Modeling of sawtooth-induced fast particle redistribution in NSTX-U

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Introduction Experimental observations from National Spherical Torus Experiment Upgrade (NSTX-U) L-mode sawtoothing discharges [1] show that sawteeth strongly redistribute passing particles from the plasma core to the edge, while trapped particles are weakly affected [2]. Some global experiment parameters, such as neutron rate can be reproduced using standard sawtooth models in the TRANSP [3] code. However, without including the dependence of fast ion phase space variables such as energy, pitch and canonical angular momentum in the sawtooth models, estimated features of fast ions, e.g. fast ion distribution function, can be different from the measurements [2]. Therefore a more comprehensive model that takes into account the characteristics of fast ion in phase space needs to be developed for quantitative simulations, so that more reliable interpretation of sawtoothing discharges can be possible. As a first step of the development of the improved model, simulations using the ORBIT code [4] have been carried out [5]. The simulation results confirm the experimental observation that fast ions are redistributed by sawtooth crash based on their orbit type and energy; passing particles in the core region are expelled and move outside the $q = 1$ surface in the simulation while a sawtooth crash does not have significant effects on trapped particles, in particular for the particles with energy higher than 30keV. The newly developed “kick model” [6, 7] has been applied for the sawtooth instability based on the ORBIT modeling. The transport probability matrix estimated from the kick model has been used as an updated input parameter for NUBEAM module [8, 9] in TRANSP [3]. Preliminary results show features of sawtooth induced fast ion redistribution that were not found from the conventional sawtooth model.

Simulation methodology Simulations have been performed based on the NSTX-U discharge #204083 using the ORBIT code [4], a Hamiltonian guiding-center code for analysing energetic particle transport by instabilities in tokamaks. In this work, we have implemented a magnetic perturbation that represents the sawtooth instability in the ORBIT code. The magnetic perturbation is applied using a scalar function α $\left(\delta\vec{B} = \nabla \times \left(\alpha\vec{B}\right)\right)$ and the radial perturbed magnetic field for the $m = 1, n = 1$ mode sawtooth instability is obtained as $\delta\vec{B}\cdot\nabla\psi_p = (mg + nI)\,\alpha\cos(n\zeta - m\theta - \omega t)/J$ where B and $\delta\vec{B}$ are the equilibrium and the perturbed magnetic fields, ψ_p is the poloidal magnetic flux, g and I are the poloidal and toroidal current functions, J is the Jacobian, (ζ, θ) are the toroidal and poloidal angle and ω is the mode frequency.

To test the dependencies of sawtooth induced fast ion transport on the phase space variables, the reduced “kick model” [6, 7] is used in conjunction with the ORBIT modeling results. Using the changes in phase space variables estimated in the ORBIT code under the given perturbation, the kick model computes the probability of the change of particle’s energy (E) and

