NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

Summary of paper to be submitted to NF special issue on IAEA TM EP

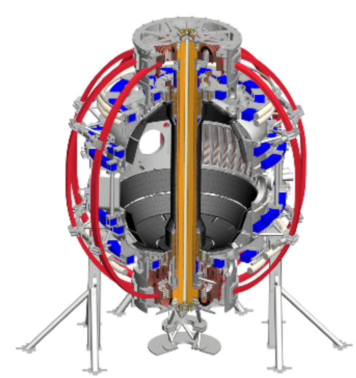
'ORBIT modeling of fast particle redistribution induced by sawtooth instability'

D. Kim[1], M. Podestà[1], D. Liu[2] and F. M. Poli[1]

[1]Princeton Plasma Physics Laboratory

[2]University of California, Irvine

NSTX-U meeting, 28 Nov 2017



Outline

- Introduction and motivation
- Simulation setting and perturbation model
- Simulation results
- Conclusion

Outline

- Introduction and motivation
- Simulation setting and perturbation model
- Simulation results
- Conclusion

Long Sawtoothing Discharges on NSTX-U with the new 2nd NBI

Major radius: 0.95 m

Aspect ratio: 1.5

Elongation: 2.7

Triangularity: 0.8

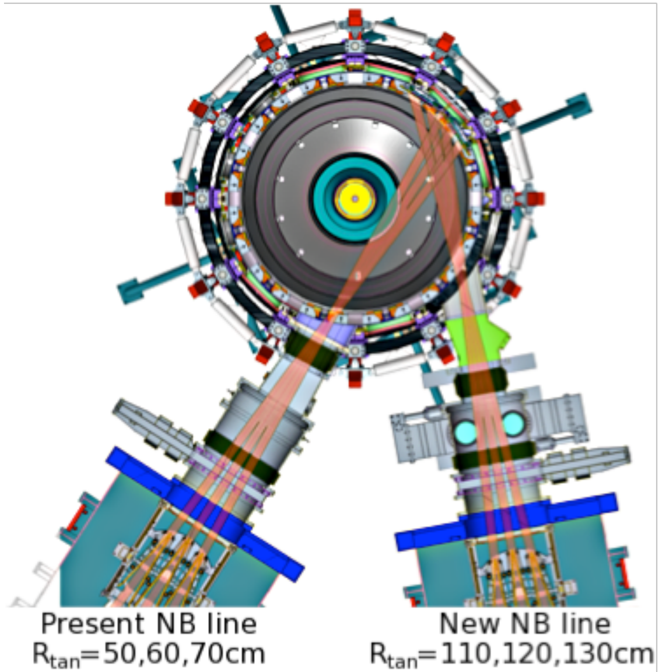
Plasma current: < 2 MA

Toroidal field: < 1.0 T

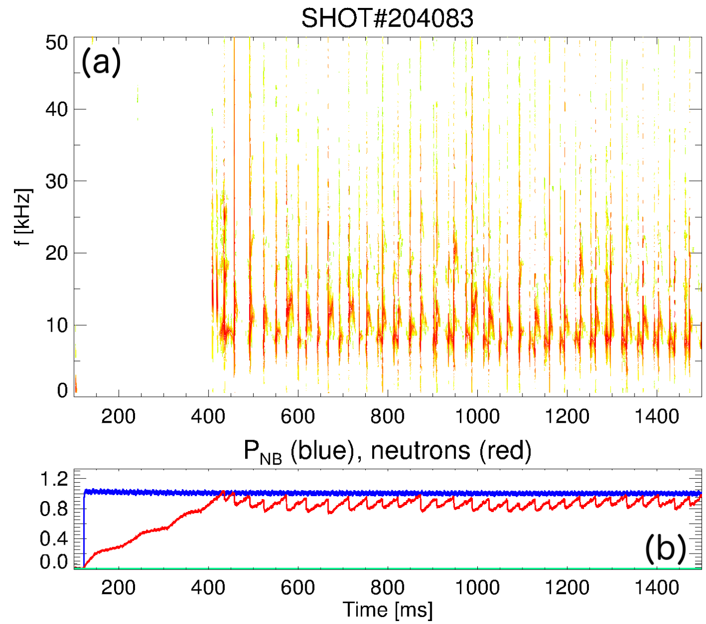
Pulse length: ~ 1 - 5 s

6 Neutral Beam sources:

$P_{NBI} \leq$ 12 MW, $E_{injection} \leq$ 95 keV



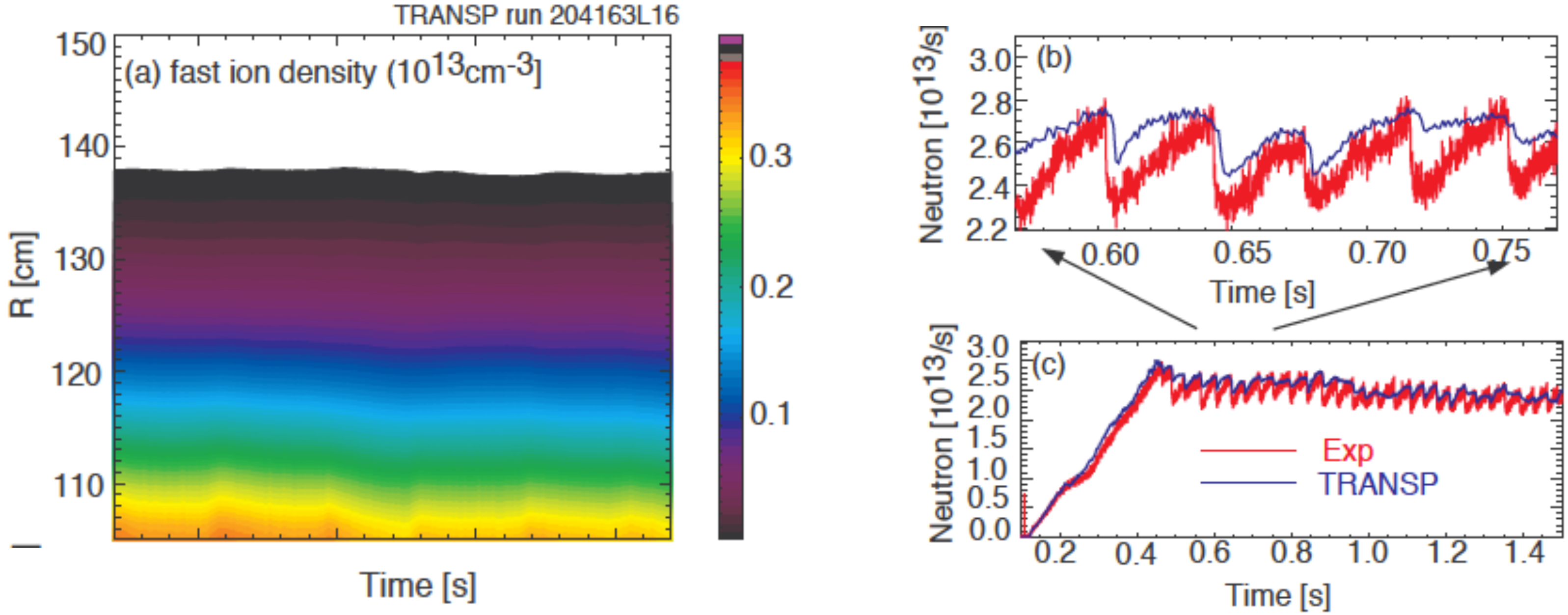
[Menard, NF 2012] [Gerhardt, NF 2012]



