TH/7-1 Multi-phase Simulation of Alfvén Eigenmodes and Fast Ion Distribution Flattening in DIII-D Experiment

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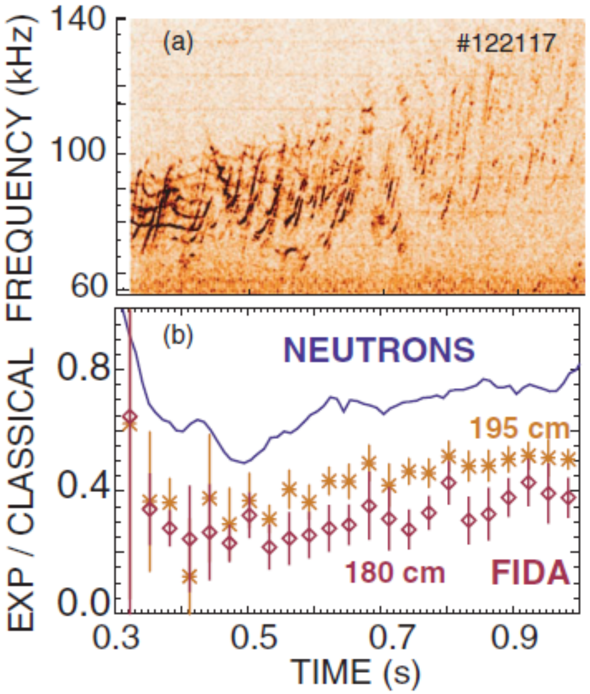
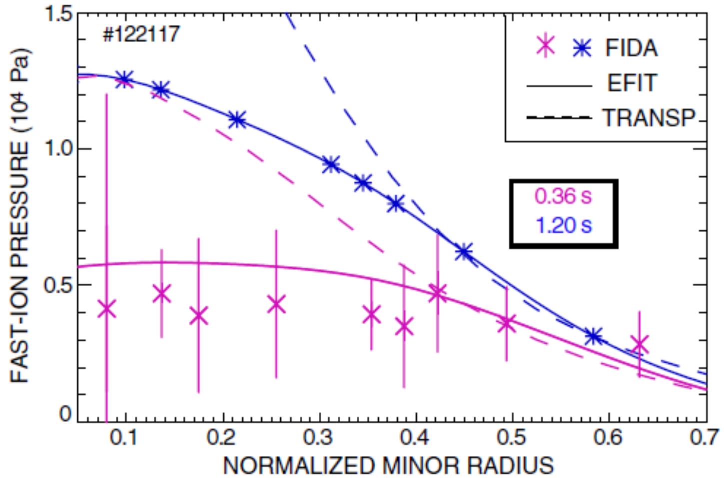
Anomalous Flattening of Fast ion Profile on DIII-D





[W. W. Heidbrink, PRL **99**, 245002 (2007)]

- Anomalous flattening of the fast-ion profile during Alfvén-eigenmode activity
- A rich spectrum of TAEs and RSAEs with reversed q profile in current ramp-up phase

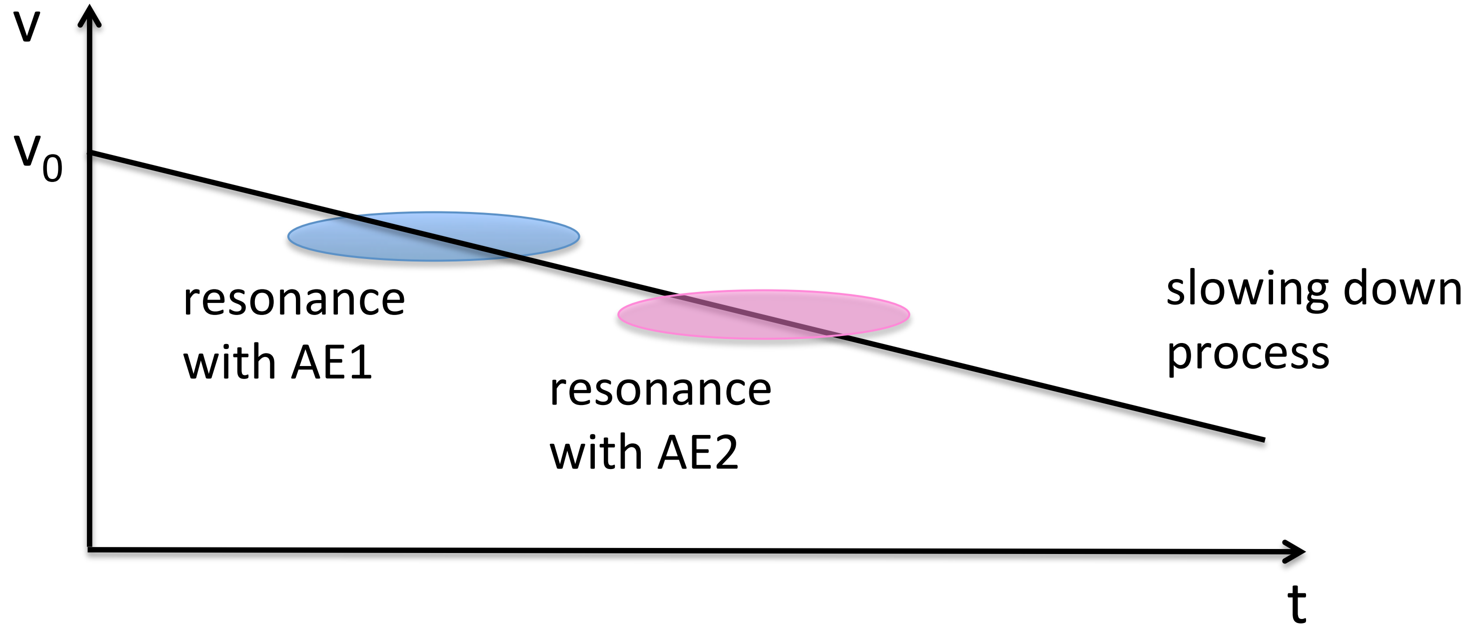
Theoretical studies related to the DIII-D experiments

- Alfvén eigenmodes
  - An excellent agreement in δTe profile between NOVA prediction (TAE mode) and ECE measurement [Van Zeeland (2009)]
  - Shearing of 2D AE profile was compared with TAEFL code [Tobias (2011)]
  - EP nonperturbative effects on TAE profile and freq. [Wang (2013)]
  - Validation of GK codes on transition from RSAE to TAE [Spong (2012)]
- EP transport
  - Multiple low amplitude modes (dB/B~10^-4) can account for significant modification of fast ion distributions [White (2010)]
  - Modeling of fast ion losses and stability of AE modes [Van Zeeland (2011, 2012)]
- Nonlinear simulations [Vlad (2009), Y. Chen (2013)]

No studies have ever tried a comprehensive simulation of AE amplitude and EP transport !

