ASIPP

Simulations of energetic-passing-ion loss and redistribution with resonant magnetic perturbations for EAST tokamak

Yingfeng Xu[1], Wenfeng Guo[1], Lei Ye[1], Xiaotao Xiao[1], Shaojie Wang[2], Siqiang Zhu[2]

[1] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China
[2] Department of Modern Physics, University of Science and Technology of China, Hefei, China

Trilateral International Workshop on Energetic Particle Physics
Nov. 10-12, 2017, Hangzhou, China

Outline

- Introduction
- Orbit following code GYCAVA
- Simulations of loss and redistribution of energetic passing ions with RMPs
  - Simulations for analytic equilibrium
  - Simulations for EAST equilibrium
- Summary

Background

- The energetic particles play an important role in heating and current drive and momentum input of tokamak plasmas.
- Fast ion transport can be induced by many static and time-dependent electromagnetic perturbations, such as perturbations induced by MHDs, external coils, ripple fields.
- The resonant magnetic perturbations (RMPs) induced by external coils can be beneficial for controlling ELMs, etc.
- However, RMPs break the axisymmetry of the tokamak plasmas and they can have a detrimental effect on the fast-ion confinement.
- According to previous orbit following simulations for ITER plasmas, RMPs can lead to significant loss of NBI ions on the order of 16–17%. (Tani, et al, NF, 2012)
- Understanding the loss mechanism of fast ions is important for prediction of performance and safety operation of future tokamak fusion devices.
- The RMP-induced loss of NBI ions has been experimentally and numerically studied in many tokamaks, such as ASDEX Upgrade, DIII-D, TEXTOR, MAST and KSTAR, etc.

Motivation and orbit codes

- Motivation
  - NBI in the tangential direction produces primarily the energetic passing ions, while NBI in the perpendicular direction produces primarily the energetic trapped ions.
  - study the effects of **RMPs** and the **magnetic drift** on the behavior of **energetic passing ions**.
- For studying the behavior of the energetic particles in the tokamak plasmas, many orbit following codes have been developed.
  - orbit codes: OFMC, ASCOT4, VENUS-LEVIS, ORBIT, etc.
- Our orbit code GYCAVA (Y. Xu et al, PoP, 2011, 2013)
  - use exact canonical variables
  - based on the Lie-transform perturbation method

Outline

- Introduction
- Orbit following code GYCAVA
- Simulations of loss and redistribution of energetic passing ions with RMPs
  - Simulations for analytic equilibrium
  - Simulations for EAST equilibrium
- Summary

Phase-space transform in GYCAVA

- GC(guiding-center coordinates) ➔ GY(gyrocenter coordinates) ➔ next GY(by evolving GY equations of motion) ➔ next GC
  - GC ➔ GY at initial time

$$\bar{Z}^i = Z^i + \langle G_1^i \rangle,$$
$$\bar{X}^i = X^i + \frac{\partial X^i}{\partial Z^j}\langle G_1^j \rangle,$$
$$\bar{\mu} = \mu + \langle G_1^\mu \rangle.$$

  - GY ➔ GC at every time

$$Z^i = \bar{Z}^i - \langle G_1^i \rangle,$$
$$X^i = \bar{X}^i - \frac{\partial X^i}{\partial Z^j}\langle G_1^j \rangle,$$
$$\mu = \bar{\mu} - \langle G_1^\mu \rangle.$$

- Phase-space transform is determined by the generating vector.

$$\langle G_1^\theta \rangle = -\langle \delta \boldsymbol{A} \rangle \cdot \frac{\partial \boldsymbol{X}}{\partial P_\theta},$$
$$\langle G_1^{\alpha_c} \rangle = -\langle \delta \boldsymbol{A} \rangle \cdot \frac{\partial \boldsymbol{X}}{\partial P_\alpha},$$
$$\langle G_1^{P_\theta} \rangle = \langle \delta \boldsymbol{A} \rangle \cdot \frac{\partial \boldsymbol{X}}{\partial \theta},$$
$$\langle G_1^{P_\alpha} \rangle = \langle \delta \boldsymbol{A} \rangle \cdot \frac{\partial \boldsymbol{X}}{\partial \alpha_c},$$
$$\langle G_1^\mu \rangle = -\mu \delta B_\parallel / B_0.$$

$$Z^i = (P_\theta, \theta, P_\alpha, \alpha_c) \qquad X^i = (\psi, \zeta, \rho_\parallel g)$$

Equations of motion used in GYCAVA

- GY equations of motion

$$\frac{d\bar{\theta}}{dt} = \frac{\partial \bar{h}^c}{\partial \bar{P}_\theta},$$
$$\frac{d\bar{P}_\theta}{dt} = -\frac{\partial \bar{h}^c}{\partial \bar{\theta}},$$
$$\frac{d\bar{\alpha}_c}{dt} = \frac{\partial \bar{h}^c}{\partial \bar{P}_\alpha},$$
$$\frac{d\bar{P}_\alpha}{dt} = -\frac{\partial \bar{h}^c}{\partial \bar{\alpha}_c}.$$

$$\frac{d\bar{\psi}}{dt} = \frac{\partial\psi}{\partial\theta}\frac{d\bar{\theta}}{dt} + \frac{\partial\psi}{\partial P_\theta}\frac{d\bar{P}_\theta}{dt} + \frac{\partial\psi}{\partial\alpha_c}\frac{d\bar{\alpha}_c}{dt} + \frac{\partial\psi}{\partial P_\alpha}\frac{d\bar{P}_\alpha}{dt}$$

- Exact canonical variables (P_α, α_c, P_θ, θ) expressed in terms of (ψ, θ, ζ, $\rho_{/\!/}g$)

$$P_\alpha = \psi - \rho_\| g,$$
$$P_\theta = \rho_\| g(q + I/g) - (\psi - \psi_0)(q(\psi_0) + \int_0^{\psi_0} \partial_\theta \delta d\psi)$$
$$+ \int_{\psi_0}^{\psi} q d\psi + \int_{\psi_0}^{\psi}\int_0^{\psi} \partial_\theta \delta d\psi d\psi - \rho_\| g(q - q(\psi_0) + \int_{\psi_0}^{\psi} \partial_\theta \delta d\psi)$$
$$\alpha_c = -\zeta + q(\psi_0)\theta - \int_{\psi_0}^{\psi} \delta d\psi.$$

- Hamiltonian:

$$\bar{h}^c(\bar{Z}^c) = \bar{h}(\bar{Z}) = \bar{H}(\bar{Z}) - \bar{U} = \bar{H}_0 + \bar{H}_1 + \bar{H}_2 - \bar{U},$$
$$\bar{H}_0 = H_0,$$
$$\bar{H}_1 = \langle \delta\phi \rangle - (\dot{\psi}_0 \langle \delta A_\psi \rangle + \dot{\theta}_0 \langle \delta A_\theta \rangle$$
$$+ \dot{\zeta}_0 \langle \delta A_\zeta \rangle + \dot{\xi}_0 \langle \delta \boldsymbol{A} \cdot \partial_\xi \boldsymbol{\rho}_0 \rangle),$$
$$\bar{H}_2 = -\frac{1}{2}\langle \{S_1, (\dot{S}_1)_0\} \rangle + \frac{1}{2}\langle |\delta \boldsymbol{A}|^2 \rangle \simeq \frac{1}{2}|\delta A_\||^2.$$

