Multiple mode-number instabilities induced energetic-ion transport in magnetic confinement plasmas

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Overall Outline

- **Branch Outline I: Avalanche transport of energetic-ions in magnetic confinement plasmas: nonlinear multiple wave-number simulation (Zhu X L et al NF 2022 62 016012)**

- **Branch Outline II: Hybrid-kinetic simulation of synergy between fishbone/sawtooth and tearing mode-induced energetic-ion transport in a tokamak plasma (Zhu X L et al NF 2023 63 036014)**

- **Last: Conclusions and discussions**

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- **Branch Outline I: Avalanche transport of energetic-ions in magnetic confinement plasmas: nonlinear multiple wave-number simulation**
- **Branch Outline II: Hybrid-kinetic simulation of synergy between fishbone/sawtooth and tearing mode-induced energetic-ion transport in a tokamak plasma**
- **Last: Conclusions and discussions**

Branch Outline I

- Introduction
- M3D-K model
- Part I: Avalanche on NSTX
- Part II: Synergy of fishbone/sawtooth(FB/ST) and tearing mode(TM) on HL-2A
- Part III: Simulation results
  - TAE avalanche observation and interpretations
  - Avalanche transport and loss of energetic-ions
  - Synergy of FB/ST and TM induced transport and loss of energetic-ions
- Part IV: Conclusions and discussions

Introduction：Avalanche is ubiquitous

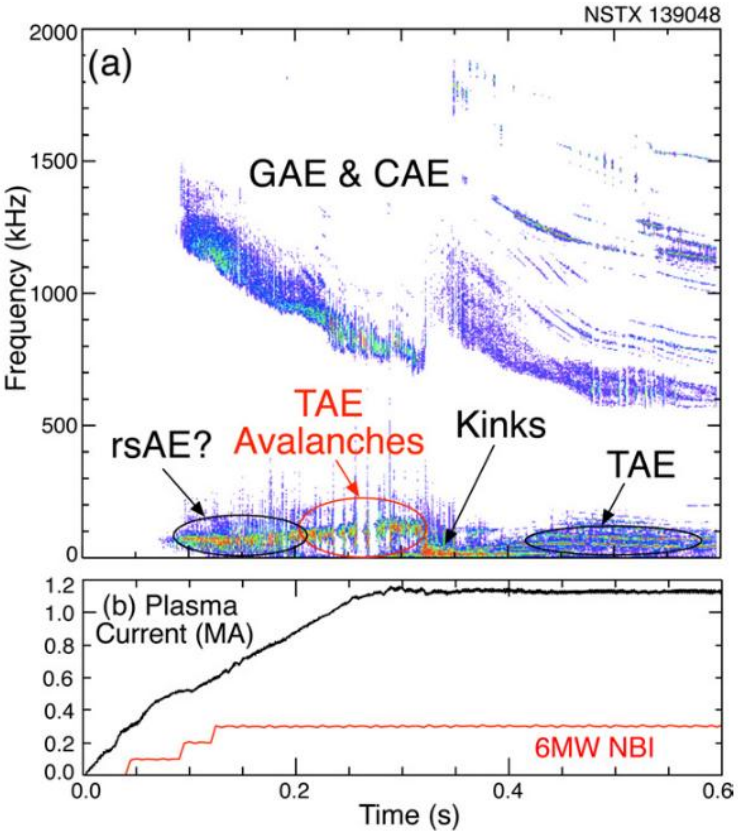
Avalanche in snow mountain

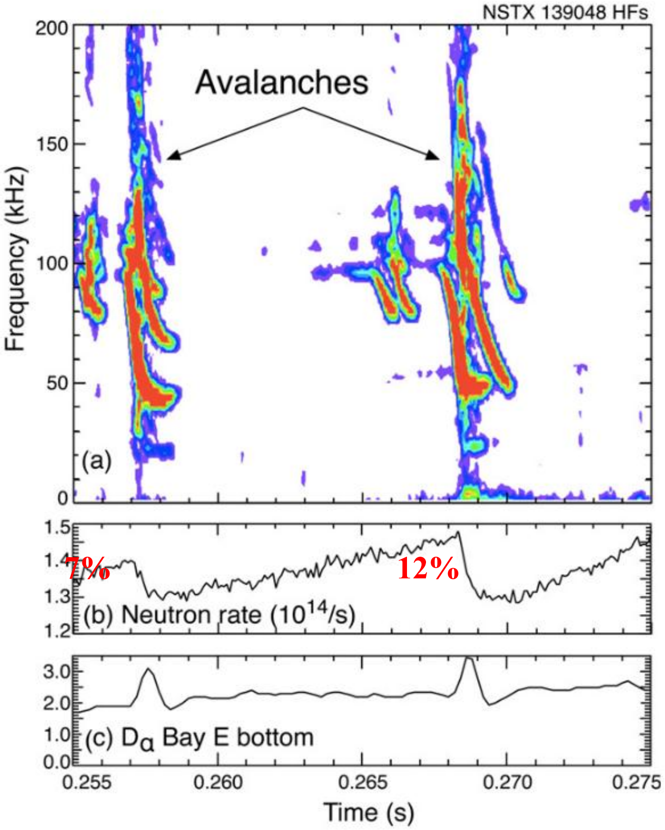
Domino effect

Solar flares- magnetic reconnection avalanche event

- Avalanche originates from the theory of self-organized criticality. Its occurrence is ubiquitous not only in nature but also in magnetic confinement fusion devices such as NSTX, JT-60U, HL-2A.

Introduction：Avalanche on NSTX (Low-density H-mode plasmas)

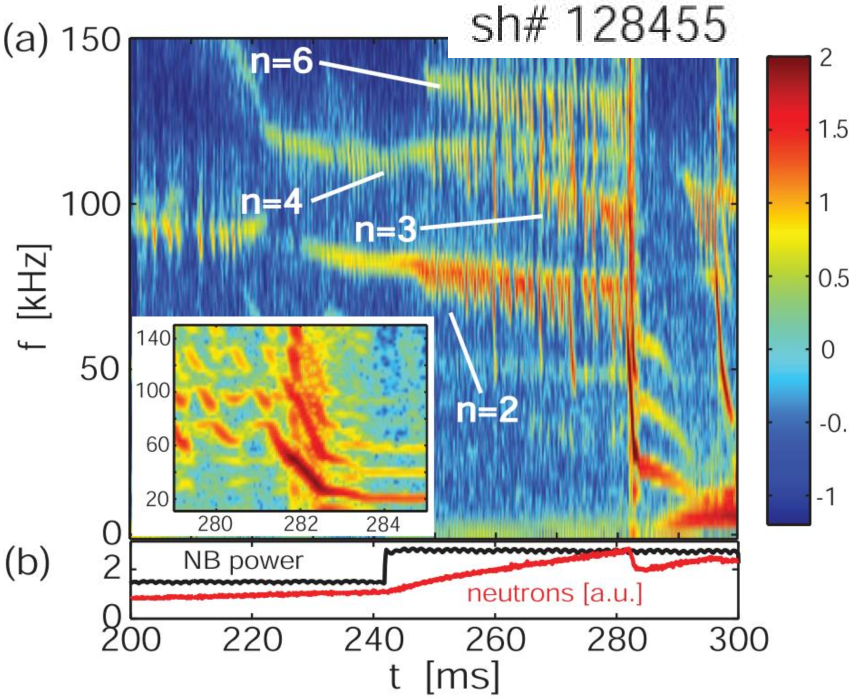


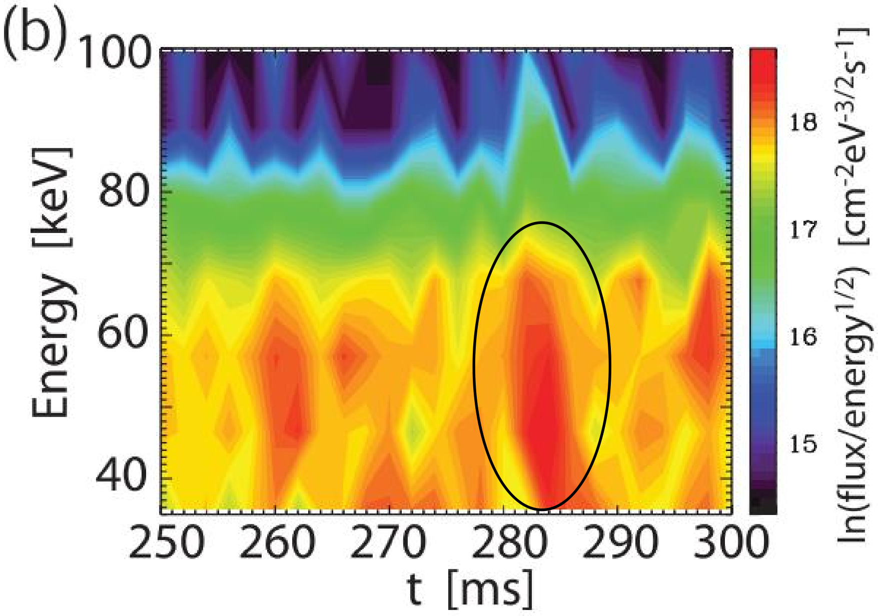


- In the low-density H-mode NSTX plasmas, **TAE avalanche** is present.
- Typically, the TAE occur as a sequence of bursts, with each burst chirping downward in frequency.
- 7% and 12% beam ion loss are seen to be correlated with the TAE avalanches.

Fredrickson E.D. *et al* 2013 NF 53 013006

Introduction：Avalanche on NSTX (helium L-mode plasmas)

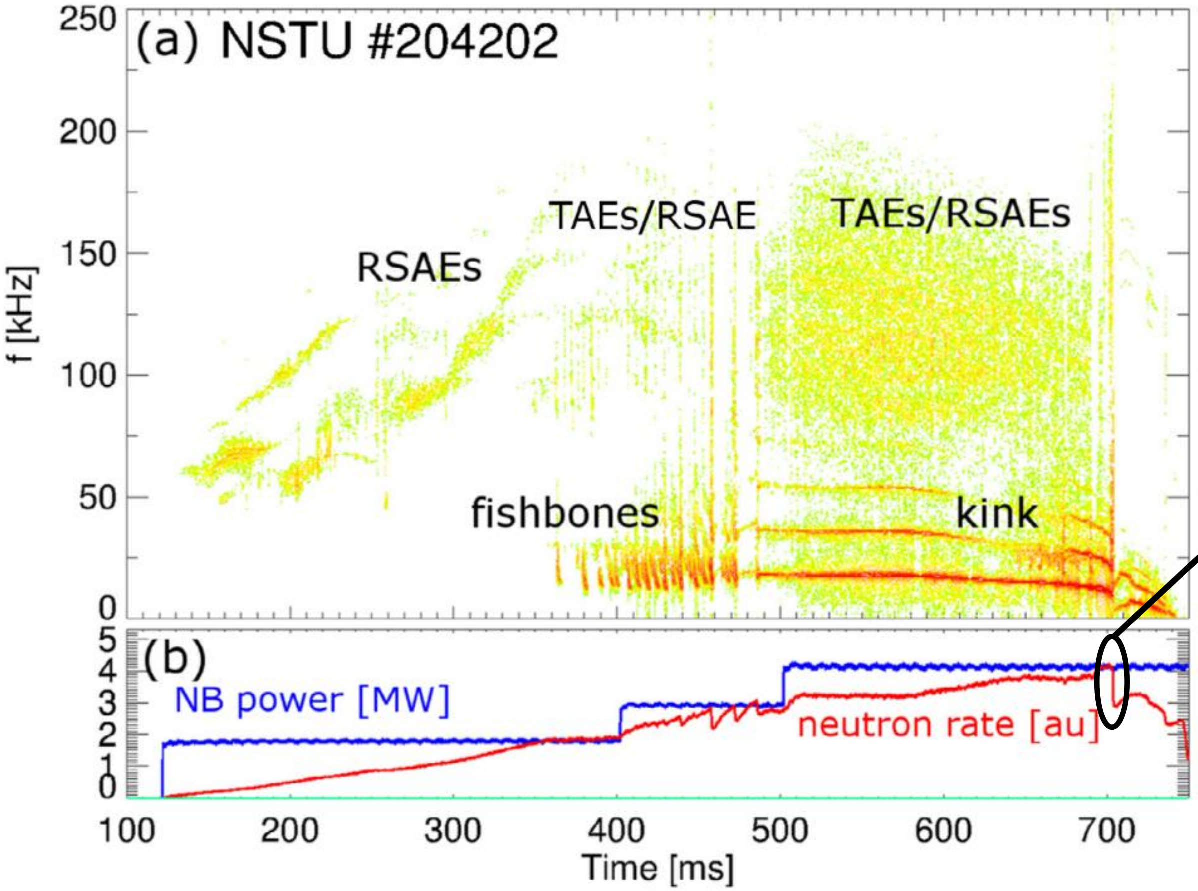




- **Slightly increasing the heating power can induce TAE avalanches with n<=6. This is detailed in the inset of where the avalanche appears as a quick frequency down-chirp over 1 millisecond which involves all the observed modes.**
- **The energy spectrum indicates an dramatic increase in lost fast-ion signal is clearly observed in low energy region shortly after TAE avalanche.**

Podesta M. *et al* 2009 POP 16 056104

Introduction: The event with multi-mode nature induced sharply increased loss rate

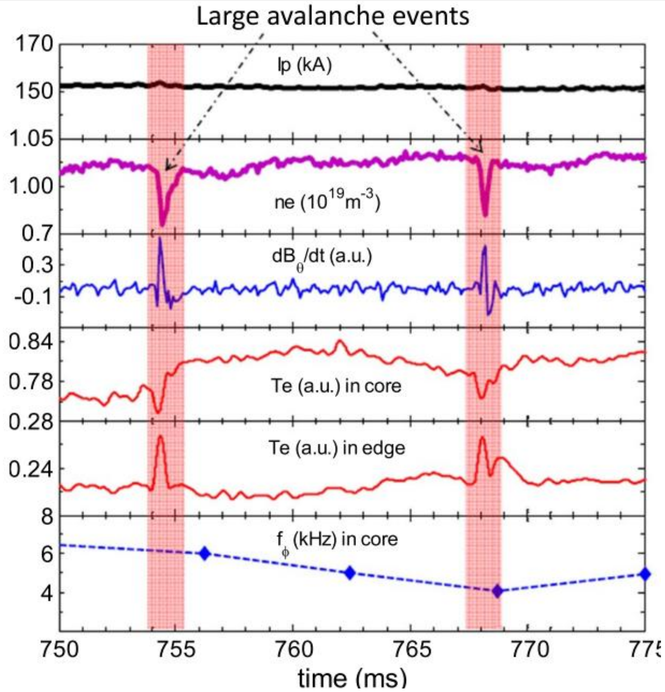


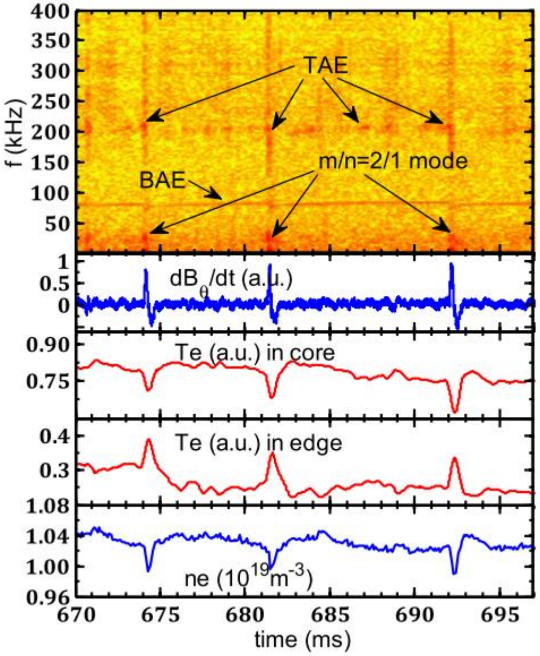
Sharply increased loss rate

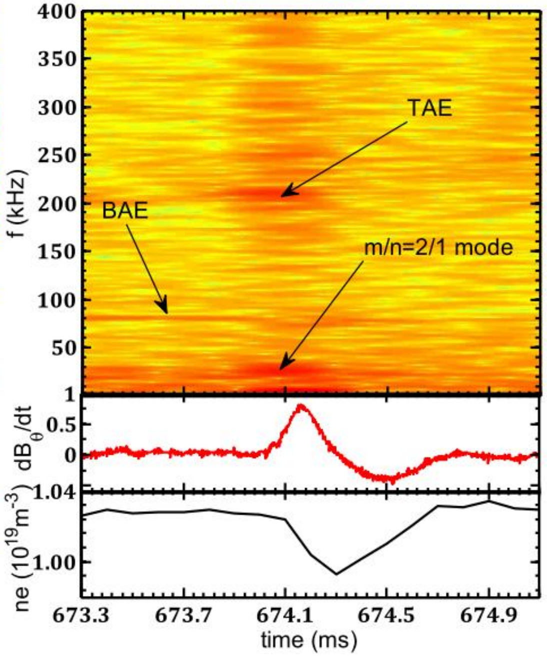
- Results from a NSTX-U discharge featuring several EP-driven instabilities show considerable degradation of plasma performance, which can be inferred from the reduction in neutron rate (namely sharp increment in loss rate).

