Simulation study of energetic particle driven instabilities using the IFERC-CSC computer

Y. Todo (NIFS, Japan)

17th NEXT Meeting

(Univ. Tokyo, Kashiwa, March15-16, 2012)

Outline

- Lighthouse project of the IFERC-CSC supercomputer
  - *4 projects:* GENE, ORB5, GT5D, MEGA
  - *MEGA Simulation of Energetic Particle Driven Instabilities in ITER and JT-60U* (MEGASEP)
  - Members: Y. Todo (NIFS), A. Bierwage (JAEA)
- NL MHD effects on AE evolution and NL MHD simulation of AE bursts
  - Y. Todo (NIFS), H. L. Berk, B. N. Breizman (IFS, Univ. Texas)

Lighthouse Project

- IFERC-CSC, helios
- Period: January – Mach, 2012
- Objective of the Lighthouse Project
  - To show both outstanding level of the simulation researches in the magnetically confined fusion (MCF) and high performance of IFERC-CSC supercomputer system,
  - To show the possibility that the fusion simulations could exploit a new research field or a frontier research in MCF by using the IFERC-CSC supercomputer,
  - To show the existence of the IFERC-CSC at Rokkasho

Performance comparison with BX900, and on MPI libraries/ compiler options

- MEGA (152x128x16 grids, 5.2x10^5 particles)
- Elapse time needed for 385000 steps (estimated from the first 250 steps)
- 64 cores of each helios and BX900 computer

Computer [MPI, compiler options]	Elapse Time [min]
CSC [intelmpi –O2]	637.6
CSC [intelmpi –O3 –xSSE4.2]	629.6
CSC [bullmpi –O2]	609.8
CSC [bullmpi –O3 –xSSE4.2]	610.6
BX900 [-O2]	528.7

Comparison with BX900 on strong scaling

- MEGA (152x128x16 grids, 5.2x10^5 particles)
- Elapse time needed for 385000 steps (estimated from the first 250 steps)

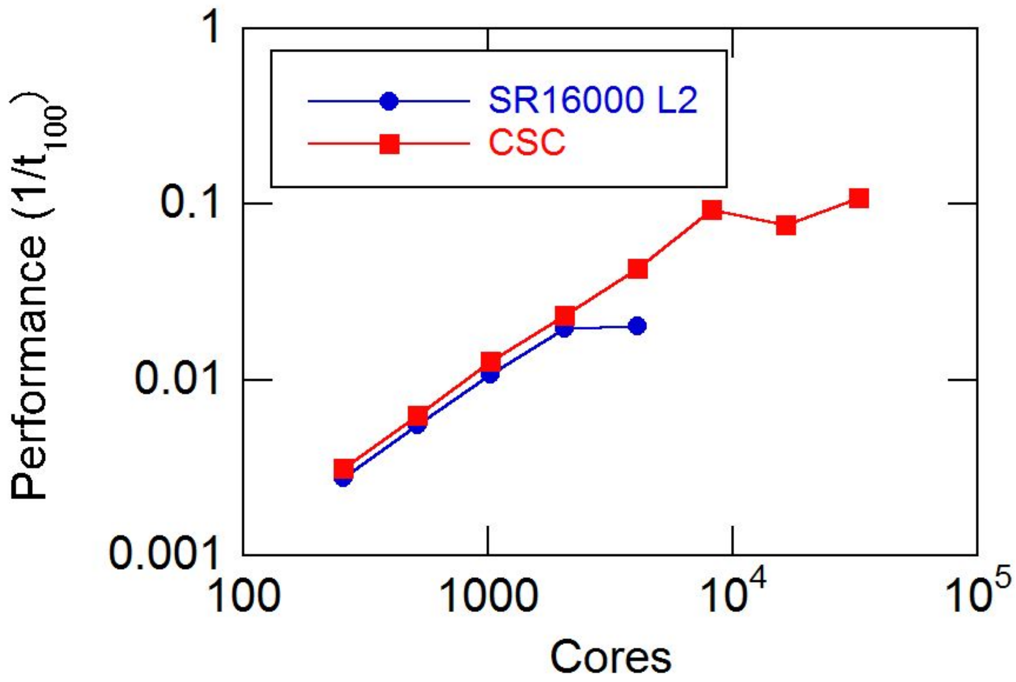
Cores	Elapse time on BX900 [min]	Elapse time on CSC [min]
128	**240**	**490**
64	530	610
32	890	950

