Simulation study of Alfvén eigenmodes in ITER and DIII-D

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Outline

- MEGA code
  - simulation model
  - strong scaling on Helios, Plasma Simulator, K
- AE modes and EP transport in ITER
  - Steady State Scenario (9MA)
- AE modes in DIII-D
  - Transition from RSAE to TAE
  - Nonlinear simulation with NBI, collisions, and losses

MEGA code

- Hybrid code with GK energetic particles (with FLR) + full MHD
- EP and MHD are coupled through EP current density in MHD momentum equation (current coupling model)
- 4th order finite difference for MHD + 4th Runge-Kutta for time integration
- Parallelized with MPI + OpenMP
- 3D domain decomposition (R, ϕ, z) + particle decomposition

MHD equations with EP current coupling

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

$$\rho \frac{\partial}{\partial t}\mathbf{v} = -\rho \vec{\omega} \times \mathbf{v} - \rho \nabla(\frac{v^2}{2}) - \nabla p + (\mathbf{j} - \mathbf{j}'_h) \times \mathbf{B}$$

$$+\frac{4}{3}\nabla(\nu \rho \nabla \cdot \mathbf{v}) - \nabla \times (\nu \rho \vec{\omega})$$

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

$$\frac{\partial p}{\partial t} = -\nabla \cdot (p \mathbf{v}) - (\gamma - 1) p \nabla \cdot \mathbf{v} + \chi \Delta(p - p_{\mathrm{eq}})$$

$$+(\gamma - 1)[\nu \rho \omega^2 + \frac{4}{3}\nu \rho (\nabla \cdot \mathbf{v})^2 + \eta \mathbf{j} \cdot (\mathbf{j} - \mathbf{j}_{\mathrm{eq}})]$$

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

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

$$\vec{\omega} = \nabla \times \mathbf{v}$$

$$\nu_n = 10^{-7} \mathrm{v}_A R_0$$

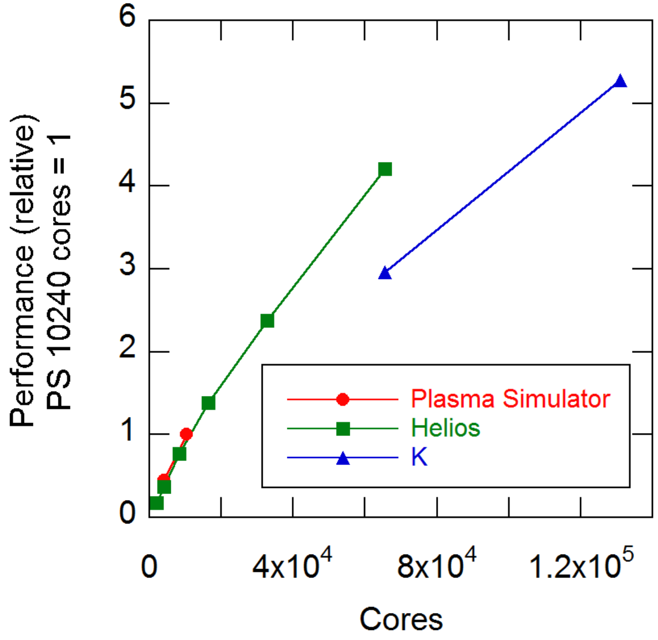
$$\nu = 10^{-7} \mathrm{v}_A R_0$$

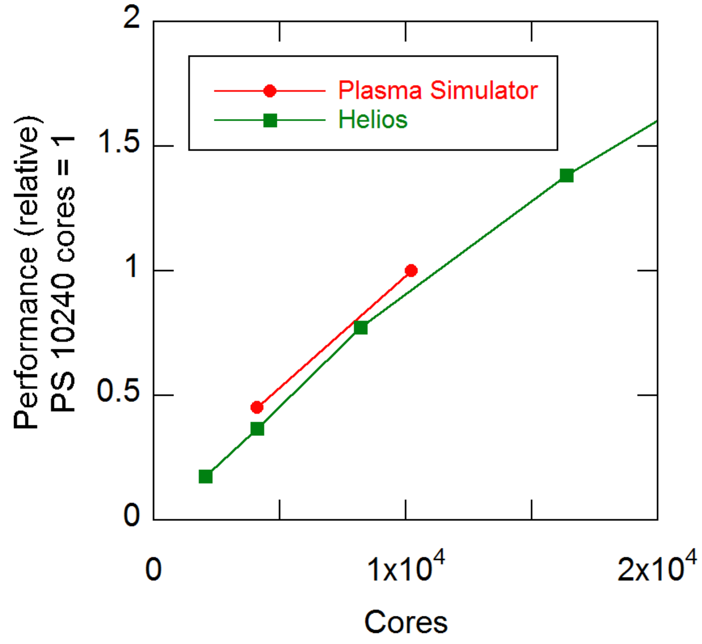
$$\eta = 10^{-7} \mathrm{v}_A R_0$$

$$\chi = 10^{-7} \mathrm{v}_A R_0$$

Performance comparison between Helios and other computers

- MEGA (512x512x320 grids, 6.7x10^8 particles)
- Helios: SandyBridge EP 2.7GHz, 21.6GF/core
  - Parallelization ratio: 99.9994%
- Plasma Simulator: POWER7 3.836GHz, 30.7GF/core
- K: SPARC 64 VIIIfx 4.0GHz, 16GF/core
  - Parallelization ratio: 99.9998%





AE modes and EP Transport in ITER Steady State Scenario (9MA)

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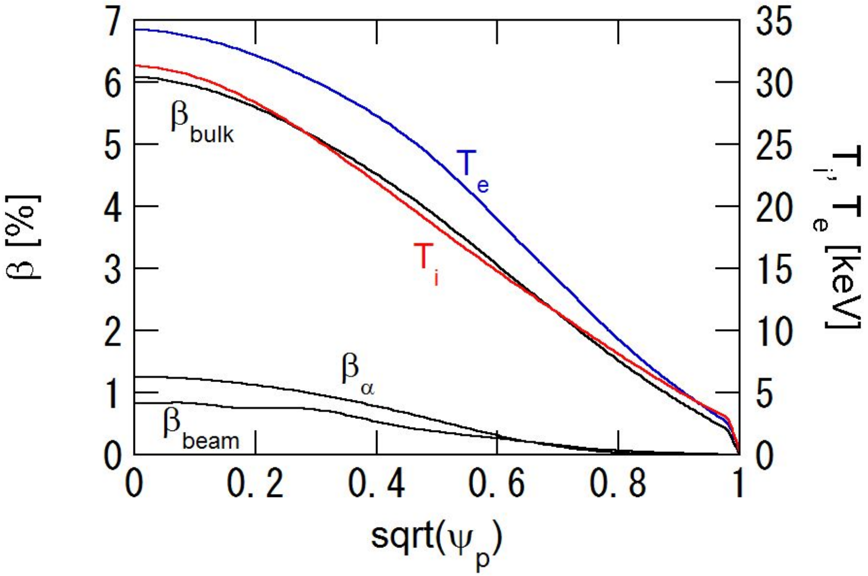
NIFS JAEA IFERC

