Fast ion profile stiffness due to the resonance overlap of multiple Alfvén eigenmodes

Y. Todo (NIFS, SOKENDAI)

collaborating with:

M. A. Van Zeeland (General Atomics)

W. W. Heidbrink (Univ. California, Irvine)

21st NEXT Workshop

(March 10-11, 2016, Kyoto)

Outline

- Validation of EP-MHD hybrid simulation on fast ion profile stiffness and electron temperature fluctuations in DIII-D

  [Y. Todo et al., NF **54**, 104012 (2014), NF **55**, 073020 (2015)].

- Fast ion profile stiffness due to the resonance overlap of multiple Alfvén eigenmodes

Energetic particles and MHD hybrid simulation

- energetic particles (fast ions, alphas) are simulated with Particle-in-cell (PIC) simulations
- bulk plasma is described as an MHD fluid
- the coupling between EP and MHD is taken into account through the EP current in the MHD momentum equation
- neutral beam injection (NBI), collisions, and losses are considered

An extended MHD model coupled with energetic particles

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

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

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

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

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

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

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

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

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

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

based on an extended MHD model given by Hazeltine and Meiss

EP effect

thermal ion diamagnetic drift

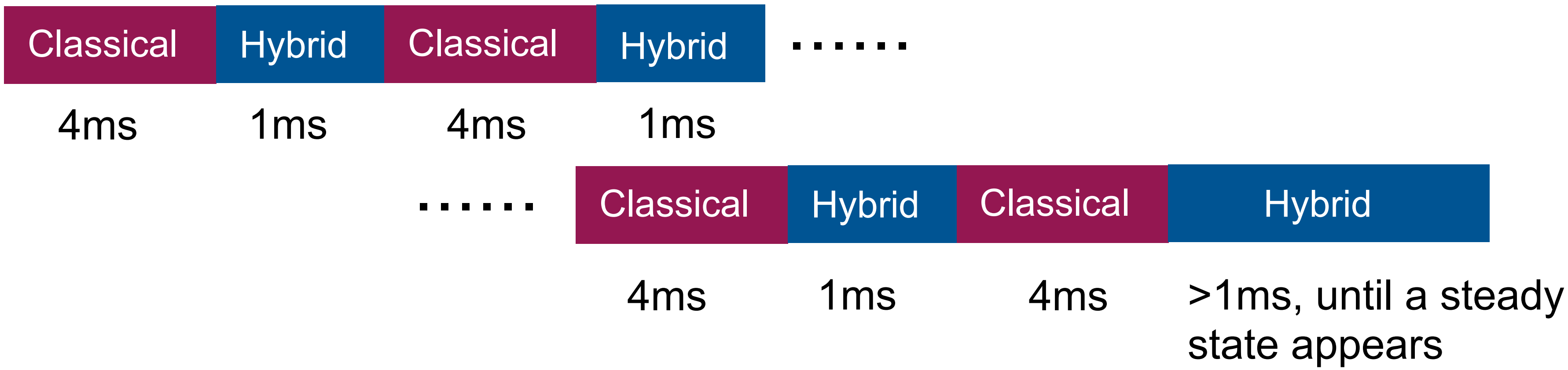
\+

equilibrium toroidal rotation

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

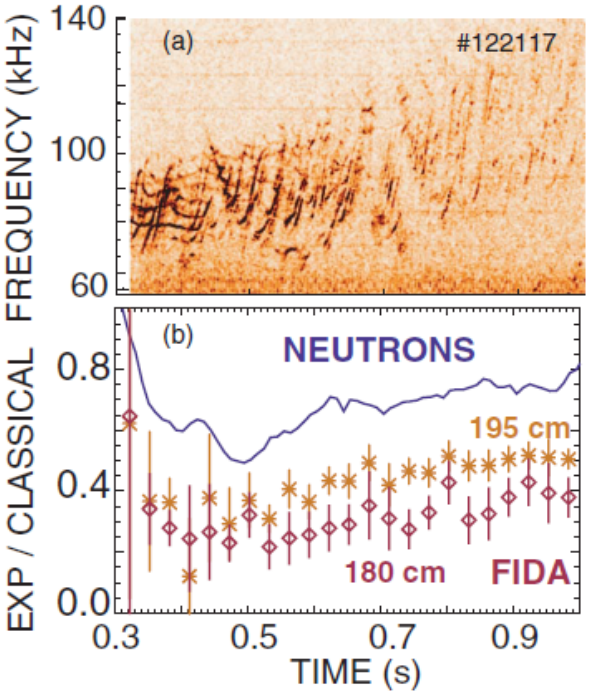
Multi-phase Simulation

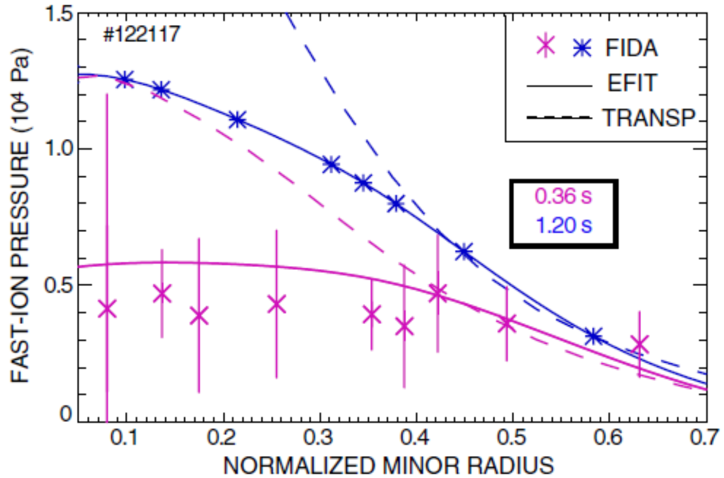
[Y. Todo, Nucl. Fusion **54**, 104012 (2014)]