Performance comparison with SR16000 L2

- MEGA (256x512x256 grids, 3.4x10^7 particles, with FLR)
- 1/(Elapse time for 100 steps)

SR16000 POWER6
4.7GHz, 18.8GF/core

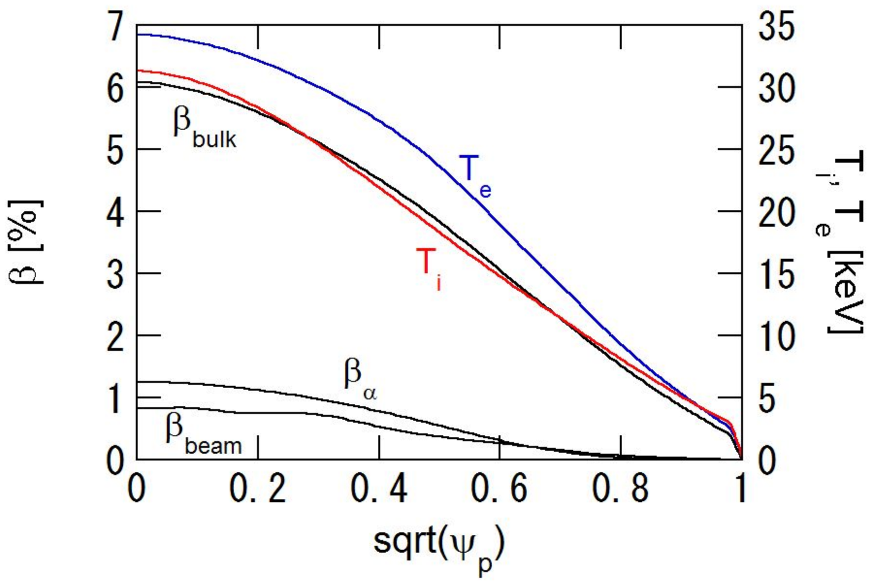
CSC SandyBridge EP
2.3GHz, 18.4GF/core

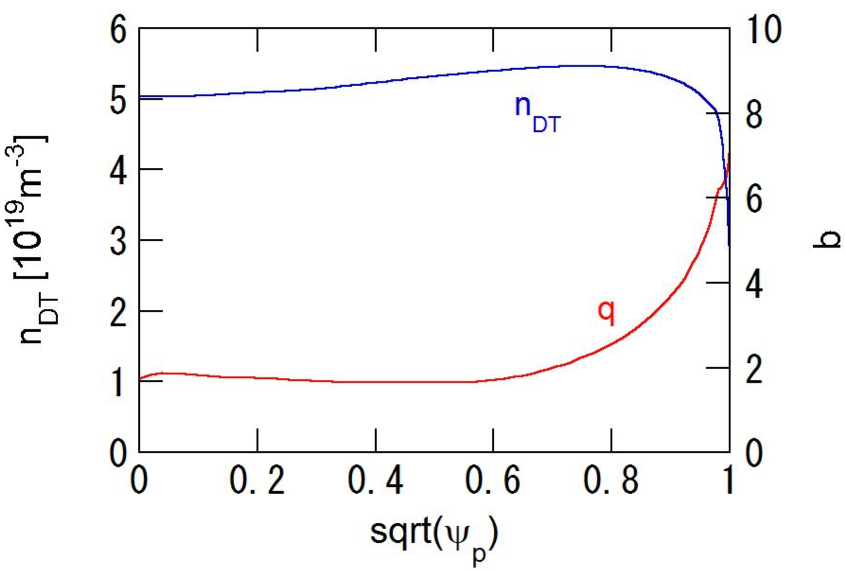


TAE MODES IN ITER STEADY STATE SCENARIO (9MA)