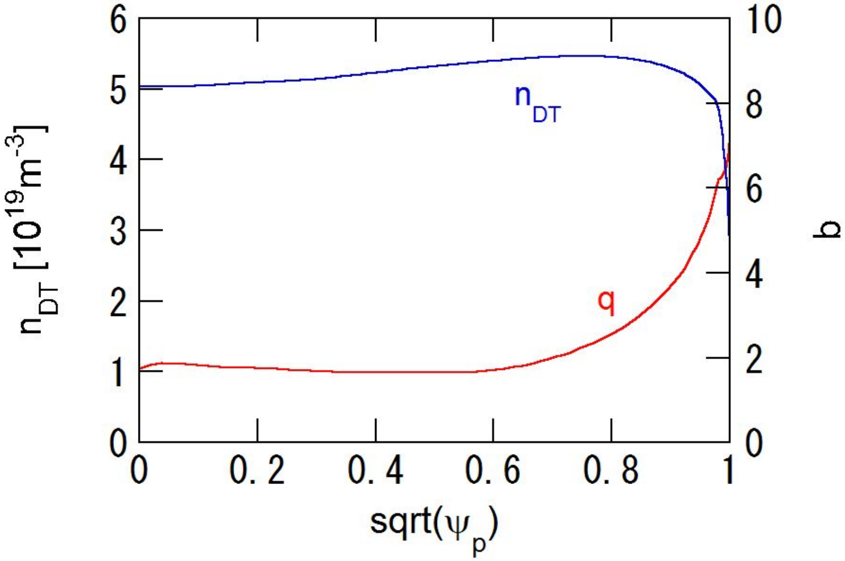
Introduction to AE modes in ITER

- Alfvén eigenmodes might be destabilized by energetic alpha particles (3.5MeV) and deuterium beam ions (1MeV)
- theoretical studies
  - Gorelenkov (2005): beam ion anisotropy in velocity space leads to destabilization of TAE modes with n~10
  - Vlad (2006), Todo (2006): low n (n~2,3) modes are unstable in EP-MHD hybrid simulations

ITER steady state scenario

- Steady state scenario (on ITER web*)
- R=6.2m, a=2m, B=5.3T, I=9MA
- ASTRA, EFIT



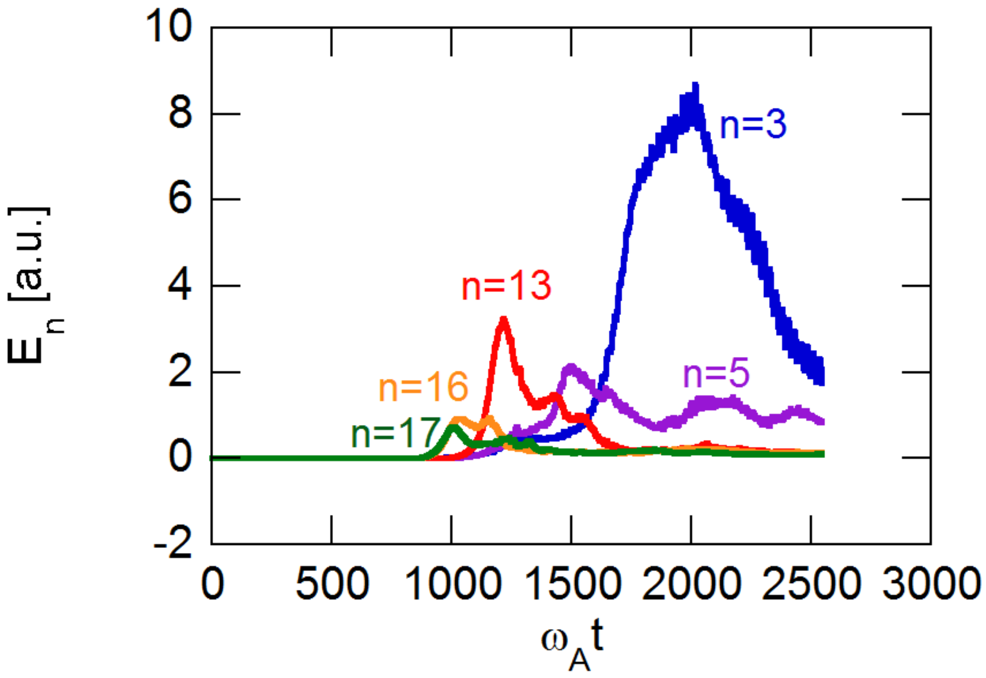


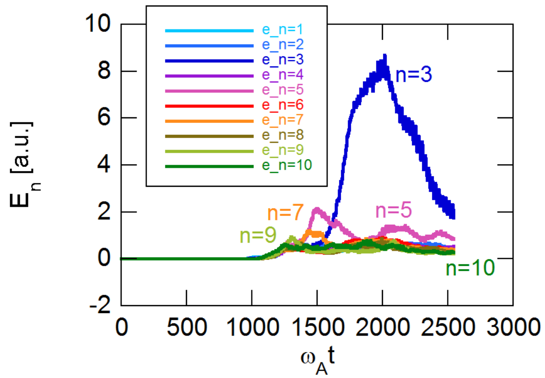
*IDM DATA folder: Plant Breakdown Structure / TBD. Plasma / 10.1.1 Plasma Confinement/EnergeticParticles / ITER reference data for EP modeling/ Equilibrium/ Update2011/ 9MA plasma equilibrium

Computational condition and method

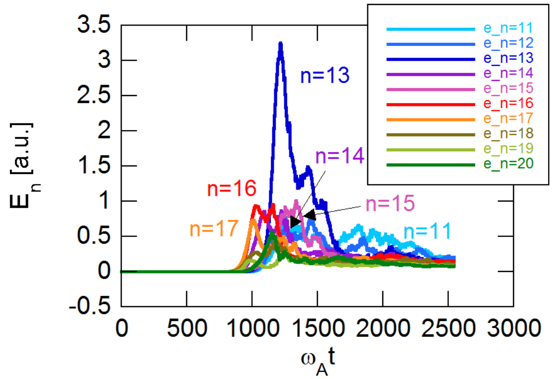
grid points for (R, ϕ, z)	256×256×512
total number of marker particles	8.4×10^6 (alpha) + 8.4×10^6 (D beam)
alpha particles	isotropic slowing down distribution (3.5 MeV) with FLR
deuterium beam	anisotropic slowing down distribution (1 MeV) exp[-(Λ-0.3)^2/0.3^2] with FLR

