Simulations of EP transport in rotating RMPs

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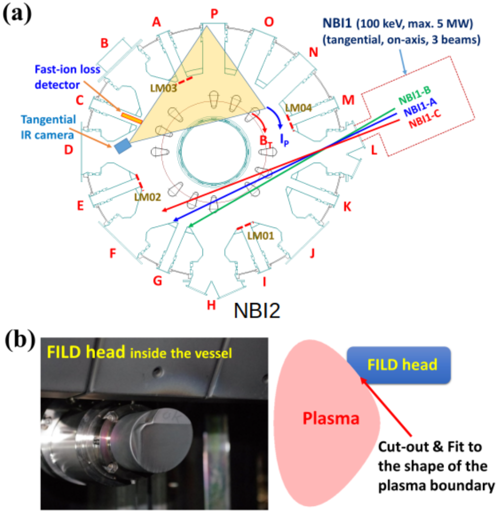
Outline

1. Motivation
2. NuBDeC code
3. Simulation results
4. Perturbation amplitude scanning
5. Summary

This presentation is based on the published paper "Simulation study of fast ion losses associated with the rotating $n = 1$ resonant magnetic perturbations in KSTAR" by Rhee *et al* 2022 *Nucl. Fusion* **62** 066028.

1. Motivation

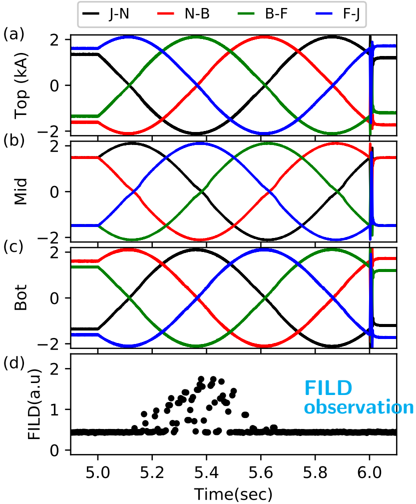
NBI and FILD in KSTAR



- In KSTAR, NBI is main heating source for ions.
- Now it has 6 beam sources but here we consider NBI1-A and C.
- Fast ion loss detector (**FILD**) is installed.[1] to study fast ion loss,
- FILD provides fast ion energy and pitch-angle
- It supports the study for fast ion transport and hitting walls.

[1] Junghee Kim *et al*, Rev. Sci. Instrument (2012)

FILD observed NB ion loss by external 3D field



- KSTAR has 3D field coil set for ELM control.
- Toroidal phase rotation of 3D field results toridal phase dependent fast ion loss.

We investigate NB ion loss by the rotating 3D field by using NuBDeC

[1]Kimin Kim *et al*, Phys. Plasmas(2019)

2. NuBDeC code

NuBDeC code is improved to include perturbed 3D field

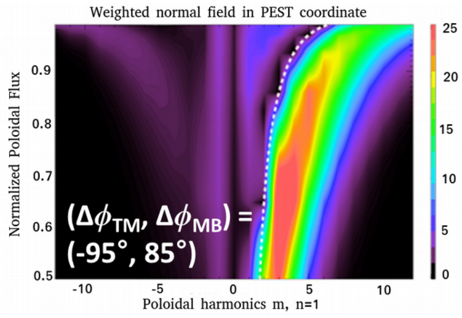
NuBDeC:

- NuBDeC code calculates neutral beam ionization and follows ionized particles' drift orbit under tokamak equilibrium magnetic field.
- It can calculate fast ion losses to the PFC and FILD in KSTAR
- Using NuBDeC, Rhee *et al* (2019) investigated the origin of heat load on the poloidal limiters.

NuBDeC Updates: Perturbations

- $\vec{B} = \vec{B}_{eq} + \vec{B}_{pert}$
  where
  $\vec{B}_{pert}(\phi) = \vec{B}_c(\rho,\theta)\cos\phi + \vec{B}_s(\rho,\theta)\sin\phi$
- IPEC code calculate $\vec{B}_c(\rho,\theta)$ and $\vec{B}_s(\rho,\theta)$
- To calculate rotating RMP, phase evolution of perturbation is controlled by
  $\phi = \phi_p + \phi_t$
  where ϕ_p and ϕ_t are geometrical toroidal angle and phase change due to perturbation change

