

Phase-space mechanisms of ICRF-driven bursting shear Alfvén waves and their suppression via phase-space engineering

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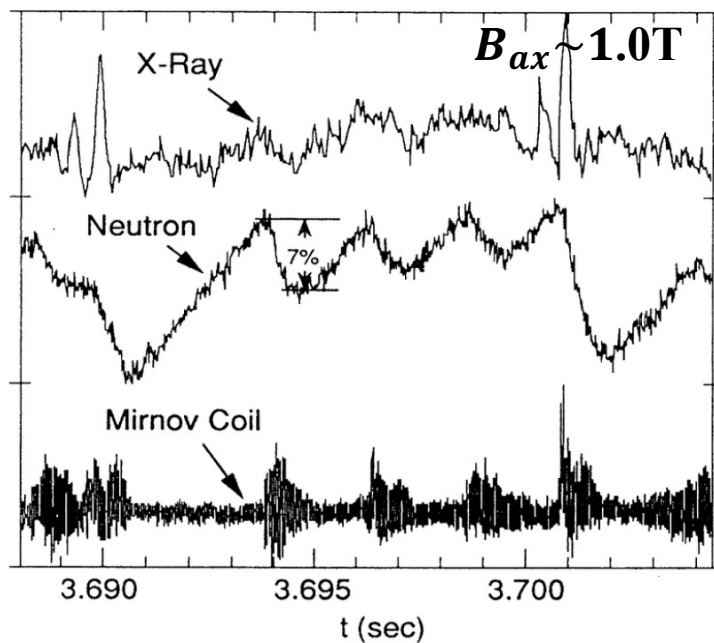
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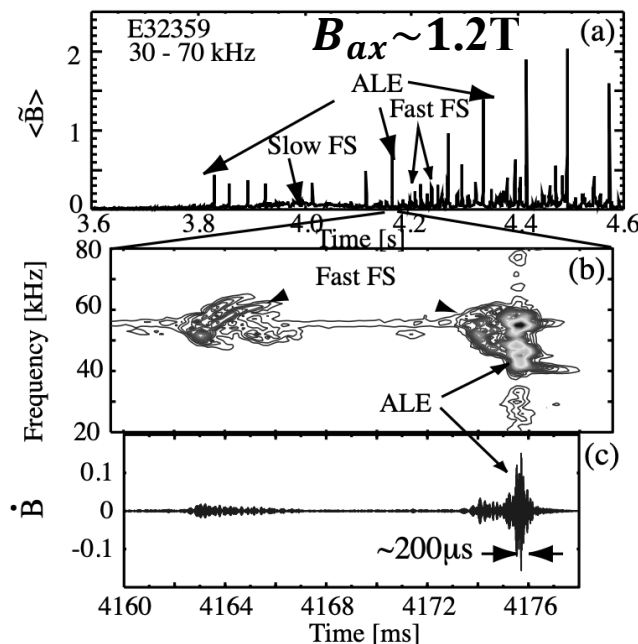
- **Background**
- **Extend MEGA with ICRF heating**
- **First-principles simulations of ICRF-driven SAWs in tokamaks (slowing-down time scale)**
 - **Bursting and non-bursting TAEs with different RF layer locations**
 - **Bursting and non-bursting TAE behaviors**
 - **Mechanism: resonant drive, energy storage and release, role of RF**
 - **Suppressing bursting SAWs by ICRH phase-space engineering: preliminary results**
- **Summary**

Bursting Alfvén waves in TFTR



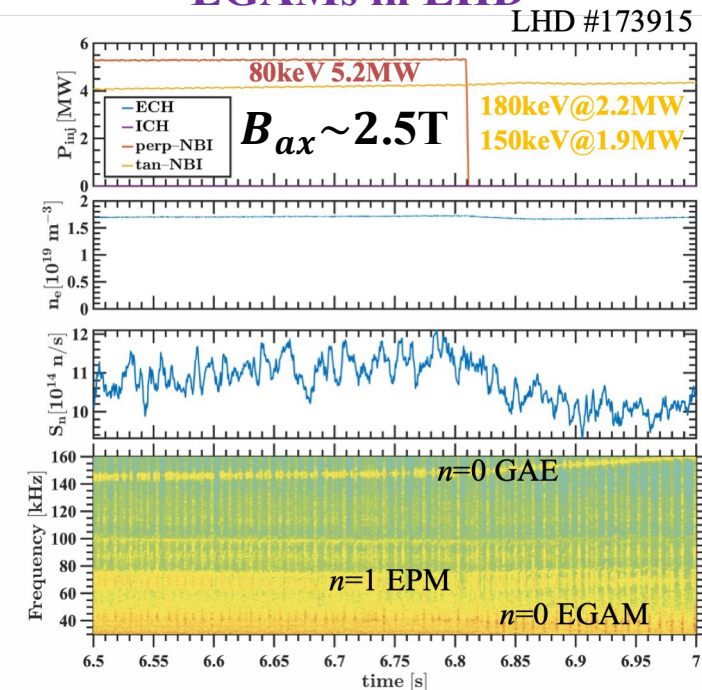
[Wong+, PRL, 1991]

Abrupt Large Events (ALEs) in JT-60U



[Shinohara+, NF, 2001]

Bursting Alfvén waves and EGAMs in LHD

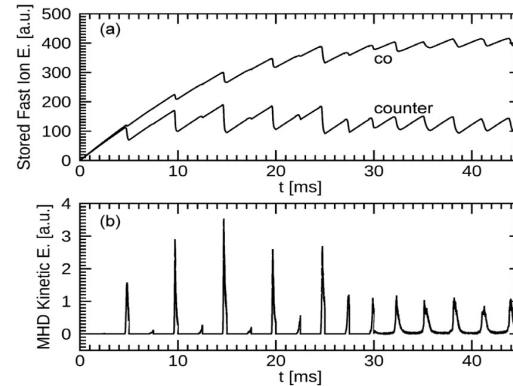


[Wang+, FEC2023]

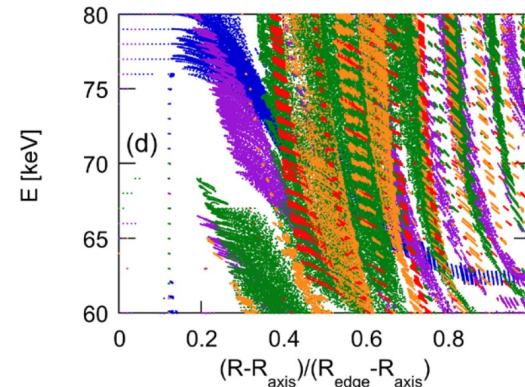
- Shear Alfvén waves (SAWs) driven by energetic particles can degrade the performance of burning plasmas.
- In NBI-heated plasmas, SAWs often burst, with fast frequency chirping.
- Recurrent bursts release the stored free energy rapidly and violently.

MEGA reproduced SAW bursts in TFTR & DIII-D

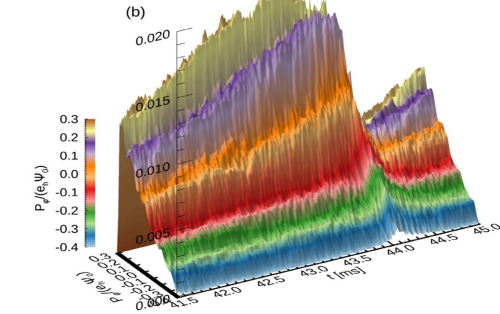
[Todo+, NF12, NF14, NF16, NF19, NJP16]



Resonance overlap

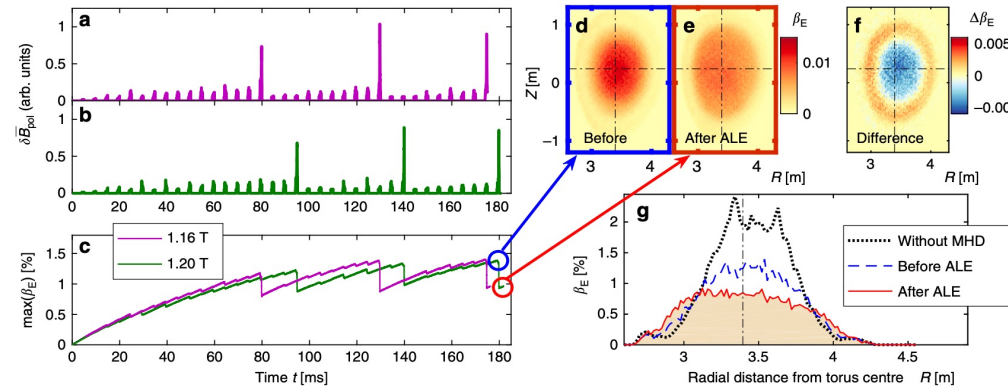


Critical EP gradient in phase space

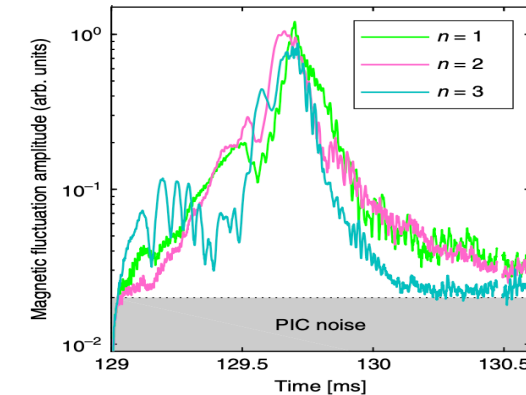


MEGA reproduced abrupt large-amplitude events (ALEs) in JT-60U

[Bierwage+, Nat. Comm., 2018]



Multiple mode coupling

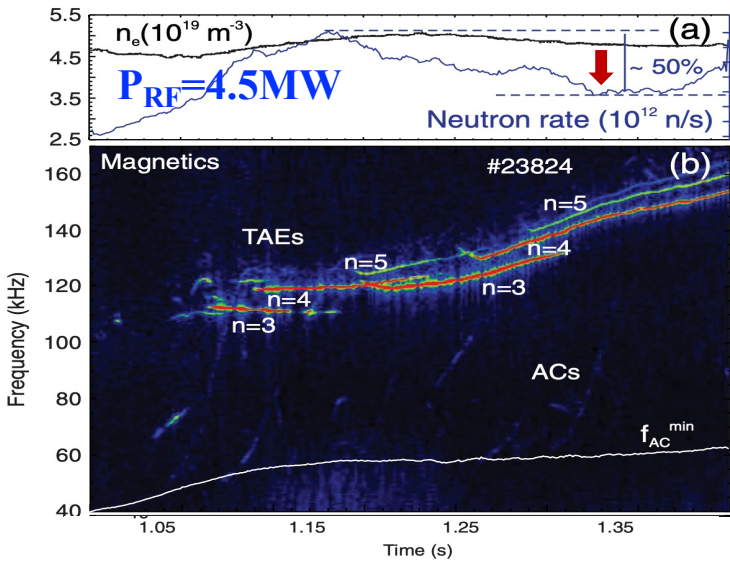


- MEGA simulated NBI-driven bursts on the collisional slowing-down time scale.
- Key factors: **resonance overlap**, a **critical EP gradient in phase space** and **multi-mode coupling**.

Shear Alfvén waves under ion cyclotron resonance heating

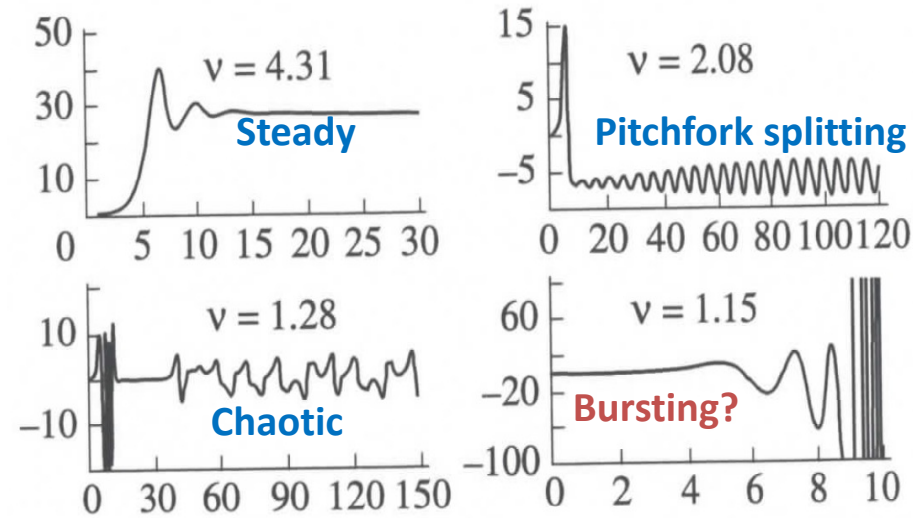


ICRF-induced TAEs in AUG



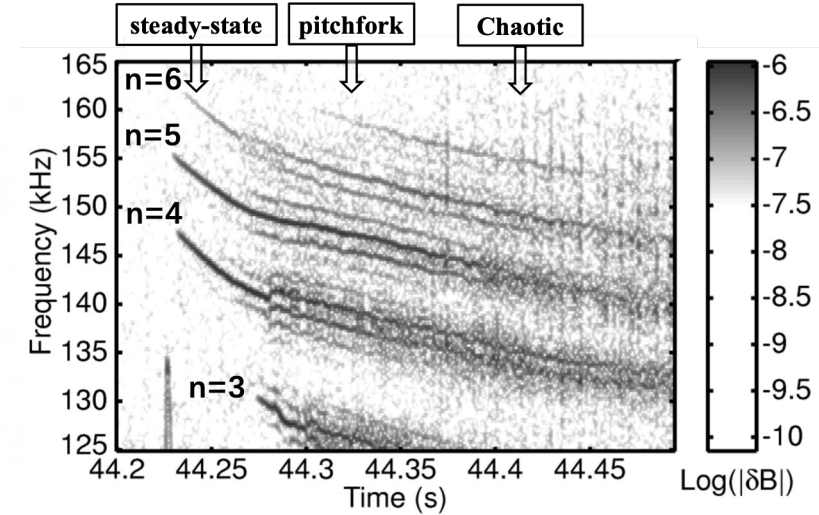
[Garcia-Munoz+, PRL, 2010]

Nonlinear states predicted by theory



[Berk+, Plasma Physics Reports, 1997]

Various AE states in JET ICRH plasmas



[Heeter+, PRL, 2000]

- Unlike beam-driven SAWs, ICRF-driven SAWs rarely burst: they are steady, split (pitchfork) or chaotic, commonly attributed to strong RF velocity-space diffusion.
- The Berk–Breizman–Pekker model of a **near-marginal 1-D bump-on-tail** instability explains these states, **except the predicted bursting state**.
- **What keeps ICRF-driven SAWs from bursting may open a new route to AE control in burning plasmas.**

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Bulk plasma (Fluid)

$$\begin{aligned}\frac{\partial \rho}{\partial t} &= -\nabla \cdot (\rho \mathbf{v}) + \nu_n \Delta (\rho - \rho_{eq}), \\ \rho \frac{\partial}{\partial t} \mathbf{v} &= -\rho \boldsymbol{\omega} \times \mathbf{v} - \rho \nabla \left(\frac{v^2}{2} \right) - \nabla p + (\mathbf{j} - \underline{\mathbf{j}}'_h) \times \mathbf{B} \\ &\quad - \nabla \times (\nu \rho \boldsymbol{\omega}) + \frac{4}{3} \nabla (\nu \rho \nabla \cdot \mathbf{v}), \\ \frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E}, \\ \frac{\partial p}{\partial t} &= -\nabla \cdot (p \mathbf{v}) - (\gamma - 1) p \nabla \cdot \mathbf{v} + (\gamma - 1) \\ &\quad \times [\nu \rho \omega^2 + \frac{4}{3} \nu \rho (\nabla \cdot \mathbf{v})^2 + \eta \mathbf{j} \cdot (\mathbf{j} - \mathbf{j}_{eq})] + \nu_n \Delta (p - p_{eq}), \\ \mathbf{E} &= -\mathbf{v} \times \mathbf{B} + \eta (\mathbf{j} - \mathbf{j}_{eq}), \\ \boldsymbol{\omega} &= \nabla \times \mathbf{v}, \\ \mathbf{j} &= \frac{1}{\mu_0} \nabla \times \mathbf{B},\end{aligned}$$

$\mathbf{E}, \mathbf{B}$

Energetic particle (drift kinetic)

$$\begin{aligned}\mathbf{u} &= \mathbf{v}_{\parallel}^* + \mathbf{v}_E + \mathbf{v}_B, \\ \mathbf{v}_{\parallel}^* &= \frac{v_{\parallel}}{B^*} (\mathbf{B} + \rho_{\parallel} B \nabla \times \mathbf{b}), \\ \mathbf{v}_E &= \frac{1}{B^*} (\mathbf{E} \times \mathbf{B}), \\ \mathbf{v}_B &= \frac{1}{Z_h e B^*} (-\mu \nabla B \times \mathbf{b}), \\ \rho_{\parallel} &= \frac{m_h v_{\parallel}}{Z_h e B}, \\ \mathbf{b} &= \mathbf{B} / B, \\ B^* &= B (1 + \rho_{\parallel} \mathbf{b} \cdot \nabla \times \mathbf{b}),\end{aligned}$$

$$\begin{aligned}m_h v_{\parallel} \frac{dv_{\parallel}}{dt} &= \mathbf{v}_{\parallel}^* \cdot (Z_h e \mathbf{E} - \mu \nabla B), \\ \mathbf{j}'_h &= \int (\mathbf{v}_{\parallel}^* + \mathbf{v}_B) Z_h e f d^3 v - \nabla \times \int \mu \mathbf{b} f d^3 v,\end{aligned}$$

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

Latest version w/ KTI
& GPU parallelization:
<https://github.com/to-do-lab-nifs/MEGA>

