Simulation study of electrostatic potentials produced by fast-ion population in toroidal plasmas

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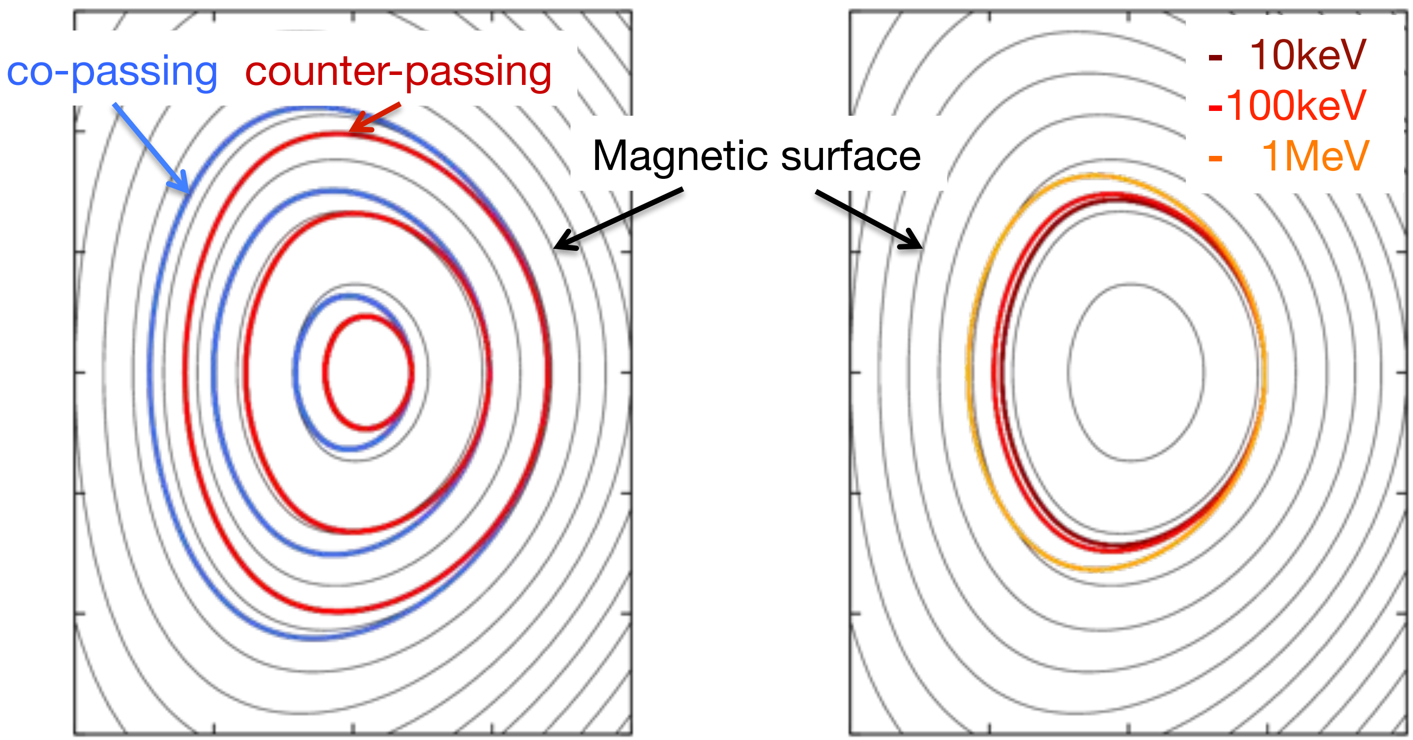
Introduction

Fast ions in fusion plasmas

- Alpha particles produced by D-T fusion reaction (E=3.5MeV)
- Fast ions produced by NBI and ICRF heating (E~100keV-1MeV)
- Primary heat source of plasma
- Potent heat load to the divertor => should be well-confined



Typical guiding-center orbit of co-passing and counter-passing fast ions in a tokamak plasma.

Energy dependence of guiding-center orbit of co-passing ions

Orbit of fast ions in toroidal plasmas

- Deviation from the magnetic surface is relatively large.
- Hardly trapped in the potential wells of the level of thermal energy
  - fast ions tend to be **non-uniformly** distributed over a magnetic surface.
  - may produce electrostatic (ES) potential varying on magnetic surface
  - Such fast-ion-induced ES potentials and their effect on plasma performance has not been investigated.

Objectives of this study

- We evaluate ES potentials produced by fast-ion non-uniformity in toroidal plasmas, on the basis of numerical simulations.
- We also consider **the presence of magnetic islands**, which may lead to **further localization of passing fast ions.**
- We investigate the effect of the ES potentials on fast ion confinement.

Fast ion model

GNET (Global NEoclassical Transport) code

$$\frac{\partial f_\mathrm{f}}{\partial t} + (\boldsymbol{v}_\parallel + \boldsymbol{v}_D) \cdot \nabla f_\mathrm{f} + \dot{\boldsymbol{v}} \cdot \nabla_v f_\mathrm{f} = C(f_\mathrm{f}) + L_\mathrm{particle}(f_\mathrm{f}) + S_\mathrm{beam}$$

f_f : fast-ion distribution function, $\boldsymbol{v}_\parallel$: parallel velocity , $\boldsymbol{v}_D$: drift velocity,
C : Linear Coulomb collision operator, L_particle : particle loss term,
S_beam : fast-ion source term (by HFREYA)

- We solve above equation for f_f in 5D phase space, using the GNET code [Murakami 2006, Nucl. Fusion] based on Monte Carlo technique.
- Guiding-center orbit is followed in Boozer coordinates with 6th-order Runge-Kutta-Hutta method.
- Pitch-angle and energy scatterings during energy slowing down
- Magnetic field and plasma geometry from VMEC
- **Extended to treat ES potentials with arbitrary Fourier modes.**

Electrostatic potential model

Adiabatic response of electrons

- ES force is assumed to be balanced by pressure gradient force in parallel direction (Boltzmann relation in parallel direction).

$$n_{\mathrm{e}} = n_{\mathrm{e0}} \exp\left(\frac{e\delta\Phi}{\kappa T_{\mathrm{e}}}\right) \approx n_{\mathrm{e0}} + \delta n_{\mathrm{e}} \Rightarrow \delta\Phi = \frac{\kappa T_{\mathrm{e}}}{e}\frac{\delta n_{\mathrm{e}}}{n_{\mathrm{e0}}}$$

