Energetic-Ion-Driven MHD Instab. & Transport: Simulation Methods, V&V and Predictions

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QST

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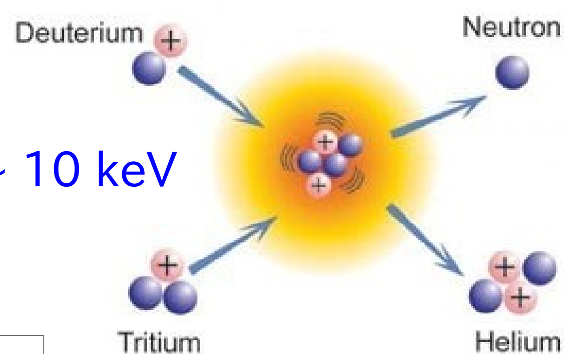
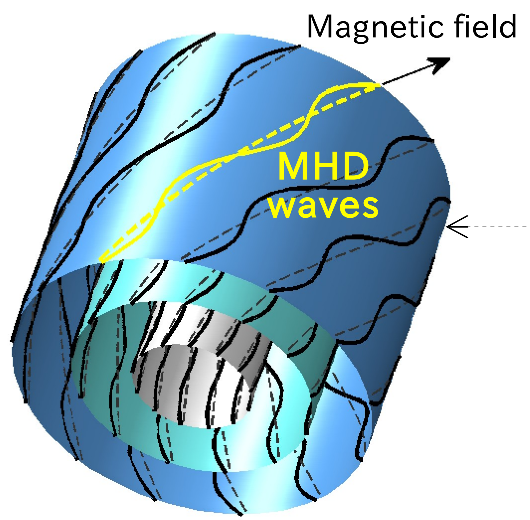
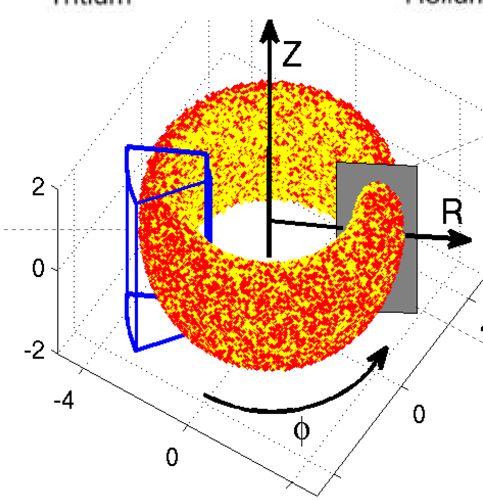
IFERC-CSC

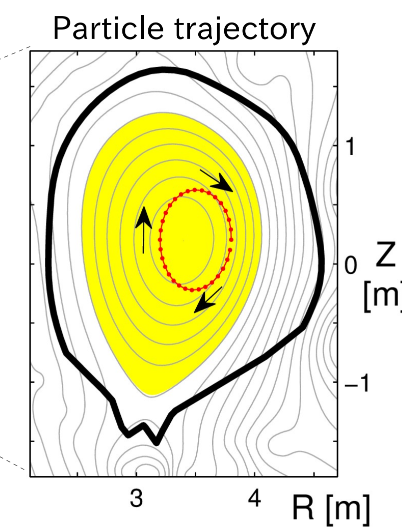
PLASMA SIMULATOR

06 Post-K Priority Issue 6









Bulk plasma (fusion fuel)

MHD fluid model

Current J, Pressure P

Interactions

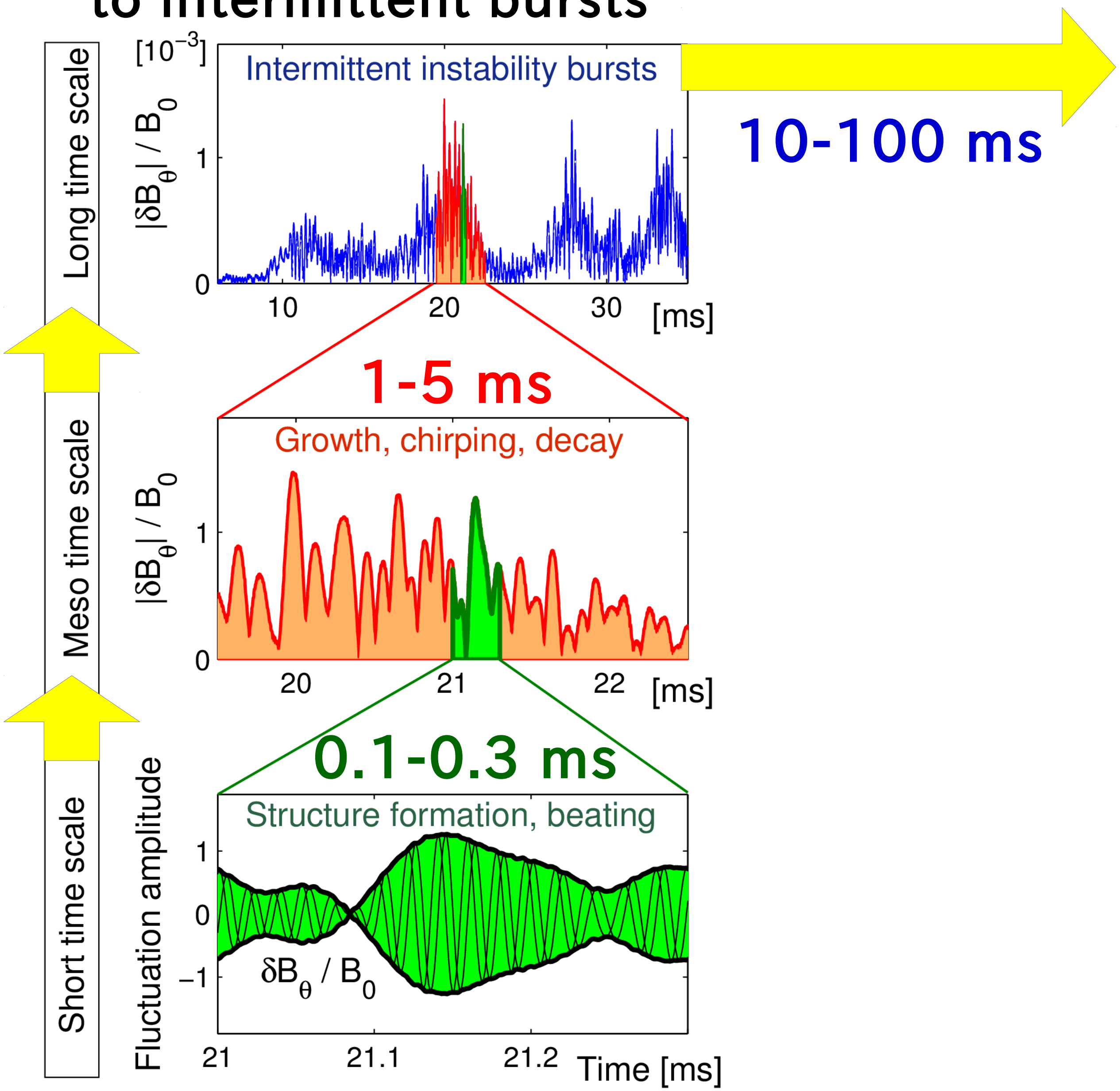
EM fields E, B

Energetic particles “EP” (fusion α, beams, heating)

Kinetic model

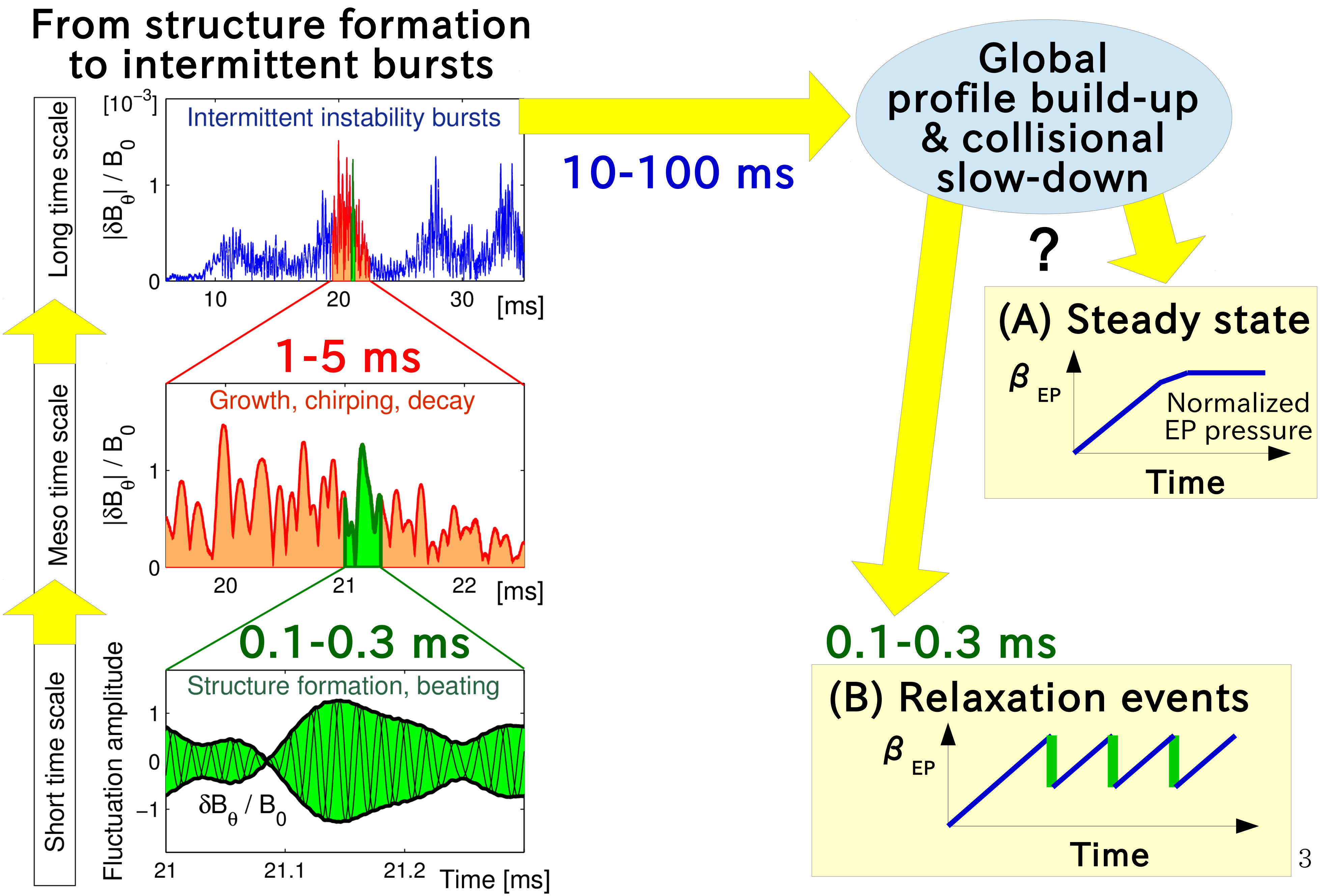
Interplay of MHD and EP dynamics on multiple time scales