Upgrade of orbit code GYCAVA

- Add loss and redistribution modules
- $\delta\mathbf{B} \Rightarrow \delta\mathbf{A}$ in GYCAVA: $\delta\mathbf{B}=\nabla\times\delta\mathbf{A}$
- For improving computation efficiency
  - GYCAVA has been parallelized by OpenMP and MPI.
  - Optimization of particle push module
- Interface to an analytical equilibrium code (including elongation and triangularity) and EFIT (gfile)
  - equilibrium codes $\Rightarrow$ the equilbrium data in terms of **cylindrical coordinates** $\Rightarrow$ the data in terms of **magnetic surface coordinates** $\Rightarrow$ orbit code GYCAVA

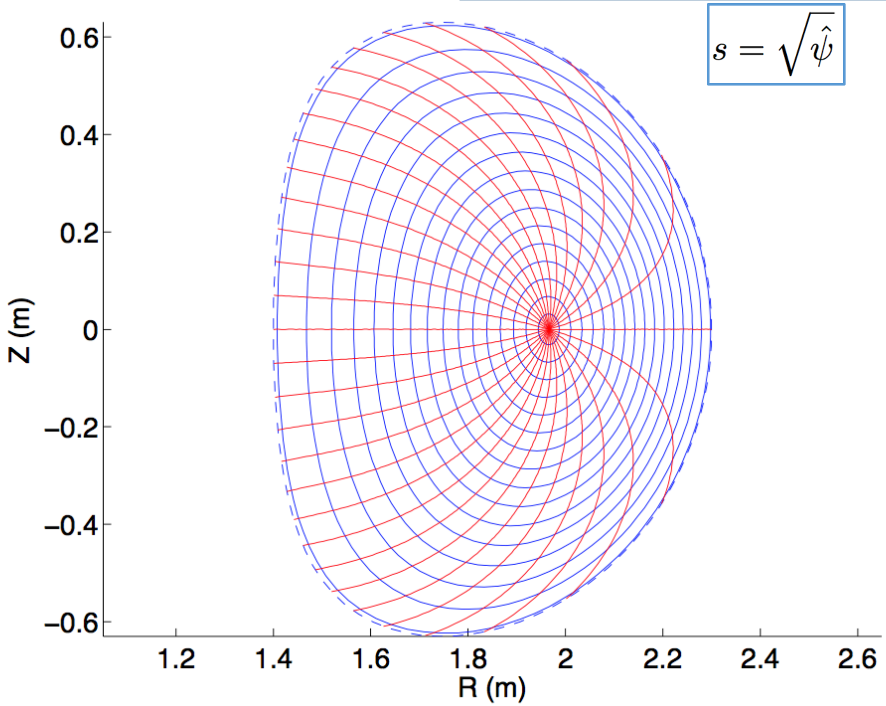
Outline

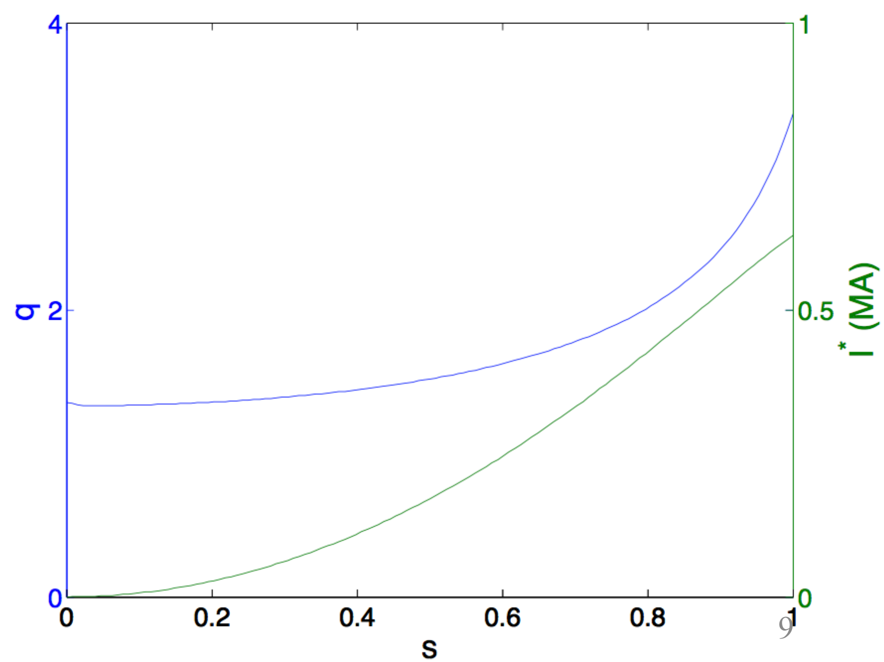
- Introduction
- Orbit following code GYCAVA
- Simulations of loss and redistribution of energetic passing ions with RMPs
  - Simulations for analytic equilibrium
  - Simulations for EAST equilibrium
- Summary

Equilibrium configuration and RMPs for the EAST-like tokamak

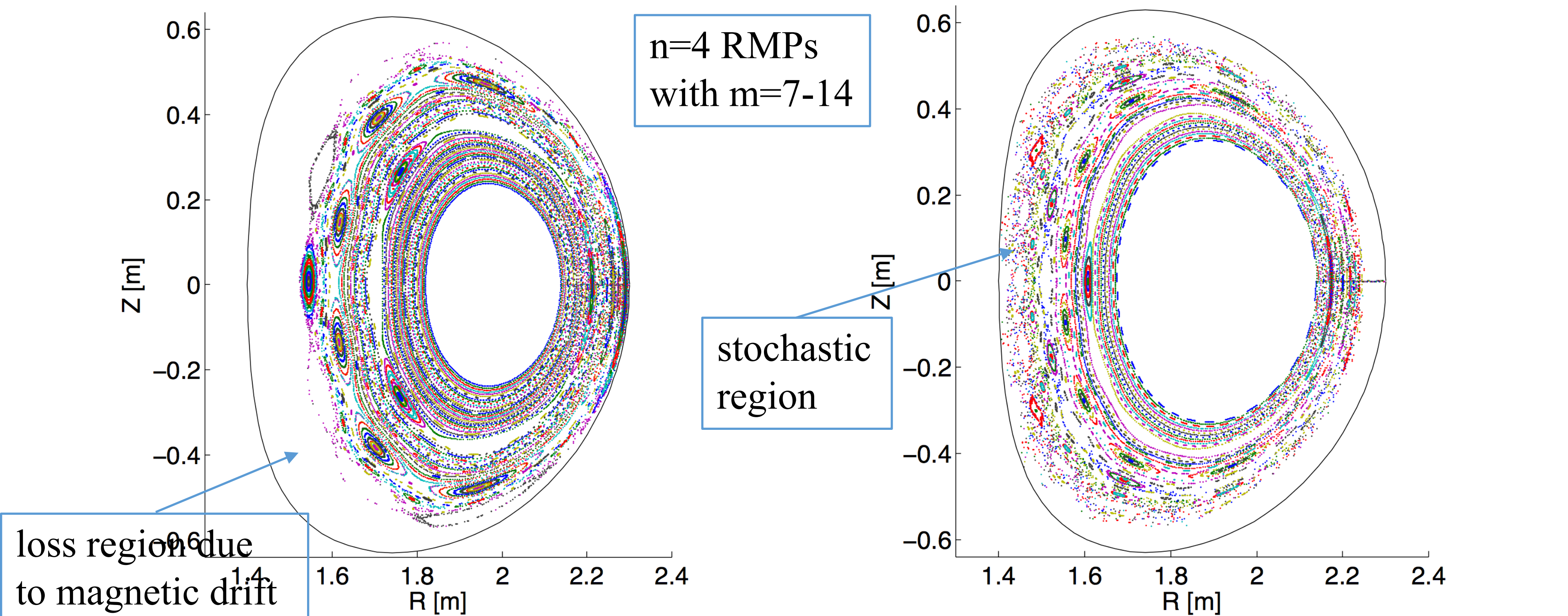
- Equilibrium parameters are close to EAST configuration.
- Safety factor: q = 1.35−3.37; given current: Ip = 0.63MA.
- The relative error of the total current < 10^{-3}, which verifies our analytical equilibrium code and interface.
- given RMPs: $\delta B_N = \epsilon_\delta s \sum_m e^{i(m\theta - n\zeta)}$ $\quad s = \sqrt{\hat{\psi}}$