- 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

Anomalous Flattening of Fast ion Profile on DIII-D



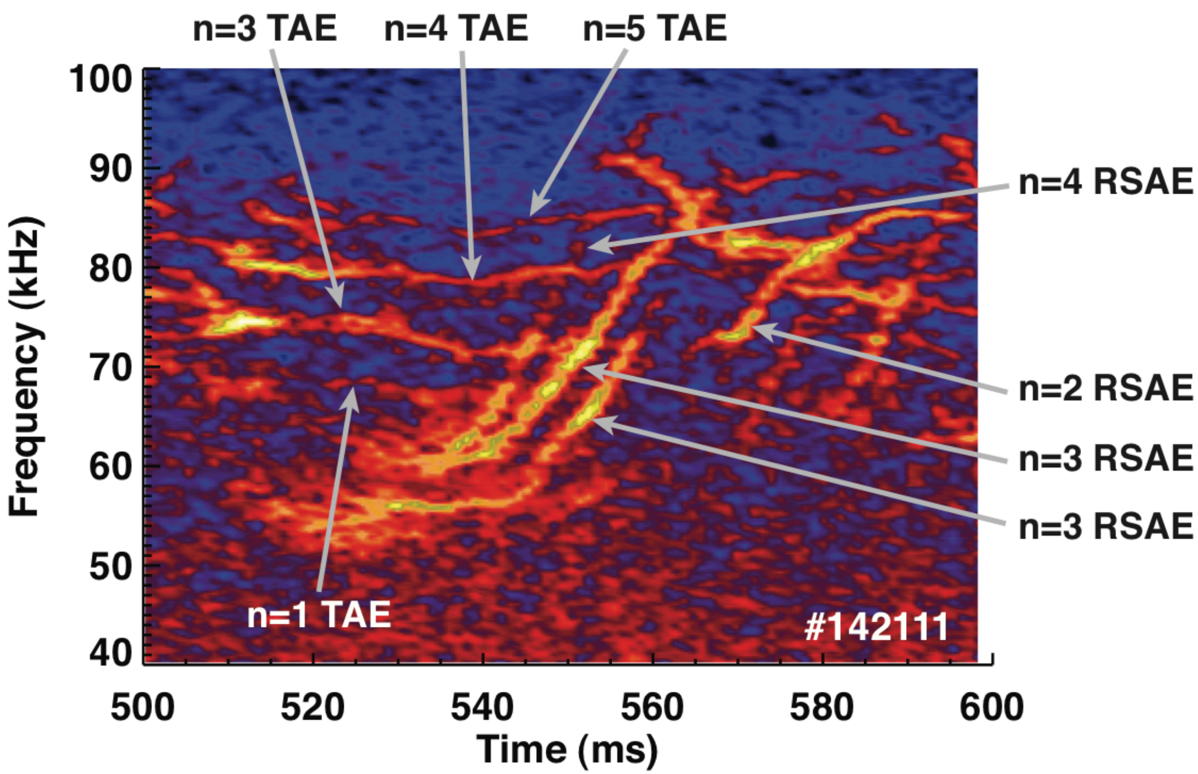


[W. W. Heidbrink, PRL **99**, 245002 (2007)]

- 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

DIII-D NATIONAL FUSION FACILITY

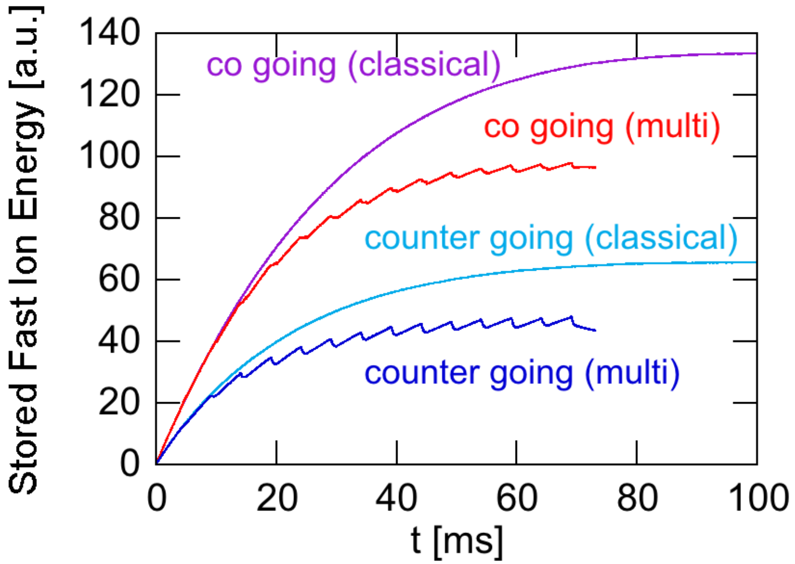
Frequency spectrum evolution in the experiment at t~525ms #142111

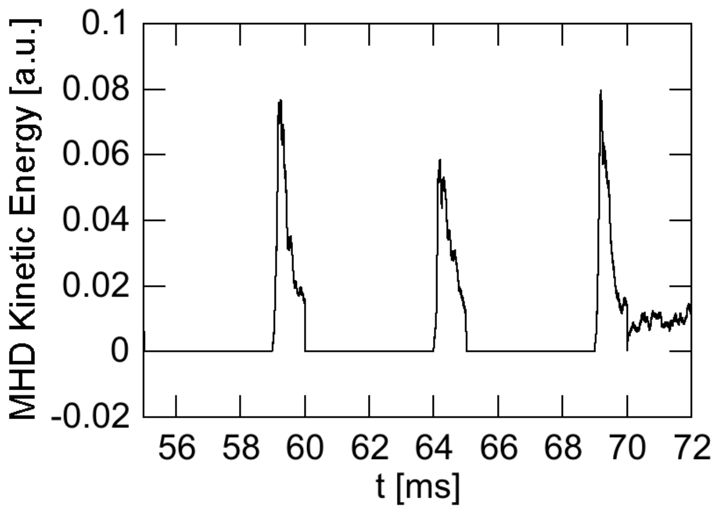


[M. A. Van Zeeland, NF **52**, 094023 (2012)]