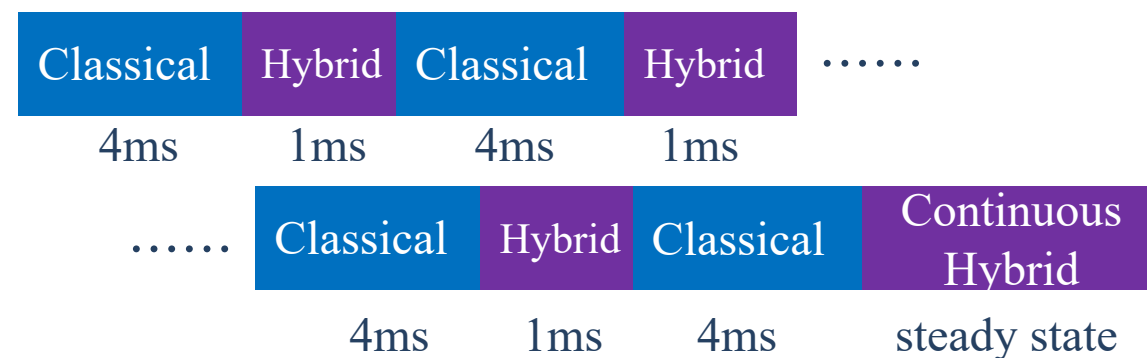
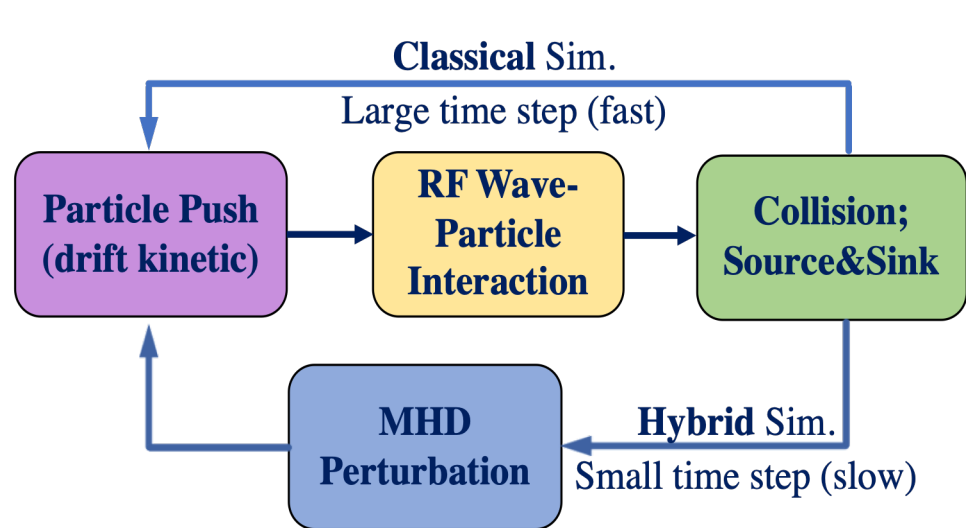
$\mathbf{j}_h$

- 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.

Extension of MEGA: ICRF heating module (tokamak case)



- **SAW nonlinear states** are determined by an interplay between **SAW electric field that flattens** fast ion distribution function and **relaxation processes that restore** the distribution function.
- MEGA code is extended with **ICRF kick, Coulomb collisions, minority ion 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: $B_0 = 1.5\text{T}$, $R_0/a = 2.6\text{m}/0.9\text{m}$, $n_0 = 3.0 \times 10^{19}\text{m}^{-3}$, $T_0 = 8\text{keV}$, $n^{(H)}/n^{(D)} = 4\%$.
- 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 $k_{\parallel} = 6\text{ m}^{-1}$ and $k_{\perp} = 34\text{ m}^{-1}$.
- **Multi-phase simulation: alternately** run classical and hybrid simulations until a steady state. ($\sim 10\text{M}$ CPU hour)



***Computational cost reduced to 1/5!**

- **RF kick**: a velocity-space kick whenever a minority ion crosses the Doppler-shifted resonance layer (Stix, NF 1975; Murakami+, NF 2006):

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

- RF kick is simulated by the Monte Carlo method.
- Wave-particle interaction time $I = \min(t_1, t_2) = \min\left(\sqrt{2\pi/n\dot{\omega}}, 2\pi(n\dot{\omega}/2)^{-1/3} \text{Ai}(0)\right)$ depends on the turning point position relative to the resonance layer. ($I = t_1$: bounce tip far away from the resonance layer; $I = t_2$: bounce tip close to the resonance layer)
- Random variable ϕ_r is the phase shift between the Larmor rotation and wave electric field.
- Left-hand polarized component of the perpendicular wave electric field E_+ , which rotates in the direction of ion cyclotron motion, can effectively interact with the minority ions.
- The latest version of MEGA has been coupled with the full-wave solver AORSA in both its 2D and 3D versions, enabling simulations of tokamak and stellarator scenarios
- In this work, we focus on the fundamental minority ion heating scheme ($n=1$).

MEGA–AORSA coupling: LHD on-axis heating



■ H-minority fundamental heating at 38.47 MHz

AORSA: solve the RF wave

Input: ion velocity distribution f

Solve wave propagation and absorption for this distribution

Output: E amplitude and phase, Power to H, bulk ions and electrons

MEGA: prepare E and k

Sum complex E modes over the torus

Take $|E_{\pm}|/\sqrt{2}$ (rotating amplitudes)

Divide by $B_{\text{unit}}v_A$, interpolate to ions

$k_{\parallel} = \omega n_{\parallel}/c$, $n_{\parallel} = 7.2156$

$k_{\perp}$: local cold-plasma dispersion

MEGA: advance particles

Follow H guiding-center orbits

Apply perpendicular RF kicks:

$\omega - k_{\parallel}v_{\parallel} - \Omega_H = 0$

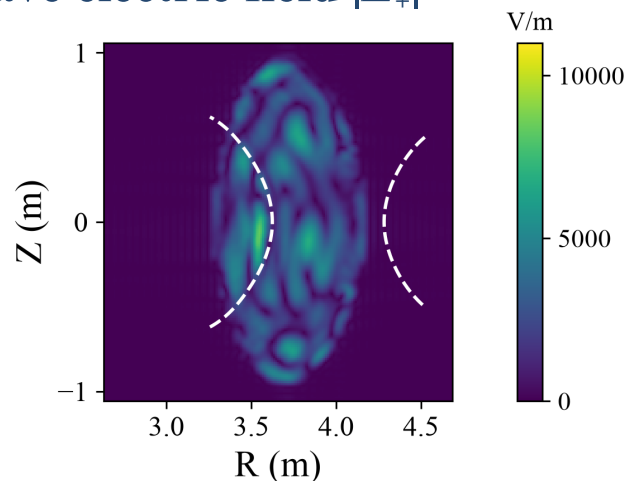
Coulomb collisions, losses + source

Output: updated H distribution f

Every 5 ms: average particles on flux surfaces, return f and its velocity gradients

Feedback updates the velocity distribution. Background density and magnetic equilibrium stay fixed.

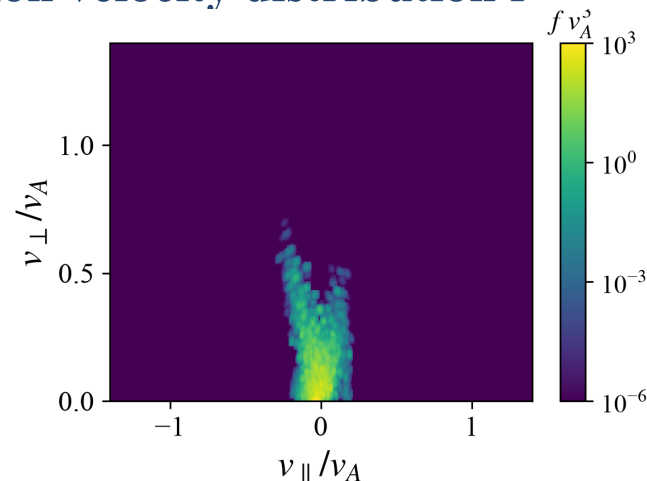
Wave electric field $|E_{+}|$



$t = 10$ ms, $\phi = 0^{\circ}$

Dashed: $\Omega_H = \omega$, $B = 2.5268$ T (MEGA)

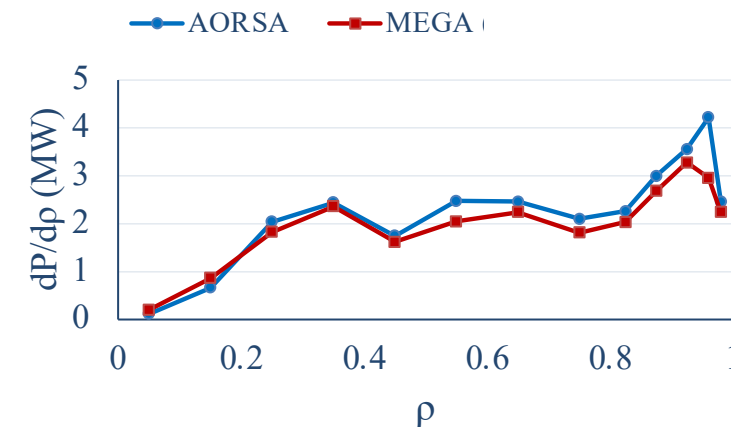
Ion velocity distribution f



$t = 10$ ms, $\rho = 0.05$

RF kicks reshape the velocity distribution

Radial RF deposition



Initial Maxwellian baseline ($\rho < 0.99$)

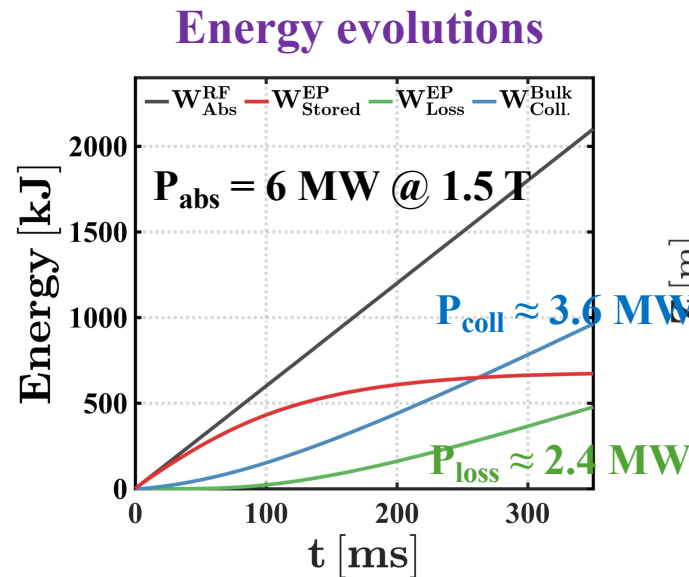
MEGA integrated power: 9.0% below AORSA

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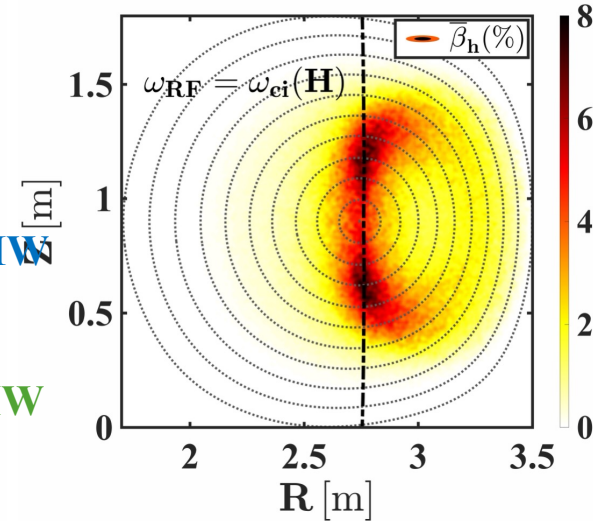
“Steady-state” EP distribution from multi-phase simulation



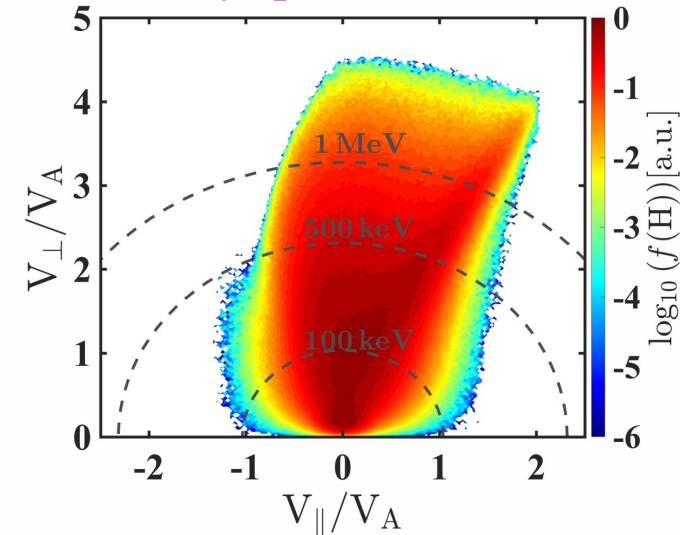
Classical simulation
without SAW relaxation



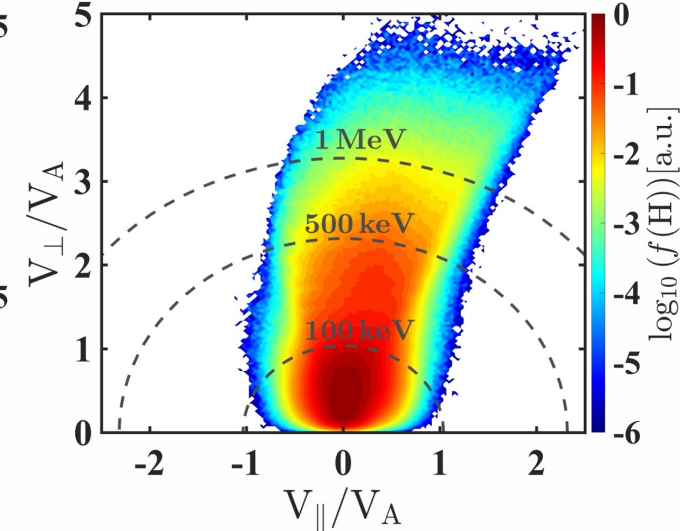
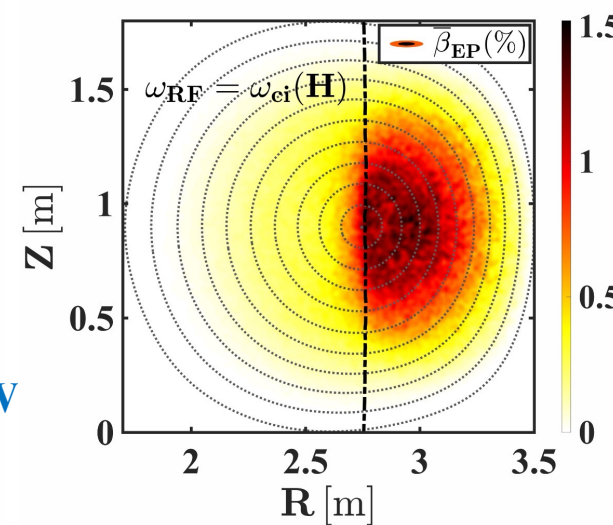
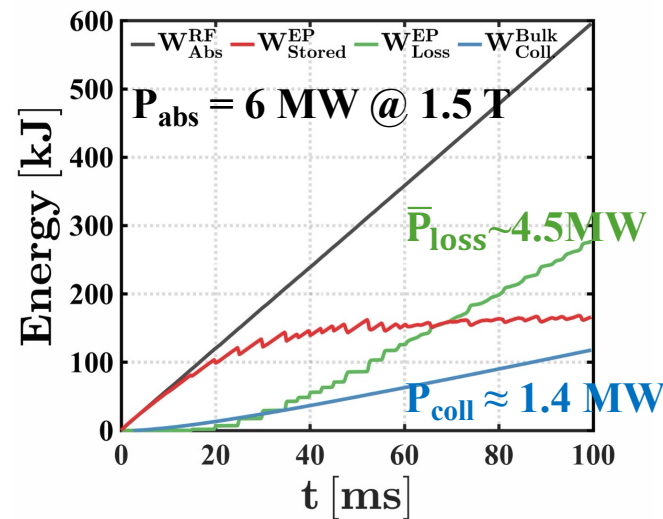
Minority hydrogen beta