From structure formation to intermittent bursts



Global profile build-up & collisional slow-down

Interplay of MHD and EP dynamics on multiple time scales



1. Hybrid model (MEGA code)

MHD-kinetic hybrid model
with collisions, sources & sinks
for multi-time-scale simulations

Contents:

MEGA code: Multi-time-scale hybrid model (0.01-100 ms)

Bulk plasma: MHD model

(t): 4th-order Runge Kutta, $\Delta t_{mhd} \approx 1$ ns

(R, ϕ, Z): finite differences, non-slip b.c.

$$\frac{\partial \rho_b}{\partial t} = -\nabla\cdot(\rho_b \delta \boldsymbol{u}_b), \qquad \mu_0 \boldsymbol{J} = \nabla\times\boldsymbol{B}$$

$$\rho_b \frac{\partial \boldsymbol{u}_b}{\partial t} = -\rho_b \boldsymbol{u}_b\cdot\nabla \boldsymbol{u}_b - \nabla p_b + (\boldsymbol{J} - \boldsymbol{J}_{h,eff})\times\boldsymbol{B} - \left[\nabla\times(\nu\rho_b\nabla\times\boldsymbol{u}_b) + \frac{4}{3}\nabla(\nu\rho_b\nabla\cdot\boldsymbol{u}_b)\right]$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla\times\boldsymbol{E}, \qquad \boldsymbol{E} = -\boldsymbol{u}_b\times\boldsymbol{B} + \eta\delta\boldsymbol{J}$$

$$\frac{\partial p_b}{\partial t} = -\nabla\cdot(p_b \boldsymbol{u}_b) - (\Gamma - 1)\left[p_b\nabla\cdot\boldsymbol{u}_b + \eta(\boldsymbol{J} - \boldsymbol{J}_{h,eff})\cdot\delta\boldsymbol{J}\right] + \nu\rho_b(\Gamma-1)\left[(\nabla\times\boldsymbol{u}_b)^2 + \frac{4}{3}(\nabla\cdot\boldsymbol{u}_b)^2\right] + \chi\nabla^2 p_b$$

$\boldsymbol{J}_{h,eff}$

Gyro-avg.

$\boldsymbol{B}, \boldsymbol{E}$

Energetic ions: Kinetic model

(t): 4th-order Runge Kutta, $\Delta t_{pic} \geqq \Delta t_{mhd}$

(f_{gc}): PIC, δf or full-f guiding center distribution

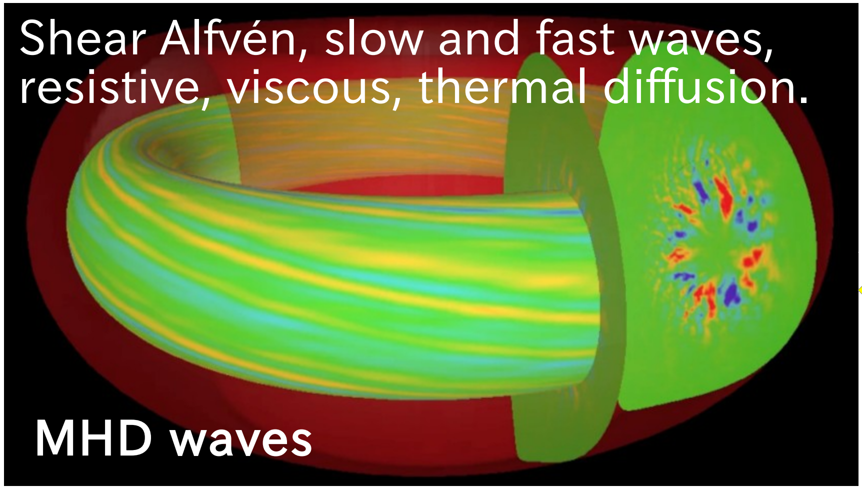
$$\frac{d\boldsymbol{R}_{gc}}{dt} = \overbrace{-\frac{\mu}{qB^*}\nabla B\times\hat{\boldsymbol{b}}}^{\boldsymbol{v}_B} + \overbrace{\frac{v_\parallel}{B^*}(\boldsymbol{B} + \rho_\parallel B\nabla\times\hat{\boldsymbol{b}})}^{\boldsymbol{v}_\parallel^*} + \overbrace{\frac{\boldsymbol{E}\times\hat{\boldsymbol{b}}}{B^*}}^{\boldsymbol{v}_E^*} \equiv \boldsymbol{U}_{gc}$$

$$m v_\parallel \frac{dv_\parallel}{dt} = \boldsymbol{v}_\parallel^*\cdot(q\boldsymbol{E} - \mu\nabla B)$$

$$\frac{d\mu}{dt} = 0 + O(\beta\epsilon_\delta) \text{ with } \epsilon_\delta \sim \frac{\rho_\perp}{L_B} \sim \frac{\omega}{\Omega_L} \ll 1$$

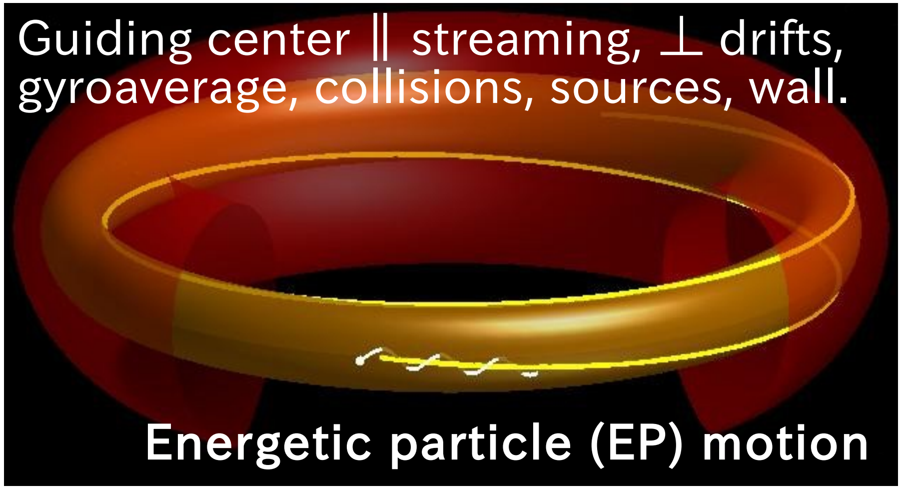
$$\mu \equiv \frac{m v_\perp^2}{2B}, \quad \rho_\parallel \equiv \frac{v_\parallel}{\omega_L}, \quad B^* \equiv B\left[1 + \rho_\parallel \hat{\boldsymbol{b}}\cdot(\nabla\times\hat{\boldsymbol{b}})\right], \quad \hat{\boldsymbol{b}} \equiv \frac{\boldsymbol{B}}{B}$$

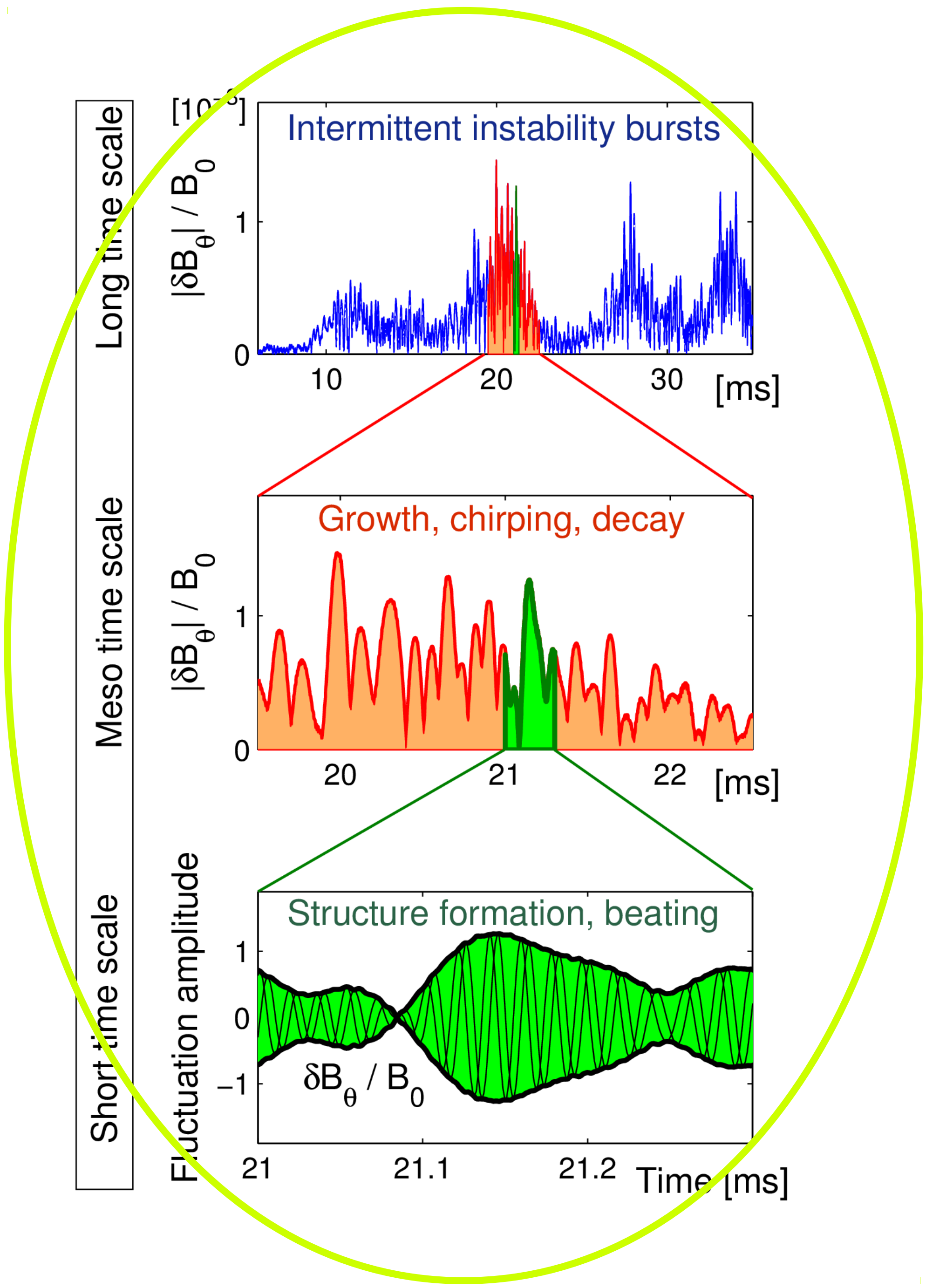
$$v'_\parallel = \frac{v_\parallel}{v}(v + \Delta v_L) + \frac{v_\perp}{v}\Delta v_T \sin\Omega, \quad v'_\perp = \sqrt{(v_L + \Delta v_L)^2 + \Delta v_T^2 - (v'_\parallel)^2}$$