- AE stability and amplitude depend on EP distribution
- EP transport depends on AE amplitude
- AEs and EP distribution should be solved in a self-consistent way. Difficulty arises from a gap between time scales:
  - slowing down time ~ 0.1-1 s, AE period ~ 10^-5 s

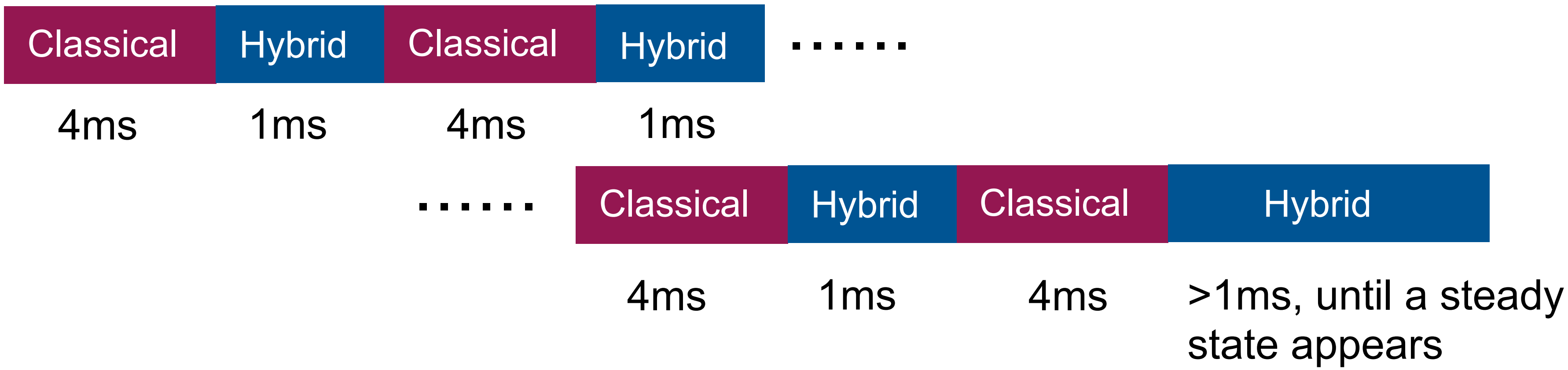
Life of an energetic particle: idea of multi-phase simulation



- in the slowing down process, energetic particle resonates with multiple AEs
- resonance regions have finite width (Δv) in velocity space
- interaction with AEs can be simulated at intervals shorter than $\tau_s * \Delta v/v$

Multi-phase Simulation

[Y. Todo, Nucl. Fusion **54**, 104012 (2014)]



- Hybrid simulation of energetic particles and an MHD fluid
- Multi-phase simulation =
  - classical simulation w/o MHD perturbations for 4ms +
  - EP-MHD hybrid simulation for 1ms; performed alternately
  - reduce computational time to 1/5

Objectives

- Multi-phase simulation of a DIII-D experiment (#142111) and validation on
  - anomalous flattening of fast ion profile
  - electron temperature fluctuation: frequency, spatial profile, and amplitude
- Analysis of fast ion transport process in the simulation result

An extended MHD model coupled with energetic particles

$$\frac{\partial \rho}{\partial t} = -\nabla\cdot(\rho\mathbf{v}) + \nu_{\mathrm{n}}\Delta(\rho\text{-}\rho_{\mathrm{eq}}) , \quad (1)$$

$$\rho\frac{\partial}{\partial t}\mathbf{v}_{\mathrm{MHD}} = -\rho\mathbf{v}\cdot\nabla\mathbf{v}_{\mathrm{MHD}} + \rho\mathbf{v}_{\mathrm{pi}}\cdot\nabla\left(\mathrm{v}_{\parallel}\mathbf{b}\right) - \nabla p + (\mathbf{j}-\mathbf{j}_h')\times\mathbf{B}$$

$$+\frac{4}{3}\nabla(\nu\rho\nabla\cdot\mathbf{v}_{\mathrm{MHD}}) - \nabla\times(\nu\rho\vec{\omega}) , \quad (2)$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\mathbf{E} , \quad (3)$$

$$\frac{\partial p}{\partial t} = -\nabla\cdot\left[p(\mathbf{v}_{\mathrm{MHD}}+\mathbf{v}_{\mathrm{tor}})\right] - (\gamma-1)p\nabla\cdot\left[p(\mathbf{v}_{\mathrm{MHD}}+\mathbf{v}_{\mathrm{tor}})\right]$$

$$+(\gamma-1)[\nu\rho\omega^2 + \frac{4}{3}\nu\rho(\nabla\cdot\mathbf{v}_{\mathrm{MHD}})^2 + \eta\mathbf{j}\cdot(\mathbf{j}-\mathbf{j}_{\mathrm{eq}})] + \chi\Delta(p\text{-}p_{\mathrm{eq}}) , \quad (4)$$

$$\mathbf{E} = -\mathbf{v}_E\times\mathbf{B} + \eta(\mathbf{j}-\mathbf{j}_{\mathrm{eq}}) , \quad (5)$$

$$\mathbf{v} = \mathbf{v}_{\mathrm{MHD}} + \mathbf{v}_{\mathrm{pi}} + \mathbf{v}_{\mathrm{tor}} , \quad \mathbf{v}_{\mathrm{pi}} = -\frac{m_i}{2e_i\rho}\nabla\times\left(\frac{p\mathbf{b}}{B}\right) , \quad (6)$$

$$\mathrm{v}_{\parallel} = \mathbf{v}_{\mathrm{MHD}}\cdot\mathbf{b} , \quad \mathbf{v}_E = \mathbf{v}_{\mathrm{MHD}} - \mathrm{v}_{\parallel}\mathbf{b} , \quad (7)$$

