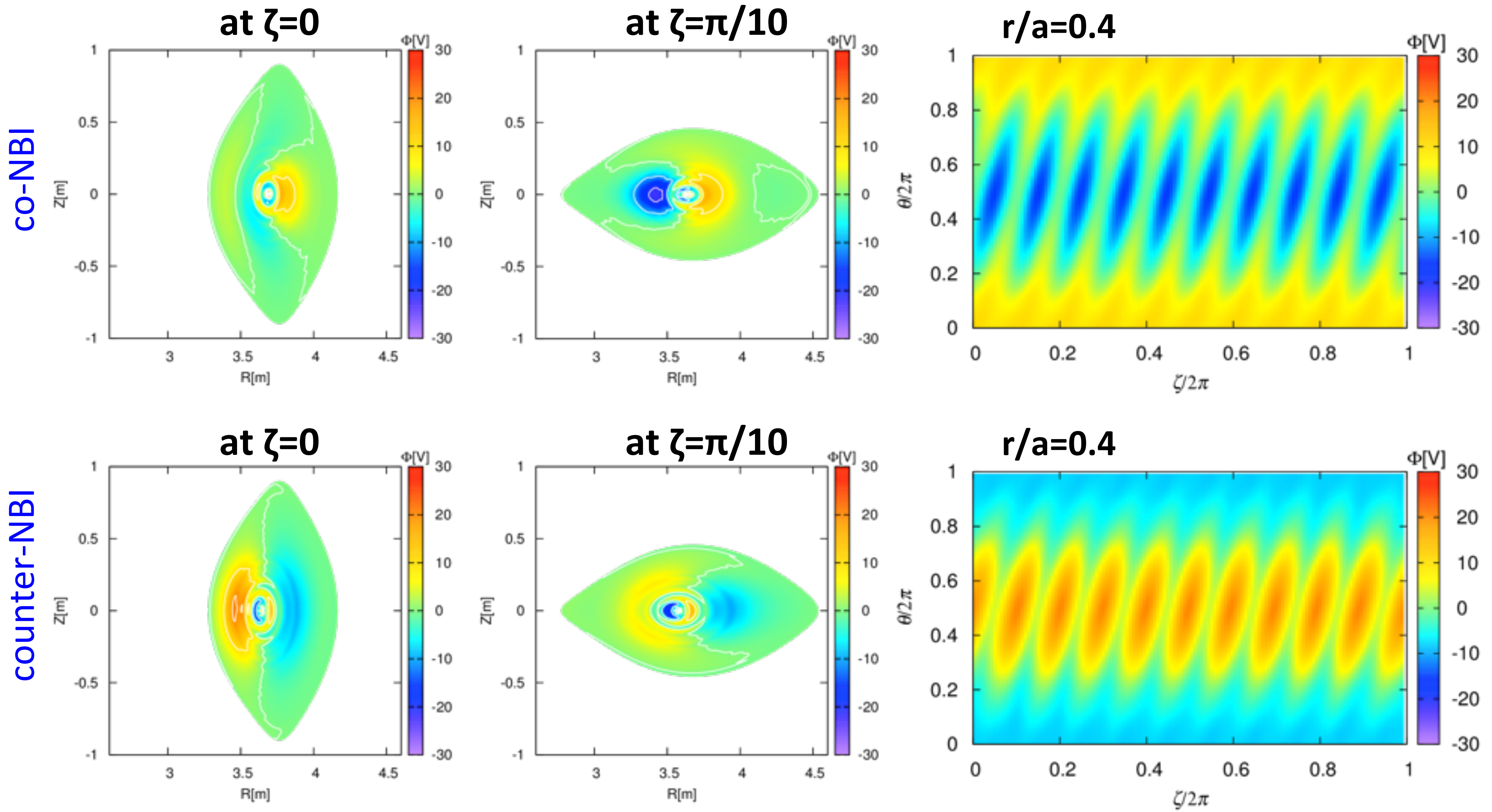
density and temperature



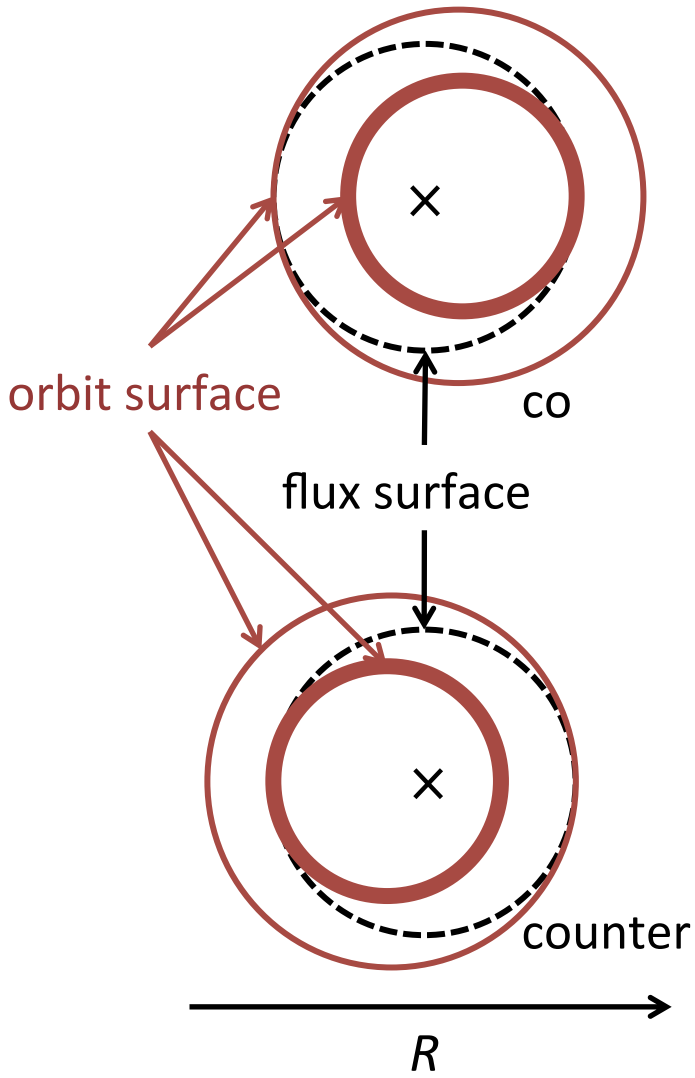
fast-ion birth points



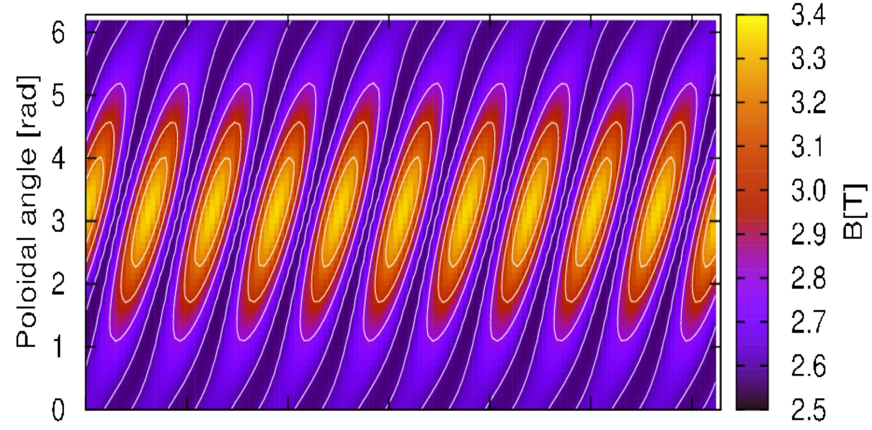
Simulation results for tangential NBI (5MW) in LHD



Horizontal shift of orbit surface of passing particles



mod-B contour on the flux surface



- Φ_{NBI} by tangential NBI is found to be dominated by a toroidicity mode (cosθ) with additional modes corresponding to the mod-B structure.
- A clear dependence on injection direction (cf. JT60-SA-like case) due to horizontal shift of orbit surface and smaller poloidal variation of pitch of field line.

Summary

- Electrostatic potentials Φ_{NBI} generated by NBI fast ions in JT60-SA-like tokamak LHD are evaluated using 5-D simulations of fast ions with the GNET code.
- In JT60-SA case, 16MW perpendicular NBI dominated $\Phi_{NBI,}$ and Φ_{NBI} by tangential NBI did not show dependence on injection direction in most of plasma volume.
- Monte Carlo calculation showed that Φ_{NBI} has significant effect on diffusion coefficient and radial velocity of W^{45+}: enhancement in the plasma core for the lower-density case.
- In LHD, the tangential NBI generated Φ_{NBI} dominated by toroidicity mode, depending on beam direction. This can be explained by the horizontal shift of drift surface.

Future works

- Comparison of Φ_{NBI} with electrostatic potential generated by other mechanism (ex. NB driven plasma rotation[2])
- Experimental validation of Φ_{NBI} using heavy-ion beam probe measurement of LHD[11].
- Calculation of W^{45+} transport in rotating plasmas
- Evaluation of Φ_{NBI} with kinetic model in tokamak and helical systems

References

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