Comprehensive simulations of ICRF-driven bursting shear Alfvén waves and their suppression via phase-space engineering

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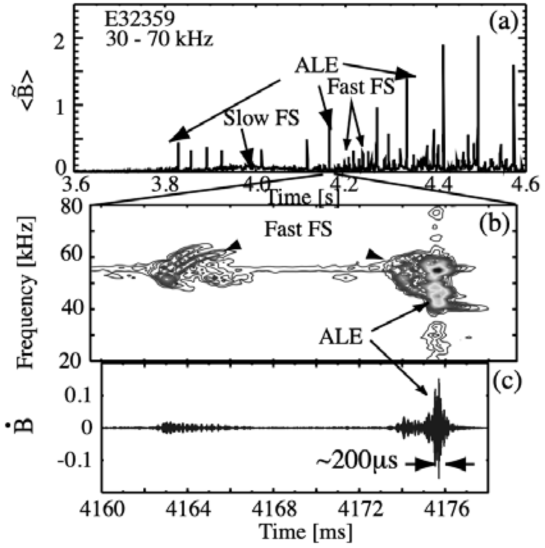
Comprehensive simulations of bursting and non-bursting shear Alfvén waves in ICRF heated tokamak plasmas;* IAEA Fusion Energy Conference (FEC) 2025, Oral talk; Nuclear Fusion, **66, 076013(2026);

Outline

- Introduction
- Simulation model: extended MEGA with ICRF heating source
- Simulation results
  - Bursting and non-bursting shear Alfvén waves (SAWs) during on-axis RF heating
  - Suppression of bursting SAWs via phase-space engineering
- Conclusion

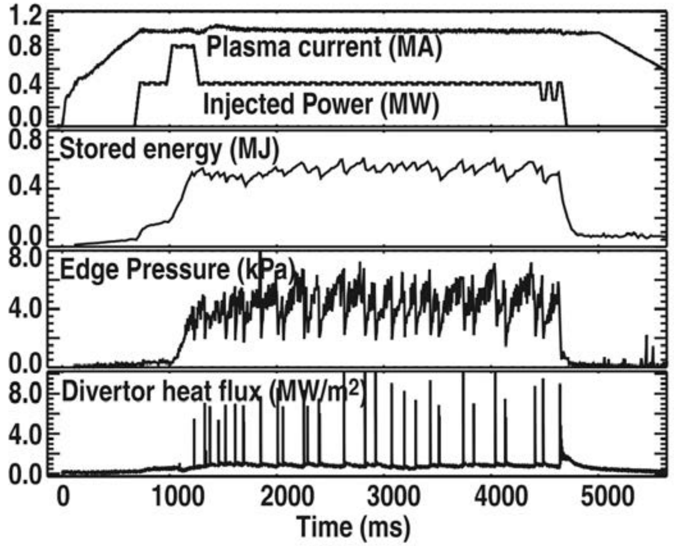
“Everything Bursts Everywhere All at Once”

Abrupt Large Events in JT-60U



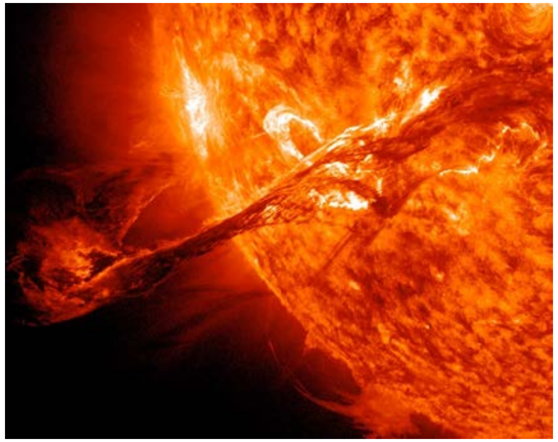
[Shinohara+, NF, 2001]

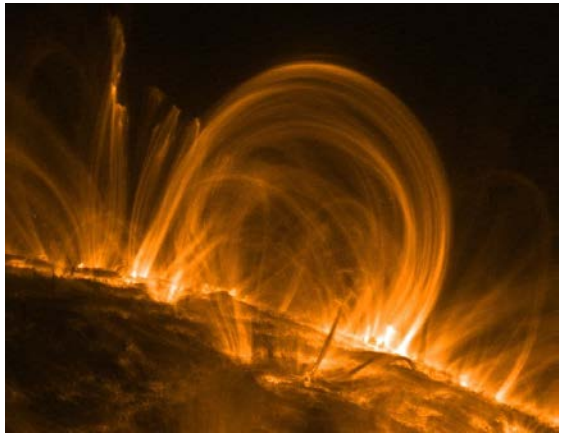
Edge Localized Mode bursts in DIII-D



[Leonard, PoP, 2014]

Coronal Mass Ejection





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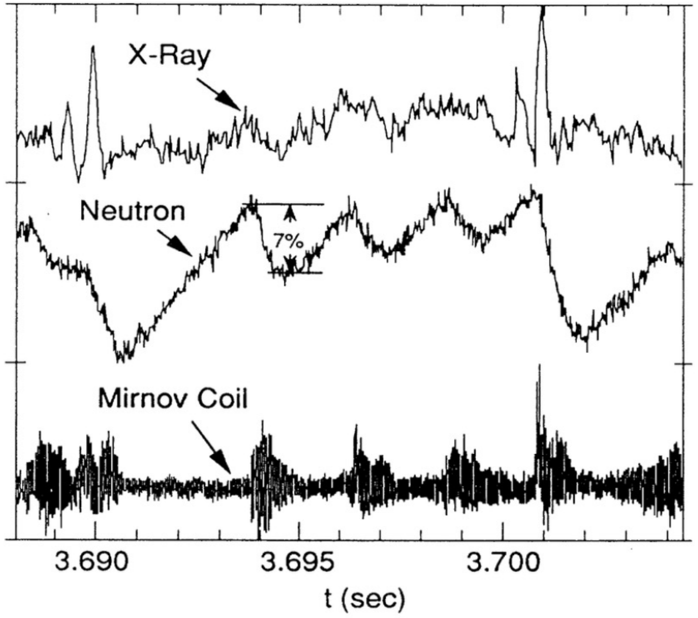
Sudden Brightening of Aurora

Fast Radio Burst from Magnetars

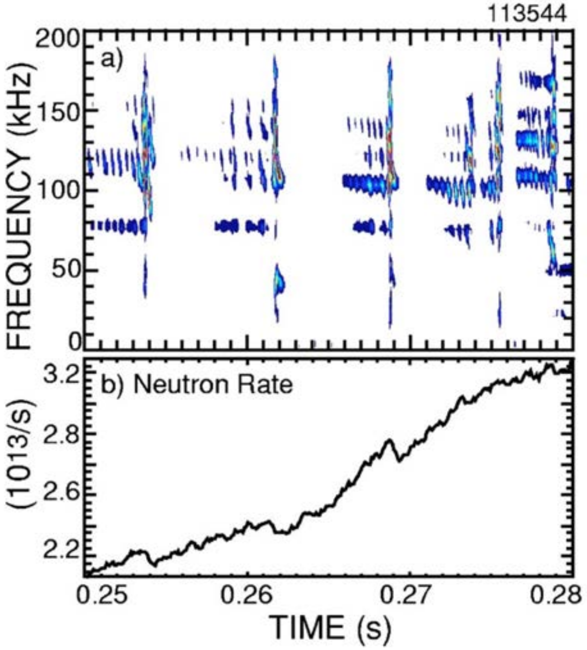
NBI-induced Alfvénic bursting events in MCF

Bursting Alfvén Waves in TFTR [Conventional Tokamak]



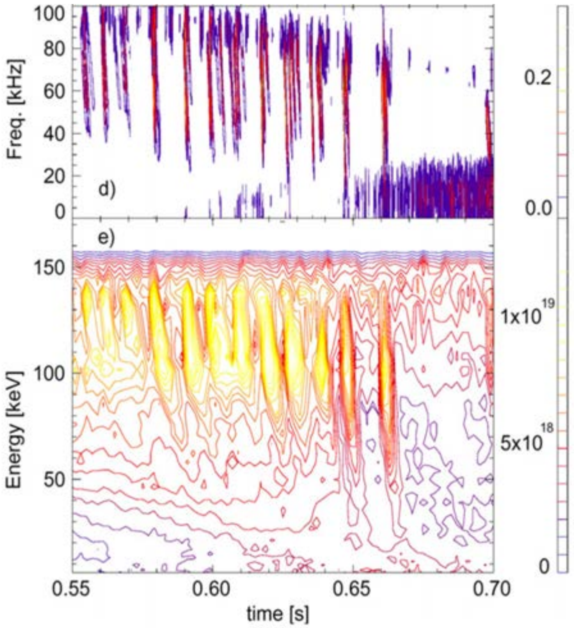
[Wong+, PRL, 1991]

SAW Avalanche in NSTX [Spherical Tokamak]



[Fredrickson+, PoP, 2005]

Bursting SAWs in LHD [Stellarator]

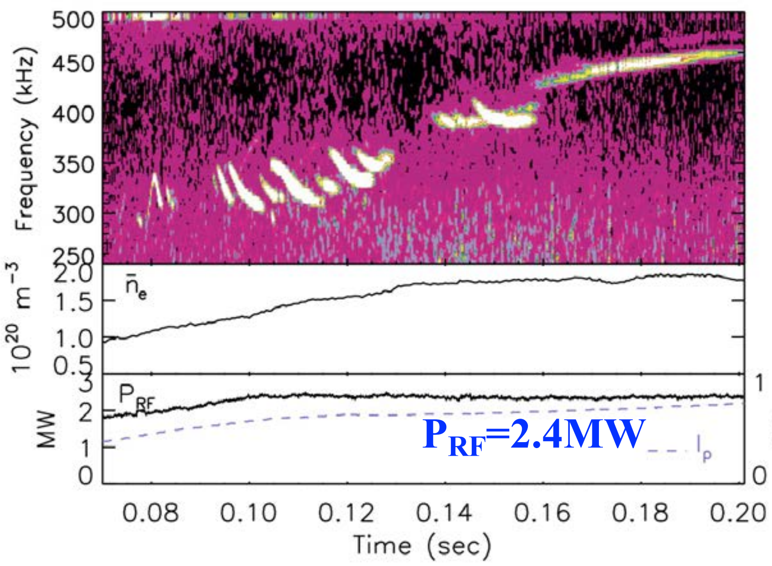


[Osakabe+, NF, 2006]