Wave-particle inter-actions

(0.01-100 ms)





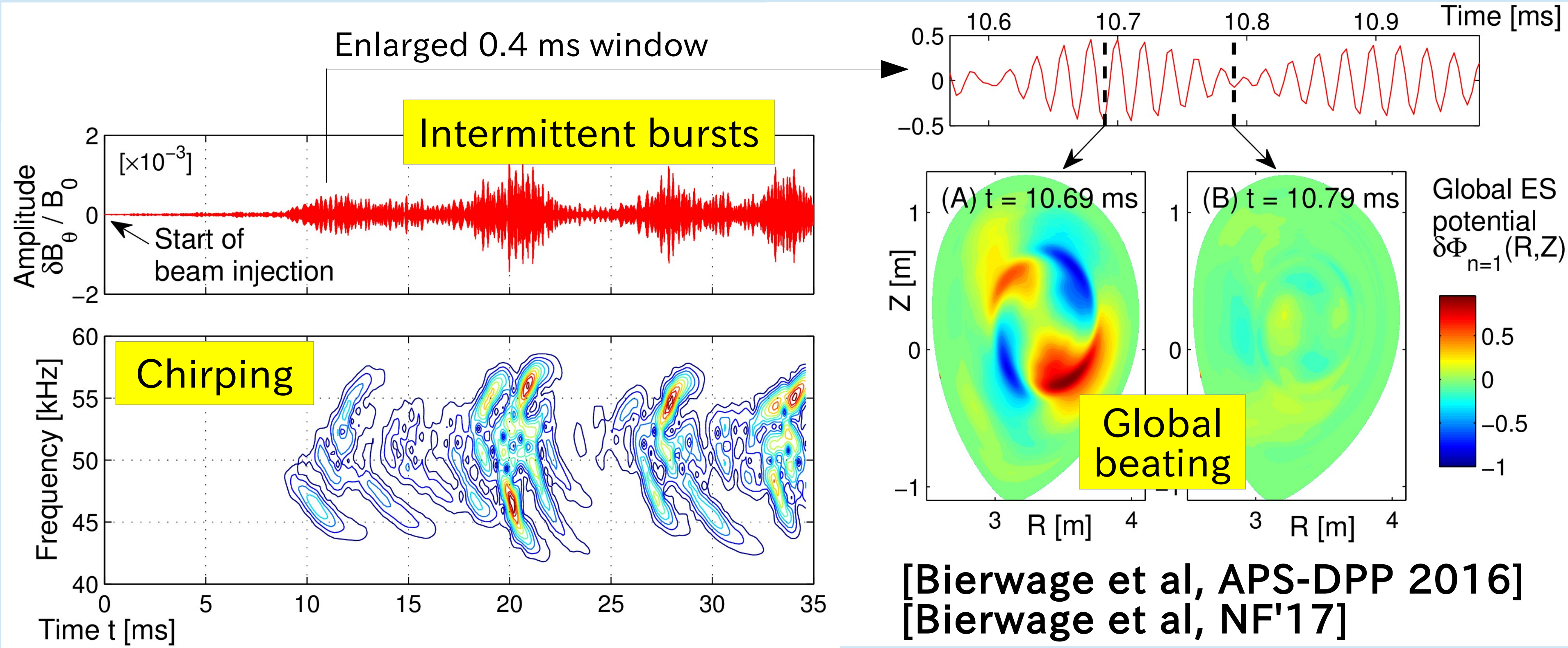
2. Multi time scale:

Short and long time scale dynamics self-consistently linked on meso time scale

Contents:

Simulation of multiple bursts of chirping modes in JT-60U

Self-consistent simulation including MHD, realistic EP source and collisions.

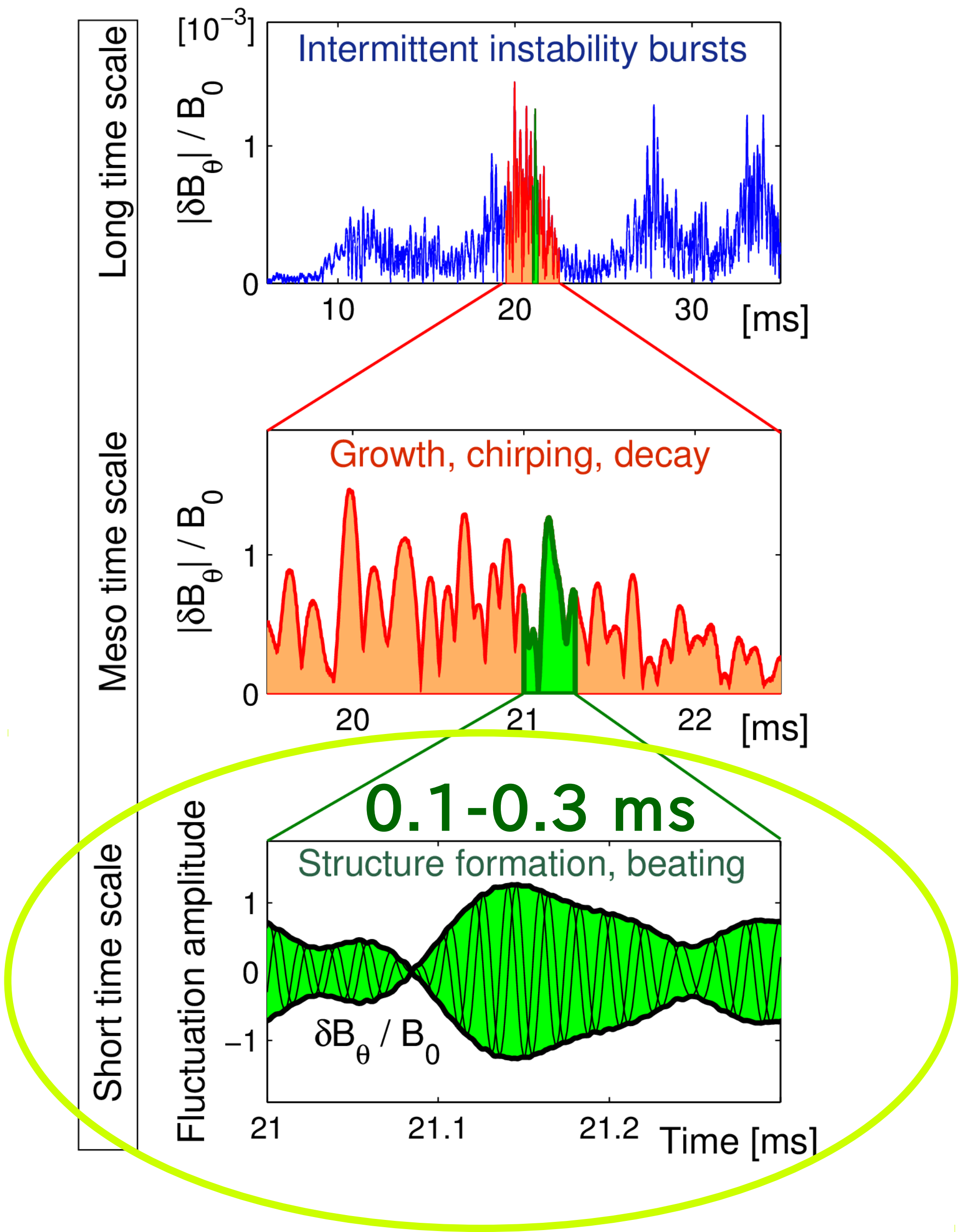


[Bierwage et al, APS-DPP 2016]
[Bierwage et al, NF'17]

Reproduced: Experimentally observed EP-driven Alfvén modes with burst periods of 5-10 ms, chirping on 1 ms scale, and global beating on 0.1-0.3 ms scale.

→ Successful validation (qualitatively, quantitatively, on multi-t scales)
→ Enables to clarify underlying physics numerically ··· but expensive:

- Took 40 days on 4096 cores (Helios) to simulate 35 ms with Δt=1 ns time steps.