$$\mathbf{j} = \frac{1}{\mu_0}\nabla\times\mathbf{B} , \quad \vec{\omega} = \nabla\times\mathbf{v}_{\mathrm{MHD}} , \quad \mathbf{b}=\mathbf{B}/B , \quad (8)$$

based on an extended MHD model given by Hazeltine and Meiss

EP effect

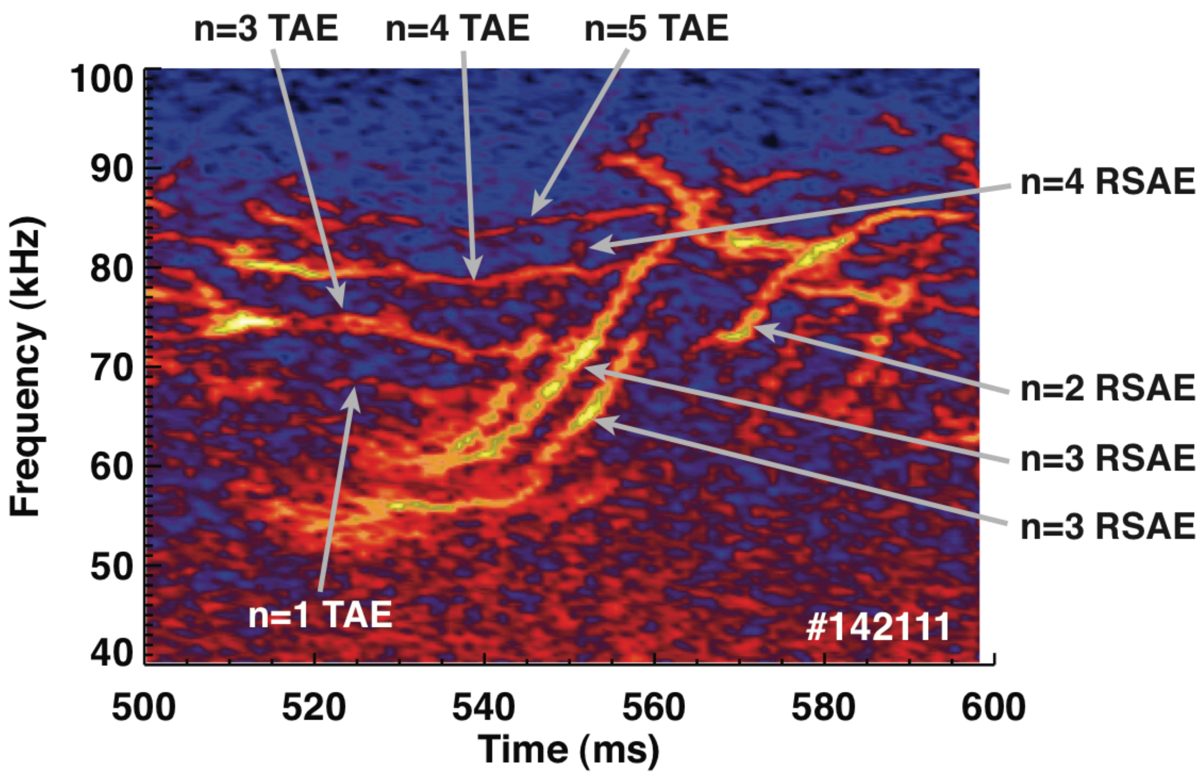
thermal ion diamagnetic drift

+

equilibrium toroidal rotation

$\nu=\eta/\mu_0=\nu_n=\chi= 5\times10^{-7} v_A R_0$

Frequency spectrum evolution in the experiment at t~525ms #142111



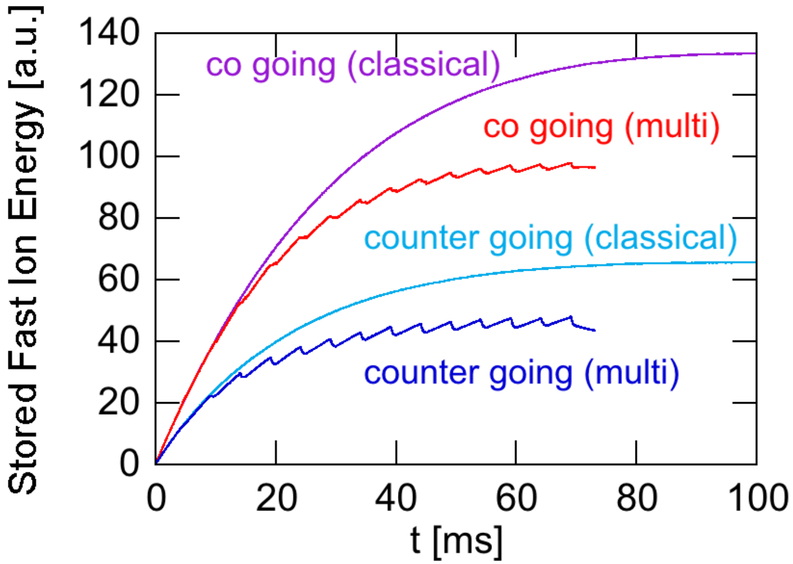
[M. A. Van Zeeland, NF **52**, 094023 (2012)]

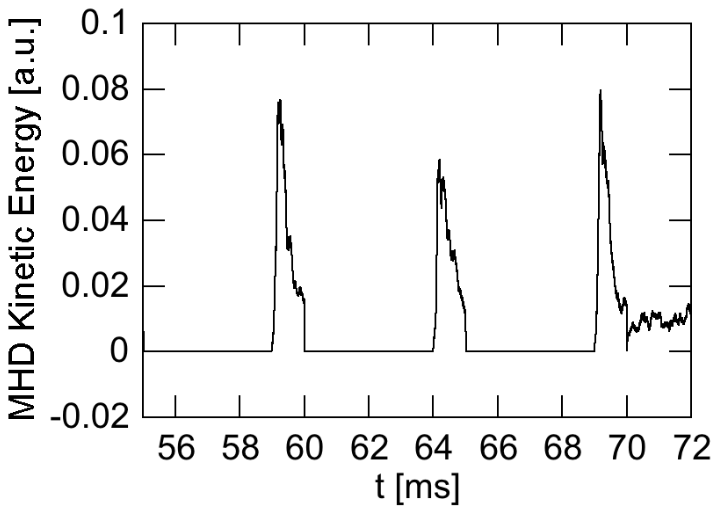
- AEs with n=1-5 are observed.
- In the simulation, energetic particle drive is restricted to n=1-5 to reduce numerical noise.

