National Spherical Torus eXperiment Upgrade

PPPL PRINCETON PLASMA PHYSICS LABORATORY

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Investigation of fast particle redistribution induced by sawtooth instability in NSTX-U

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Introduction

Motivation

- ☐ NSTX-U L-mode sawtoothing discharges analysis [1] using TRANSP code [2]
  - Conventional sawtooth models cannot fully reproduce the behaviour of fast ion during sawtooth crashes
    - Some global features (e.g. neutron rate) can be reproduced
    - Fast ion properties (e.g. distribution function) may not be adequately be recovered
  - Free parameters in TRANSP (e.g. redistribution and/or reconnection fraction) need to be determined in priori
- ☐ A more reliable model to describe sawtooth-induced fast ion transports is required
  - Phase space dependences (fast ion energy, pitch, canonical momentum, etc.) needs to be considered
  - Kick model [3] is applied to provide modelling results as an input for NUBEAM [4] in TRANSP

Simulation tools

- ☐ ORBIT [5]: Hamiltonian guiding-centre code
  - Analyse energetic particle transport induced by instabilities in tokamaks
  - Sawtooth instability is applied as (1,1) mode magnetic field perturbation using a linear displacement

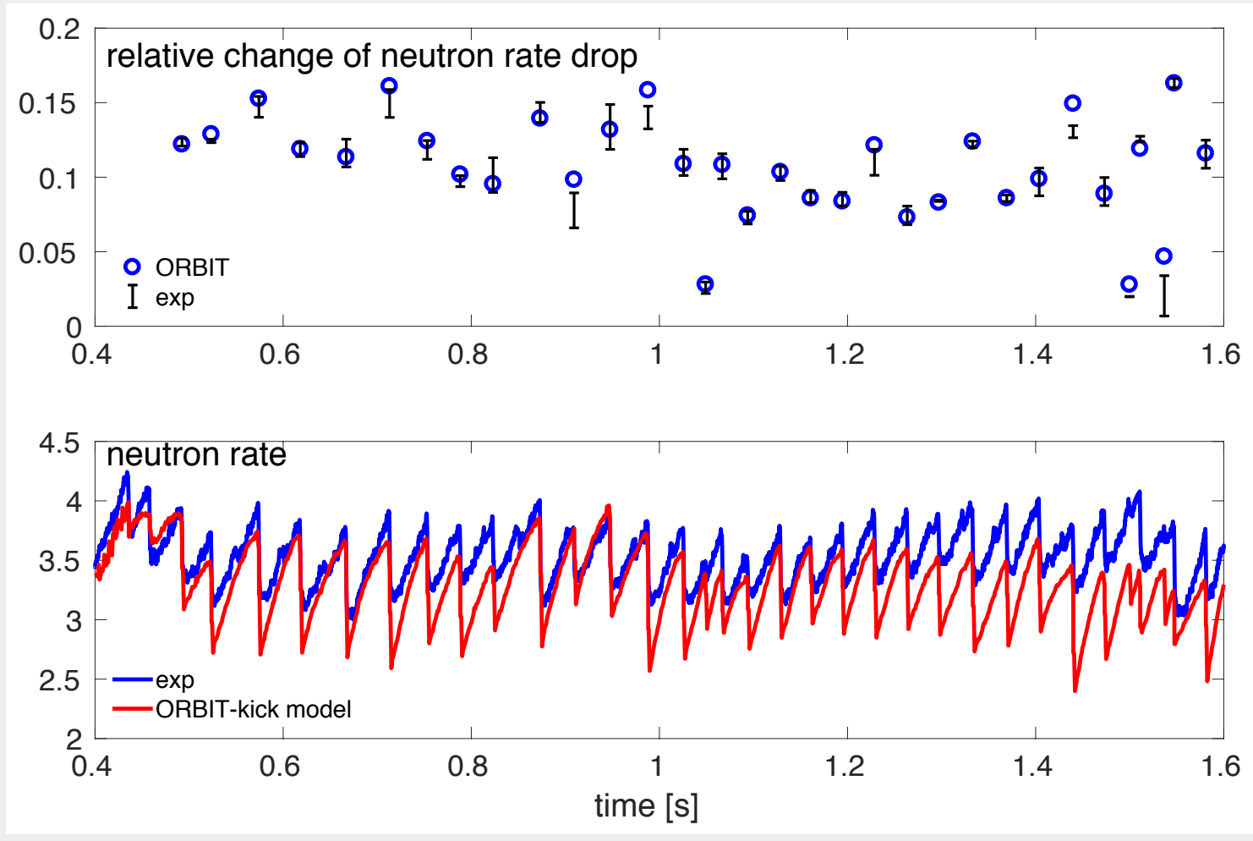
$$\delta\vec{B} = \nabla \times \left(\alpha\vec{B}\right) \quad \alpha_{mn} = \frac{m/q - n}{mg + nI}\xi_{mn}$$

$$\delta\vec{B}\cdot\nabla\psi_p = \sum_{m,n}\frac{mg + nI}{J}\alpha_{mn}\cos\left(n\zeta - m\theta - \omega t\right)$$

- ☐ Kick model [3]: Reduced fast ion transport model
  - Compute transport probability matrices to represent the fast ion transport induced by instabilities
  - Test the dependencies of fast ion redistribution during sawtooth crashes on the fast ion phase space variables
- ☐ TRANSP / NUBEAM [4]: Tokamak transport code / Monte Carlo module
  - Enable time dependent integrated interpretative/predictive simulations of tokamak discharges
  - Use the probability matrix from ORBIT-kick model as an input for NUBEAM calculation in TRANSP simulation
- ☐ FIDASIM [6]
  - Calculate a synthetic FIDA diagnostic signal
  - Predict and integrate the active D_α emission for FIDA profile to compare with measurements