- Reproducible sawtoothing L-mode discharges are obtained on NSTX-U
  - Neutron rate can drop as large as ~15% at sawtooth crash
  - Flattening of T_e in the core indicated by MPTS and Soft x-ray diagnostics
  - No MSE measurement is available for these discharges

TRANSP results indicate significant effect of thermal profile evolution on neutron rate

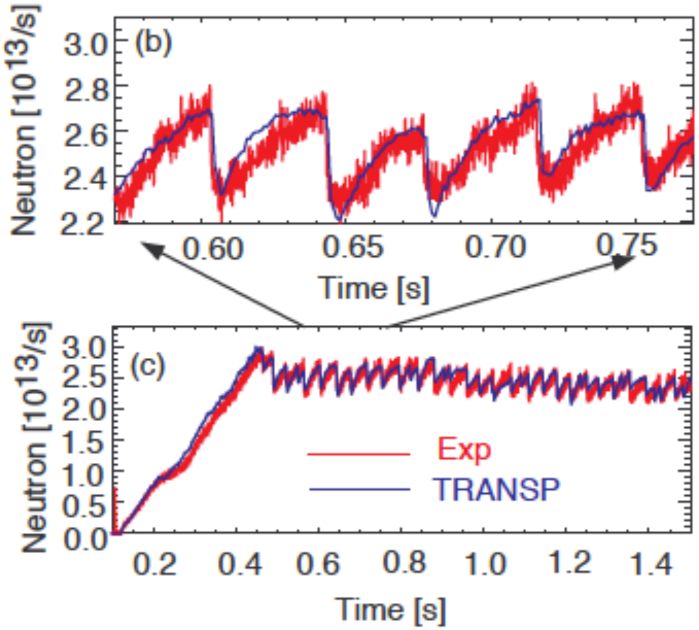
[Liu, to be submitted to NF]

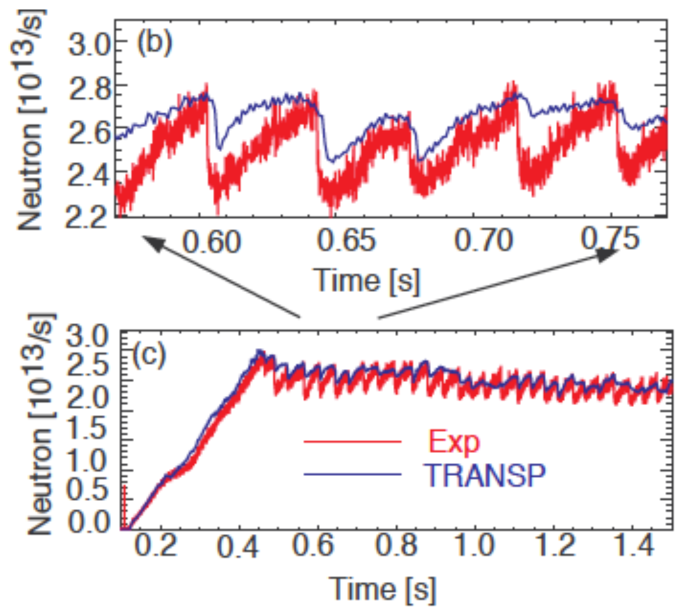


- TRANSP run using thermal profiles from conditional average reconstruction
  - Sawtooth model **ON** for q-profile evolution
  - Sawtooth model **OFF** for fast ions: Little/no modulation of fast ion profile
- Thermal plasma variation can account for up to 50% of neutron rate drops
  - What are the effects of fast ions?

TRANSP results can match experimental ones by adjusting free parameters

[Liu, to be submitted to NF]

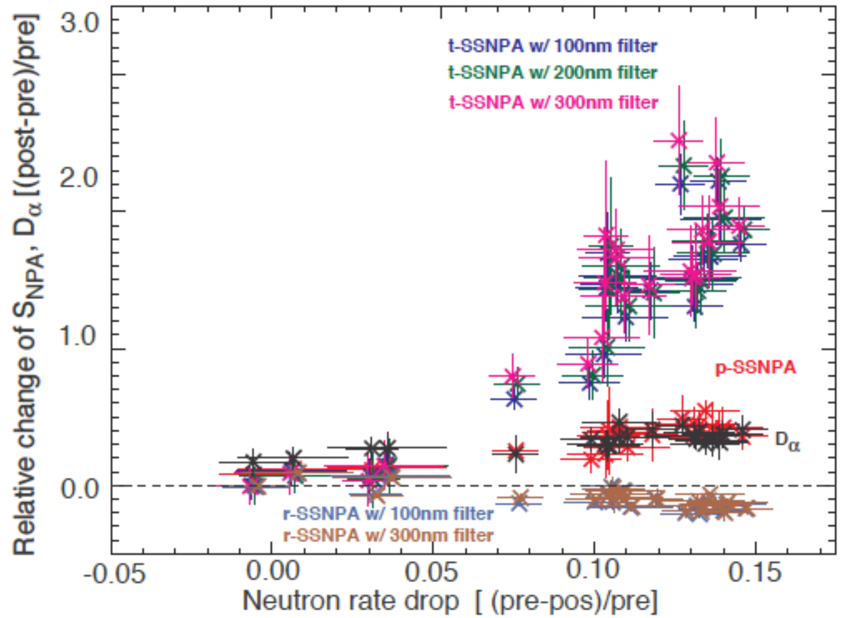




- Adjusting free parameters in TRANSP sawtooth model can bring reproduction of the experimental result
  - Sawtooth model **ON** for both q-profile and fast ion evolution
  - Need to find a proper free parameter sets
    - Reconnection type, (partial) reconnection fraction, fraction of fast ions involving in sawtooth mixing, etc.

Sawtooth model in TRANSP brings the same effect of sawtooth on different orbit types

[Liu, to be submitted to NF]



- Experiments show that passing particles are more affected by sawtooth than trapped ones
- TRANSP sawtooth model treats particles with different orbit type in the same way as thermal particles
  - No pitch angle or energy dependence on present sawtooth model

Can effect of fast particle transport improve sawtooth model?