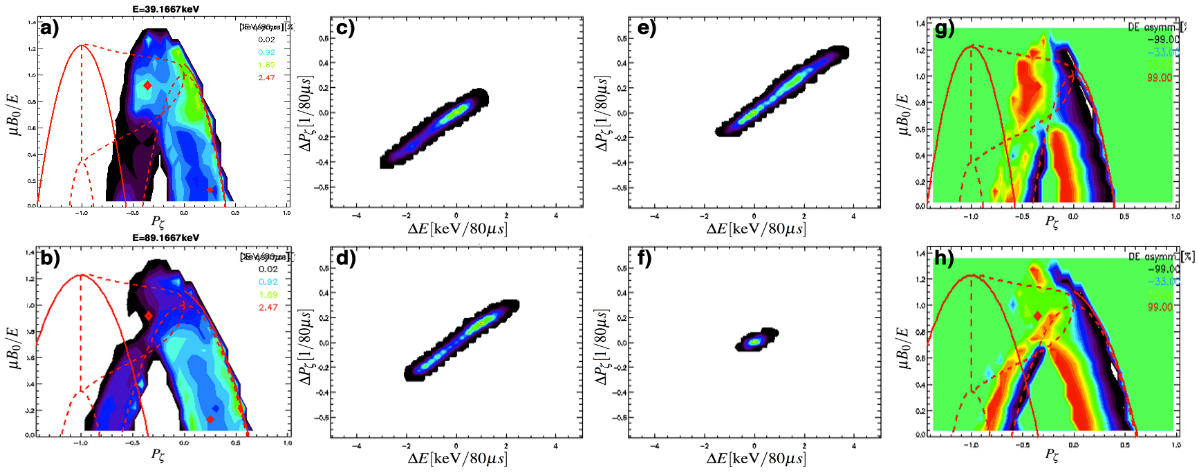

Figure 1: a,b) The variation of particle energy due to a sawtooth crash for two different particle energy cases. Red diamond at lower μ value is a location of passing particles in phase space while the higher μ case represents trapped particles. $c-f$) Calculated probability matrices from the kick model for passing and trapped particles. $g-h$) The averaged value of the probability matrix at each location in phase space.

canonical angular momentum (P_ζ) around a certain phase space position defined by particle's energy, canonical angular momentum and magnetic moment (μ). The resulting probability matrix $p(\Delta E, \Delta P_\zeta | E, P_\zeta, \mu)$ from the kick model is an input to the NUBEAM module [8, 9] in TRANSP [3], a Monte Carlo module that calculates the evolution of energetic particles based on neoclassical physics, to include the effects of instabilities in the NUBEAM calculation and the results are passed back to TRANSP.

ORBIT modeling With the given mode amplitude and the perturbation shape, the kick probability matrix of particle's energy and canonical momentum has been calculated in ORBIT for each sawtooth crash. One example from a time slice (1093ms) is shown in the Fig. 1. Two rows present two different energy cases (39 and 89keV on average). The first column (Fig. 1a,b) shows the average change of particle's energy due to a crash in terms of phase space variables. For both energies, most of passing particles are affected by a sawtooth crash. The effect of sawtooth instability on trapped particles is similar to passing particle for the lower energy case (39keV), while almost no change in particle energy is found for the higher energy case (89keV). This is consistent with the redistribution criteria from Ref. [10] and the simulation results from Ref. [5].

The kick probability of passing and trapped particles at a certain phase space (red diamonds at $\mu B_0/E \sim 0.1, 0.9$ from Fig. 1a,b) are depicted in the second and the third columns, respectively. The probability is calculated for a time step of every 80μs in the ORBIT modeling. For the lower energy passing particles, the variations of P_ζ and E are mostly negative; this indicates that particles are expelled from the centre due to a crash. In this case, the chosen phase space location is near the magnetic axis in real space. For the higher energy case, the averaged positive and negative probabilities are balanced thus the redistribution is not clear. In this case as the same P_ζ and E position is shifted in phase and real space, particles are located near the inversion radius.