ORBIT Modelling Results

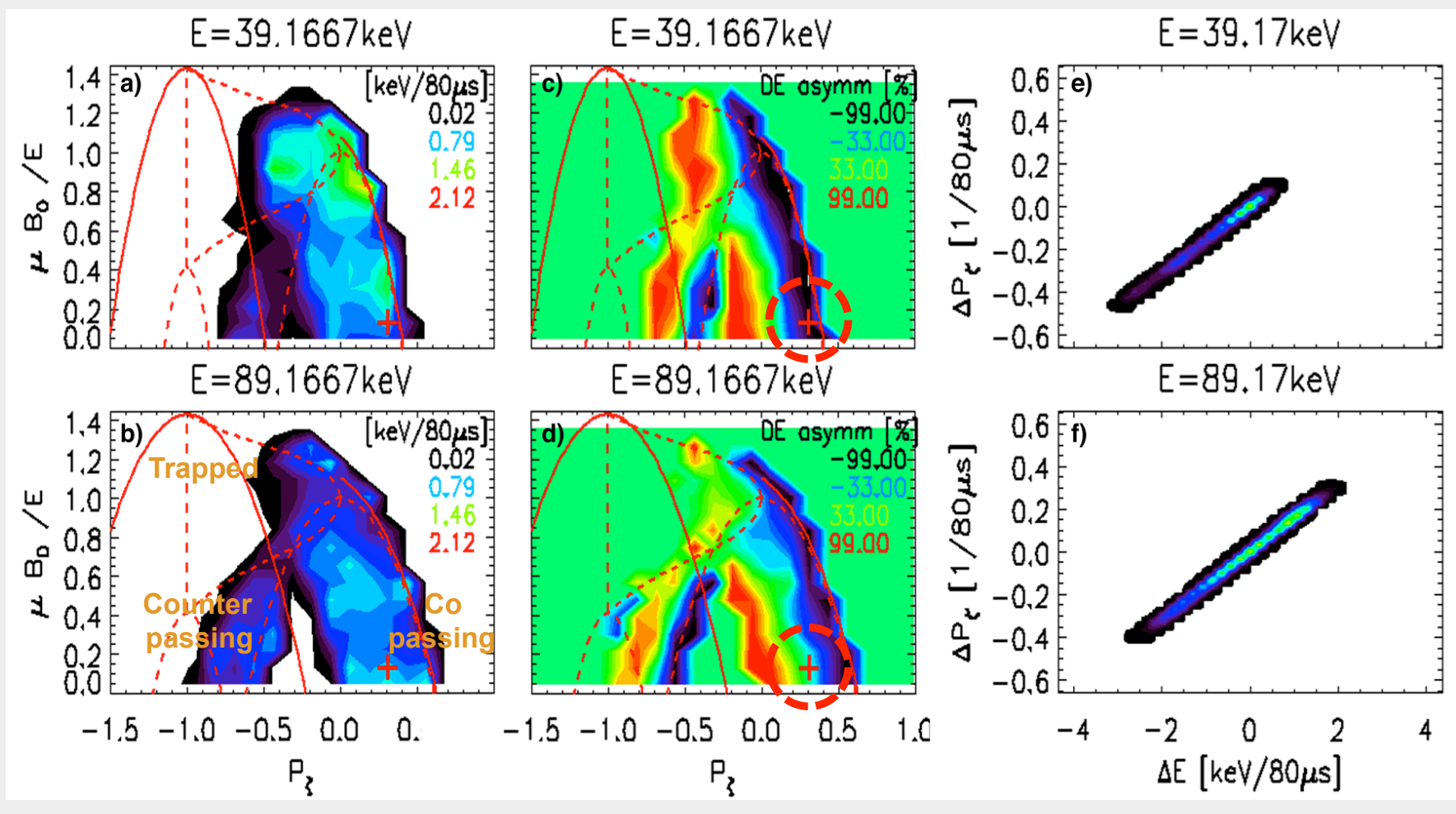
☐ Mode amplitude estimation using ORBIT code and application of kick model to ORBIT modelling



- Relative change of neutron rate drop: ORBIT [10] vs measurements

$$\Delta\text{neut\_rate} = \frac{\sum_k n_{d0,k}S_{0,k}\sqrt{E_{0,k}}dV_k - \sum_k n_{df,k}S_{f,k}\sqrt{E_{f,k}}dV_k}{\sum_k n_{d0,k}S_{0,k}\sqrt{E_{0,k}}dV_k}$$