- Equilibrium- and perturbed parts of electron density:

$$n_{\mathrm{e0}} = n_{\mathrm{i0}} + \langle n_{\mathrm{f}} \rangle$$
$$\delta n_{\mathrm{e}} = n_{\mathrm{f}} - \langle n_{\mathrm{f}} \rangle,$$

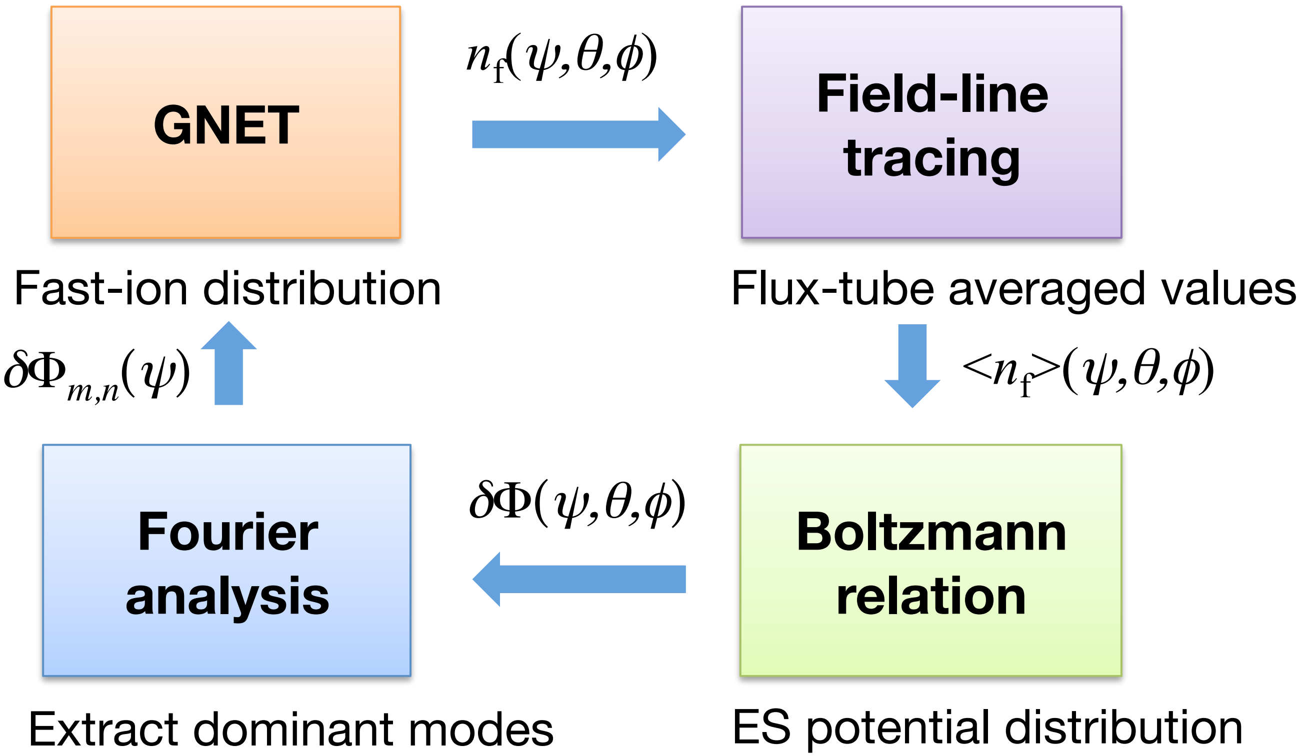
- T_{e} and n_{i0} are assumed to be constant along each field lines.
- $\langle n_{\mathrm{f}} \rangle$: the flux-tube averaged fast-ion density (by field-line tracing)

$$\langle n_{\mathrm{f}} \rangle \equiv \int n_{\mathrm{f}} \frac{\mathrm{d}l}{B} \Big/ \int \frac{\mathrm{d}l}{B}$$

Iterative simulation

Data flow in the iteration

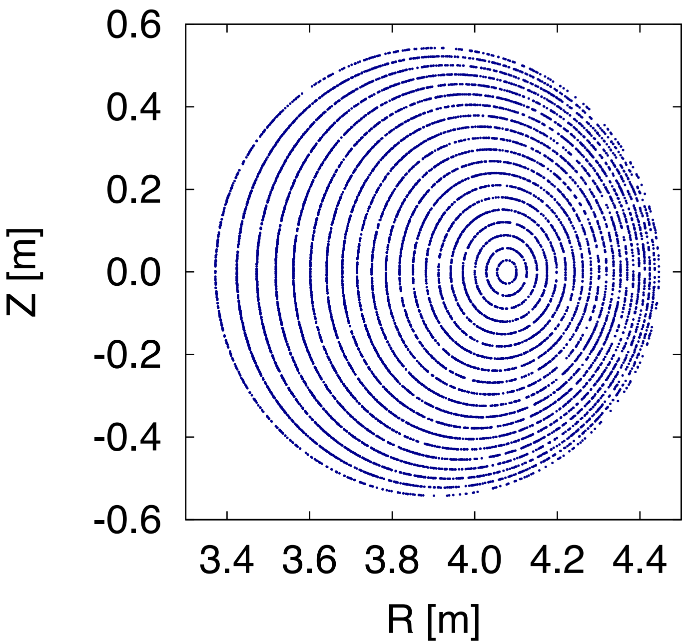
- We have extended GNET to **ES potentials with arbitrary Fourier mode**.
- Self-consistent fast-ion distributions and ES potentials can be obtained by the following iteration (background ion is assumed rest).