- **Incompressible shear Alfvén waves (SAWs) are deleterious to the performance of burning plasmas.**
- **SAWs in NBI heated plasmas often exhibit a bursting state in present-day tokamaks.**
- **Recurrent bursting Alfvénic instabilities will lead to a rapid and violent release of stored free energy.**

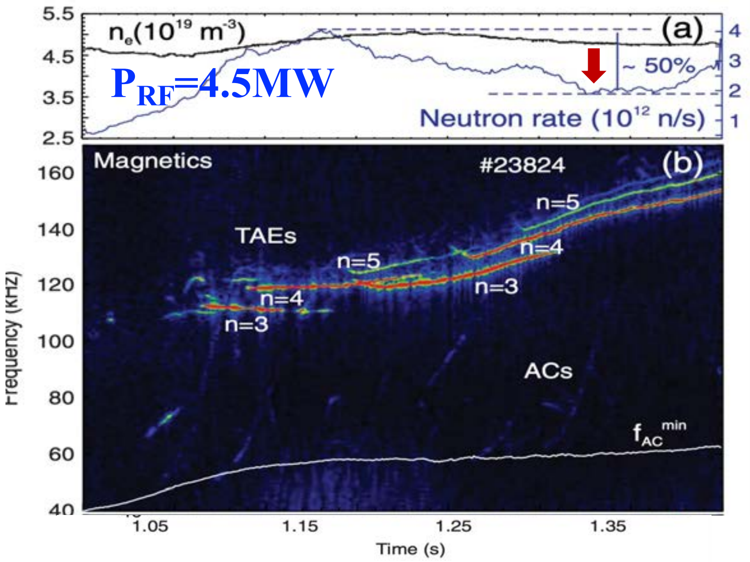
Can SAWs also burst in ICRF-heated plasmas?

ICRF-induced AEs in C-Mod



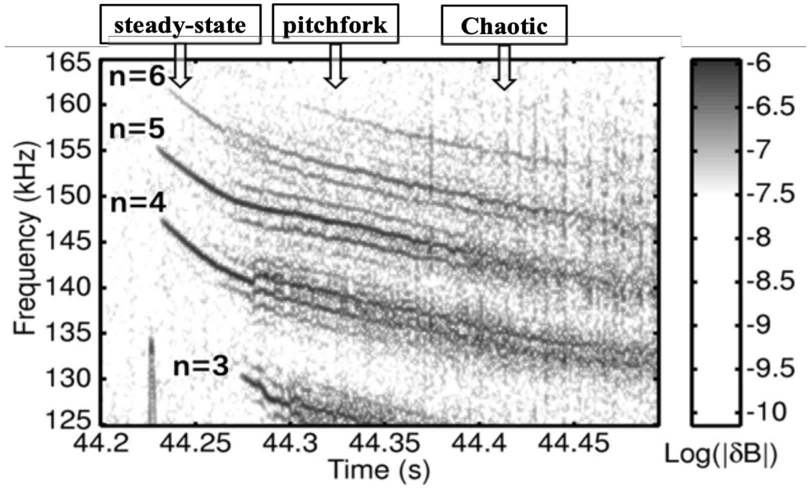
[Snipes+, PPCF, 2000]

ICRF-induced TAEs in AUG



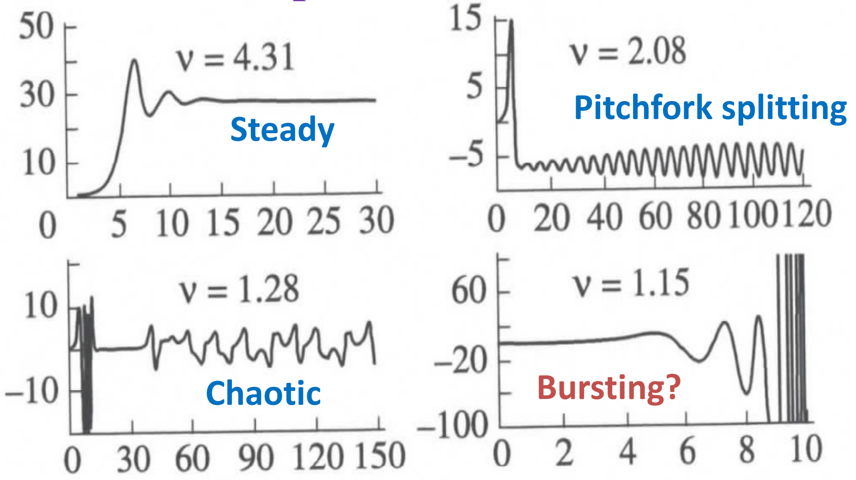
[Garcia-Munoz+, PRL, 2010]

AE States in JET ICH Plasmas



[Heeter+,PRL, 2000]

Theoretical predicted Nonlinear States

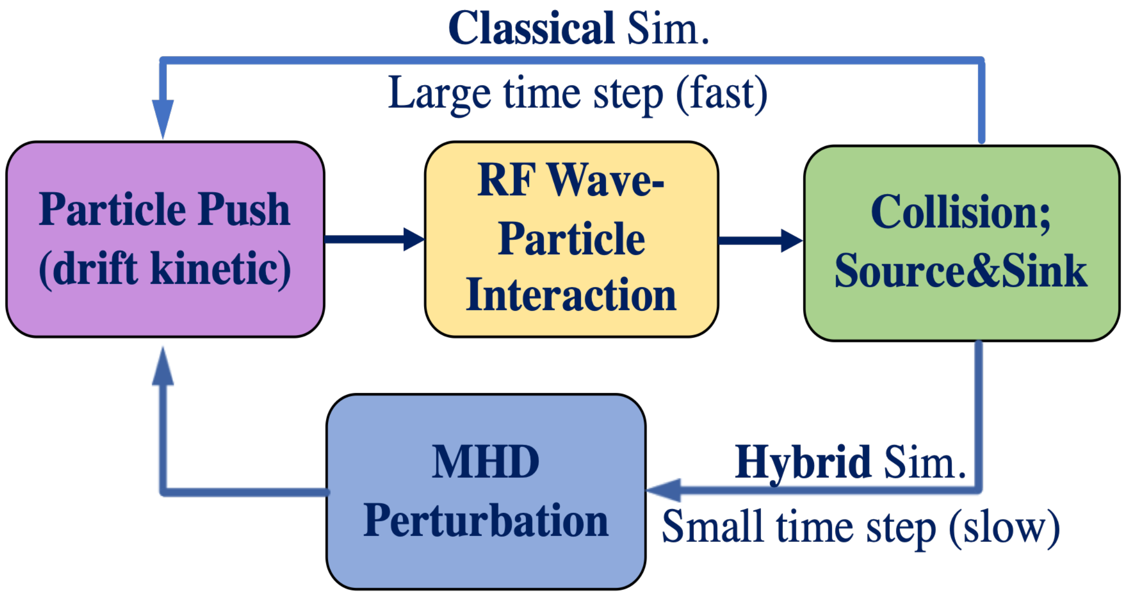


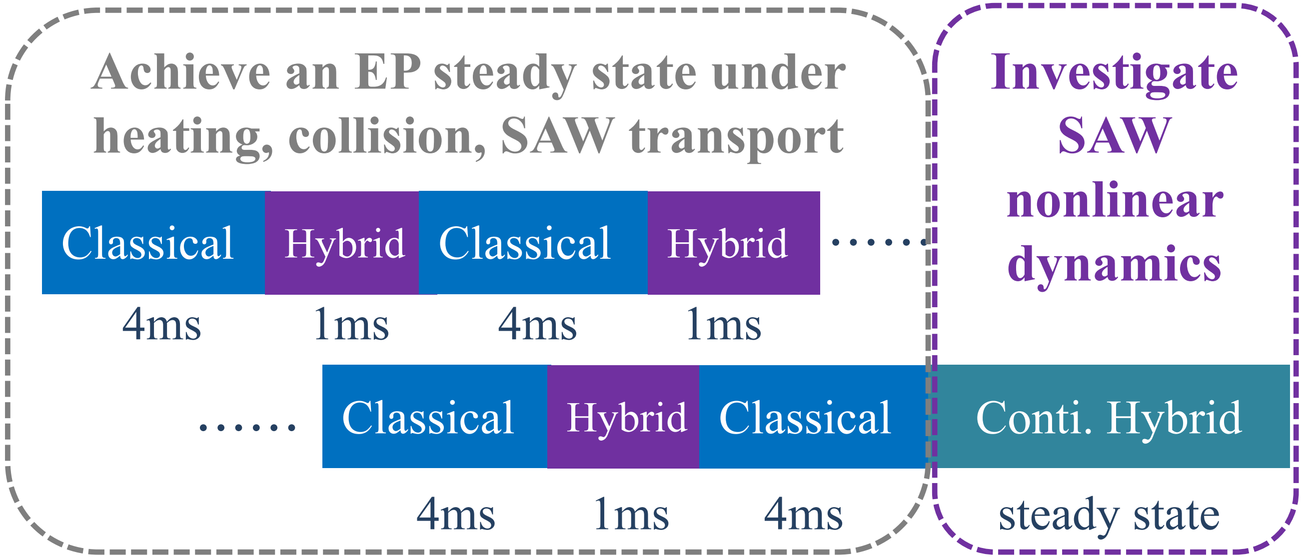
[Berk+, Plasma Physics Reports, 1997]

- Unlike beam-driven SAWs, ICRF-induced SAWs generally have **steady amplitude**, pitchfork splitting state, or chaotic state.
- ICRF-induced SAWs can be well explained by famous Berk-Breizman-Pekker 1-D model, **except predicted bursting state**.
- **Motivation:** Understand mechanism that preventing ICRF-induced SAWs being bursting or under which conditions could burst.