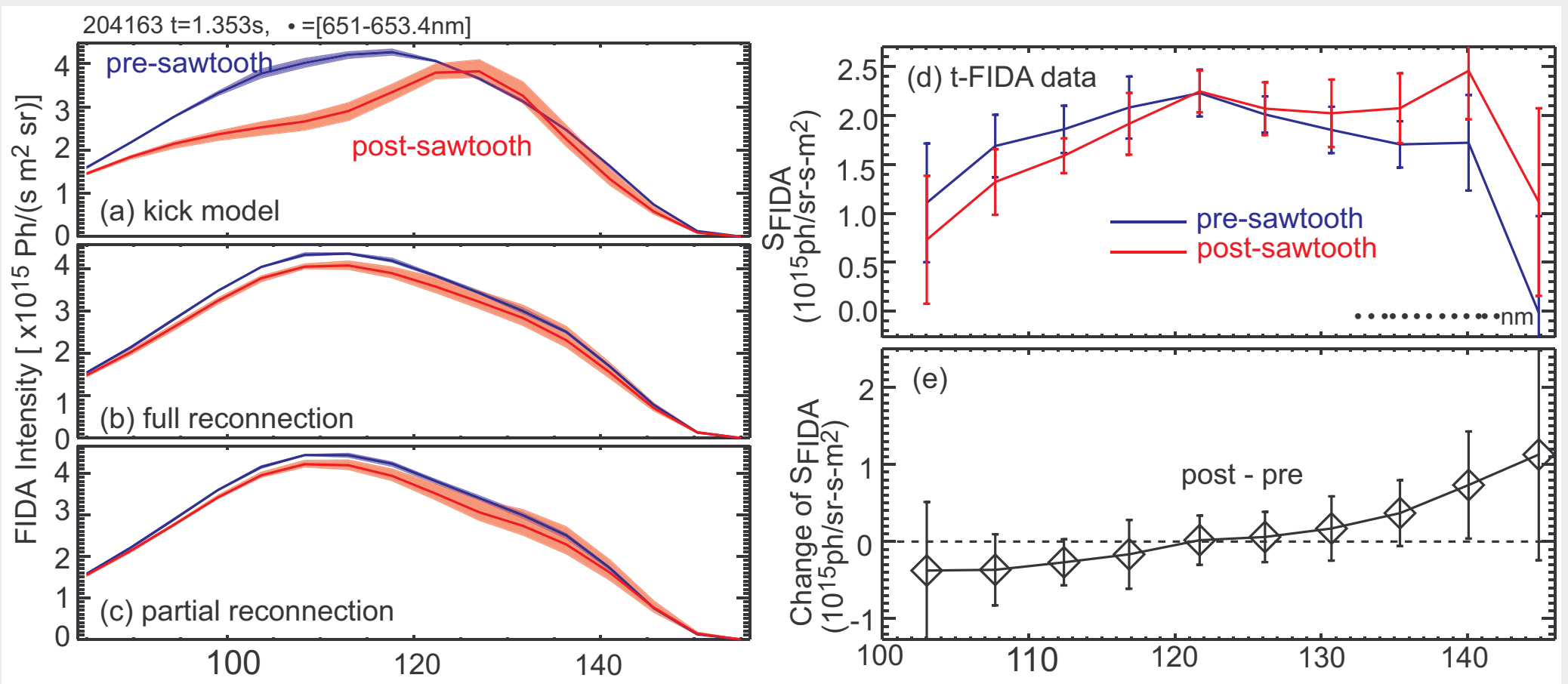
- Kick model is applied for the probability matrix calculation
  - ΔE and ΔP_ζ calculation with the ORBIT-estimated mode amplitudes
- Comparison of neutron rate from simulations and experiments
  - TRANSP using kick model results over-estimates neutron rate
  - Input data for the estimation of mode amplitude has uncertainties
  - The amplitude in ORBIT modelling remains as a free parameter



- The probability matrix depends on the particles' position in phase (orbit type) and real space (relative location to ρ_{inv})
- Passing particles in all energy range are affected by a crash
- Trapped particles under a certain energy are redistributed
- Negative averaged ΔP_ζ (blue): particles move outside ρ_{inv}
- Positive averaged ΔP_ζ (red): particles move inside
- Balanced averaged ΔP_ζ (green): particles are initially located near ρ_{inv} and move similarly both inside and outside

Comparison of Simulation Results with Experiments / Theory

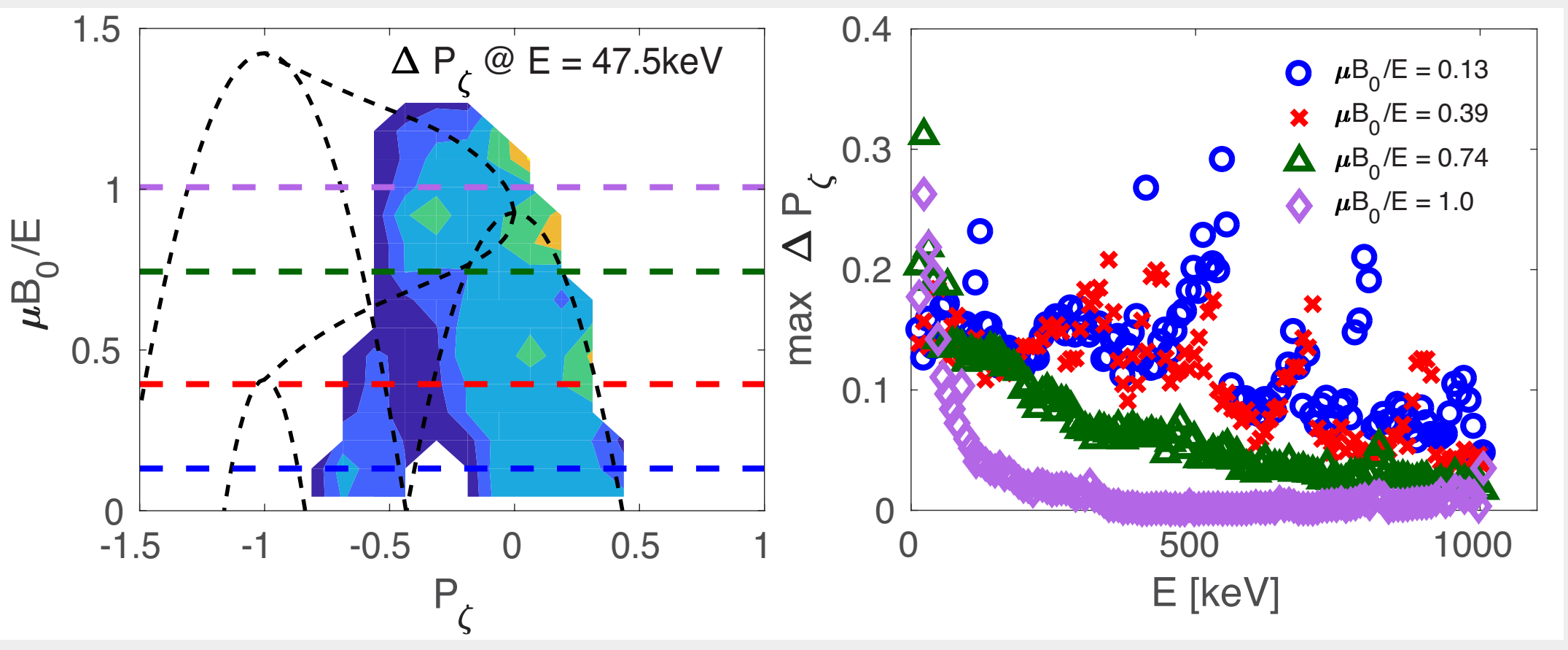
☐ Comparison of fast ion distribution functions with FIDA measurements