Setup of simulation

- DIII-D discharge #142111 at t=525ms is investigated using an equilibrium data reconstructed with EFIT code.
- Realistic beam ion deposition profile (full, half, and third energy components) is given by TRANSP code.
- Collisions (slowing down, pitch angle scattering, energy diffusion) with realistic parameters are taken into account.
- Particle losses take place at the plasma boundary (r/a=1).
- 8 million particles are injected with constant time intervals in 150ms.
- Beam injection power is 6.25MW.

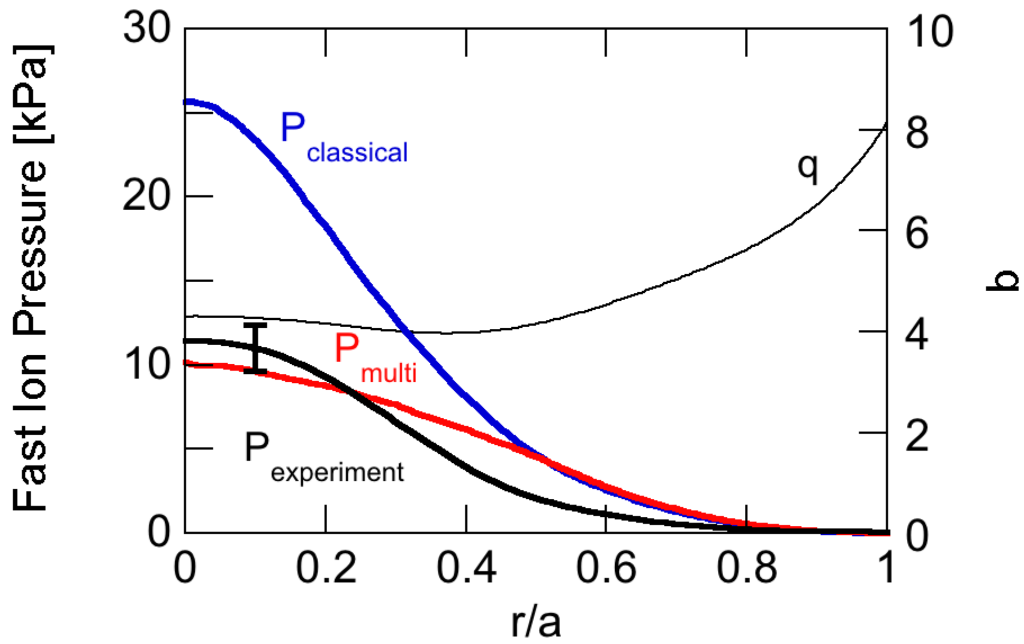
Time evolution of stored fast ion energy and MHD kinetic energy





- Multi phase simulation: classical phase is run w/o MHD for 4ms and then hybrid phase is run with MHD for 1ms. This combination is repeated until stored fast ion energy is saturated at t=70ms.
- After t=70ms, the MHD fluctuation reaches to a steady level.

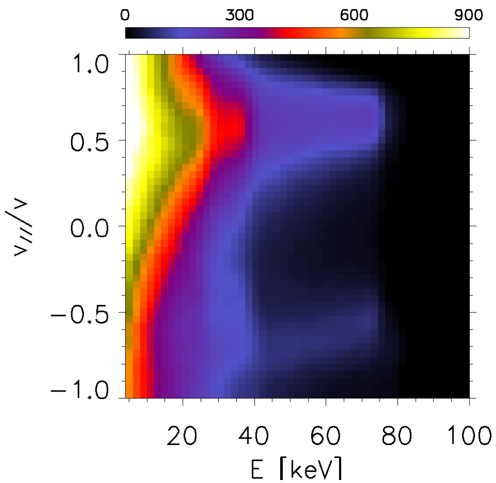
Comparison of fast ion pressure profiles (classical, multi-phase, exp.)



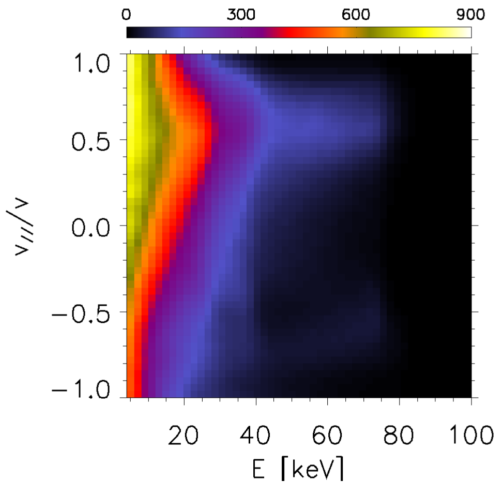
- Fast ion pressure profile flattening takes place in the multi phase simulation.
- The fast pressure profile in the multi-phase simulation is close to that in the experiment.