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

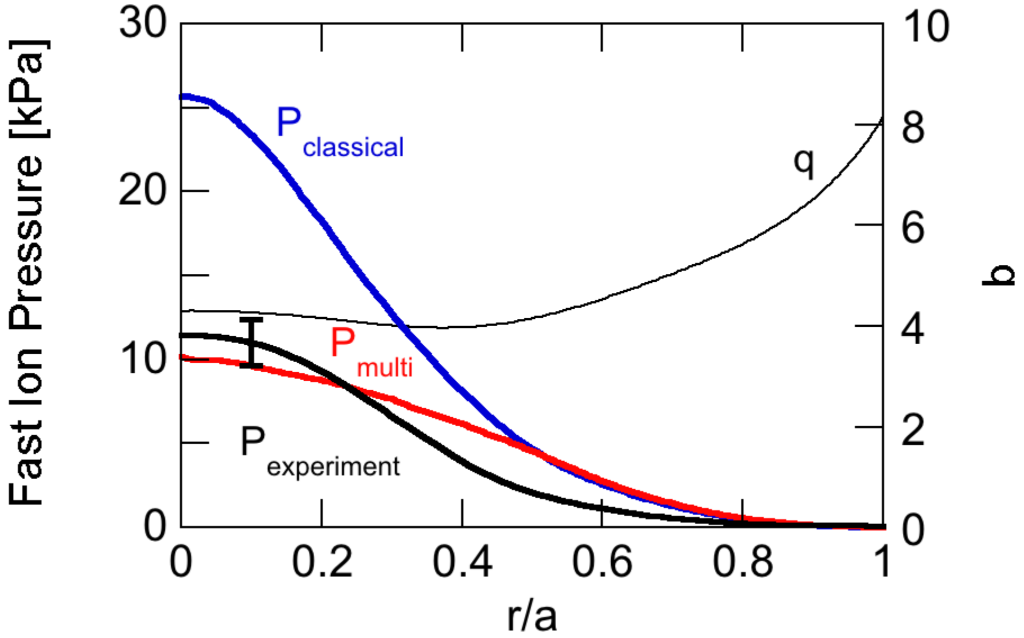
Time evolution of stored fast ion energy and MHD kinetic energy





- 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.

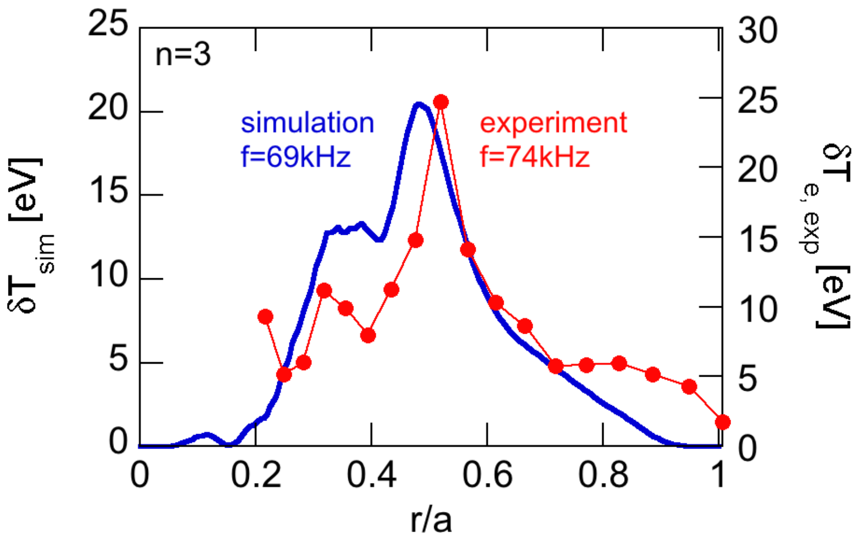
Comparison of fast ion pressure profiles (classical, multi-phase, exp.)

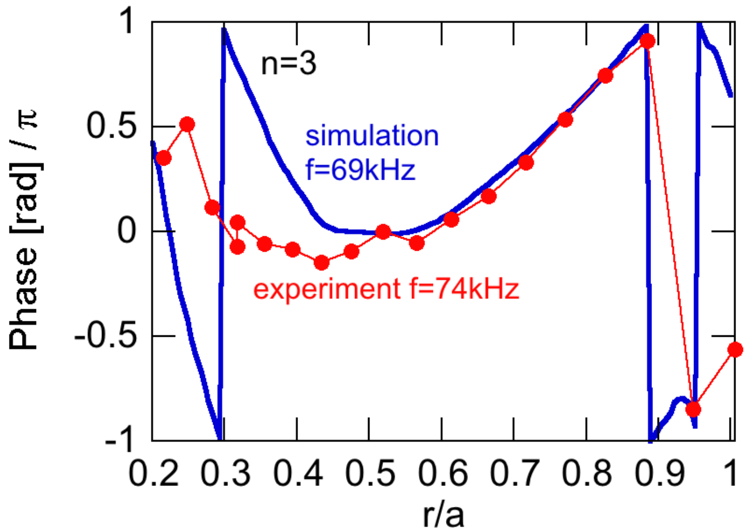


[Y. Todo et al., NF **55**, 073020 (2015)]

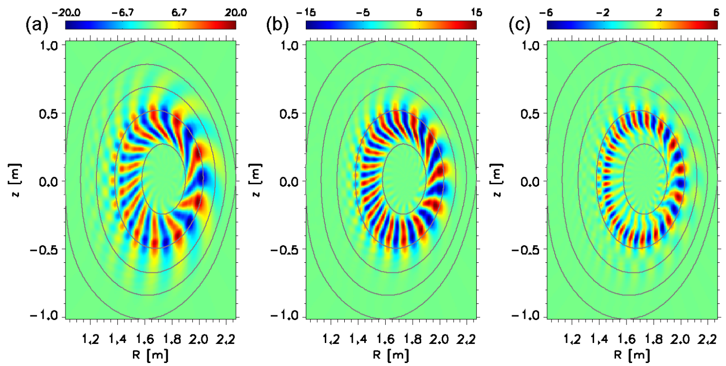
- Fast ion pressure profile flattening takes place in the multi phase simulation.
- The fast pressure profile in the multi-phase simulation is close to that in the experiment.