- Synthetic FIDA signal from FIDASIM using TRANSP simulation results with different models
  - Comparison of measured FIDA spatial profiles
- Average simulated FIDA profiles over 1, 3, 5ms before and after a crash
  - compensate the FIDA temporal resolution (10ms)
- Measurement from t-FIDA (mostly sensitive to passing particles) is considered

- FIDA measurement: fast ions in the centre are expelled to outside the inversion radius (R~122cm) after a crash
- Kick model: qualitatively reproduces the measured FIDA signal
  - After a crash t-FIDA signal drops up to 50% inside the inversion radius (R~125cm)
  - The shoulder of increased signal is seen outside the inversion radius
- Full/partial reconnection: no clear sign of the sawtooth-induced fast ion redistribution
  - t-FIDA signal decreases all across the radius after a crash
  - Can be similar to kick model case with larger fast ion redistribution fraction (with largely over-estimated neutron rate)

☐ Comparison of critical energy with theory [11]



- Redistribution criterion for trapped particles

$$v << r_{\text{mix}}\omega_{\text{B}}\left(\frac{4\pi}{\varepsilon_{\text{mix}}\tau_{\text{cr}}\omega_{\text{B}}}\right)^{\frac{1}{2}}$$

- No-redistribution condition for passing particles

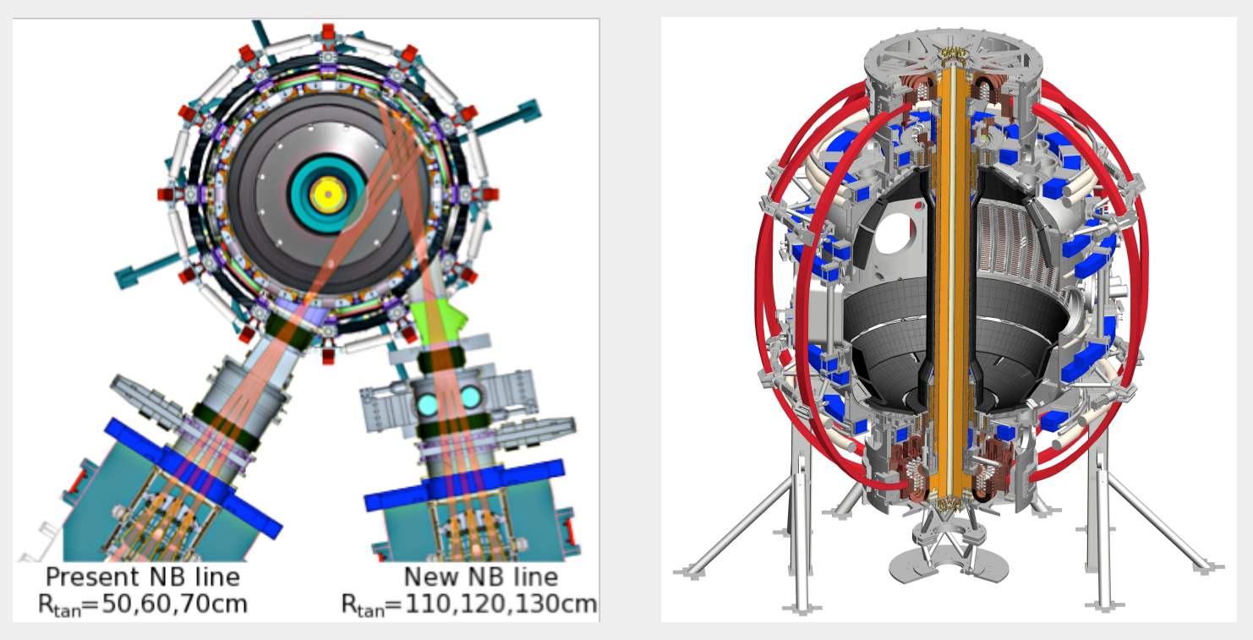
$$v >> r_{\text{mix}}\omega_{\text{B}}\left|q-1\right|/G\left(\kappa\right)$$