Extended MEGA with ICRF heating

- Kinetic-MHD hybrid code MEGA is extended with **ICRF kick, Coulomb collisions, particle source and sink**.
- Both **RF kick** and **Coulomb collisions** are simulated by the **Monte Carlo method**.
- Minority ions are simulated using a **full-*f*** particle-in-cell method [~0.5 billion markers].
- TFTR-like plasma: $B_0 = 1.5\text{T}$, $R_0/a = 2.6\text{m}/0.9\text{m}$, $n_0 = 3.0\times10^{19}\text{m}^{-3}$, $T_0 = 8\text{keV}$, ${}^{n(H)}/_{n(D)} = 4\%$.
- A parabolic safety factor profile $q(r/a) = q_0 + (q_a - q_0)\cdot(r/a)^2$ with q_0=1.2 and $q_a = 3.0$.
- A modelled ICRF wave electric field profile is adopted for simplicity with $k_\parallel = 6\ \text{m}^{-1}$.
- **Multi-phase simulation**: **alternately** run classical and hybrid simulations until a steady state. (~10M CPU hour)

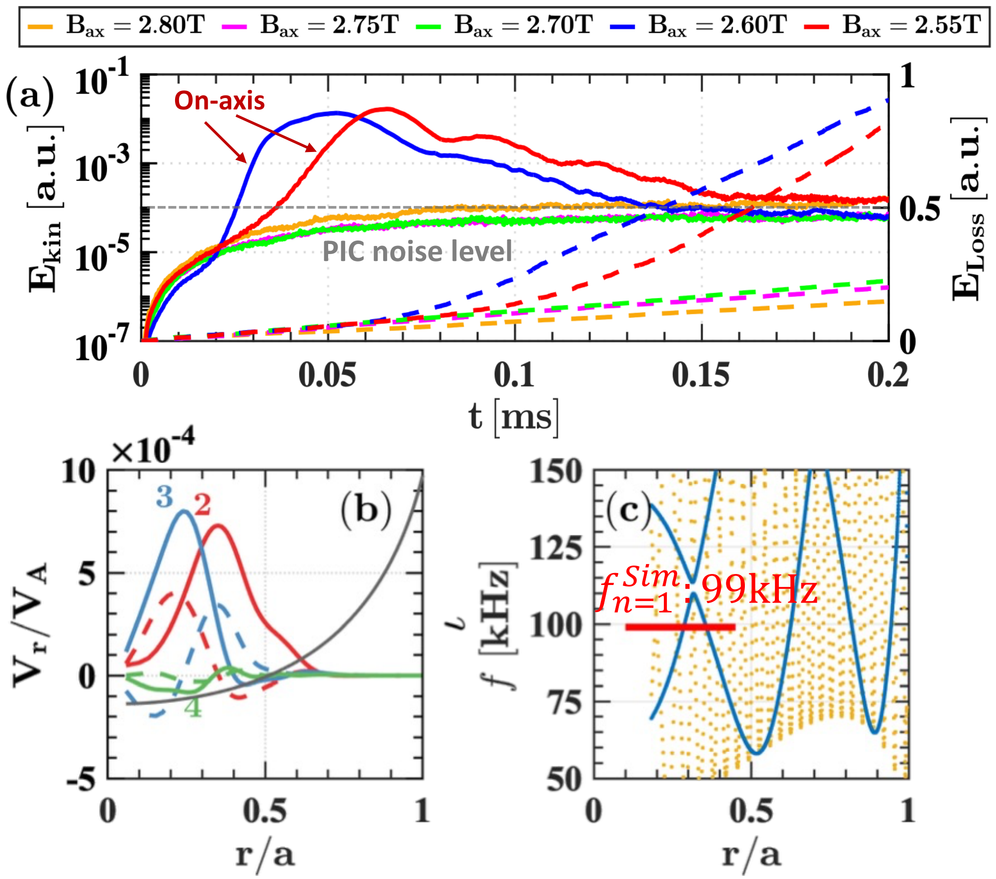




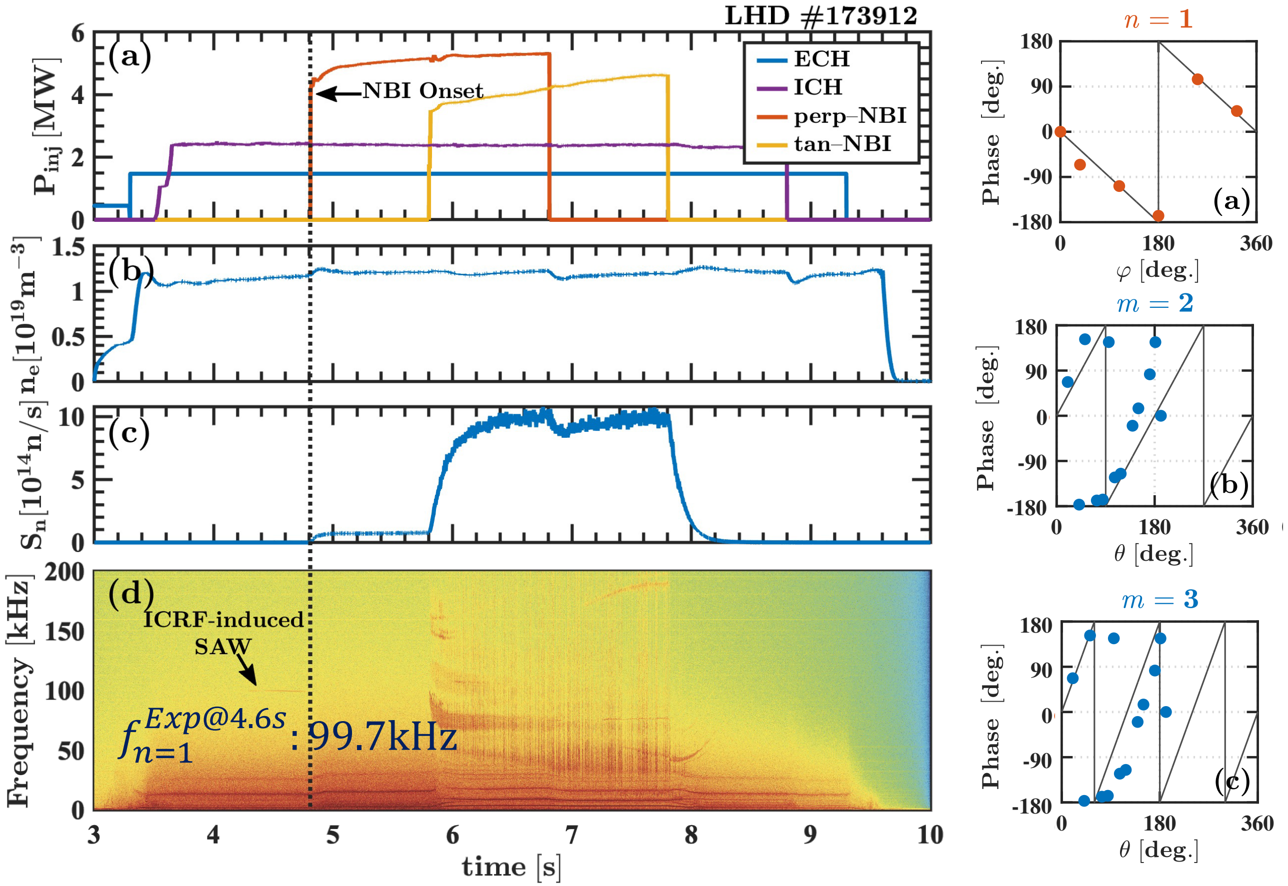
***Reduce computational time to 1/5 !**

Code Validation: Prediction of ICRF-induced SAWs in LHD

MEGA predicted ICRF-induced SAWs in LHD



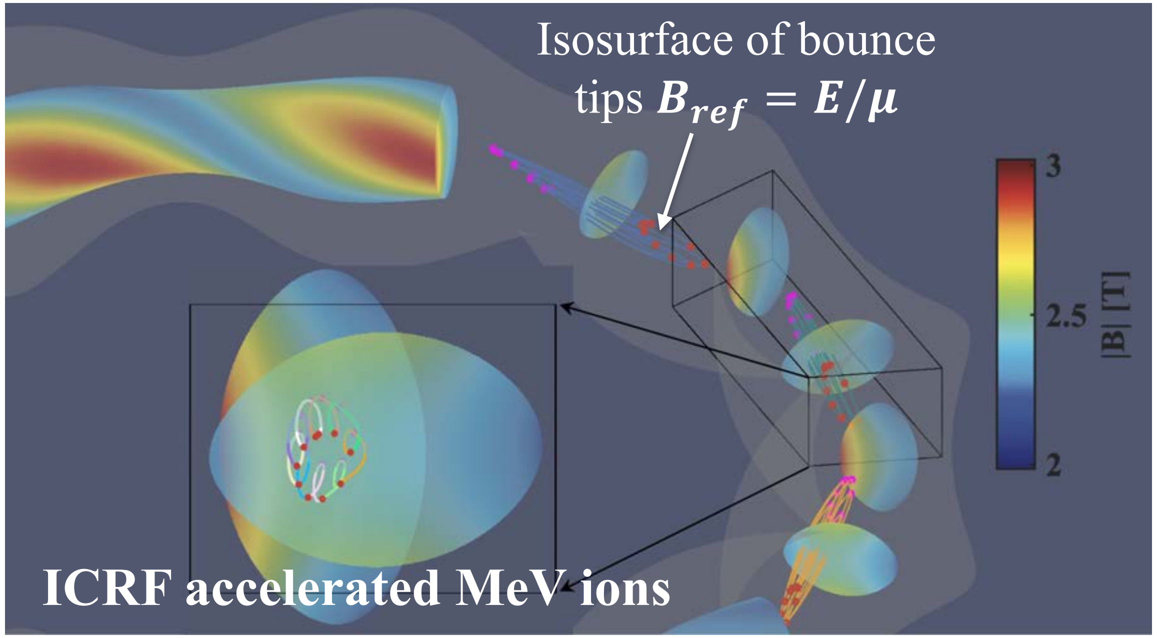
Experimental validation of ICRF-induced SAW in LHD



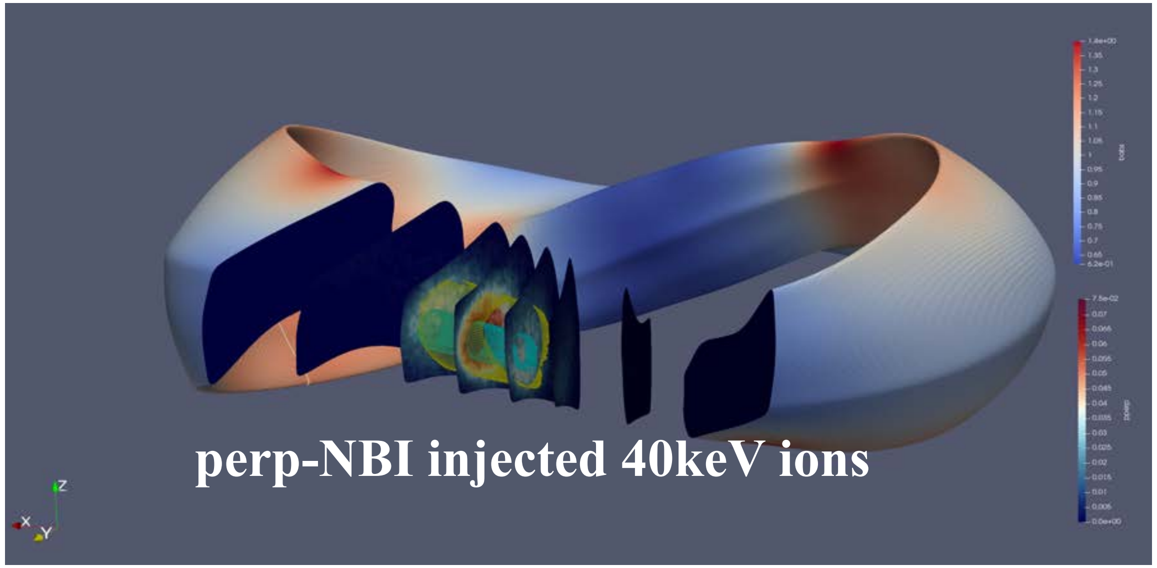
- **Extended MEGA has successfully predicted an ICRF-induced SAW in LHD.** [J. Wang+, FEC2023]
- **4/9 shots with B_0=2.5T (#173911-#173919) show clear evidence of predicted SAWs.**