Simulation conditions

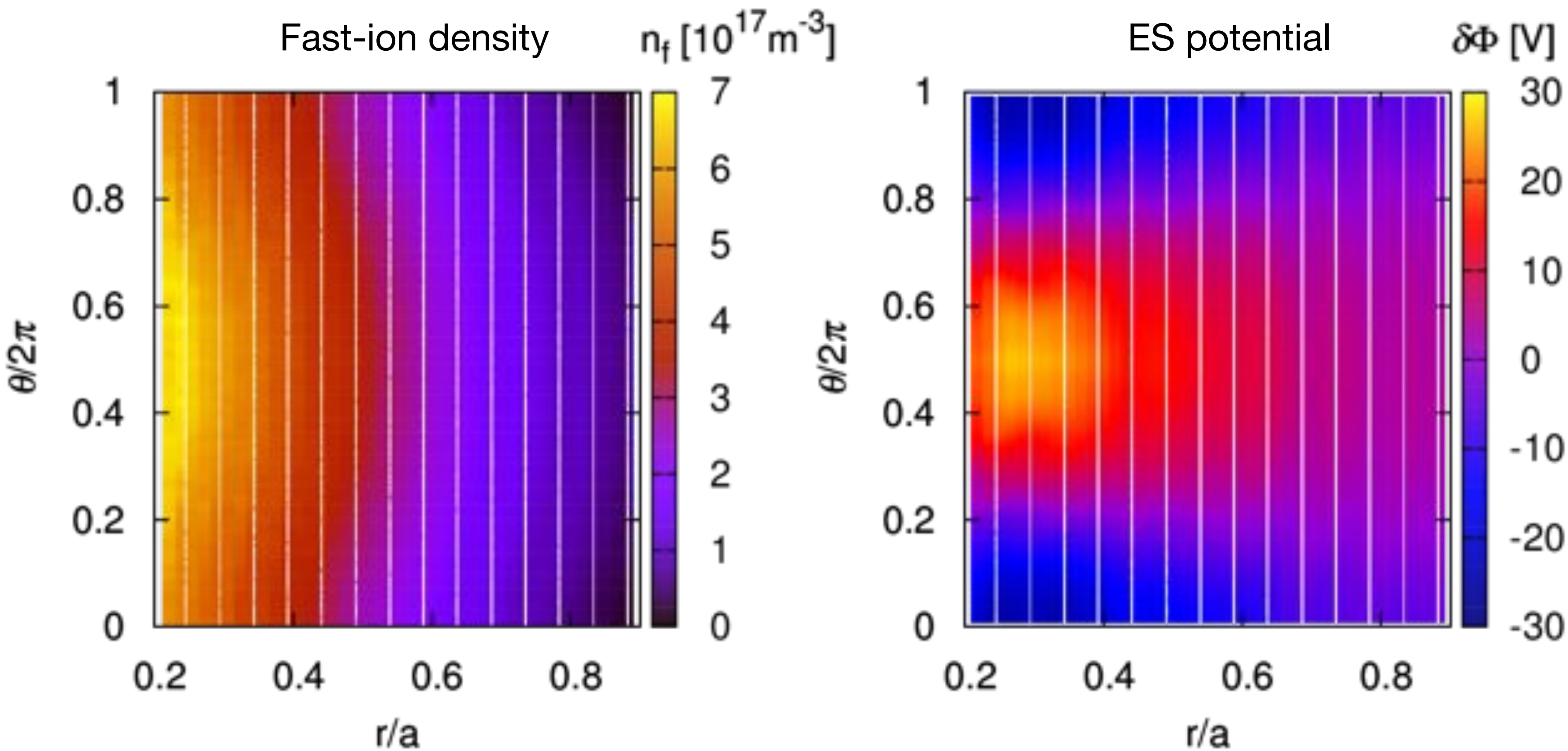
Assumed equilibrium, plasma profiles, and fast-ion source

- We consider a tokamak plasma with a circular cross-section.
- Electron density and electron- and ion temperatures at the center are n_e=3x10^{19}m^{-3} and T_e=T_i=3 keV.
- A co-current NBI injected with E=80 keV is assumed. (no sub-components)
- NB absorption power is set to 5 MW.



Major radius	3.9	m
Minor radius	0.58	m
Plasma volume	24	m^3
Magnetic field strength	3	T
$n_e(0)$	3×10^{19}	m^{-3}
$T_e(0)$, $T_i(0)$	3	keV
Fast-ion source	co-NBI	
Fast-ion energy	80	keV