- The maximum ΔP_ζ values vs energy show that
  - The critical energy for passing particles redistribution is not clearly seen (blue and red, estimated E_{crit} ~ 1.1MeV)
  - Trapped particles with energies over ~30keV are weakly affected by the crash (green, violet, estimated E_{crit} ~ 28keV)
- The kick model estimation is consistent with the theory [11] and ORBIT modelling [10]

References [1] D. Liu *et al., Nucl. Fusion* **58**, 082028 (2018), [2] R. Hawryluk, An empirical approach to tokamak transport Physics Close to Thermonuclear Conditions vol 1 ed B. Coppi *et al.* (Brussels: Commission of the European Communities) p 19. (1980), (http://w3.pppl.gov/~pshare/help/transp.htm), [3] M. Podestà *et al.*, *Plasma Phys. Control. Fusion*, **56**, 055003 (2014), [4] A. Pankin *et al.*, *Comput. Phys. Commun.*, **159**, 157 (2004), [5] R.B. White *et al.*, *Phys. Fluids*, **27**, 2455 (1984), [6] W.W. Heidbrink *et al.*, *Ncommun. Comput. Phys.*, **10**, 716 (2011), [7] J. Menard *et al.*, *Nucl. Fusion*, **52**, 083015 (2012), [8] M. Podestà *et al.*, *Rev. Sci. Instrum.* **79** 10E521 (2008) [9] D. Liu *et al.*, *Rev. Sci. Instrum.* **85** 11E105 (2014) [10] D. Kim *et al.*, *Nucl. Fusion* **58**, 082029 (2018), [11] Ya.I. Kolesnichenko, V.V. Lutsenko and Yu.V. Yakovenko, *Phys. Plasmas*, **4**, 2544 (1997)

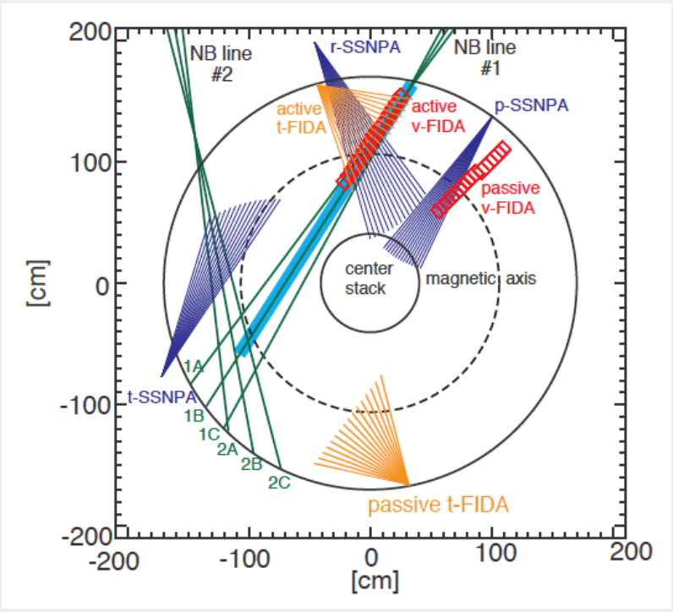
Experimental Scenario

National Spherical Torus Experiment Upgrade (NSTX-U) [7]



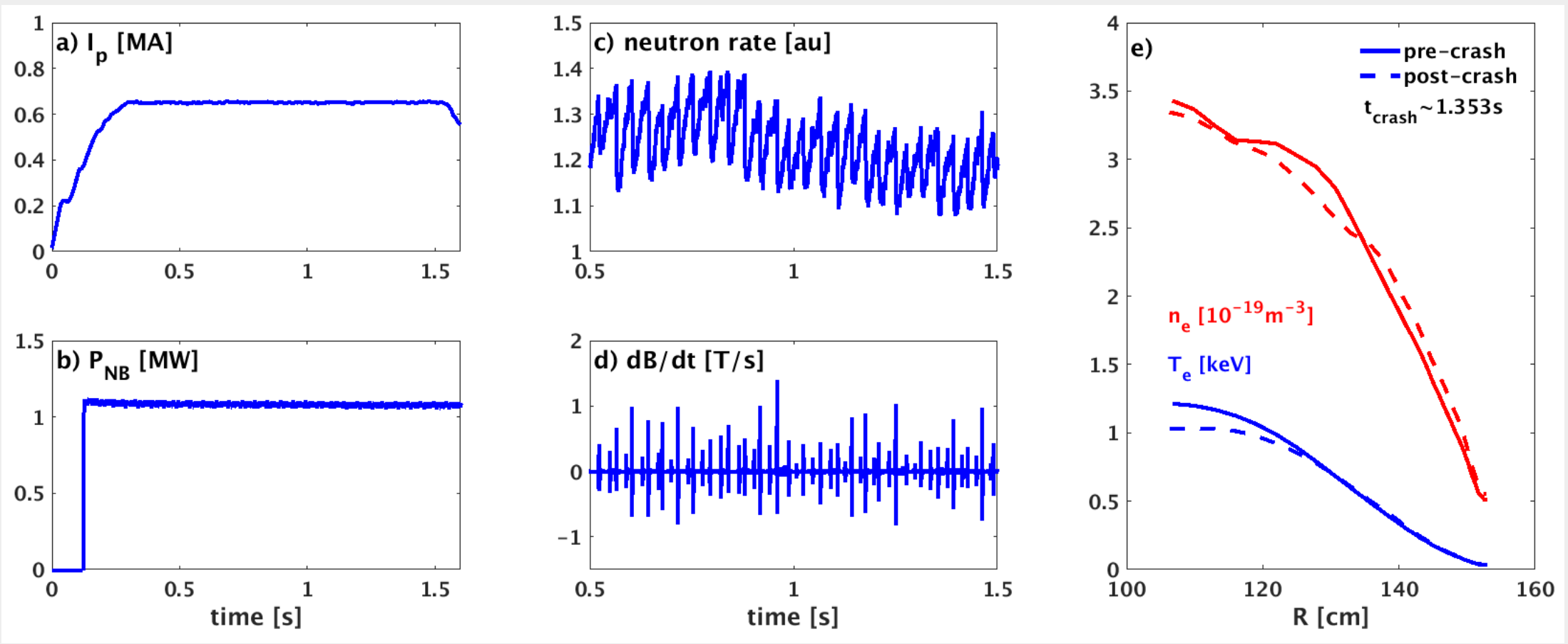
Major radius: 0.95 m
Aspect ratio: 1.5
Plasma current: < 2 MA
Triangularity: 0.8
Toroidal field: < 1.0 T
Elongation: 2.7
pulse length: ~ 1 - 5 s
6 Neutral Beam sources:
P_{NBI} ≤ 12 MW, $E_{injection}$ ≤ 95 keV