1. n=4 RMPs with m=7-14
2. n=1 RMPs with m=2-4

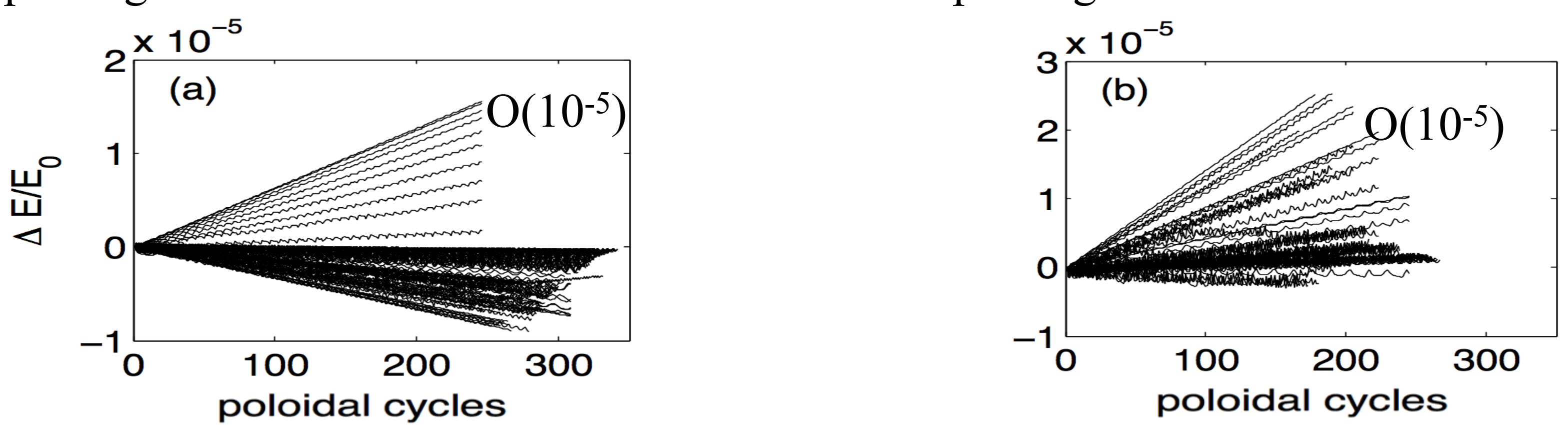




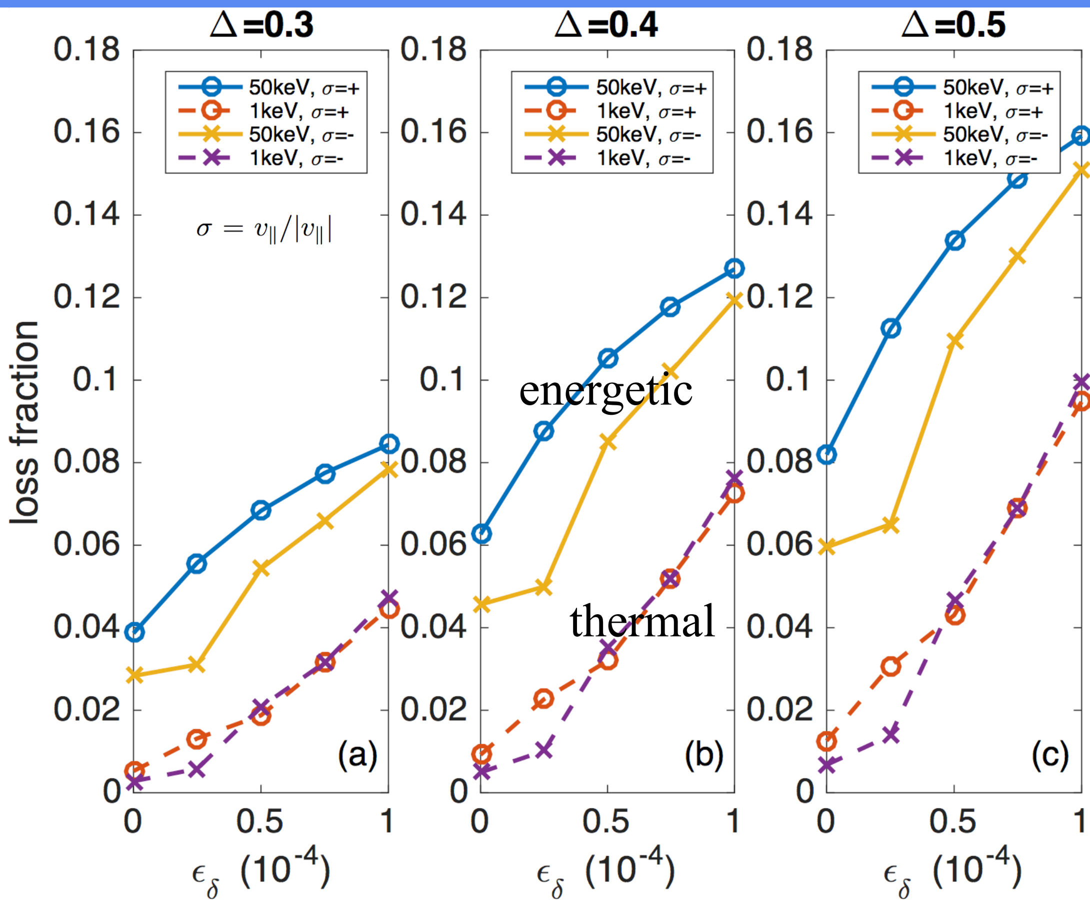
Poincare plots for co/counter-passing energetic ions (50keV) with n=4 RMPs



Co-passing ions: drift islands with m=6-8 Counter-passing ions: drift islands with m=8-12