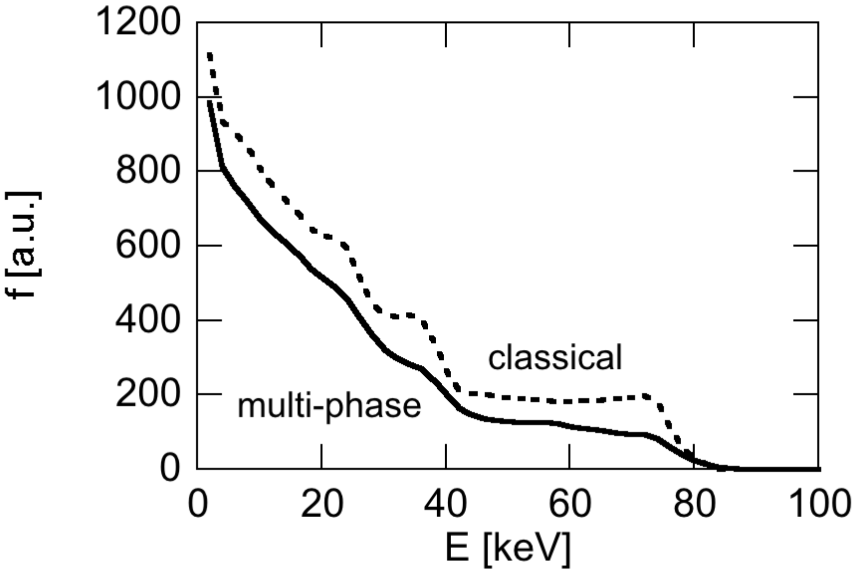
Fast ion distribution in velocity space

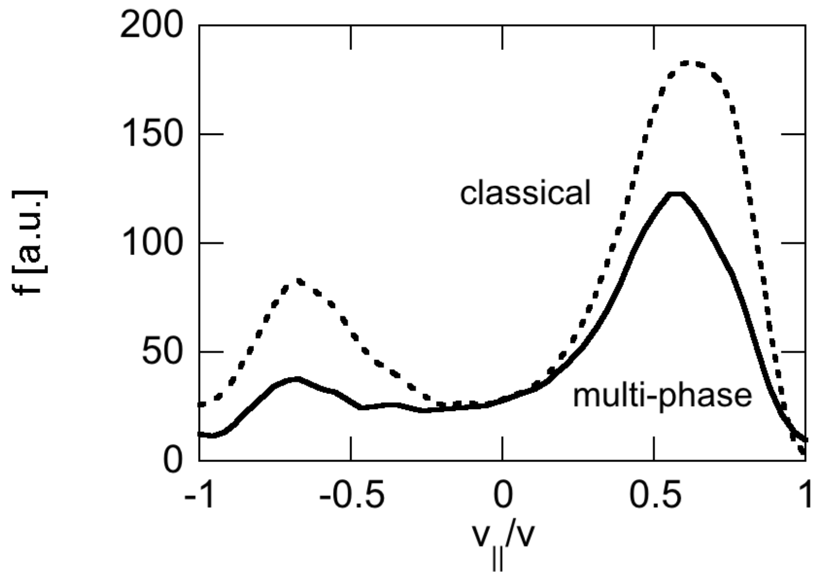
Classical



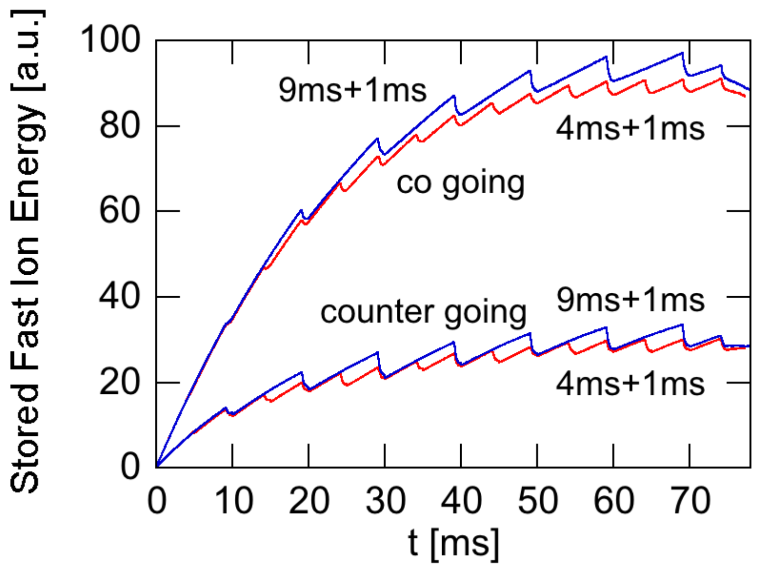
Multi-phase

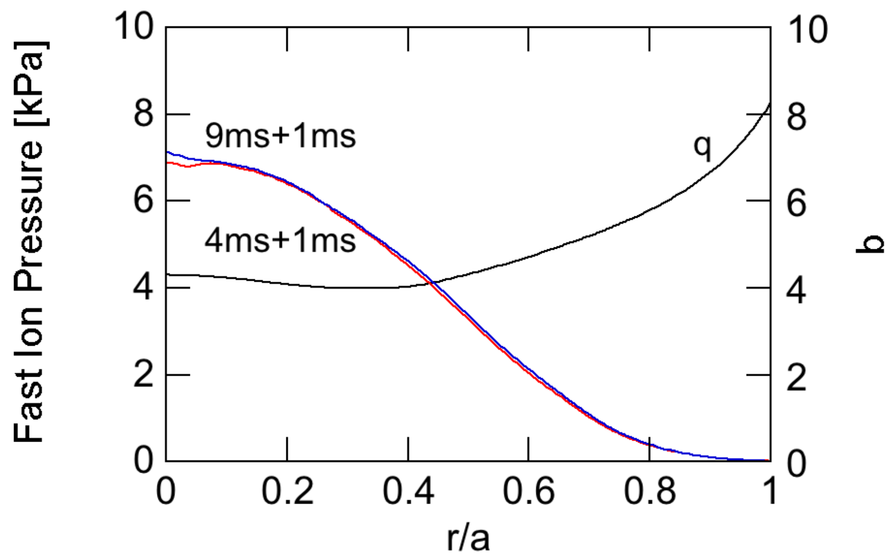


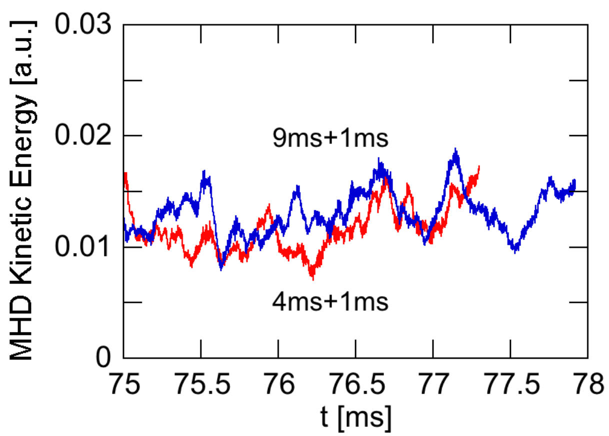