Diagnostics for Fast Ion Measurements



- ☐ Fast Ion Deuterium Alpha (FIDA) [8]
  - Measures the Doppler-shifted D_α emission of re-neutralized fast deuterons
  - Fast ion distribution function from active/passive tangential and vertical FIDA
- ☐ Solid State Neutral Particle Analyser (SSNPA) [9]
  - Measures neutral particle fluxes from CX reactions between fast ions and neutrals
  - Consists of r-SSNPA (radial component), t-SSNPA (tangential component) and p-SSNPA (passive signal)

NSTX-U #204163 – L-mode sawtoothing discharge

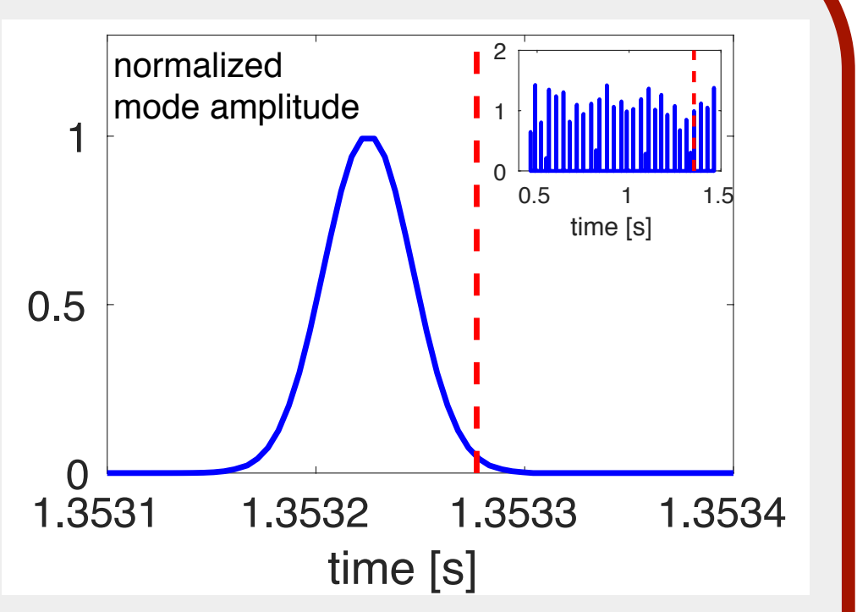


- Flat-top plasma current: I_p = 0.7MA
- NBI power: P_{inj} = 1.1MW (E_{inj} = 72keV)
- Sawtooth crashes are identified by
  - Neutron rate drops at each crash
  - n=1 signal from Mirnov coil
- T_e/n_e profiles are conditionally averaged
  - Sampling time of diagnostics (Thompson, CHERS) is comparable to sawtooth periods
- Reconstructed profiles are averaged before and after ~10ms a sawtooth crash at t = 1.353s