Velocity space distribution

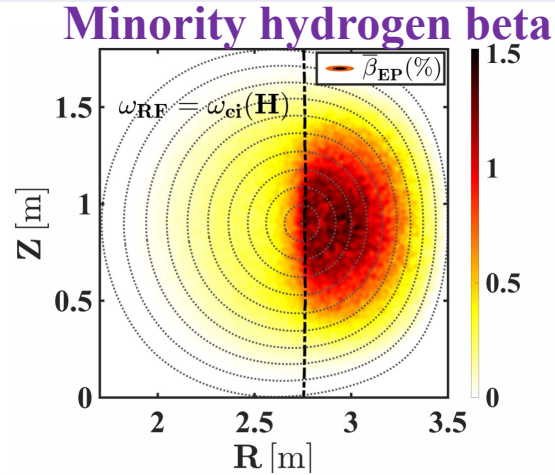


Multi-phase simulation
with SAWs

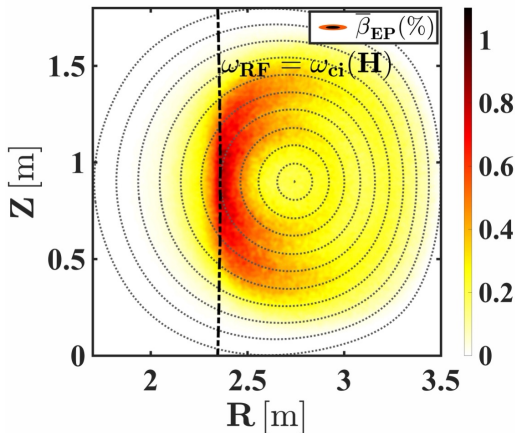


ICRF-driven bursting shear Alfvén waves

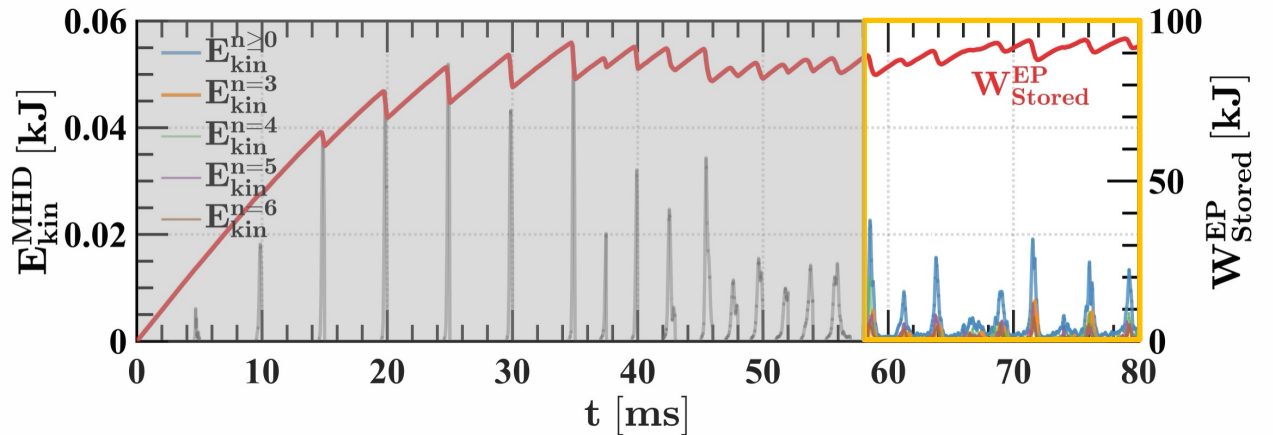
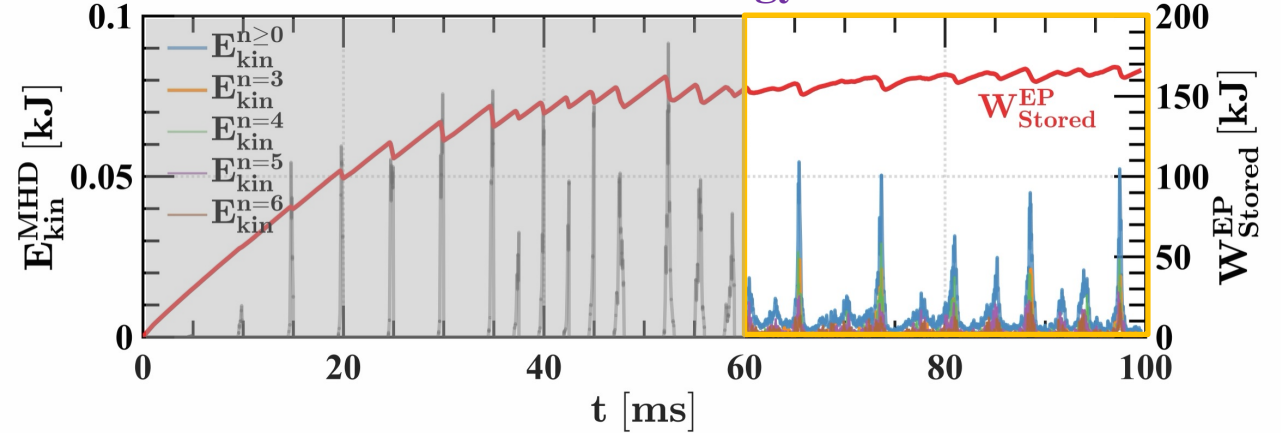
On-axis ICRH
with $P_{RF} = 6$ MW



HFS ICRH
with $P_{RF} = 6$ MW



MHD kinetic energy evolutions



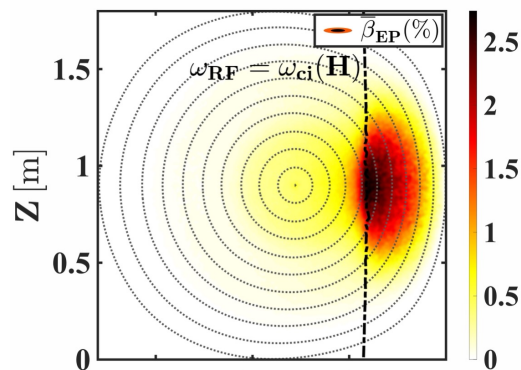
- **Recurrent bursting SAWs** appear in the continuous hybrid phase ($t \geq 60$ ms) when the RF resonance layer is **on the magnetic axis or on the inboard side**.
- During the multi-phase period ($t < 60$ ms), every restart of the MHD fluctuations overshoots, so the evolution always looks bursting.

Non-bursting TAEs with LFS ICRH

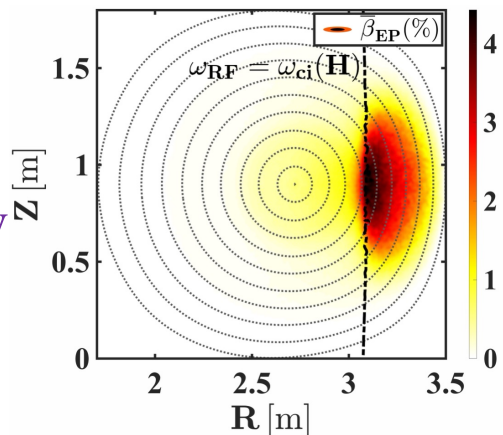


Minority hydrogen beta

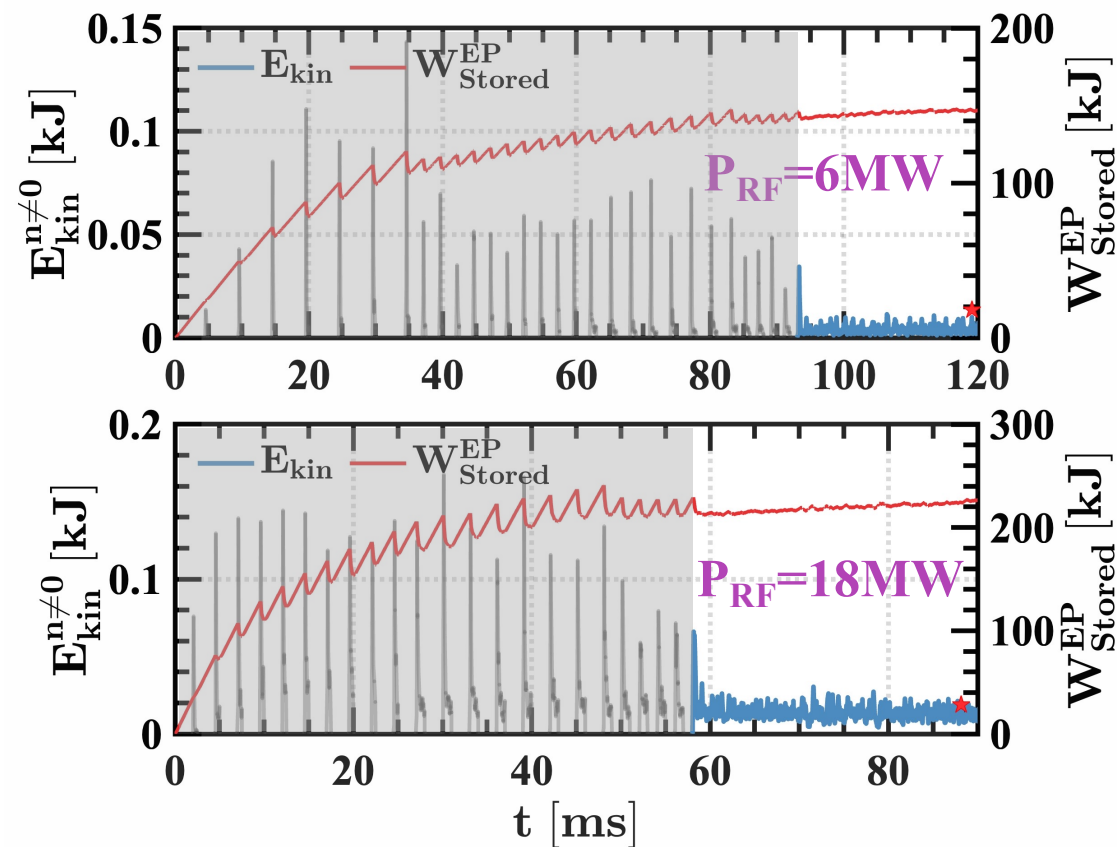
LFS ICRH
with $P_{RF} = 6$ MW



LFS ICRH
with $P_{RF} = 18$ MW



MHD kinetic energy evolutions



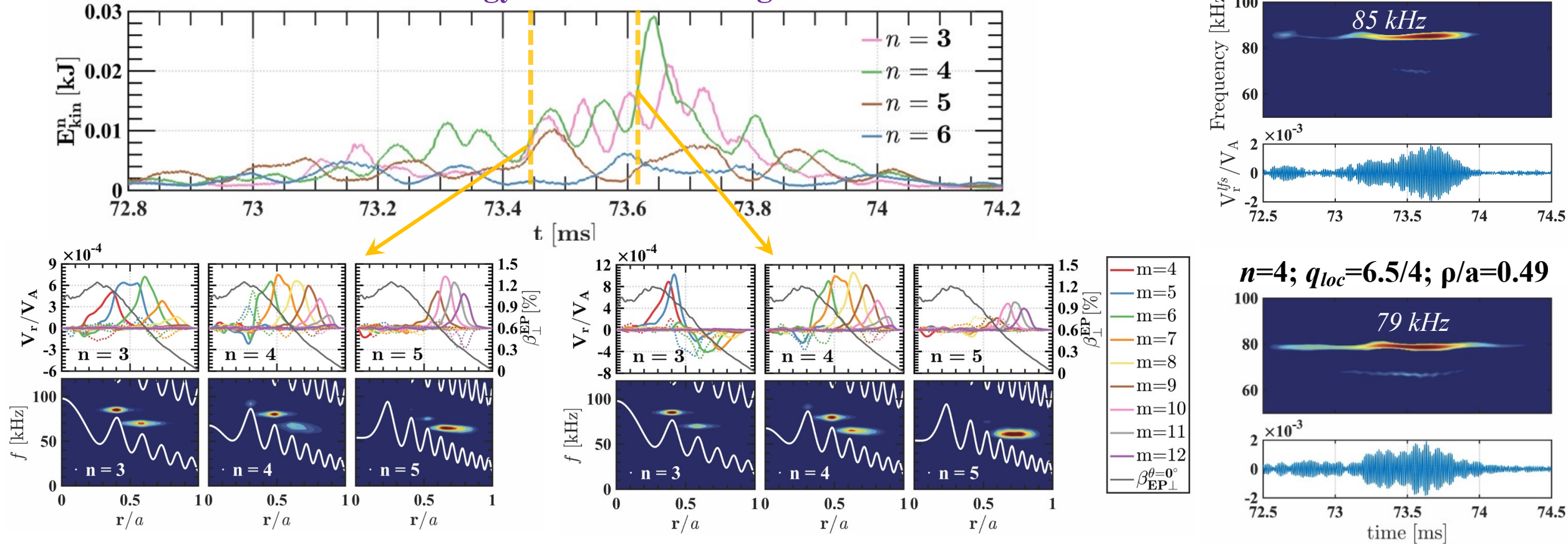
- With the RF resonance layer on the outboard side, only **non-bursting (grassy) modes** appear, even at 18 MW.

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Bursting case: radially separated TAEs without chirping



MHD kinetic energy evolutions during one burst

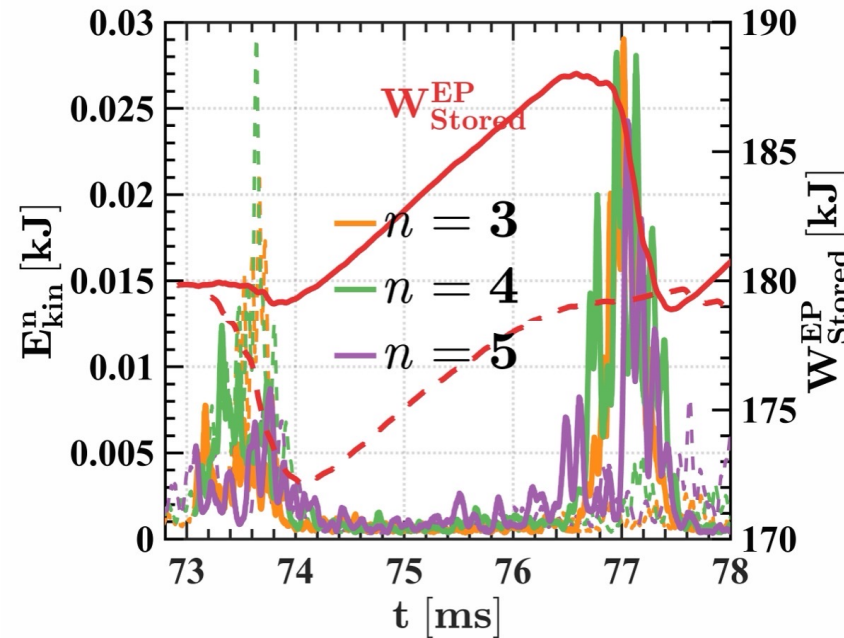


- **Discrete, non-chirping TAEs** form above the Alfvén continuum tips for each n .
- Adjacent TAEs **overlap in space**.
- The primary modes of different n grow and decay together: the toroidal harmonics interact.

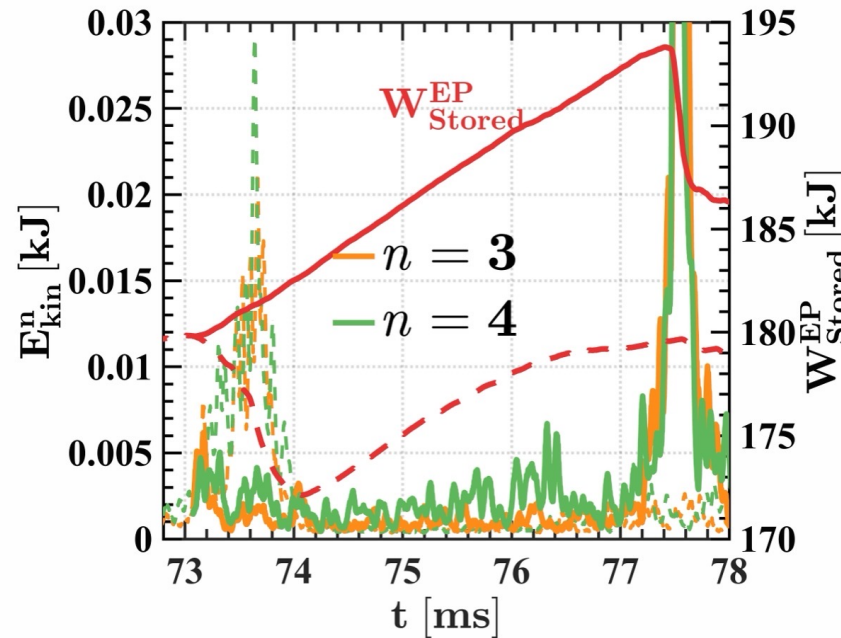
Synergy of toroidal harmonics in TAE bursts



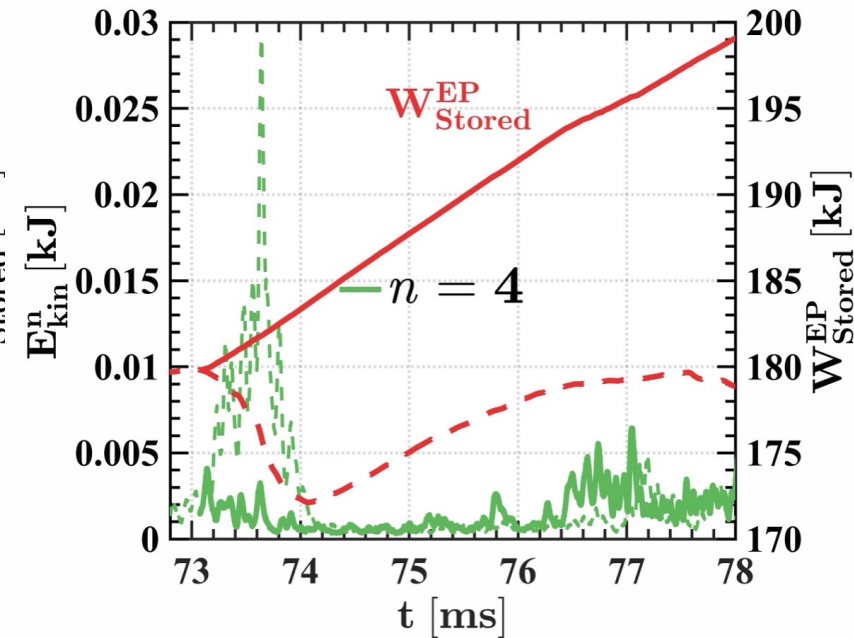
Restart at 73.07 ms: $n = 3-5$ only
(dashed: baseline with $n = 3-6$)