ITER steady state scenario

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

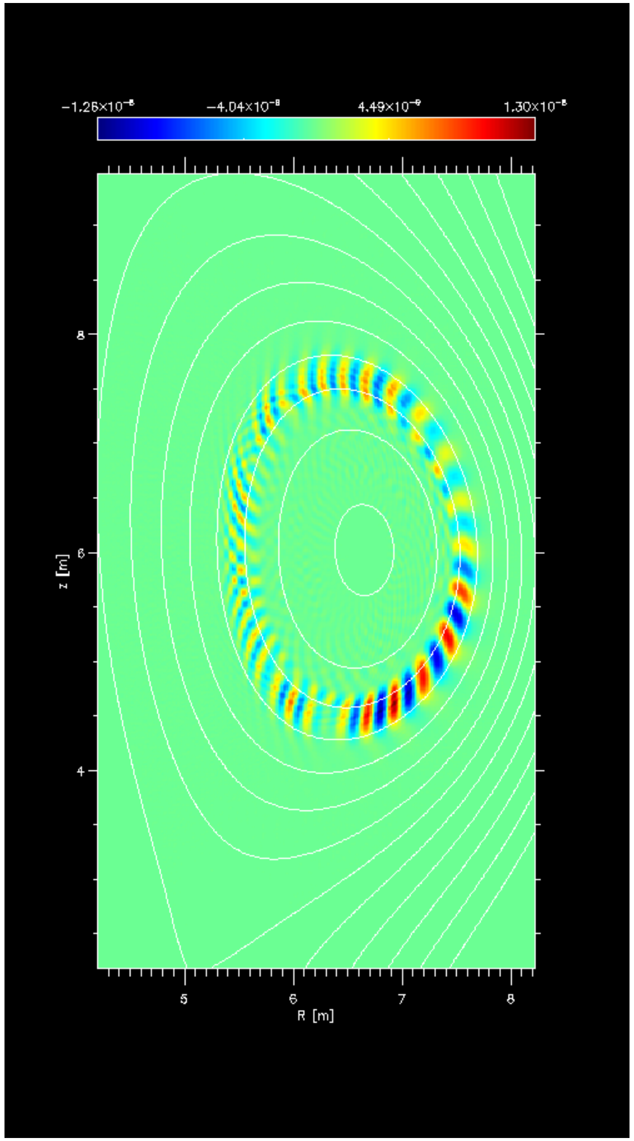




Computational condition and method

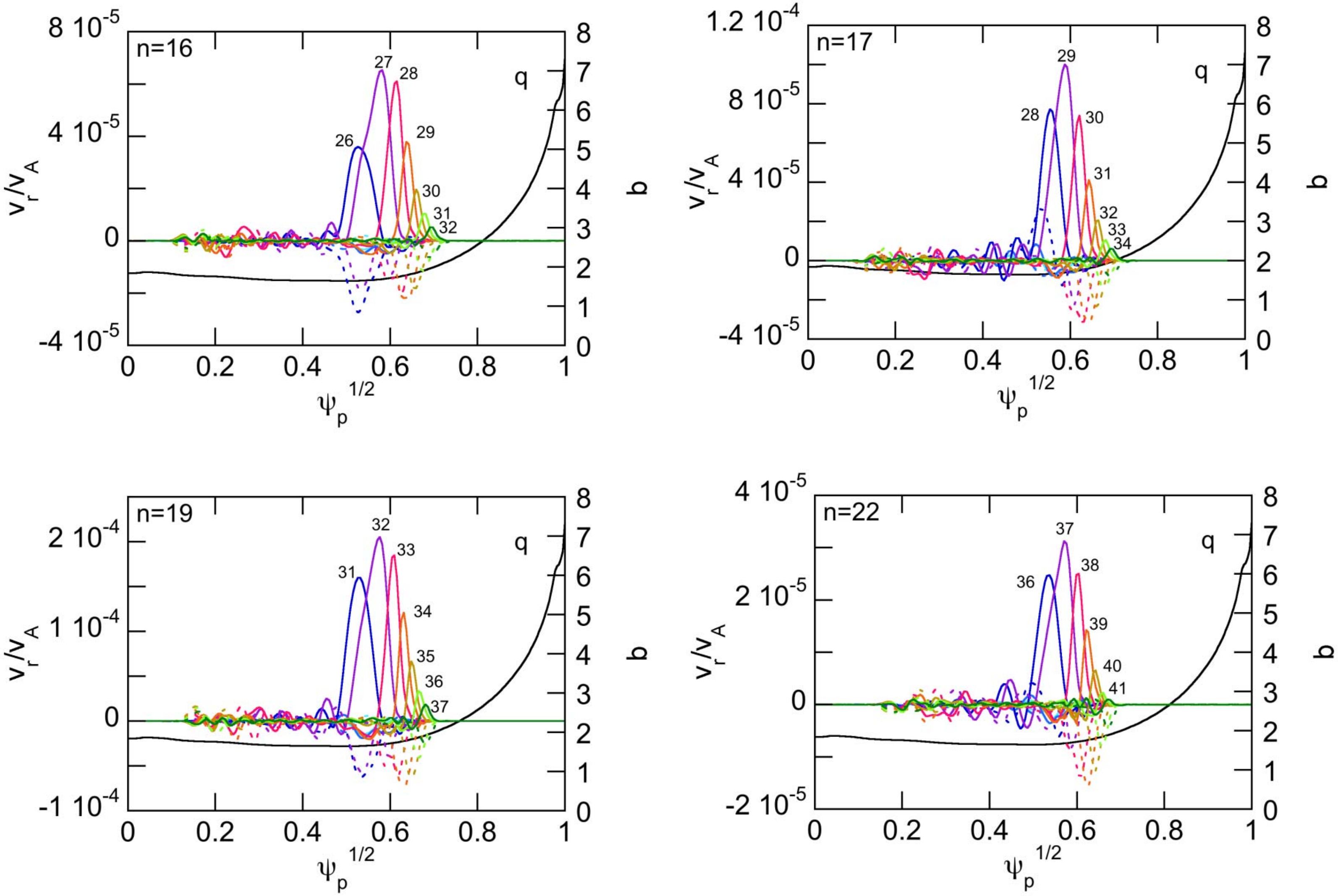
grid points for (R, φ, z)	256×256×512
total number of marker particles	1.67×10^7 (alpha) + 1.67×10^7 (D beam)
alpha particles	isotropic slowing down distribution (3.5 MeV) with FLR
deuterium beam	isotropic slowing down distribution (1 MeV) with FLR