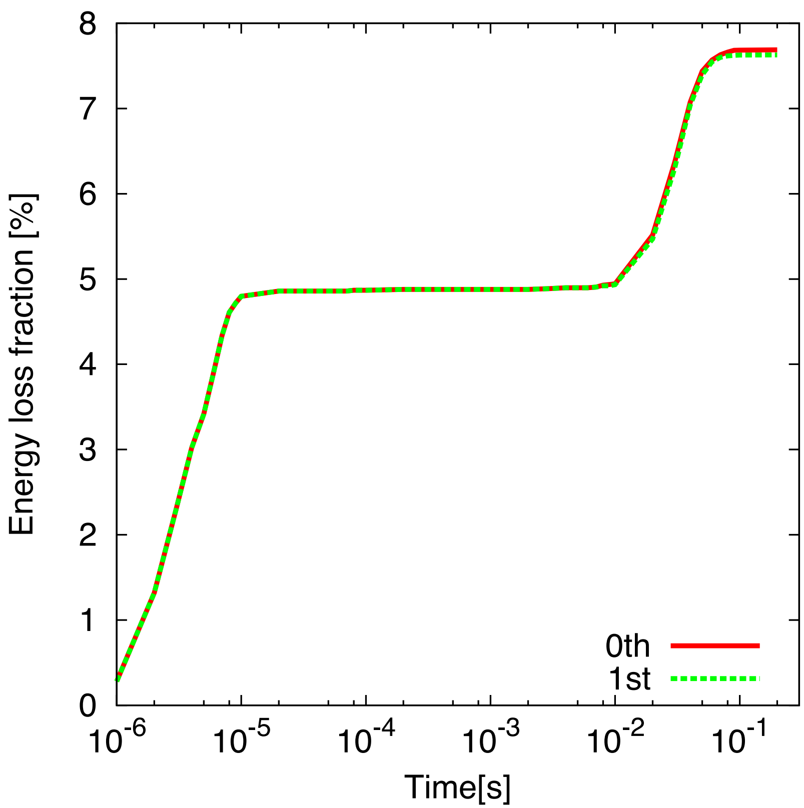
Simulation results I

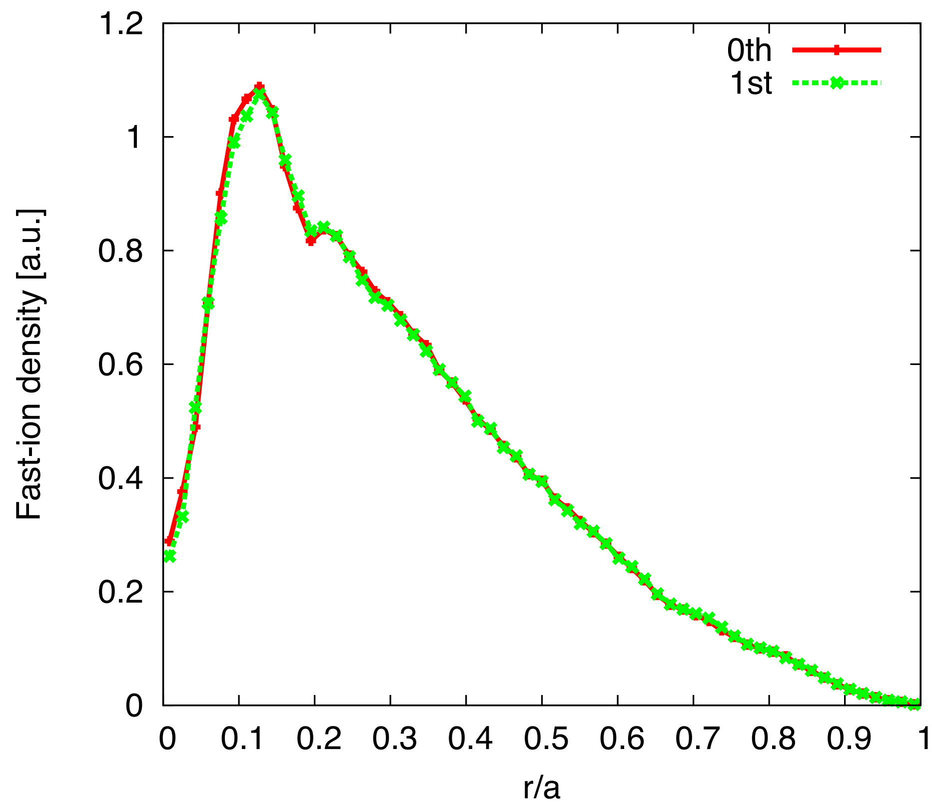


- Fast-ion density varies over magnetic surfaces (white lines) with the dominant poloidal mode number of 1 due to toroidicity.
- ES potential ~ 20V is produced by the non-uniformity of fast ions.

Result of iterative simulation

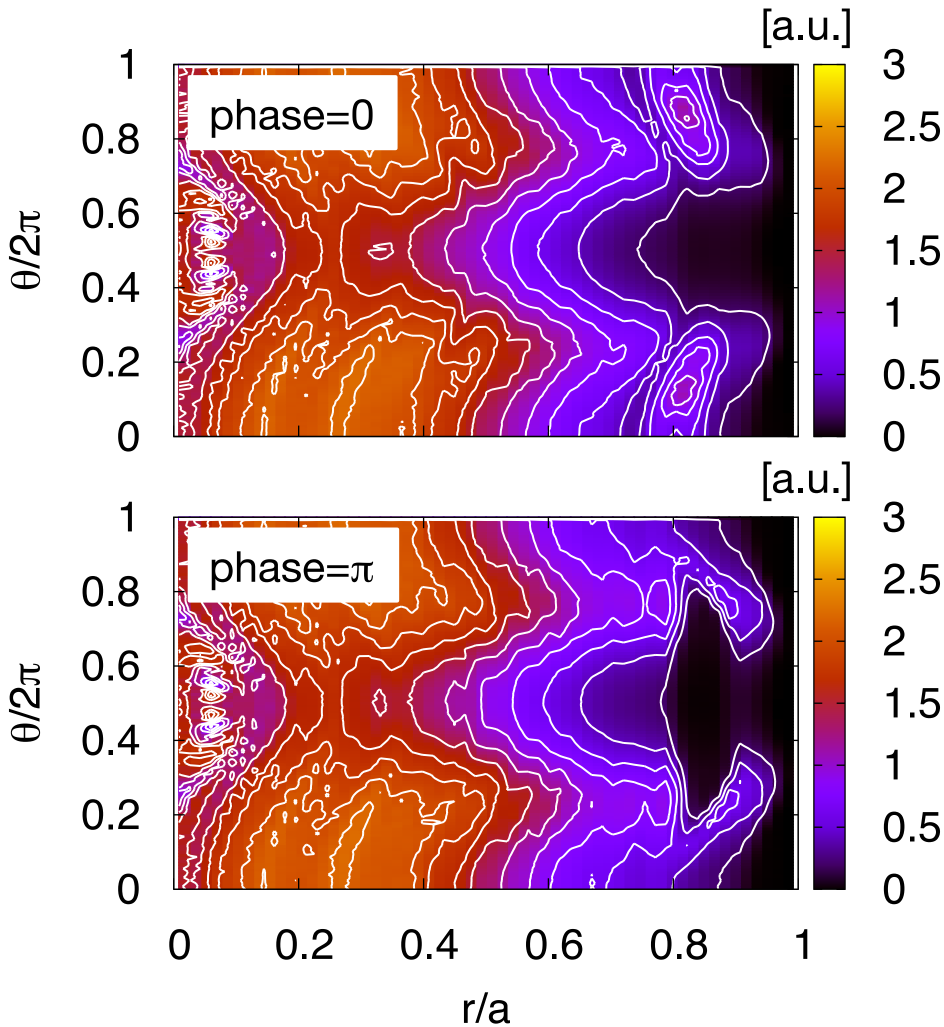
- In the absence of magnetic islands, no clear change was found before and after a single iteration.





Fast ion localization by magnetic islands

NBI beam pressure with magnetic island in the LHD



- Previously, we performed NBI heating simulation of LHD (Large Helical Device) plasma with magnetic islands by RMP (Resonant Magnetic Perturbation). (ITC25, 2015)
- We have found that the tangentially-injected fast beam ions form highly-localized beam ion pressure profiles near the resonant magnetic surface.
- Next, we investigate ES potentials produced by fast ions in presence of magnetic islands.