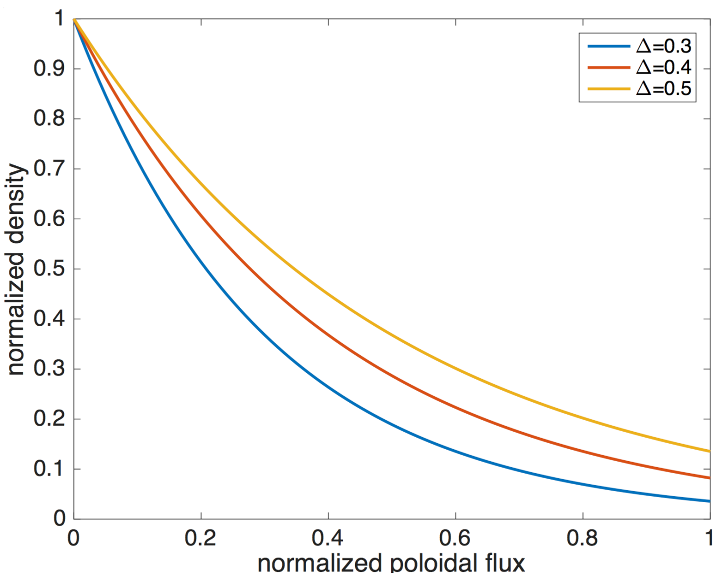


Loss induced by RMPs and magnetic drift



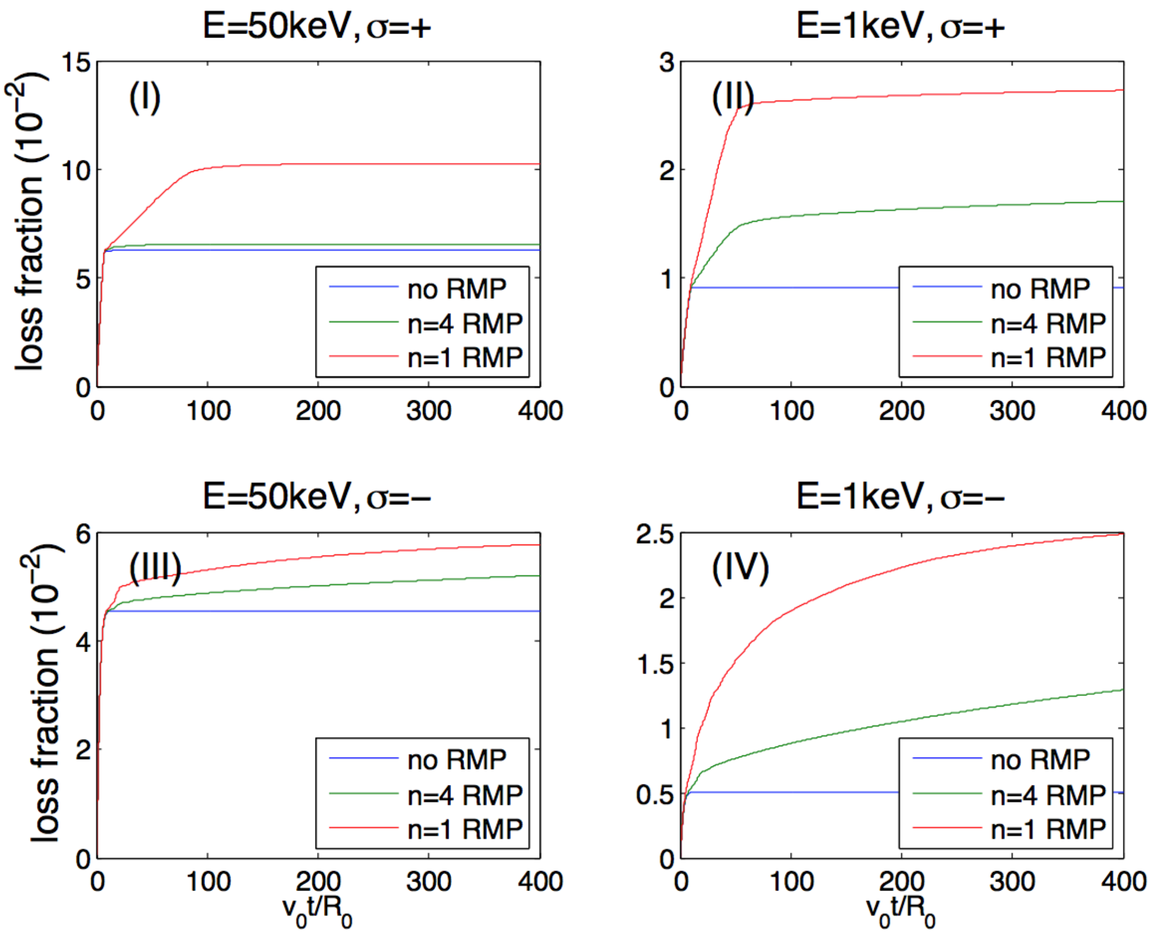
Initial radial profile of passing ion density:

$$\hat{n} = \exp(-\hat{\psi}/\Delta).$$



- The loss fractions for all cases are almost in the **steady state**.
- The loss fractions **increase with perturbation amplitude** and **width of density profile** $\triangle$.
- The loss of **energetic** passing ions $>$ the loss of **thermal** passing ions.
- For energetic ions, the extra loss induced by **RMPs** $\sim$ the loss induced by the **magnetic drift**, when amplitude parameter of RMPs is about 10^{-4}.

Temporal evolution of loss fraction of passing ions

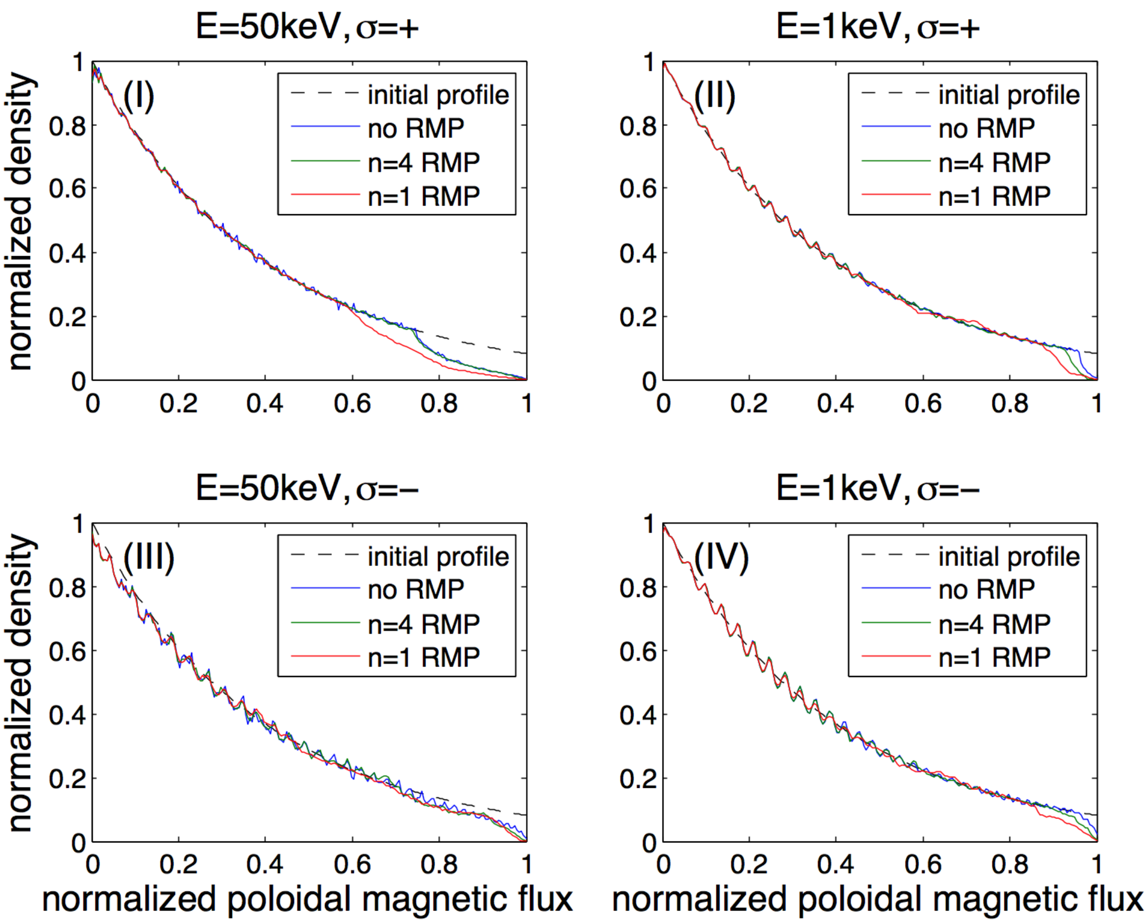


- The loss fraction of the **energetic** ion cases > that of the **thermal** ion cases.
- The loss fraction of the **co-passing** ion cases > that of the **counter-passing** ion cases.
- The loss rate induced by **stochasticity** << that induced by the **magnetic drift** and that by the **drift island**.
- For each case, the loss fraction with **n=1** RMPs > that for **n=4** RMPs.