TAE modes (n=12-22) are unstable

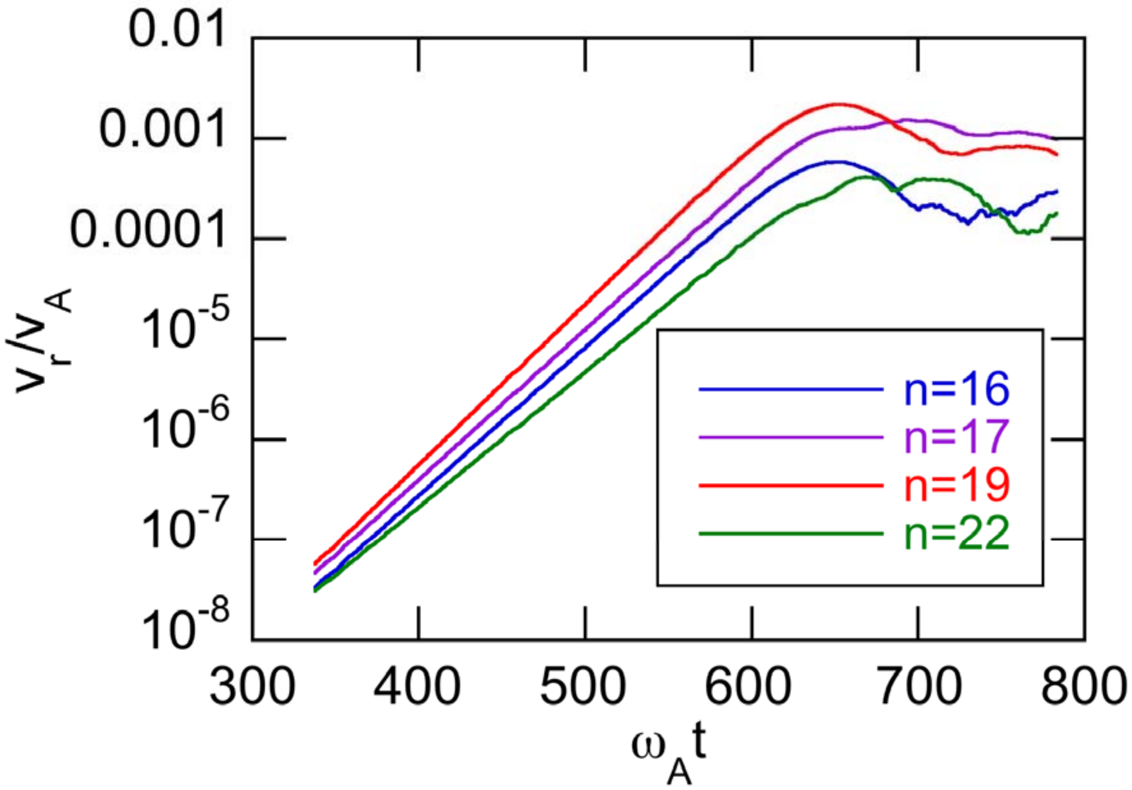


The most unstable mode is an n=19 mode.
Toroidal electric field in the linearly growing phase is shown in the figure.