Code Validation: Prediction of ICRF-induced SAWs in LHD

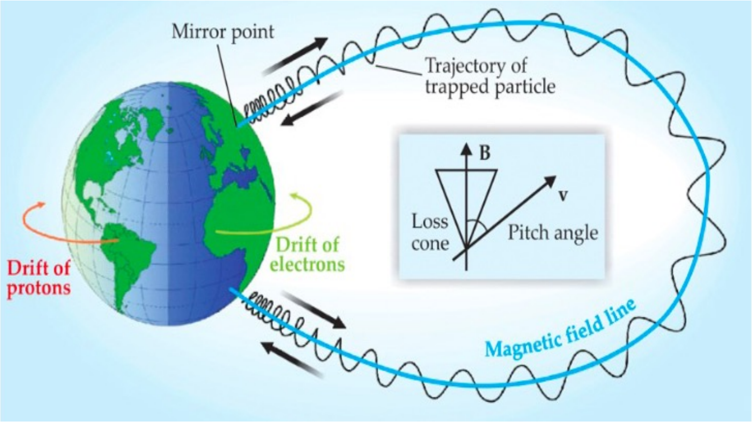
Guiding center trajectories of localized trapped EPs in LHD (res. particles drive SAW)



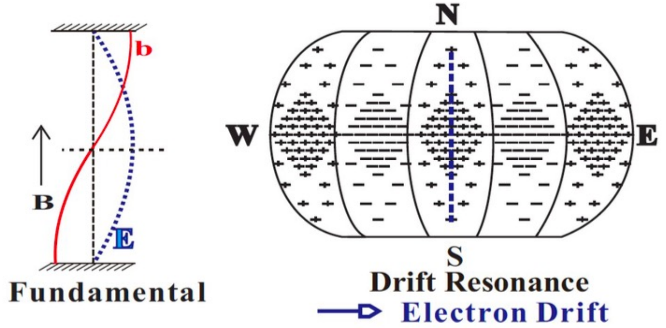
Guiding center trajectories of localized trapped EPs in an advanced quasi-isodynamic (QI) stellarator



Mirror trapped particle in magnetosphere



Mirror trapped particle driven ultra-low-frequency (ULF) waves



Drift res. (N=0): $\Omega = m \cdot \omega_d$ ~~$+ N \cdot \omega_b$~~

Ω: wave frequency

m: azimuthal mode number of wave

ω_d/ω_b : particle drift/bounce frequency

[Zong+, Ann. Geophys., 2022]

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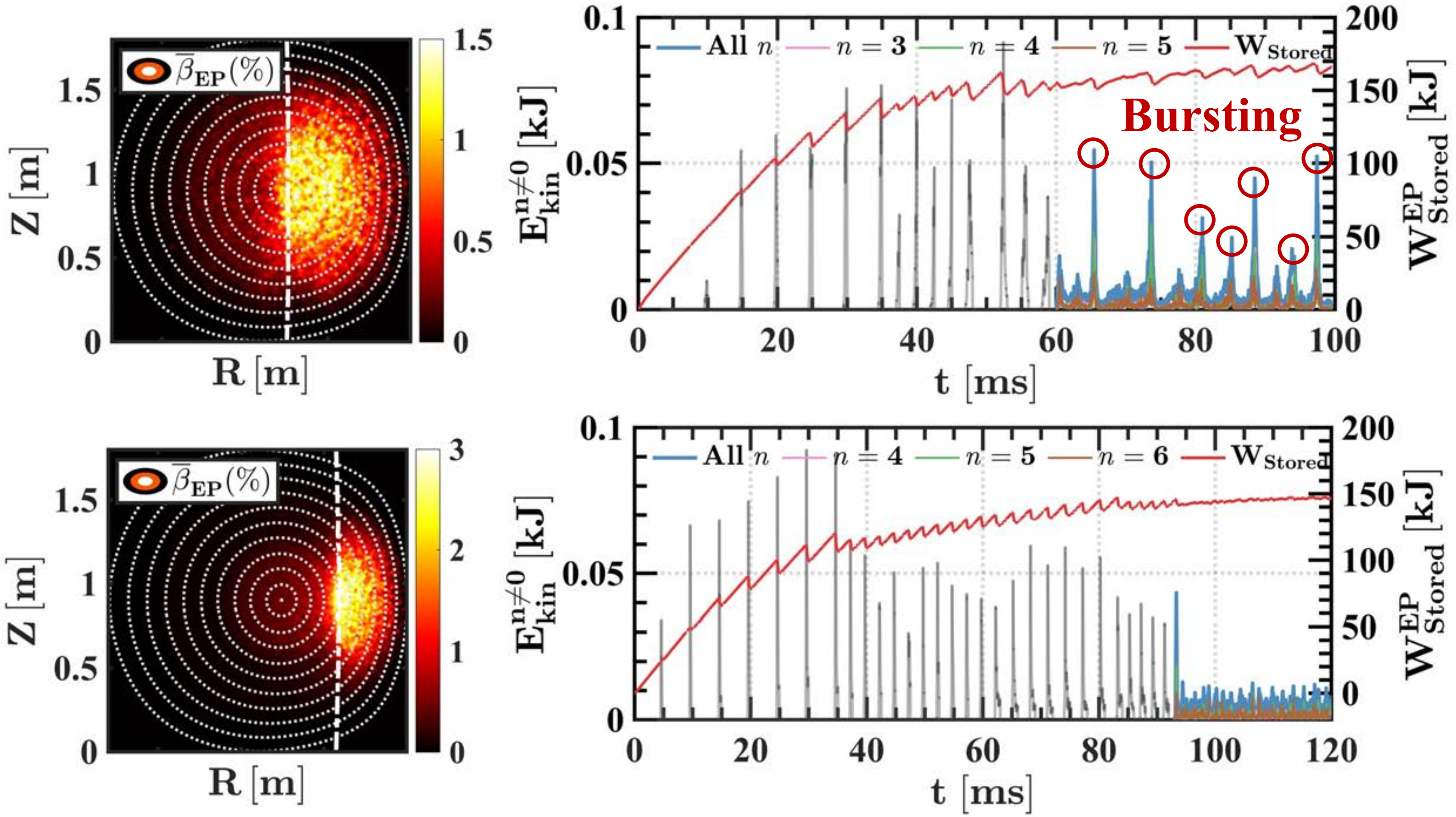
Bursting and non-bursting ICRF-induced SAWs