Comparison among classical phase durations

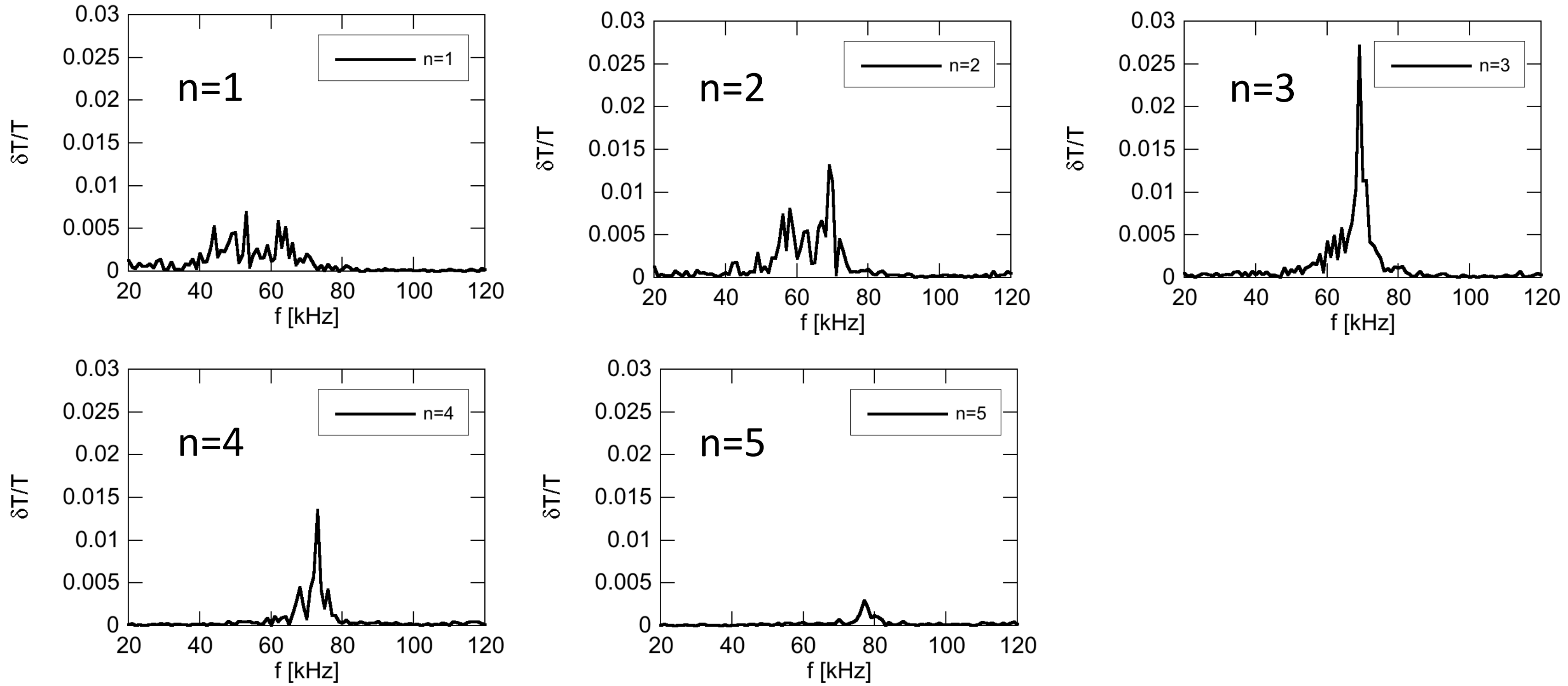






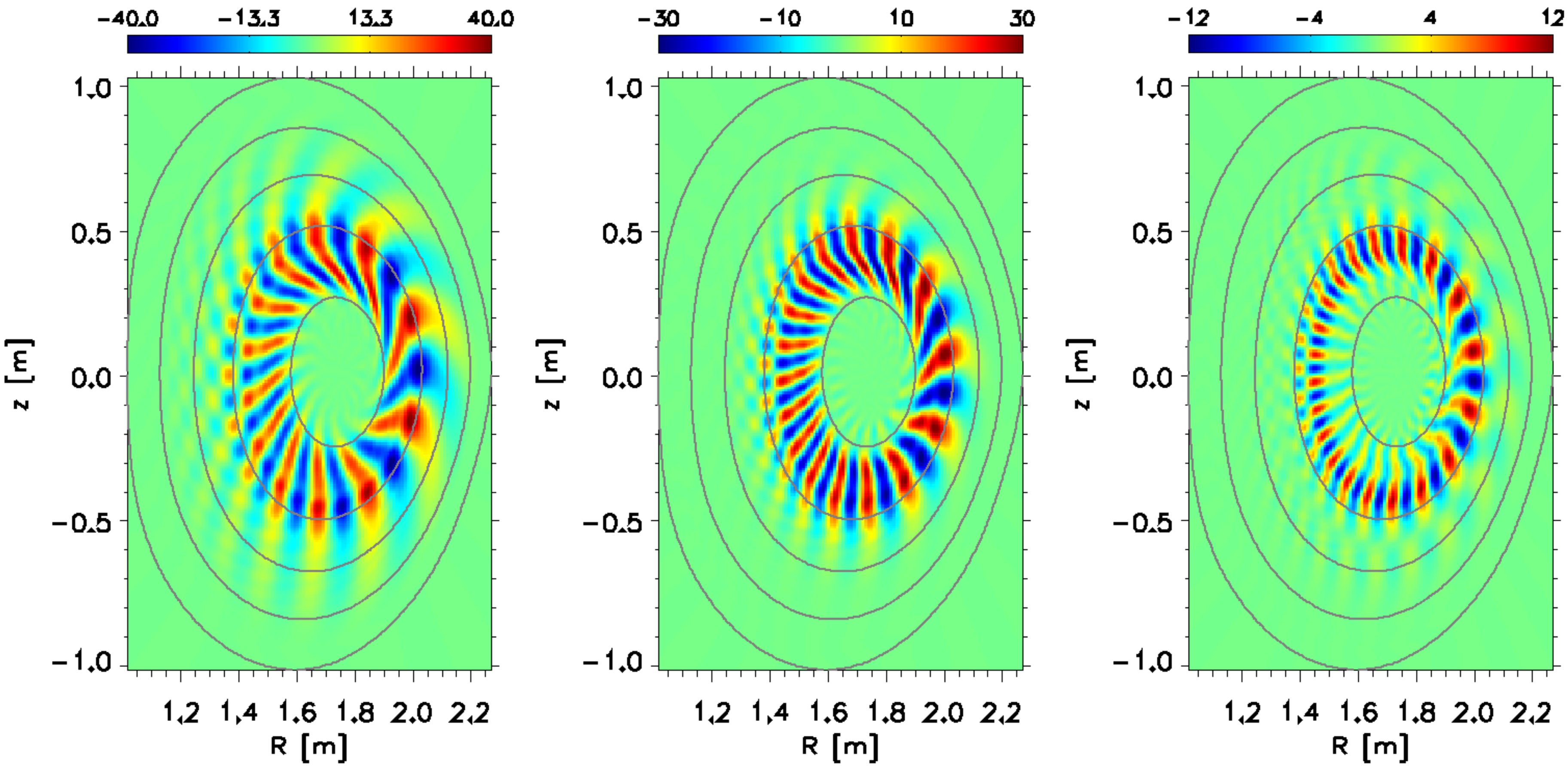
- two classical phase durations (4ms and 9ms) are compared
- very good agreement in fast ion pressure profile (top right)
- similar MHD fluctuation level (bottom)