- For the cases without RMPs, the loss occurs in about one poloidal transit period of ion.
- Two key factors contribute the extra loss induced by RMPs:
  1. **drift island structure** induced by RMPs and the magnetic drift;
  2. **stochasticity** induced by overlap of magnetic islands.

Redistribution of passing ions

Redistribution at the final time ($v_0 t/R_0$=400)



For the energetic co-passing ions:

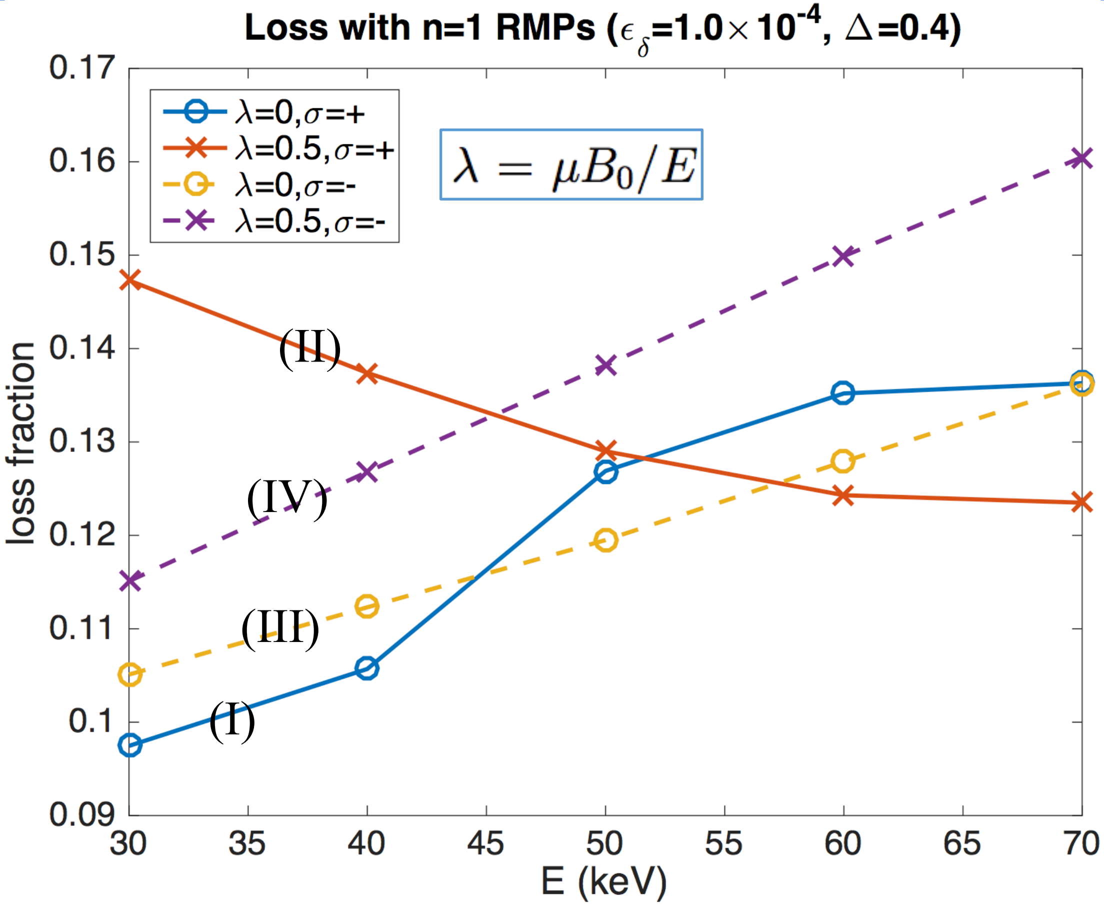
- The loss region with **n=1** RMPs > that with **n=4** RMPs.
- The safety factor near the edge is **not large** (q_{edge}=3.37) → **little stochasticity**
- island width: $w_{mn} = 4\sqrt{\left|\frac{\rho b_{mn}}{nS}\right|_{q=q_s}} \propto \frac{1}{\sqrt{n}}$
- The loss induced by drift islands for **n=1** RMPs > that for **n=4** RMPs.
- The drift island effect is significant for n=1 RMP case.

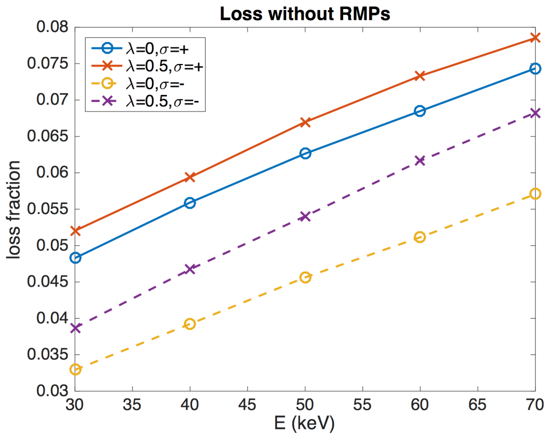
For energetic counter-passing ions:

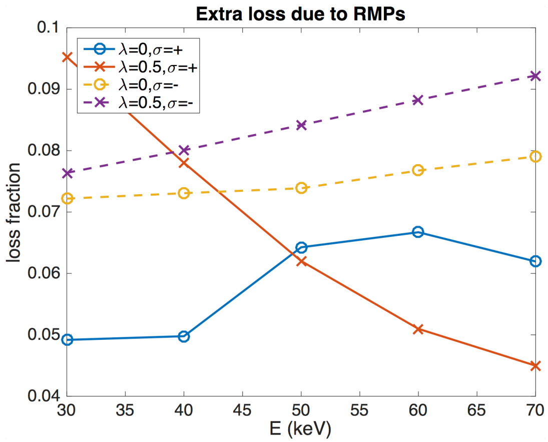
- The loss region for the cases **with** RMPs ~ that for the case **without** RMPs.

- The redistribution near the edge is related to the loss induced by RMPs and the magnetic drift.
- The oscillation of the redistribution is mainly due to the magnetic drift.
- The difference between the redistribution and the initial profile denotes the **loss region**.

Energy and pitch scan for loss fraction







Loss with RMPs:

- The loss fraction for cases I, III and IV **increases with energy**, which is mainly due to the **magnetic drift**.
- The loss fraction for case II **decreases with energy**, which is related to the **drift islands** induced by RMPs and the magnetic drift.

Loss without RMPs:

- The loss induced by the magnetic drift increases with energy for each case.