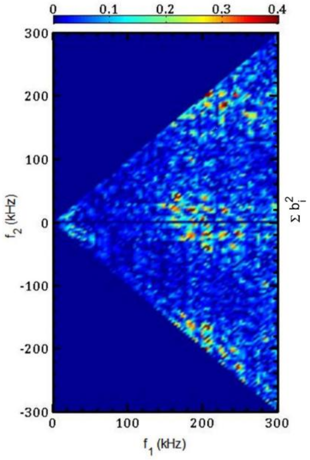
Podesta M. *et al* 2019 NF 59 106013

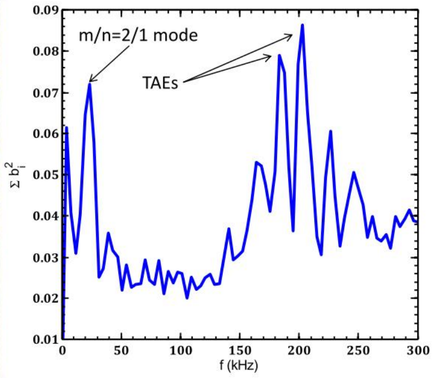
Introduction: Avalanche electron heat transport event on HL-2A







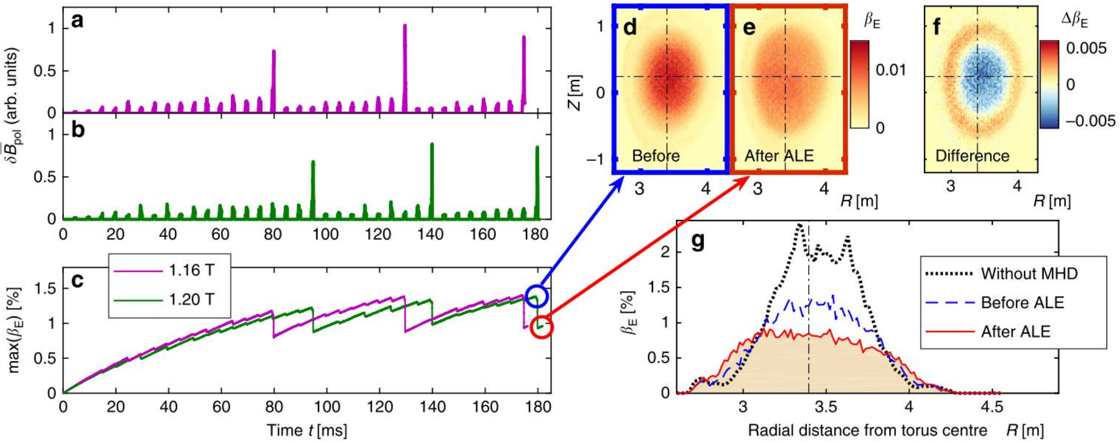


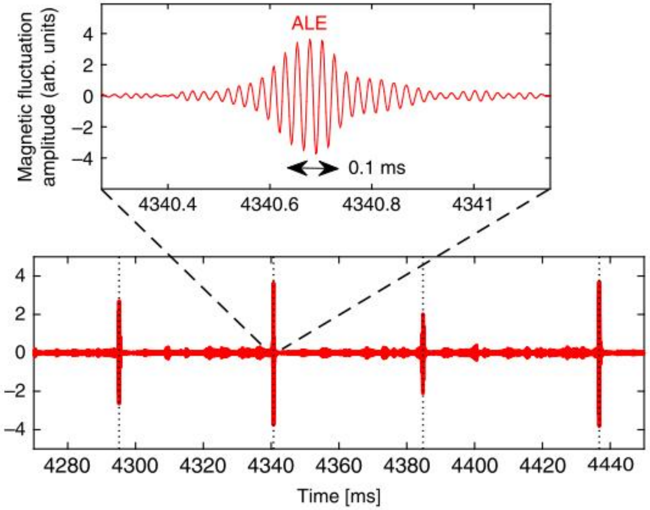


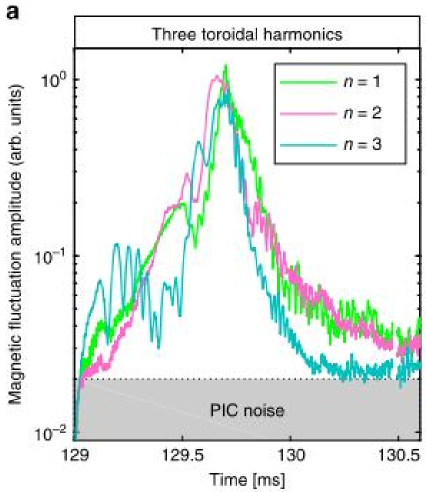
- ➢ **The heat avalanche is proposed as a process for profile relaxation under the condition of the SOC system near marginal stability.**
- ➢ **The avalanche is triggered while the NMCs occur between the core-localized TAEs and m/n = 2/1 fishbone.**

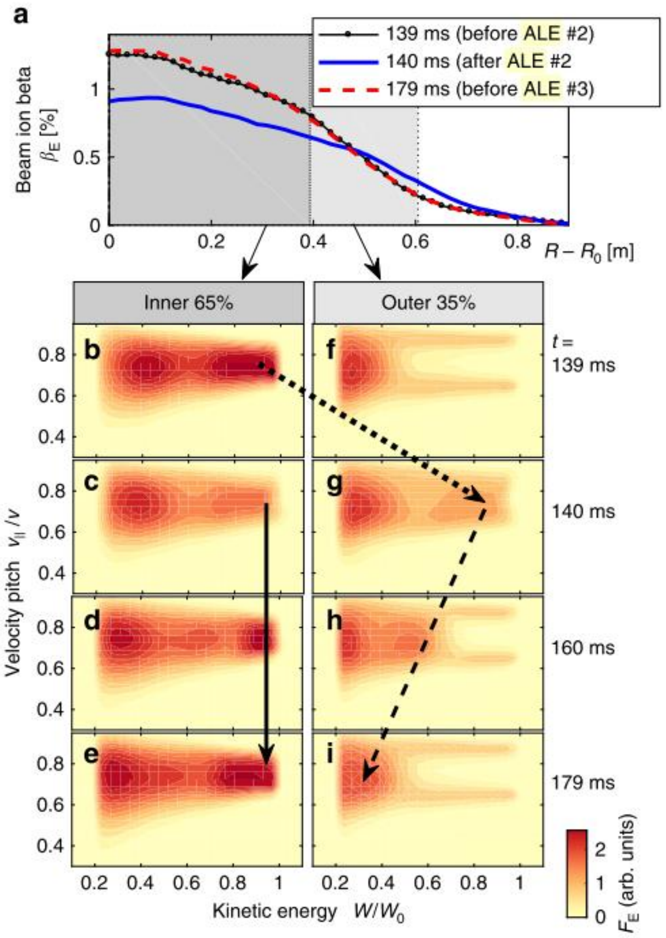
Chen W. *et al* 2020 NF 60 094003

Introduction: Abrupt Large-amplitude Event (avalanche) on JT-60U







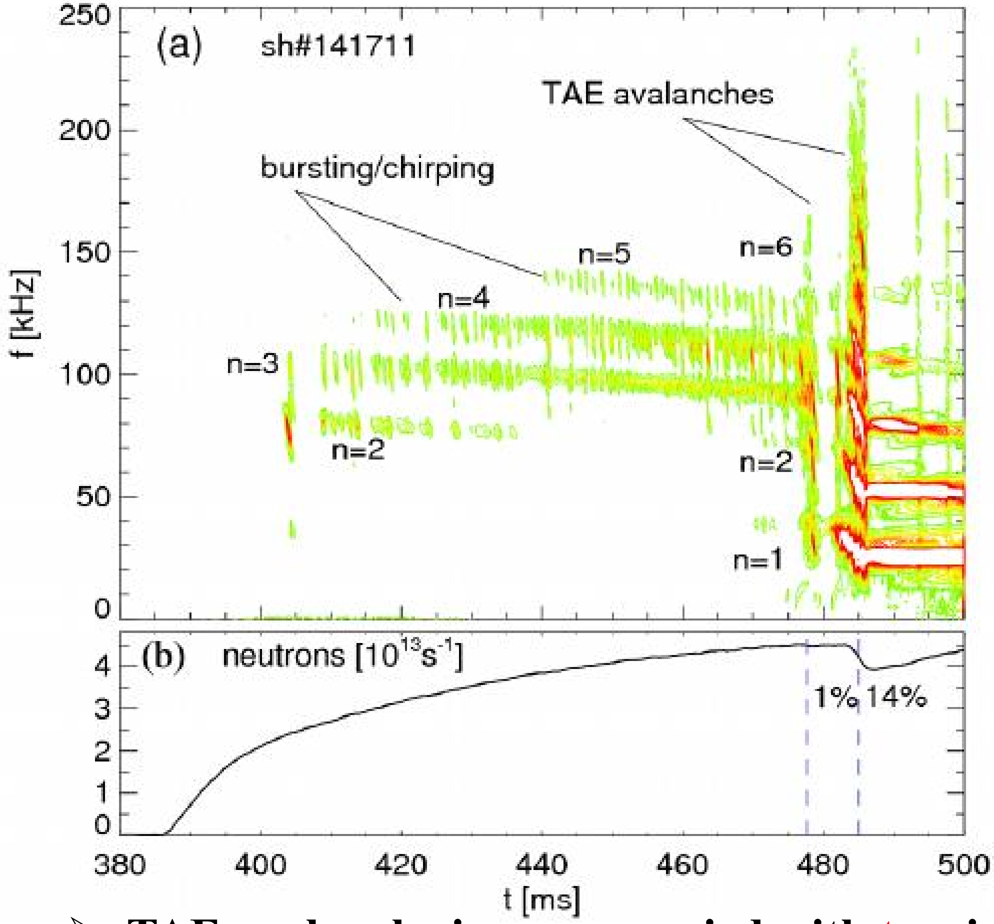


- ALE results from the synergy of different instabilities with multiple-mode nature.
- ALE results in abrupt massive migrations of energetic beam ions.

Bierwage A. *et al 2018 Nature Communication 9 3282*

Introduction：TAE Avalanche on NSTX (focus of our work, L-mode, n=1-6)

low-density L-mode NSTX plasmas



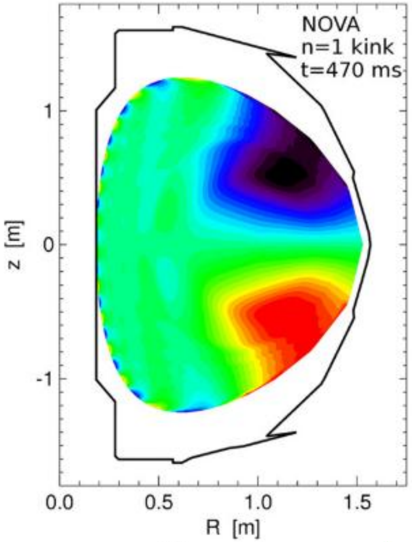
- **Firstly**, large bursts with simultaneous frequency chirping of n=1-4 modes lead to TAE avalanche, which is followed by the observation of a nearly constant frequency for each modes.

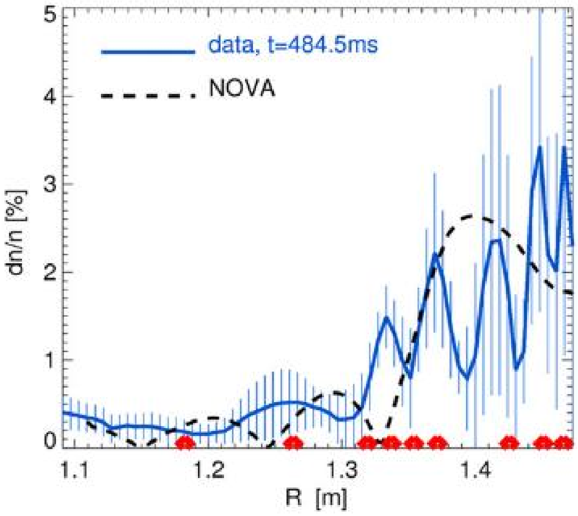
- **Secondly**, significant drop in the neutron rate indicates avalanche causes large energetic-ion losses.

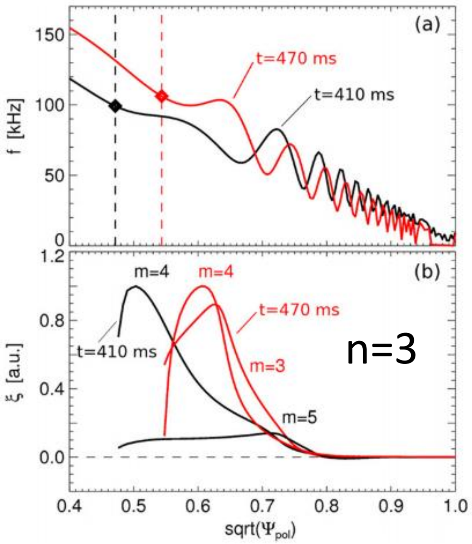
- **TAE avalanche is accompanied with two important experimental phenomena.**
- **The n = 1 low-frequency mode plays a vital role in the nonlinear mode–mode coupling during the bursting of TAE avalanche.**

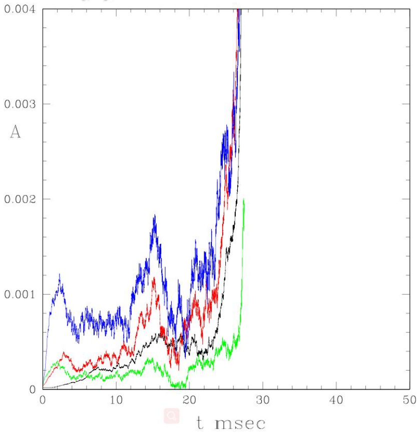
Podesta M. *et al* 2012 NF

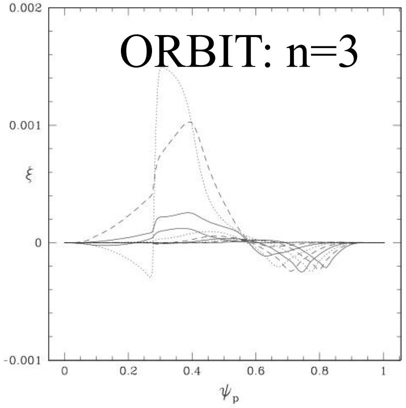
Introduction: The previous study of TAE avalanche and unsolved problems

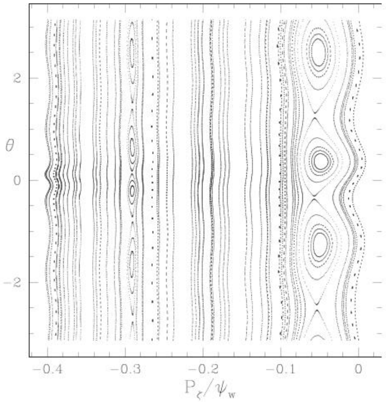








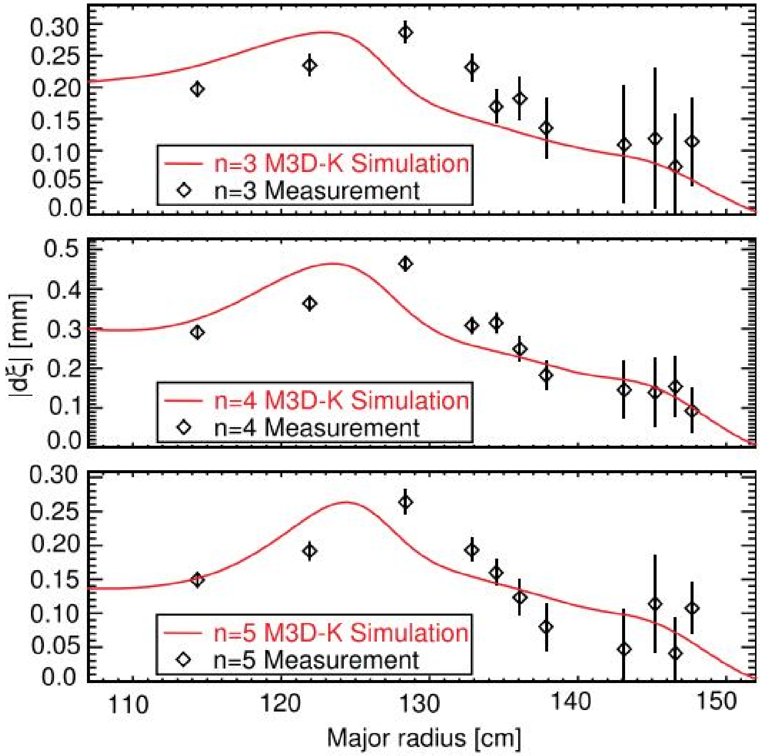


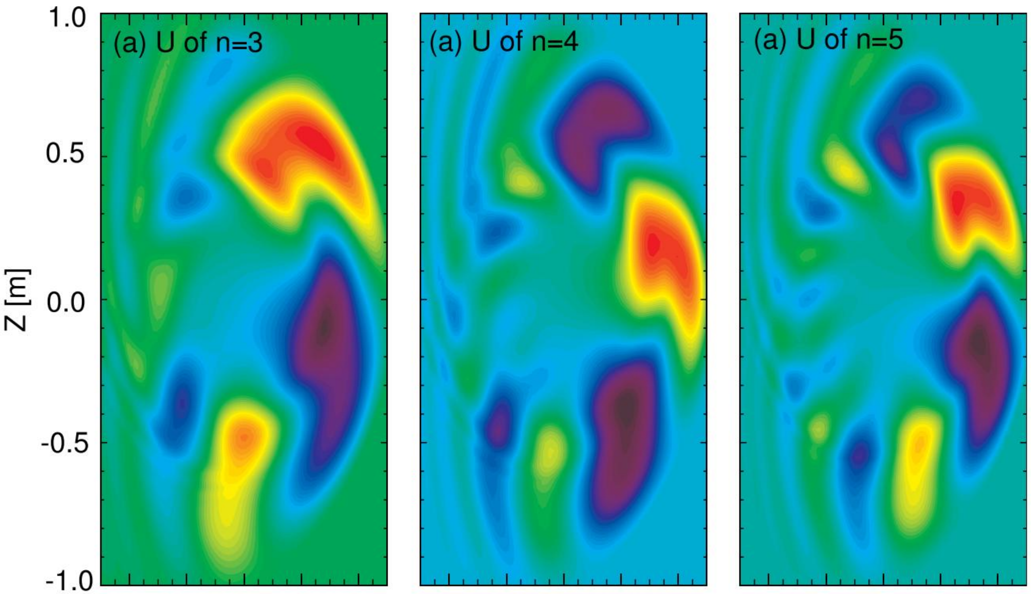


- **NOVA and ORBIT - eigenvalue and (quasi-)linear simulation, cannot capture the actual mode structure, EP distribution self-consistent evolution and the nature of frequency-chirping.**