Bulk temperature fluctuation spectra at r/a=0.49 at t≥70ms



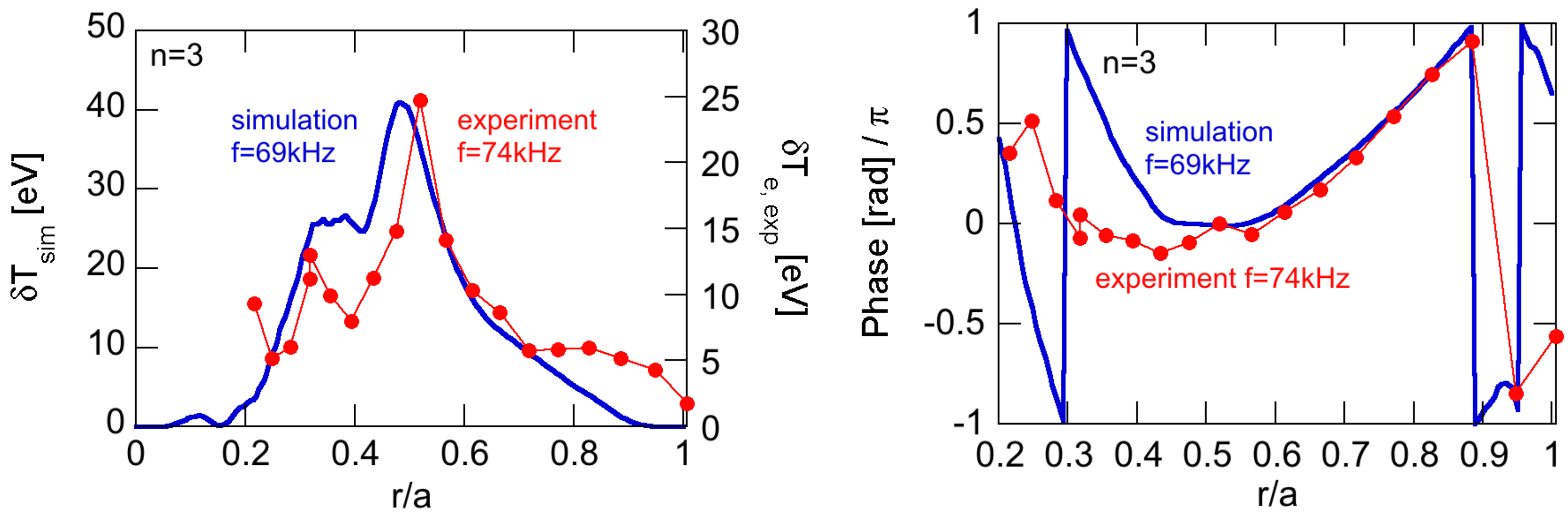
- Comparison in frequency (sim., exp.): n=1 (62kHz, 68kHz), n=3 (69kHz, 74kHz), n=4 (73kHz, 79kHz), n=5 (77kHz, 84kHz)
- n=2 mode is missing at the simulated moment in experiment

δTe Spatial Profiles in multi-phase simulation



n=3, f=69kHz n=4, f=73kHz n=5, f=77kHz

Comparison of temperature fluctuation profile with ECE measurement for n=3



- good agreement in spatial profile (left)
- good agreement in **amplitude** within a factor of 2 (left)
- good agreement in phase profile (right)

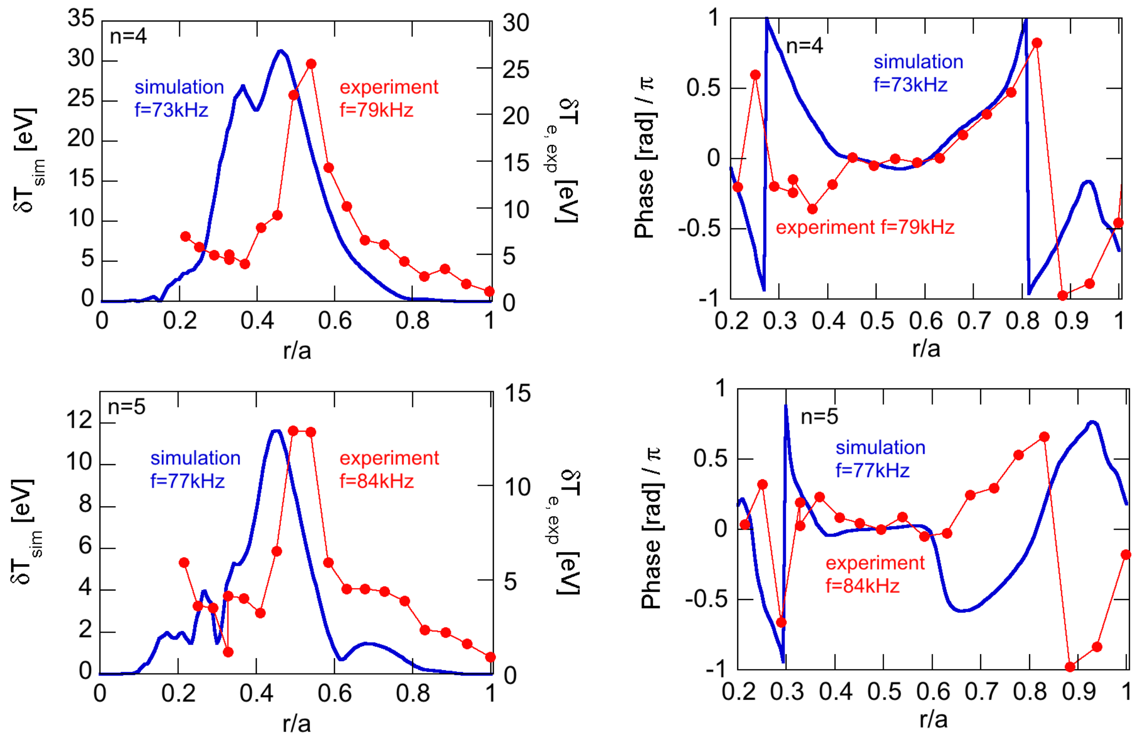
Comparison of temperature fluctuation profiles with ECE measurement for n=4 and 5