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





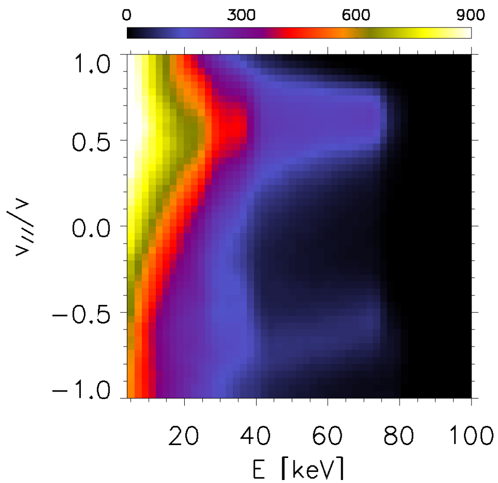
- good agreement in spatial profile
- good agreement in **absolute amplitude**
- good agreement in phase profile



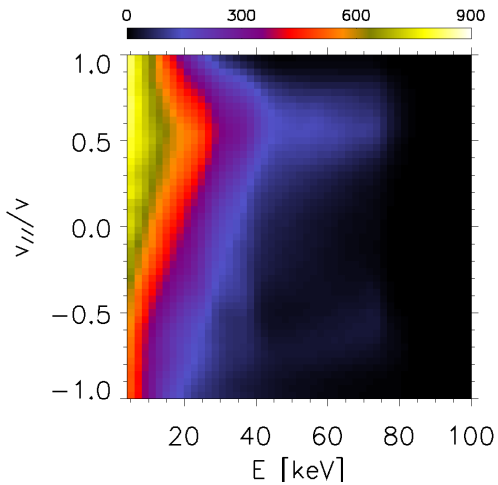
[Y. Todo et al., NF **55**, 073020 (2015)]

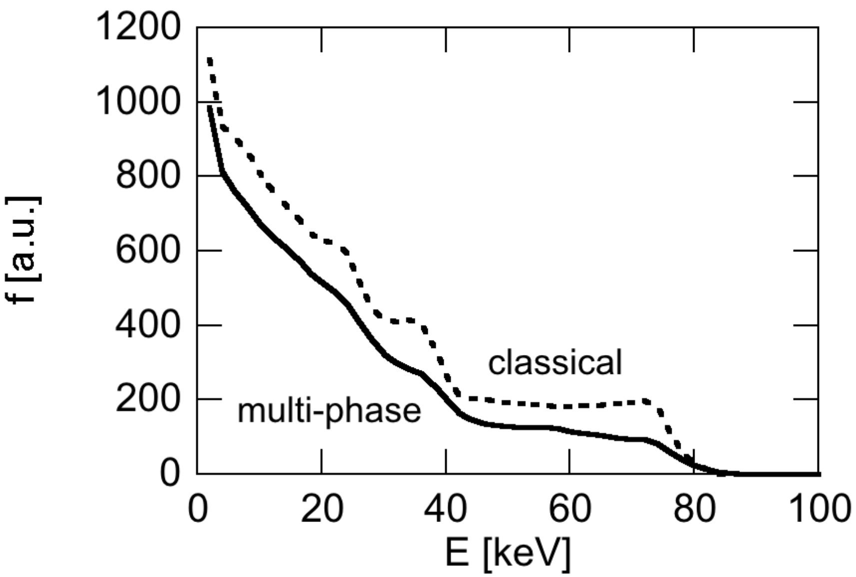
Velocity space distribution of fast ions