On-axis RF heating with P_{RF}=6MW

Outboard RF heating with P_{RF}=6MW

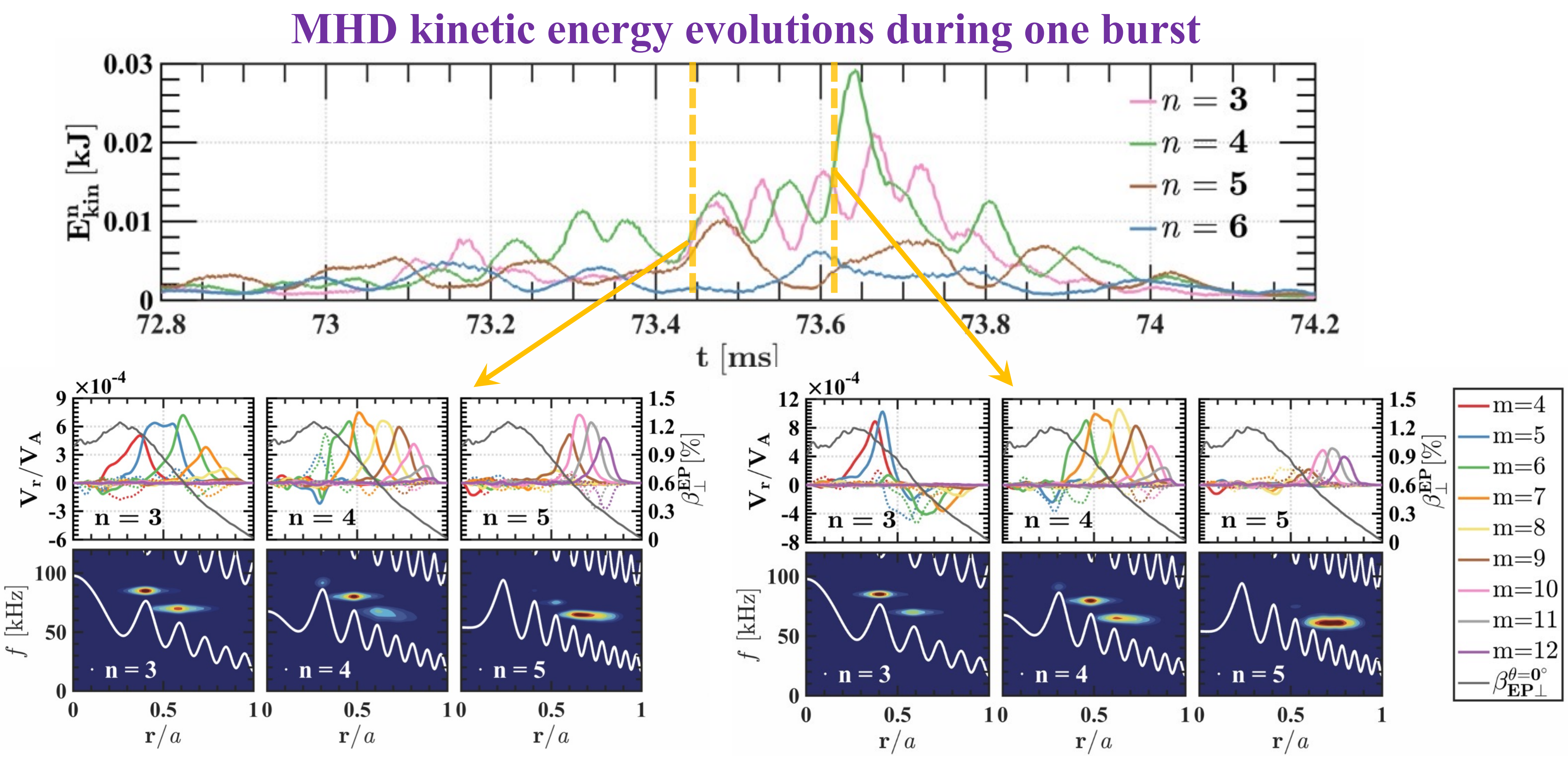


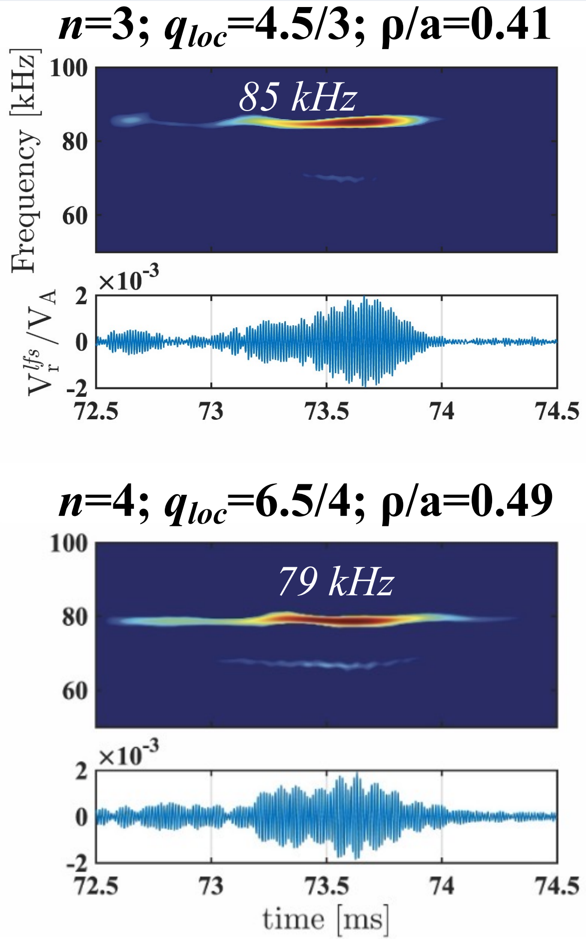
Multi-phase: 0~60ms
Cont. hybrid:60ms~

Multi-phase: 0~93ms
Cont. hybrid:93ms~

- **Bursting SAWs** are observed when RF resonance layer is located **at the magnetic axis [or inboard]**.
- **When RF resonance layer is located at the outboard region, only non-bursting are observed.**
- **Non-bursting case has a much higher EP beta.**
- **Nonlinear states are only identified during continuous hybrid phase due to significant overshoots in MHD fluctuations in multi-phase simulations.**

Mechanism 1: Radially discrete TAEs are formed during burst





- **Discrete and non-chirping** TAEs above Alfvén continuum tips are formed for each ***n***.
- There is a **spatial overlap** region between adjacent TAEs.
- Onset and end time of primary modes are similar, which confirms an interaction between different toroidal harmonics.

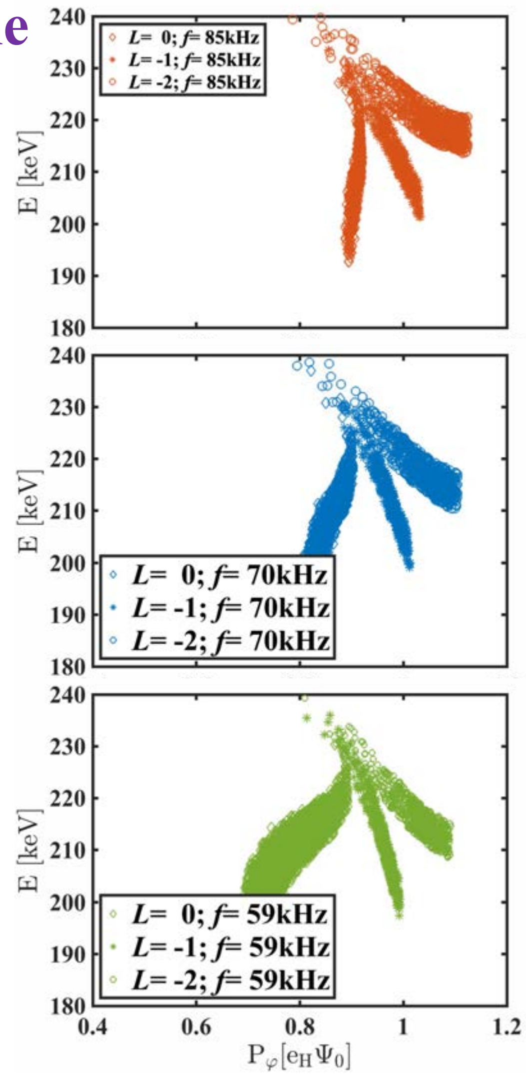
Mechanism 2: Resonance overlap in phase space