Energy evolution of each n





n=1-10

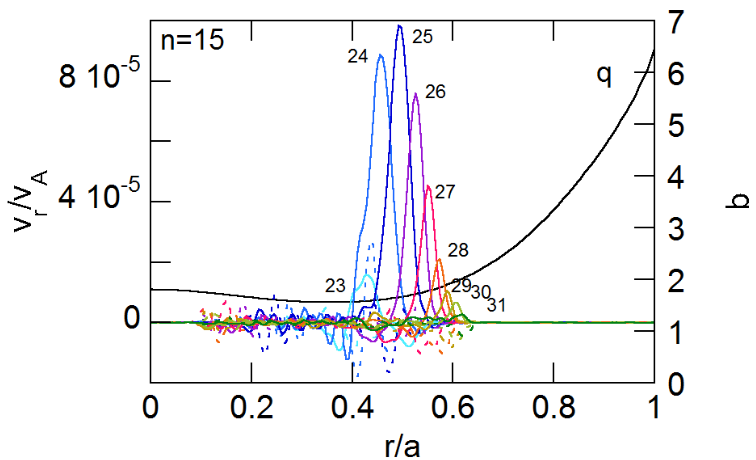


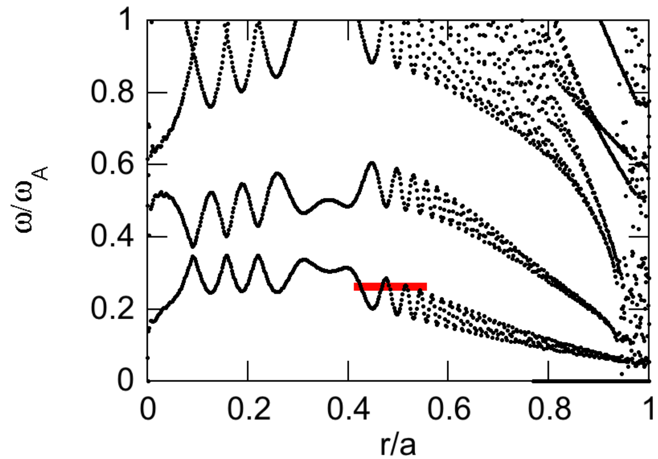
n=11-20

- The most unstable modes in the linear phase are the TAE modes with n=13-17.
- BAE modes with n=3 and 5 become dominant in the nonlinear phase.

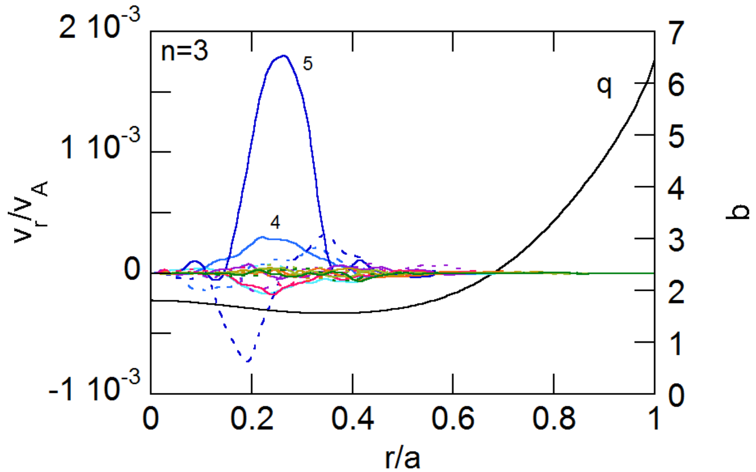
AE spatial profiles and Alfvén continuum