3. Short time scale:

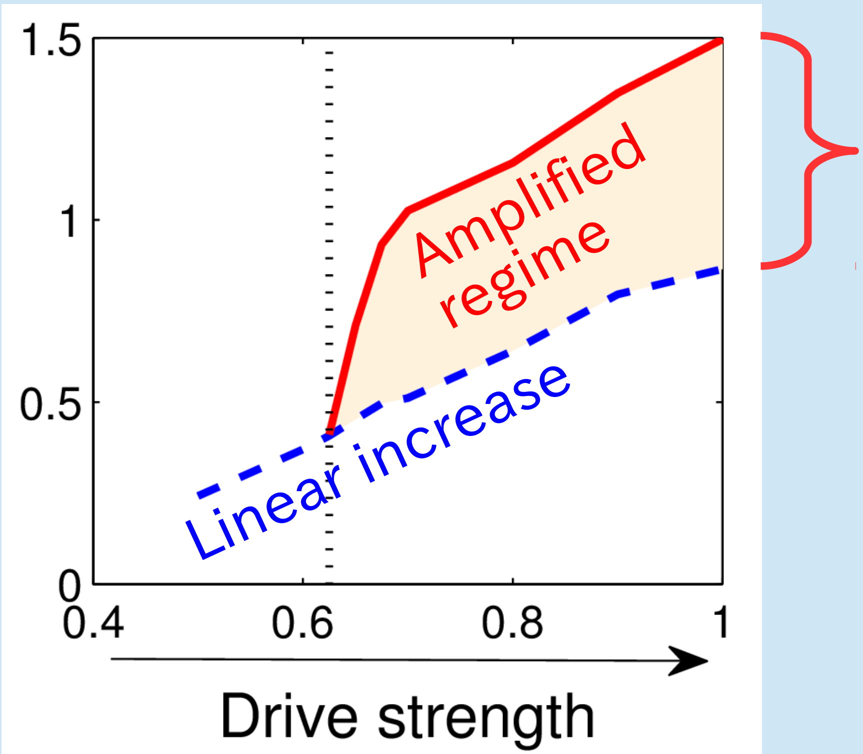
Stability and plasma response

Contents:

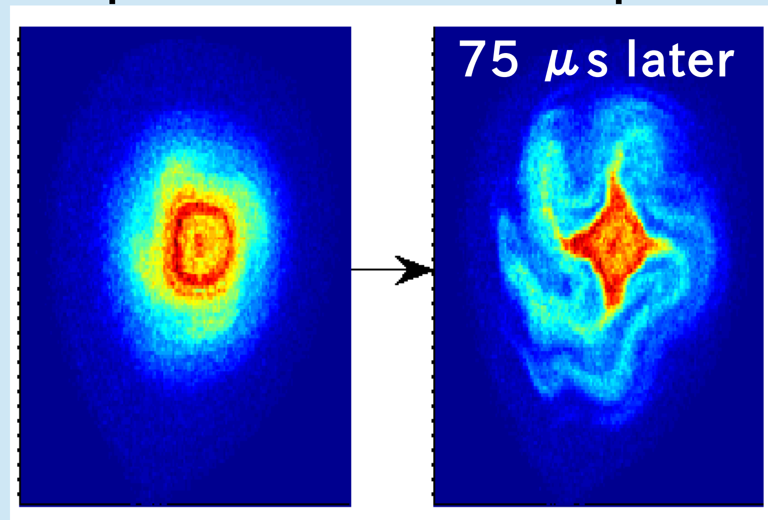
Transition from weak to strong EP transport in JT-60U

[Bierwage et al, NF'14, NF'16]

Peak amplitude of EP-driven n=3 shear Alfven waves as function of drive strength:



EP pressure field in R-Z plane:



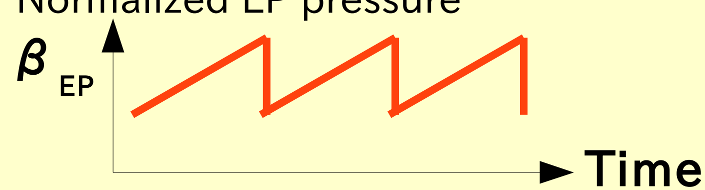
Demonstrated:

Possibility of distinct transitions from weak to strong EP transport …

… even for a long-wavelength mode with single toroidal harmonic (n=3).

Potential relevance:

This may play a role in triggering relaxation events (EP avalanches).

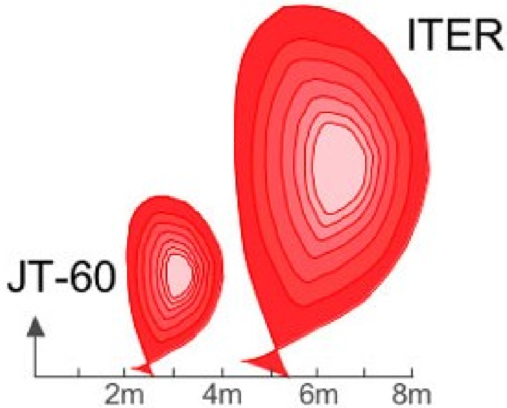


Predict Alfvén mode excitation and EP transport in ITER

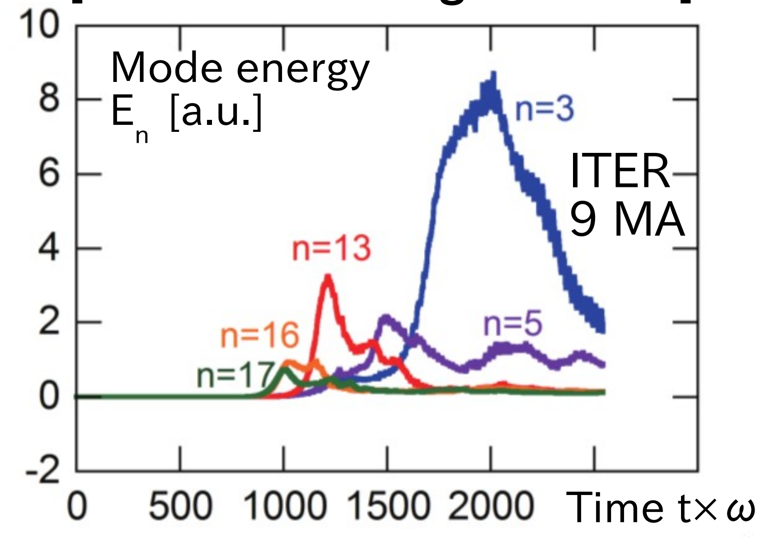
3D global simulation of ITER-scale plasmas are highly demanding computationally.

↓

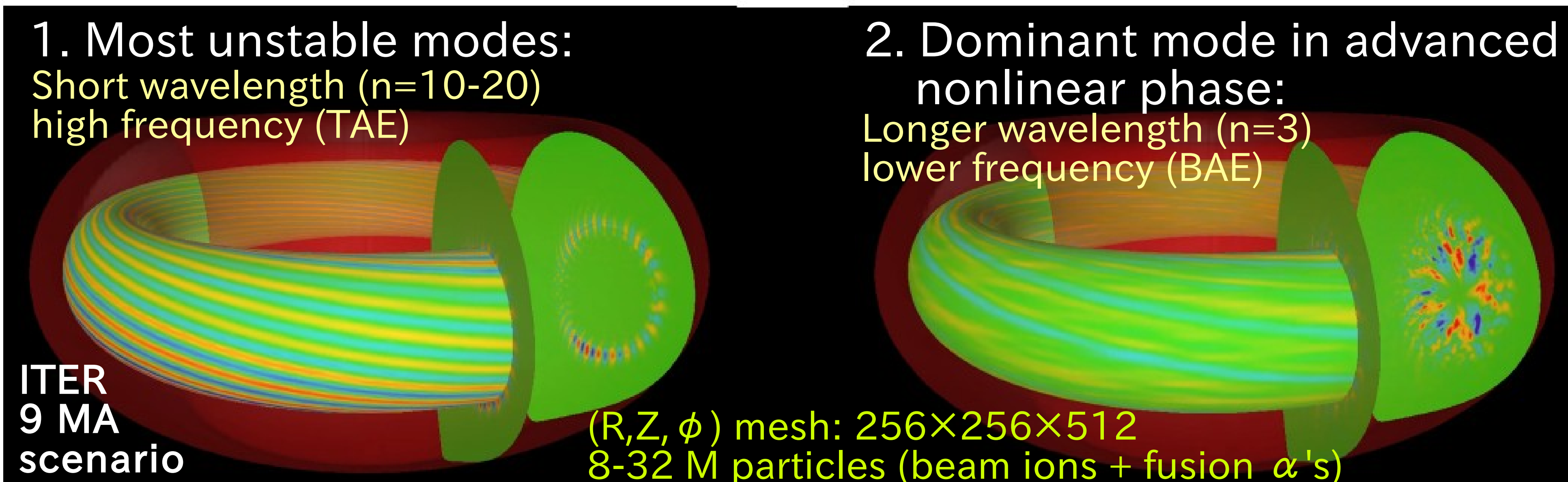
Only short time window simulated with MEGA.



[Todo & Bierwage PFR'14]