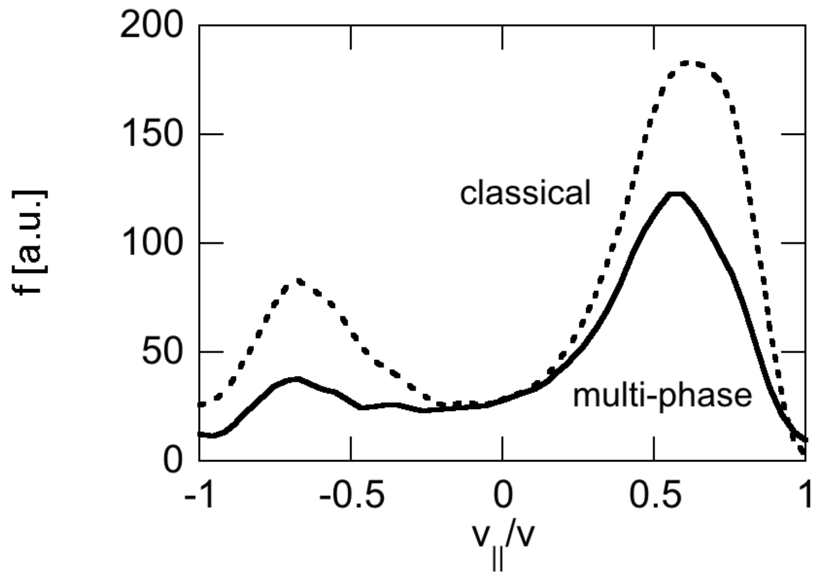
Classical



Multi-phase



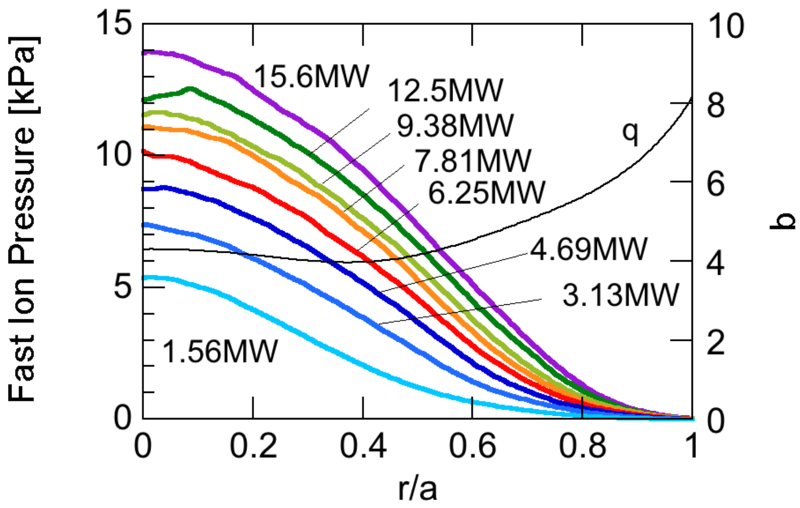


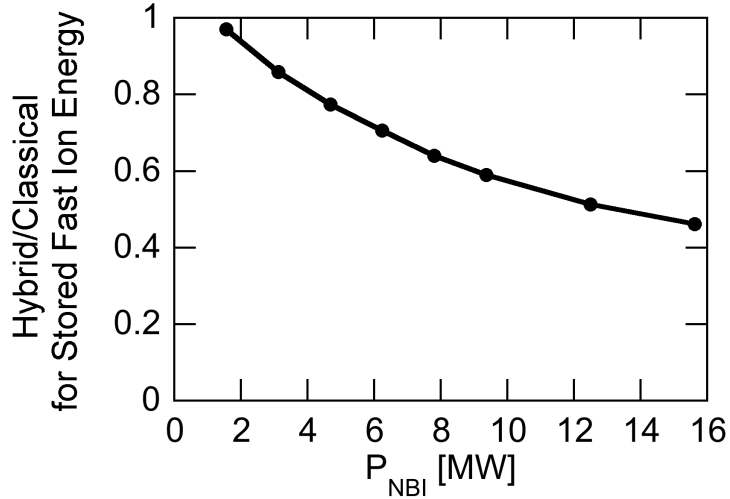


Study of fast ion profile stiffness with beam deposition power scan

- With the same equilibrium and beam deposition data as the validation study for #142111 at t=525ms.
- Beam deposition power scan from 1.56MW to 15.6MW with the experimental value 6.25MW.

Fast ion pressure profiles and stored fast ion energy



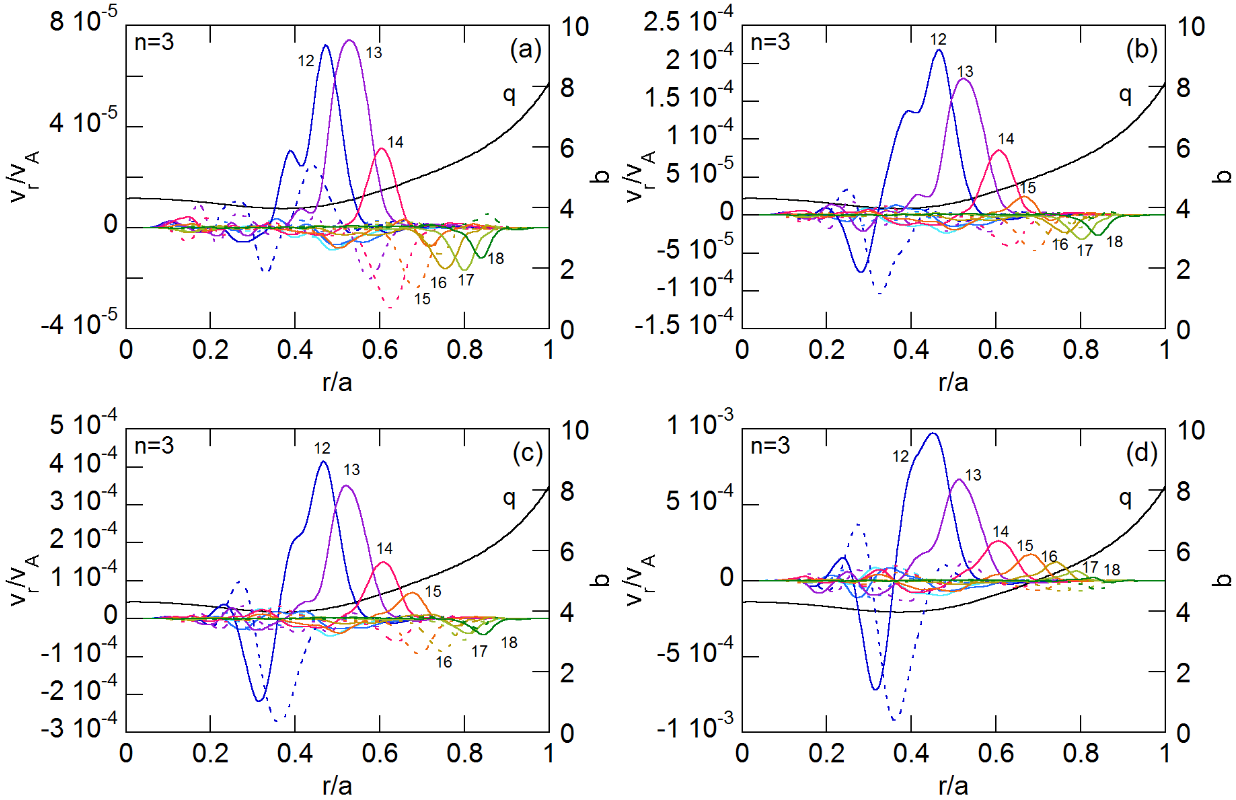


- （left）Fast ion pressure increases with increasing NBI power, but
- （right）the ratio of stored fast ion energy to the classical (w/o MHD) simulation is degraded monotonically.