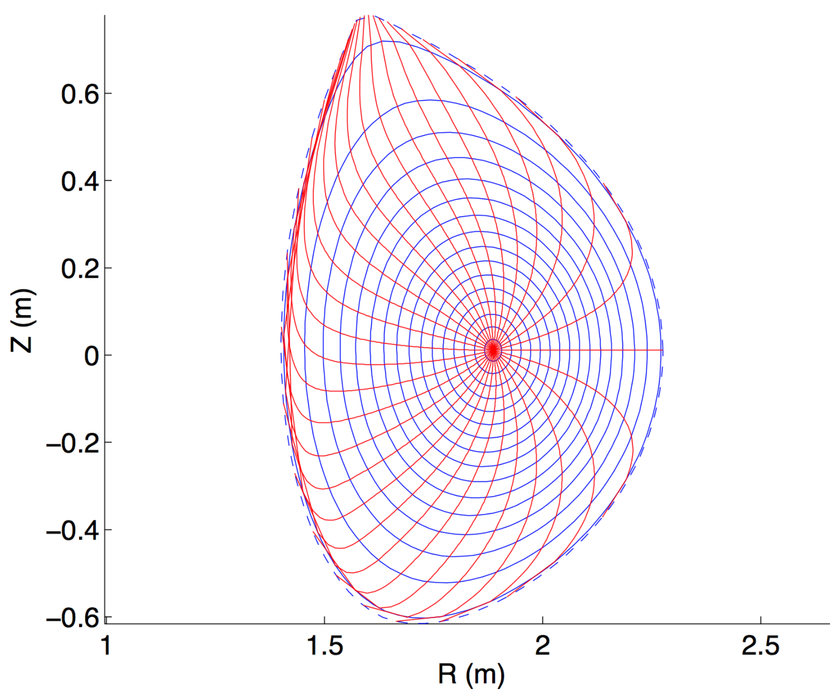
Outline

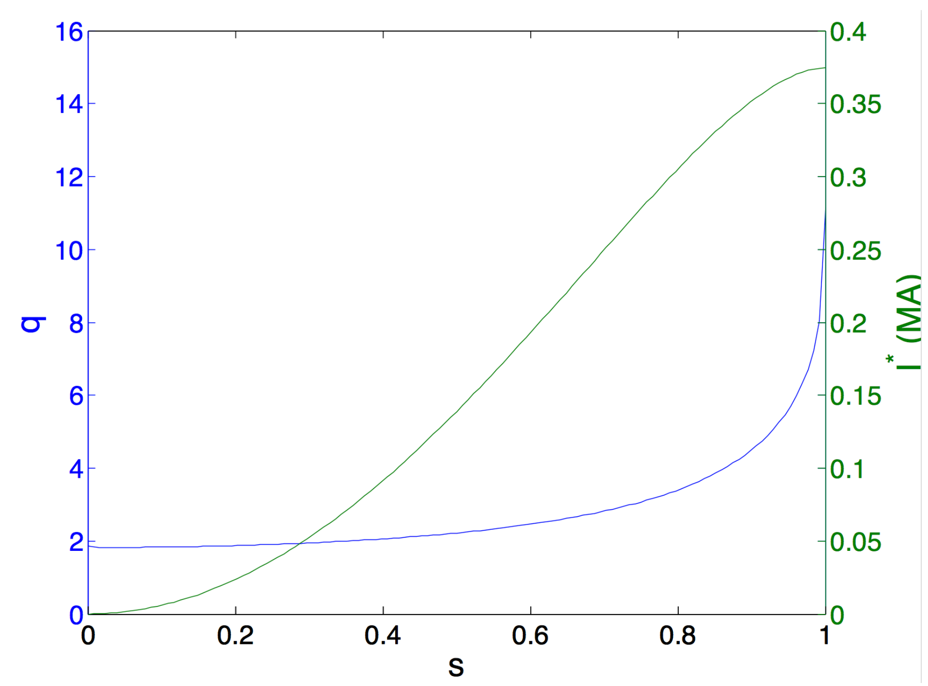
- Introduction
- Orbit following code GYCAVA
- Simulations of loss and redistribution of energetic passing ions with RMPs
  - Simulations for analytic equilibrium
  - Simulations for EAST equilibrium
- Summary

EAST equilibrium configuration and RMPs

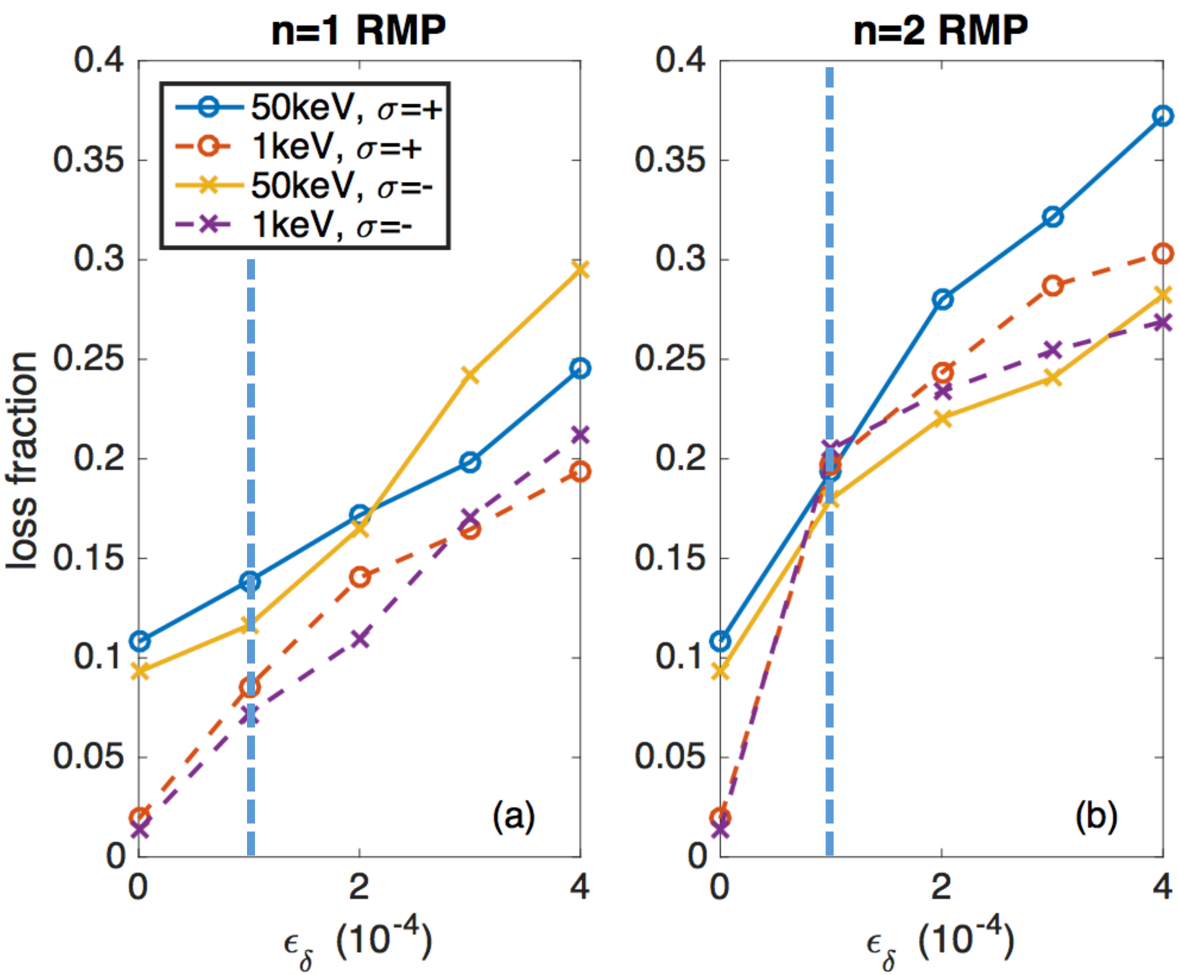
- EAST equilibrium configuration (#73999) is used in the following simulations.
- Safety factor: q = 1.87−11 with q_{95}=6.6, current: Ip ~ 0.4MA.
- given RMPs: $\delta B_N = \epsilon_\delta s \sum_m e^{i(m\theta - n\zeta)}$