White R.B. *et al* 2020 POP 27 022117; Podesta M. *et al* 2012 NF 52 094001

Introduction: The previous study of TAE avalanche and unsolved problems





- **Linear simulation using M3D-K finds that unstable TAEs with n = 3, 4, or 5 can be excited and toroidal rotation can have a significant destabilizing effect when the rotation is comparable or larger than the experimental level.**
- **TAE avalanche with strong frequency chirping on NSTX is an intrinsically highly nonlinear activity with multiple wave-number nature.**
- **Self-consistent nonlinear multiple-n simulations are badly needed to reproduce TAE avalanche.**

Liu D. *et al* 2015 POP 22 042509

M3D-K model equation

M3D-K is a global nonlinear kinetic/MHD hybrid simulation code for toroidal plasmas

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E}$$

$$\mu_0 \boldsymbol{J} = \nabla \times \boldsymbol{B}$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \eta \boldsymbol{J}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\rho \frac{d\boldsymbol{v}}{dt} = \boldsymbol{J} \times \boldsymbol{B} - \nabla p + \mu \nabla^2 \boldsymbol{v} - \nabla \cdot \boldsymbol{P_h}$$

$$\frac{dp}{dt} = -\gamma p \nabla \cdot v + \rho \nabla \cdot \left(\kappa \cdot \nabla \frac{p}{\rho}\right)$$

$$\boldsymbol{P_h} = P_\perp \boldsymbol{I} + (P_\parallel - P_\perp)\boldsymbol{bb}$$

$$P_\parallel(\boldsymbol{x}) = \int M v_\parallel^2 \delta(\boldsymbol{x} - \boldsymbol{X} - \rho_{\boldsymbol{h}}) F(\boldsymbol{X}, v_\parallel, \mu) d^3\boldsymbol{X} dv_\parallel d\mu d\theta$$

$$P_\perp(\boldsymbol{x}) = \int \frac{1}{2} M v_\perp^2 \delta(\boldsymbol{x} - \boldsymbol{X} - \rho_{\boldsymbol{h}}) F(\boldsymbol{X}, v_\parallel, \mu) d^3\boldsymbol{X} dv_\parallel d\mu d\theta$$

$$F = F(\boldsymbol{X}, v_\parallel, \mu) = \sum_i \delta(\boldsymbol{X} - \boldsymbol{X_i}) \delta(v_\parallel - v_{\parallel,i}) \delta(\mu - \mu_i)$$

$$\frac{d\boldsymbol{X}}{dt} = \frac{1}{B^{**}}\left[v_\parallel \left(\boldsymbol{B}^* - \boldsymbol{b_0} \times \left(\langle E \rangle - \frac{1}{e}\mu \nabla (B_0 \langle \delta B \rangle)\right)\right)\right] \qquad (*)$$

$$m\frac{dv_\parallel}{dx} = \frac{e}{B^{**}}\boldsymbol{B}^*\left(\langle E \rangle - \frac{1}{e}\mu \nabla (B_0 - \langle \delta B \rangle)\right)$$

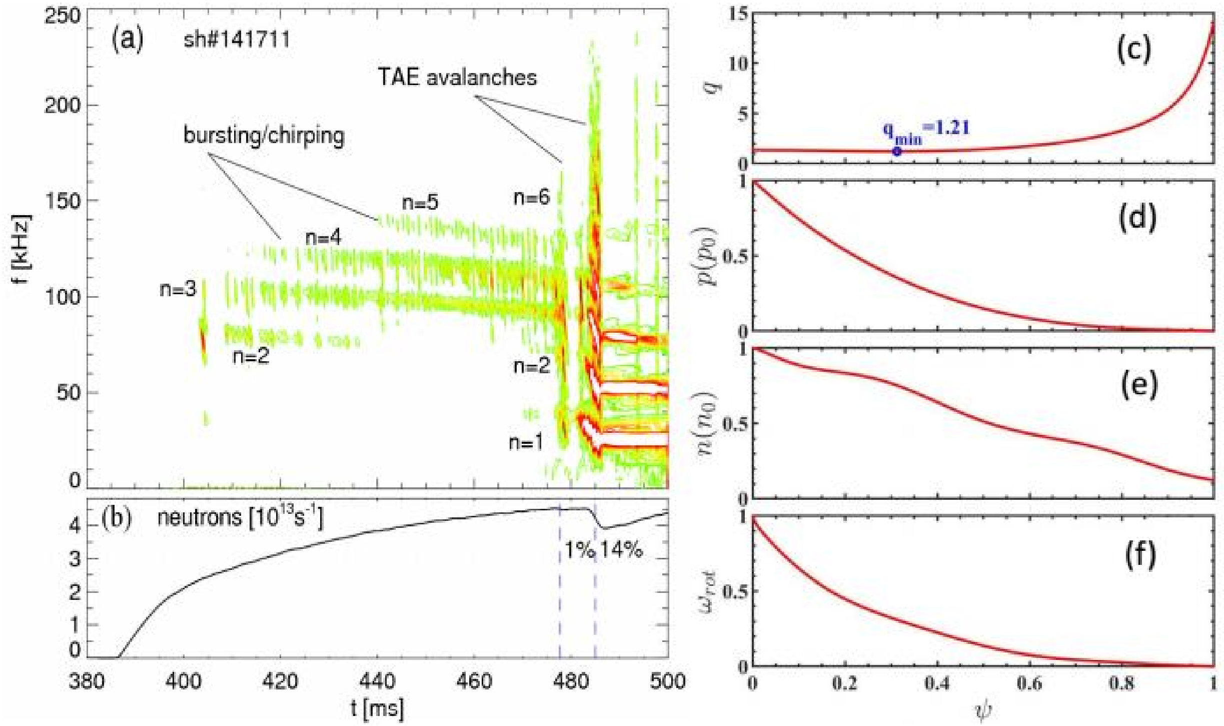
$$\dot{\mu} = 0, \ \boldsymbol{\rho_h} = \boldsymbol{v}_\perp \times \boldsymbol{b}/\boldsymbol{\Omega}$$

$$\boldsymbol{B}^* = \boldsymbol{B_0} + \langle \delta \boldsymbol{B} \rangle + \frac{m v_\parallel}{q} \nabla \times \boldsymbol{b_0}, \ B^{**} = \boldsymbol{B}^* \cdot \boldsymbol{b_0}$$

The angular brackets ⟨ ⟩ represent gyro-average.

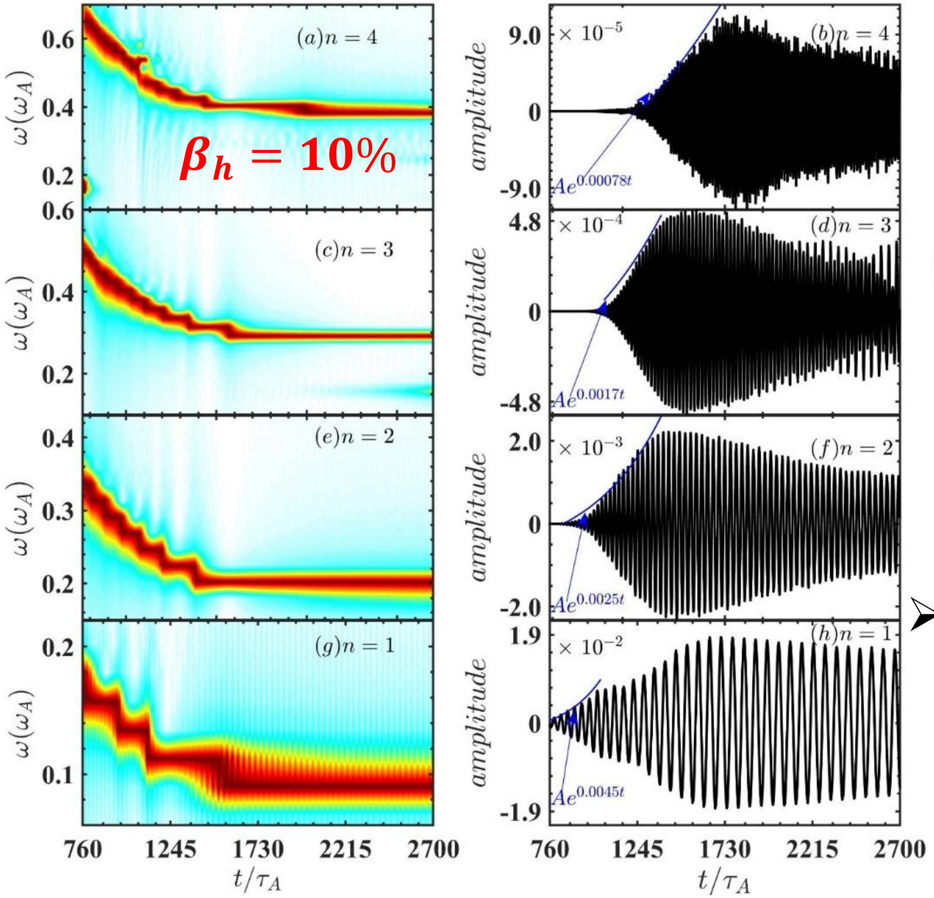
- **The energetic particle pressure enters through the particle stress tensor $\boldsymbol{P_h}$, which is calculated by gyro-kinetic or drift-kinetic equation via PIC. The equation(∗) is gyro-kinetic equation, while it is drift-kinetic equation irrespective of ⟨ ⟩. In the simulation, drift-kinetic equation is employed.**
- **EP effect is considered with the *non-perturbative* method (growth rate, structure and frequency all changed).**

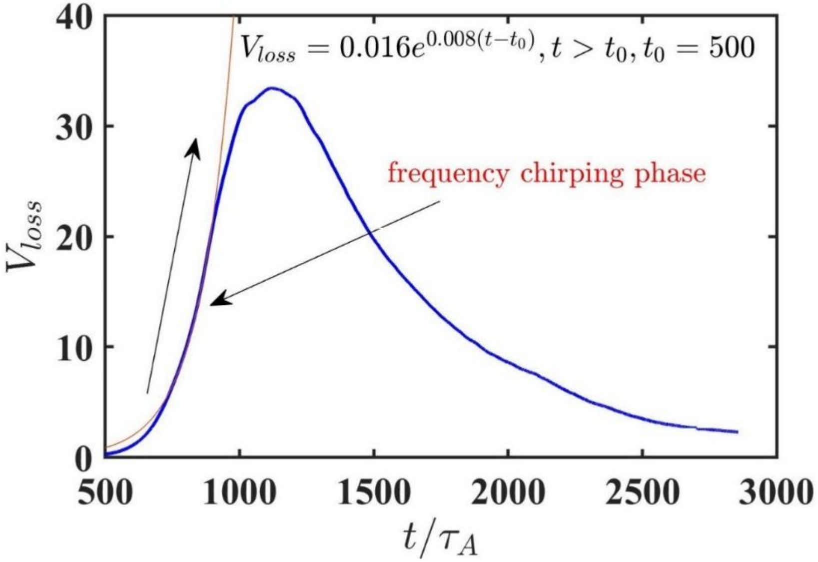
Profile and Parameter Setup in Simulation



- **Parameters：** B_0=0.55 T, R/a=0.85m/0.67m, from shot 141711 t=470 ms shortly before the bursting TAE avalanche, n(0)=4.7×10^{13} cm^{-3} $\delta = 0.38$ $\kappa = 1.88$
- **Plasma beta value at magnetic axis** $\beta_t(0) = 18.77\%$, $\beta_h(0) = 10\%$
- **Inclusion of toroidal rotation in equilibrium，** $q_{min} = 1.21@\psi = 0.31$。
- **EP parameters：** $\Lambda_0 = 0.6$ $\Delta\Lambda = 0.3$ $\Delta\psi = 0.2234$ $\frac{v_c}{v_A} = 0.6$ $\frac{v_h}{v_A} = 2.46$ $\frac{\rho_h}{a} = 0.173$

Simultaneous frequency-chirping of multiple-n=1-4 modes and exponential loss rate



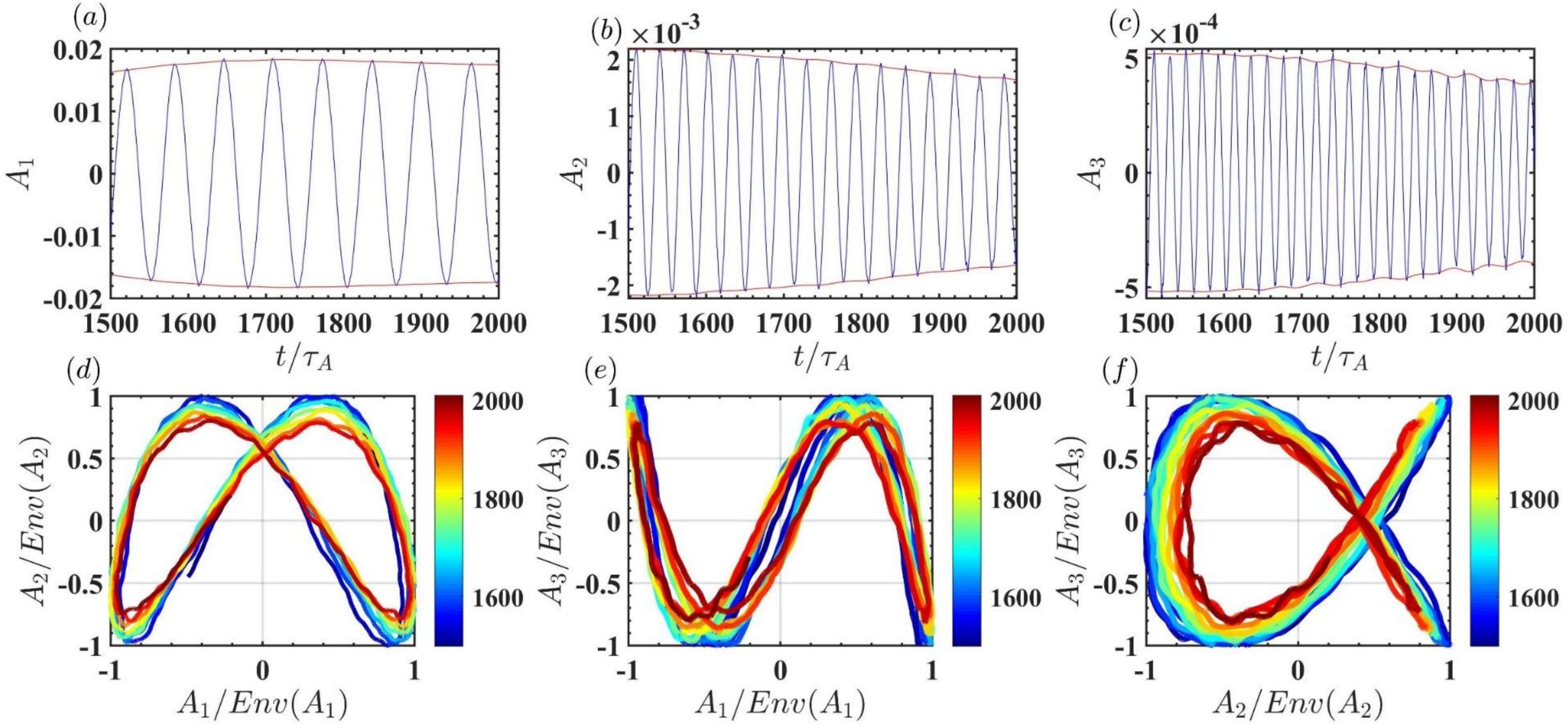


- Loss rate first increases with the time evolution of the TAE avalanche and then decreases. And in the increment stage, the loss rate is satisfied with the exponential scaling.

- Simulations show that the four modes show the phenomenon of first simultaneous frequency chirping and then keeping nearly constant mode frequency during the TAE avalanche, which is qualitatively consistent with the NSTX experiments.