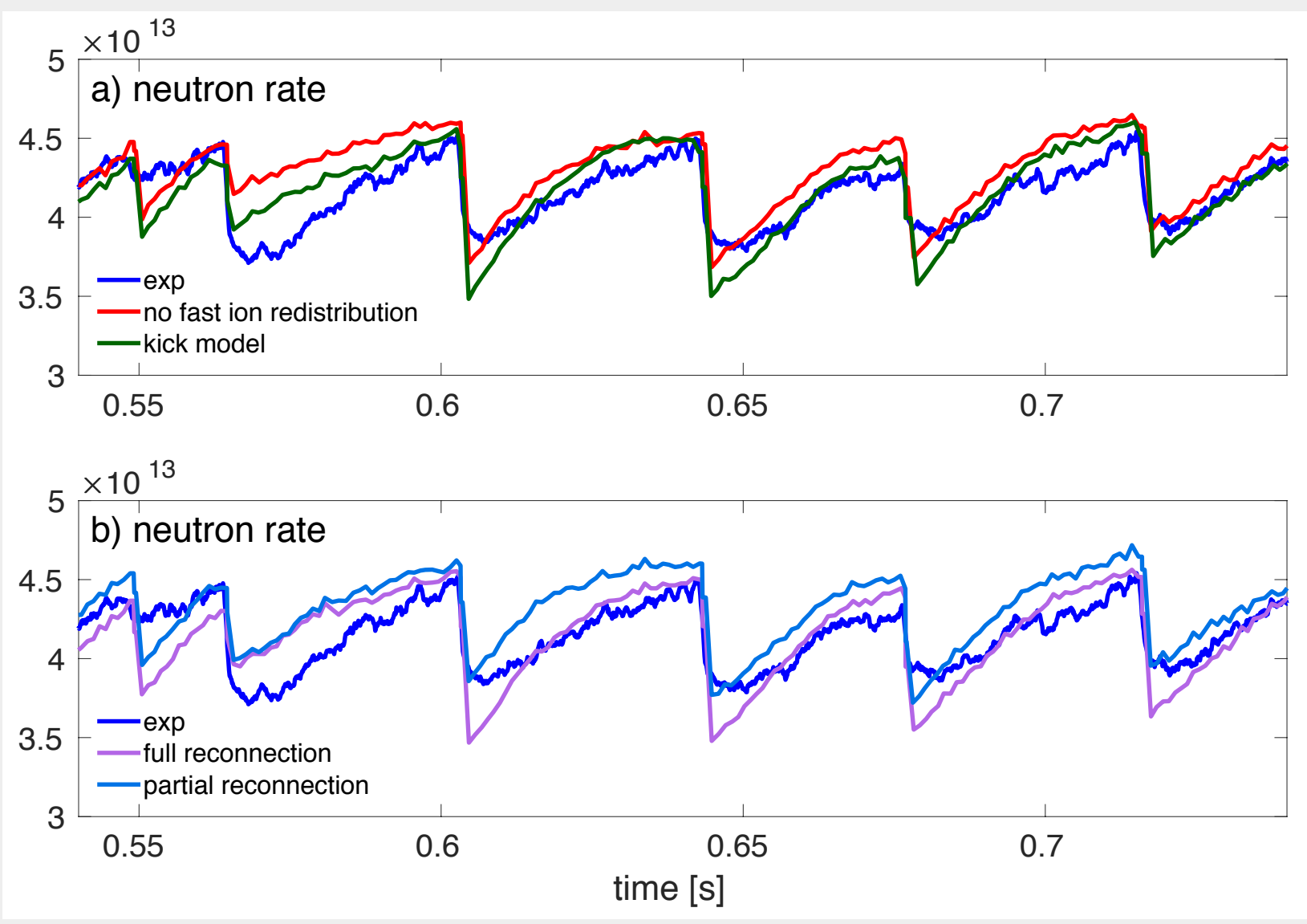
Application to TRANSP Simulations

☐ Interpretative TRANSP simulations for sawtoothing discharges

- Sawtooth crash time is given by measurements (no prediction using crash criteria)
- Input thermal profile data include the sawtooth effect
- Reconnection of flux surface, q-profile, fast ion redistribution are described based on models (full/partial reconnection, kick model) at each crash time
- Free parameters for full/partial reconnection: fraction of fast ion redistribution, partial reconnection fraction, etc.
- Input data for kick model: mode amplitudes and probability matrices



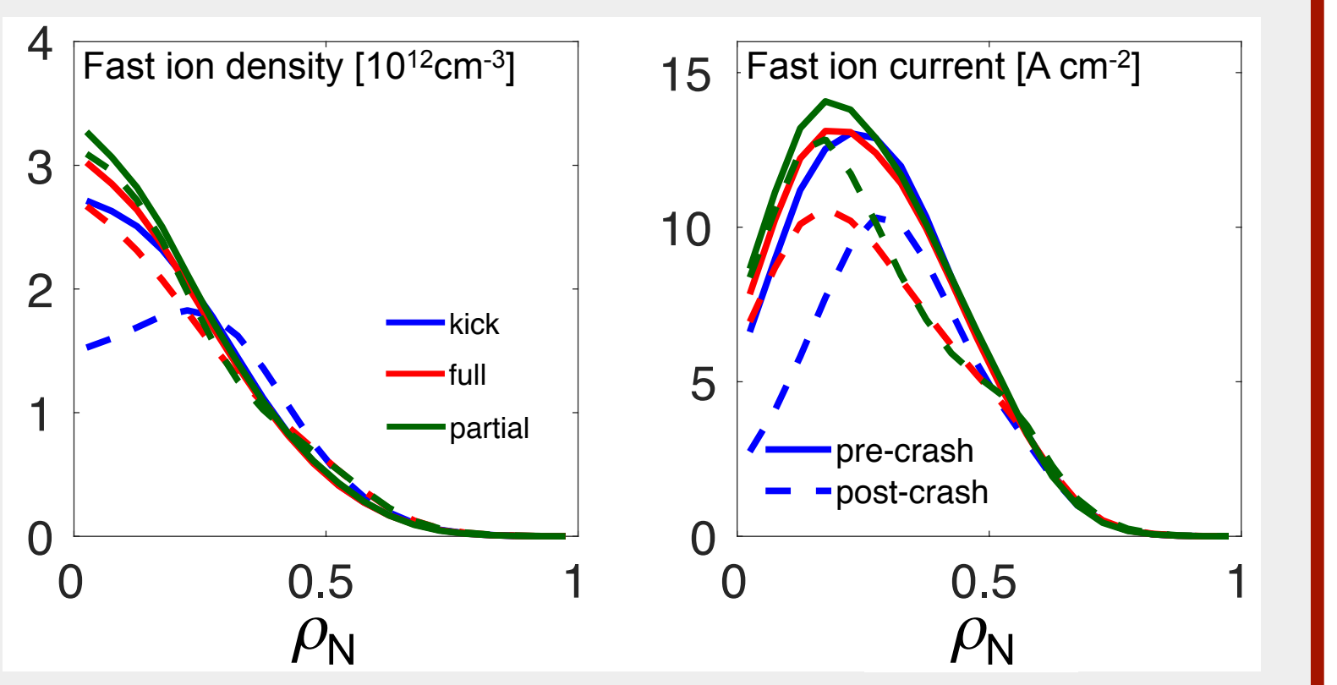
☐ Comparison of neutron rate using kick model and conventional sawtooth models