1. n=1 RMPs with m=2-14
2. n=2 RMPs with m=2-14





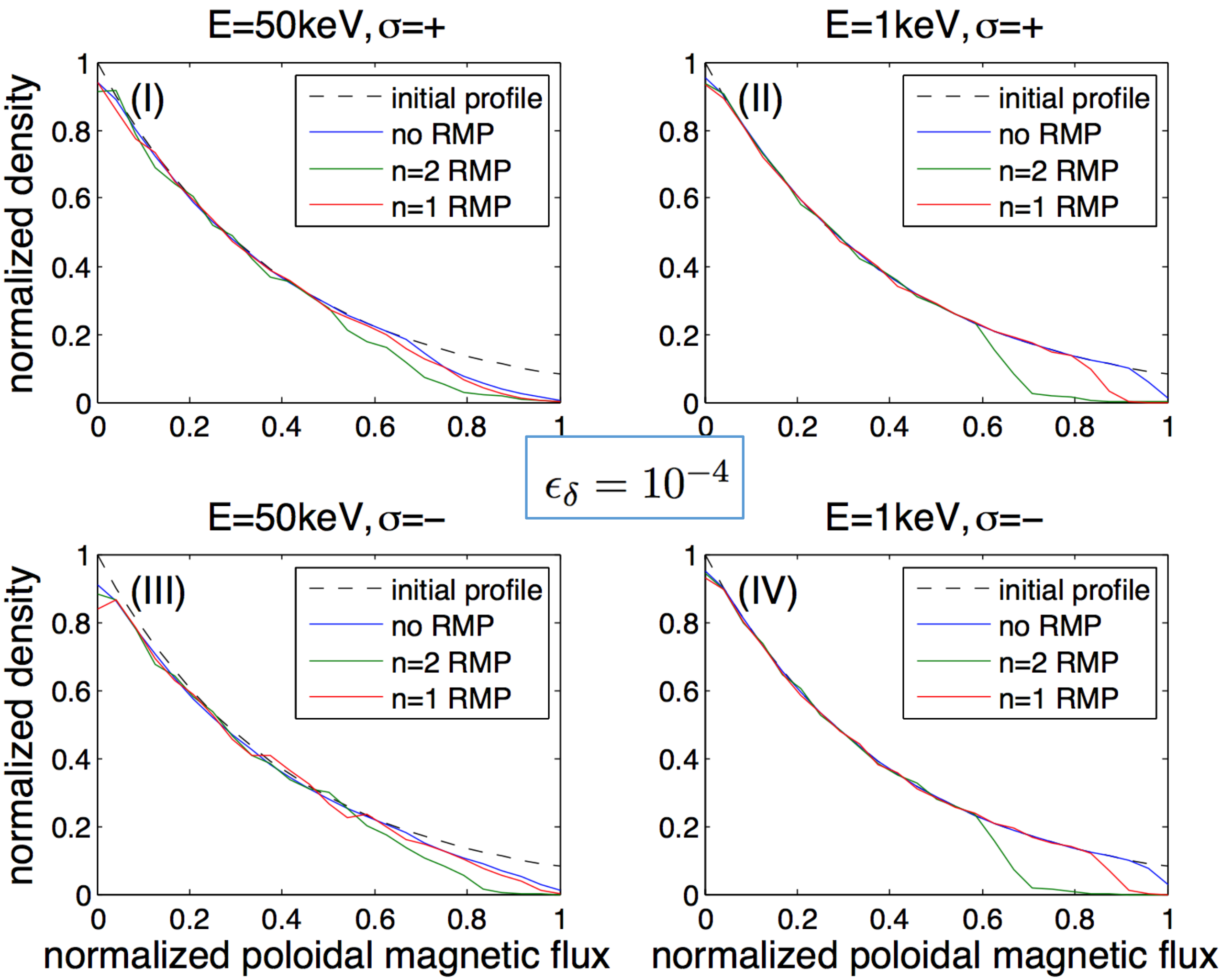
Perturbation amplitude scan for loss fraction of passing ions



- The loss fraction of passing ions for each case **increases** with the **amplitude** of RMPs.
- For n=1 RMPs: magnetic drift → loss of energetic ions > loss of thermal ions
- For n=2 RMPs: the effect of the **magnetic stochasticity** dominates the loss of energetic ions when epsilon≥2x10^{-4}.

- For epsilon=10^{-4}, loss with **n=2** RMPs > loss with **n=1** RMPs for each case.