Magnetic island model

Perturbation model for magnetic island

- We use a well-known analytic form of magnetic perturbation, δB, producing magnetic island at resonant rational surface.

$$\boldsymbol{B}_{\text{total}} = \boldsymbol{B} + \delta\boldsymbol{B} \quad , \qquad \delta \mathrm{B} = \nabla \times (\alpha \mathrm{B}) \quad , \qquad \alpha = \alpha_{m,n}(r)\cos(m\theta - n\zeta + \delta)$$

$$\dot{\psi} = -\frac{1}{\Gamma}\left(\frac{e^2 B}{m}\rho_\parallel^2 + \mu\right)(g\partial_\theta B - I\partial_\zeta B) - \frac{1}{\Gamma}e\,(g\partial_\theta\Phi - I\partial_\zeta\Phi) + \frac{g_3}{\Gamma}\frac{e^2 B^2}{m}\rho_\parallel$$

$$\dot{\rho}_\parallel = -\frac{1}{\Gamma}\left(\frac{e^2 B}{m}\rho_\parallel^2 + \mu\right)(-g_2\partial_\theta B + g_1\partial_\zeta B) - \frac{1}{\Gamma}e\,(-g_2\partial_\theta\Phi + g_1\partial_\zeta\Phi)$$
$$-\frac{g_3}{\Gamma}\left(\frac{e^2 B}{m}\rho_\parallel^2 + \mu\right)B'$$

$$\dot{\theta} = \frac{g}{\Gamma}\left\{\left(\frac{e^2 B}{m}\rho_\parallel^2 + \mu\right)B' + e\Phi'\right\} - \frac{g_2}{\Gamma}\frac{e^2 B^2}{m}\rho_\parallel$$

$$\dot{\zeta} = \frac{-I}{\Gamma}\left\{\left(\frac{e^2 B}{m}\rho_\parallel^2 + \mu\right)B' + e\Phi'\right\} + \frac{g_1}{\Gamma}\frac{e^2 B^2}{m}\rho_\parallel$$

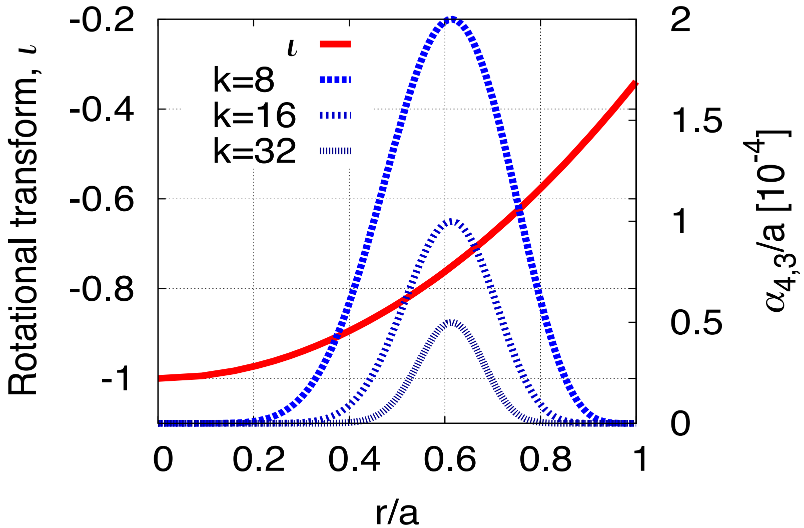
$$\Gamma = e\left[g\{(\rho_\parallel + \alpha)I' + \alpha' I + 1\} - I\{(\rho_\parallel + \alpha)g' + \alpha' g - \iota\}\right]$$

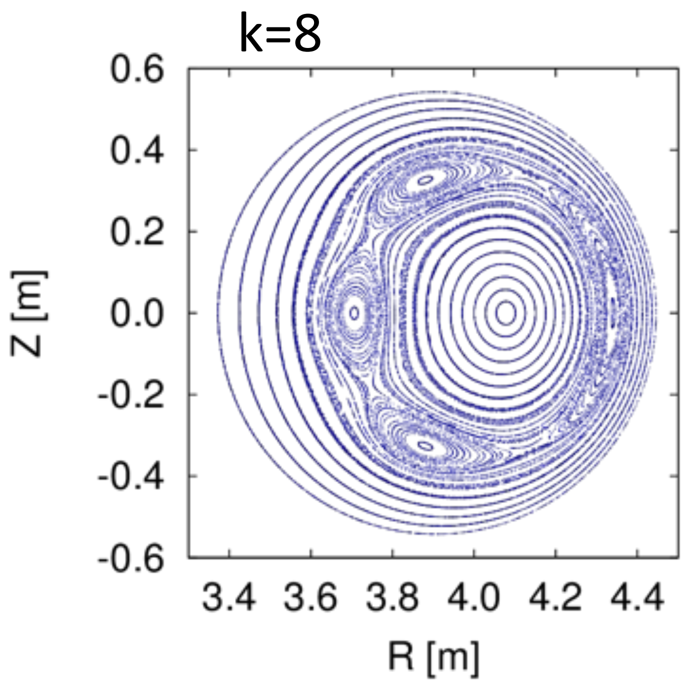
$$g_1 = (\rho_\parallel + \alpha)I' + \alpha' I + 1$$