Most unstable modes are n=16, 17, 19, 22

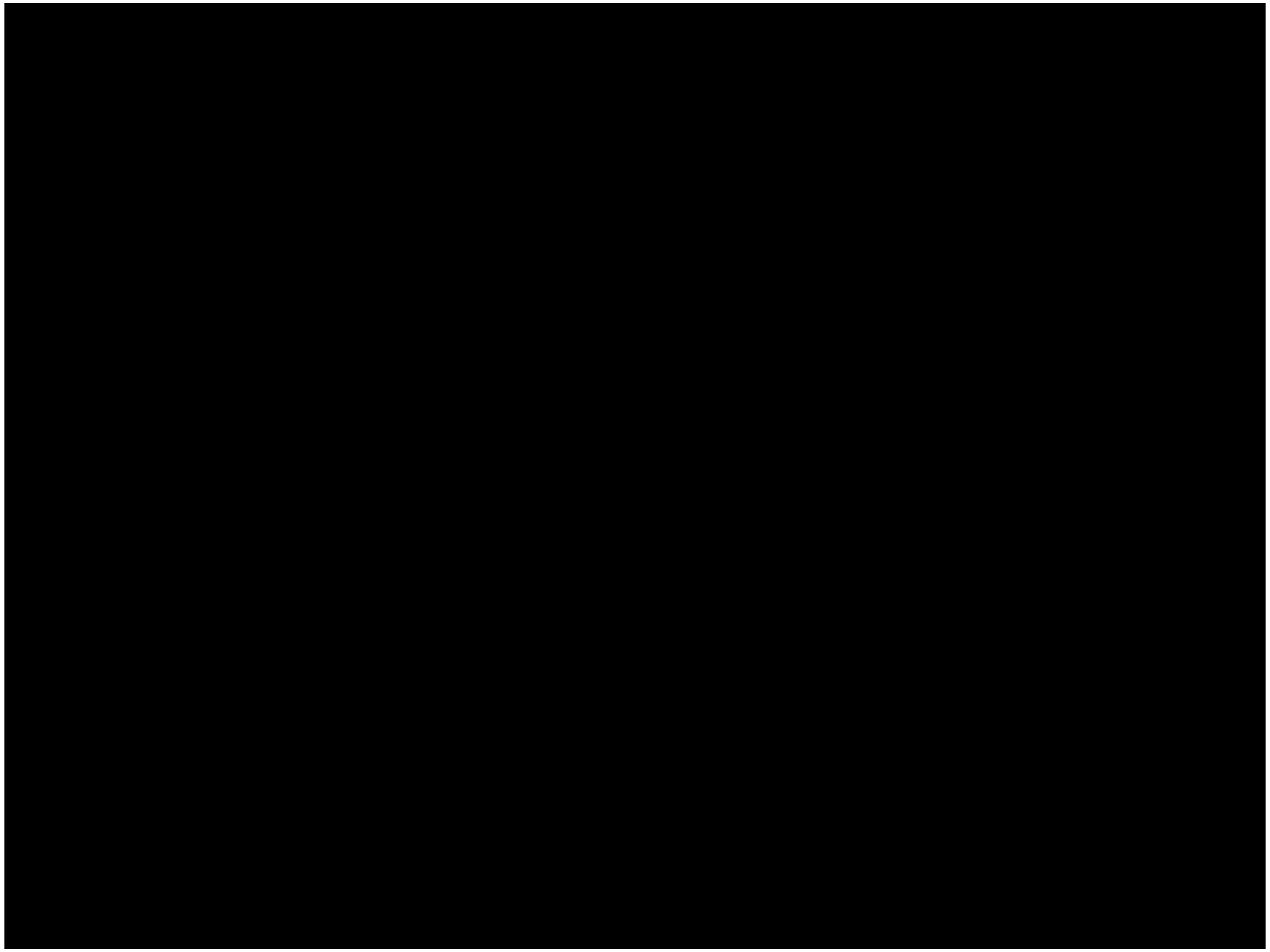


Amplitude evolution of the TAE modes

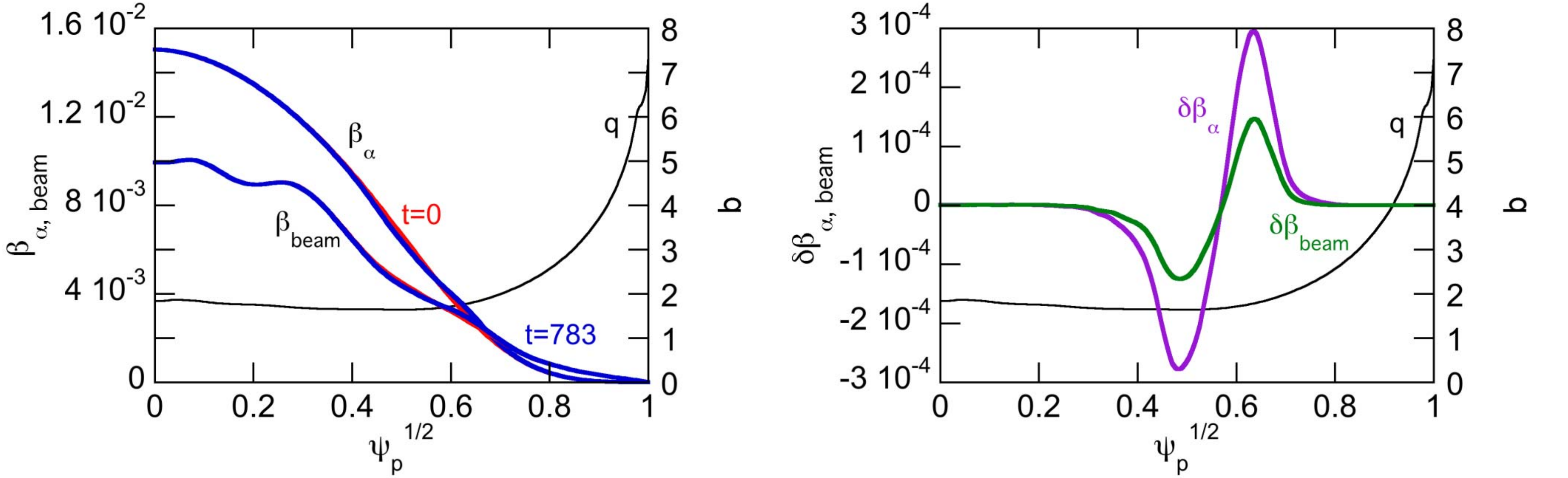


- The saturation level is $v_r/v_A \sim \delta B_r/B \sim 2 \times 10$^-3.