Restart at 73.07 ms: $n = 3, 4$ only



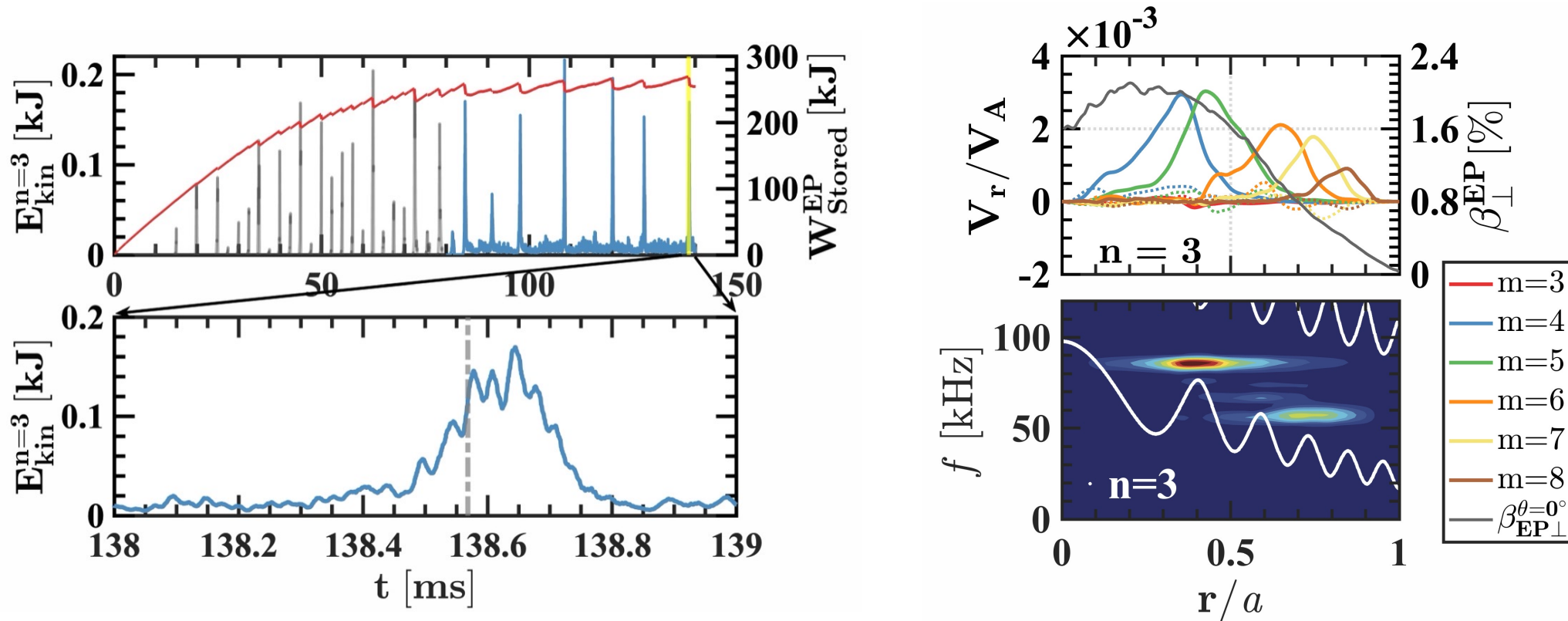
Restart at 73.07 ms: $n = 4$ only



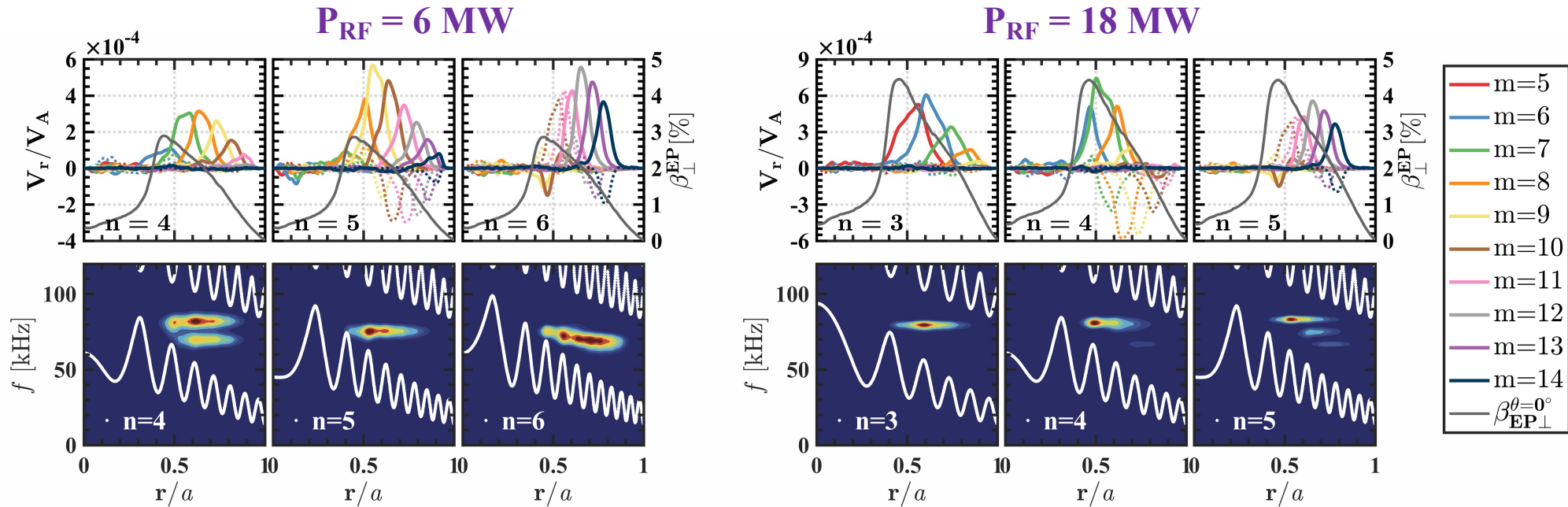
- The simulation is restarted at the onset of a burst with a reduced set of toroidal harmonics.
- The burst is dominated by $n = 3$ and 4 , yet removing even a non-dominant harmonic ($n = 6$) **delays its onset significantly**.
- **Is the synergy of toroidal harmonics indispensable, or does it only lower the threshold?**

Bursting TAEs with a single toroidal harmonic ($n = 3$)

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.



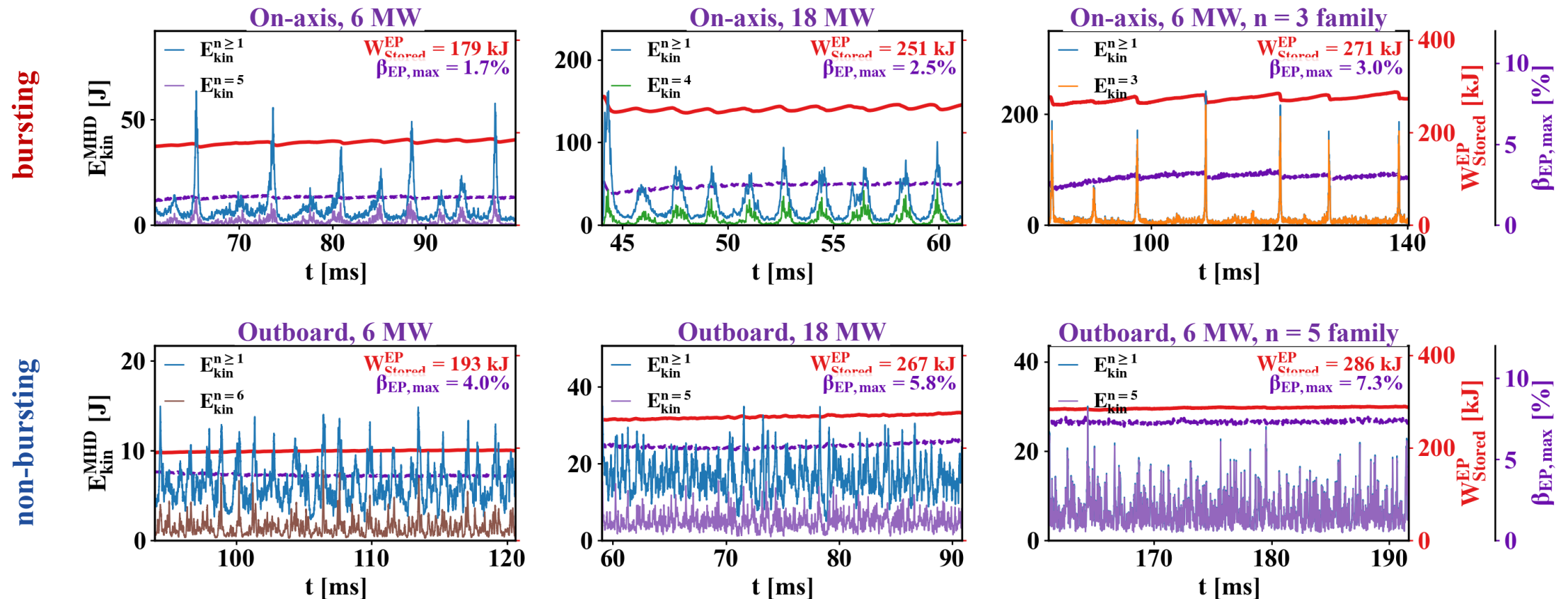
- TAEs with a single n can also trigger the burst with a longer time interval of two adjacent bursts.
- No clear reduction in TAE frequency associated with the increased pressure gradient [β_{EP}^{perp} : 1.2% $\rightarrow$ 2.0%].
- Oscillatory growth of energy results from the frequency mismatch between inner and outer TAEs.



- For outboard RF heating, the primary TAE of each n has a **broad, coherent structure** at nearly the same frequency.

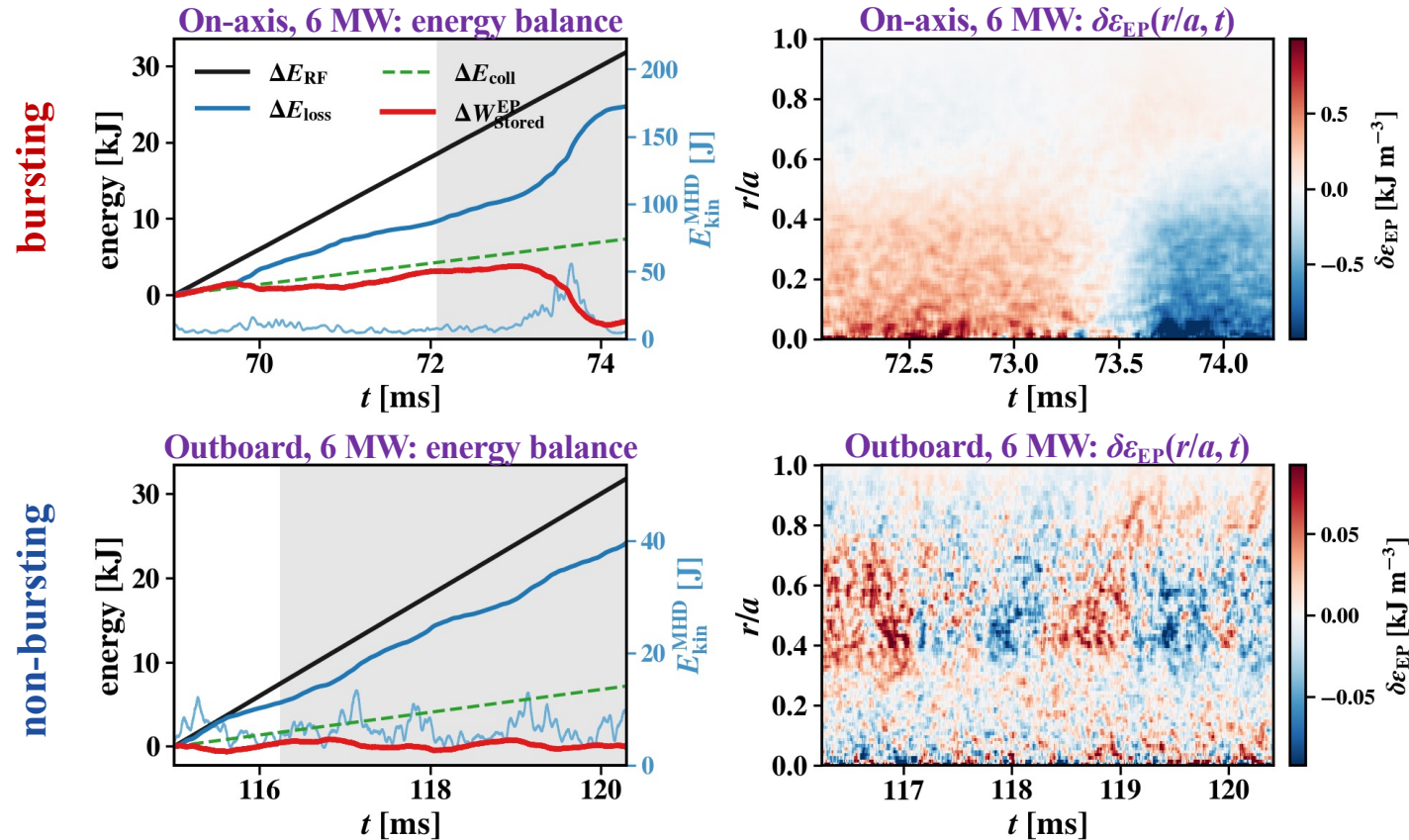
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What separates bursting from non-bursting SAWs?



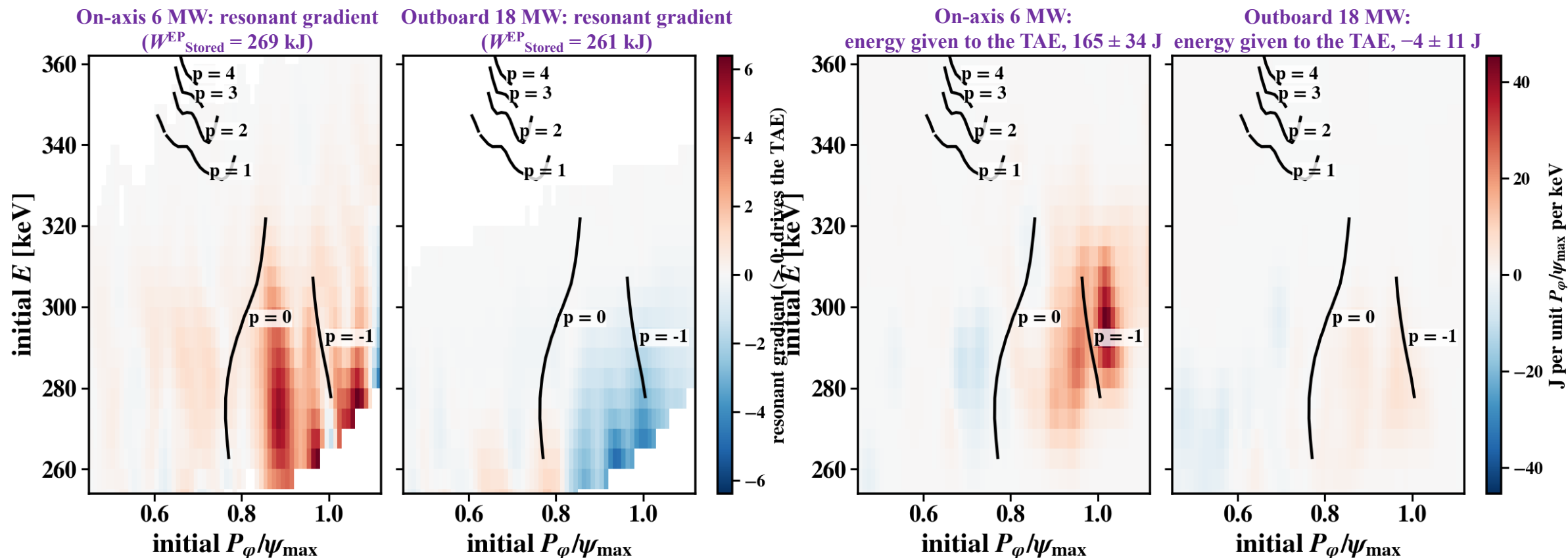
- On-axis and inboard (HFS) ICRH give **recurrent TAE bursts**; outboard ICRH gives only low-level fluctuating modes, even at 18 MW.
- Stored EP energy (180–290 kJ) and peak EP beta (2–7 %) are not larger in the bursting runs: **they do not decide bursting**.
- The difference comes from **the resonant free energy the RF builds and how the modes extract it**.