Resonant particle in phase space

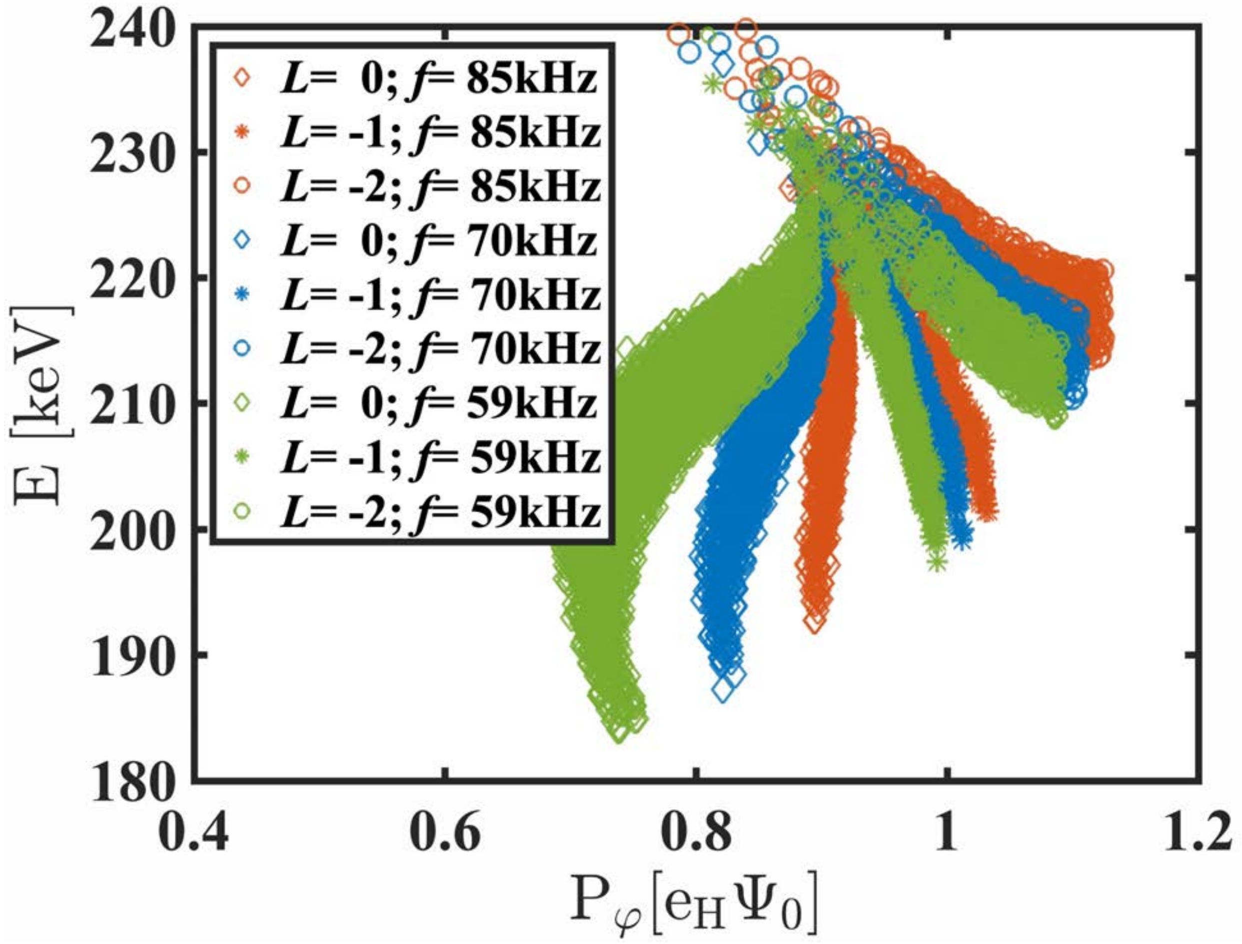
$\mu = 1.2; n = 3$
$f = 85$ kHz

$\mu = 1.2; n = 3$
$f = 70$ kHz

$\mu = 1.2 ; n = 3$
$f = 59$ kHz



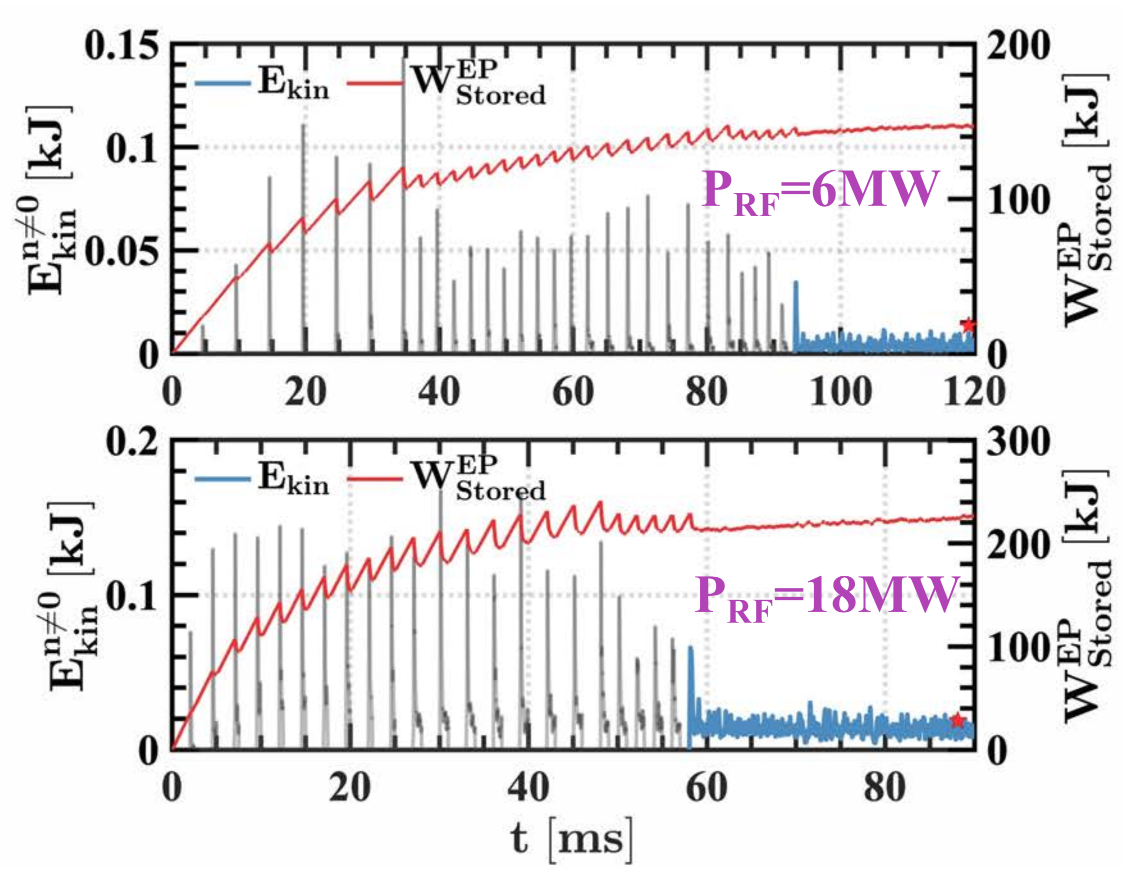
Resonance Condition: $\omega_{AE} - L * \omega_{\theta} - n * \omega_{\phi} = 0$



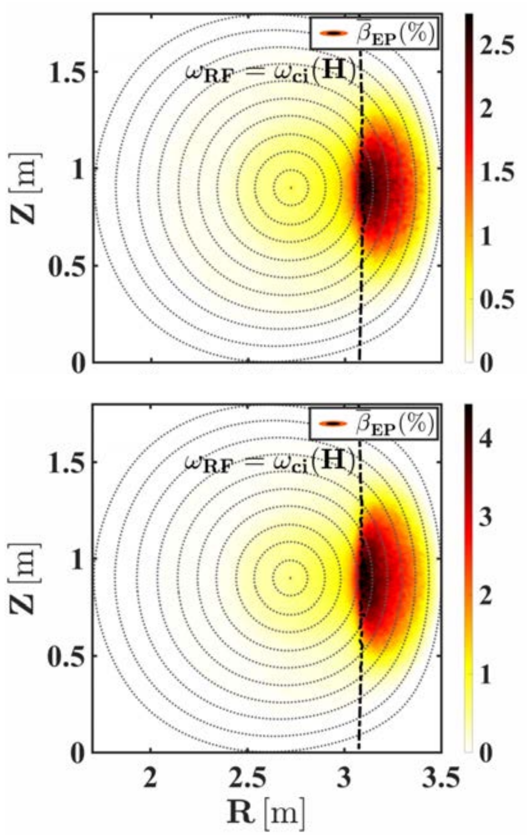
- **Resonance overlap** is possible even for single *n* non-chirping TAEs with discrete frequencies.

Non-bursting TAEs during outboard heating

Kinetic Energy Evolutions

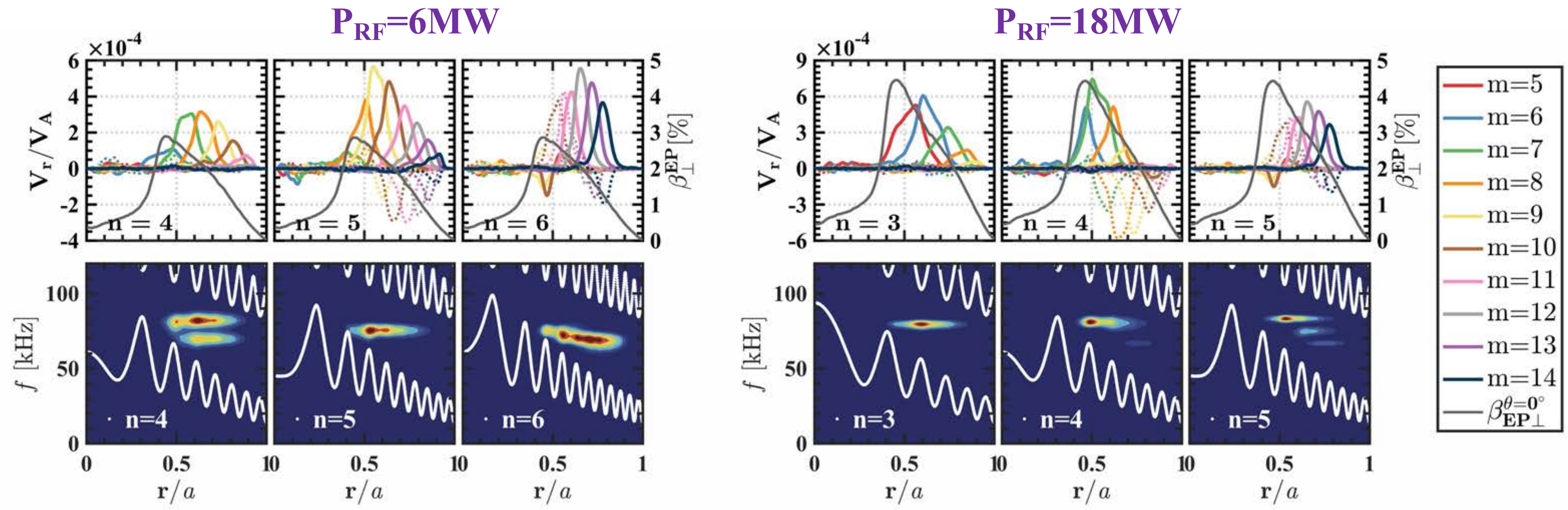


Minority Hydrogen Beta



- When the RF resonance layer is located at the outboard region, only non-bursting/grassy modes are observed, even at a high power of 18MW.
- A significant number of minority ions are close to the RF resonance layer, indicating that resonant particles interacting with SAWs also easily experience strong RF-induced velocity space diffusion.

Non-bursting TAEs during outboard heating

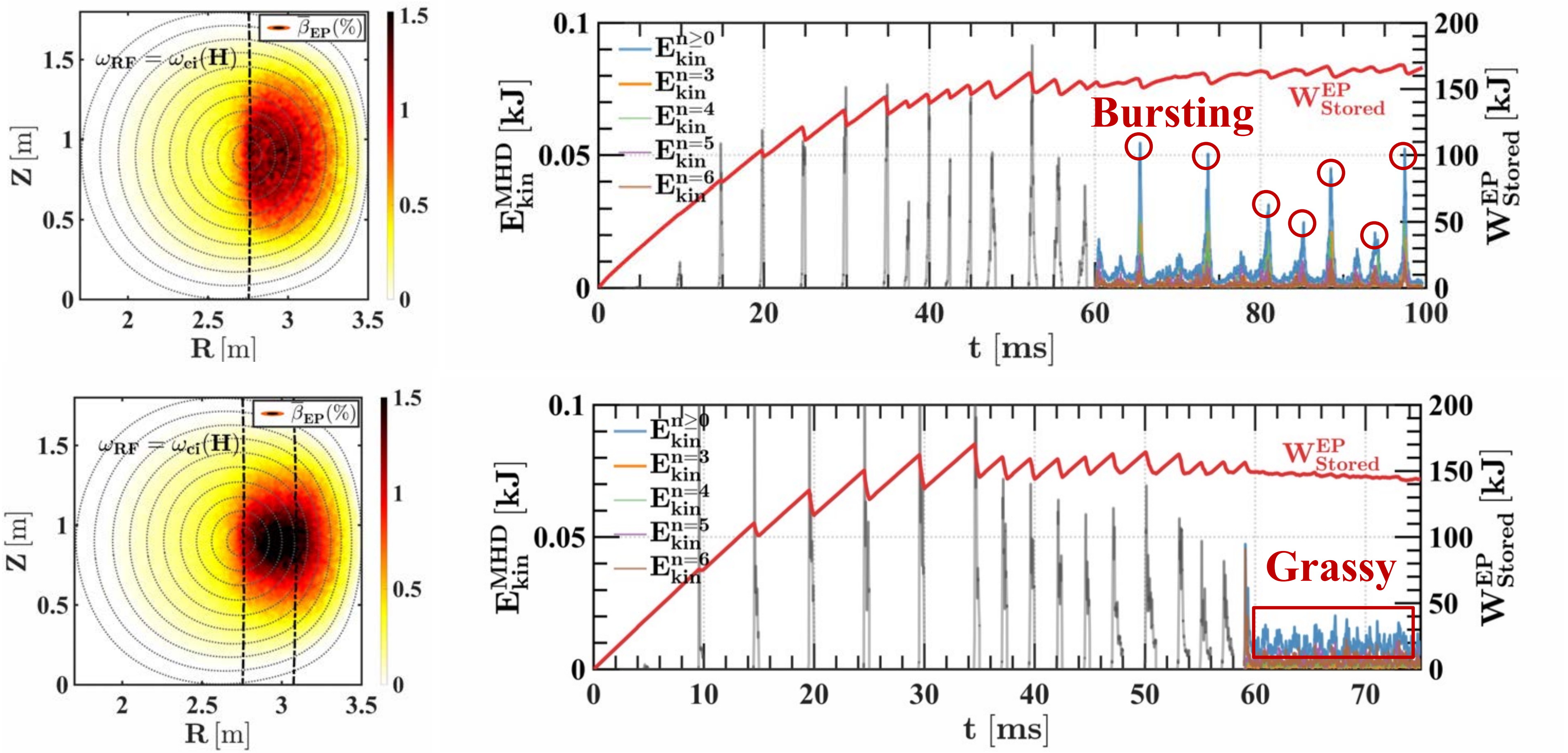


- **For outboard RF heating, primary TAEs of each toroidal mode show a broad and frequency-locked coherent structure.**
- **RF-induced strong velocity-space diffusion keeps scrambling resonant particles and preventing continuous particle trapping in radial direction, which drives the system to form this broad structure.**
- **Such a long-lasting broad and coherent structure will prevent the accumulation of free energy to trigger a bursting event.**