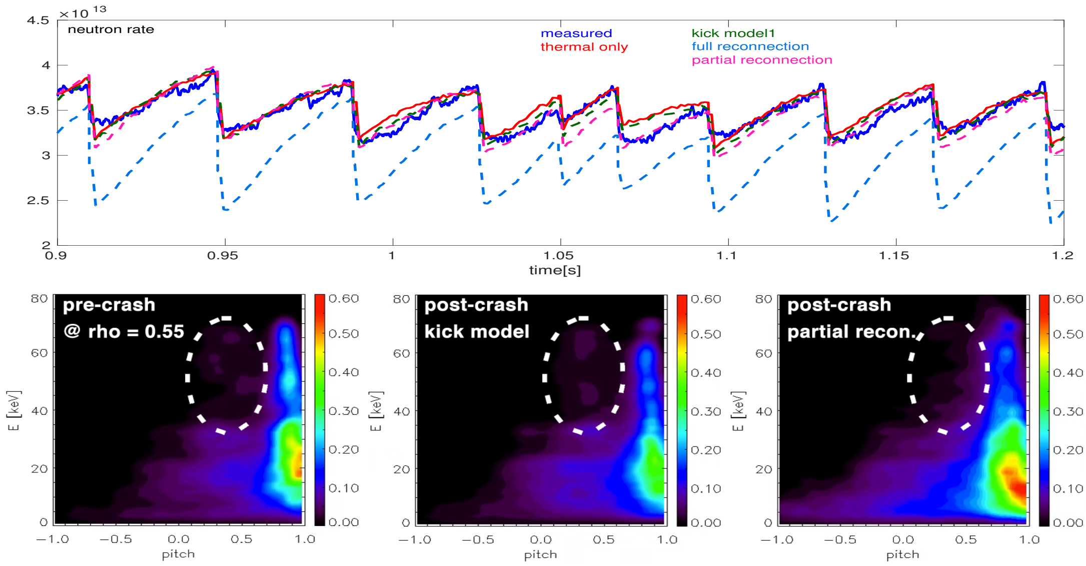

Figure 2: Neutron rates from experiment and TRANSP simulations using different model for sawtooth induced fast ion redistribution. Without including fast ion redistribution, neutron rate is almost the same as the measurement. Using kick model and partial reconnection model can also reproduce the experimental neutron rate while full reconnection model over estimates the drop of neutron rate at each crash. Although the neutron rate is similar the change of fast ion distribution before and after a sawtooth crash is different based on the model.

Unlike passing particles, the probability matrix for trapped particles with lower energy is more positive (particles move inside the inversion radius), while the change in (P_ζ, E) vanishes for higher energy particles.

The redistribution of fast ions with different orbit type can be intuitively found from the rightmost column. These figures show the balance of the averaged positive and negative energy kicks at each location. Blue (red) colours mean that ΔP_ζ is mostly negative (positive). One can picture in the real space that particles are expelled from near axis (blue region, see Fig. 1c) or move inside (red, see Fig. 1e) during a crash based on their initial position with reference to the inversion radius. The green region between the blue and red corresponds to the inversion radius (see Fig. 1d).

Application to TRANSP simulations The calculated probability matrix has been applied to TRANSP simulations for modeling the fast ion redistribution induced by a sawtooth crash. A matrix from one time slice (1093ms) is used for all the crash times. The mode amplitudes for each time slice are taken from measurement and are normalised using the mode amplitude at 1093ms. The simulation results are compared with several cases; without fast ion redistribution, using full/partial reconnection for the sawtooth model and the comparisons are shown in Fig. 2.

In Fig. 2 upper panel, the neutron rate from TRANSP simulations is comparable with the measured one even without fast ion redistribution (thermal particle redistribution only). This means that most of the neutron rate drop is caused by changes in the thermal profiles. For the kick model and partial reconnection (reconnection fraction is 0.5), the amplitude of sawtooth instability seems too small to affect the neutron rate significantly and the neutron rate is similar to the case without fast ion redistribution and measurement. The fast ion redistribution estimated using full reconnection is more significant so that the neutron rate drop is almost twice the other cases. As seen in Ref. [5], in order for the fast ion redistribution to contribute to the neutron rate drop comparable to the one caused by redistribution of thermal plasma, the amplitude needs to be larger. The estimated amplitudes from ORBIT have also been tested (not shown in Fig. 2) but over-estimate the neutron rate drop.

Although the simulated neutron rate using the kick model and partial reconnection are comparable to the measured one, detailed simulation results from each model have different features. For instance, the fast ion distribution functions just outside the inversion radius ($\rho = 0.55$) before and after a sawtooth crash shown in Fig. 2 (second row) show different results. Since the pre-crash distribution functions from the kick model and partial reconnection cases are similar to the case without fast ion redistribution, pre-crash distribution of thermal only case is taken as a reference. The distribution function after a crash is different for both cases. The shape of fast ion distribution keeps the pre-crash feature for the kick model case, while it is different for partial reconnection case. In addition, as previously discussed, trapped particles (pitch ~ 0) with higher energy over $\sim$ 40keV are not affected by sawtooth as the distribution function does not change much for kick model case (white circle). Using partial reconnection, trapped particles also experience redistribution. Compared to kick model case, larger modification on counter passing particles (pitch $\sim$ -1) distribution is also found.

As seen in Fig. 2, the application of the kick model shows that taking into account the phase space dependence of transport can bring different features of fast ions from the conventional sawtooth models. In order to validate the improvement from the kick model, the simulation results need to be compared with the experimental measurement. The comparison would be done when the measured fast ion distribution function is available. Although the validation of the model are not feasible, the application of the kick model can be a starting point for the development of a more quantitative model.

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