Bursting: slow refill, fast release of stored EP energy



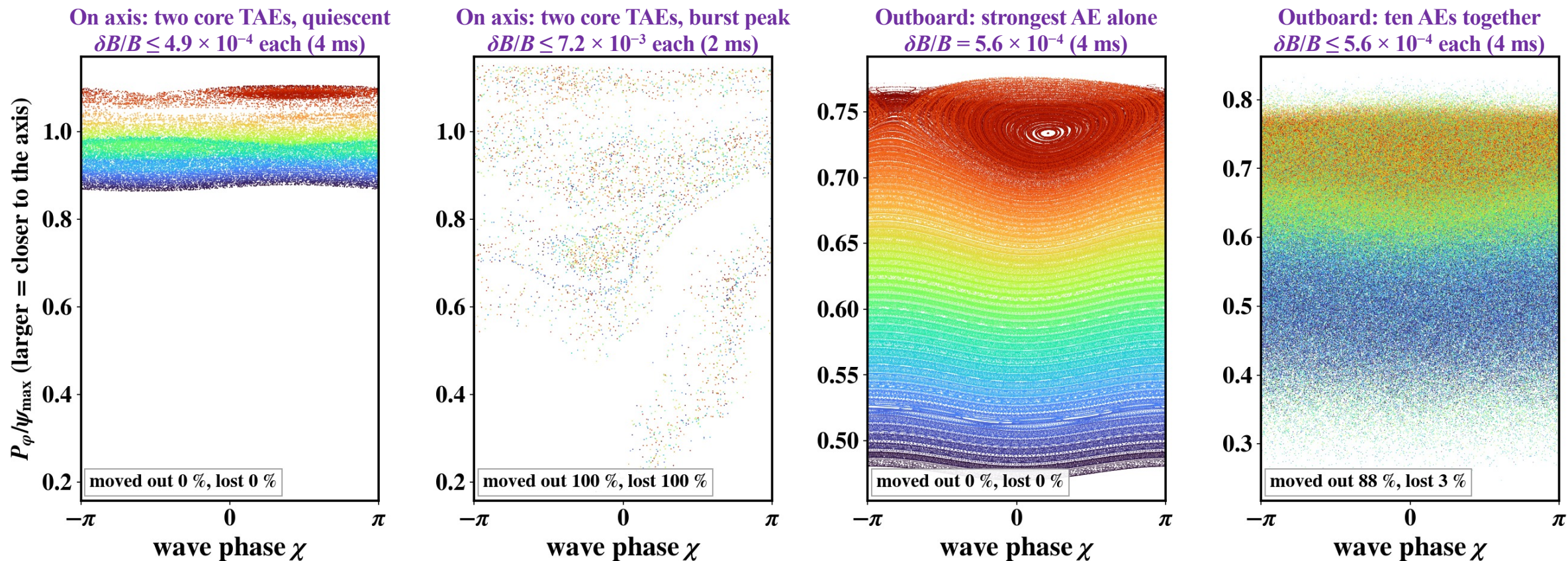
- On axis the stored EP energy rises for 1–4 ms, then **drops by 3–6 % within 0.5 ms**; the core charges, then empties.
- Outboard the stored energy shows only small fluctuations: it also grows in quiet phases, but it is never released in a concentrated way.
- Bursting is **a slow refill and a fast concentrated release of the stored EP energy**; why the outboard runs never release it this way is the key question.

What drives the burst TAEs: a resonant gradient



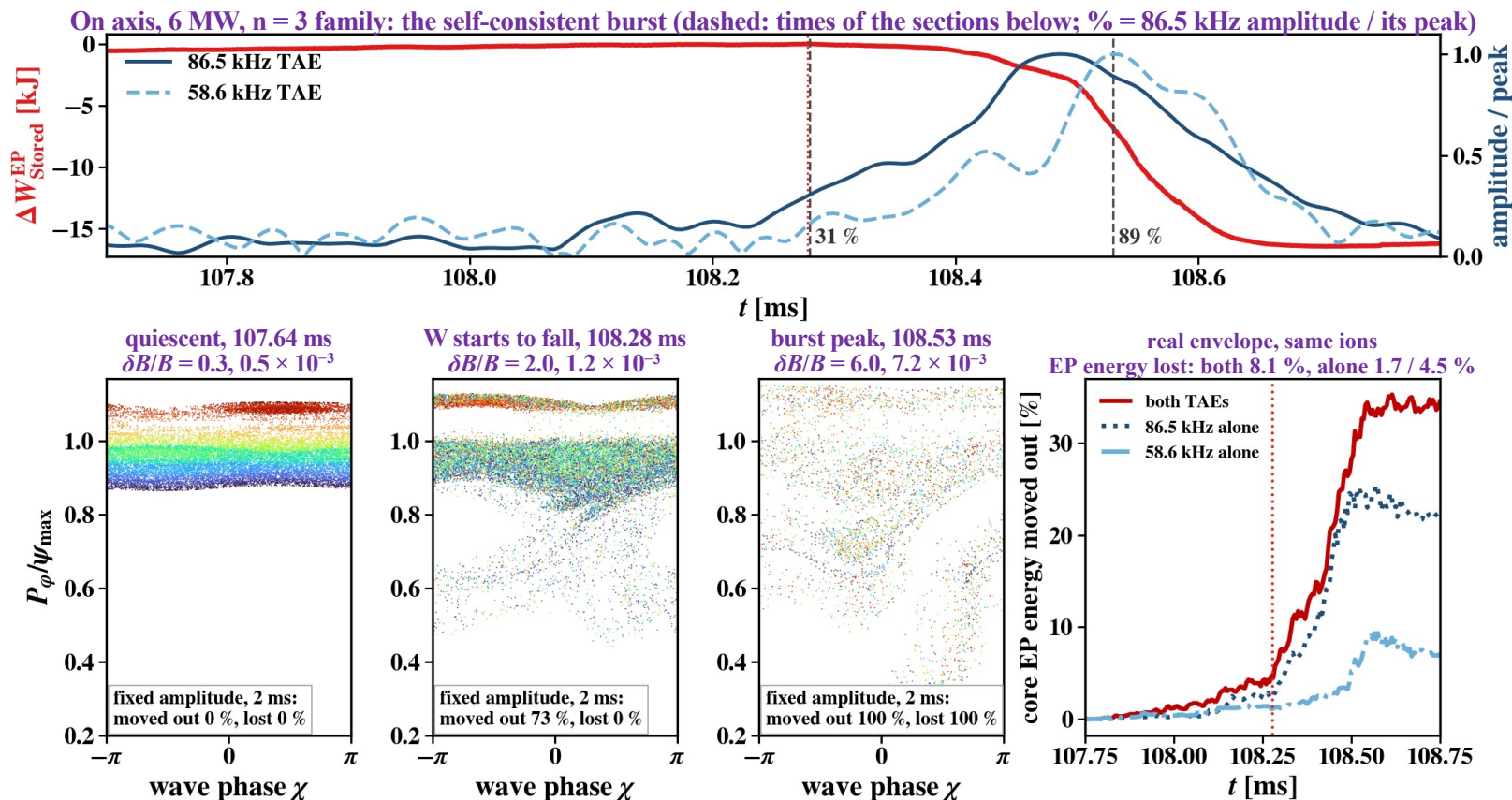
- Same two-TAE field ($n=3$: 86.5kHz&58.6kHz) are applied to two distributions with about the same μ band ($\mu \approx 1.6\text{--}1.8 / 199\text{--}224 \text{ keV/T}$) and similar stored energy (260-270kJ): on axis the gradient is **positive along the $p=0$ and $p=-1$ resonances**; at 18 MW outboard it is negative.
- The drive comes from **the resonant free energy of the distribution**. Outboard RF generated EPs cannot drive the burst of on-axis heating.

Transport of heated ions in prescribed fields



- On-axis with $n = 3$ family (two core TAEs): little transport at quiescent amplitude; strong transport at burst-peak amplitude (all ions lost in 2 ms).
- Outboard with multi- n TAEs: one AE alone moves no ion, ten AEs together move 88 % out in 4 ms; in the full on-axis run the quiescent modes also transport ions.
- Several resonances acting together **strengthen the transport of EPs in bursting phase of on-axis heating and steady phase of outboard heating.**

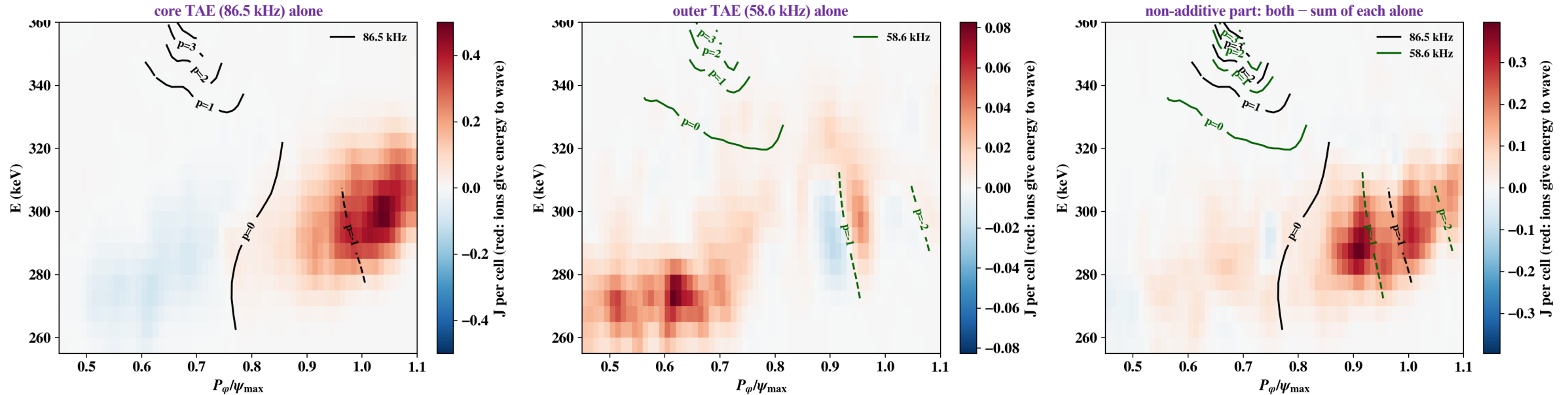
Release of a burst in the real envelope



- The stored energy turns down at 108.28 ms while the TAEs grow (86.5 kHz at ≈ 30 % of its peak); held at that amplitude, the field moves most core ions out in 2 ms.
- Both TAEs together deplete the core much more over the burst than either alone (non-additive transfer).
- The release is outward transport by the growing TAEs.

Where the non-additive transfer occurs

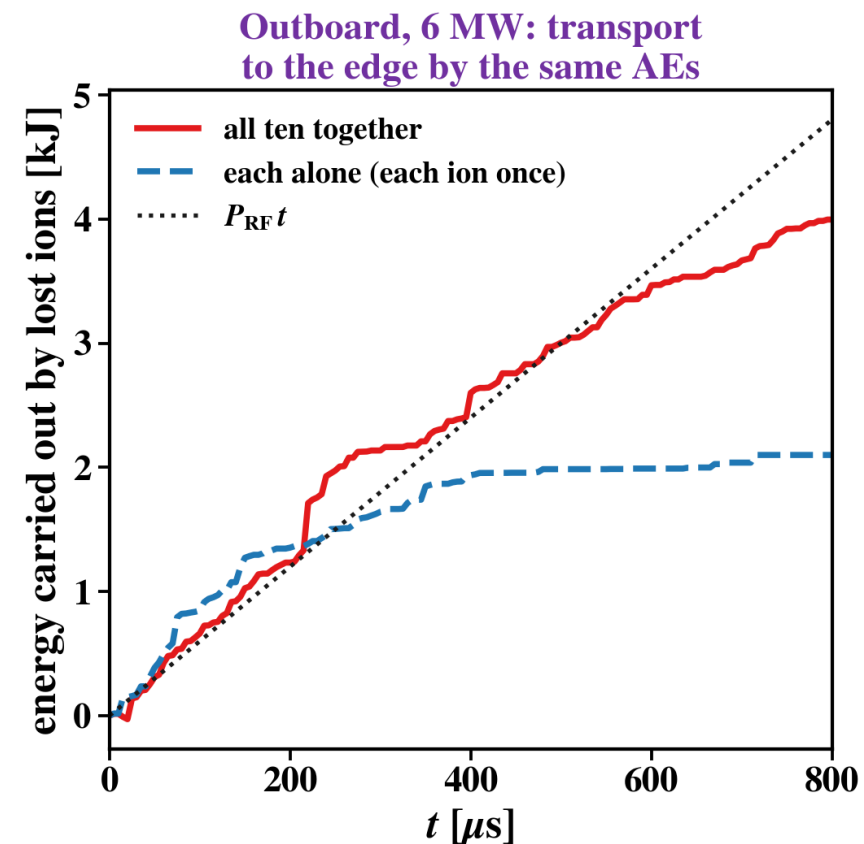
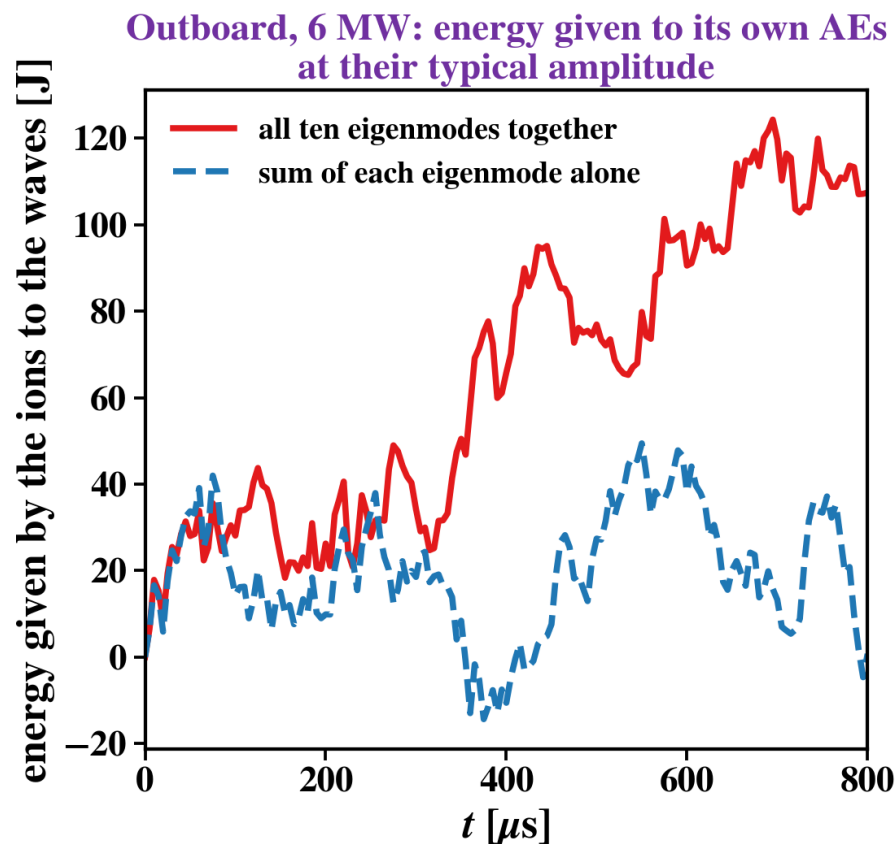
Real ions with $\mu = 1.70 \pm 3\%$, quiescent phase to burst peak; lines: resonances of the unperturbed orbits of the same ions (p labelled)



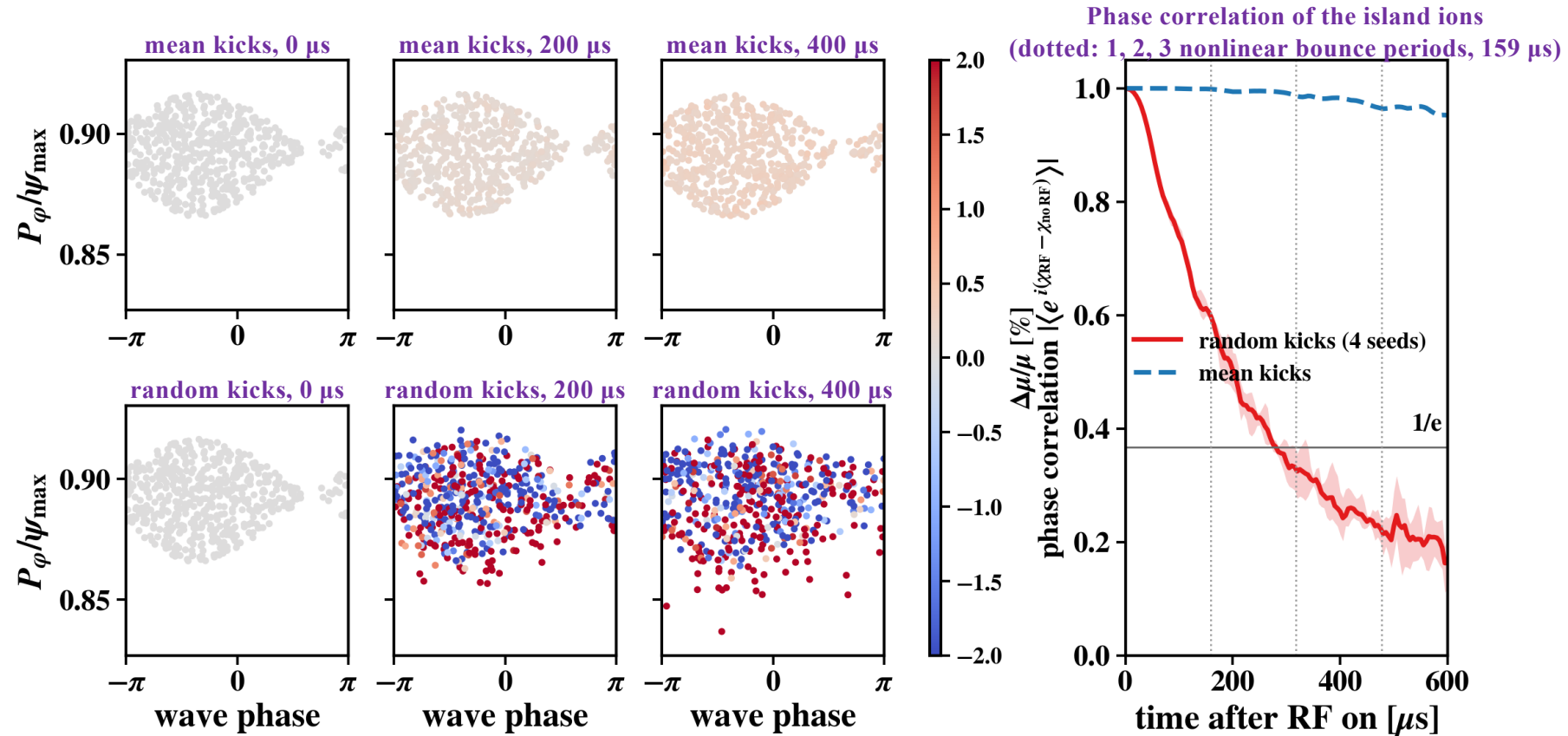
On-axis $n = 3$ family: energy transferred by real ions with $\mu = 1.70 \pm 3\%$, quiescent phase to burst peak; lines: resonances of the unperturbed orbits (p labelled)

- In (P_ϕ, E) the non-additive transfer lies where the resonances of the two TAEs interleave in the core. This is a finite-amplitude effect, not a sum of linear resonances.