Evolution of TAE modes ($r*v_r$)



Energetic Particle Redistribution



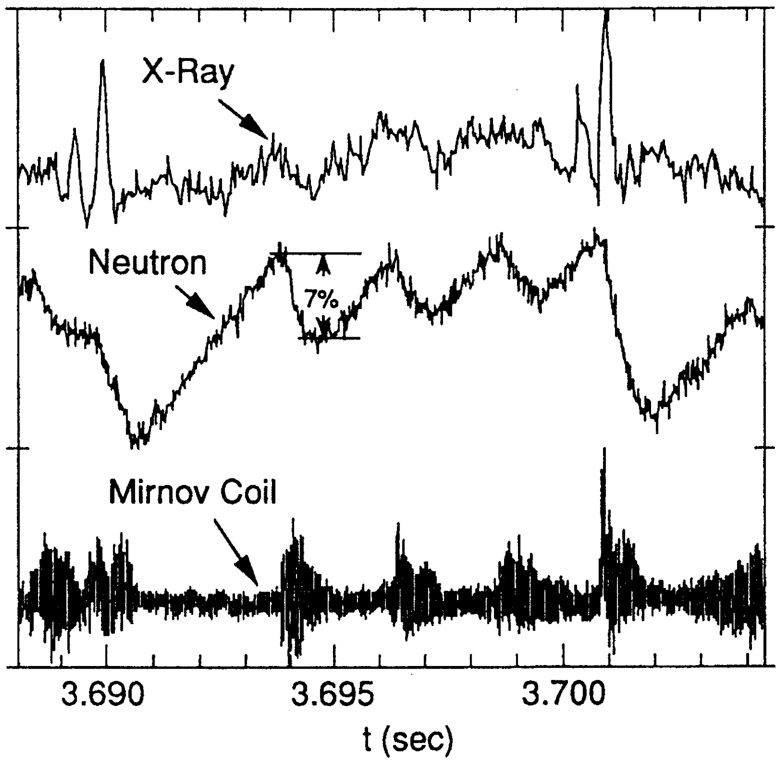
Slight redistributions takes place for both alphas and beam deuterium ions.
$\delta\beta_\alpha$~0.03%, $\delta\beta_{beam}$~0.01%.