Phase-space engineering: Suppression of bursting SAWs

P_{RF}=6MW on-axis

P_{RF}=6MW on-axis
+
P_{RF}=3MW outboard



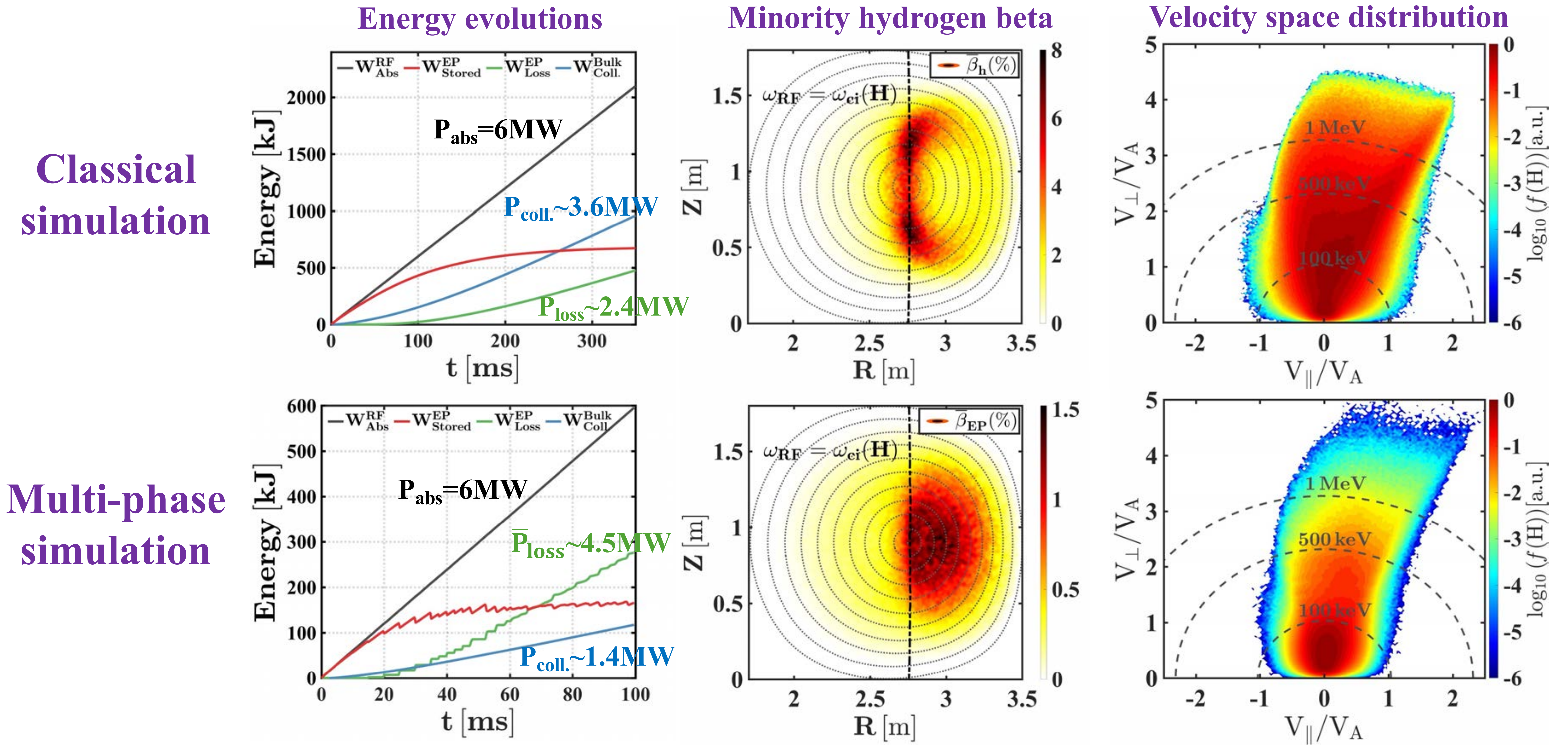
- **Recurrent bursting state of on-axis ICRF-induced SAWs can be suppressed and replaced by non-bursting (grassy) SAWs when a second outboard ICRF is applied.**
- **This is the first self-consistent simulation demonstrating the mitigation of SAWs via ICRF phase-space engineering.**

Summary

- ◆ **Developed an ICRF heating module in the kinetic–MHD hybrid code MEGA for self-consistent, slowing-down-time-scale simulation of shear Alfvén waves (SAWs) in tokamaks and stellarators.**
- ◆ **Predicted and experimentally confirmed the first ICRF-driven SAWs in a stellarator.**
- ◆ **Both bursting and non-bursting ICRF-driven TAEs are reported: bursting TAEs when the ICRF resonance is at the axis / inboard (both multi-*n* and single-*n*); non-bursting for outboard resonance, even at a higher RF power.**
  - **Bursting: Energetic particles transported away from RF layer → discrete TAEs accumulate free energy → phase-space resonance overlap → avalanche with strong outward transport.**
  - **Suppression: RF-driven phase-space engineering (velocity-space scattering) breaks resonant-particle coherence.**
- ◆ **First self-consistent proof that ICRF induced phase-space diffusion can suppress bursting TAEs — a new route for energetic-particle transport control.**

Thanks for your attention!

Realistic steady state is achieved in multi-phase simulation



- **Steady-state minority ion distribution in classical simulation is seriously overestimated.**

Kinetic-MHD hybrid code: MEGA

Bulk plasma (Fluid)

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) + \nu_n \triangle(\rho - \rho_{eq}),$$

$$\rho \frac{\partial}{\partial t}\mathbf{v} = -\rho \boldsymbol{\omega} \times \mathbf{v} - \rho \nabla\left(\frac{v^2}{2}\right) - \nabla p + (\mathbf{j} - \underline{\mathbf{j}_h'}) \times \mathbf{B}$$
$$- \nabla \times (\nu \rho \boldsymbol{\omega}) + \frac{4}{3}\nabla(\nu \rho \nabla \cdot \mathbf{v}),$$

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

$$\frac{\partial p}{\partial t} = -\nabla \cdot (p\mathbf{v}) - (\gamma - 1)p\nabla \cdot \mathbf{v} + (\gamma - 1)$$
$$\times \left[\nu \rho \omega^2 + \frac{4}{3}\nu \rho (\nabla \cdot \mathbf{v})^2 + \eta \mathbf{j} \cdot (\mathbf{j} - \mathbf{j}_{eq})\right] + \nu_n \triangle(p - p_{eq}),$$

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \eta(\mathbf{j} - \mathbf{j}_{eq}),$$

$$\boldsymbol{\omega} = \nabla \times \mathbf{v},$$

$$\mathbf{j} = \frac{1}{\mu_0}\nabla \times \mathbf{B},$$

$\boldsymbol{E}, \boldsymbol{B}$ →

← $\boldsymbol{j_h}$

Energetic particle (drift kinetic)

$$\mathbf{u} = \mathbf{v}_\parallel^* + \mathbf{v}_E + \mathbf{v}_B,$$

$$\mathbf{v}_\parallel^* = \frac{v_\parallel}{B^*}(\mathbf{B} + \rho_\parallel B \nabla \times \mathbf{b}),$$

$$\mathbf{v}_E = \frac{1}{B^*}(\mathbf{E} \times \mathbf{B}),$$

$$\mathbf{v}_B = \frac{1}{Z_h e B^*}(-\mu \nabla B \times \mathbf{b}),$$

$$\rho_\parallel = \frac{m_h v_\parallel}{Z_h e B},$$

$$\mathbf{b} = \mathbf{B}/B,$$

$$B^* = B(1 + \rho_\parallel \mathbf{b} \cdot \nabla \times \mathbf{b}),$$

$$m_h v_\parallel \frac{dv_\parallel}{dt} = \mathbf{v}_\parallel^* \cdot (Z_h e \mathbf{E} - \mu \nabla B),$$

$$\mathbf{j}_h' = \int (\mathbf{v}_\parallel^* + \mathbf{v}_B) Z_h e f d^3 v - \nabla \times \int \mu \mathbf{b} f d^3 v,$$

[Y. Todo & T. Sato, PoP, 1998]

- **Energetic particle (drift kinetic) contribution is included in MHD momentum equation.**
- **Equations are solved using fourth-order Runge-Kutta and finite difference schemes in cylindrical coordinates (R, φ, Z).**
- **FLR effect is neglected to save simulation resource, regardless of MeV particles.**

Quasi-linear RF kick model

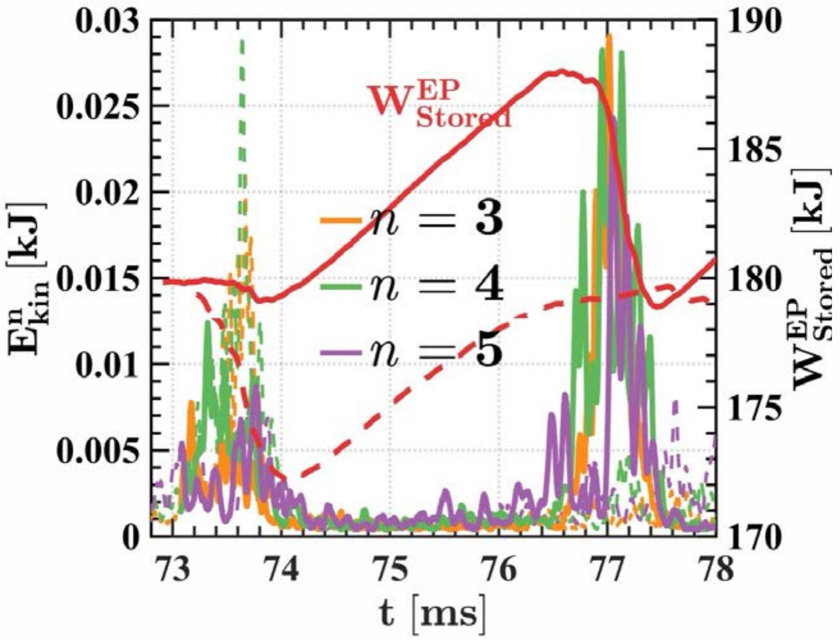
- **RF kick: Kick in velocity space when minority particle crosses the Doppler-shifted resonance layer** (Stix, NF, 1975; Murakami+, NF, 2006) **:**

$$\Delta v_{\perp} = \frac{q}{2m_h} \boldsymbol{I}\, exp(-in\boldsymbol{\phi_r})\left[|\boldsymbol{E_+}|\boldsymbol{J_{n-1}(k_\perp \rho_h)} + |E_-|J_{n+1}(k_\perp \rho_h)\right]$$