Outboard AEs act together at typical amplitude



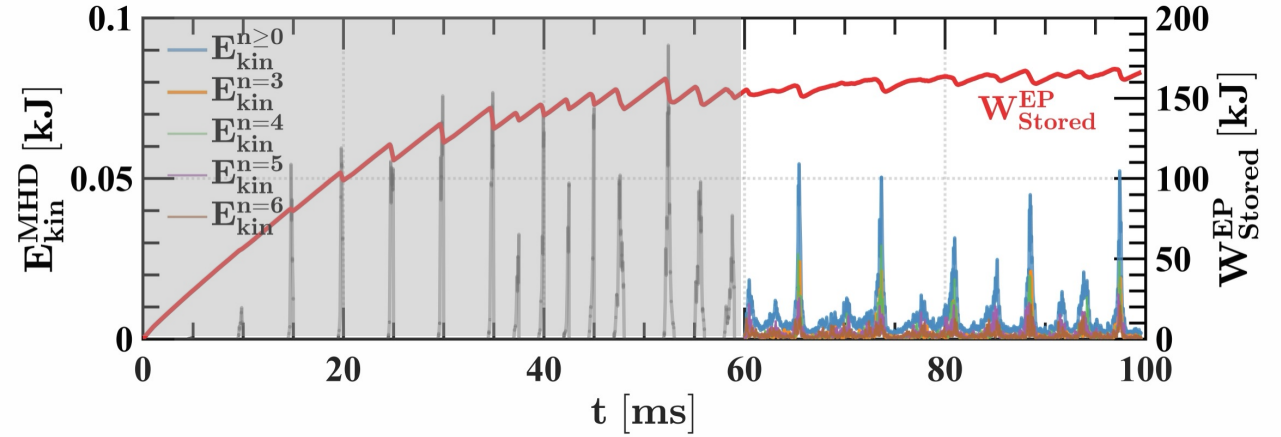
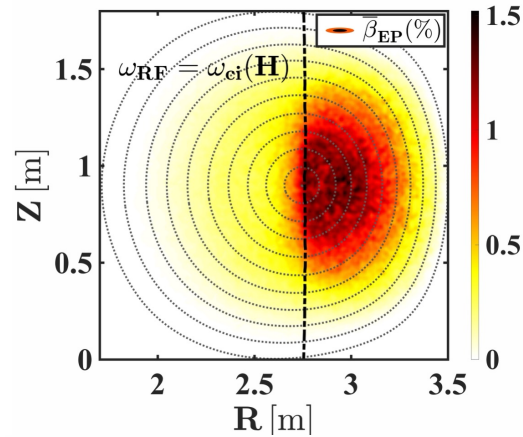
- At typical amplitude, the ten outboard AEs together take 107 J from the heated ions in 0.8 ms; each AE alone takes almost nothing.
- Together they also carry far more energy to the edge than the single-AE runs (finite time, existing distribution, no RF).
- Several AEs **extract and transport jointly at low amplitude**.



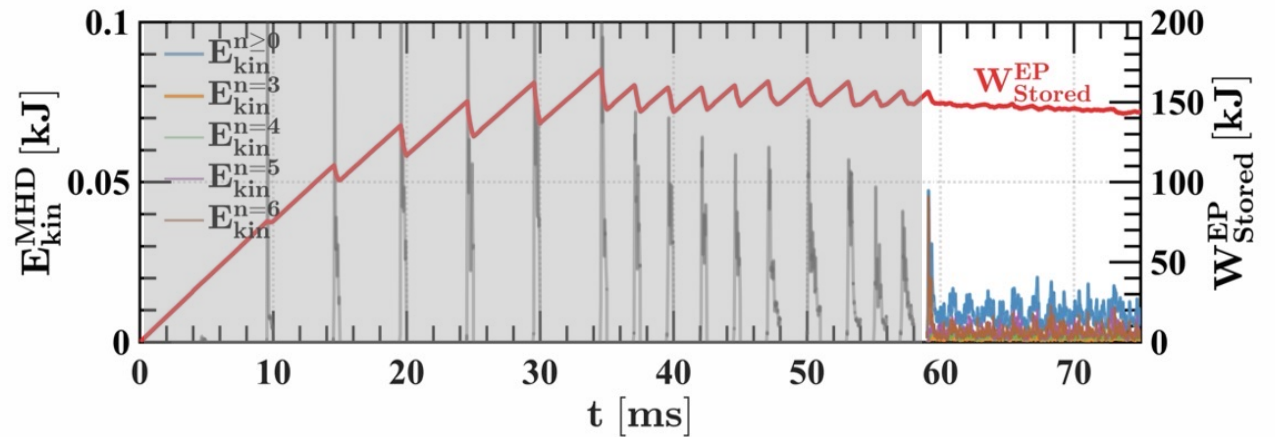
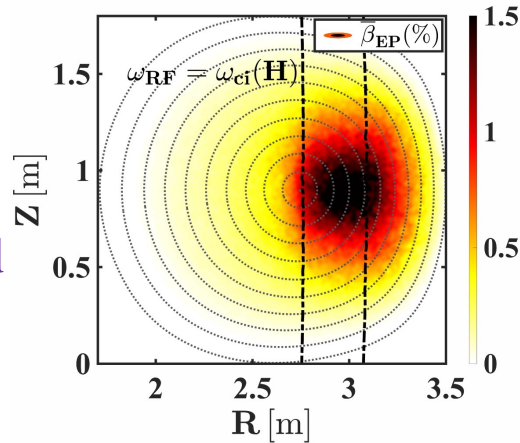
- EPs trapped in one outboard TAE get either **random kicks** (MEGA's operator: a random-phase kick at each pass through the layer) or **their mean** (same heating, no spread in velocity direction).
- With random kicks the trapped ions lose their bounded phase and slip out of the island (full RF, 18 MW: 25–45 % in 0.4–0.8 ms); with mean kicks none do.
- RF both restores the drive and detraps resonant ions; **its role in the timing of the release is not yet determined.**

- Background
- Extend MEGA with ICRF heating
- **First-principles simulations of ICRF-driven SAWs in tokamaks (slowing-down time scale)**
 - Bursting and non-bursting TAEs with different RF layer locations
 - Bursting and non-bursting TAE behaviors
 - Mechanism: resonant drive, energy storage and release, role of RF
 - **Suppressing bursting SAWs by ICRH phase-space engineering: preliminary results**
- Summary

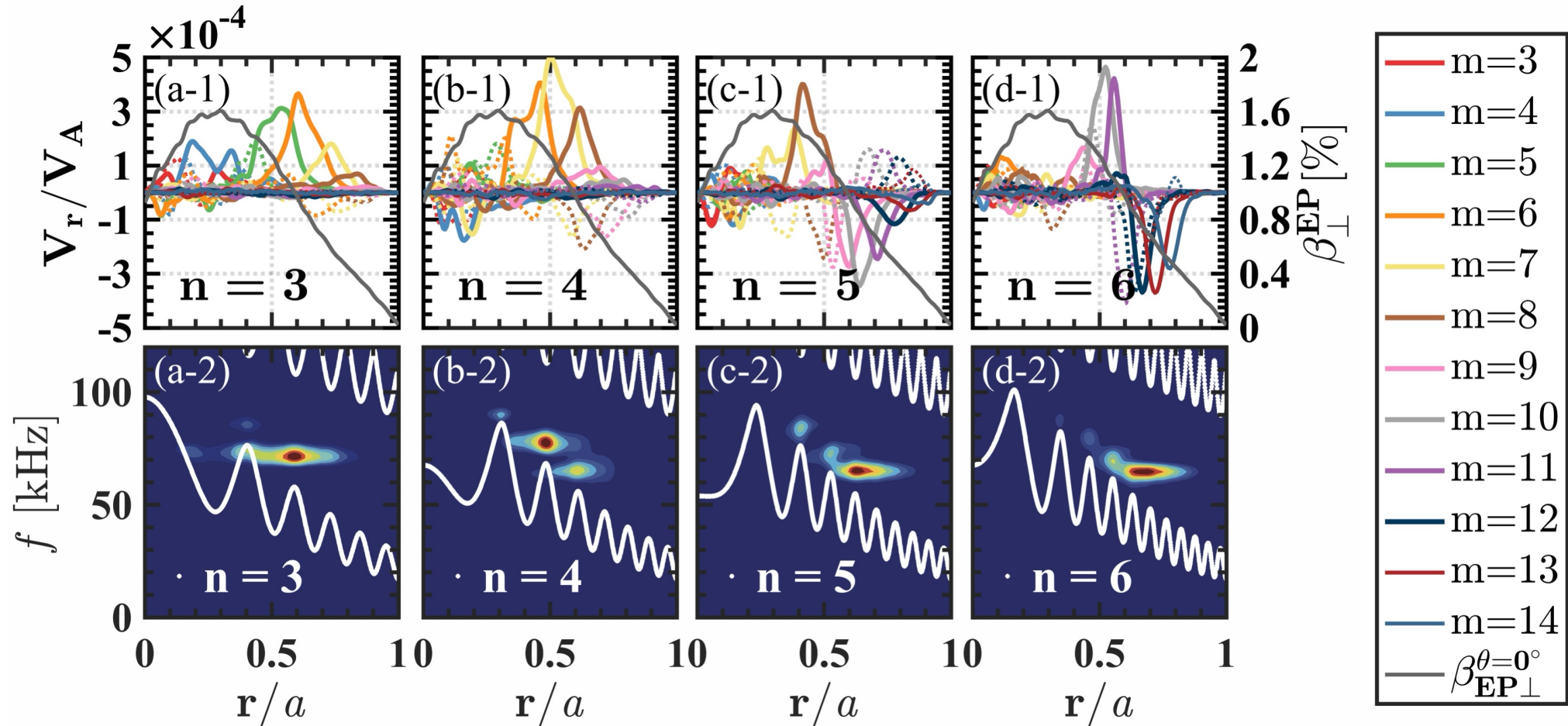
On-axis ICRH
with $P_{RF} = 6$ MW



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

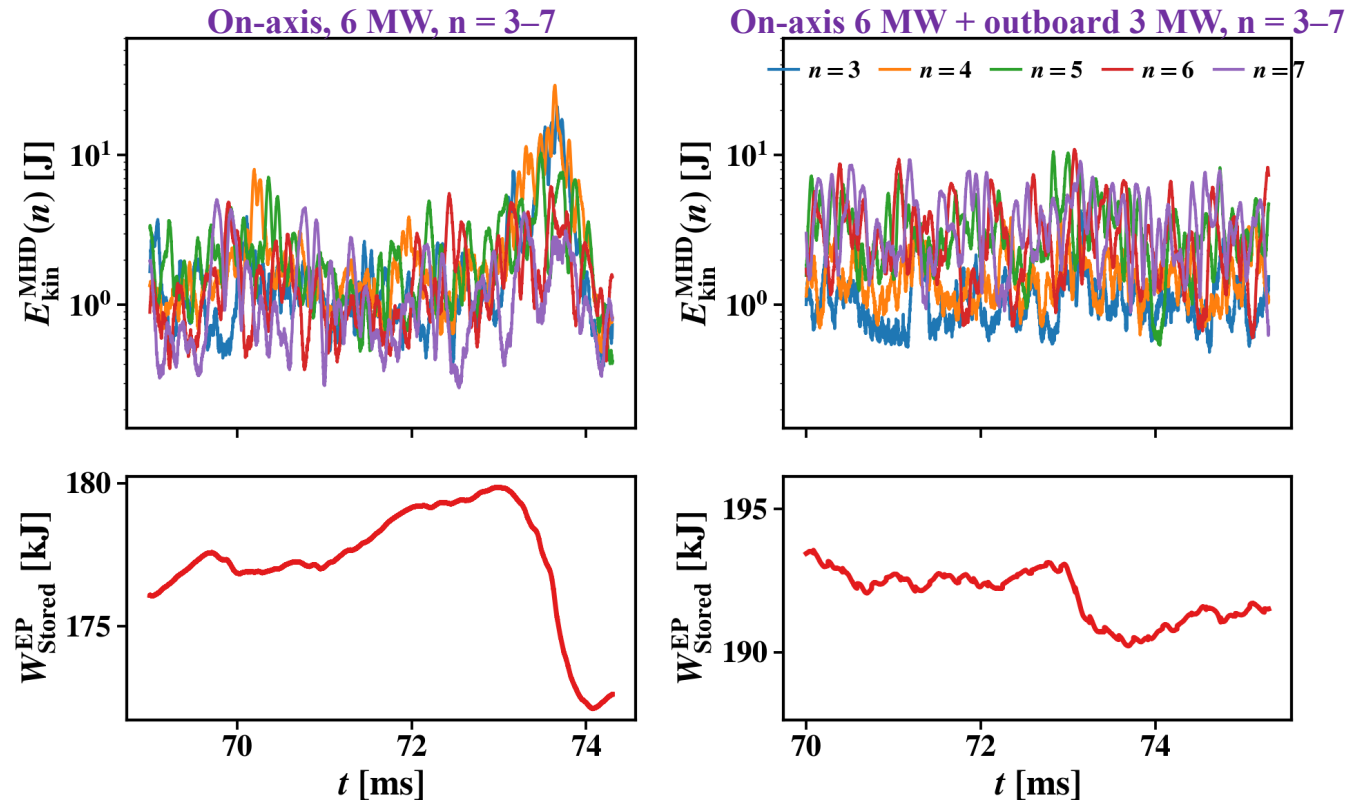


- On-axis ICRF bursts are **suppressed and replaced by non-bursting (grassy) SAWs** when a second outboard ICRF is applied.



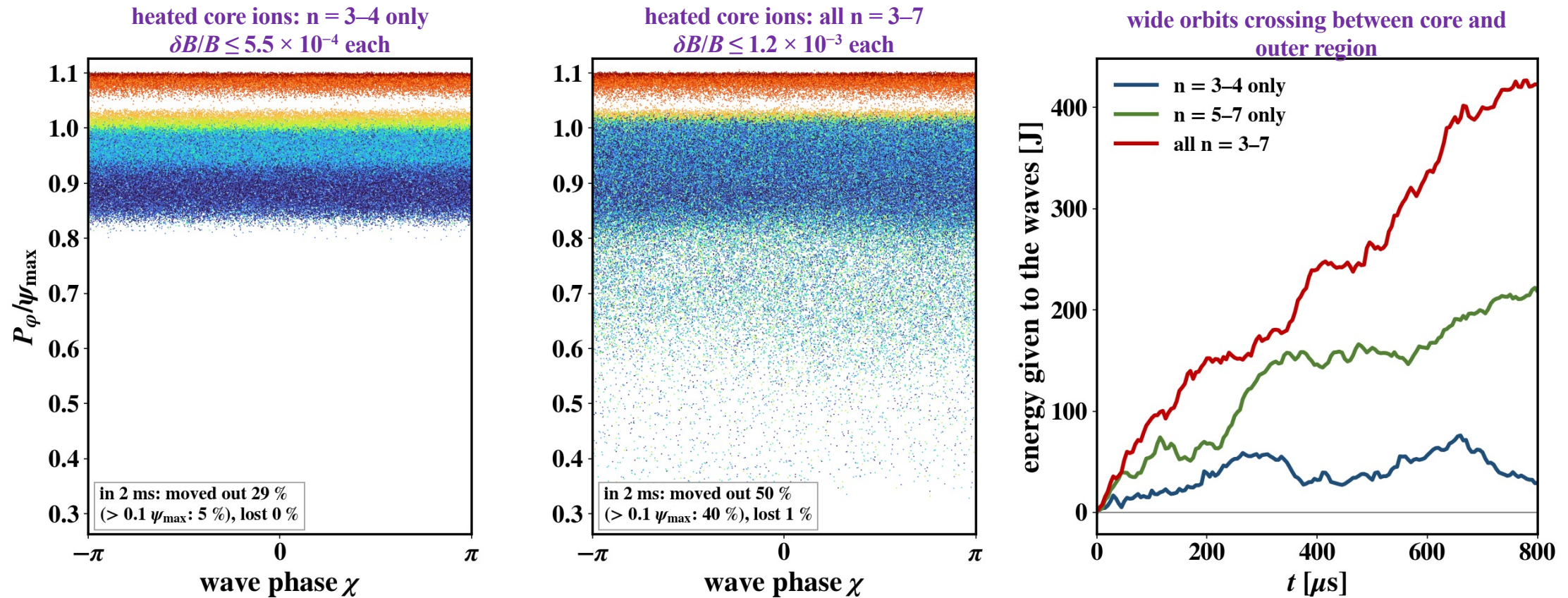
- Compared to the bursting TAEs under on-axis heating alone, the TAEs that were previously well-separated in radial and frequency spaces begin to smear out.

What changes with a second outboard ICRF



- On-axis RF alone: all harmonics stay low for ≈ 4 ms, then grow together, and the stored energy drops by 4 %.
- With 3 MW added outboard, the $n = 5-7$ AEs are always present and the stored energy fluctuates by less than 1 %.
- The added outboard source **changes the mode spectrum and how the stored energy is extracted**; the next slides test the role of the $n = 5-7$ AEs.