- Sawtooth modelling in TRANSP [transpweb.pppl.gov]
  - Several free parameters (e.g. partial reconnection fraction) in the model ➔ need to find an optimum set for each case
  - Need to determine self-consistent parameter setting for predictive simulation

- Improvement of sawtooth model for fast ion redistribution in phase space?
  - ORBIT simulations can be a guidance to develop a more comprehensive model for fast particle transport by sawteeth
  - Implementation of a fast particle model into TRANSP is expected to enable self-consistent modelling including more physics
  - NSTX-U data can guide model development and be used for validation

Outline

- Introduction and motivation
- Simulation setting and perturbation model
- Simulation results
- Conclusion

Simulation setting

- Simulation code: ORBIT [White PoF84]
  - Hamiltonian guiding center particle motion code
  - Use of numerical equilibrium, field perturbations in flux coordinates (Boozer coordinate in this work)
  - Analyzing test particle transport (especially energetic ions)

- Target discharge: NSTX-U #204083
  - Equilibrium data (eqdsk file from TRANSP) from one time slice before sawtooth crash (1093ms)
  - Initial distribution of fast particles from TRANSP (NUBEAM)
  - Number of particle for calculation: 10,000
  - Radial displacement for the application of linear perturbation from sawtooth instability (constant in time)

Displacement from sawtooth crash induces perturbed magnetic field δB

- Perturbation magnetic field from displacement

$$\delta\vec{B} = \nabla\times\left(\vec{\xi}\times\vec{B}\right)$$

- Radial displacement model [Farengo NF13, ZhaoPoP97]
  - $\xi(\rho, t, \theta, \zeta) = \Sigma\xi_{m,n}(\rho, t)\cos(n\zeta - m\theta - \omega t)$
  - (m, n): poloidal and toroidal mode numbers
  - (θ, ζ): poloidal and toroidal angles
  - (1,1) mode is applied
  - Tested on cylindrical coordinate in Farengo NF13 ➔ toroidal geometry effect, e.g. toroidal mode coupling, may need to be considered

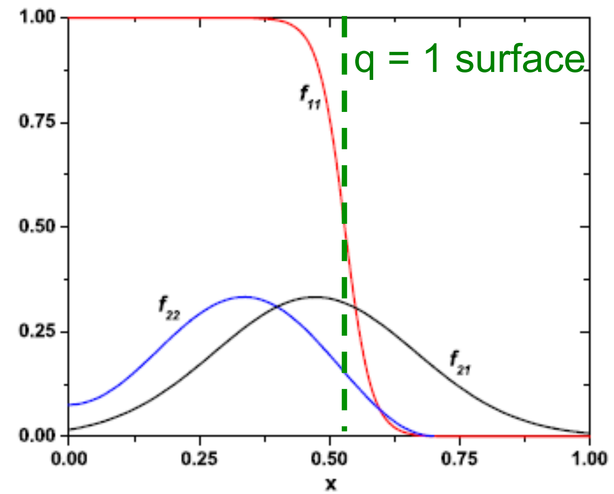
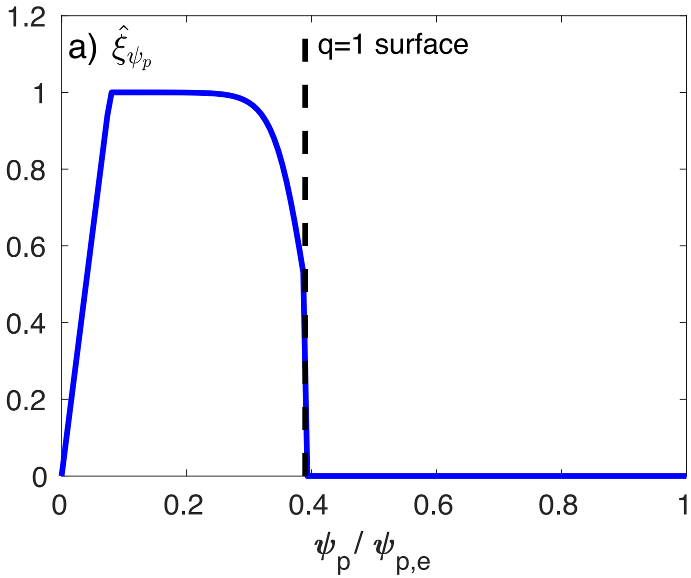
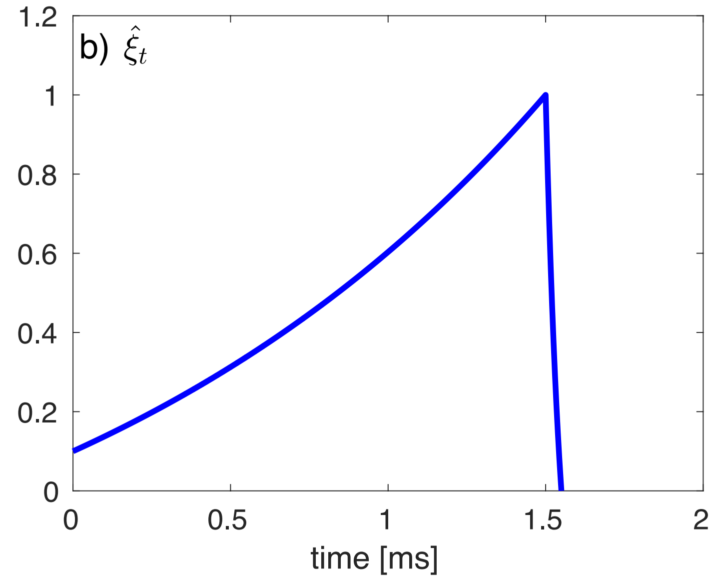


Figure from [Farengo NF13]

Radial profile is modified and the temporal variation of the amplitude is set





- Modification on radial profile
  - Central region is modified to avoid numerical problem in ORBIT
  - Perturbation outside the q=1 surface is ignored (not sensitive)
- Temporal variation of amplitude based on (average) exp results
  - Perturbation grows from 10% to 100% of the maximum perturbation amplitude during 1.5ms
  - Amplitude goes to zero (full reconnection) after the crash during 50μs

Relative change of neutron rate – comparison with experimental result

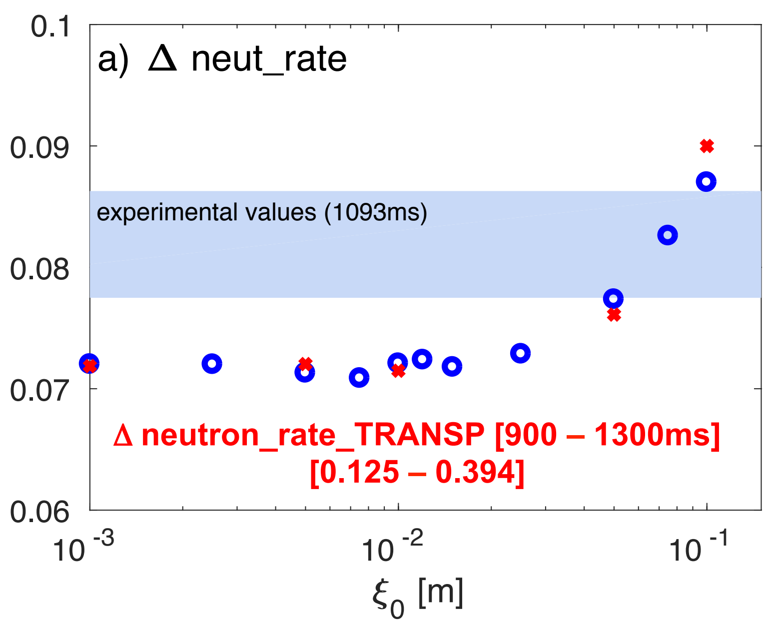
- Estimate relative neutron rate change
  - Using deuterium density at each fast particle position, cross section, particle energy of each particle energy and volume element