Redistribution of passing ions for RMPs with different n

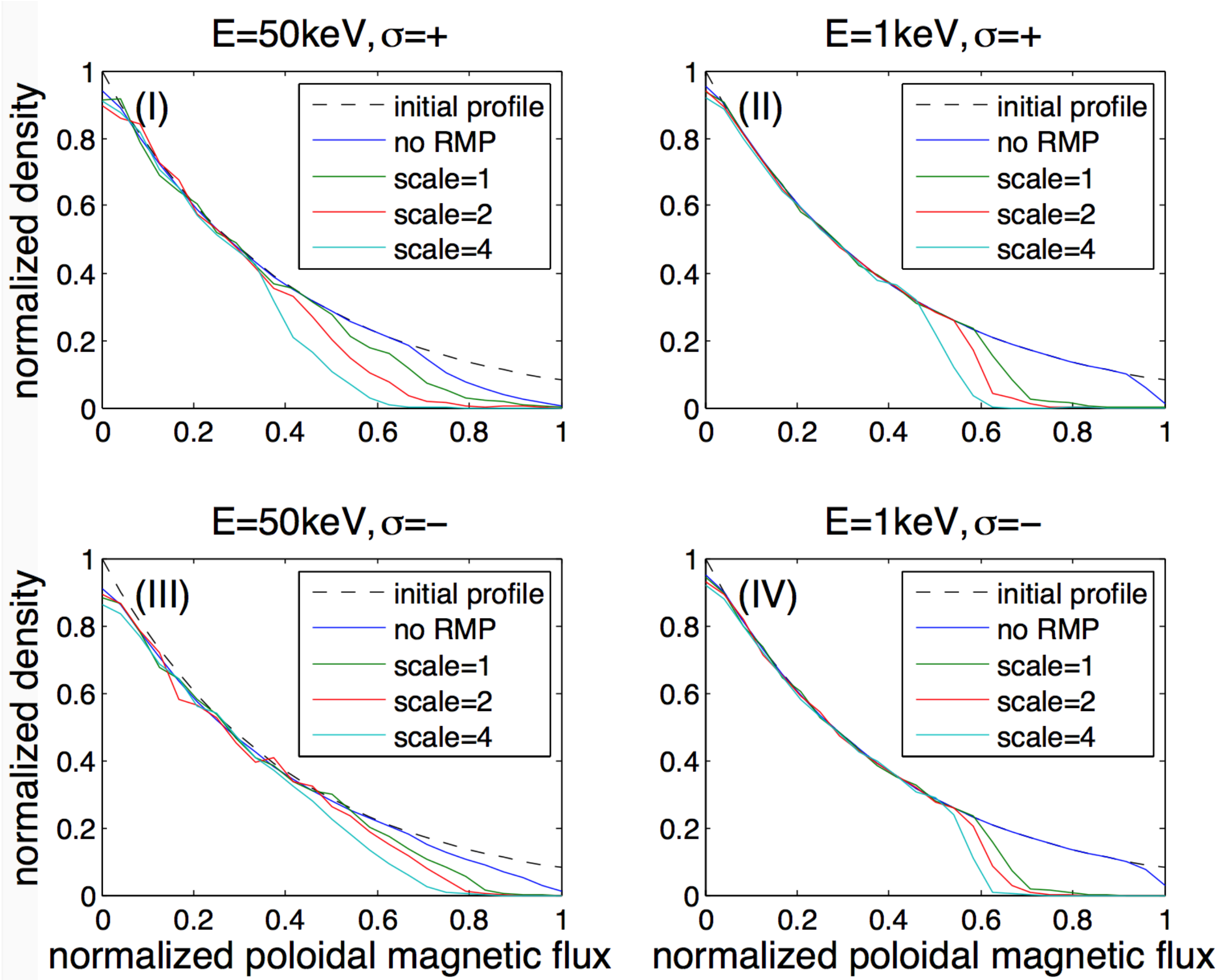


for energetic ions:

- loss region with **n=1** RMPs ~ loss region **without** RMPs
- loss region with **n=2** RMPs > loss region with **n=1** RMPs

- loss fraction/region with **n=2** RMPs > those with **n=1** RMPs for each case.
  - q_{edge} is **large** (q_{95}=6.6) , and the **number of magnetic islands** induced by n=2 RMPs > that induced by n=1 RMPs → **more stochasticity** for n=2 RMPs

Redistribution for n=2 RMPs with different amplitudes



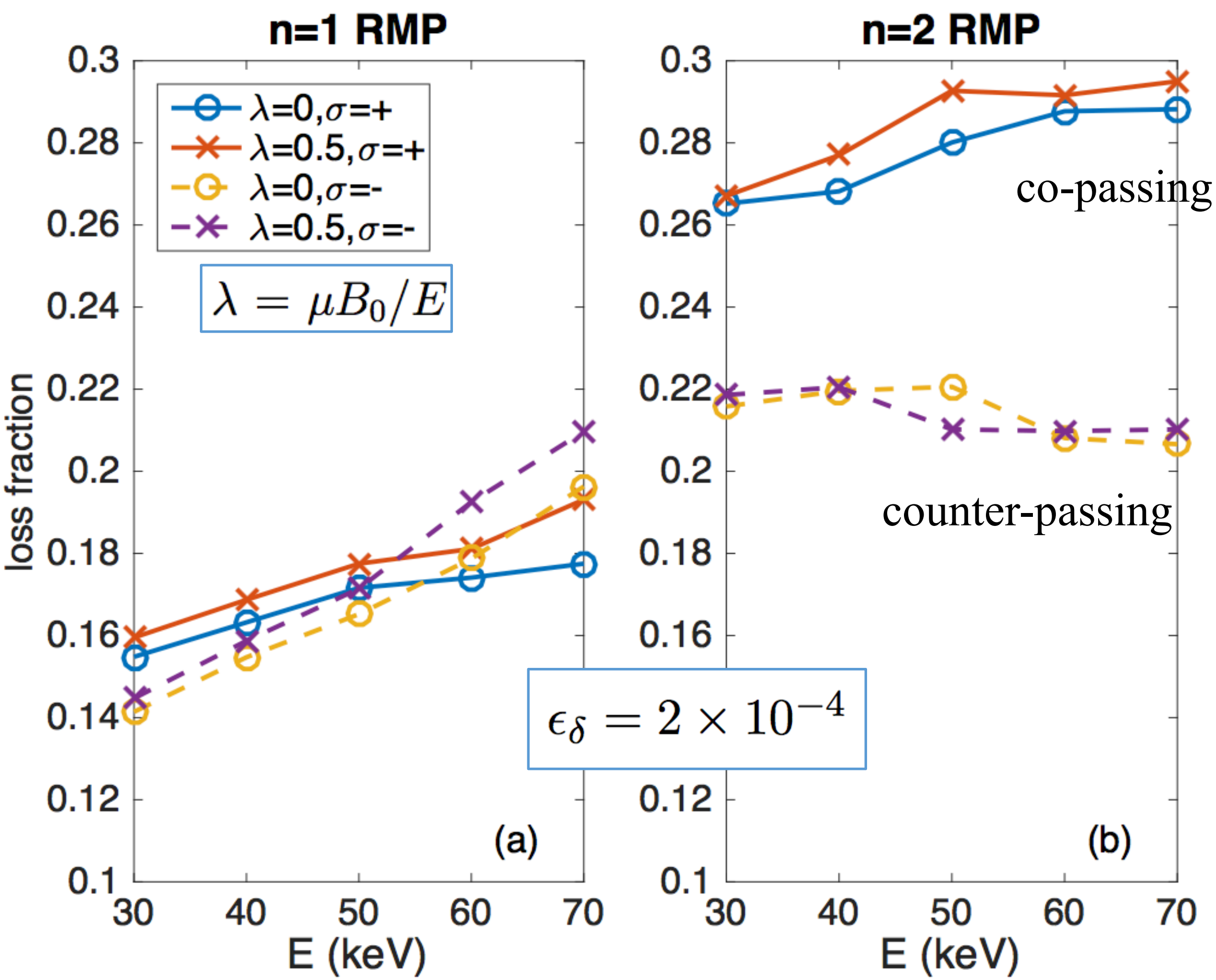
$$\delta B_N = \epsilon_\delta s \sum_m e^{i(m\theta - n\zeta)}$$

$$\epsilon_\delta = scale \times 10^{-4}$$

- For each RMP case, the loss region of **energetic** ions is different from that of **thermal** ions.
- This difference is mainly due to the **magnetic drift**.

- Loss region of passing ions **increases with the amplitude** of RMPs for each case.
- The loss region of **co-passing** ions > that of **counter-passing** ions.

Energy and pitch scan for loss fraction of energetic passing ions



n=1 RMP:

- Loss fraction **increases with energy** for each case.
- The change of loss fraction for **counter-passing** ions $>$ that for **co-passing** ions.

n=2 RMP:

- Loss fraction of **co-passing** ions $>$ loss fraction of **counter-passing** ions.
- The loss fraction of **counter-passing** ions changes little with energy increasing.

Outline

- Introduction
- Orbit following code GYCAVA
- Simulations of loss and redistribution of energetic passing ions with RMPs
  - Simulations for analytic equilibrium
  - Simulations for EAST equilibrium
- Summary

Summary

- The orbit following code GYCAVA has been upgraded for studying the behavior of passing ions induced by RMPs.
- The loss and redistribution of energetic and thermal passing ions with different RMPs have been numerically studied for EAST.
  - The loss fraction and the loss region of passing ions increase with the amplitude of RMPs.
  - For the energetic passing ions, the extra loss induced by RMPs can be comparable to the loss induced by the magnetic drift.
  - The extra loss of passing ions induced by RMPs is related to the drift island structure induced by RMPs and the magnetic drift, and the stochasticity induced by overlap of magnetic islands.
  - The dependence of the loss fraction and loss region on the toroidal mode number of RMPs is related to the safety factor.
    - For low q_{edge}, the effect of drift islands on the loss of energetic passing ions is significant for the n=1 RMP case.
    - For high q_{edge}, the loss is dominated by the magnetic stochasticity.
  - The pitch angle and energy of particle can impact the loss of energetic passing ions.

Thank you!