$$g_2 = (\rho_\parallel + \alpha)g' + \alpha' g - \iota$$

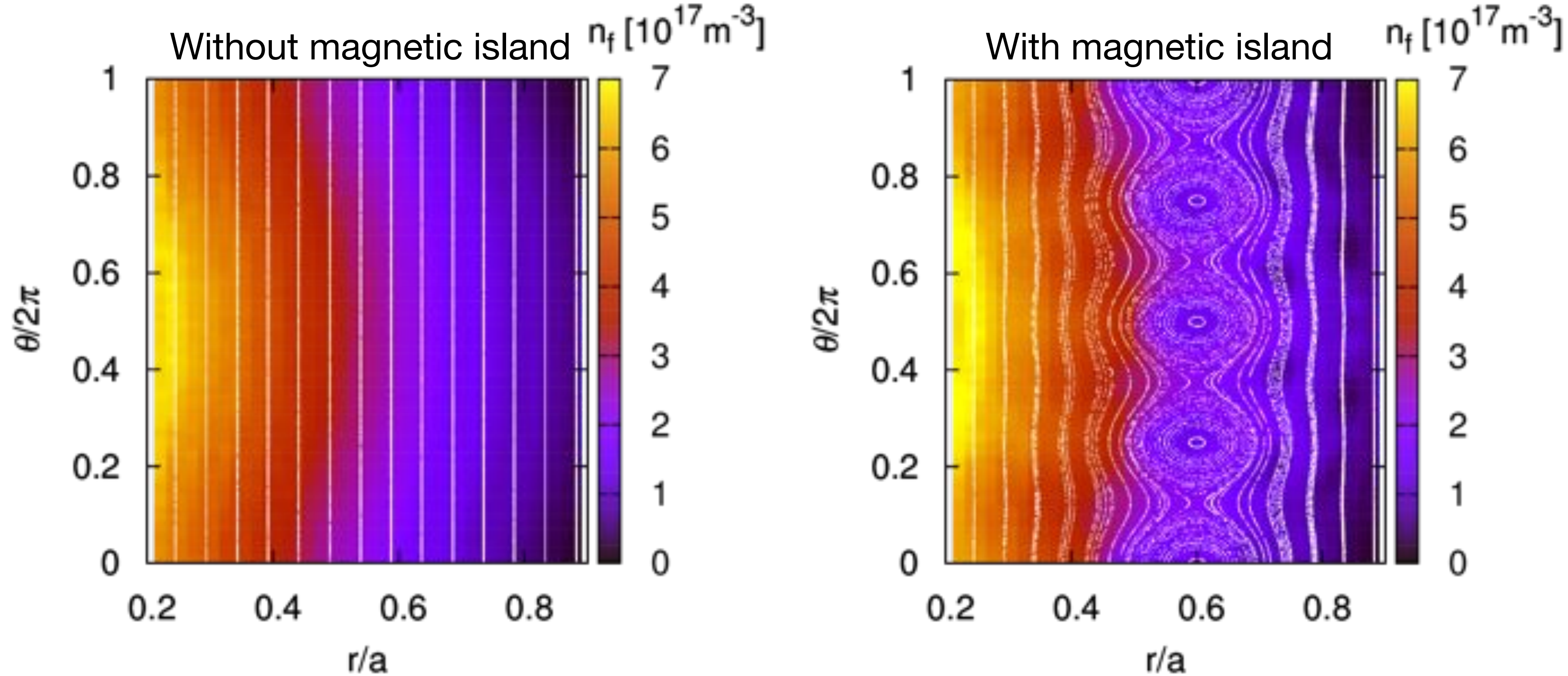
$$g_3 \equiv g\frac{\partial \alpha}{\partial \theta} - I\frac{\partial \alpha}{\partial \zeta},$$

- We consider a static (m,n)=(4,3) mode whose resonant surface locates at r/a~0.61.