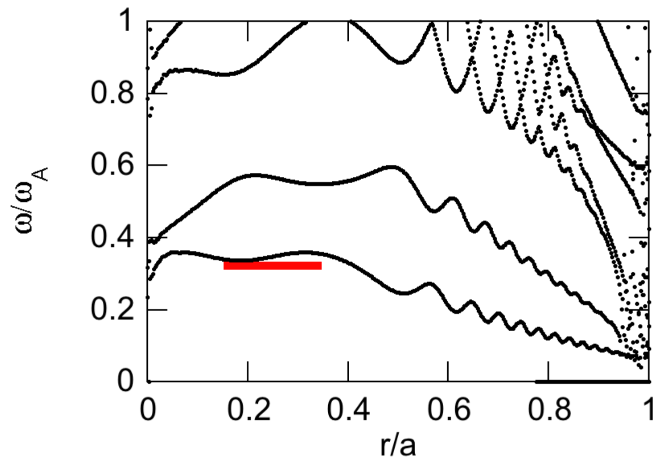
n=15 TAE
$\omega_A t=900$



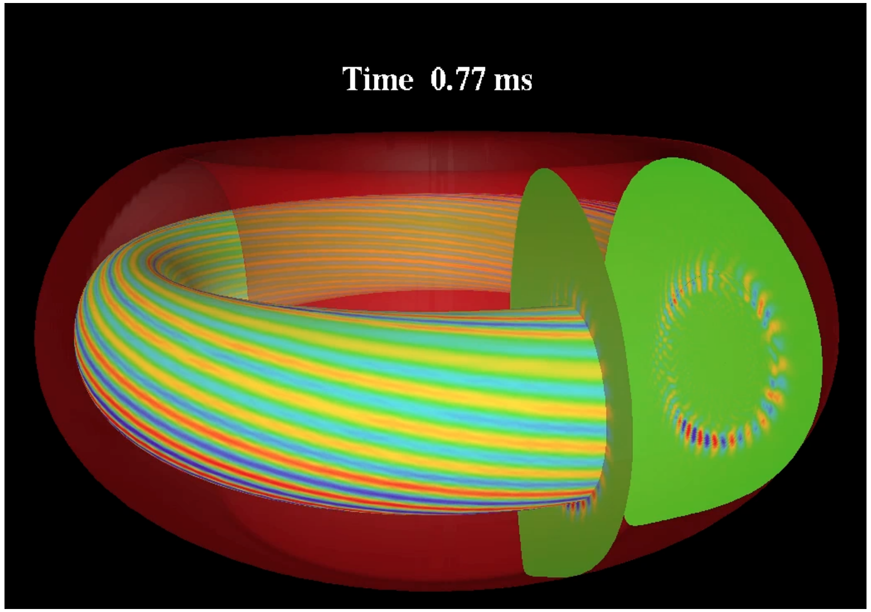


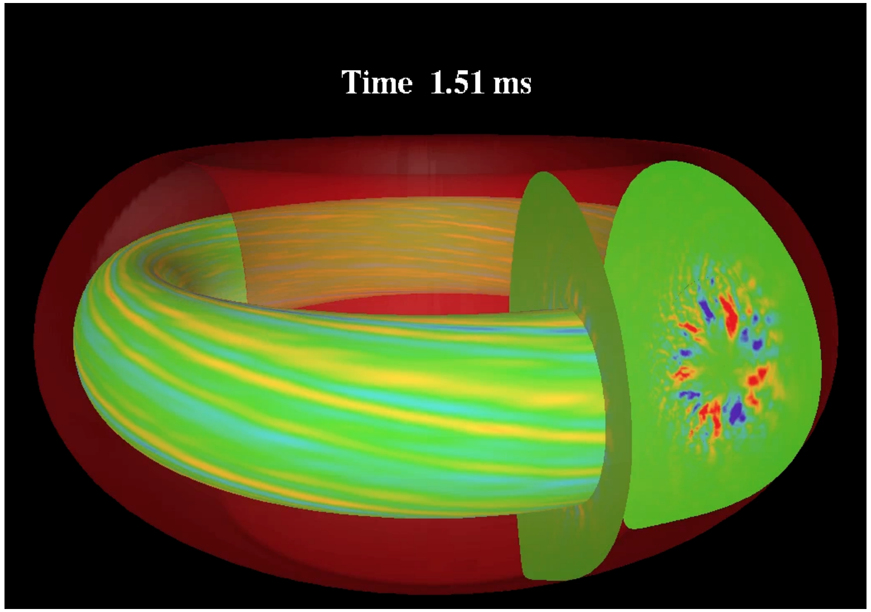
n=3 BAE
$\omega_A t=1600$



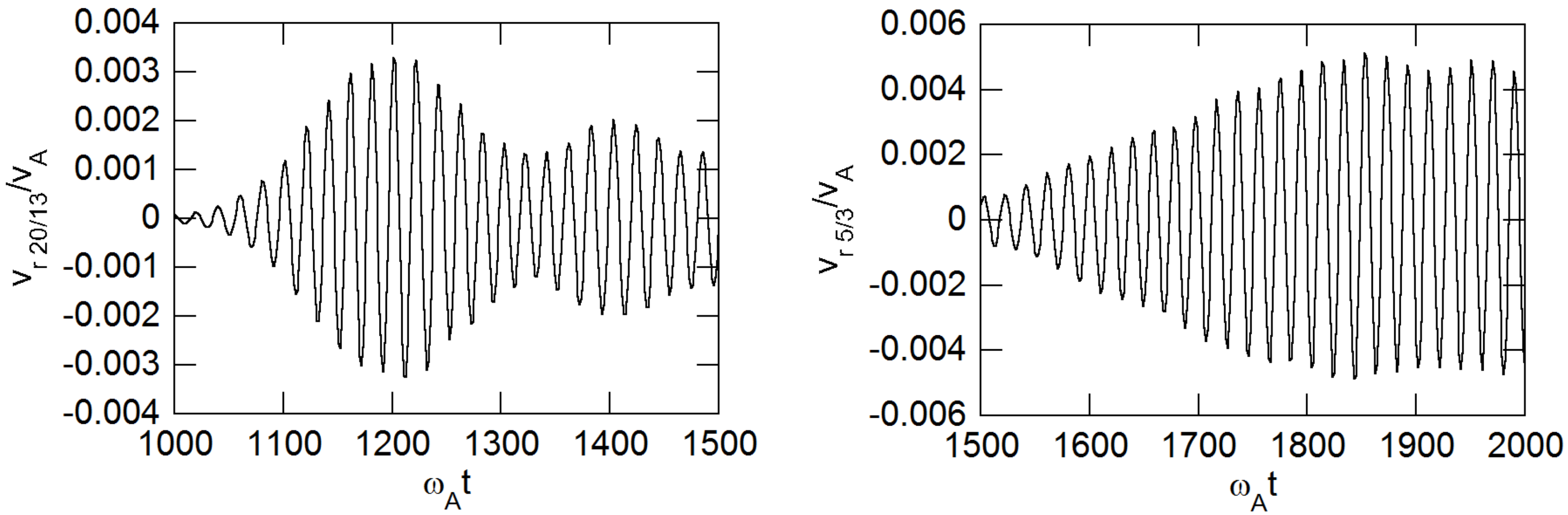


Movie of rv_r evolution



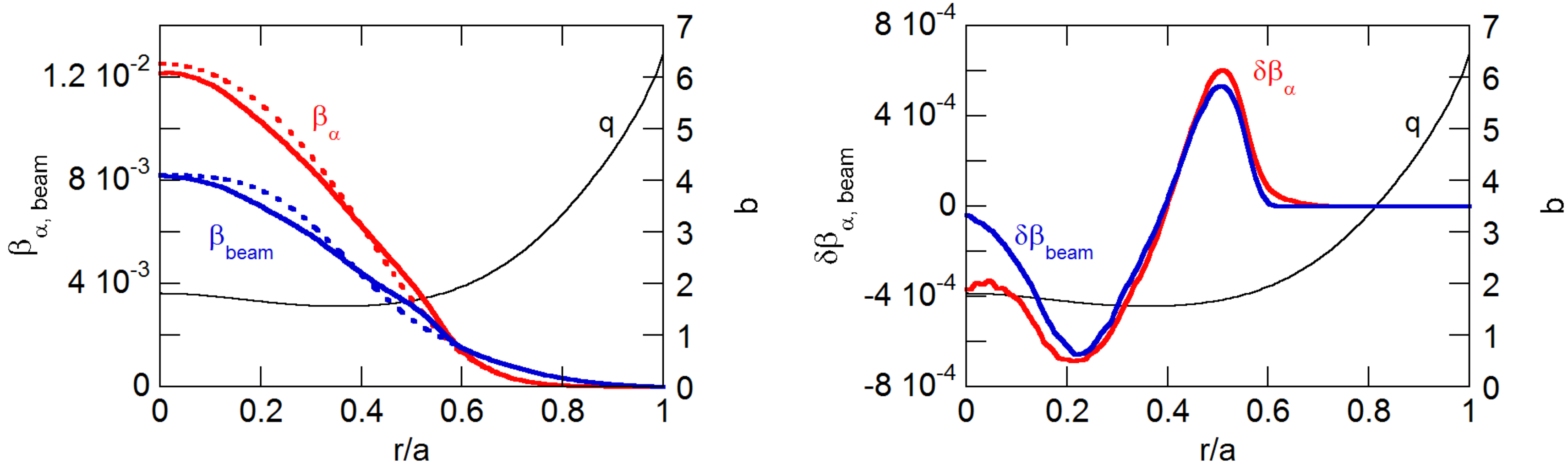


Saturation amplitude



Saturation amplitude is
v/vA~3x10^-3 (m/n=20/13 left) and
v/vA~4x10^-3 (m/n=5/3 right)

Energetic Particle Redistribution



Slight redistributions take place for both alphas and beam deuterons.
db_a~0.07%, db_{beam}~0.07%.