Spatial profile of the dominant TAE (n=3)

P_{NBI}=1.56MW
72kHz

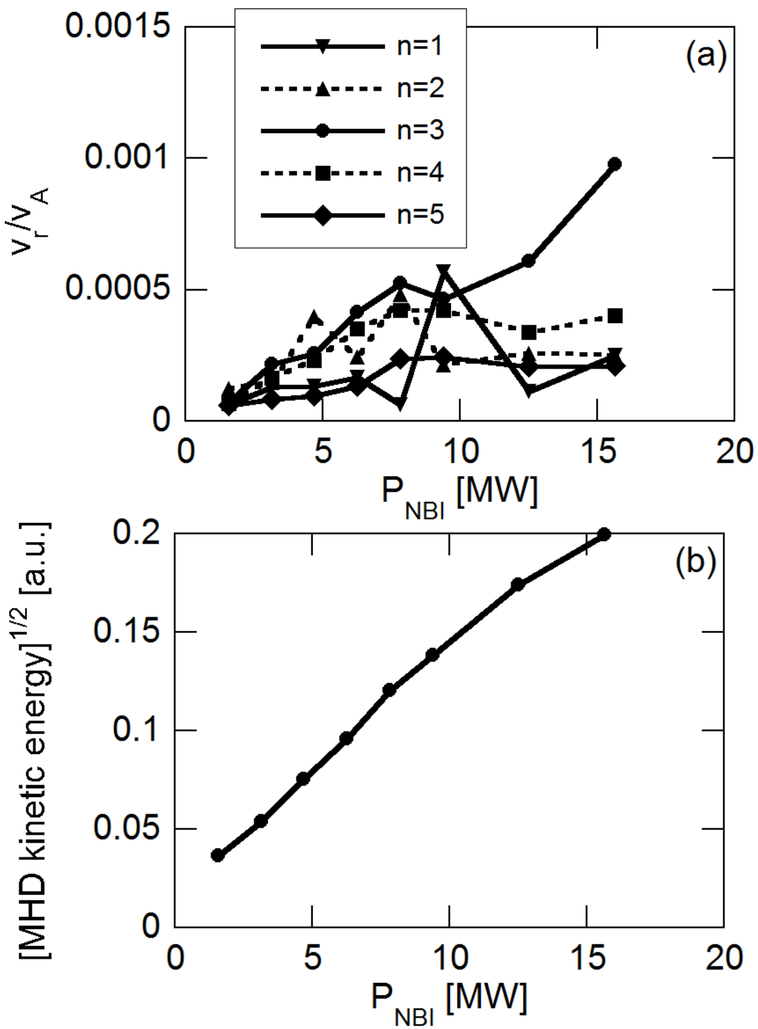
P_{NBI}=3.13MW
72kHz



P_{NBI}=6.25MW
69kHz

P_{NBI}=15.6MW
67kHz

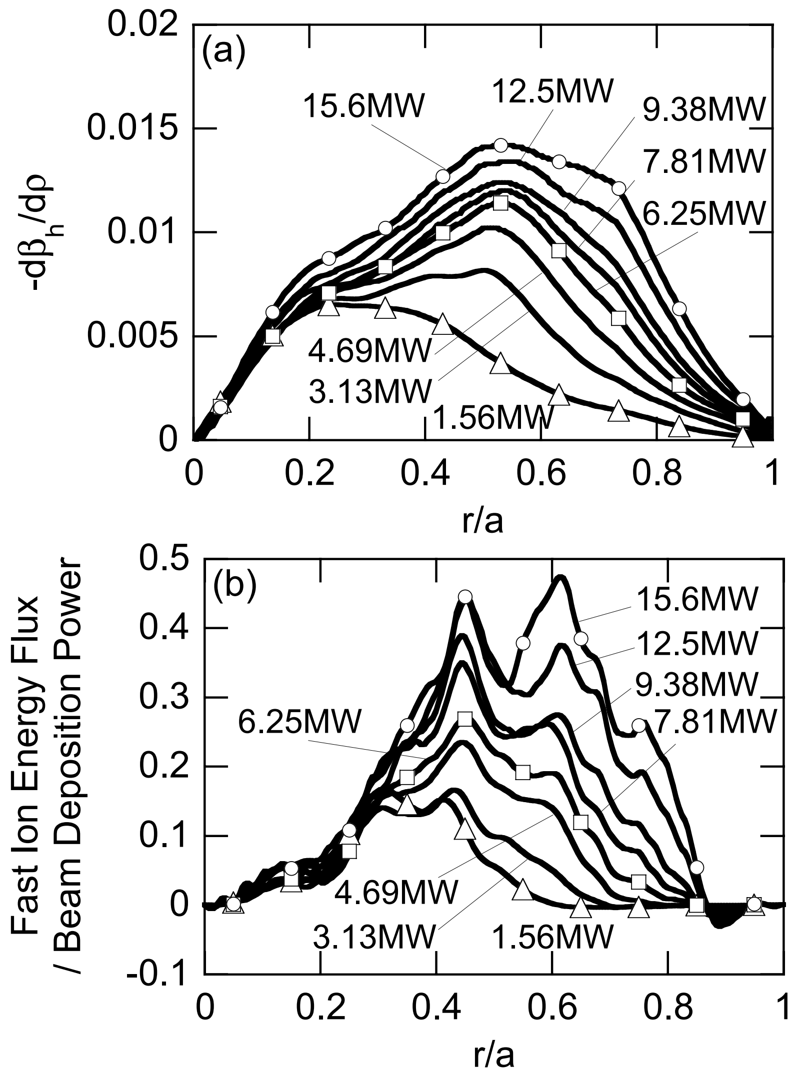
TAE amplitudes increases linearly with increasing NBI power