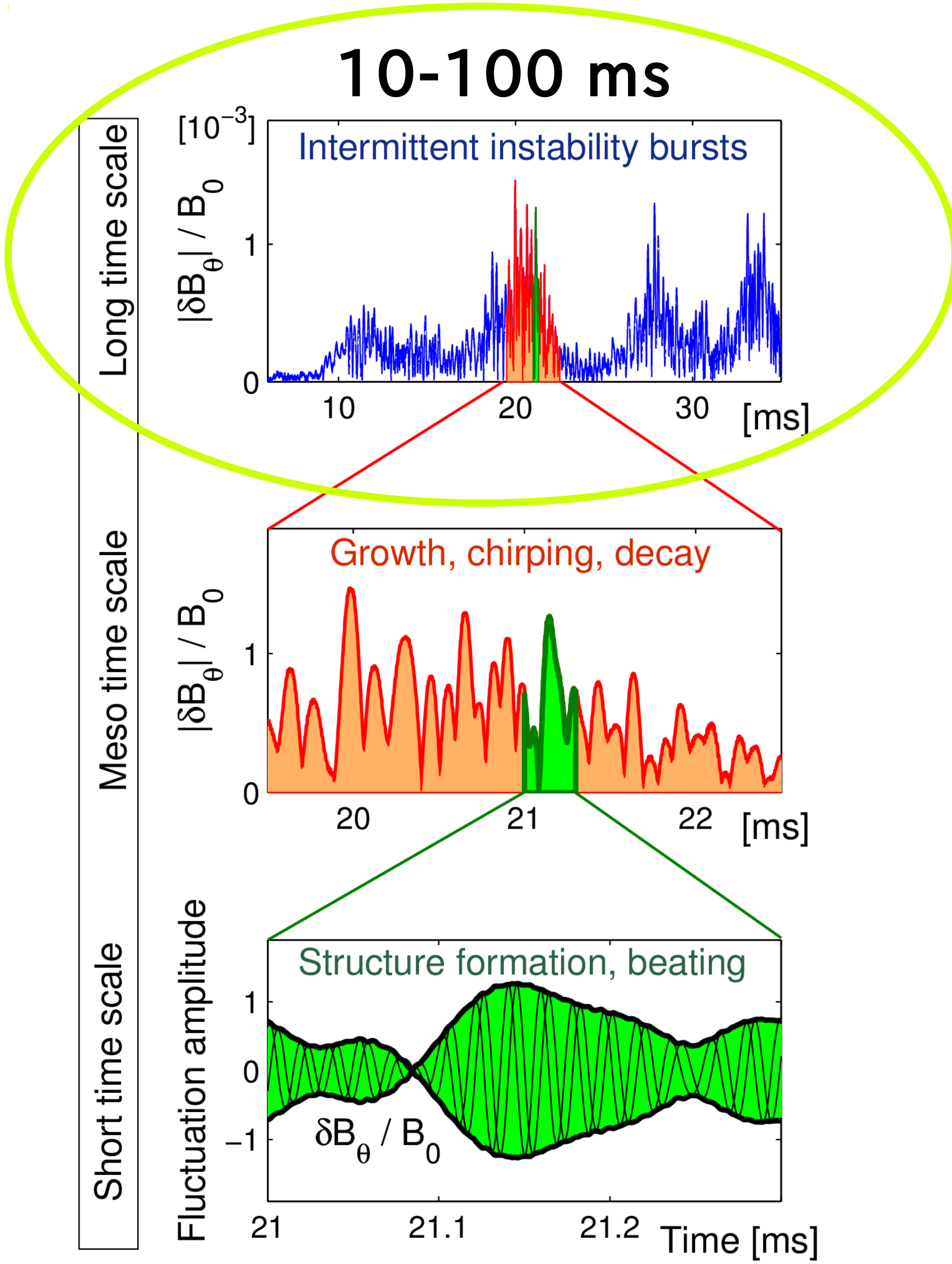


Prediction: Resonant modes cause benign or negligible EP transport



→ Encouraging result for ITER ...

... but remains to be verified, because initial EP profiles were not computed self-consistently.



4. Long time scale:

Confinement of energetic particle subject to ...

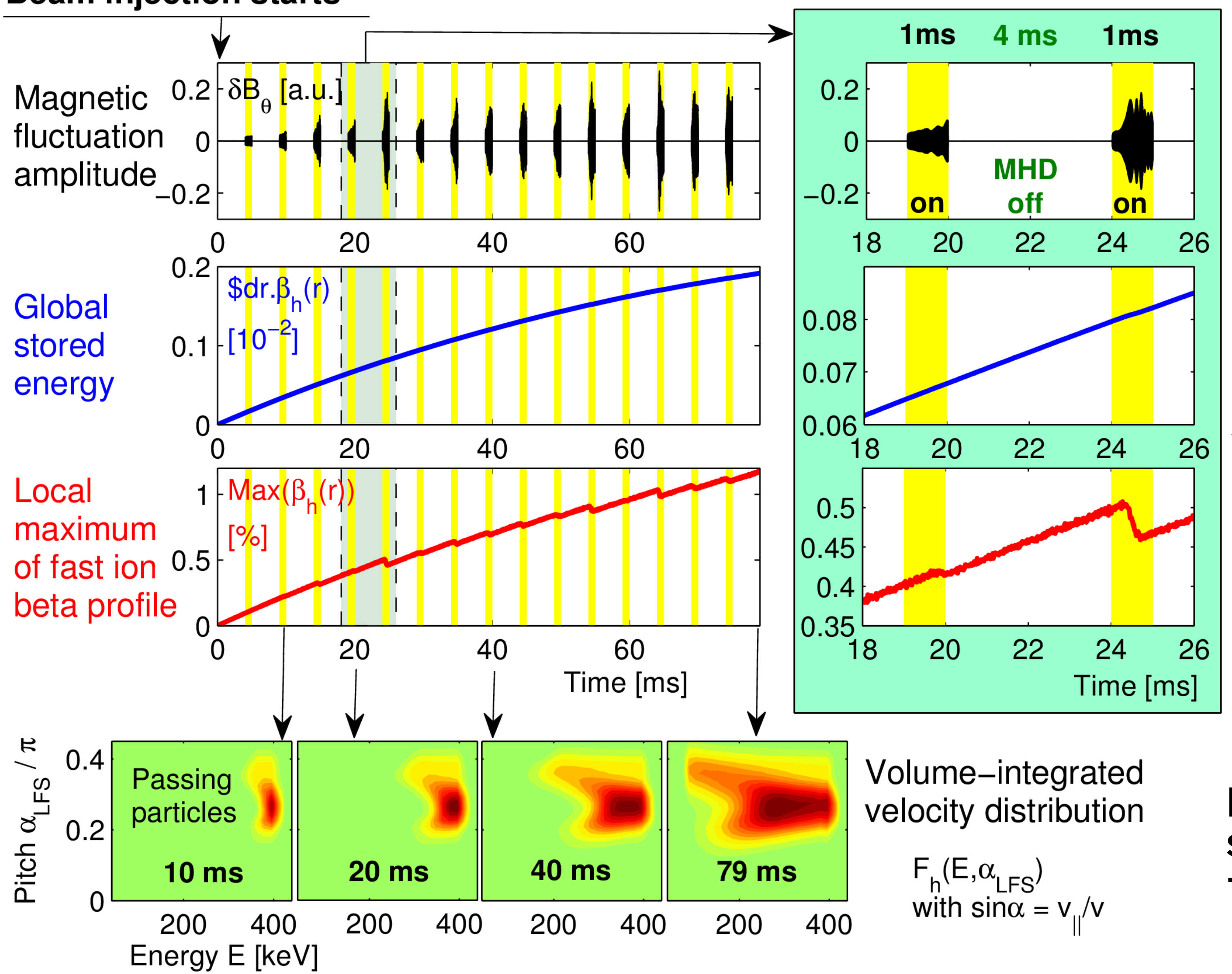
(A) steady fluctuations,
(B) large relaxation events

Contents:

“Multi-phase” method for long-time simulations [Todo NF'14]

Interlaced classical (no MHD) and hybrid (with MHD) simulation phases.

→ Speed-up by × (2⋯5) gives access to long time scale of steady-state formation (> 50 ms).



Example: JT-60U with 5 MW of N-NBI at 400 keV

Benchmark study submitted to CPC.
→ See poster.

Application of multi-phase method

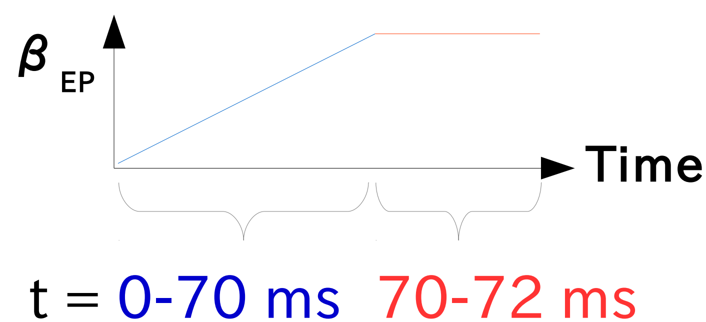
(A) Steady moderate Alfvénic fluctuations in DIII-D tokamak (General Atomics, San Diego, USA)

[Todo et al, NF'15]

4 ms	1 ms	4 ms	1 ms		4 ms	1 ms	4 ms	Continuous
Classical	Hybrid	Classical	Hybrid	…	Classical	Hybrid	Classical	Hybrid …

t=0: Start of beam injection

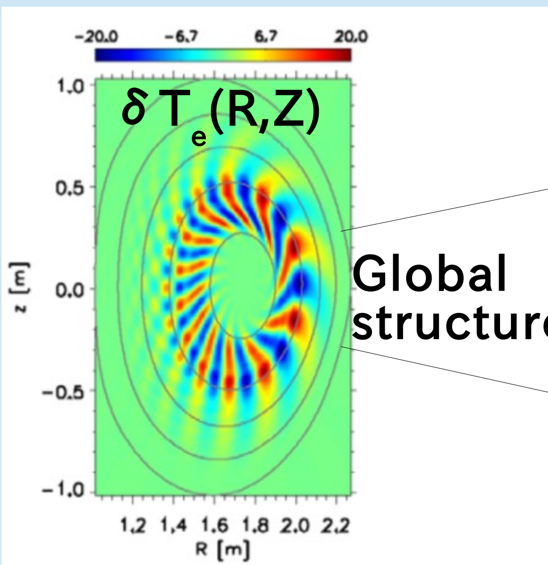
t≈70 ms: Reached steady state



(A) Steady moderate Alfvénic fluctuations in DIII-D tokamak

Comparison between self-consistently simulated δT_e fluctuations and ECE measurements in beam-driven DIII-D tokamak plasma:

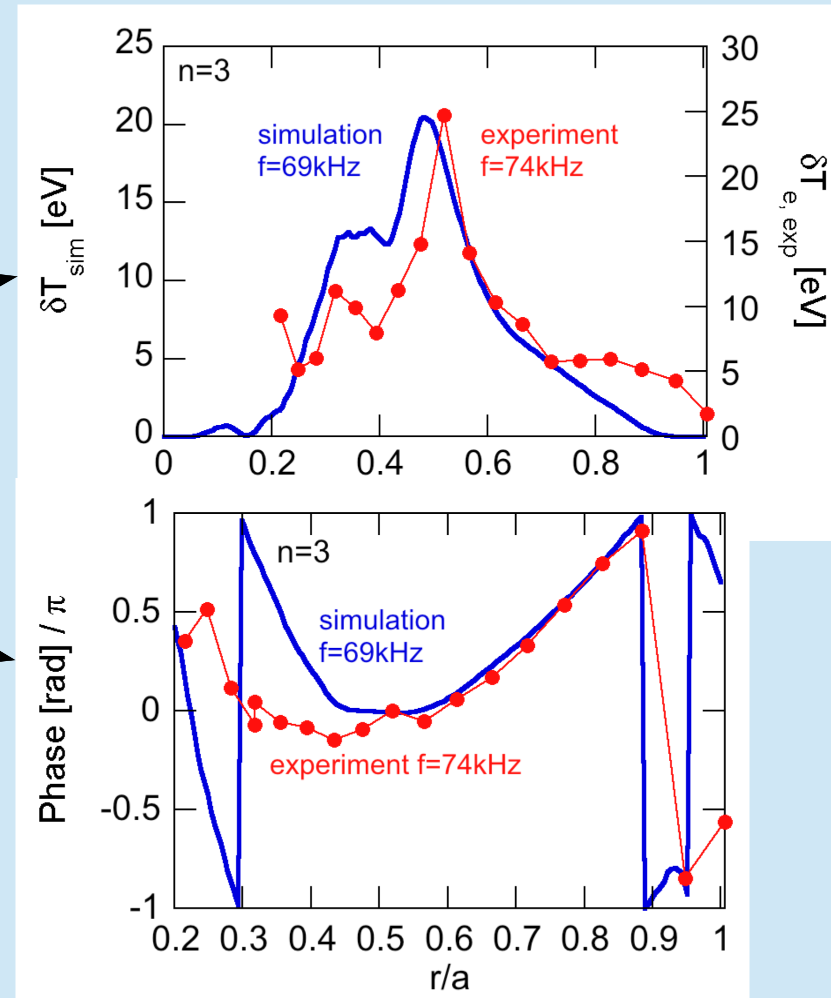
[Todo et al, NF'15]



Global structure

Amplitude profile

Phase profile



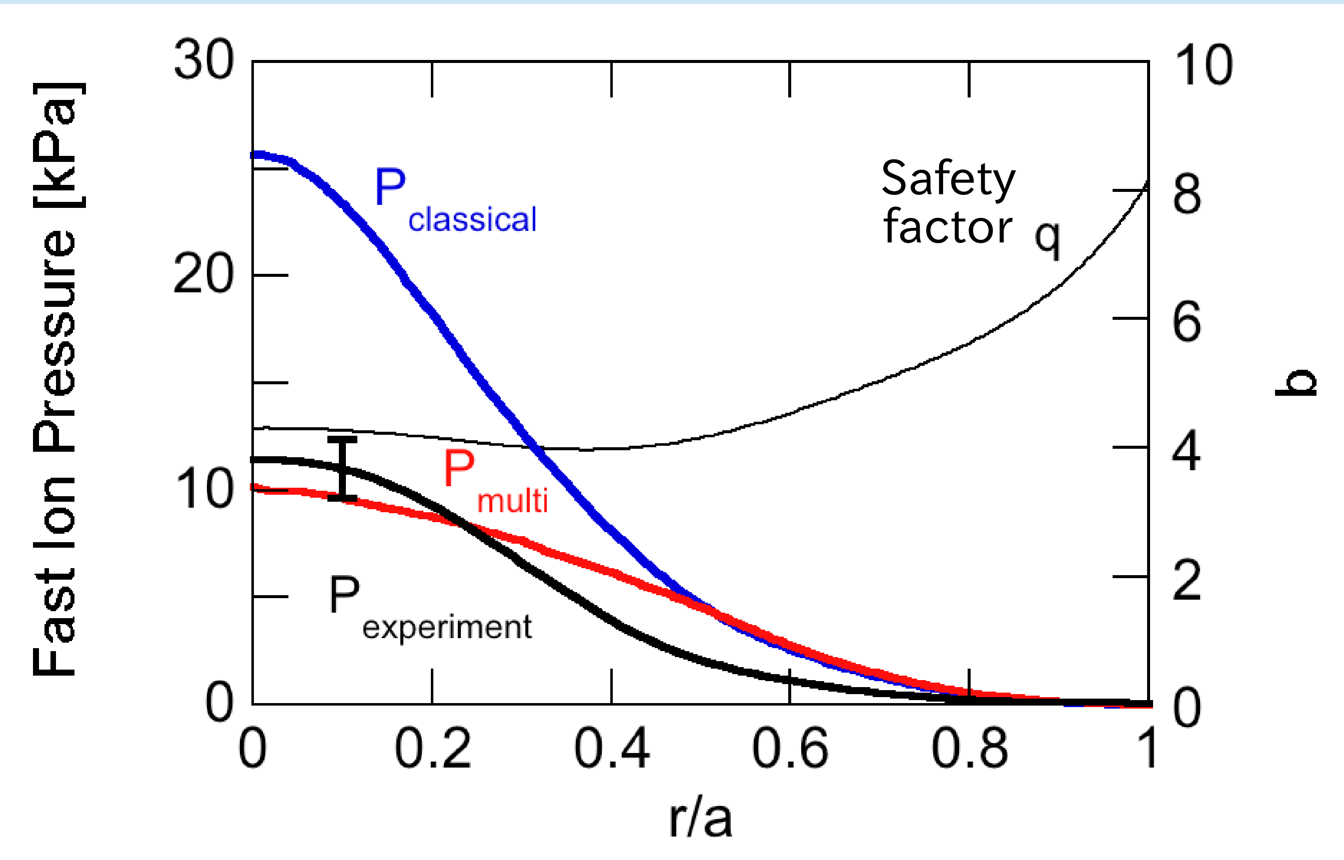
<u>Found:</u> For mode with longest wavelength (n=3) frequency and mode structure agrees well with experiment.

→ Successful validation in regime where use of MHD is justified.

(A) Improved prediction for EP pressure profile in DIII-D

Comparison of steady-state EP pressure profiles: **[Todo et al, NF'15]**

- $P_{exp}(r)$ estimated from experimental measurements,
- $P_{class}(r)$ from "classical" Monte-Carlo simulation (EP source + collisions)
- $P_{multi}(r)$ from multi-phase simulation (interlaced hybrid and classical)



Found: Steady low-amplitude Alfvén mode activity reduces EP pressure in the plasma core by up to 60%.

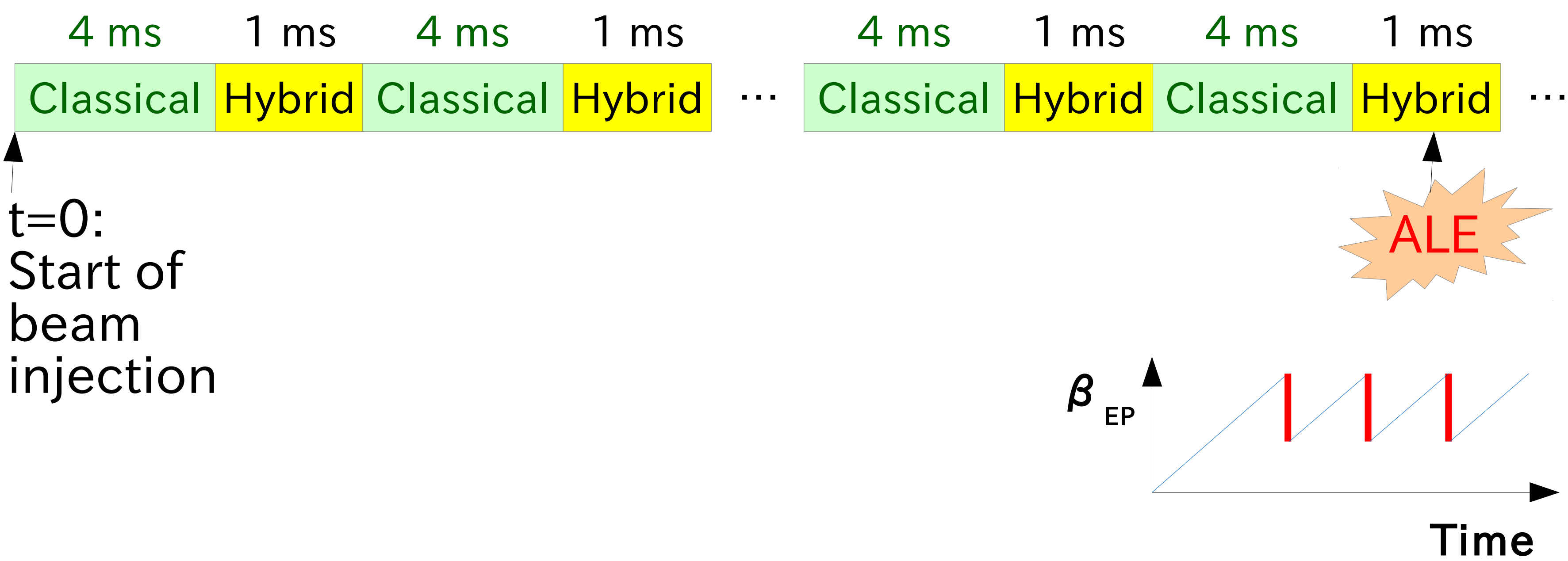
Multi-phase sim. result is very close to exp. error bars.

→ This result together with successful validation of δT_e amplitudes convincingly confirms that transport is caused by Alfvén modes.