Zhu X.L. *et al* 2022 NF 62 016012

Mode-mode nonlinear coupling of four components in multiple wave-number simulation



- Different shapes of Lissajous curves indicate different locked phase differences between two modes. The phase locking condition is readily satisfied.
- The n = 1and n = 2 modes lock at θ = π/4, n = 1 and n = 3 modes lock at θ = 0 and n = 2 and n = 3 modes lock at θ = π.
- Frequency matching condition $\frac{\omega_1}{\omega_2}=\frac{1}{2}$ $\frac{\omega_3}{\omega_1}=\frac{3}{1}$ $\frac{\omega_2}{\omega_3}=\frac{2}{3}$

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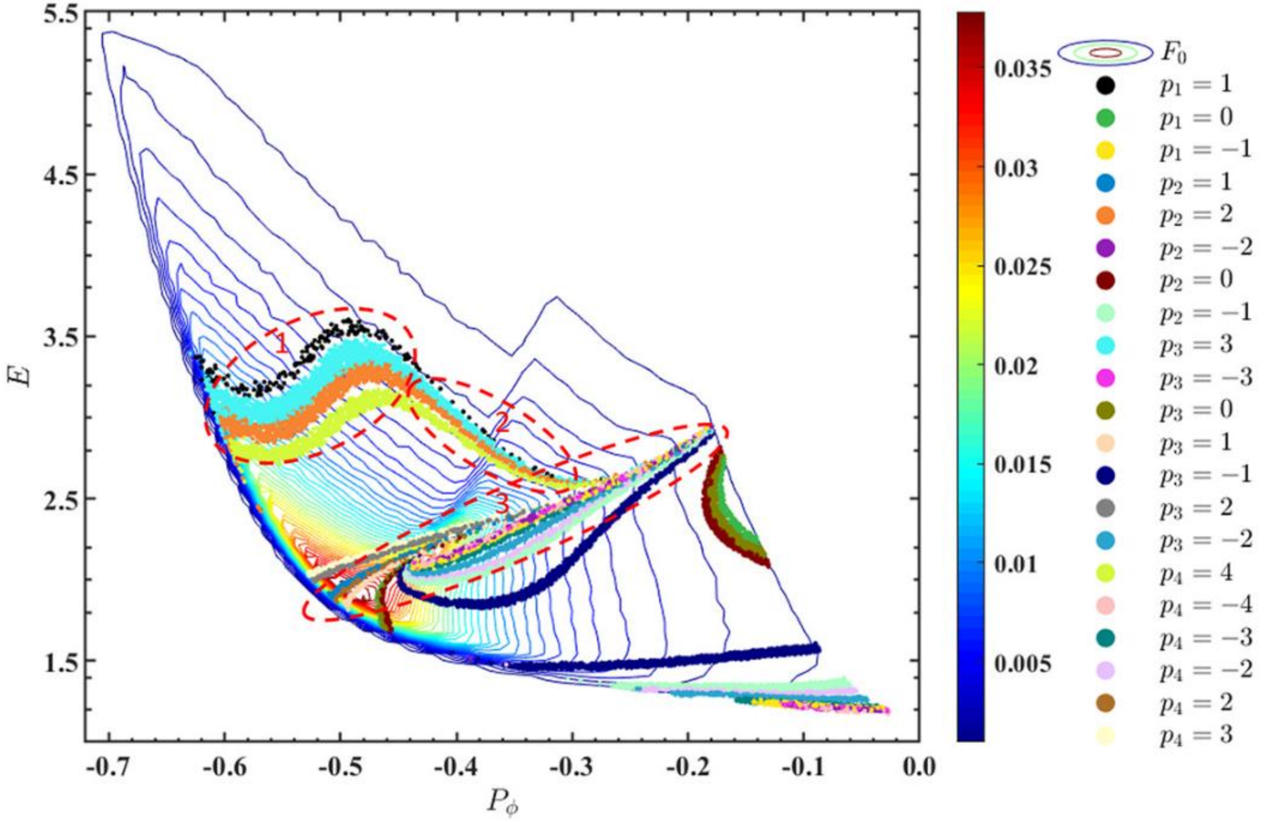
Wave-particle interaction of four components in multiple wave-number simulation



- The wave–particle resonant interaction in the TAE avalanche is very complex. Multiple resonance conditions leading to the resonance overlap, can result in the large scale stochastic losses.
- Once the resonances overlap, the broadened phase-space regions of the EP distribution can supply sufficient free energy to sustain an explosive growth of the TAE avalanche

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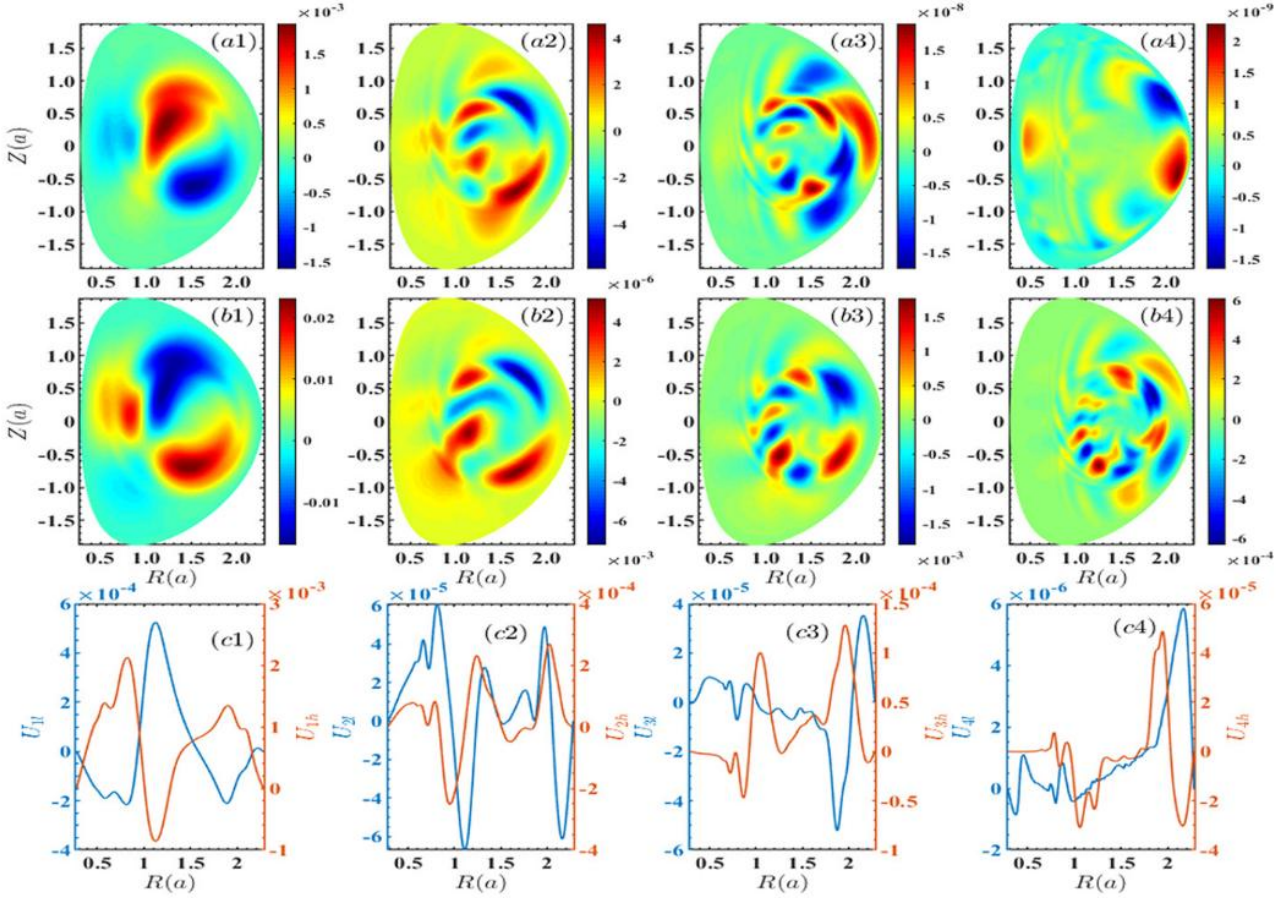
Comparison of mode structures during avalanche



$\beta_h = 10\%$

$\beta_h = 14\%$

- **The** **global mode structure** **during the TAE avalanche can be clearly observed.**
- **The** **increment of β_h** **from 10% to 14% can directly** **enhance** **the magnitude of the fluctuation amplitude at least** **one order**, **triggering a** **large fraction of EP losses** **and the very** **fast loss rate.**

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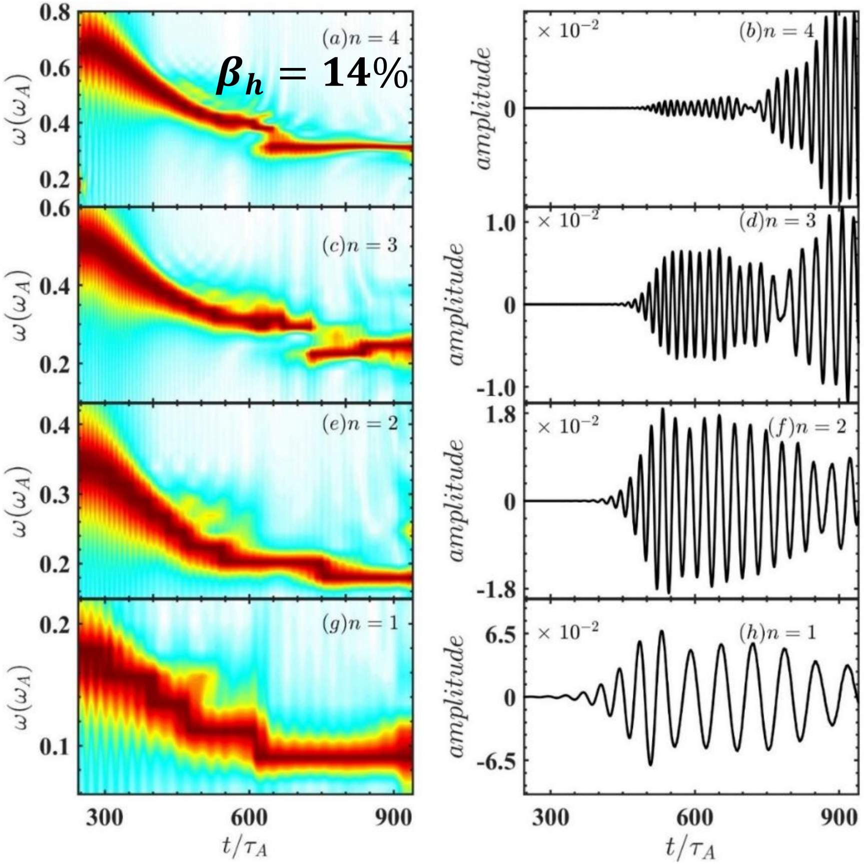
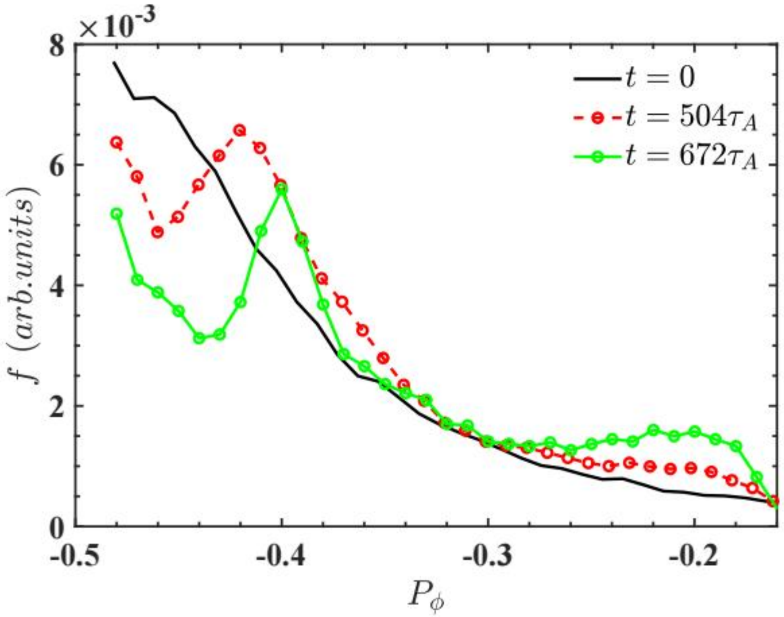
Avalanche transport and loss of energetic-ions





- **1D EP distribution in the center is clearly decreased and the increment at the edge is also observed, especially at the frequency-chirping moment and at the nearly-constant-frequency moment, which can be responsible for the synergy between wave–wave nonlinear couplings and wave–particle resonances.**

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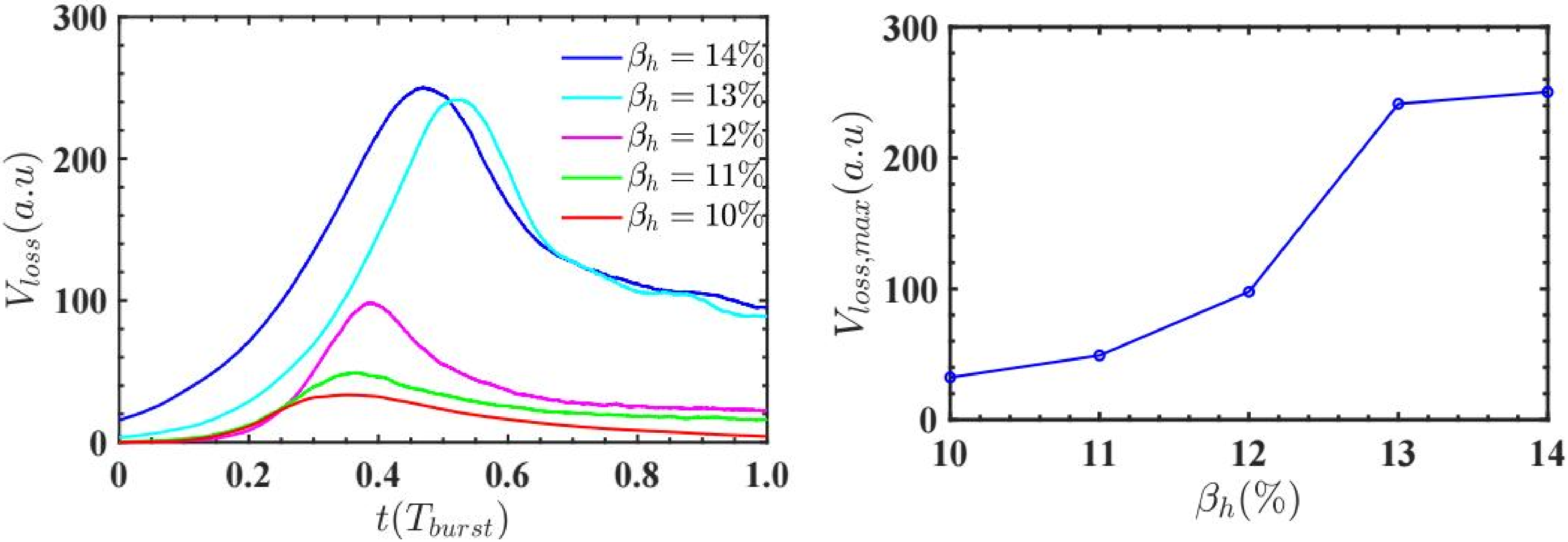
Avalanche transport and loss of energetic-ions



- When β_h is increased from$\beta_h = 10\%, 11\%, 12\%$ to 13%, the EP loss rate sharply augments, which is approximately a 150% increment.
- When the EP drive β_h continues to increase to 14%, the maximum of the EP loss rate keeps almost unchanged.
- The threshold value of EP drive to the onset of the stronger TAE avalanche exists.
- Strong enough drive provides enough free energy to simultaneously destabilize the multiple wave-number modes and keeps the modes above the marginal stability, which can provide a path for large scale stochastic loss of EPs.

Zhu X.L. *et al* 2022 NF 62 016012

Conclusions and discussions I

We have performed multiple wave-number simulation, self-consistently including n = 1–4 modes simultaneously, based on the experimental observation of TAE avalanche on NSTX using M3D-K.

- The four modes show the phenomenon of first simultaneous frequency-chirping downwards and then keeping nearly constant mode frequency during the TAE avalanche, which is qualitatively consistent with the experimental observation on NSTX.
- TAE avalanche is highly nonlinear event as a result of synergy between wave–wave nonlinear coupling and wave–particle resonant interaction. In our simulation, the evidences of the wave–wave nonlinear coupling and wave–particle resonant interaction are both found.
- The achievement of enough strong EP drive is an essential ingredient of the onset of stronger TAE avalanche. The EP loss rate dramatically increases when the EP drive exceeds a critical threshold value.
- Sometimes, the microscopic turbulence is also involved in the avalanche, which will refer to various spatio-temporal scales, which will be left for our future publications.