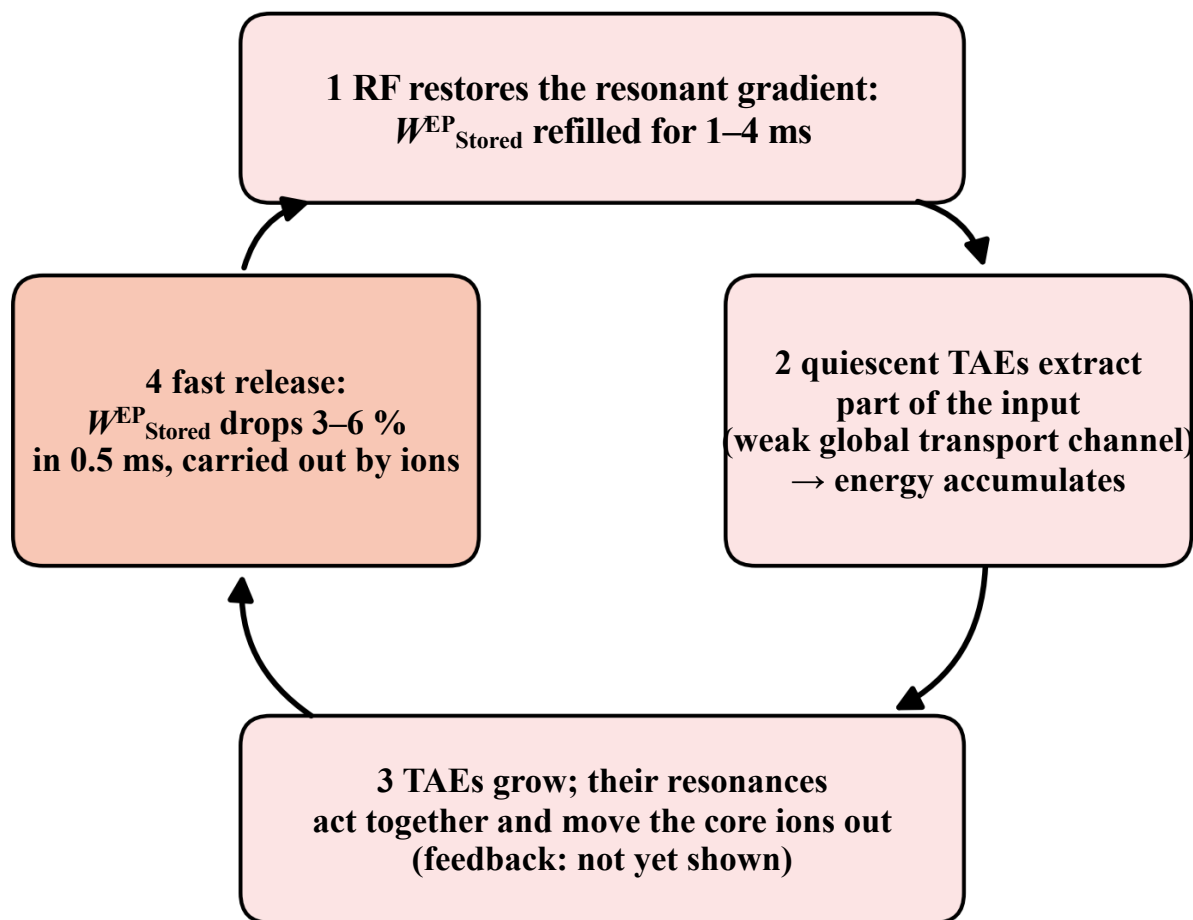
Wide orbits couple the core to the added outboard AEs



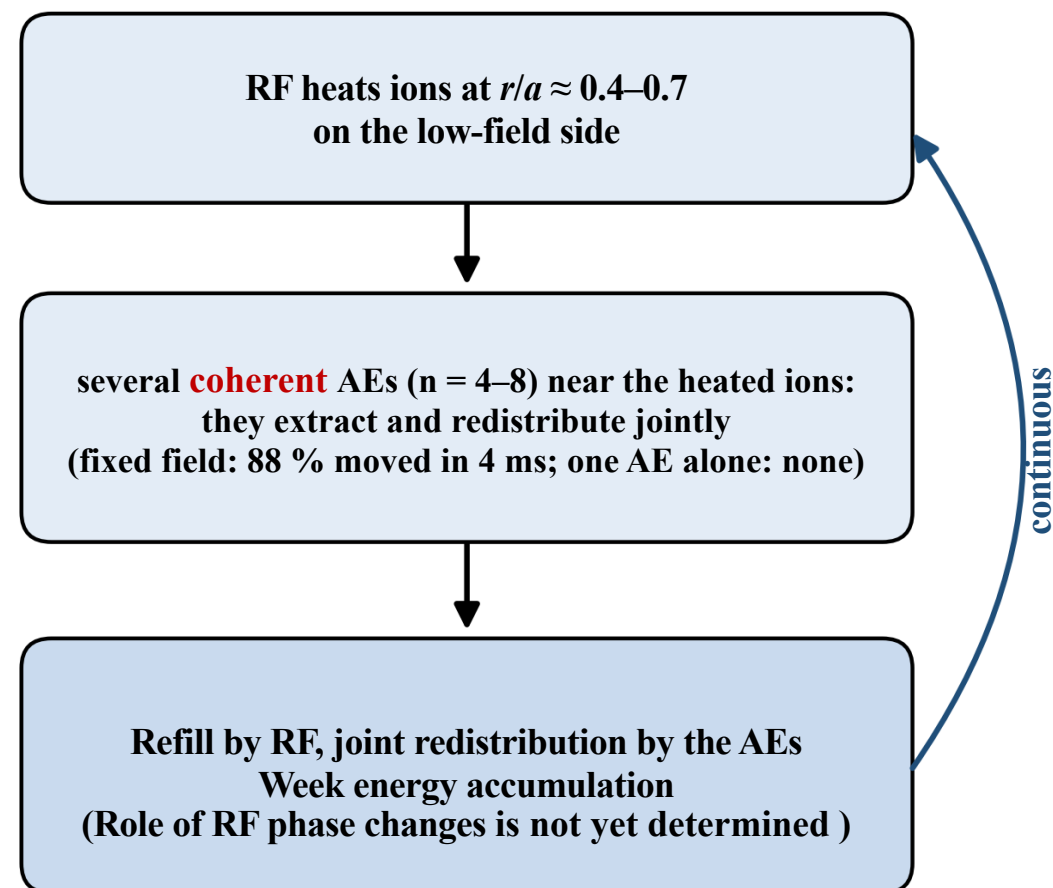
- Core ions in the combined run's modes: with $n=3-4$ only, 5 % move beyond $0.1 \psi_{\max}$; with all $n=3-7$, 40 % do.
- Ions on wide orbits crossing between core and outer region give the waves 423 J with all modes, 218 J with $n=5-7$, 29 J with $n=3-4$.
- Wide orbits and the persistent $n=5-7$ spectrum **take part in regulating the stored energy**

- MEGA was extended with a quasi-linear ICRF module for self-consistent SAW simulations on the slowing-down time scale, in tokamaks and stellarators.
- In a TFTR-like plasma, on-axis ICRH gives recurrent bursting TAEs, outboard ICRH steady TAEs; the TAE frequencies do not chirp.
- **Bursting** (on-axis, also inboard ICRH): the RF restores a resonant gradient, the stored EP energy is refilled for 1–4 ms and released within 0.5 ms, mainly by outward transport of energetic ions; **several discrete TAEs** acting together deplete the core much more than one.
- **Non-bursting** (outboard ICRH): the heated ions are trapped orbits on the low-field side; **several board coherent AEs** extract and redistribute their energy jointly, and the stored energy grows only in small steps without a concentrated release.
- RF restores the drive and, and detrap resonant ions through its randomness; its role in the release timing is being tested . A second outboard ICRF changes the mode spectrum; without the fast-ion drive of its $n = 5-7$ AEs, energy accumulates again.

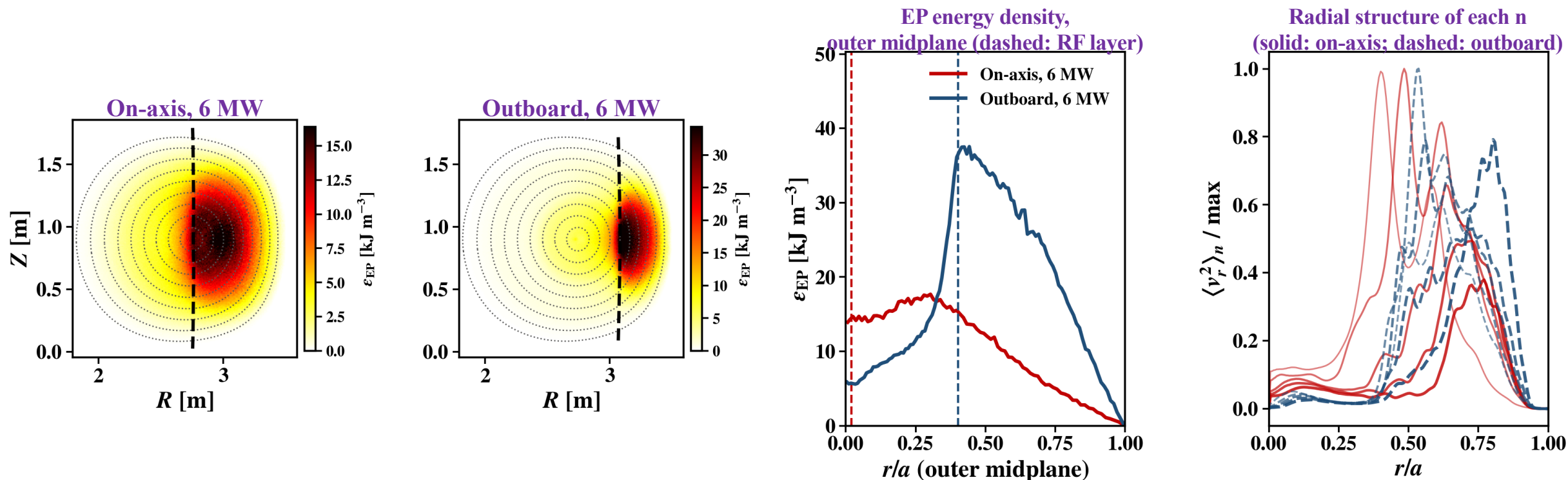
Bursting runs: slow refill, fast release



Outboard heating: no concentrated release

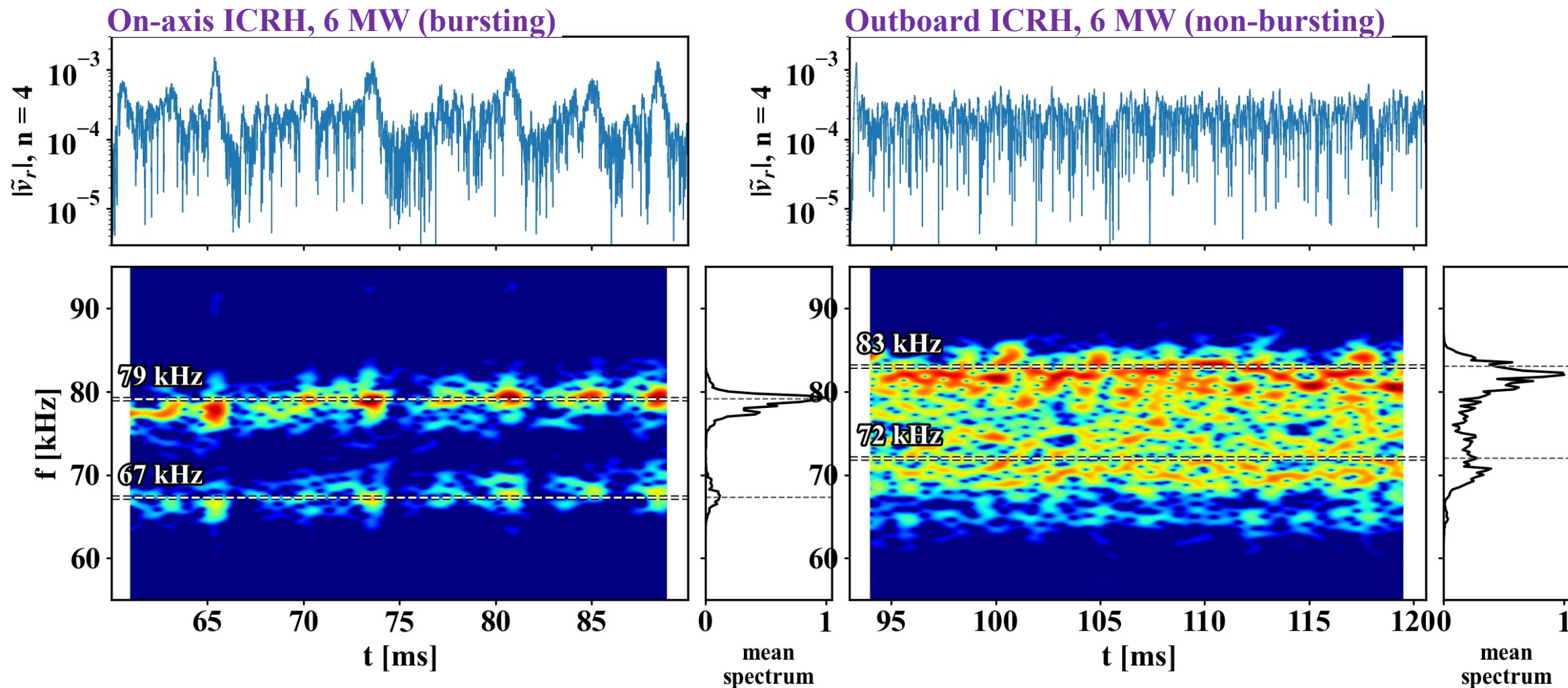


Thanks for your attention!



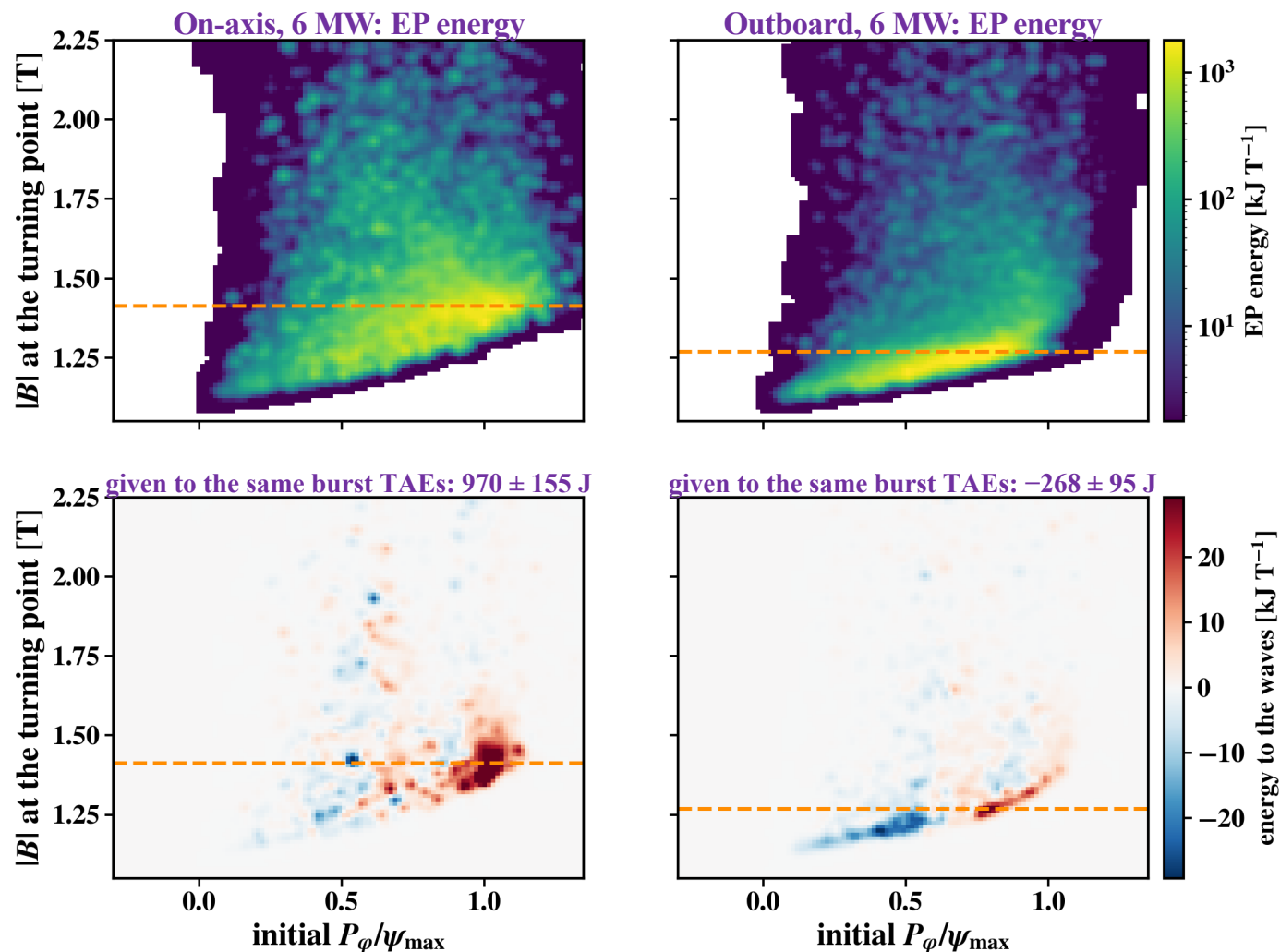
- On-axis ICRH heats ions at the axis; outboard ICRH heats trapped ions with turning points on the layer at $r/a \approx 0.4$ – 0.7 .
- Moving the layer changes the heated orbits, their resonances and the gradient, and the AE spectrum near the heated ions.
- The RF layer acts through **which orbits are heated and which resonant gradient they form**; the number of modes alone does not explain the difference.