Summary of AE Modes in ITER Steady State Scenario (9MA)

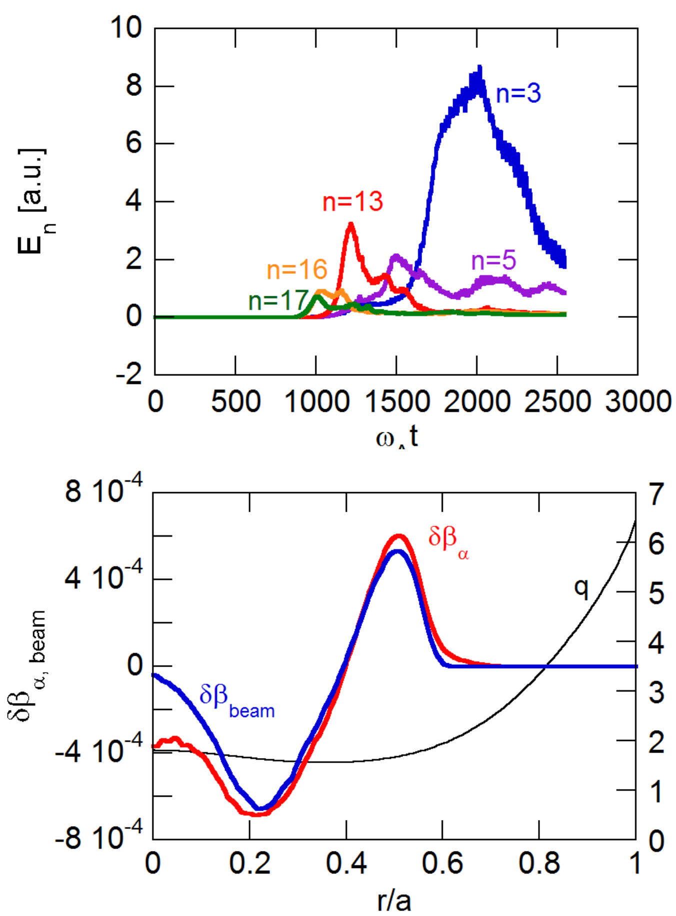
- TAE modes with n=13-17 are most unstable in the linear phase
- BAE modes with n=3 and 5 become dominant in the nonlinear phase

- saturation level $v_r/v_A \sim dB_r/B \sim 3\text{-}4\times10^{-3}$
- redistribution $db_a \sim 0.07\%$, $db_{beam} \sim 0.07\%$

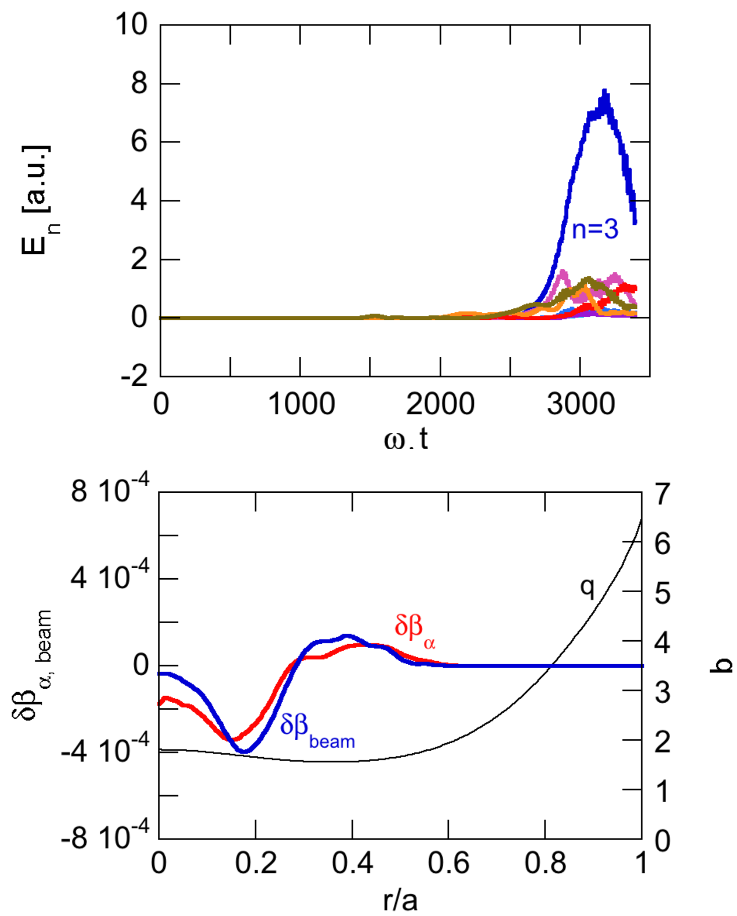
- Any effects of multiple modes?

Multiple modes enhance energetic particle transport

all n



restricted to n≤8



Future work

- Kinetic effects of bulk plasma
  - BAE modes might be stabilized by thermal ion Landau damping, several damping mechanisms for AE modes
  - interaction with zonal flow and field
- Long time evolution with source and sink
  - bursts, steady amplitude, frequency chirping
  - validation with experiment
- Prediction of ITER plasmas
  - this work is just a beginning, so many cases should be investigated

Nonlinear Simulation of Alfvén Eigenmodes in DIII-D

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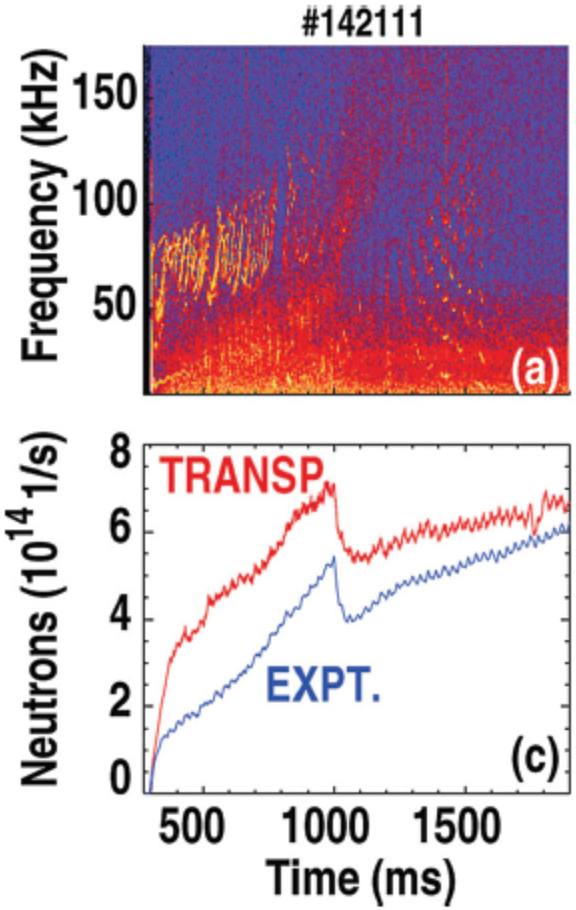
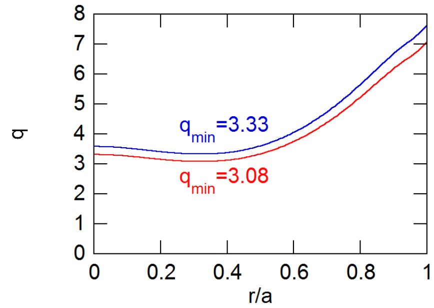
Introduction