Overall Outline

- Branch Outline I: Avalanche transport of energetic-ions in magnetic confinement plasmas: nonlinear multiple wave-number simulation

- **Branch Outline II: Hybrid-kinetic simulation of synergy between fishbone/sawtooth and tearing mode-induced energetic-ion transport in a tokamak plasma**

- Last: Conclusions and discussions

Branch Outline II

- Introduction
- Part I: Experimental observation of synergy of FB/ST and TM on HL-2A and simulation setup
- Part II: Simulation results **(Zhu X. L. *et al* 2023 NF 63 036014)**
  - ◆ Case I: Interaction between only 2/1 TM and EPs
  - ◆ Case II: Synergy between FB/ST and TM triggers onset of sawtooth collapse
  - ◆ Synergy of FB/ST and TM induced transport and loss of energetic-ions
- Part IV: Conclusions and discussions

Branch Outline II

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- Part I: Experimental observation of synergy of FB/ST and TM on HL-2A and simulation setup
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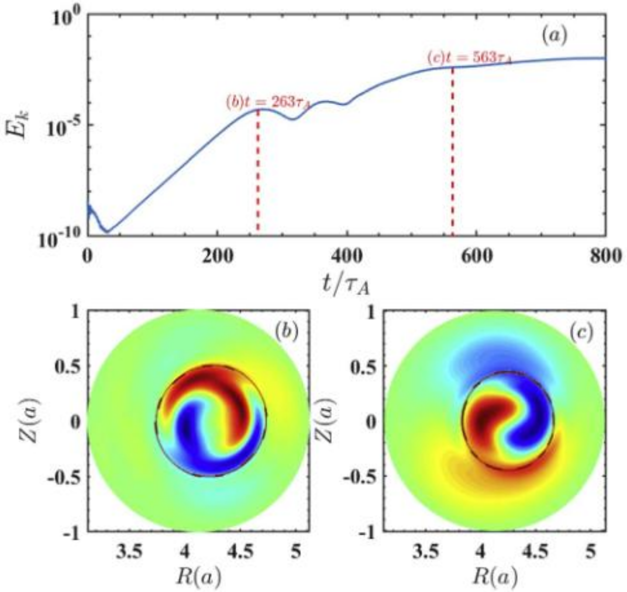
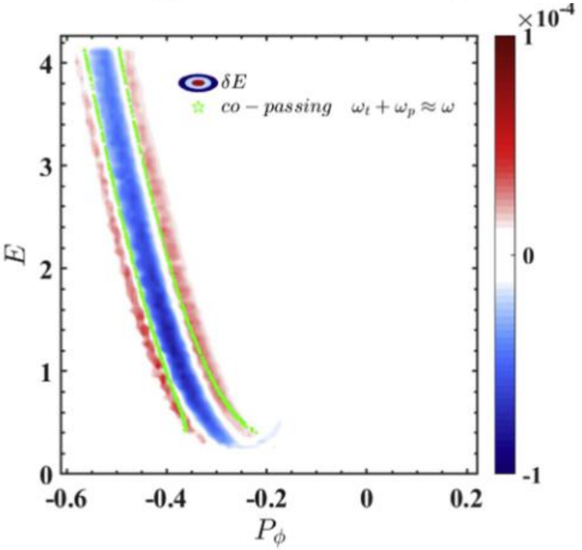
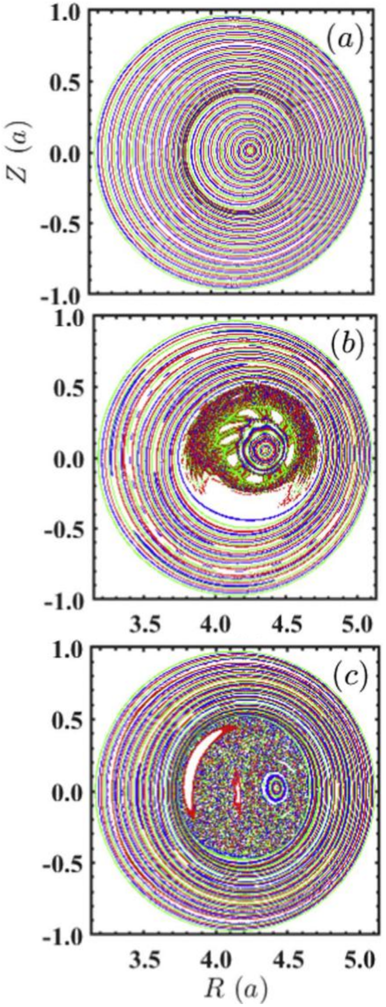
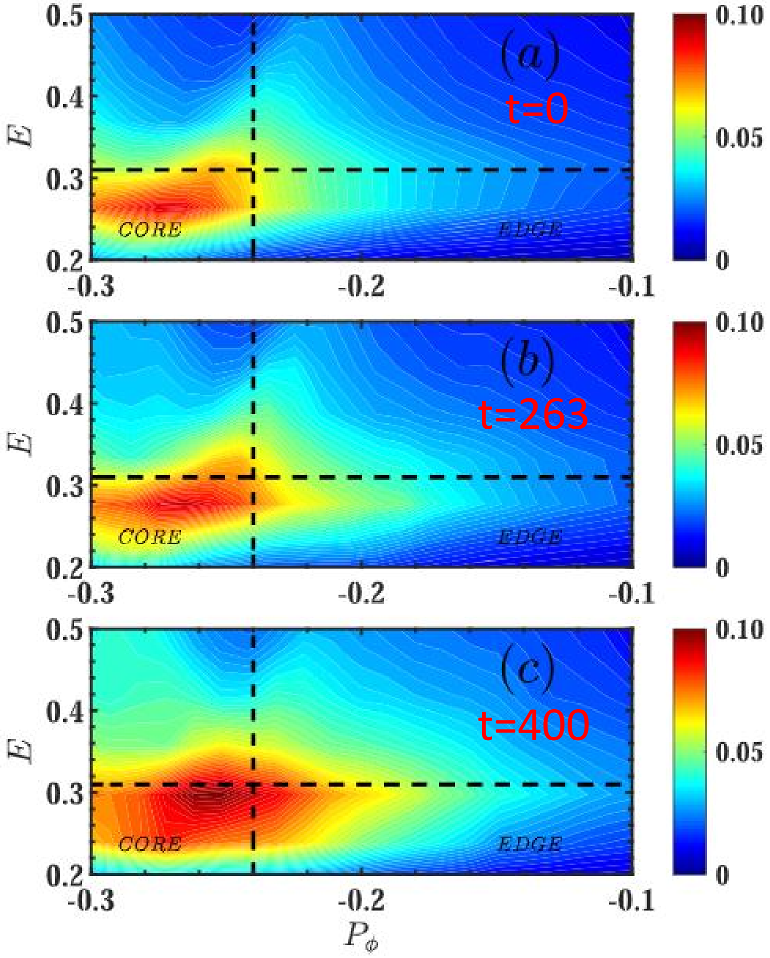
Introduction: Interaction between only NRK/FB and EPs on HL-2A





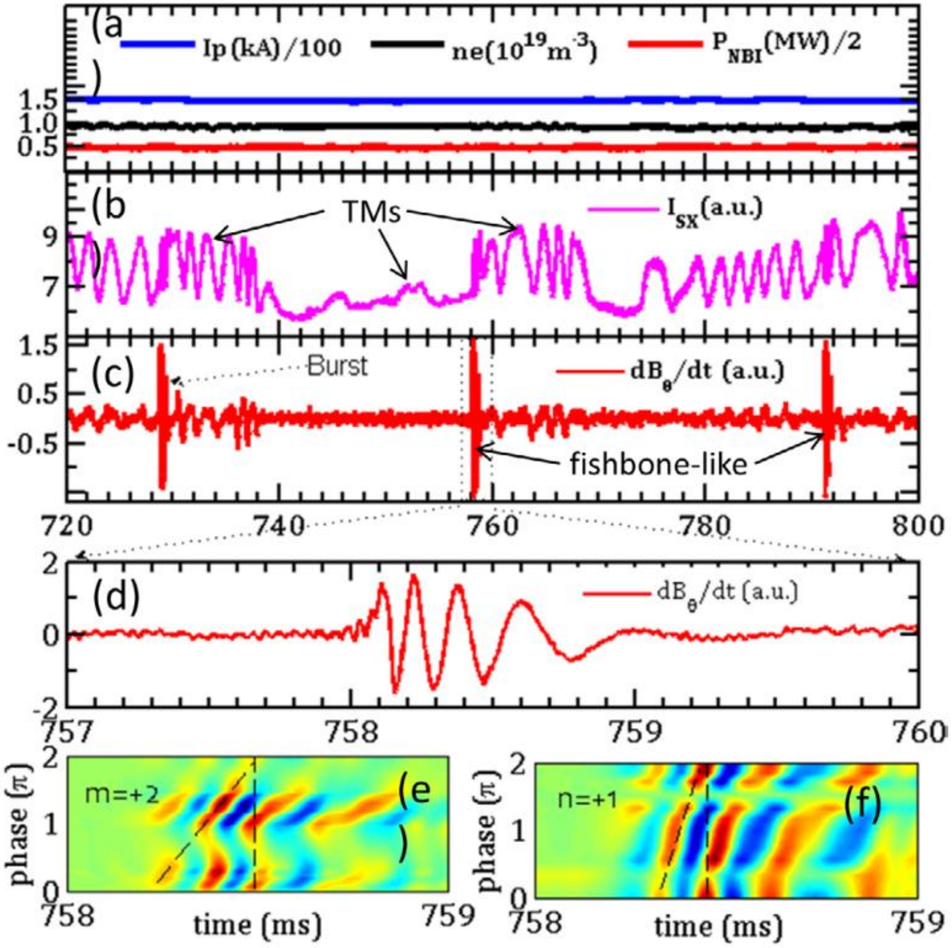


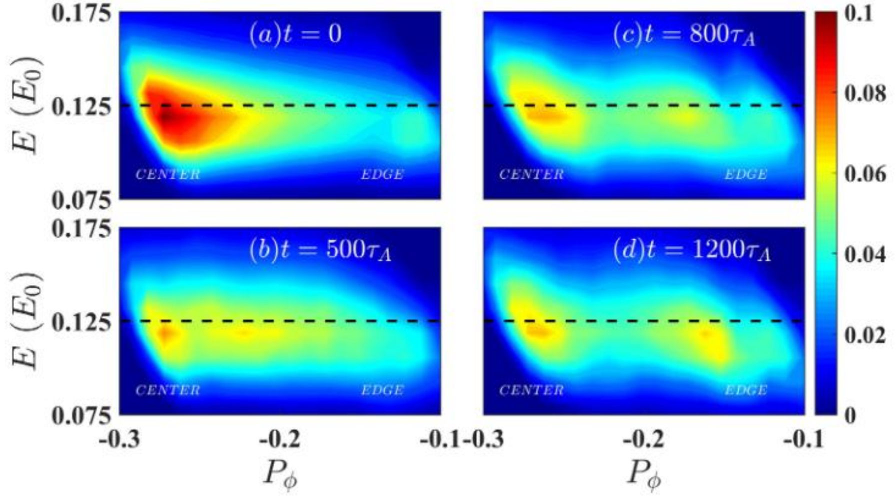


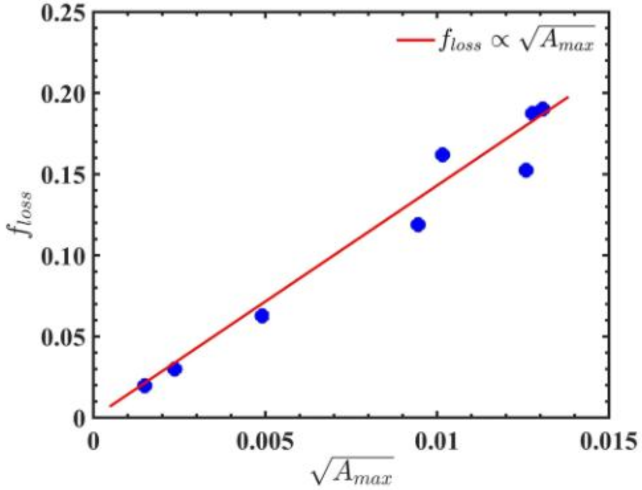
- The resonance between EPs and NRK/FB induces the significant EP redistribution and loss.

Zhu X.L. *et al* 2022 PST 24 025102

Introduction：Interaction between only 2/1 TM and EPs on HL-2A





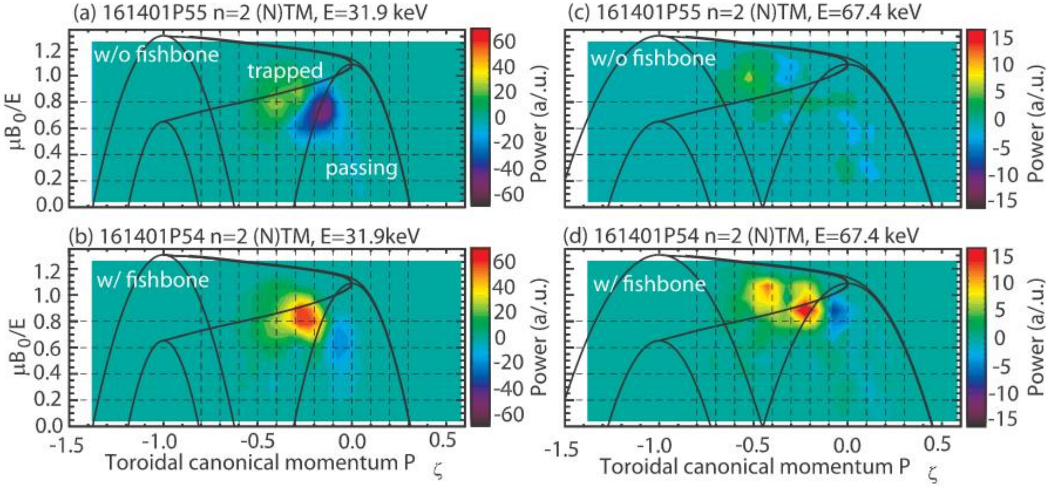


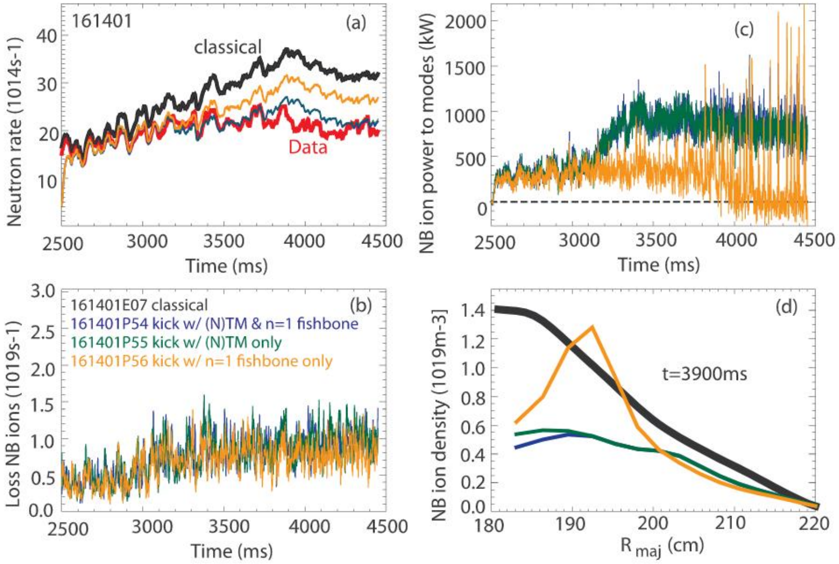
- **The resonance between co-passing EPs and TM is responsible for the observations.**
- **The dependence of EPs loss level on the fluctuation amplitude satisfies at linear scaling, indicating that such loss is convective**

Zhu X.L., Chen W. *et al* 2020 NF 60 046023; Chen W., Zhu X. L. et al 2019 NF 59 096037

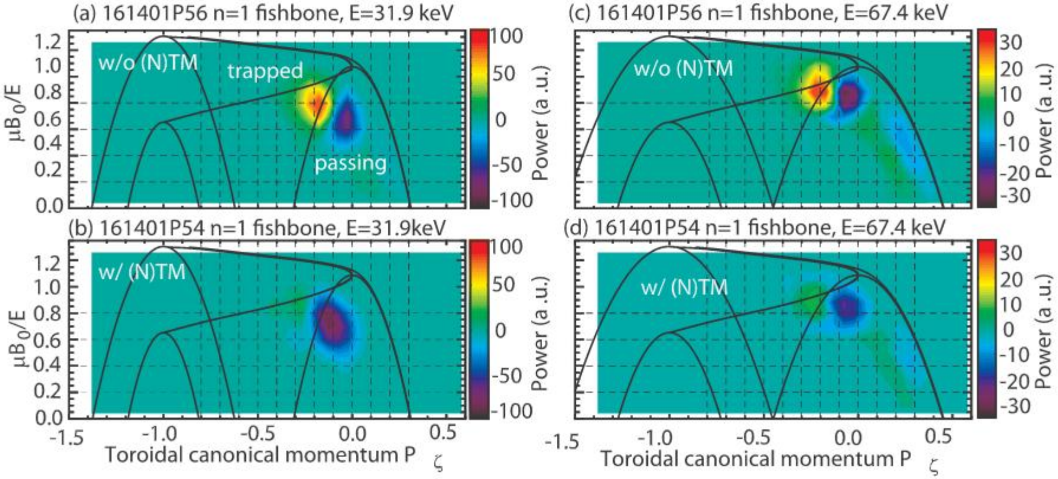
Introduction：synergy of (N)TM and FB induced EP transport on DIII-D