Backup: why prescribed-field test particles work here



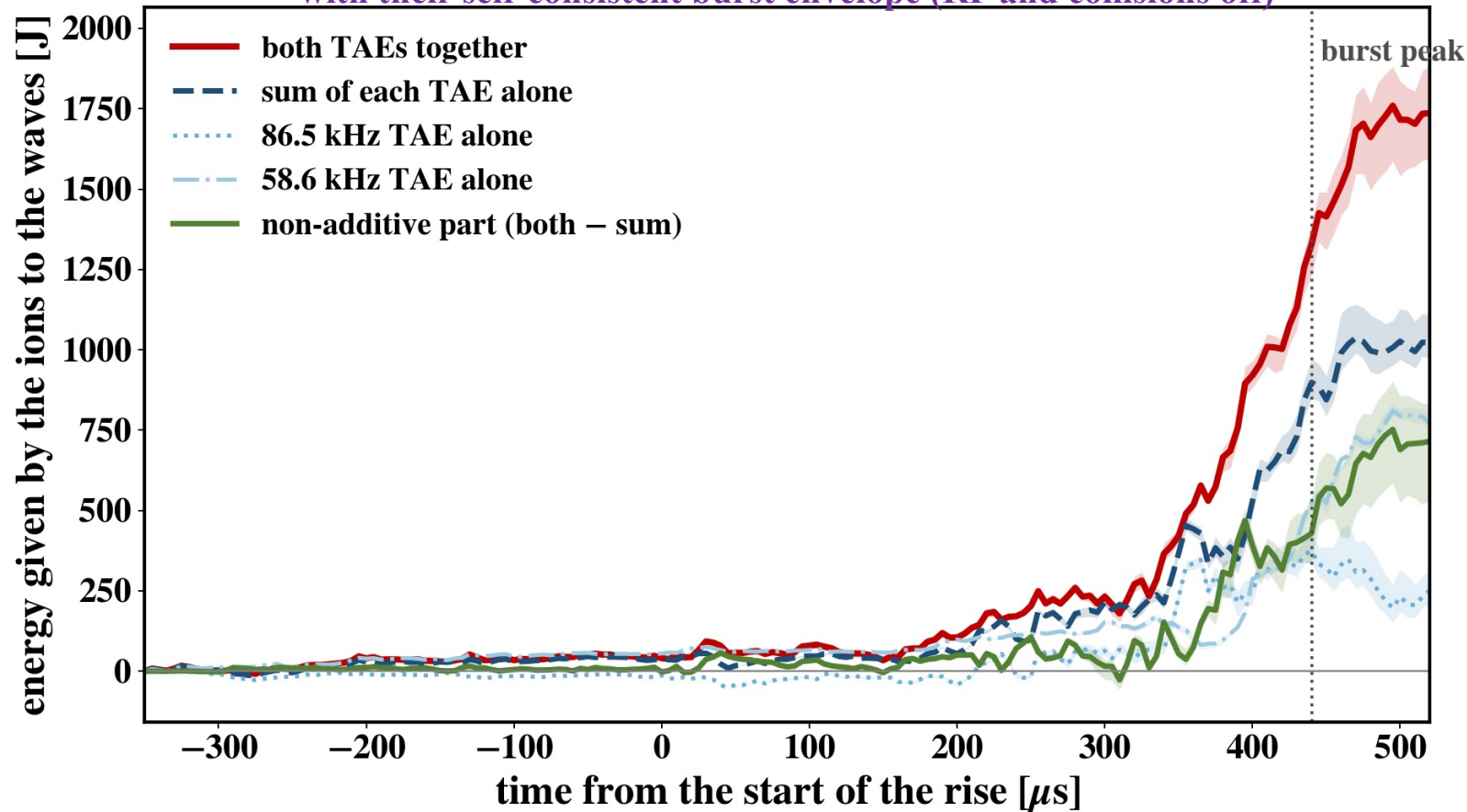
- The TAE frequencies do not chirp: **each TAE is a fixed (n, f) eigenmode**, so its fitted field can be replayed with test particles, one factor at a time.

Backup: exchanging the fast-ion populations



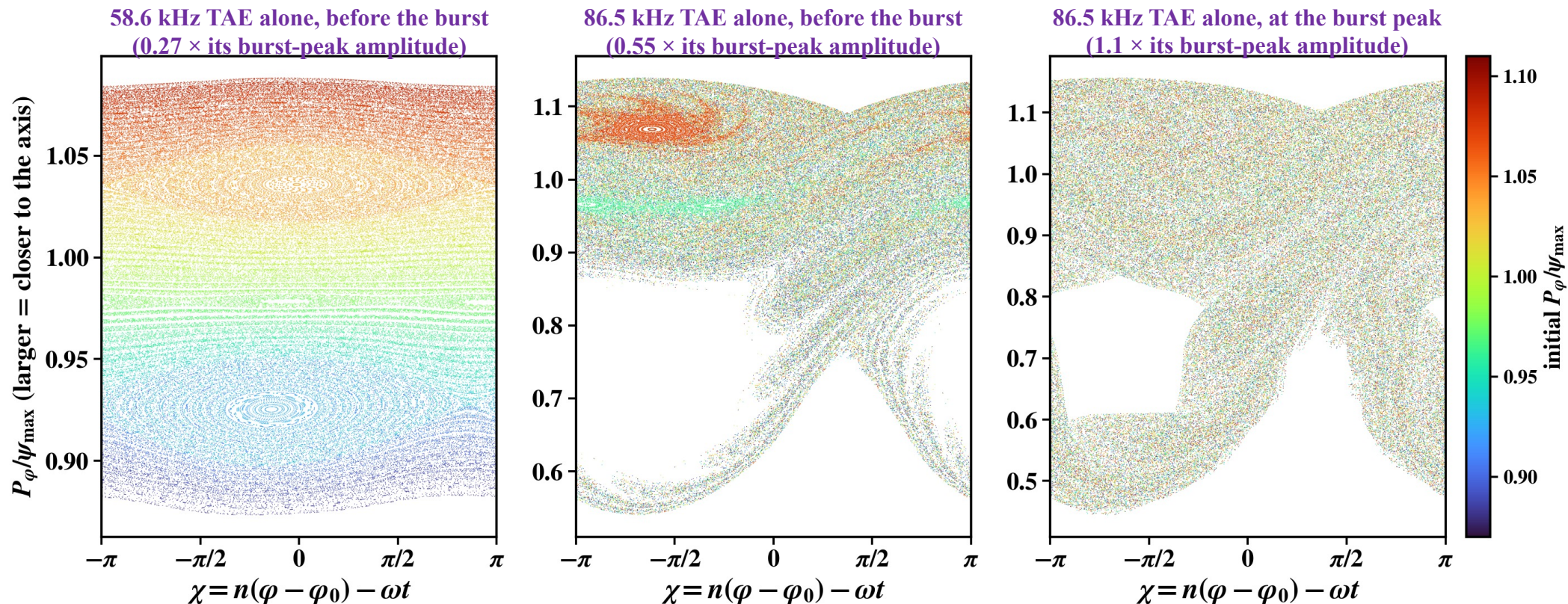
- The burst TAEs are driven by **core ions with turning points on the on-axis layer**; they take almost nothing from outboard ions.

On-axis, 6 MW, $n = 3$ family: the two burst TAEs
with their self-consistent burst envelope (RF and collisions off)



- A single TAE stops extracting before the peak; the two TAEs together keep extracting through the burst peak (prescribed envelope).

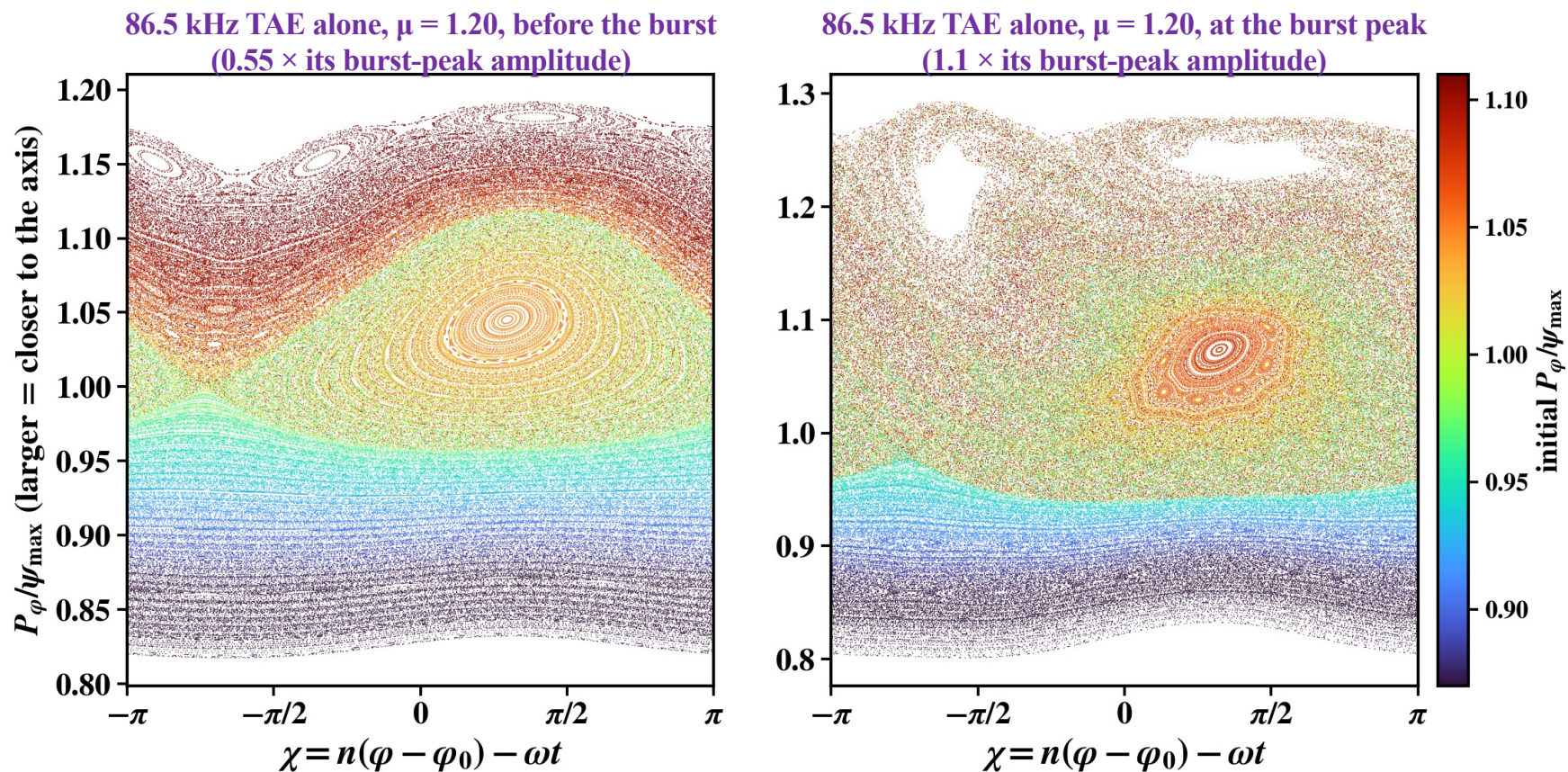
Backup: single-TAE sections at $\mu = 1.70$



Poincaré sections (θ -return) on one surface $E' = E - (\omega/n)P_\phi = \text{const}$ through the core, $\mu = 1.70$; each TAE alone; amplitude relative to its own amplitude at the self-consistent burst peak

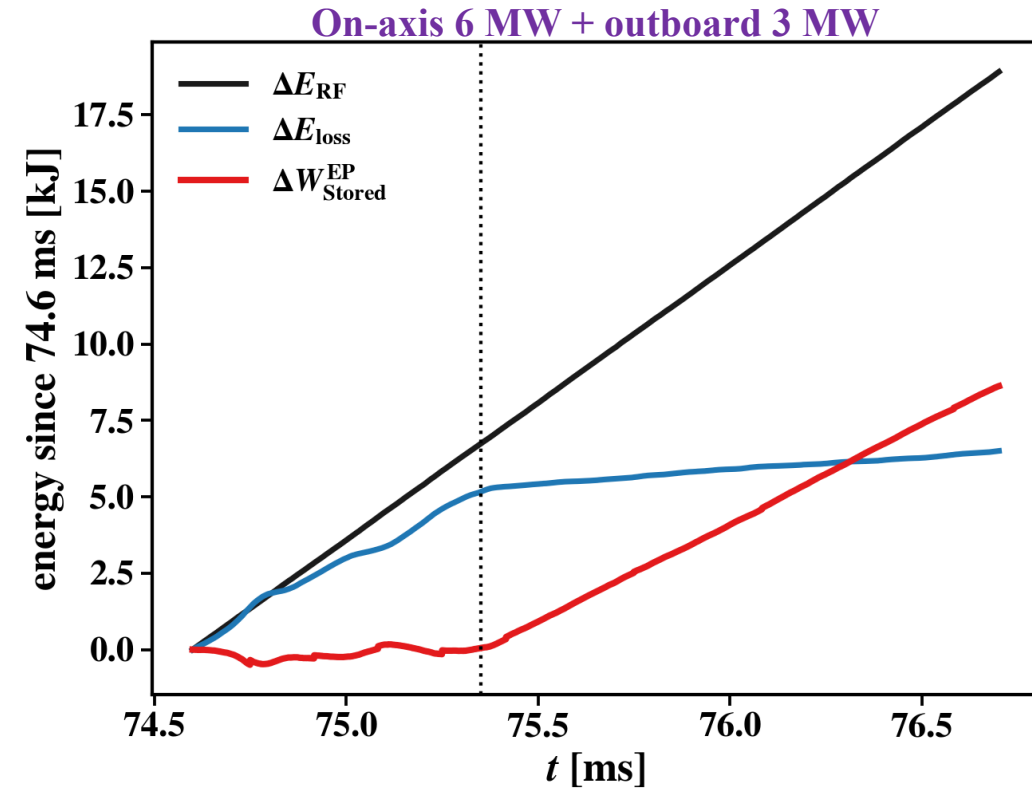
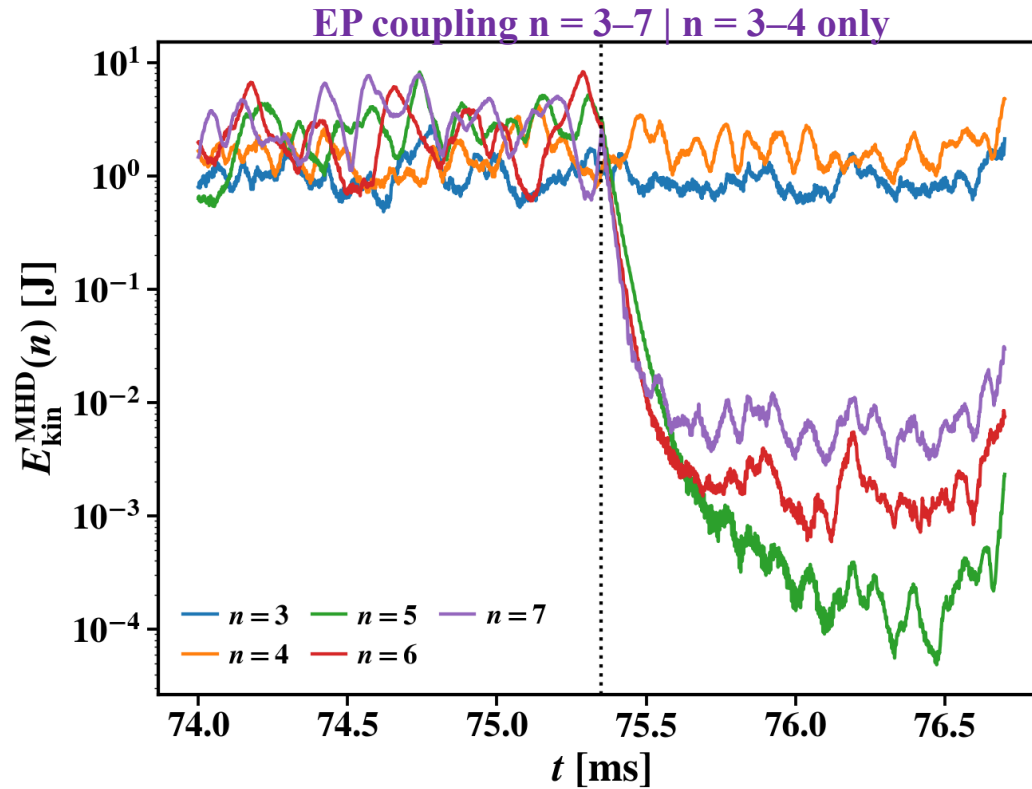
- Before the burst the outer TAE has **separated island chains**; the core TAE has overlapping islands in the core that connect outward only through narrow tongues.
- **At the burst-peak amplitude the core TAE opens a broad stochastic region from the core ($P_\phi/\psi_{\max} \approx 1.15$) out to ≈ 0.45 .** At $\mu = 1.20$ a stochastic region also opens at the burst peak but stays at $P_\phi/\psi_{\max} \gtrsim 0.95$ (backup).

Backup: core sections at $\mu = 1.20$



- Before the burst the island chains are separated and most of the surface is regular.
- **At the burst-peak amplitude a stochastic region opens as for $\mu = 1.70$, but it stays at $P_\phi/\psi_{\text{max}} \gtrsim 0.95$ and does not reach out to ≈ 0.45 . The widest channel is in the μ band that releases most energy in the self-consistent burst.**

Restart with fast-ion feedback kept only for $n = 3-4$



- With the fast-ion feedback kept only for $n = 3-4$, the $n = 5-7$ modes decay by 3–4 orders of magnitude within 0.2 ms.
- Same RF input: the loss falls from 0.77 to 0.11 of the RF power, and the stored energy rises by 4.5 % in 1.35 ms.
- Without the drive of the $n = 5-7$ AEs **the energy accumulates again.**