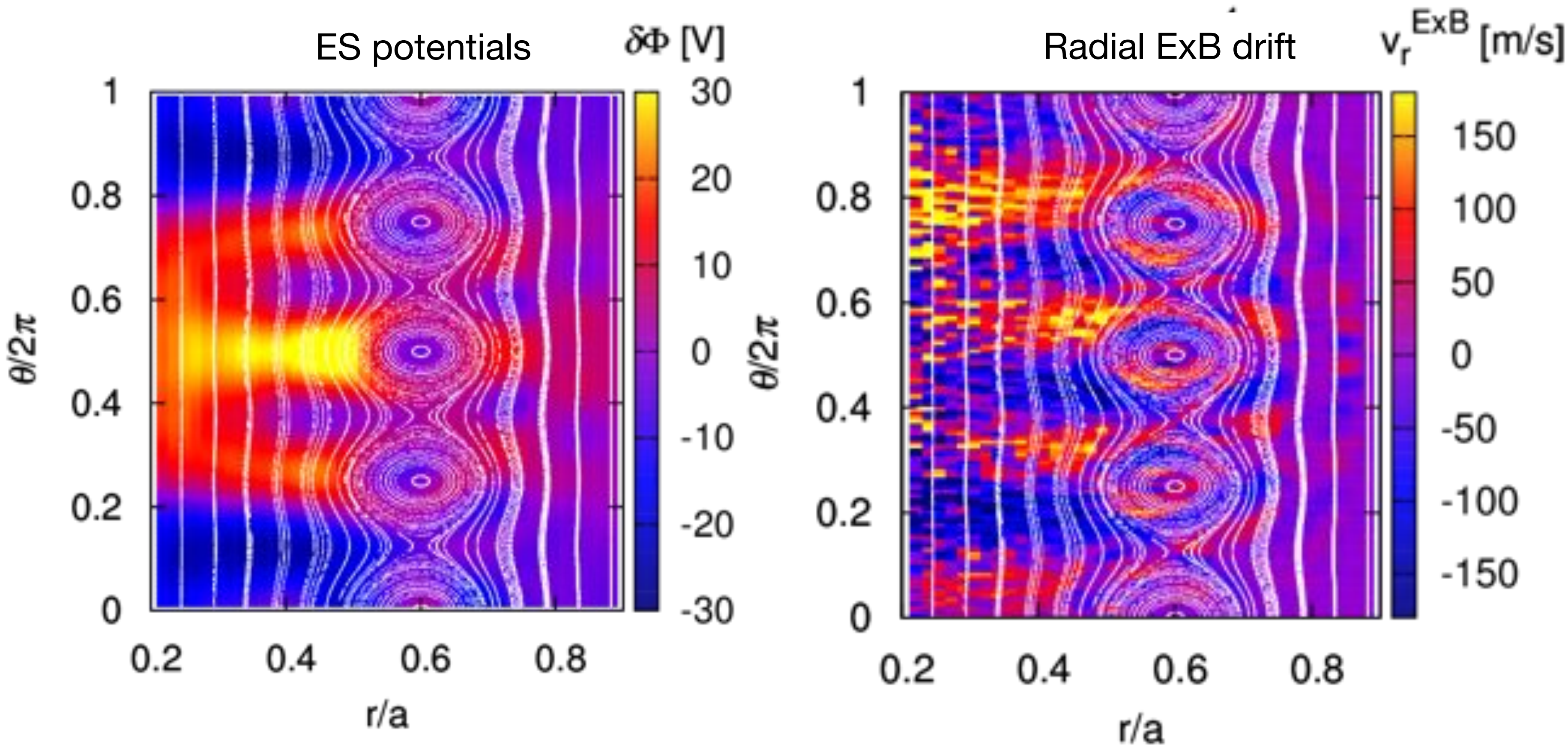


Fast ion density with magnetic island



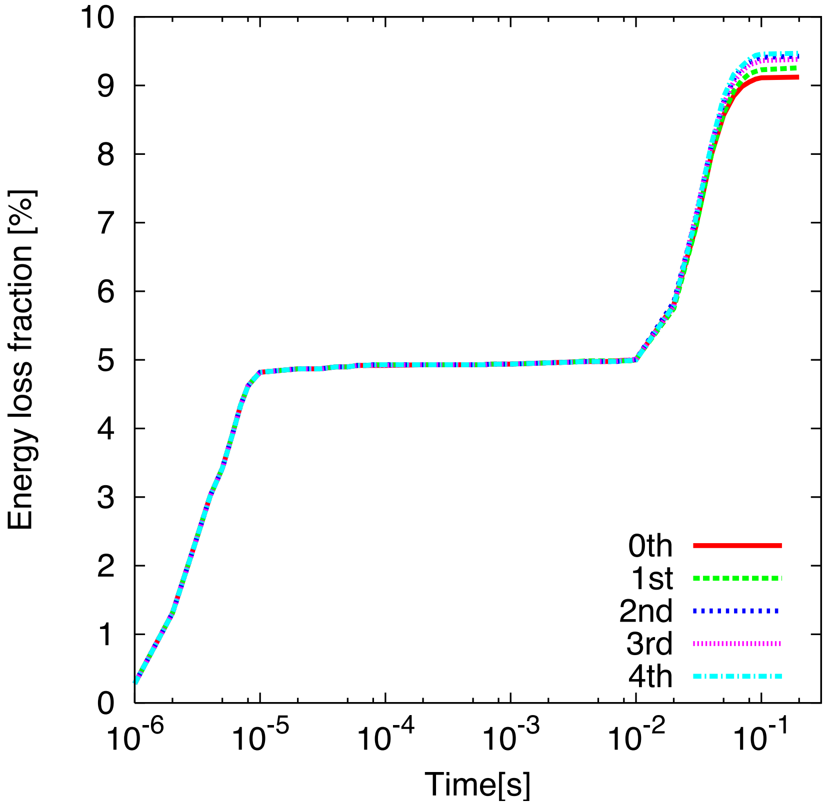
- Equilibrium magnetic surfaces are distorted and torn into magnetic island at the resonant rational surface by the superimposed magnetic perturbation.
- Drift island structure appears in the fast-ion density profile in the presence of magnetic island.

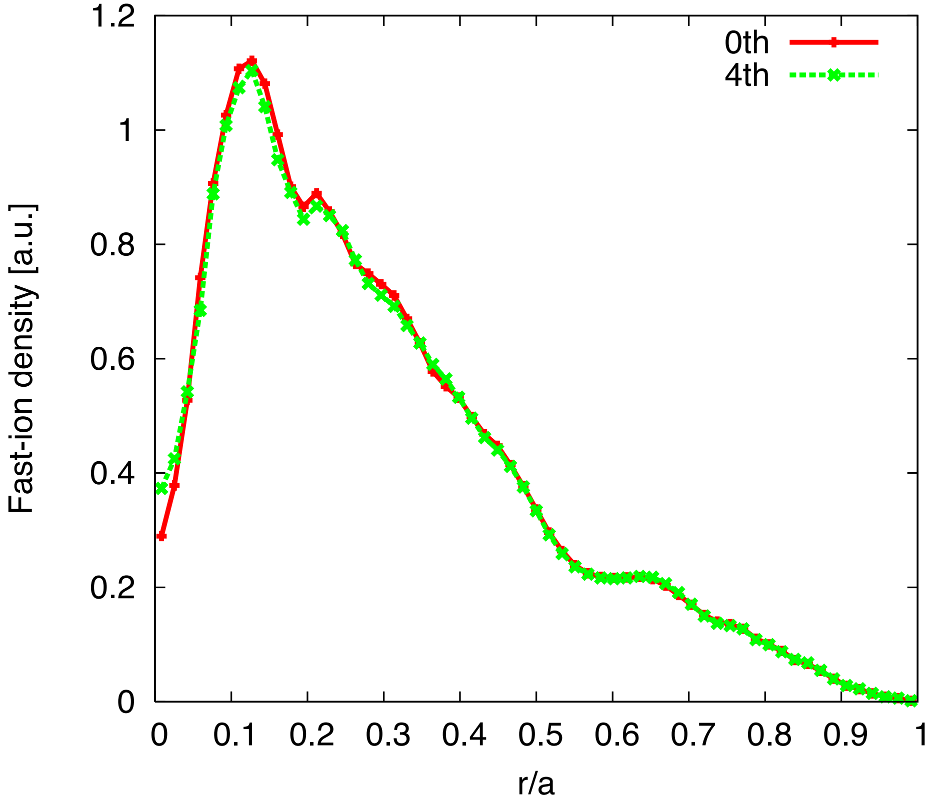
ES potentials with magnetic island



- Potential wells are formed along the axis of drift islands.
- ExB convection cells across magnetic surfaces are formed.