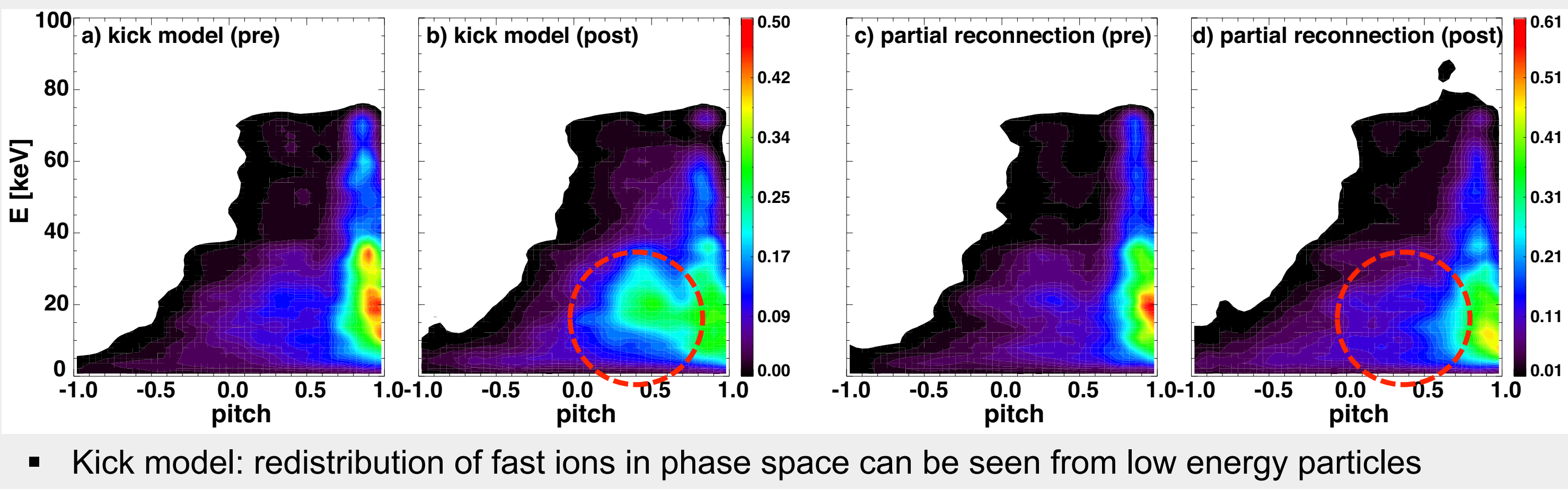
- Simulation condition for kick model
  - One probability matrix with normalised mode amplitudes
  - Mode amplitudes are estimated using neutron rate drops
- Free parameter setting for Full/Partial reconnection
  - Fast ion redistribution fraction: 20% / 50%
  - Partial reconnection fraction: 50%
- Reference data
  - Normalised measured neutron rate (blue)
- Without considering sawtooth effects on fast ion redistribution (red), the neutron drop can be reproduced
- The neutron rates from full/partial reconnection, kick model cases match the measurement with the given parameters
- Comparison of neutron rate is not sufficient to determine a model to describe the sawtooth effect on fast ion transport

☐ Comparison of fast ion density profiles

- Kick model (blue): clear effect from sawteeth
  - Drop at the centre and increase outside ρ_{inv}
- Full/partial (red/gree) reconnection: negligible change
  - Lower fast ion redistribution fraction (20%, 50%)
- Fast ion driven current profiles
  - About 50% of central drop for the kick model case
  - Larger drop near ρ_{inv} for full/partial reconnection case



☐ Fast ion distribution functions in phase space (outside the *q=1* surface, ρ_N~ 0.55)



- Kick model: redistribution of fast ions in phase space can be seen from low energy particles
  - Passing particles (high pitch): max. ~60% decrease
  - Trapped particles (low pitch): max.~100% increase
- Partial reconnection case: no significant variation after a crash
  - Decrease of passing particles (~20%) but no clear change in trapped particles
- Kick model can show changes of fast ion features that the conventional models cannot describe

Summary and Future work

- ☐ Conventional sawtooth models in TRANSP have a limited capability to reproduce experimental results
- ☐ Application of kick model to TRANSP simulation improves the modelling of fast ion redistribution
  - TRANSP simulation can take into account the phase space variables using kick probability matrix in NUBEAM
  - Neutron rate is in a good agreement with the measurement
  - Fast ion distribution function from synthetic FIDASIM results qualitatively match the FIDA measurement
- ☐ The simulation results confirm the theoretical criteria for fast ion redistribution
  - Fast ions with energy higher than the critical energy are less affected by sawteeth for the redistribution
  - More quantitative criteria to describe the level of redistribution of fast ions beyond the 0-D prediction are required
- ☐ The improvement from the application of kick model needs to be validated on other tokamaks

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