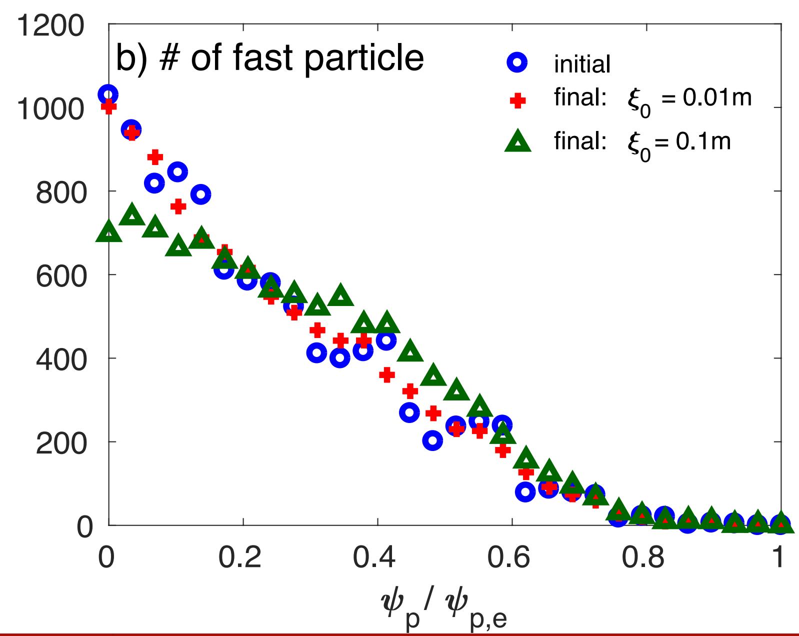
$$\Delta = \frac{\sum_{k}^{N_0} n_{d0,k} S_{0,k} \sqrt{E_{0,k}}\, dV_{0,k} - \sum_{k}^{N_f} n_{df,k} S_{f,k} \sqrt{E_{f,k}}\, dV_{f,k}}{\sum_{k}^{N_0} n_{d0,k} S_{0,k} \sqrt{E_{0,k}}\, dV_{0,k}} \quad (\mathrm{k} = \text{fast particle index})$$

- Relative neutron rate change from experiment
  - Difference between neutron rate post and pre crash is normalized by neutron rate before sawtooth crash
  - Depending on calibration parameter, values are slightly different

Measurement of neutron rate drop is used to determine perturbation amplitude in simulations

- Determination of perturbation amplitude
  - Δ calculation using ξ amplitude of [0.001 to 0.1m]
  - In lower amplitude case, Δ is almost constant since fast particles are not redistributed much
  - Amplitude of between [0.055, 0.097m] can reproduce experimental value
  - Amplitude of 0.075m is taken for the further analysis



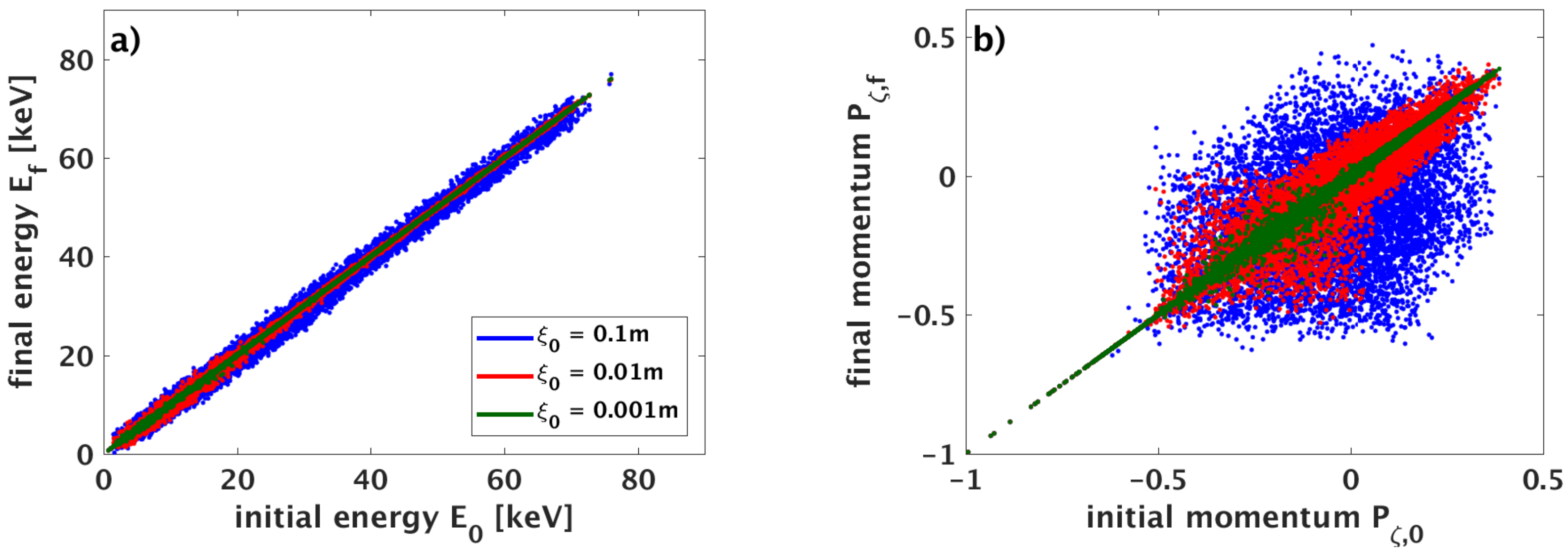


Outline

- Introduction and motivation
- Simulation setting and perturbation model
- Simulation results
- Conclusion