Effect on fast ion transport

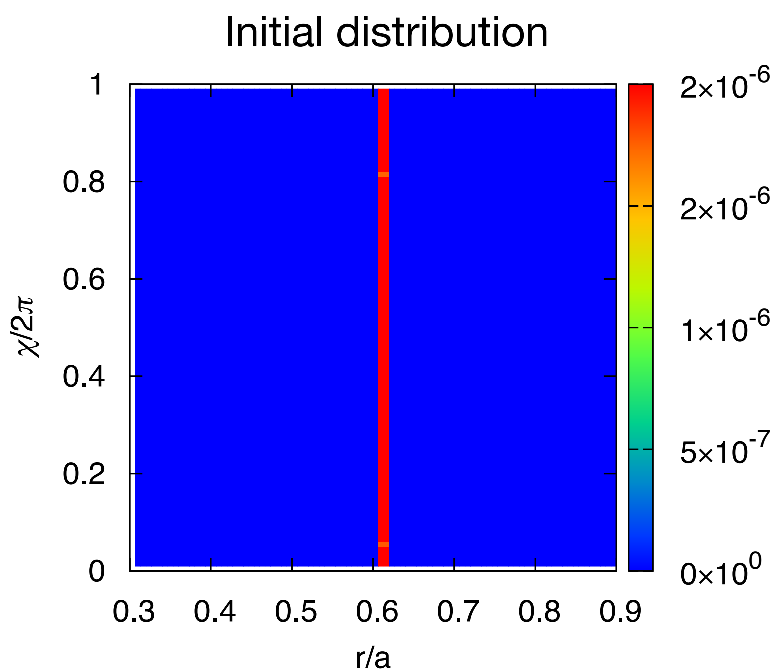




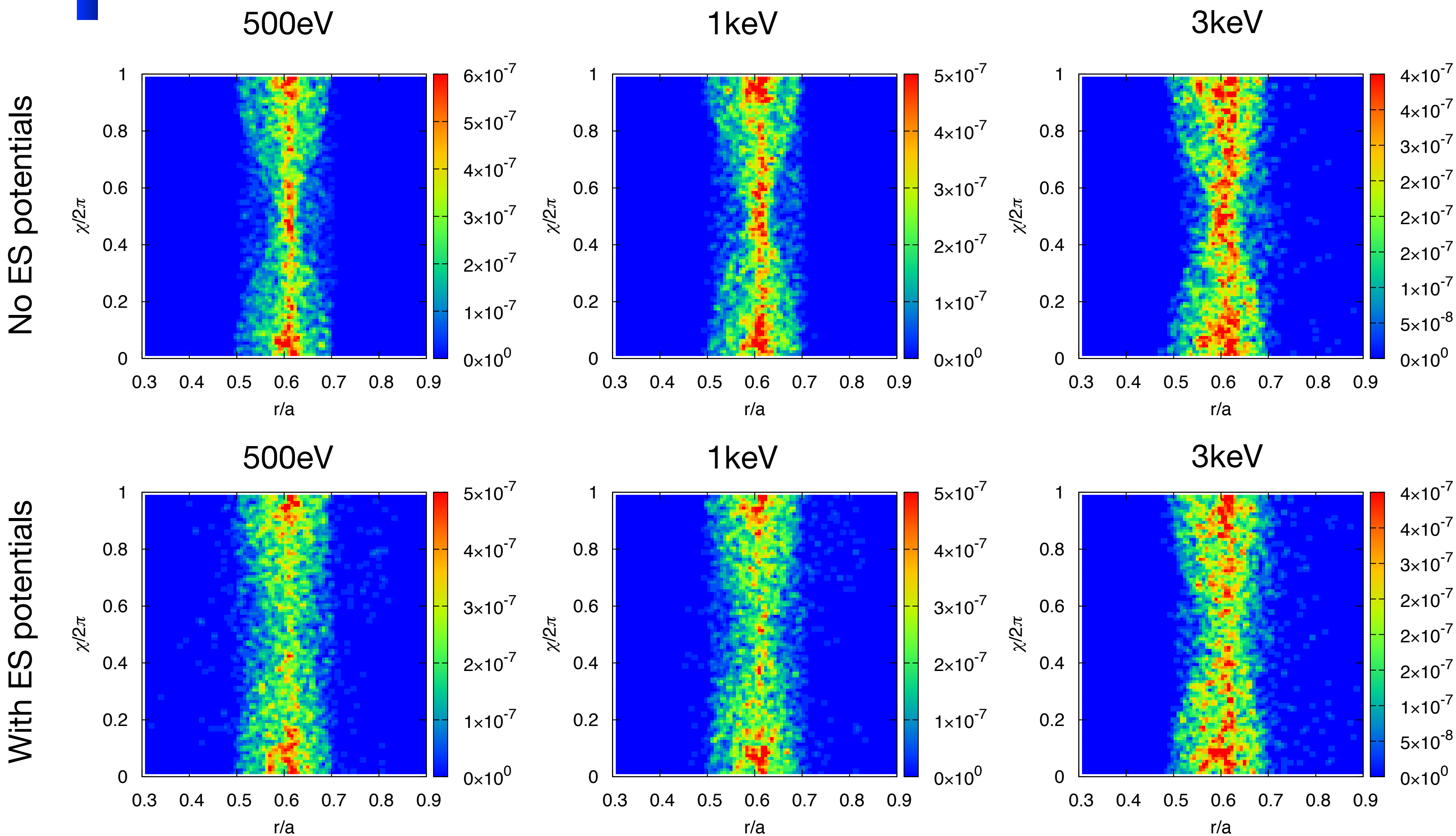
- We performed several iterative simulation of NBI fast ions and ES potentials.
- The energy loss fraction of fast ions slightly (<1%) increased and the fast ion density decreased in the central region after 4 iterations.
- The effect on fast ion transport is very small.

Effect on thermal ion transport

- We distributed 5000 isotropic and mono-energetic test particles initially at the resonant surface.
- We followed the test particles with three different energy (500eV, 1keV, and 3keV) for 10 ms and investigated the effect of fast-ion-induced ES potentials on spatial diffusion in presence of magnetic islands.



- $\chi = 4\theta - 3\phi$
- In the absence of ES potentials, ions tends to remain on the resonant magnetic surface.
- We can see clear enhancement of diffusion due to ES potentials especially near the X point for each energies.


No ES potentials
With ES potentials
500eV
1keV
3keV
χ/2π
r/a
0x10^0
1x10^-7
2x10^-7
3x10^-7
4x10^-7
5x10^-7
6x10^-7
5x10^-8

Summary

- We have evaluated electrostatic (ES) potentials produced by non-uniformity of fast-ion density along field lines in toroidal plasmas, using GNET code.
- In a tokamak plasma, an ES potential ~ 30 V with the dominant toroidal mode number of 1 is formed due to toroidicity.
- Magnetic islands have strong localization effect on fast ions
- The effect of ES potential in the presence of magnetic island
  - On fast ions: very small (slight decrease in the central density)
  - On thermal ions: clear change in the spatial diffusion was found.

Future task

- Detailed study on the particle diffusion (evaluation of diffusion coefficient)
- Dependency of fast-ion-induced ES potentials on the island phase
- ES potentials formation by NBI fast ions in the LHD and its effect on particle transport
- Diffusion/confinement of fast ions in low-frequency, rotating magnetic island of NTM