3D field including ideal MHD response is considered

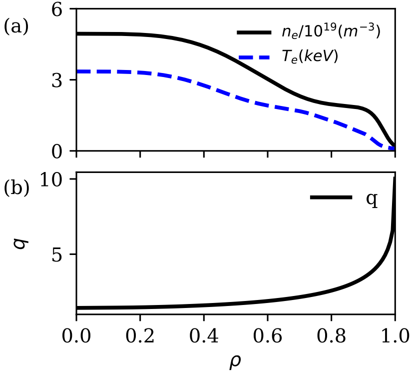


- Ideal MHD response to external 3D field shields the perturbation at the resonance flux surface.
- Magnetic island formation at the resonance flux surface is prohibited.
- Thermal particles hardly make the island.
- But largely drifting energetic particles can make resonant orbit island.[1]
- Resonance can yield transport.[2]

[1] Mynick PoFB 1993

[2] Sanchis *et al.* PPCF 2019

Simulation condition reflects the experiment



Simulation conditions

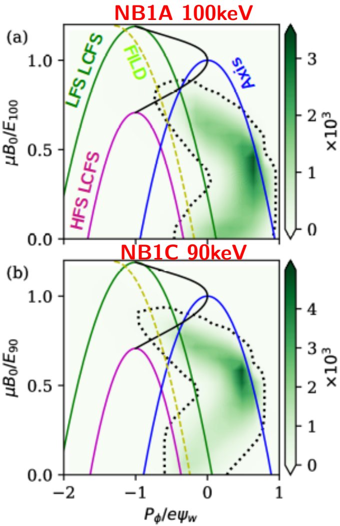
- NBI1-A and C are tested to simulate the experiment.
- Each energy is 100keV and 90keV.
- Simulation sampled 200k particles and 95k and 105k particles are tested for NBI1-A and C.
- Profiles do not evolve during simulation.

Simulation limits

- Only single toroidal mode $\mathbf{n} = \mathbf{1}$ is considered.
- Collision and **E** field is not included.

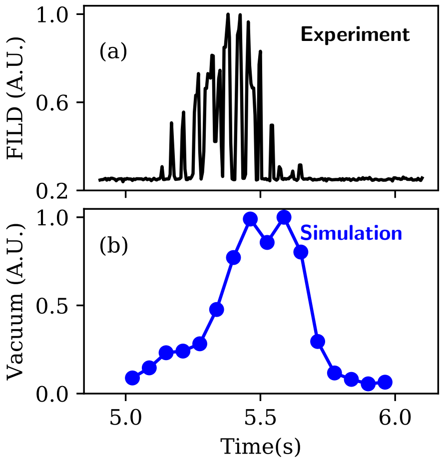
3. Simulation results

Initial beam deposition of NB1-A and C on phase space



- Beam deposition profile is presented on the phase space of $P_\phi/e\psi_w$ - $\mu B_0/E_0$
- FILD is presented as a yellow line on phase space.
- Deposition profile crosses FILD line on phase space, i.e. detection by FILD
- High and low pitch-angle branches are crossing.

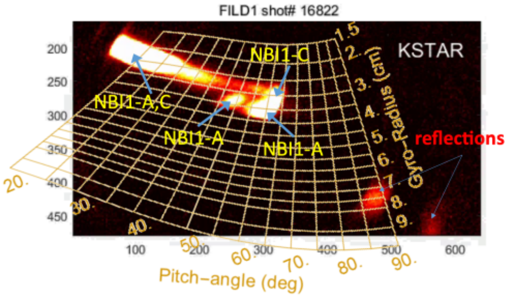
Simulation results agreeable time evolution of FILD observation



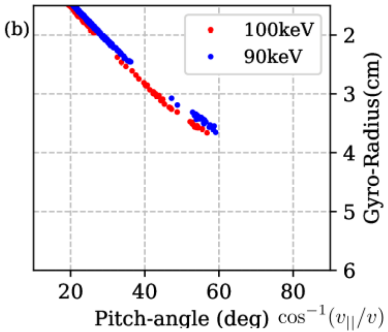
- Time evolution of FILD under rotating RMP is examined in the simulation.
- Peak time is reproduced.
- Simulated time evolution follows the experimental trend though there is some time delay of fast ion loss.