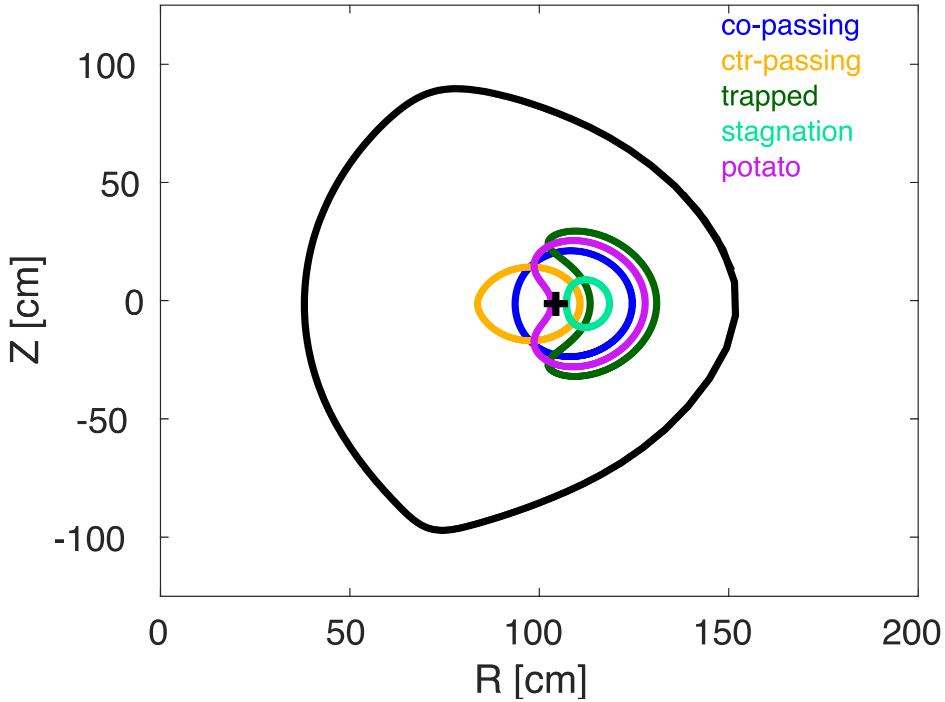
Fast ion energy is not changed significantly by sawtooth

- ORBIT calculation shows the final energy is not deviated much from the initial energy
  - With 100 times different amplitude (0.001 to 0.1), the change is little
- As perturbation amplitude increases, particle redistribution in phase space becomes more significant
  - Need to focus on particle redistribution



Classification of orbit type allows to identify particle redistribution

- Movement of particle movement of each orbit type and the change of orbit type due to sawtooth
- Based on the initial energy and pitch angle, the boundaries of orbit types are determined using the Hamiltonian equation of motion and conservation of canonical angular momentum P_ζ

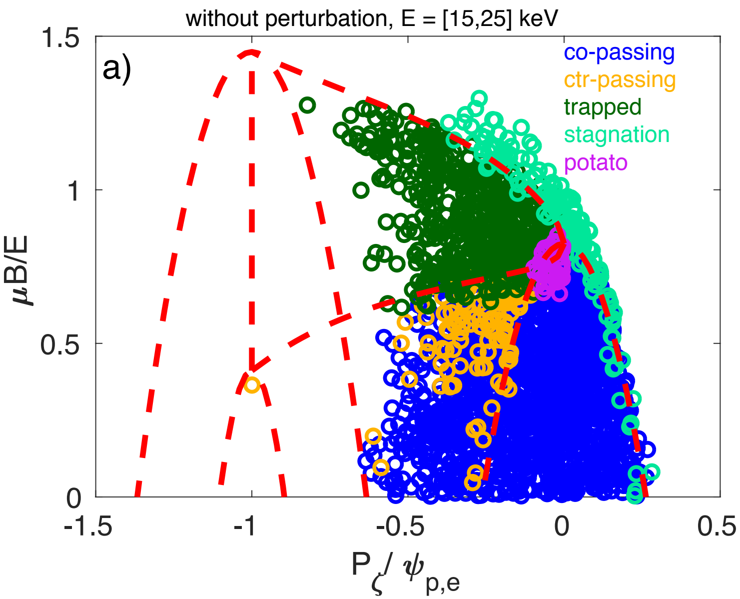


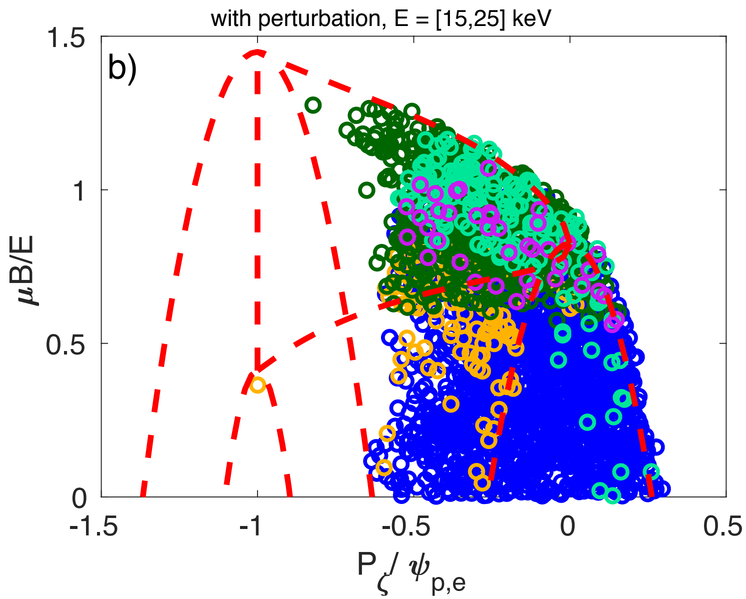
$$H = \rho_\parallel^2 B^2 / 2 + \mu B + \Phi$$

$$P_\zeta = g\rho_\parallel - \psi_p$$

Redistribution of different types and energy level particles in phase space

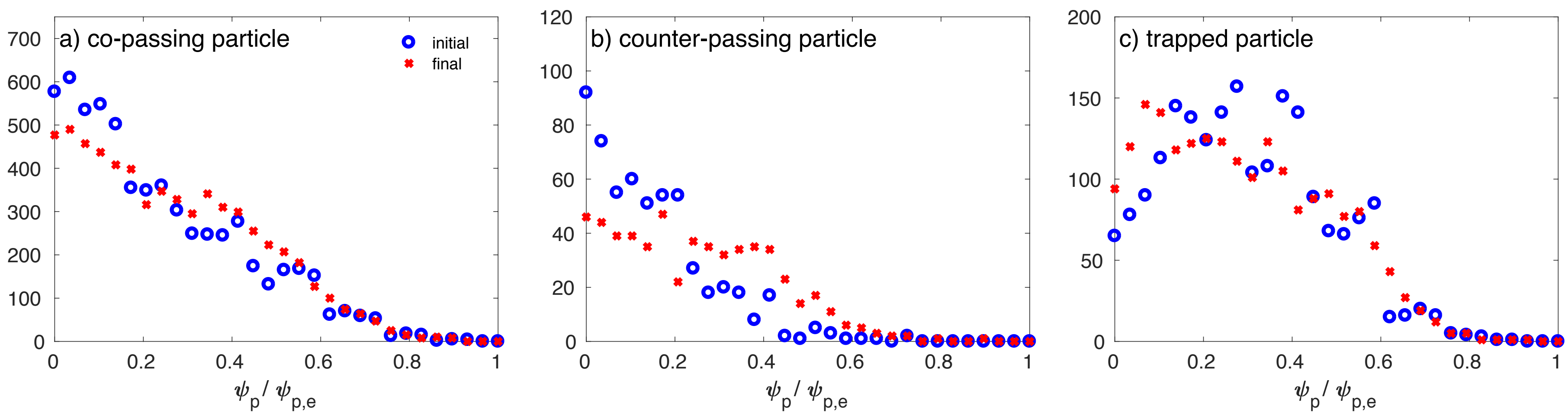
- Applying the perturbation (amplitude = 0.075m) results in the redistribution of particle in phase space and the change of orbit type in low and high initial particle energy case
- Initially all the particles are well located within each boundary while particles with initial orbit type flag move around after the crash