Summary of the Lighthouse Project for MEGA

- Performance benchmark of the CSC supercomputer (helios)
  - Performance per core is comparable to BX900 and SR16000 L2
  - Good strong scaling was found up to 512 nodes of helios for MEGA with 256x512x256 grids.
- TAE modes in ITER steady state scenario
  - n=12-22 TAE modes are unstable
  - saturation level $v_r/v_A \sim \delta B_r/B \sim 2 \times 10^{-3}$
  - slight redistribution $\delta\beta_\alpha \sim 0.03\%$, $\delta\beta_{beam} \sim 0.01\%$

NL MHD EFFECTS ON AE EVOLUTION AND NL MHD SIMULATION OF AE BURSTS

Alfvén Eigenmode Bursts



Results from a TFTR experiment [K. L. Wong et al., Phys. Rev. Lett. 66, 1874 (1991).] (see also DIII-D results [H. H. Duong et al., NF 33, 749 (1993)])

Neutron emission: nuclear reaction of thermal D and energetic beam D -> drop in neutron emission = energetic-ion loss

Mirnov coil signal: magnetic field fluctuation -> Alfvén eigenmodes

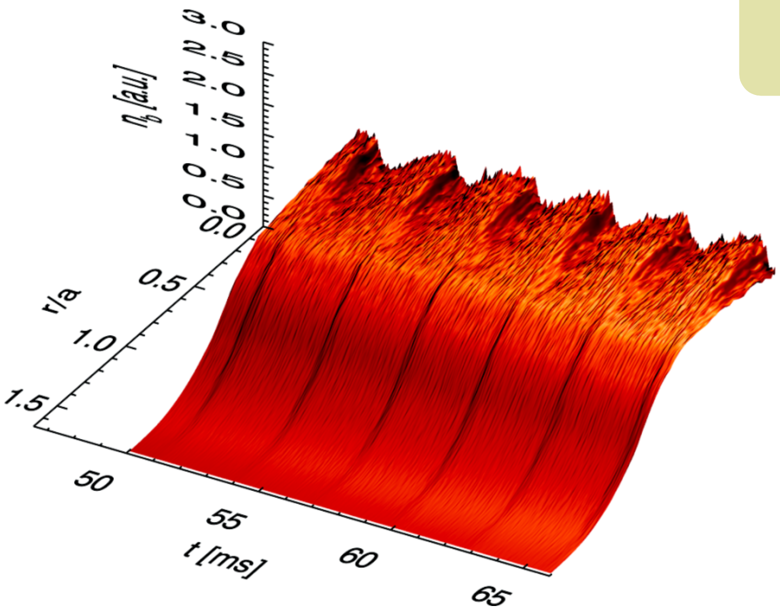
- Alfvén eigenmode bursts take place with a roughly constant time interval.
- 5-7% of energetic beam ions are lost at each burst.