amplitudes of TAE

square root of MHD kinetic energy

Fast ion pressure gradient and fast ion energy flux profile



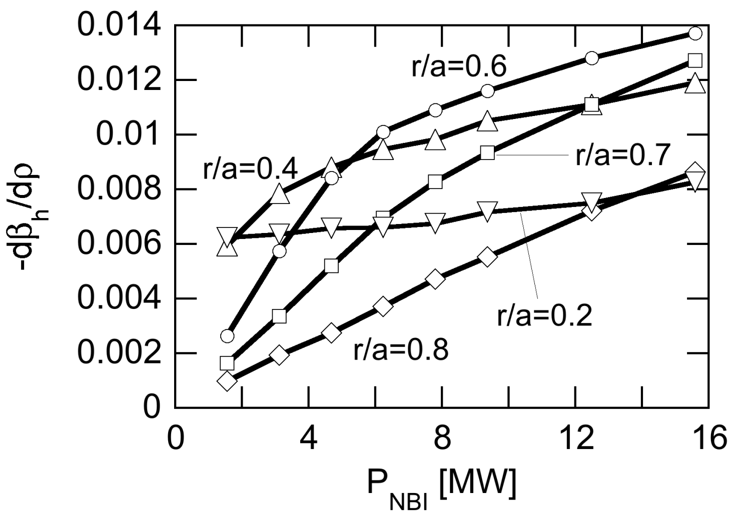
fast ion pressure gradient

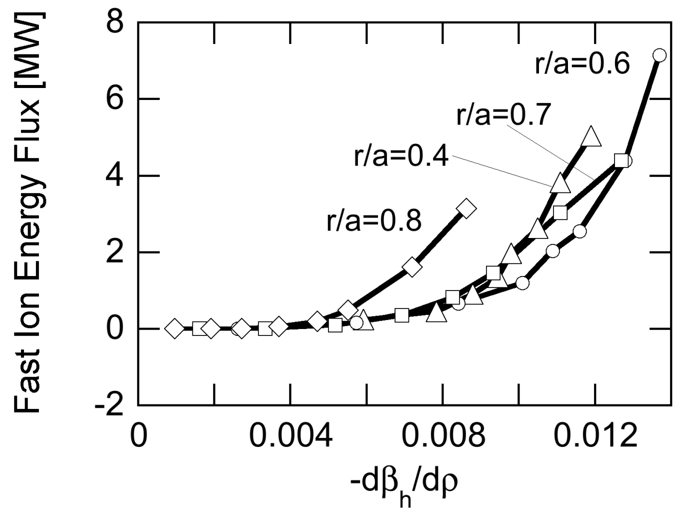
is saturated around 0.01, and spreads outward with increasing NBI power.

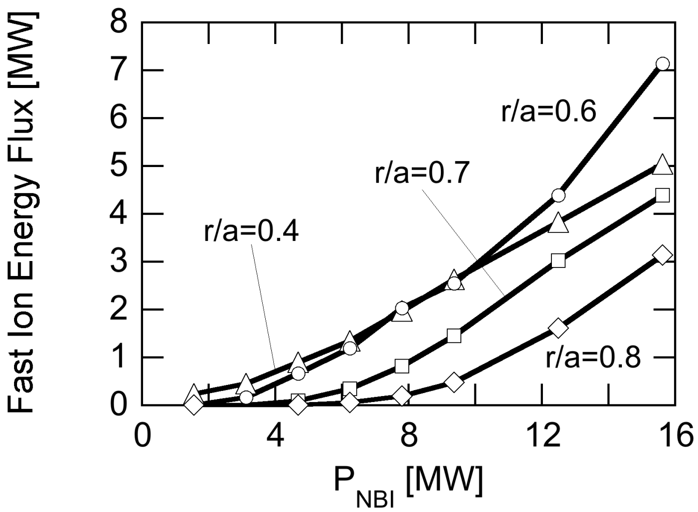
fast ion energy flux profile normalized by NBI power

significantly increases with increasing NBI power, especially at r/a>0.5.