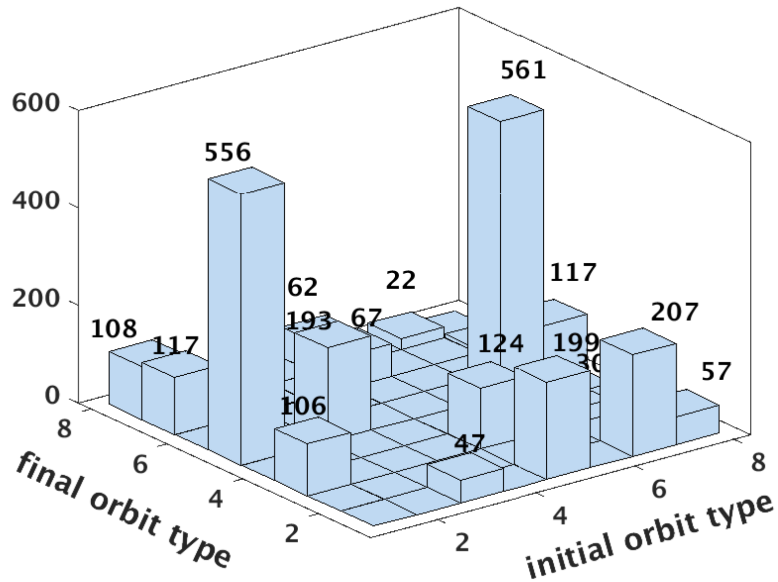
Redistribution of different orbit type particles in real space

- The number of fast ions is changed along the minor radius by sawtooth crash
- Co- and counter-passing particles experience larger effect from sawtooth crash on the radial redistribution than trapped particle
- Consistent with previous experimental results [Liu NF to be submitted, Muscatello PPCF12]



During redistribution, particles experience the change of orbit type

Orbit type 1: co-pass confined	**Orbit type 3: ctr-pass confined**	**Orbit type 5: trapped confined**	**Orbit type 7: stagnation**
Orbit type 2: co-pass lost	**Orbit type 4: ctr-pass lost**	**Orbit type 6: trapped lost**	**Orbit type 8: potato confined**



Amplitude = 0.075
26.0% of 10k particles' orbit type change

(i,f) = (*a*,*b*) : initially ***a*** type turns into ***b*** type

- The largest orbit type changes from co-passing/stagnation to trapped particle as well as large amount of counter-passing and potato particles
- Trapped particles mostly become co- or counter-passing particles
- Orbit type change is relevant for quantitative comparison with phase space resolved measurements (e.g. FIDA, SSNPA)

Redistribution of particles – comparison with theory [Kolesnichenko PoP97]

- Criteria for sawtooth induced fast particle redistribution

Trapped particle

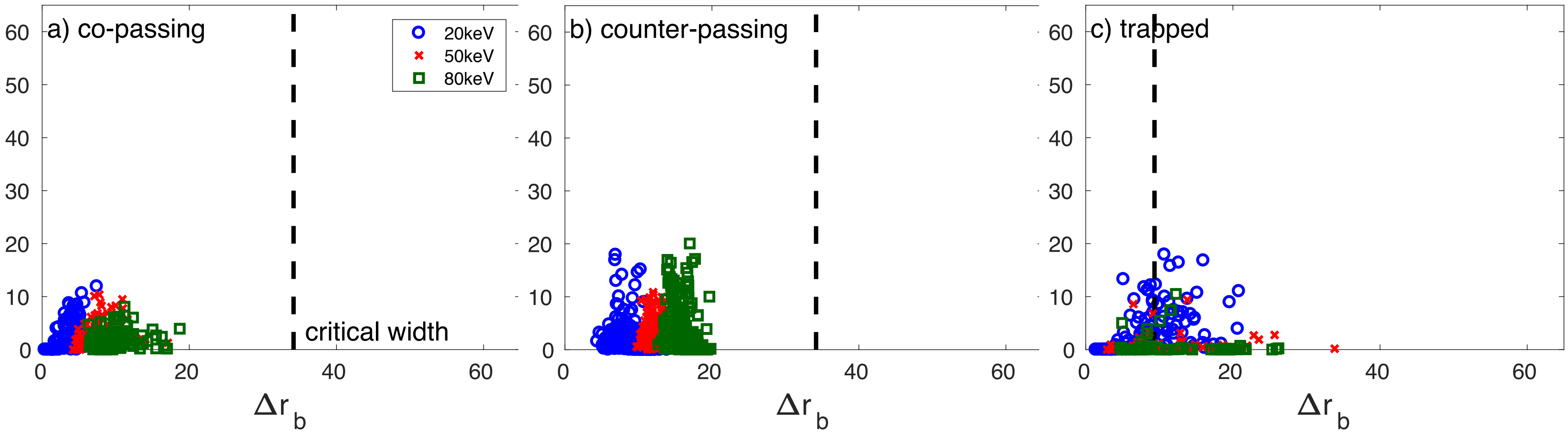
$$\Delta r_b << r_{crit} = \frac{r_{mix}}{\left(\varepsilon_{mix}\tau_{cr}\omega_B / 4\pi\right)^{1/2}}$$

Passing particle

$$\Delta r_b << r_{crit} = r_{mix}$$

Δr_b = orbit width, r_{mix} = sawtooth mixing radius assuming full reconnection
ε_{mix} = inverse aspect ratio at r_{mix}, τ_{cr} = crash time, ω_B = ion cyclotron frequency

Redistribution of particles – comparison with theory



- Radial position change (Δr) vs initial orbit width (Δr_b) – Comparison with critical value for different particle energy level and orbit type
  - Passing particles: criterion is well satisfied
    - Radial position change occurs only for orbit width smaller than the critical one
    - Co-passing: Δr decreases with energy
    - Counter-passing: Δr increases with energy
  - Trapped particle: not clear
    - Particles with orbit width bigger than the critical one experiences radial position change with lower energy while higher energy cases shows almost zero Δr