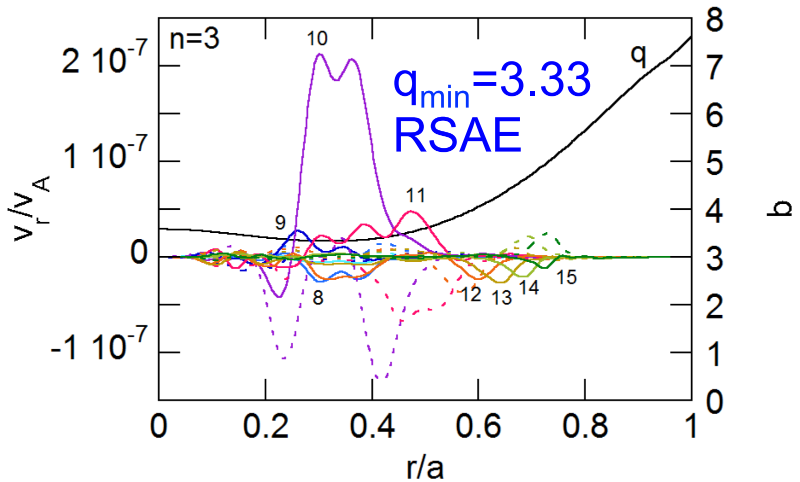
- DIII-D discharge #142111
  - Many TAE and RSAE modes are observed
  - Weakly reversed q profile in current ramp-up phase
  - Neutron deficit compared with TRANSP simulation
  - B=2T, P_{NB}~6.8MW

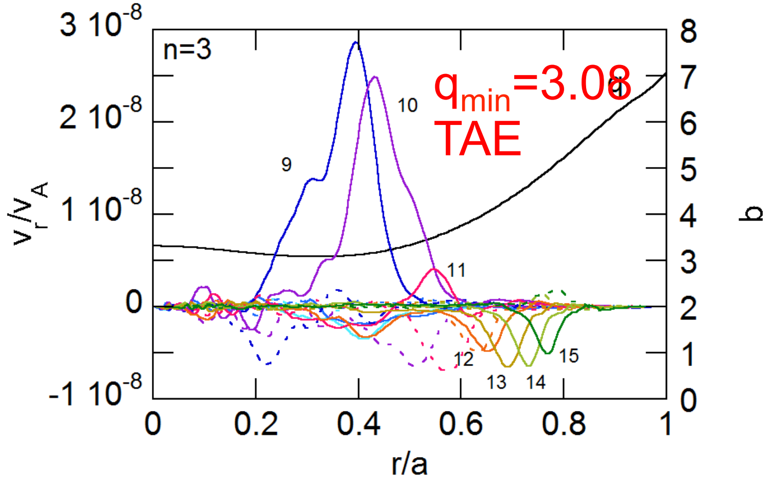


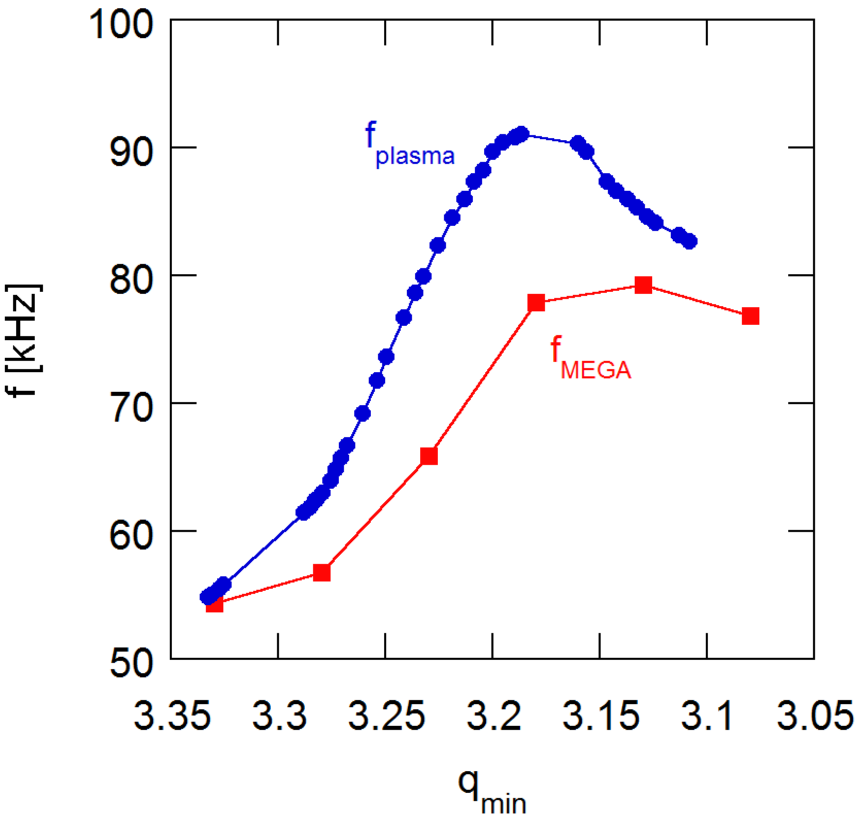
Van Zeeland, PoP (2011)