Simulation also reproduces pitch and gyro-radius map

Experiment

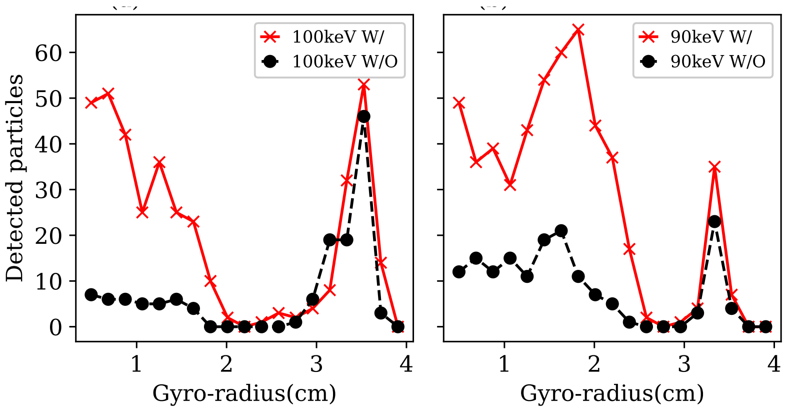


Simulation

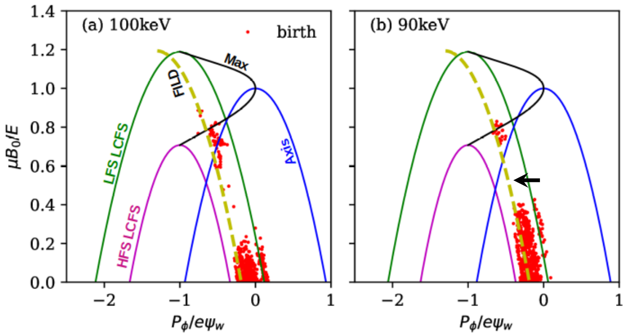


- Lost particles are projected on phase space of pitch-angle and gyro-radius (energy) by FILD.
- NBI1-A (100keV) and NBI1-C (90keV) particles are detected.
- Isolated low, middle, and high pitch-angle particles islands are shown.
- Simulation reproduces isolated energy islands for each beam in the same phase space.

Simulation shows that low pitch-angle particle losses are dominant

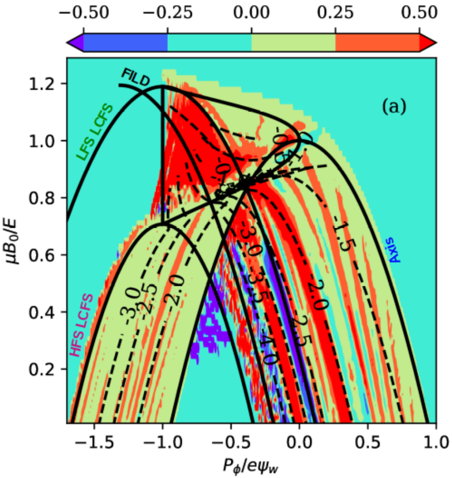


Birth of detected particles on phase space shows P_ϕ transport



- Static 3D field cause breaking of P_ϕ conservation still keeping μ conservation.
- Thus the broadly neighboring particles to FILD are move to FILD on phase space.
- Interesting isolated strip ($q_{eff} \sim 2.5$) is found near low field side LCFS. $\rightarrow$ investigation in **Section 4** .

$\langle \Delta P_\phi \rangle$ map shows resonance transport of fast ions



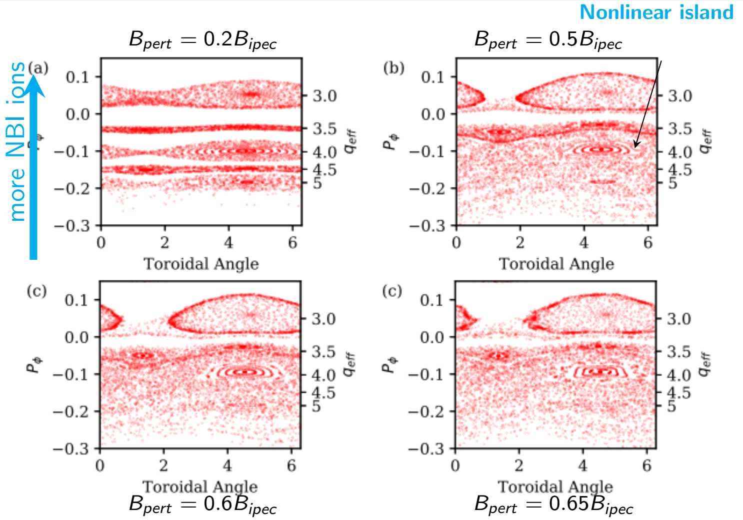
- We tested averaged $\langle \Delta P_\phi \rangle$ values for 100keV test particles on the phase space.[1]
- Positive means inward and negative outward transport.
- $q_{eff} = \omega_\phi/\omega_\theta$ is overlaid. (ω_ϕ and ω_θ are toroidal and poloidal transit frequency)
- Integer q_{eff} lines of 100keV particles is center of strong transport.
- Positive and negative transports hints orbit islands centered integer q_{eff} surface.
- Near $q_{eff} = 4$ shows negative resonant transport to FILD probe.
- We can also find the fractional lines which is nonlinear resonance.[2]