Application of multi-phase method

(B) Abrupt Large relaxation Events (ALE) in JT-60U tokamak (JAEA, Naka, Japan)

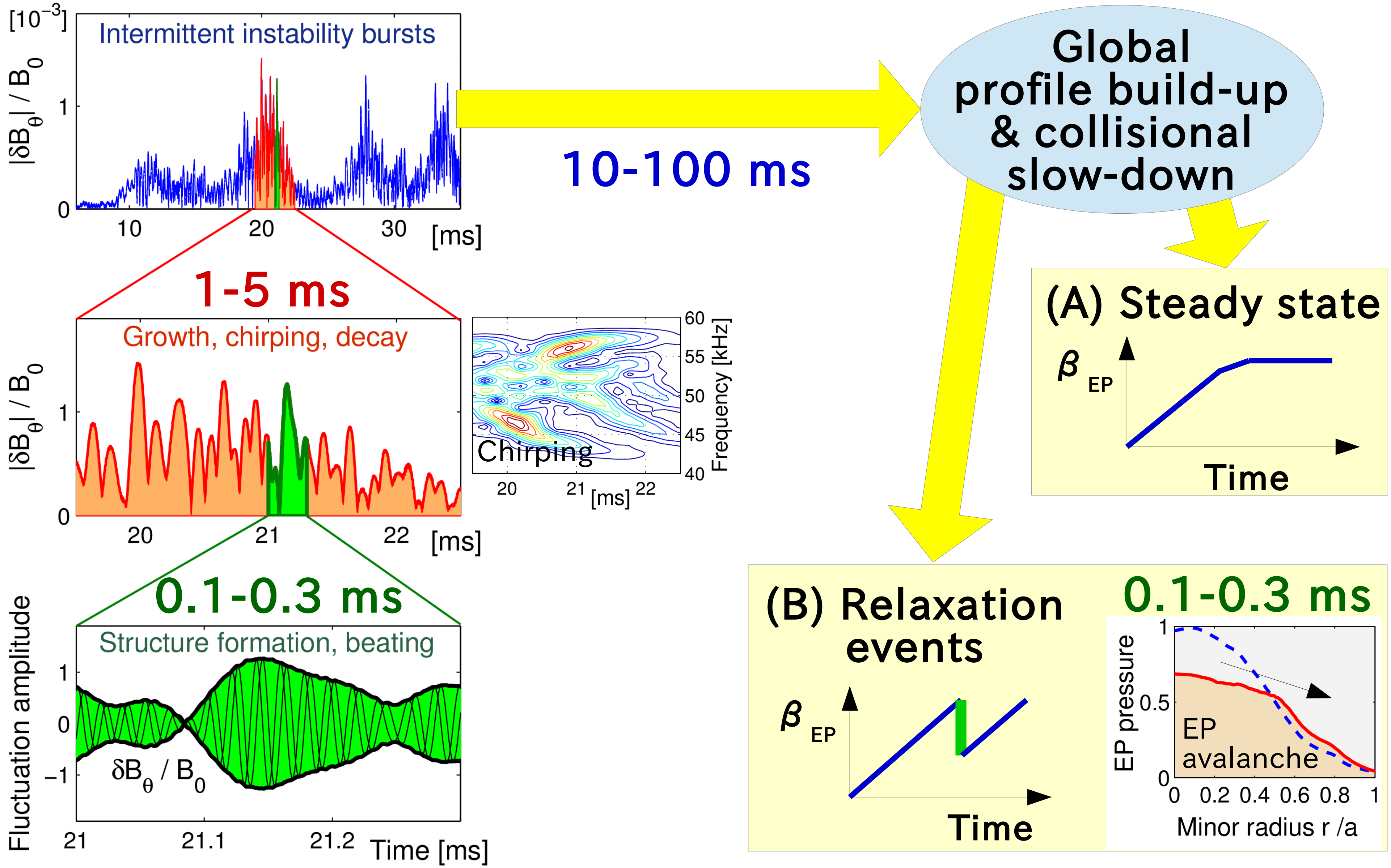
[Bierwage et al, IAEA FEC 2016]



[UNPUBLISHED MATERIAL CUT]

SUMMARY

Within the regime where MHD is valid *(long wavelength, high frequency)* the hybrid code MEGA has largely succeeded in the simulation of MHD and EP dynamics, and their interplay on a wide range of t-scales.



OUTLOOK: ◯ Reproducibility ◯ Application ◯ Extension

Within the regime where MHD is valid *(long wavelength, high frequency)* the hybrid code MEGA has largely succeeded in the simulation of MHD and EP dynamics, and their interplay on a wide range of t-scales.

Try to reproduce with modified plasma and simulation parameters to check reliability.

→ Work in progress

Apply to study & explain observations (e.g. ALE trigger mechanism).

Use insights to develop effcient reduced models for predictive simulations.

Extend to low-frequency regime where shear Alfvén waves couple strongly with ion sound waves.

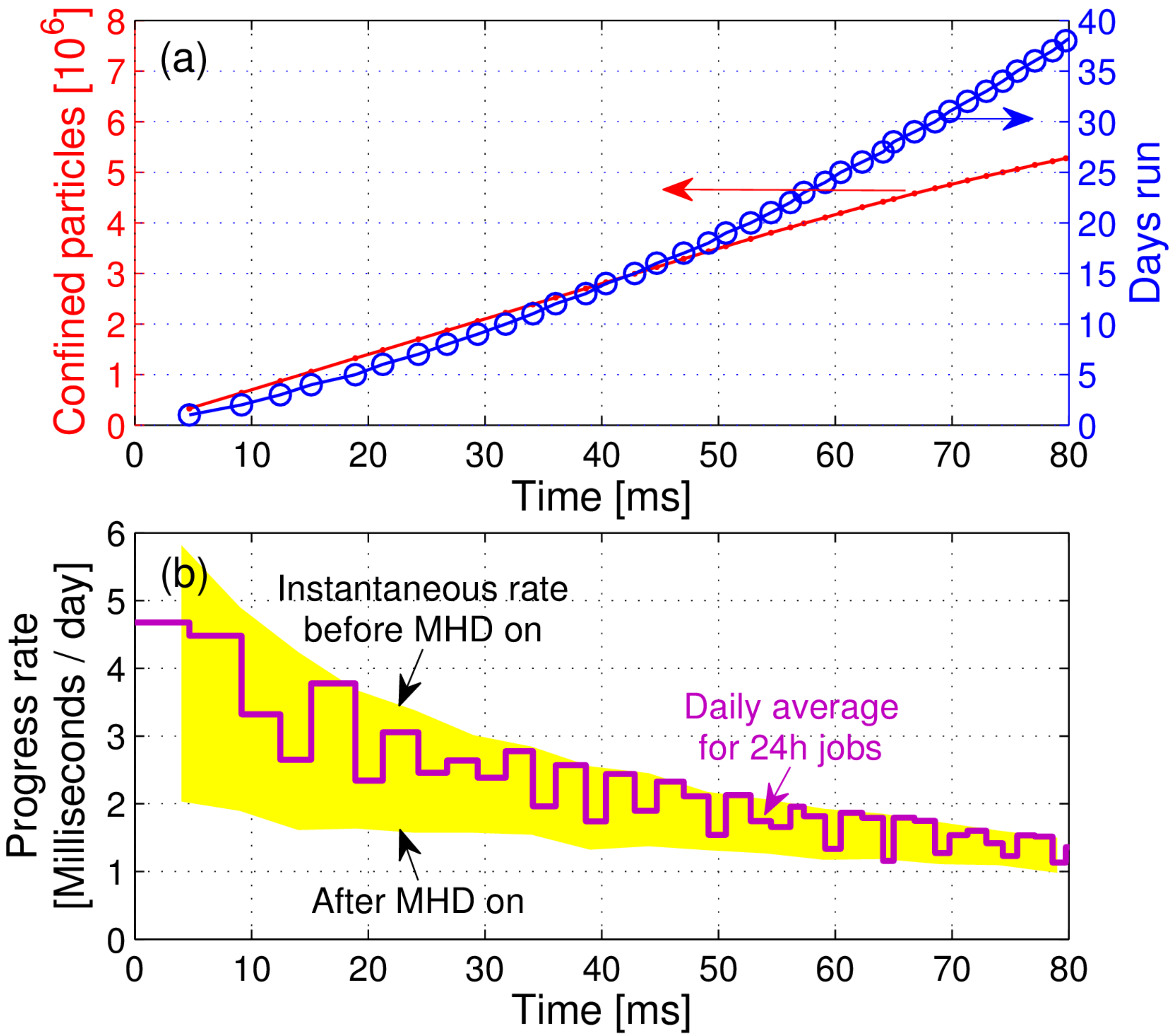
→ Kinetic bulk ion model

- Straightforward extension for kin. compression.
- Difficult to capture FLR effects (i.e., ITG. KBM, drift-Alfven micro-turbulence)

Appendix

Performance of “multi-phase” method

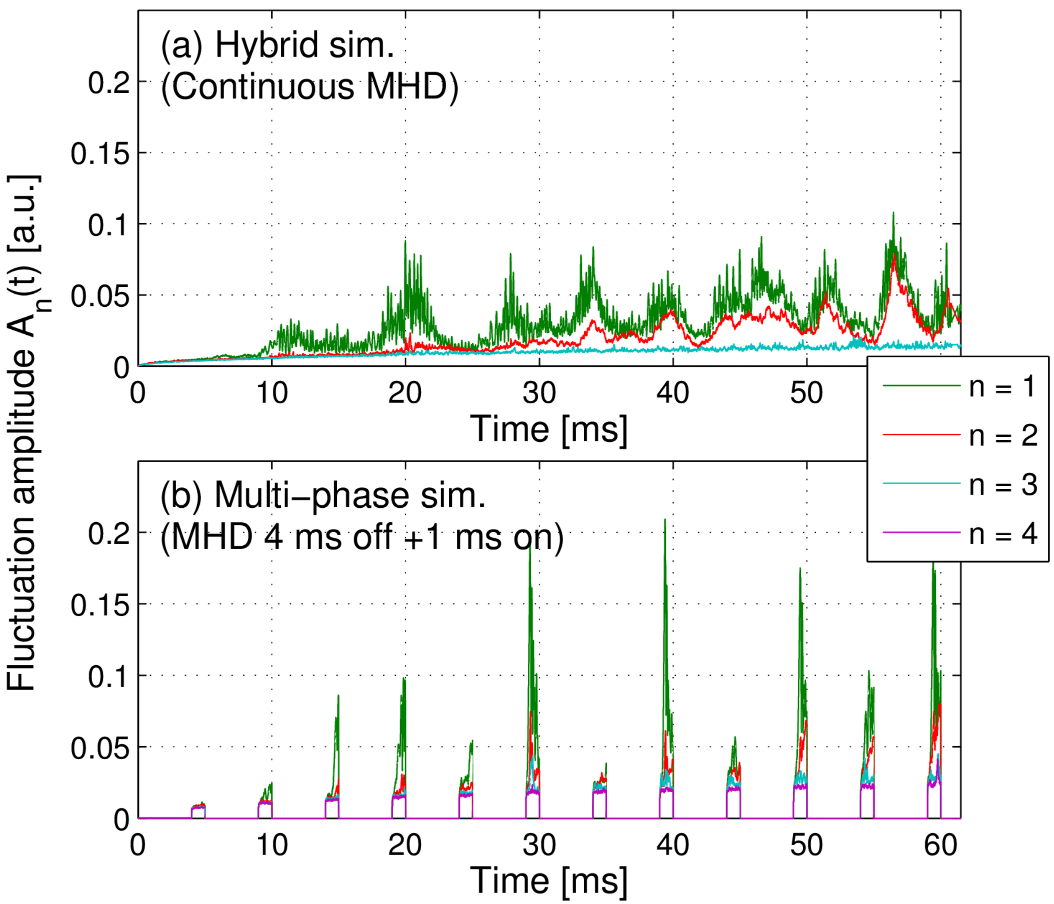
[Bierwage & Todo, submitted to CPC]