Transition from RSAE to TAE for n=3 at t=725ms





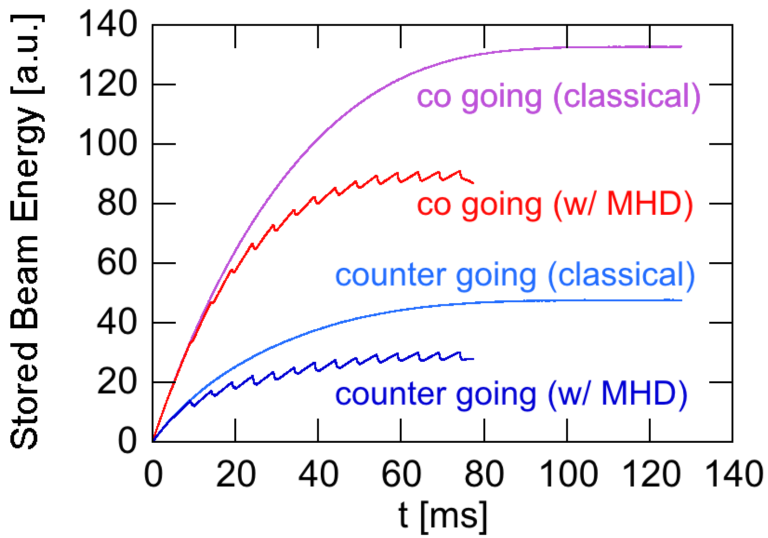


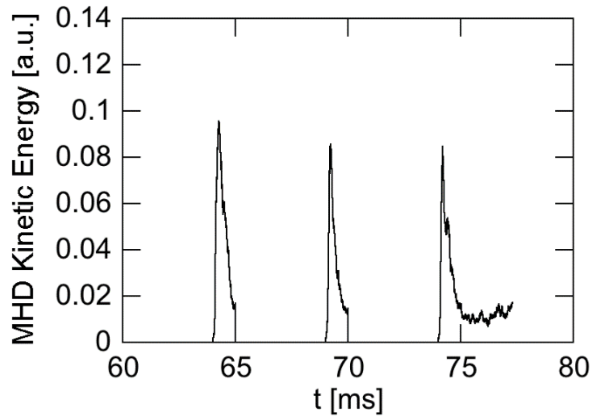


Nonlinear simulation model

- Neutron deficit or anomalous flattening of fast ion profile investigated for DIII-D discharge #142111 at t=525ms.
- Realistic beam ion deposition profile (primary energy) calculated with TRANSP code is employed.
- 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 a constant time interval in 150ms (both classical and hybrid simulations are terminated before t=150ms).
- Beam injection power is 4.95MW.

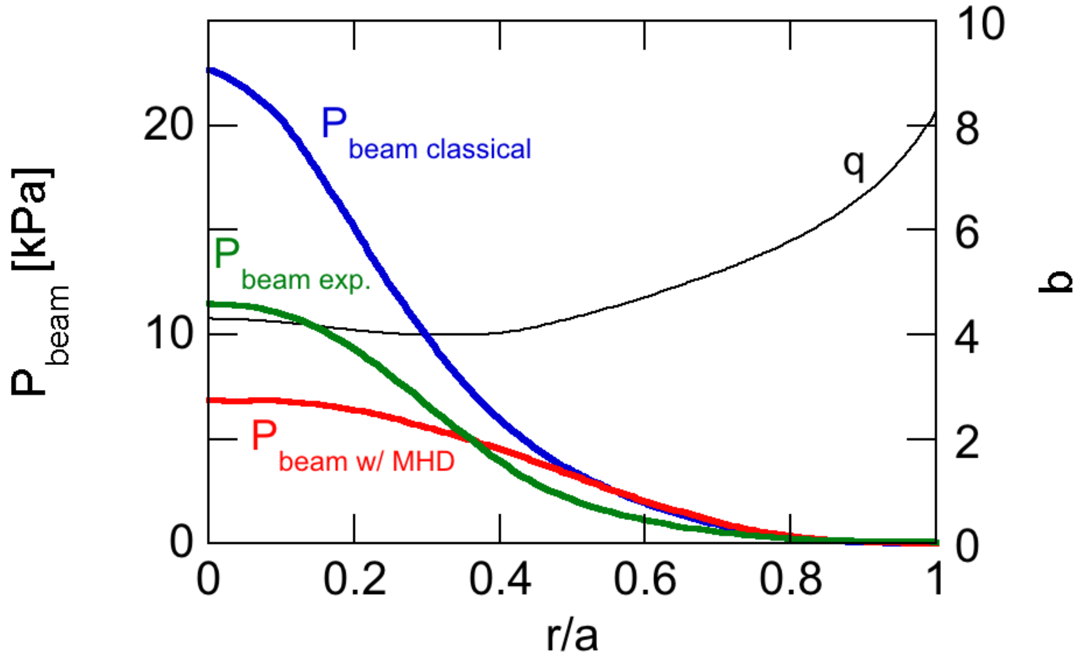
Time evolution of stored beam energy





- Hybrid simulation is compared with classical simulation in stored beam energy.
- The hybrid simulation was run w/o MHD for 4ms and then run with MHD for 1ms. This set is repeated until stored beam energy is saturated at t=75ms.
- At t=75ms, the MHD fluctuation reaches to a steady level.

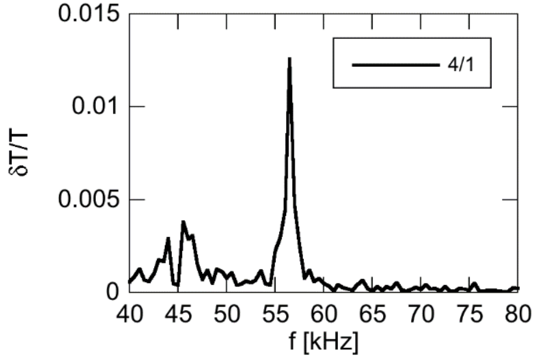
Comparison of beam pressure profiles (classical, hybrid, exp.)



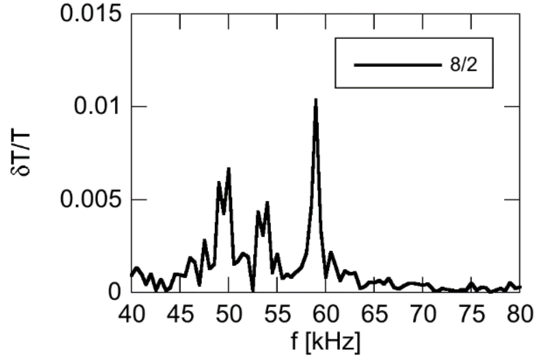
- Anomalous flattening of beam pressure profile takes place in the hybrid simulation (w/ MHD).
- However, the flattening is greater than that in the experiment.

Bulk temperature fluctuation spectra at r/a=0.4 at t≥75ms

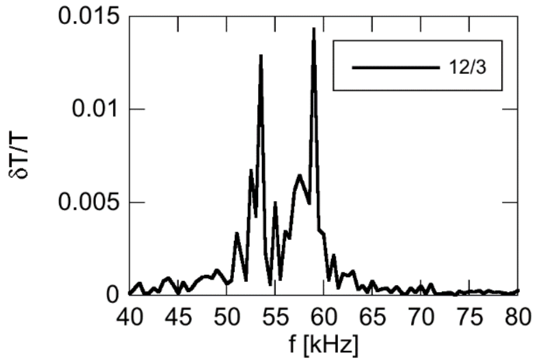
m/n=4/1



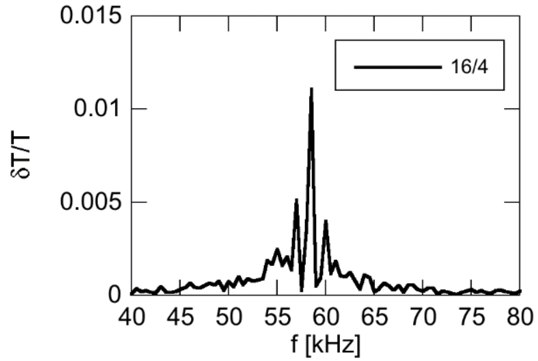
m/n=8/2



m/n=12/3



m/n=16/4



- δ T/T ~ O(10^-2) that is comparable to the experiment.
- Dominant fluctuations are TAE modes at ~60kHz. This is consistent with the experiment if plasma rot. is considered.