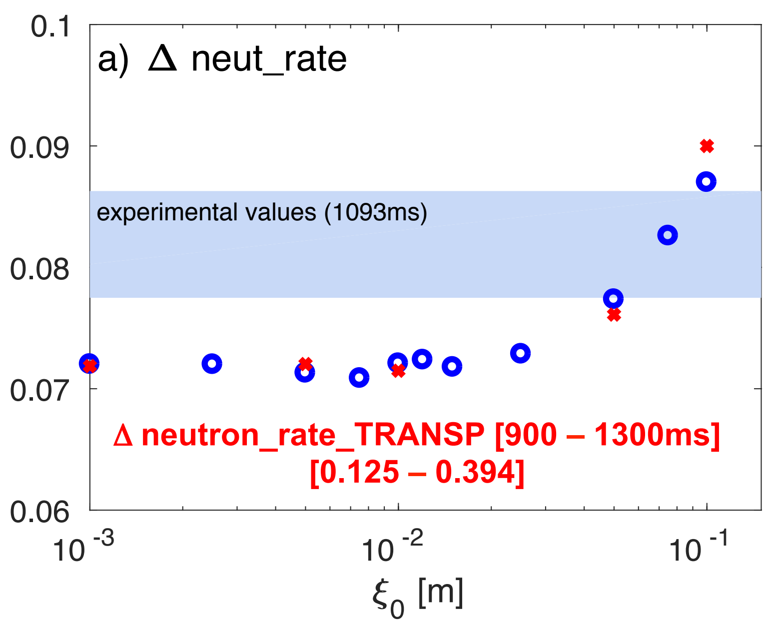
Conclusions and outlook

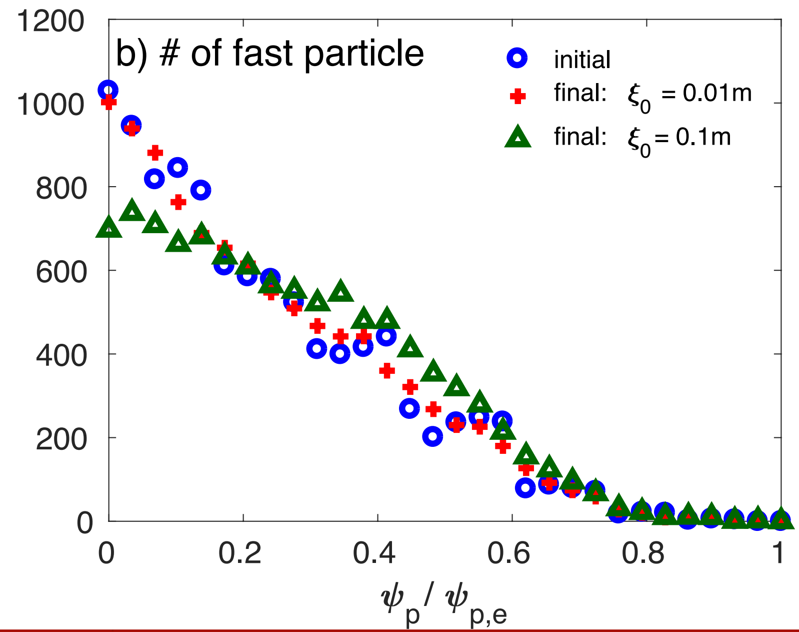
- Sawtooth perturbation model implementation in the ORBIT code
- Relative change of neutron rate induced by sawtooth crash is compared with experimental value
  - Relative change of neutron rate drop increases as mode amplitude grows from amplitude
  - Experimental value can be reproduced by amplitude range of [0.055, 0.097]
- Energy and particle redistribution due to sawtooth crash is investigated
  - Regardless the amplitude of perturbation, E is not changed significantly while P_ζ variation becomes significant with increase of mode amplitude
  - With a sufficiently large perturbation amplitude, particles are redistributed by sawtooth in phase space and orbit types are also changed
  - The effect of sawtooth crash is stronger on passing particles and trapped ones
- Redistribution of Passing particle is well explained by theory while trapped particle redistribution does not well agree with theory
  - Need to find better way to apply the theory
  - This part will be extended to set a model for TRANSP sawtooth model

Back up slides

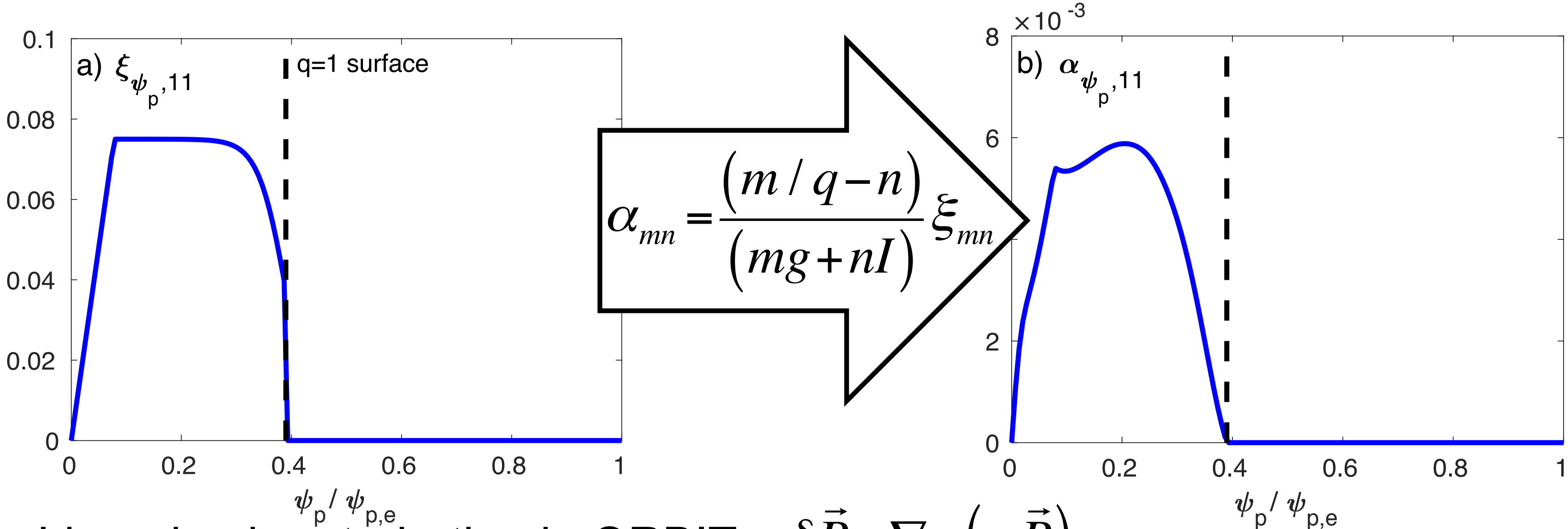
Relative change of neutron rate – comparison with experimental result

- Determination of perturbation amplitude
  - With perturbation outside the q=1 surface, the result is almost the same
  - Conditional average of the input experimental profiles in TRANSP due to insufficient temporal resolution of diagnostics
  - Re-sample the experimental plasma profiles on the 1ms time scale after conditional average