[1] Podesta *et al.* PPCF 2014 [2] Sanchis *et al.* PPCF 2019

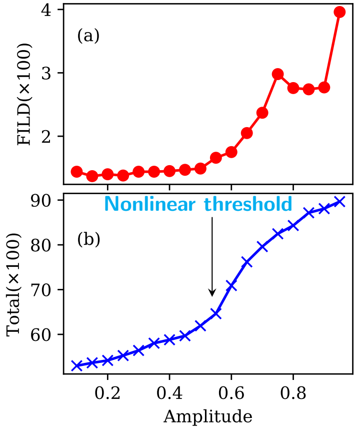
4. Perturbation amplitude scanning

Orbit islands are found

- Poincaré map can be obtained on the surface of $P_{phi}\ (q_{eff}) - \phi$ surface.
- Orbit islands are found in the linear (q_{eff} integer) and non-linear (q_{eff} half integer) resonant surface.
- Radial extension of orbit depends on the island toroidal position $\rightarrow$ **dependency of fast ion loss on 3D toroidal field**
- Large transport in the resonance region is relevant to the orbit islands.
- KAM surface at $q_{eff} = 3.5$ disappears due to **islands overlap when B_{pert} exceeds $0.5B_{pert}$** .
- Island overlap makes orbit stochastization and transport path to outward.

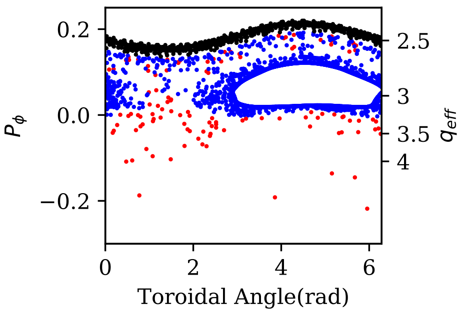


Orbit island overlap is relevant to transport threshold behavior



- Nonlinear threshold amplitude of B_{pert} for particles losses is found at $B_{pert} = 0.55B_{ipec}$.
- At threshold amplitude island overlap and disappearance of KAM surface are found in Poincaré map.
- NB ions deposited in the inner region where more ions are deposited are transported by 3D perturbation.

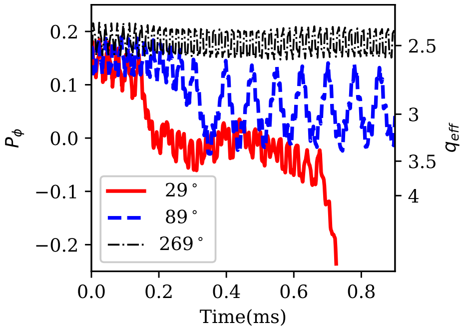
Particle loss depends on initial toroial position



red: $q_{eff} = 2.5$, blue:$q_{eff} = 3.0$, red: lost particles

- We tested Poincaré map for the particle near $q_{eff} \sim 2.5$ which hits FILD probe: lost band near LFS LCFS for 100keV
- Poincaré map is plotted with different initial toroidal positions.
- At $q_{eff} = 3$ orbit island is found.
- Thus some are confined near $q_{eff} = 2.5$ and some form a island near $q_{eff} = 3$ and rest of them lost.
- Outer resonance surfaces does not show the island because those islands may cross the limiters.

Inner particles can be lost by resonance with 3D field.



- There are 3 types of path by initial toroidal position.
- First one is confined at $q_{eff} = 2.5$ but shows radial oscillation.
- Second one is oscillate at $q_{eff} = 3$ and it seems to make orbit island.
- Last one hit the wall.
- Large radial push is achieved by 3D field during long time at resonant surface of $q_{eff} = 3$ and $q_{eff} = 4$ and it hit the wall.

5. Summary

Summary

- We simulated NBI ion loss by rotating 3D field.
- Simulation results consist with experimental results.
- Radial extension of orbit depends on the island toroidal position and it determines fast ion loss dependency on toroidal phase of 3D field.
- $\langle \Delta P_\phi \rangle$ study reveals transport layer and resonance between NBI ions and static 3D field is main transport mechanism
- Orbit islands overlap on Poincaré map provides radial route for abundant inner NB ions and it causes nonlinear threshold of fast ion losses.