Frequency spectrum evolution in the experiment at t~525ms

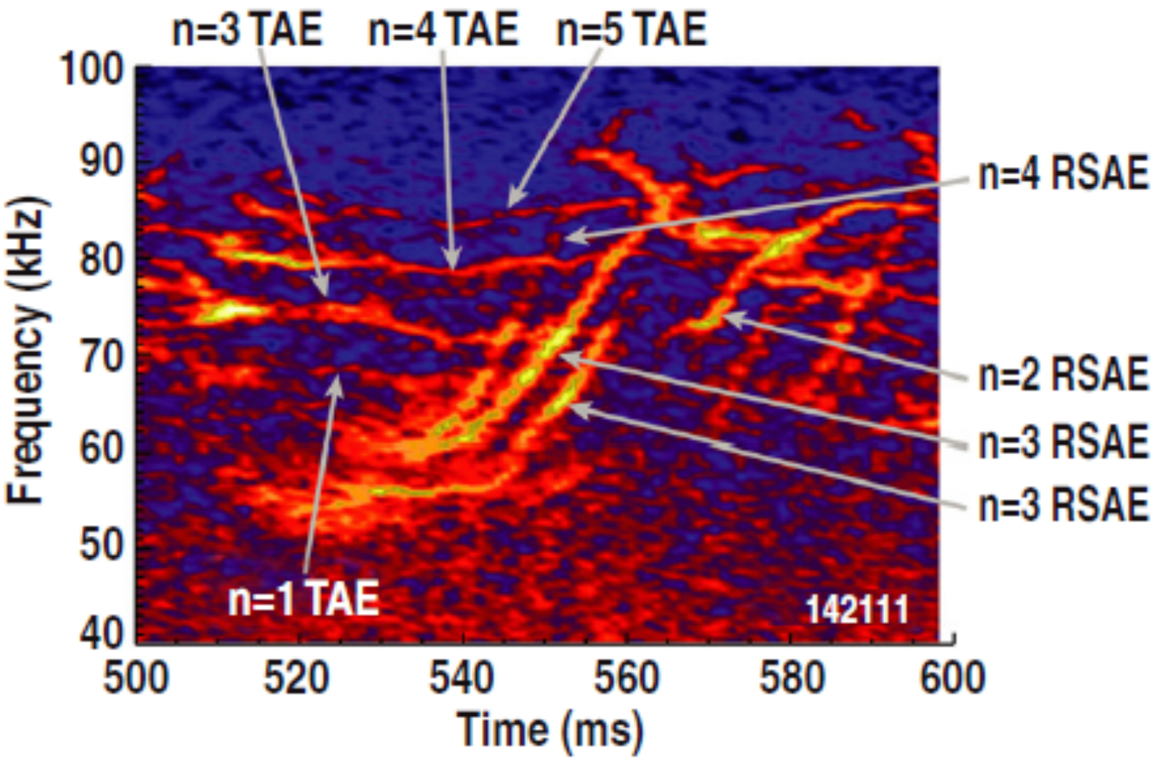
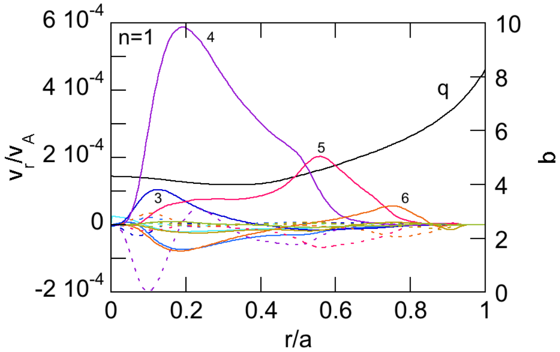


Figure 4. ECE spectrogram from figure 1(*a*) with modes identified for comparison to table 1.

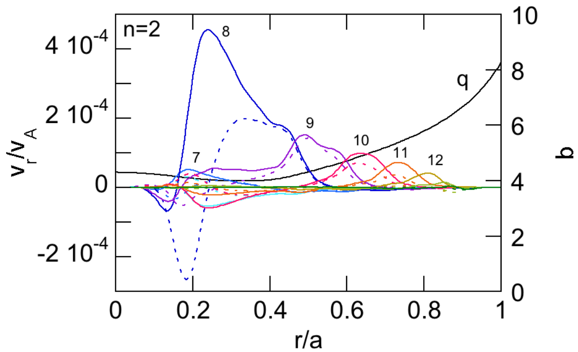
Van Zeeland, NF (2012)

Spatial profile of TAE modes at the steady state (t≥75ms)

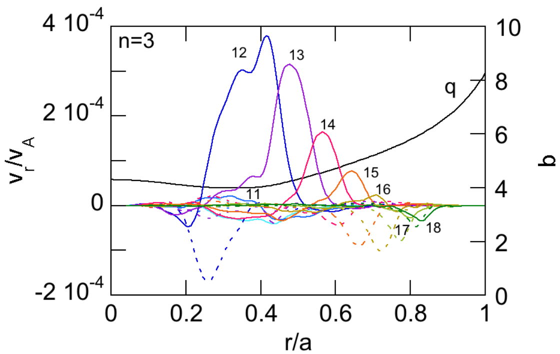
n=1
56.5kHz



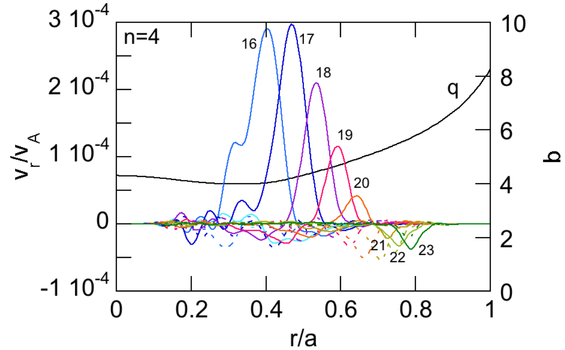
n=2
59.0kHz



n=3
59.0kHz



n=4
58.5kHz



- Amplitude of TAE modes is v_r/v_A ~ 3-6 x 10^-4
- This is larger than $\delta B_r/B$ ~ 1.5 x 10^-4 [Van Zeeland, NF (2012)] by a factor of 3.

Summary of DIII-D simulation

- A self-consistent hybrid simulation with beam injection, collisions, and losses has been successfully carried out, and a steady fast ion profile is found.
- The anomalously flattened fast ion profile is maintained by transport due to multiple AE modes with amplitude $v_r/v_A \sim O(10^{-4})$.
- Comparisons in detail
  - anomalous flattening and AE amplitude are larger than experiment => if AE modes amplitude is reduced, fast ion profile will become closer to the experiment
  - bulk temperature fluctuation ~ 1%, consistent with the experiment
  - TAE modes are the dominant fluctuations, consistent with the experiment around t=525ms