In ORBIT code, perturbation is defined using α, not ξ



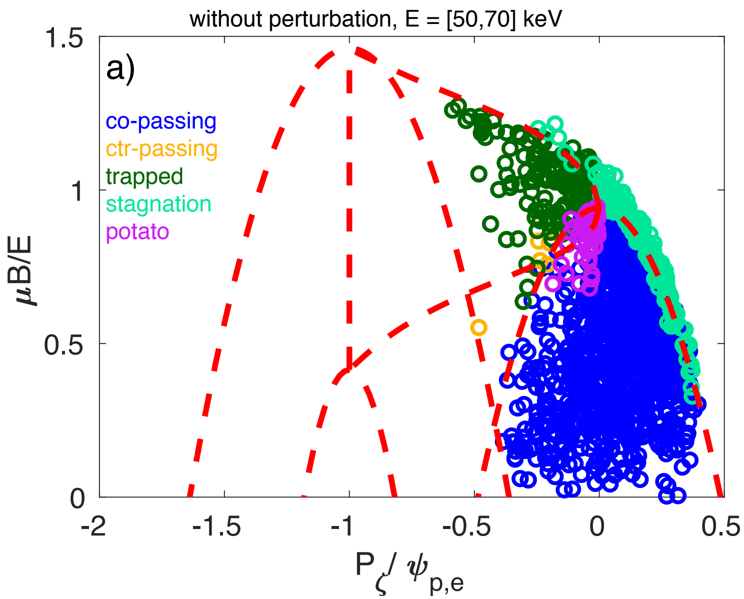
- Linearized perturbation in ORBIT: $\delta\vec{B} = \nabla\times(\alpha\vec{B})$
  - ξ can be transformed into α [White PoP13]
  - Radial component of resultant perturbation is equivalent to ξ model

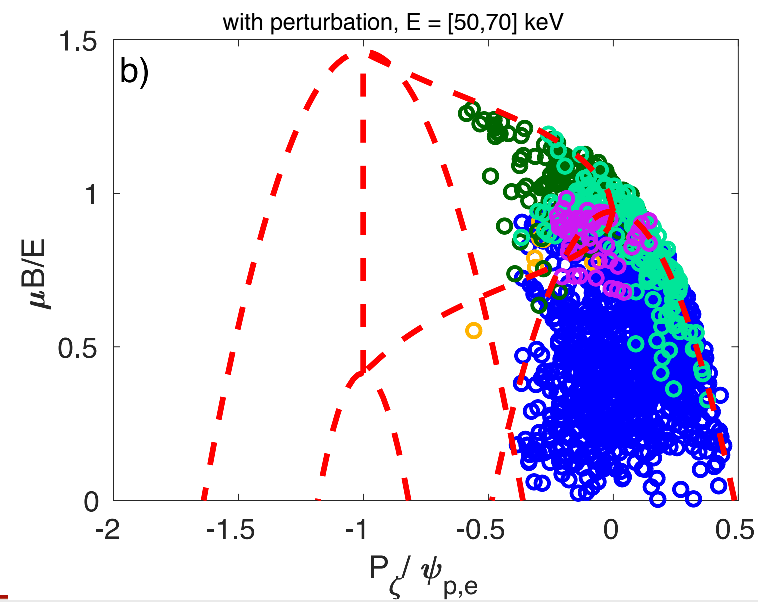
$$\delta\vec{B}\cdot\nabla\psi_p = \sum_{m,n}\frac{mg+nI}{J}\alpha_{m,n}\cos(n\zeta - m\theta - \omega t)$$

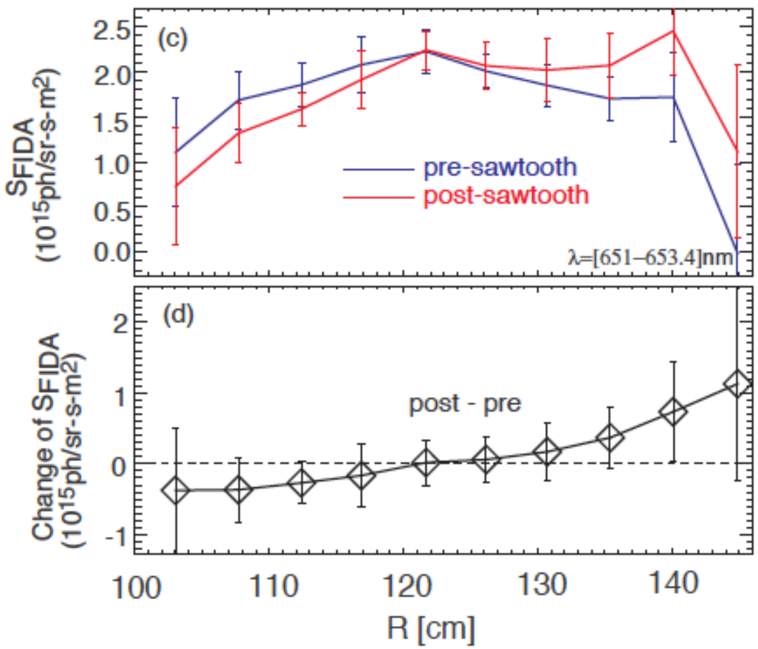
  - Mode amplitude is prescribed for ξ and is used for α after normalisation
  - The resultant a shape is similar to that from [Zhao PoP97]

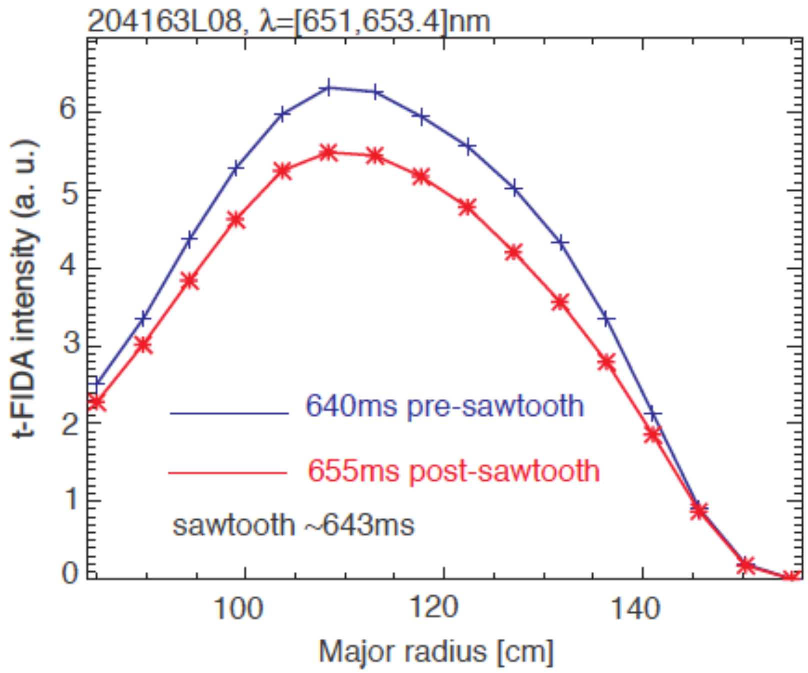
Redistribution of different types and energy level particles in phase space

- Applying the perturbation (amplitude = 0.075m) results in the redistribution of particle in phase space and the change of orbit type in low and high initial particle energy case
- Initially all the particles are well located within each boundary while particles with initial orbit type flag move around after the crash






(c)
(d)
SFIDA (10^15ph/sr-s-m2)
Change of SFIDA (10^15ph/sr-s-m2)
pre-sawtooth
post-sawtooth
λ=[651–653.4]nm
post - pre
R [cm]


204163L08, λ=[651,653.4]nm
t-FIDA intensity (a. u.)
640ms pre-sawtooth
655ms post-sawtooth
sawtooth ~643ms
Major radius [cm]