Critical fast-ion pressure gradient for sudden increase in energy flux





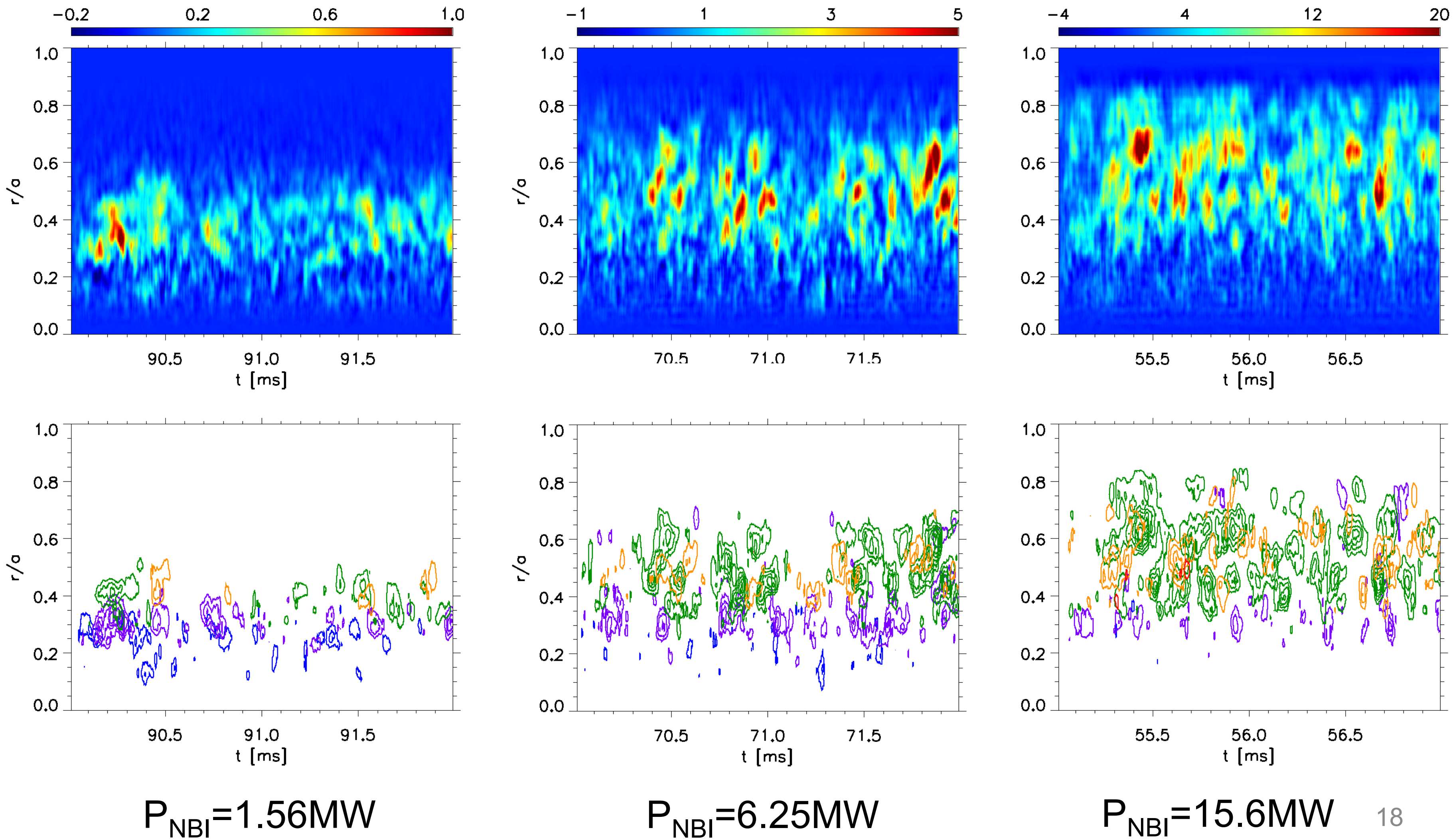


(top left) normalized pressure gradient is saturated around 0.01.

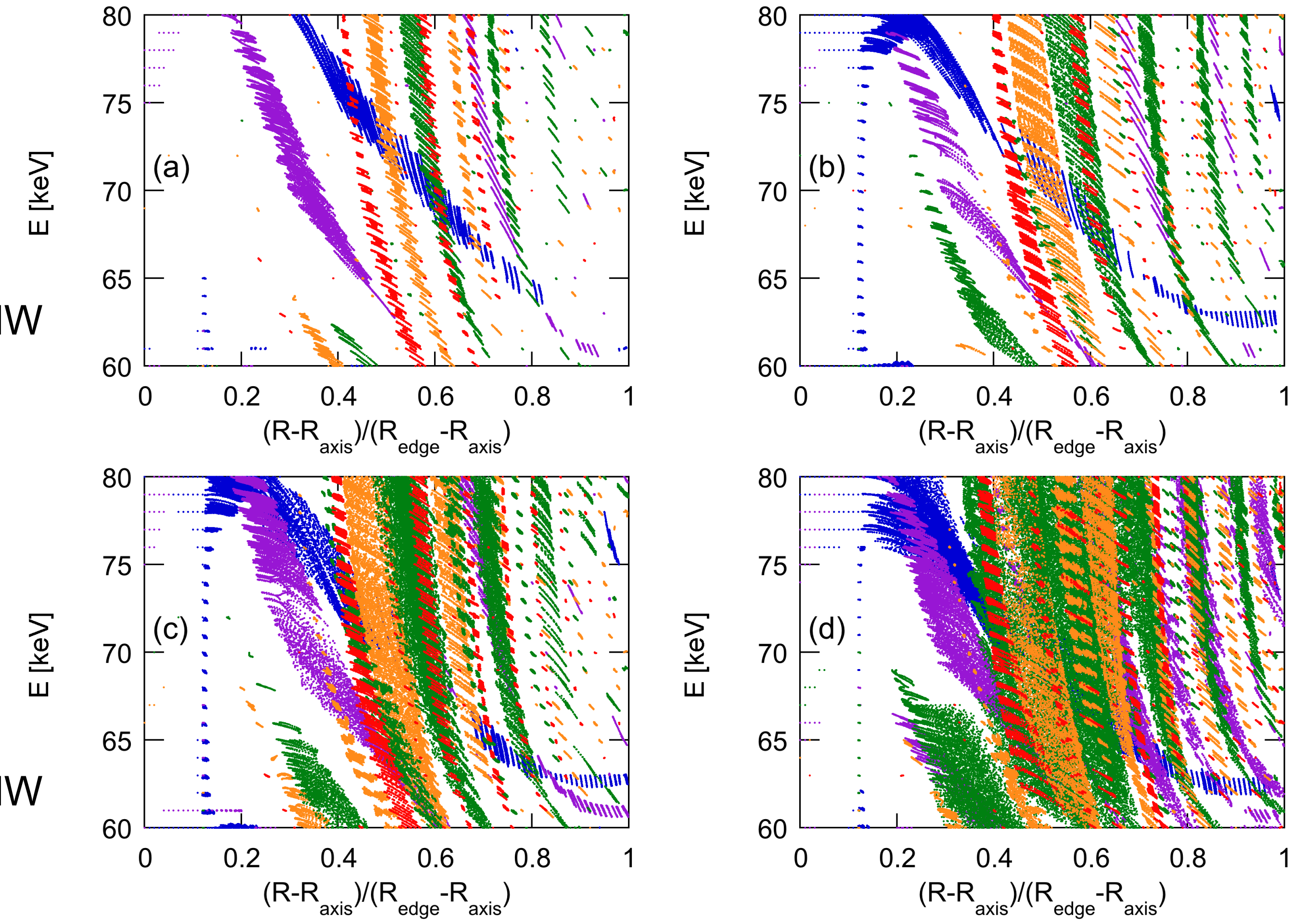
(top right) critical gradient for sudden increase in energy flux

(bottom) critical beam power depends on radial location.

Time evolution of fast ion energy flux profile [intermittency, avalanches, multiple modes, spreads outward]



Resonance overlap in (R,E) phase space [blue (n=1), purple (n=2), green (n=3), orange (n=4), red(n=5)]



P_{NBI}=1.56MW

P_{NBI}=3.13MW

P_{NBI}=6.25MW

P_{NBI}=15.6MW

Summary

- The hybrid simulation was successfully **validated on fast ion profile flattening and electron temperature fluctuations measured** in the DIII-D plasma
- **Fast ion profile stiffness with critical gradient**
  - transport flux increasing suddenly above a critical gradient
  - leading to the fast ion profile stiffness.
  - the critical gradient and the corresponding critical beam power depends on radial location.
  - fast ion pressure gradient stays moderately above the critical value, and the fast ion profile spreads outward.
  - the sudden increase in fast ion energy flux can be attributed to the **Resonance Overlap of multiple Alfvén eigenmodes.**