Energy transferred by EPs to (N)TM





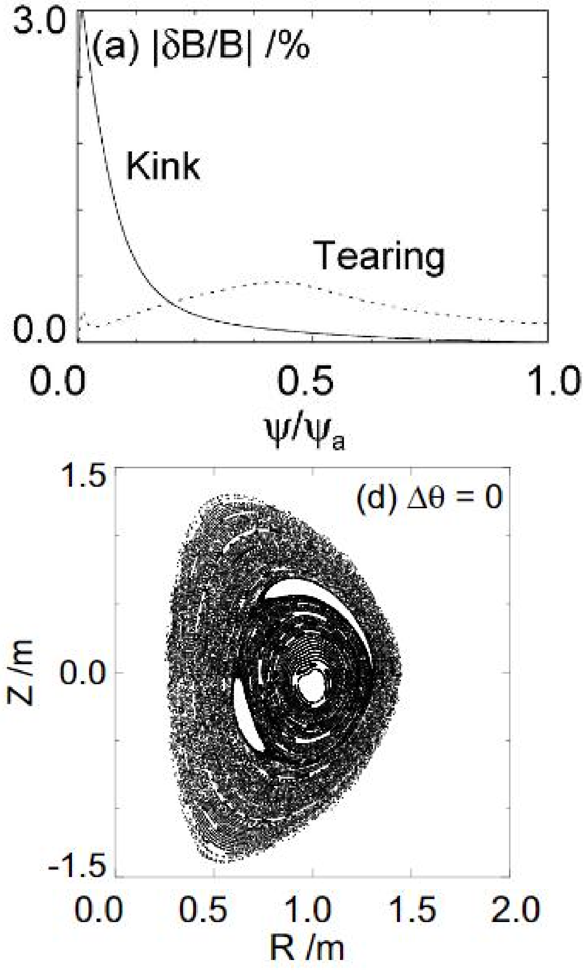
Energy transferred by EPs to FB

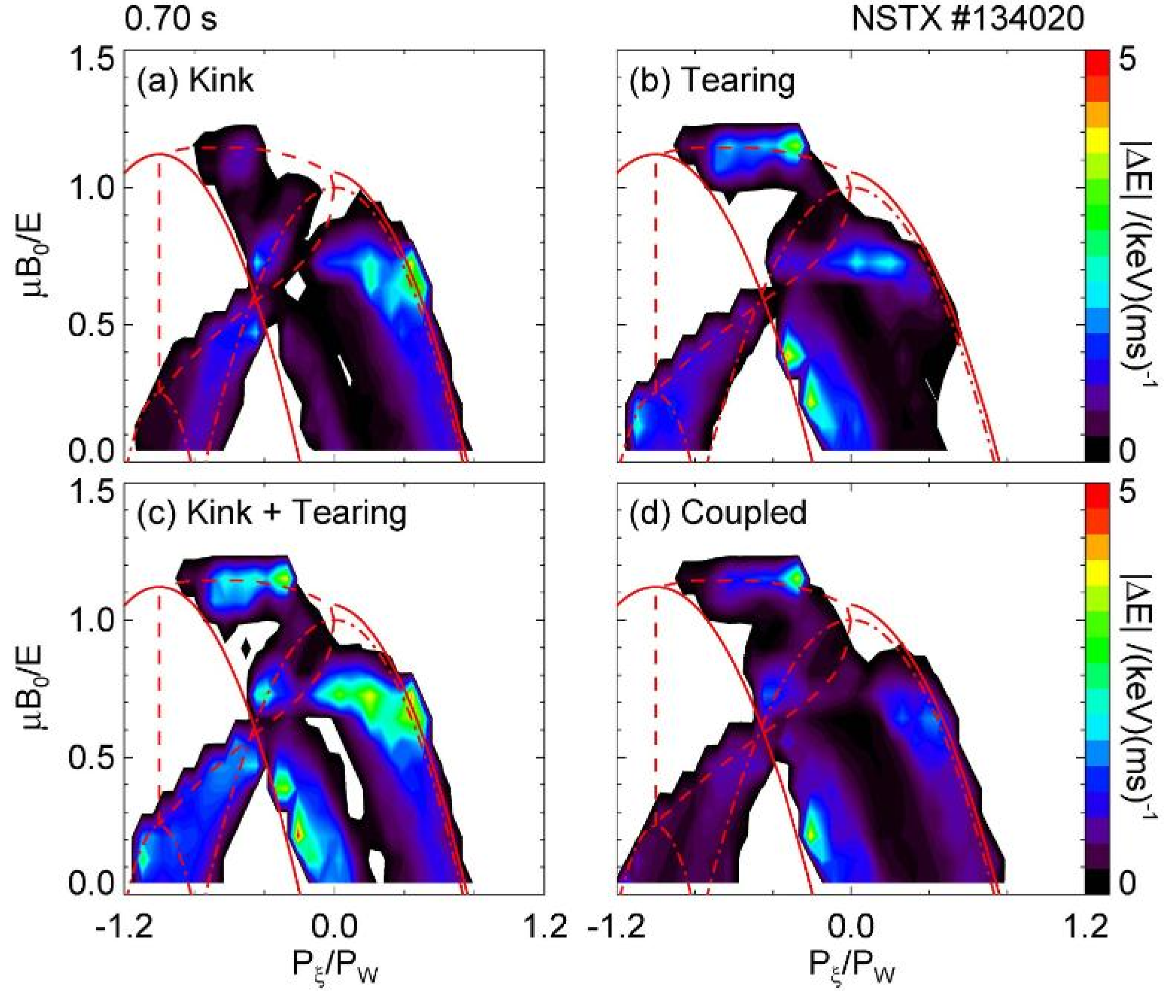


- **TRANSP-kick simulation reveals the strong synergy between (N)TM and FB.**
- **The Upper: FB enhances the energy transferred from EP to (N)TM.**
- **The lower: (N)TM decrease the drive of FB from EP.**

Liu D. *et al* 2020 NF 60 112009

Introduction：synergy of TM and kink induced EP transport on NSTX (kick+NUBEAM)

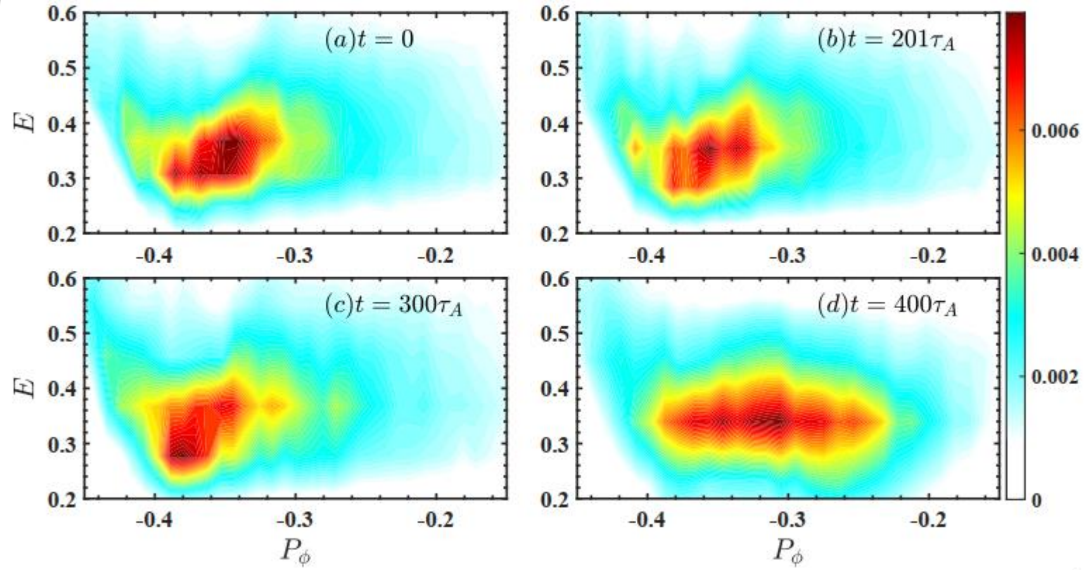




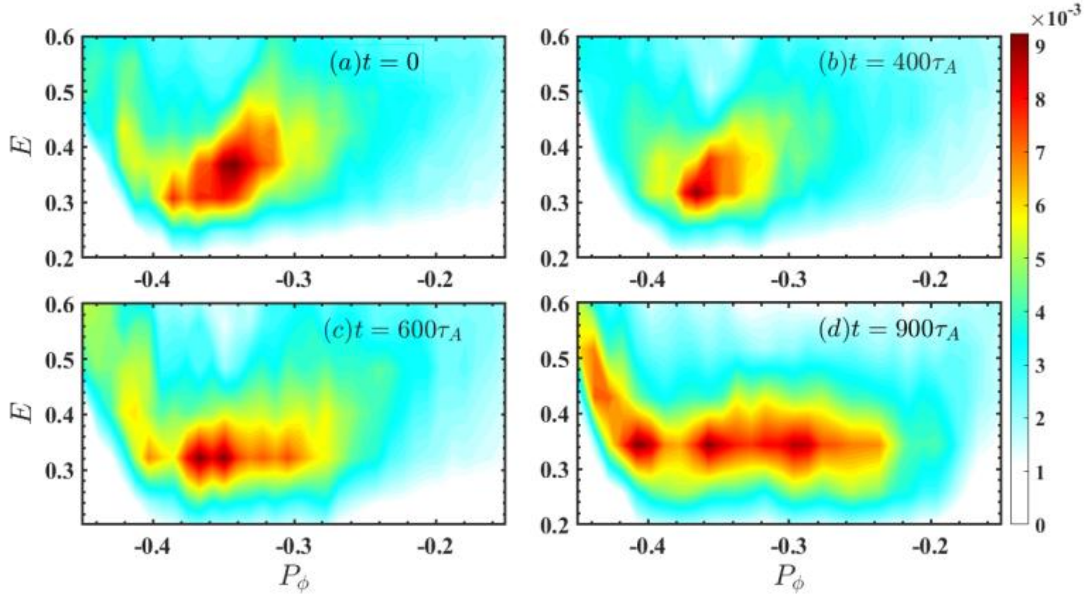
- **Energy transfer from the coupled kink and tearing modes is different from the combined energy transfers from the individual kink and tearing modes, indicating the strong synergy between the two modes.**

Yang J. *et al* 2021 PPCF 63 045003; Yang J. *et al* 2022 PPCF 64 095005

Introduction：synergy of TM and kink induced EP transport on NSTX (M3D-K NL simulation)



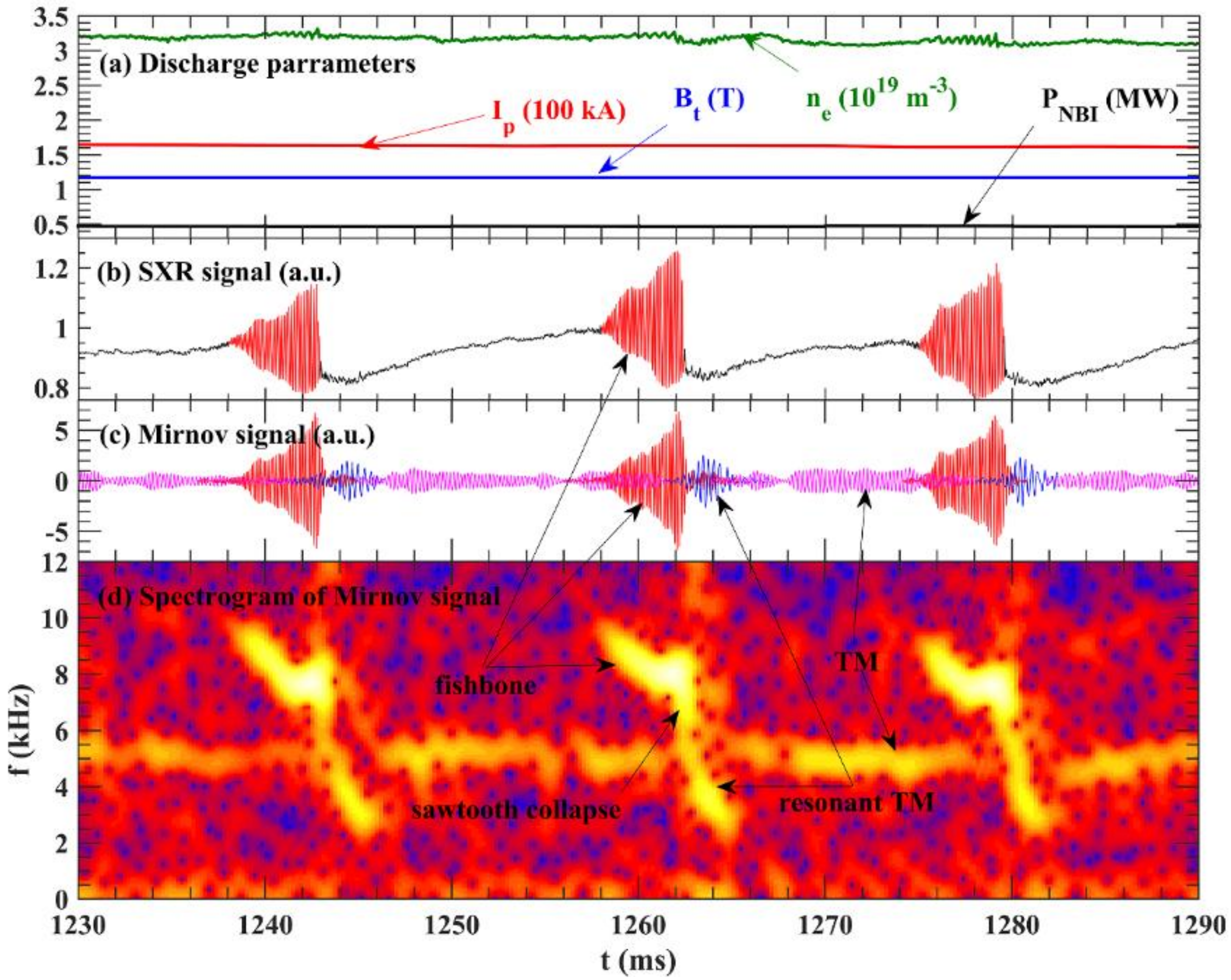
- **NRK induces dominant EP redistribution and transport , which is radial outwards.**



- **Synergy of TM and kink induces remarkable EP redistribution and transport , which is radial outwards. Besides, the transport along energy-increasing direction is also remarkable.**

Zhu X. L. *et al* 2023 APS in press

A typical example of synergy between FB/SW and TM on HL-2A



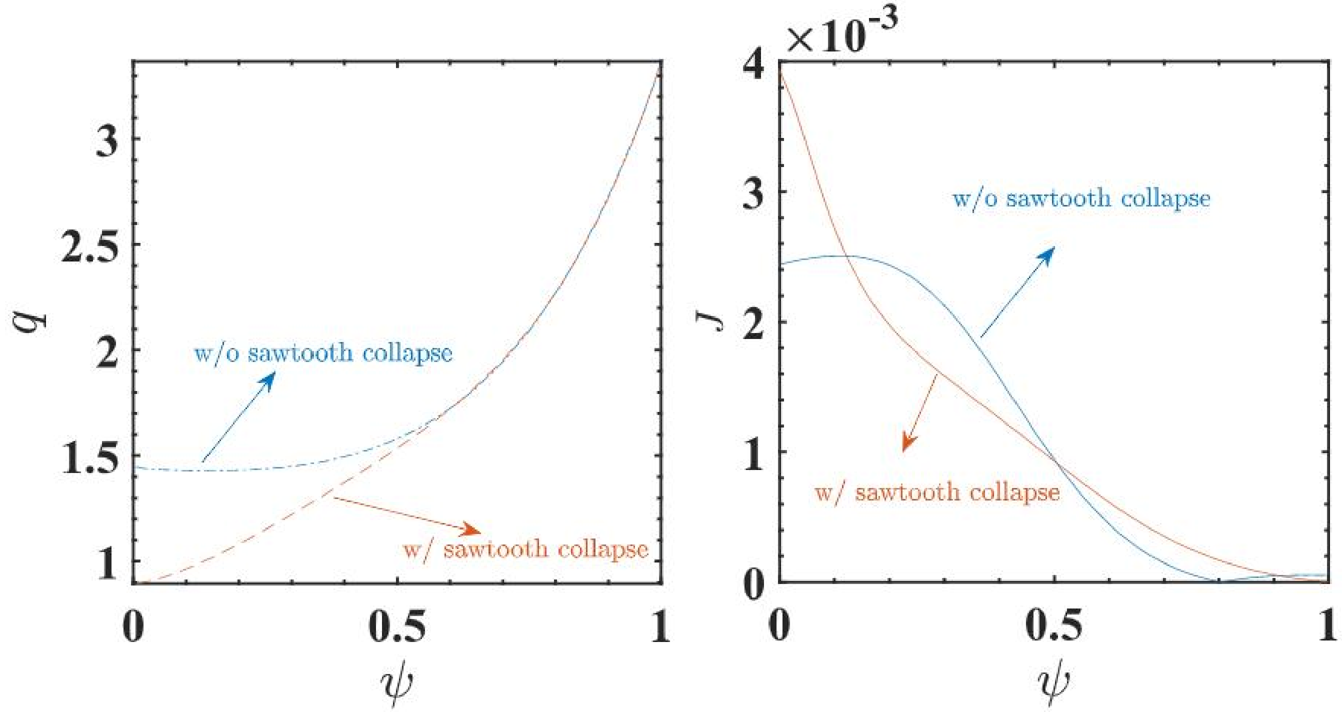
- The resonant interaction between 2/1 TM and EPs redistributed by 1/1 FB/SW collapse has been observed recently in HL-2A NBI-heated high-density plasmas. This event essentially results from a synergistic effect with a multiple-mode nature.

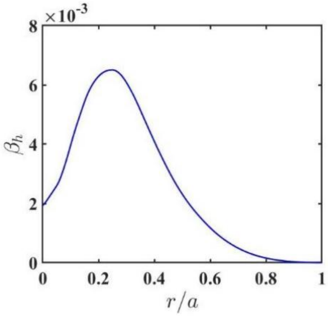
Zhu X.L. *et al* 2023 NF 63 036014; Yu L.M., Zhu X.L. *et al* NF 2023 in review

Branch Outline II

- Introduction
- **Part I: Experimental observation of synergy of FB/ST and TM on HL-2A and simulation setup**
- Part II: Simulation results (Zhu X. L. *et al* 2023 NF 63 036014)
  - ◆ Case I: Interaction between only 2/1 TM and EPs
  - ◆ Case II: Synergy between FB/ST and TM triggers onset of sawtooth collapse
  - ◆ Synergy of FB/ST and TM induced transport and loss of energetic-ions
- Part IV: Conclusions and discussions

Simulation setup





Onetwo computing results.