n=4

n=4 phase

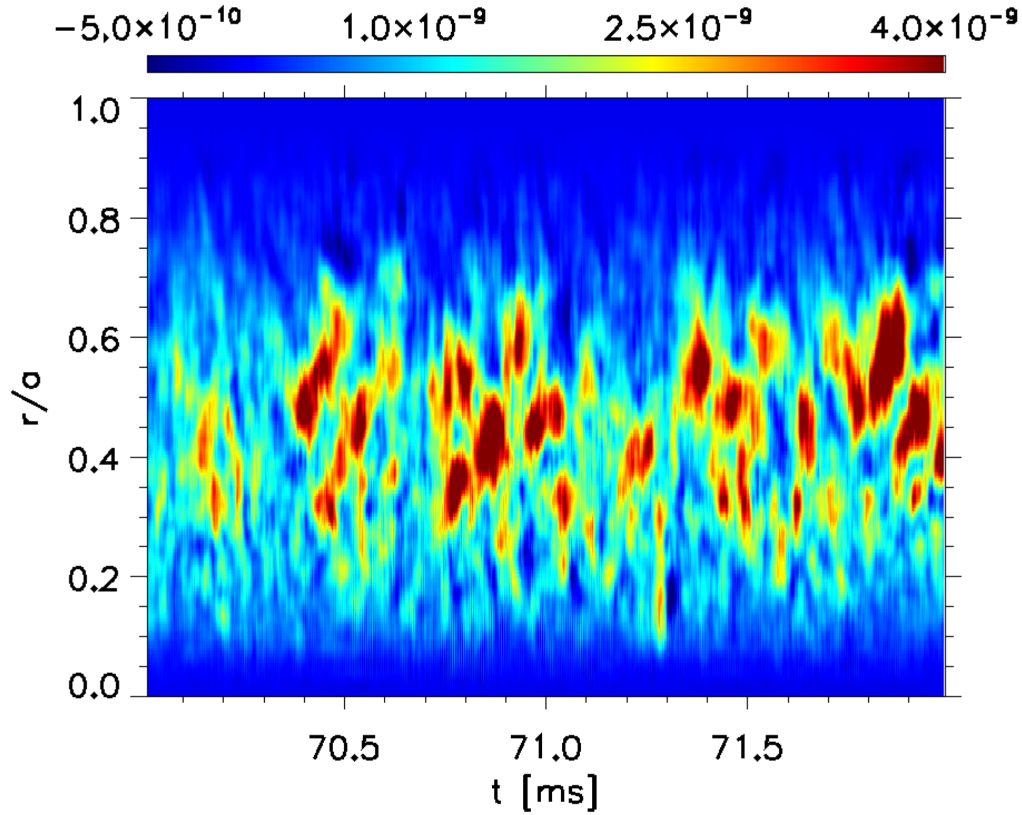
n=5

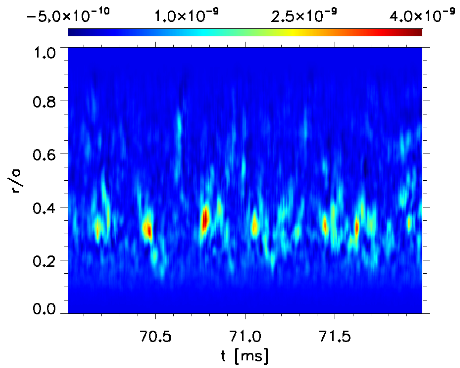
n=5 phase



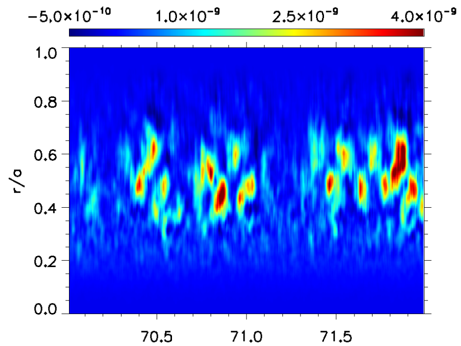
- good agreement in spatial profile (left)
- good agreement in **amplitude** within 20% (left)
- good agreement (n=4) and reasonable agreement (n=5) in phase profile (right)

Time evolution of fast ion energy flux profile

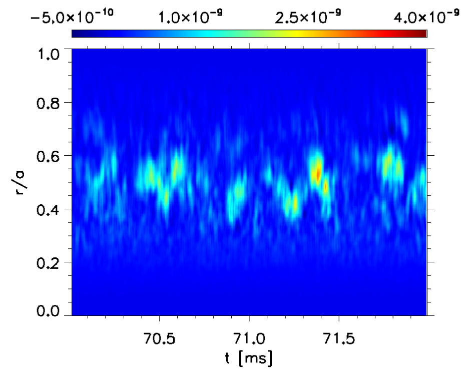




n=2



n=3



n=4

- steady and intermittent flux
- avalanches with multiple modes

Summary

- First comprehensive simulation that predicts
  - nonlinear saturated amplitude of AEs
  - and fast ion pressure profile consistent with measured values in experiment
- Temperature fluctuation profiles brought about by three of TAEs in the simulation are compared with experiment.
  - good agreement in radial profiles of amplitude and phase
  - good agreement in absolute amplitude within a factor of 2
- Steady and intermittent fast ion energy flux with avalanches
- The multi-phase simulation is useful for the prediction of AE activity and EP transport in burning plasmas