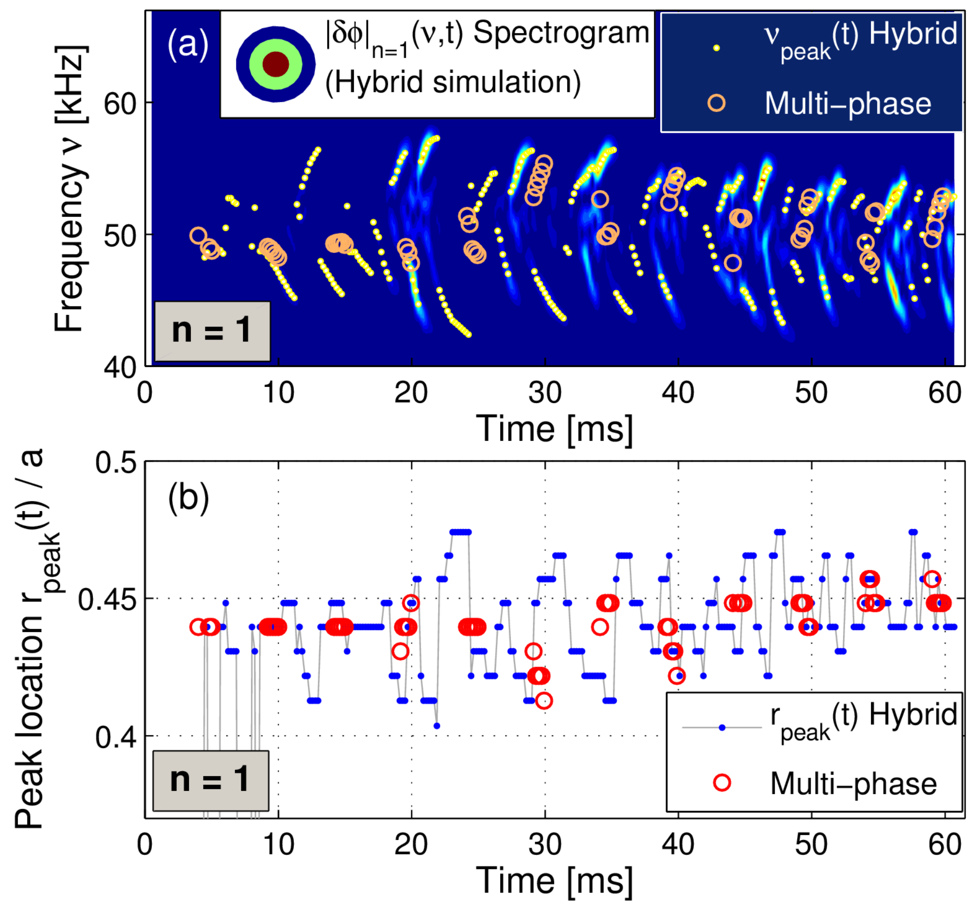
Benchmark of “multi-phase” method

[Bierwage & Todo, submitted to CPC]

Fluctuation amplitudes



Mode frequency and location (n=1)



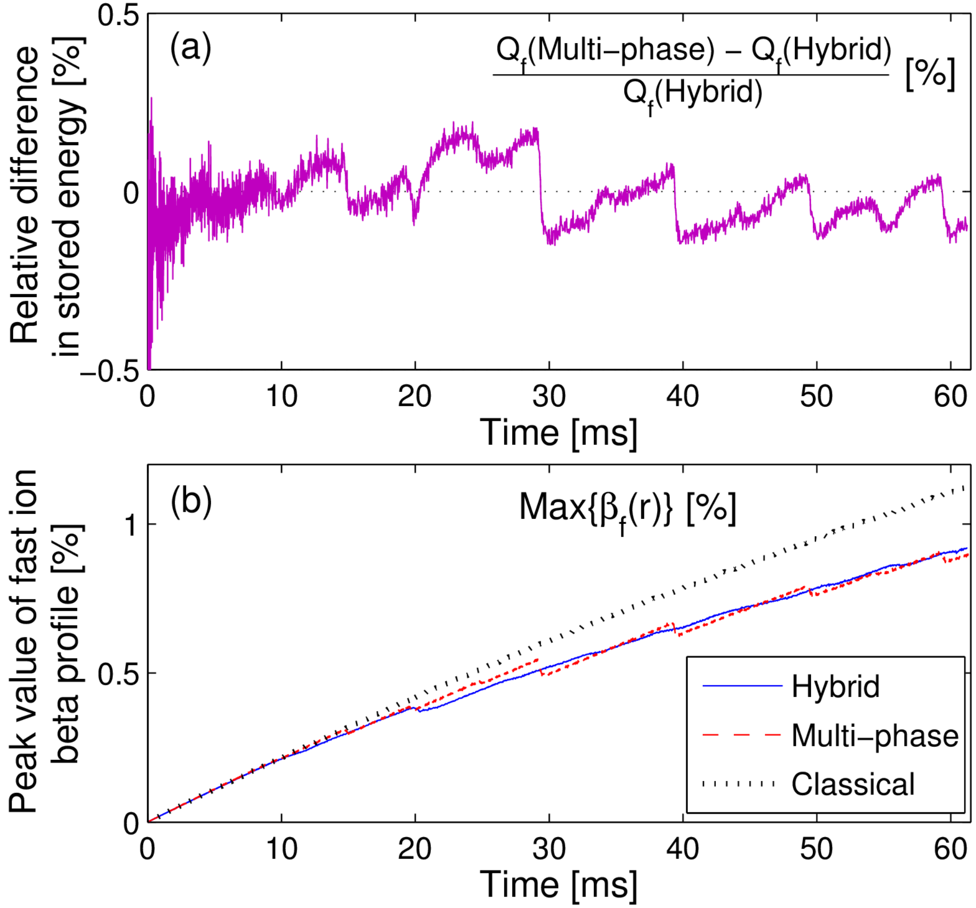
- Agreement:
  n=1 dominant, followed by n=2
- Disagreement:
  Multi-phase sim. amplitudes overshoot, as they must in order to cause similar transport in 1/5 of the time.

- Agreement:
  n=1 chirping range, radial location (similar for n=2, not shown)

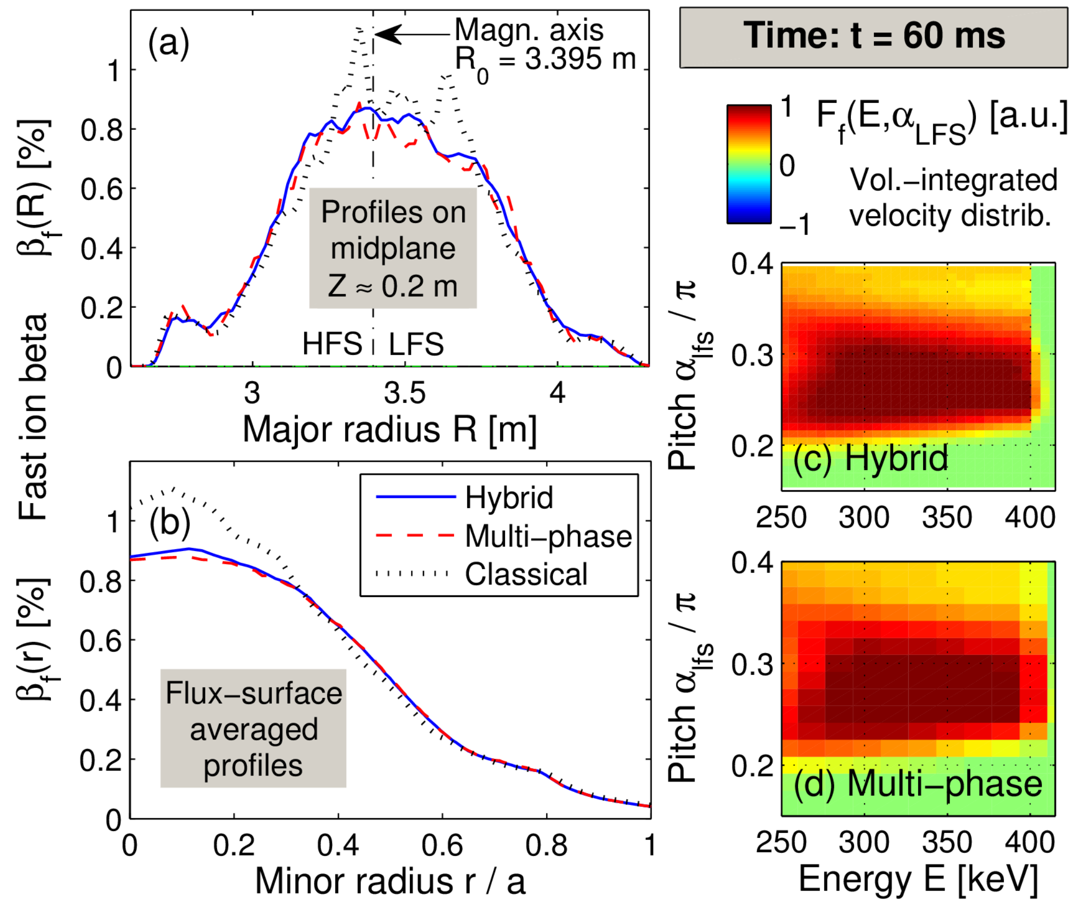
Benchmark of “multi-phase” method

[Bierwage & Todo, submitted to CPC]

EP beta and stored energy



EP beta profile and velocity distrib.



- EP distributions agree well
- Note difference between $\beta_{EP}(R)$ [local] and $\beta_{EP}(r)$ [flux-surf. avg.]

EP losses (wall + thermalization):

- Hybrid 3.5%
- Multi-phase 4.5%

} Negligible difference w.r.t. confined EPs but significant for wall heat load