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
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

\[
\frac{\partial f_f}{\partial t} + \left( v_\parallel + v_D \right) \cdot \nabla f_f + \dot{v} \cdot \nabla_v f_f = C(f_f) + L_{particle}(f_f) + S_{beam}
\]

- \( f_f \): fast-ion distribution function
- \( v_\parallel \): parallel velocity
- \( v_D \): 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).

\[ n_e = n_{e0} \exp \left( \frac{e \delta \Phi}{\kappa T_e} \right) \approx n_{e0} + \delta n_e \]

\[ \delta \Phi = \frac{\kappa T_e}{e} \frac{\delta n_e}{n_{e0}} \]

- Equilibrium- and perturbed parts of electron density:

\[ n_{e0} = n_{i0} + \langle n_f \rangle \]

\[ \delta n_e = n_f - \langle n_f \rangle, \]

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

\[ \langle n_f \rangle = \int n_f \frac{dl}{B} / \int \frac{dl}{B} \]
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).

\[ n_f(\psi, \theta, \phi) \]

\[ \Phi_m(n,\psi) \]

\[ \Phi(\psi, \theta, \phi) \]

\[ \langle n_f \rangle(\psi, \theta, \phi) \]

- **GNET**
- **Field-line tracing**
- **Fourier analysis**
- **Boltzmann relation**
- Fast-ion distribution
- Flux-tube averaged values
- Extract dominant modes
- ES potential distribution
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 $n_e=3\times10^{19}\text{m}^{-3}$ and $T_e=T_i=3\text{keV}$.
- A co-current NBI injected with $E=80\text{keV}$ is assumed. (no sub-components)
- NB absorption power is set to 5 MW.
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.
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, $\delta B$, producing magnetic island at resonant rational surface.

\[ B_{\text{total}} = B + \delta B, \quad \delta B = \nabla \times (\alpha B), \quad \alpha = \alpha_{m,n}(r) \cos(m\theta - n\zeta + \delta) \]
\[
\Gamma = e \left[ g \{ (\rho_{\parallel} + \alpha) I' + \alpha' I + 1 \} - I \{ (\rho_{\parallel} + \alpha) g' + \alpha' g - i \} \right] \\
g_1 = (\rho_{\parallel} + \alpha) I' + \alpha' I + 1 \\
g_2 = (\rho_{\parallel} + \alpha) g' + \alpha' g - i \\
g_3 \equiv g \frac{\partial \alpha}{\partial \theta} - I \frac{\partial \alpha}{\partial \zeta},
\]

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