- Parameters： B_0=1.2 T, R/a=1.65 m/0.4 m, Before synergy: shot 38645 t=1256 ms, n(0)=3.0 ×10^{19} m^{-3} and $\eta_0 = 2 \times 10^{-4}$
- $\beta_t(0) = 0.73\%$, $\beta_h(0) = 0.65\%$ （From Onetwo ）
- EP: $\Lambda_0 = 0.0$ $\Delta\Lambda = 0.3$ $\Delta\psi = 0.3$ $\frac{v_c}{v_A} = 0.6$ $\frac{v_h}{v_A} = 0.7$ $\frac{\rho_h}{a} = 0.07$

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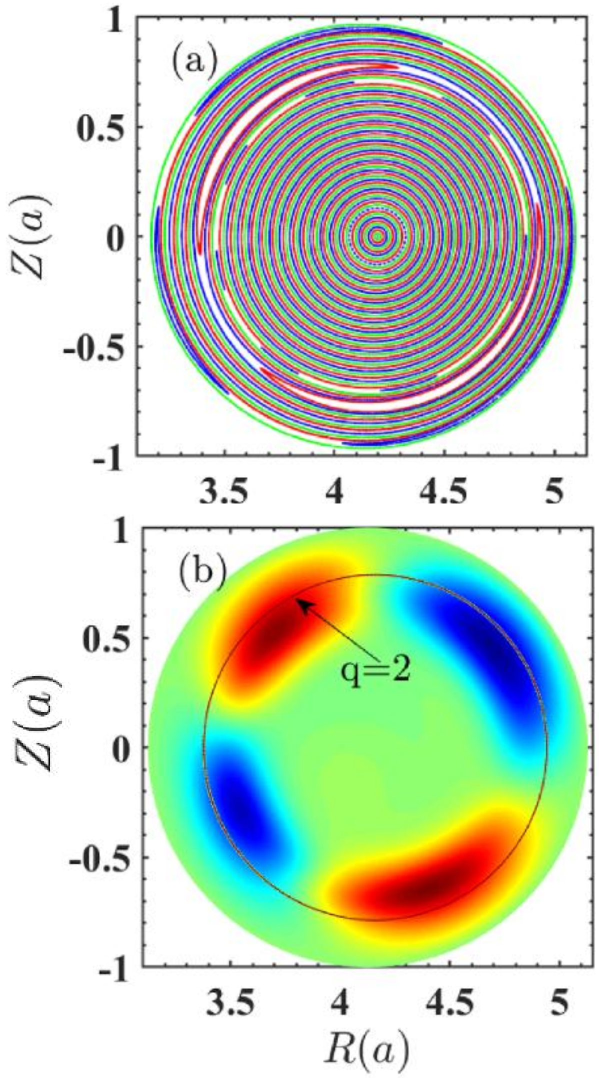
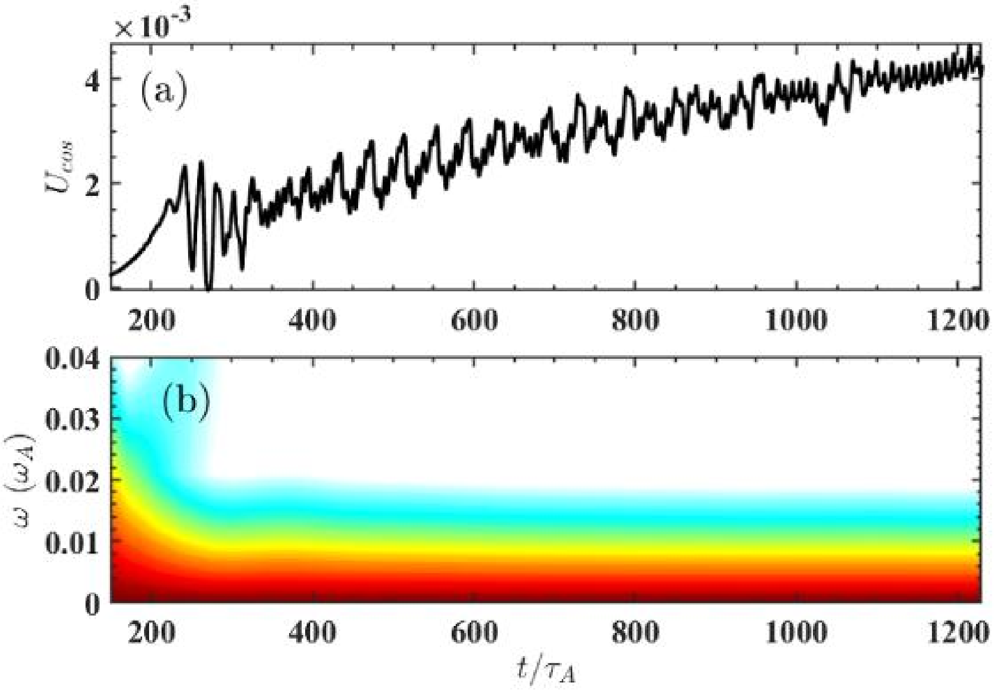
Case1: Interaction between only 2/1 TM and EP





- 2/1TM: island + mode structure
- Gain energy from EP → burst of mode amplitude, but lower amplitude than the case with synergy, influence the transport.
- Chirping → wave-particle resonance.

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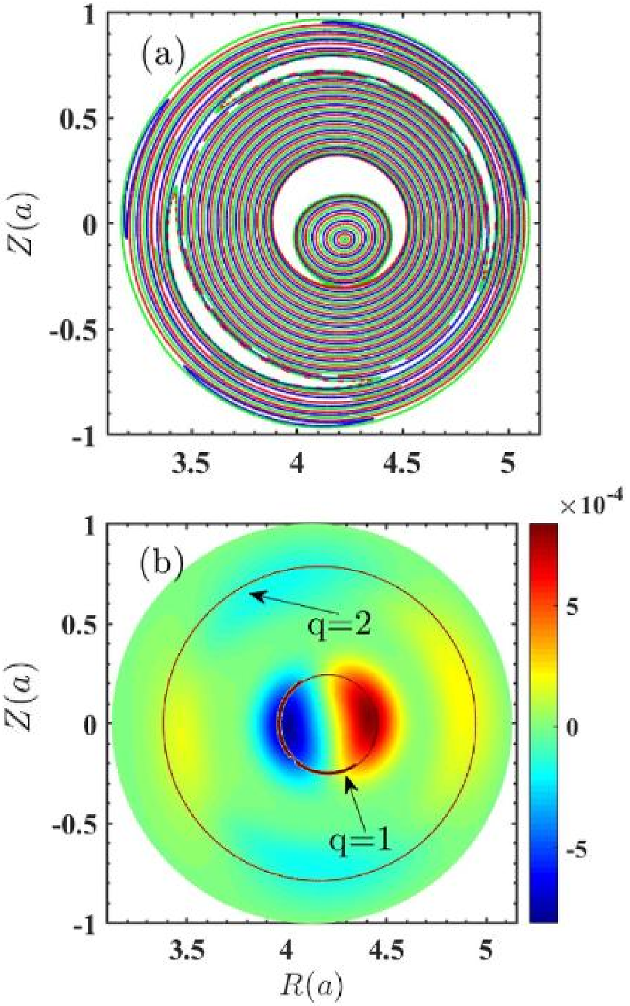
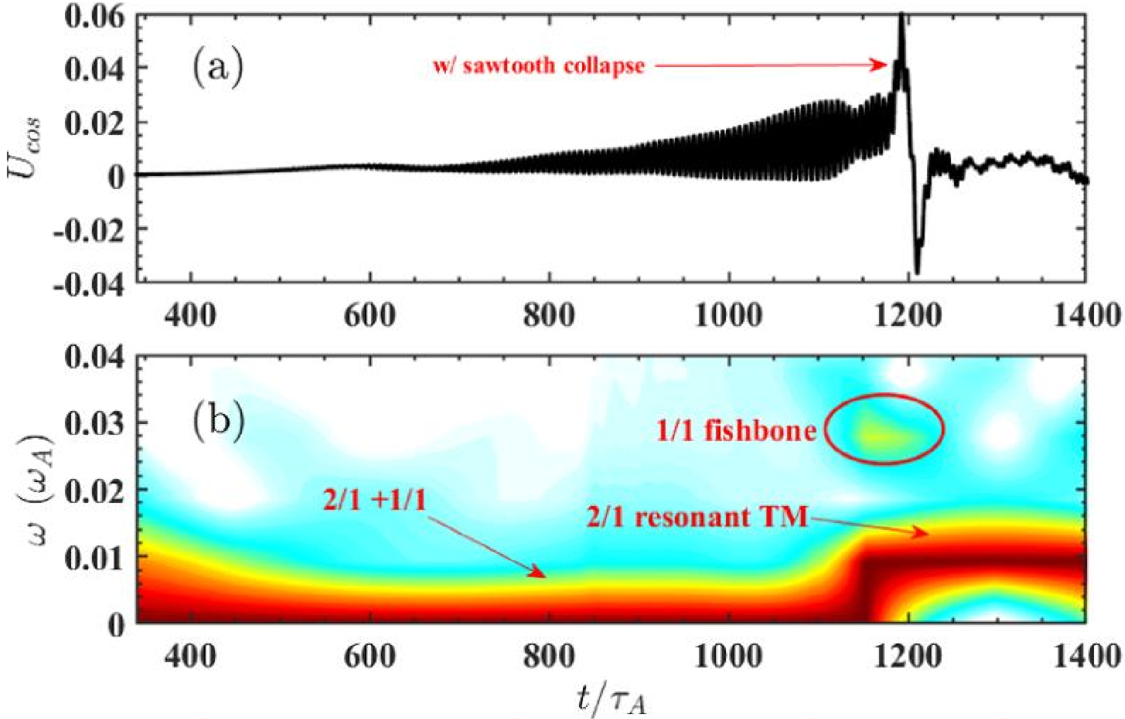
Case2: Synergy between FB/ST and TM triggers onset of sawtooth collapse





- **EP drive 1/1 mode，current density drive 2/1 mode，synergy triggers SW collapse.**
- **Before collapse: nearly zero-frequency 1/1+2/1 mode;**
  at collapse：high-frequency 1/1 mode + low-frequency 2/1 mode

Branch Outline II

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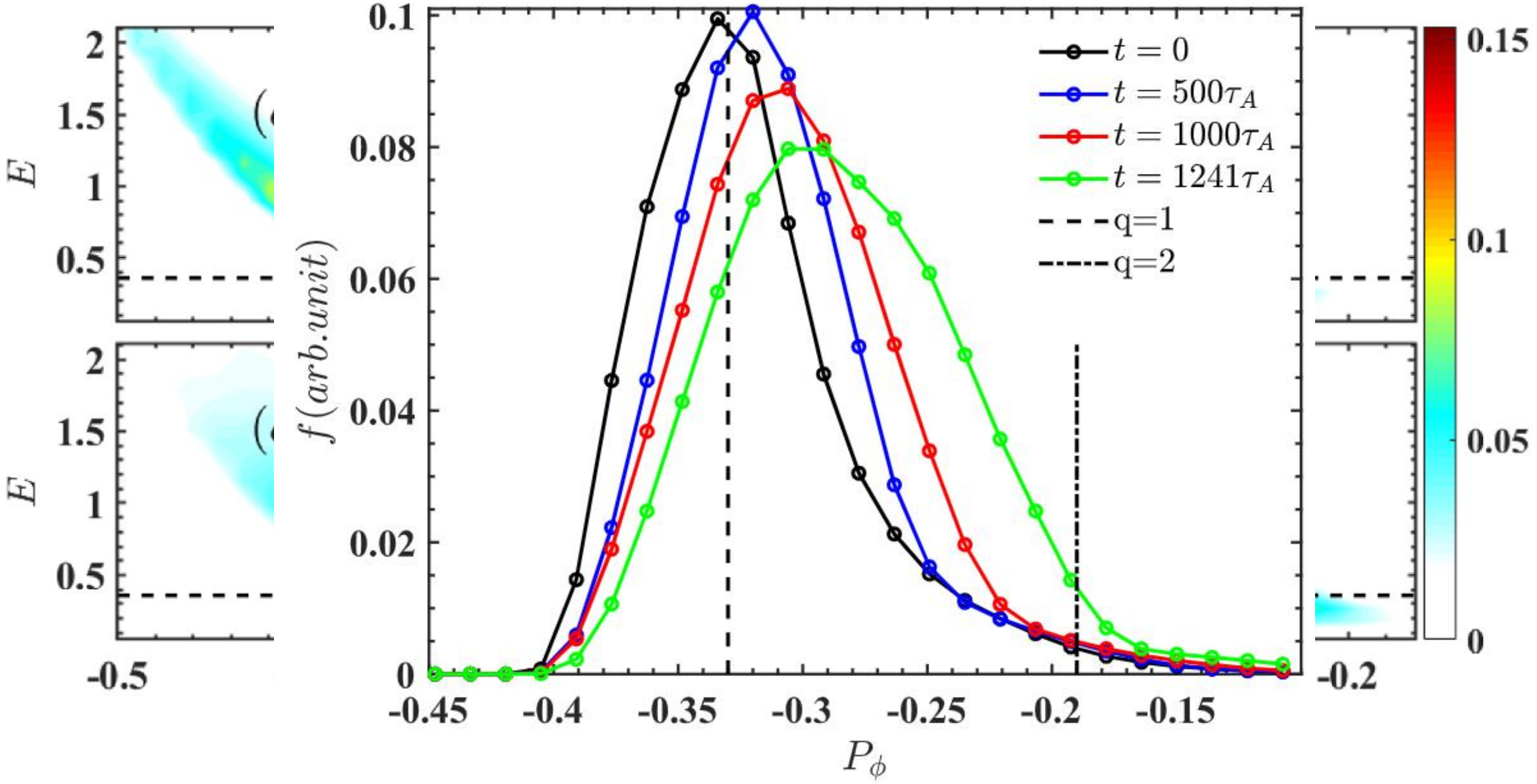
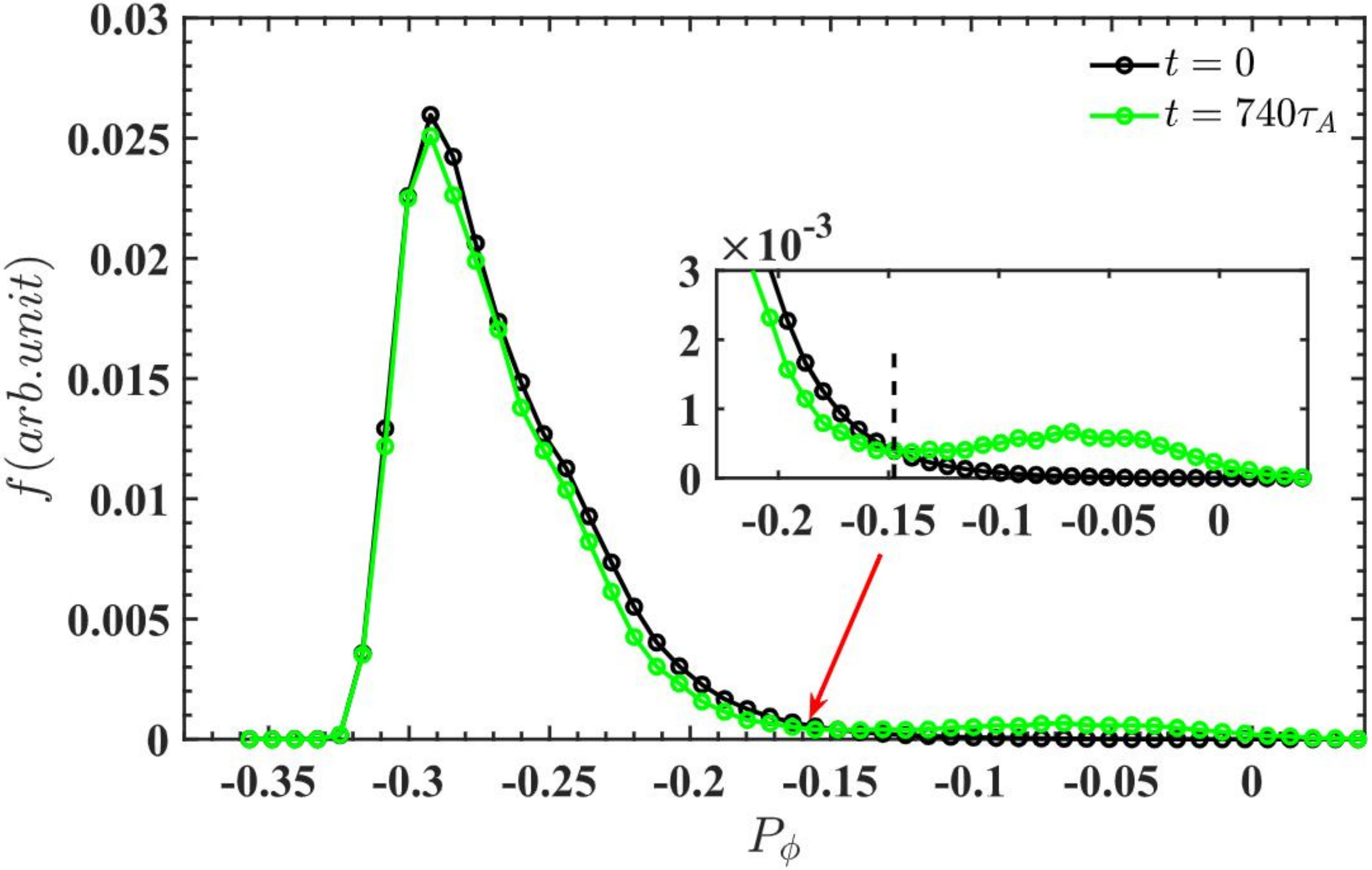
- Part IV: Conclusions and discussions

Case2: Synergy between FB/ST and TM induces the significant EP transport and redistribution



- Transport and redistribution of EP is found to be remarkably significant in both larger P_ϕ and smaller E directions.
- EPs redistributed by 1/1 FB/SW located around the q=1 surface may change the phase-space gradient of f around the q=2 surface.