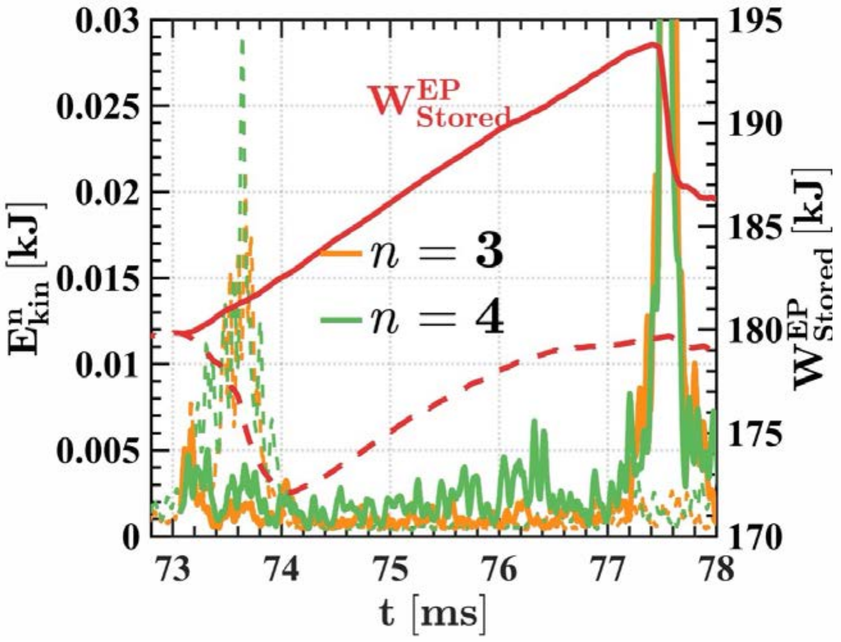
- **RF kick is simulated by the Monte Carlo method.**
- **Wave-particle interaction time** $\boldsymbol{I = \min(t_1, t_2) = \min\left(\sqrt{2\pi/n\,\dot{\omega}},\, 2\pi\left(n\,\ddot{\omega}/2\right)^{-1/3} \mathrm{Ai}(0)\right)}$ **depends on the turning point position relative to the resonance layer. (**$\boldsymbol{I = t_1}$**: bounce tip far away from the resonance layer;** $\boldsymbol{I = t_2}$**: bounce tip close to the resonance layer)**
- Random variable $\boldsymbol{\phi_r}$ is the phase shift between the Larmor rotation and wave electric field.
- Left-hand polarized component of the perpendicular wave electric field $\boldsymbol{E_+}$, which rotates in the direction of ion cyclotron motion, can effectively interact with the minority ions. A modeled $\boldsymbol{E_+}$ profile is used in this work for simplicity.
- In this work, we focus on the fundamental minority ion heating scheme (n=1).

Synergistic effect between different toroidal harmonics

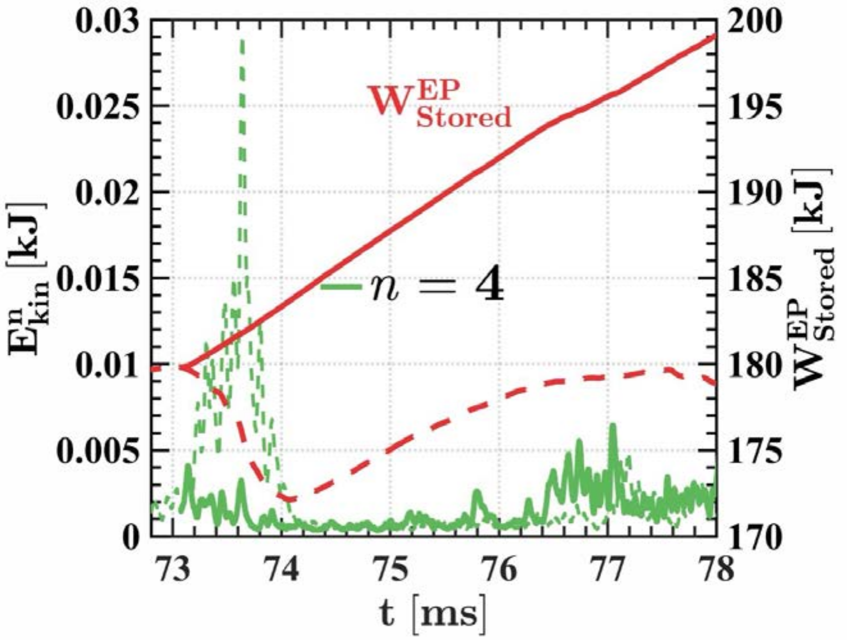
Repeated simulation from 73.07ms with only *n*=3,4,5
(Dashed curves: baseline case w/ *n*=3-6)



Repeated simulation from 73.07ms with only *n*=3,4



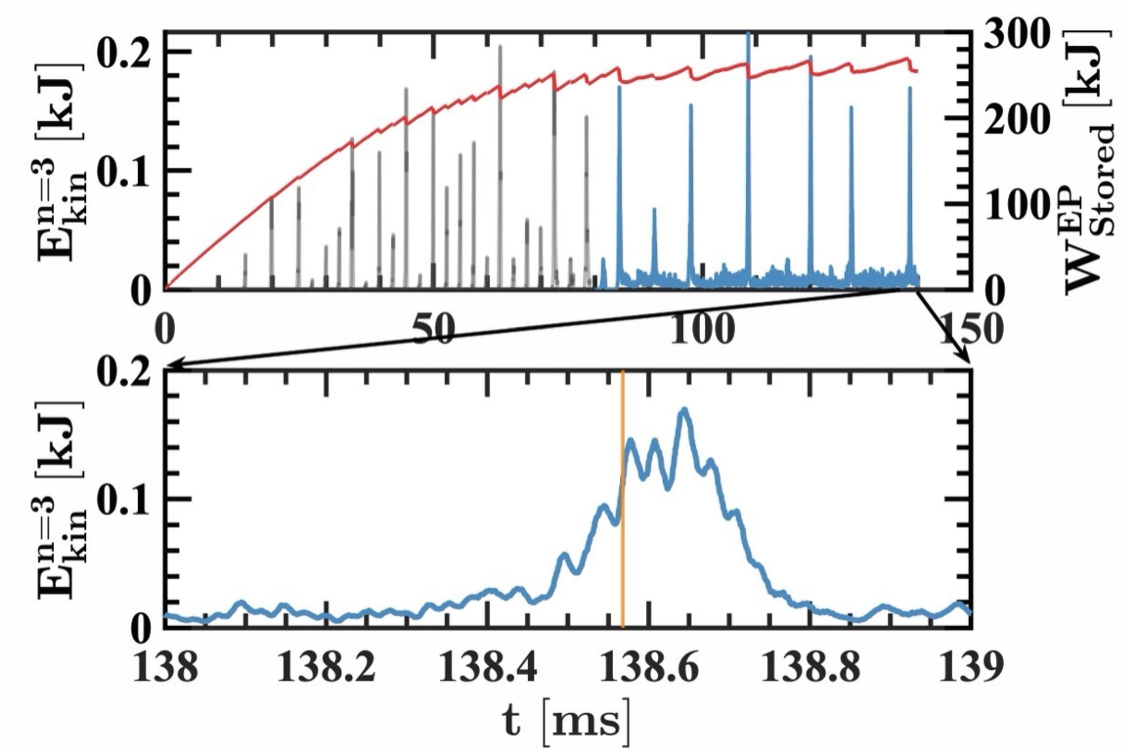
Repeated simulation from 73.07ms with only *n*=4

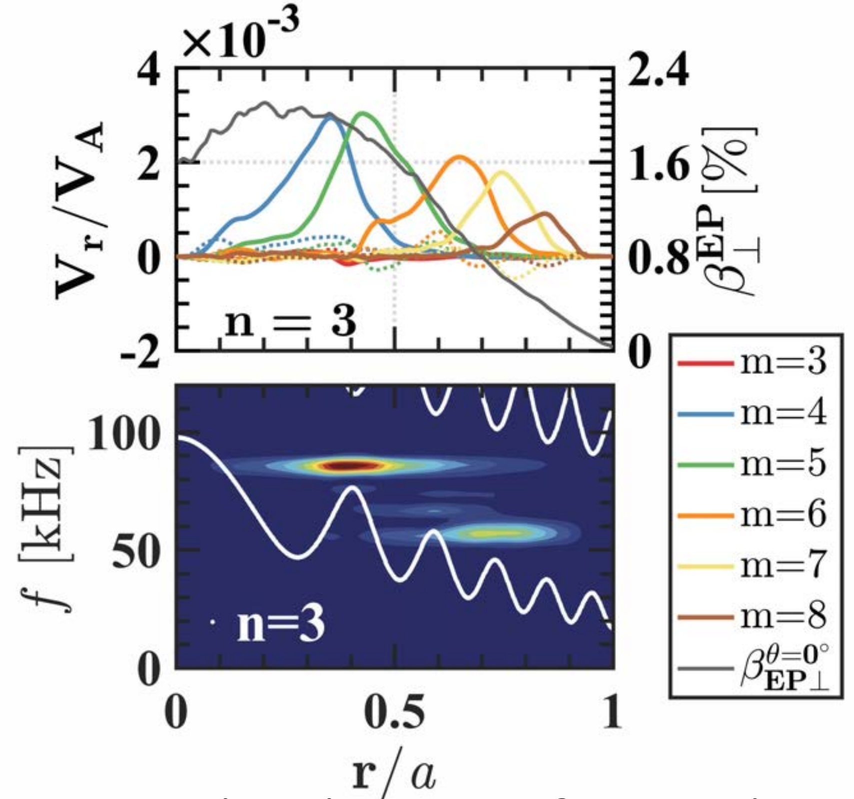


- We repeated simulation at the onset of burst with including only one toroidal harmonic at a time.
- The burst is primarily dominated by only two toroidal harmonics (*n*=3 and *n*=4), even the absence of a single non-dominant mode (like *n*=6) significantly delays the onset of the burst.
- Is synergy of different toroidal harmonics truly indispensable, or does it merely reduce the threshold?

Single-*n* induced bursting SAWs (*n*=3)

Single-*n* simulation with $n = 3$ toroidal mode family: $n = 3$ mode is directly driven by fast particles, while $n = 0, 6, 9$ MHD perturbations are retained, which contribute to the TAE nonlinear saturation.





- **TAEs with a single *n* can also trigger the burst with a longer time interval of two adjacent bursts. [Higher critical TAE amplitudes are required to trigger the TAE avalanche.]**
- **Similar to the multi-*n* case, a series of discrete TAEs with different frequencies is formed.**
- **Oscillatory growth of kinetic energy results from different frequencies of inner and outer TAEs.**