Case1: only 2/1 TM induces the poorly significant EP transport and redistribution

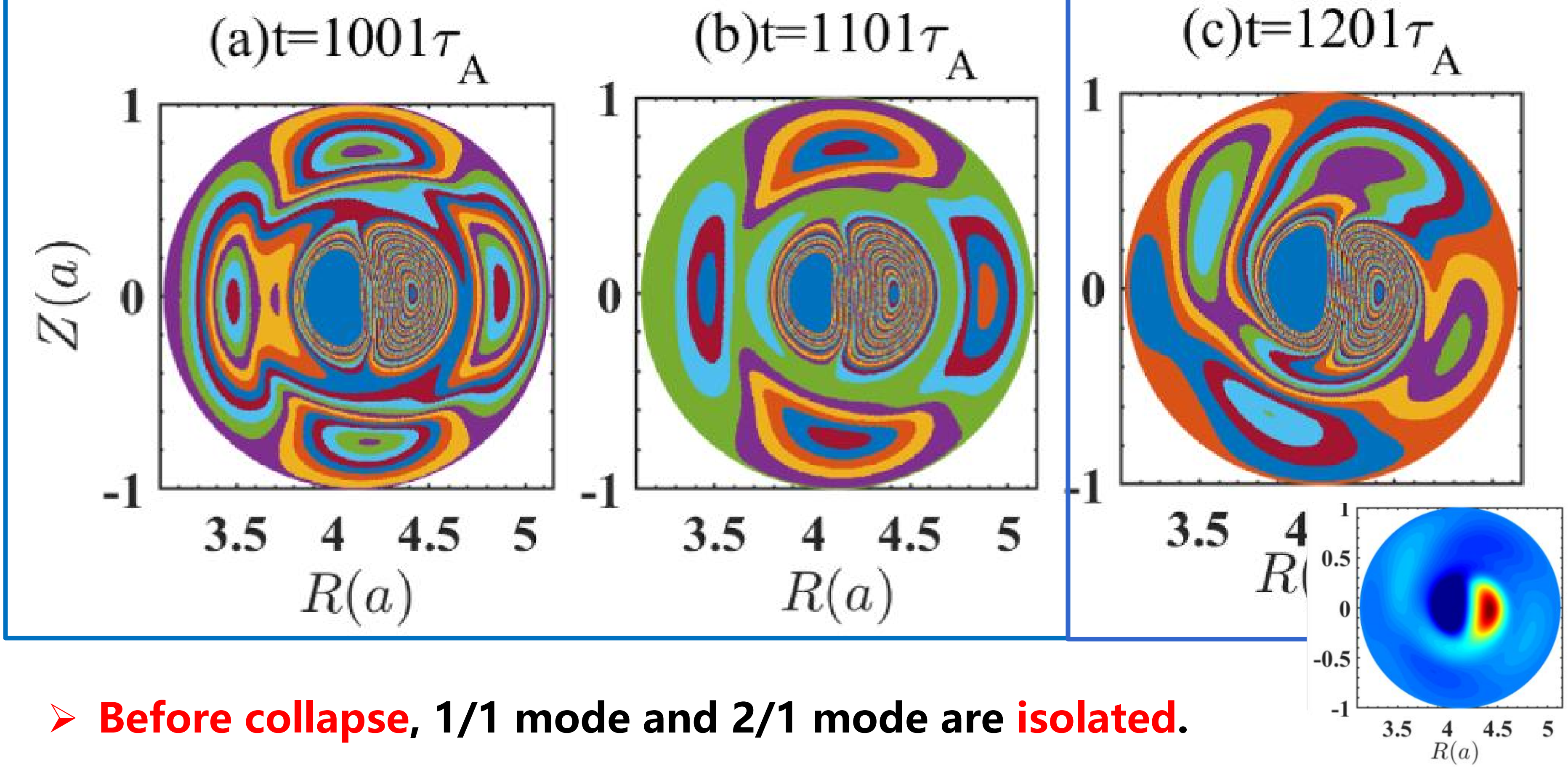


- Compared with the case with synergy, the transport and redistribution of EPs is relatively weaker in the center of plasmas, especially near the location of q=1 surface. The flattening of 1D f near q=2 surface is observed.

Case2: Synergy between FB/ST and TM: mode structure evolution

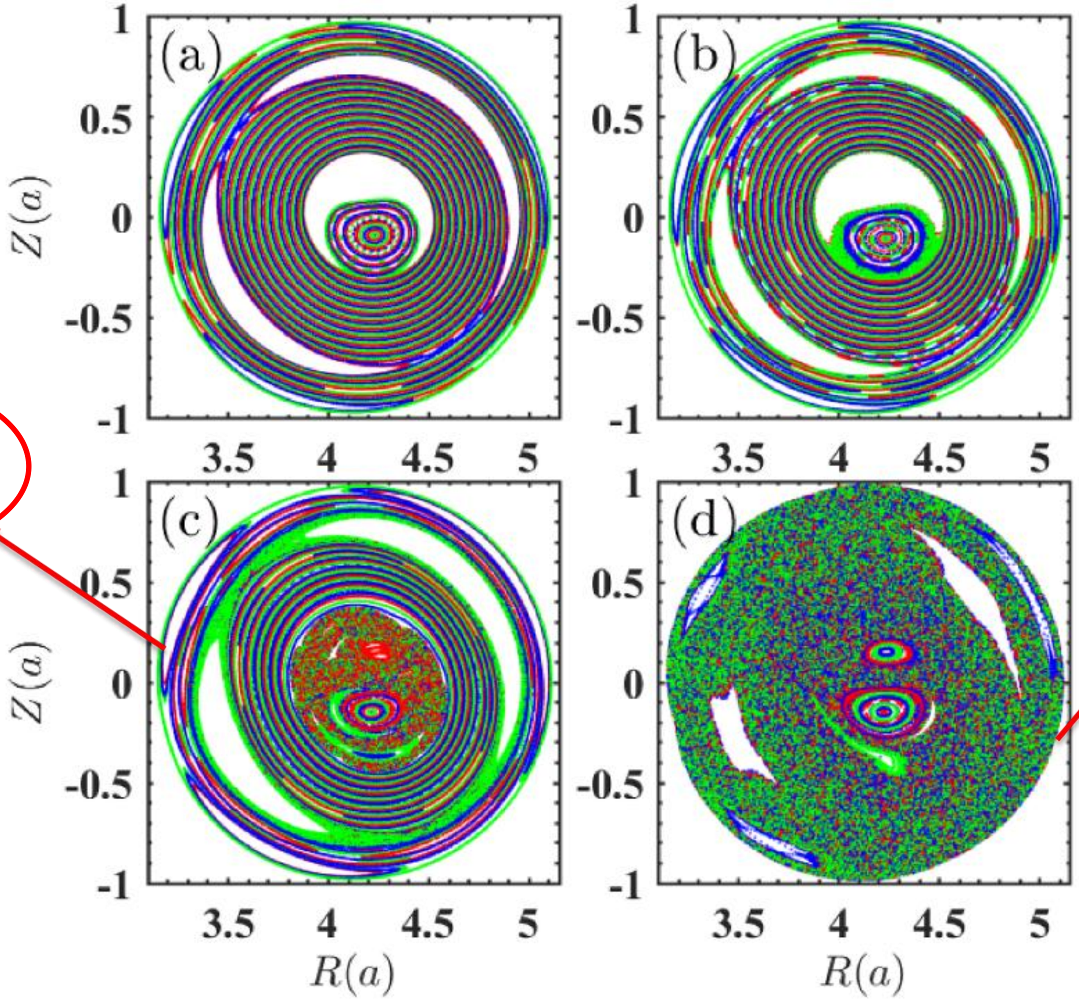
Before collapse

Collapse onset



- **Before collapse**, 1/1 mode and 2/1 mode are **isolated**.
- **At the onset of collapse**, **the overlapping of 1/1 and 2/1 modes** is observed. The amplitude of 1/1 is obviously larger than 2/1 mode.

Case2: synergy of 1/1 FB/SW and 2/1 TM: partially/totally stochastic magnetic topology

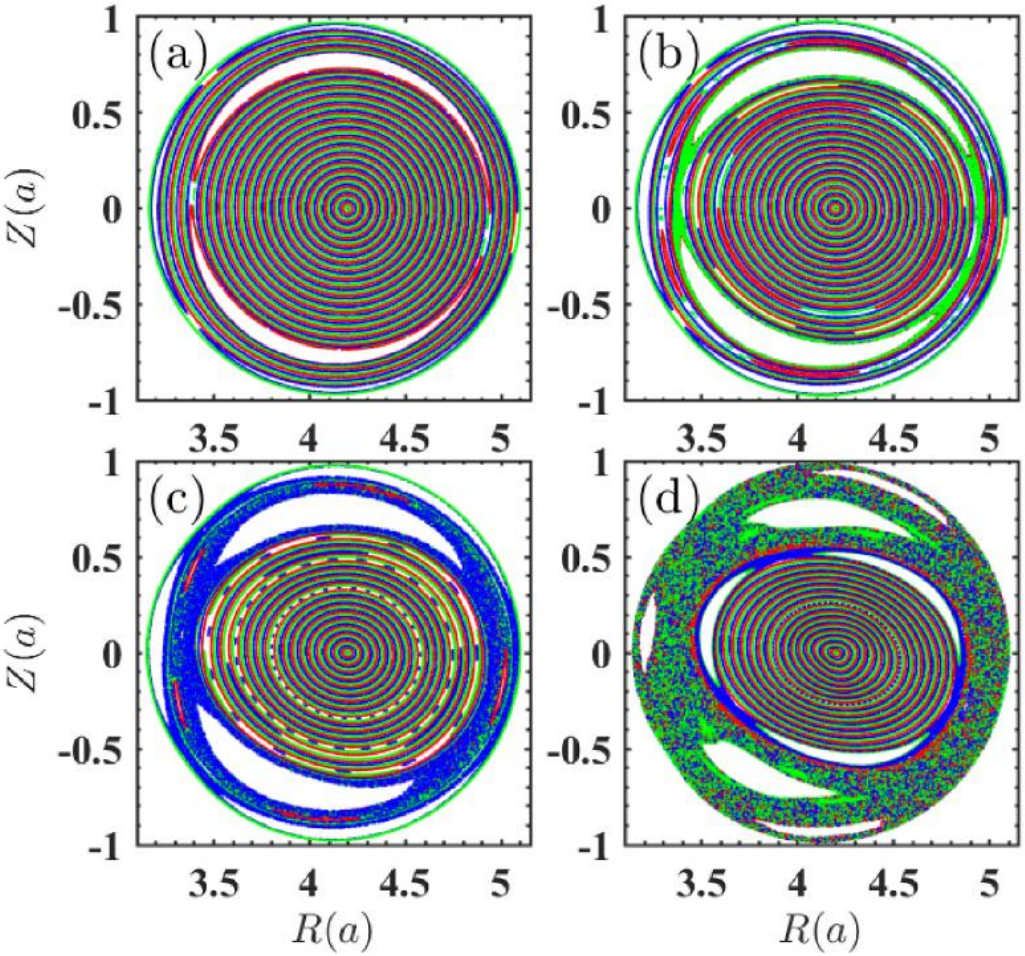


before sawtooth collapse

sawtooth collapse onset

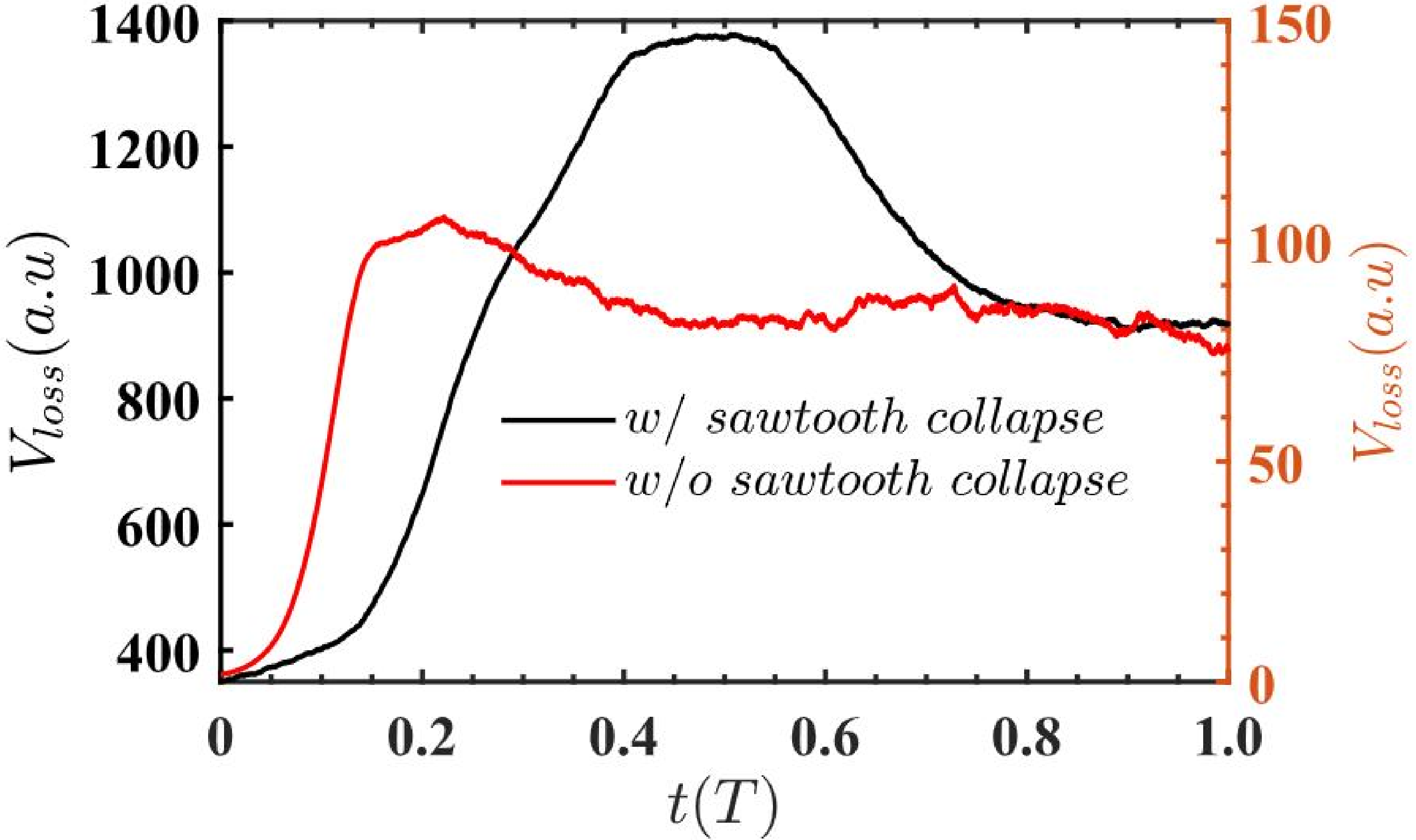
- 1/1 island **gradually stochastic** → 2/1 island **partially stochastic** → **totally stochastic topology** → **decreased confinement**
- Open up a channel from core to edge for lost EPs.

Case1: Only 2/1 TM: magnetic topology outwards q=2 gradually totally stochastic



- The EPs located inside q=1 are well confined due to the good magnetic topology.
- Topology outwards q=2 partially stochastic → totally stochastic

Loss rate comparison of case I and II



- M3D-K simulation shows: synergy of 1/1 and 2/1 modes triggering the collapse onset is highly nonlinear event, resulting in the significant enhancement of EPs.
- It is far from the case with only 2/1 mode. It is needed to find some strategies to avoid or control such events.

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Conclusions and discussions II

Based on the new reproducible experimental observations of synergy between FB/ST and TM resulting in amplitude-bursting and intense perturbations accompanied with frequency-chirping and sawtooth collapse behaviors in HL-2A, we have performed the self-consistent numerical simulations using the global nonlinear hybrid kinetic-MHD initial code M3D-K.

- This experimental activity is intrinsically confirmed with multiple-m nature.
- The present work mainly focuses on the transport, redistribution and loss of EPs induced by the synergy between 1/1 FB/ST and 2/1 TM. It is found that the FB/ST can redistribute the EPs located around the location of q=1, triggering the onset of sawtooth collapse, and the redistributed energetic ions further migrate towards the q=2 resonance surface, interacting with 2/1 TM. The redistributions of EPs near q=1 and q=2 resonant surfaces are both significant.
- The stochasticities of 1/1 and 2/1 magnetic islands occur in sequence, resulting in the overlapping of 1/1 and 2/1 magnetic islands followed by the totally stochastic phenomenon. These combined effects can open up an efficient EP loss channel that connects the plasma core and edge. Thus, during the period of synergy, the loss rate is found to be dramatically fast.
- Sometimes, the microscopic turbulence is also involved in the avalanche, which will refer to various spatio-temporal scales, which will be left for our future publications.

Overall Outline

- Branch Outline I: Avalanche transport of energetic-ions in magnetic confinement plasmas: nonlinear multiple wave-number simulation

- Branch Outline II: Hybrid-kinetic simulation of synergy between fishbone/sawtooth and tearing mode-induced energetic-ion transport in a tokamak plasma

- **Last: Conclusions and discussions**

Conclusions and discussions

- Not all EP redistribution and loss are necessarily bad. "α-channeling" is a good example, waves that take energy from α's while transporting them outwards and then damping on the thermal plasmas.
- Controlled thermo-nuclear fusion means EPs and α particles must transfer their energy to thermal ions and gracefully leave the plasmas.
- The major concern is developing the ability to predict losses of fusion products alphas in future ignited plasma devices such as ITER. Current and past studies have studied the transport, loss and redistribution of D-D fusion products, beam ions, RF-generated ion tails and some limited D-T fusion products.
- EP transport is a significantly important but intricate issue for the magnetic confinement fusion plasmas. Accurate prediction and assessment of the EP transport, loss and redistribution level is a comprehensive and challenging task. Integrate modelling based on the first principle, considering as much factors as possible, to predict the EP transport under the multiple MHD perturbations or others, is badly needed, although it is usually time-consuming.