Reduced Simulation of Alfvén Eigenmode Bursts

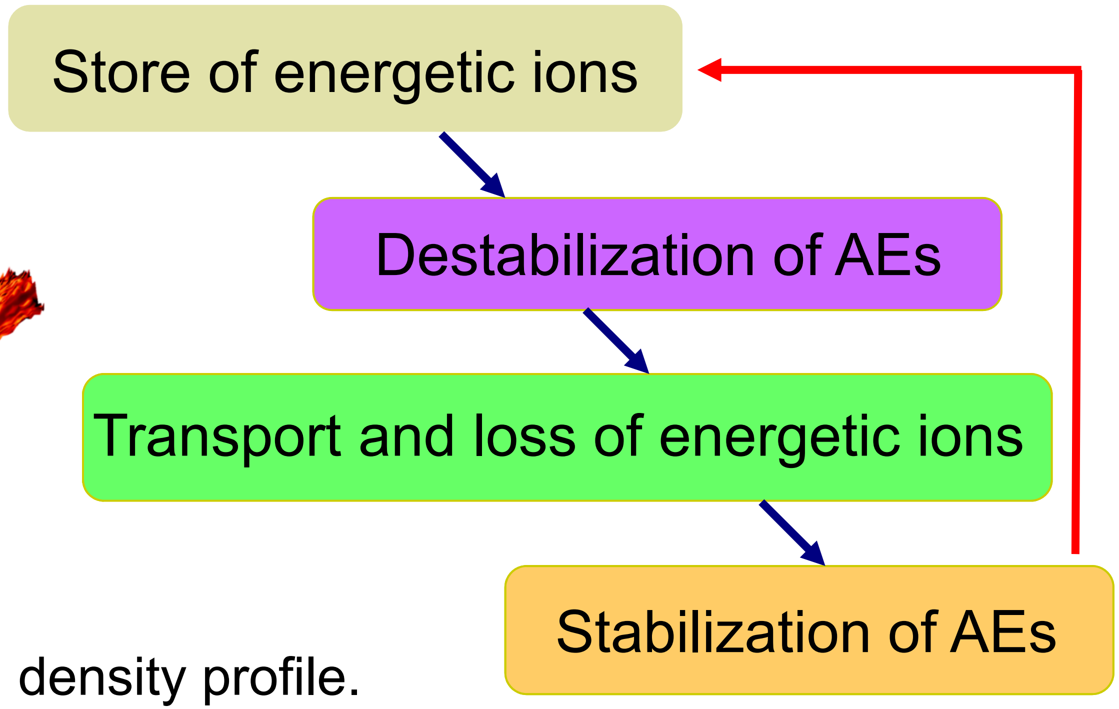
[Todo, Berk, Breizman, PoP **10**, 2888 (2003)]

• Nonlinear simulation in an open system: **NBI, collisions, losses**

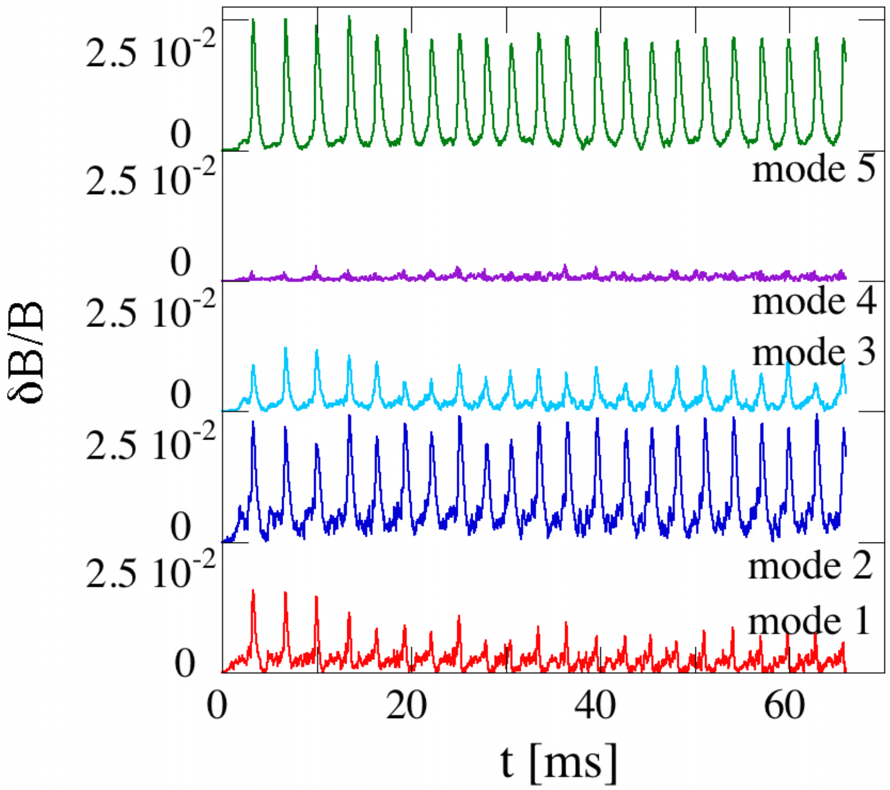
• Many aspects of the TAE bursts in the TFTR experiment [Wong et al. PRL **66**, 1874 (1991)] were reproduced quantitatively.

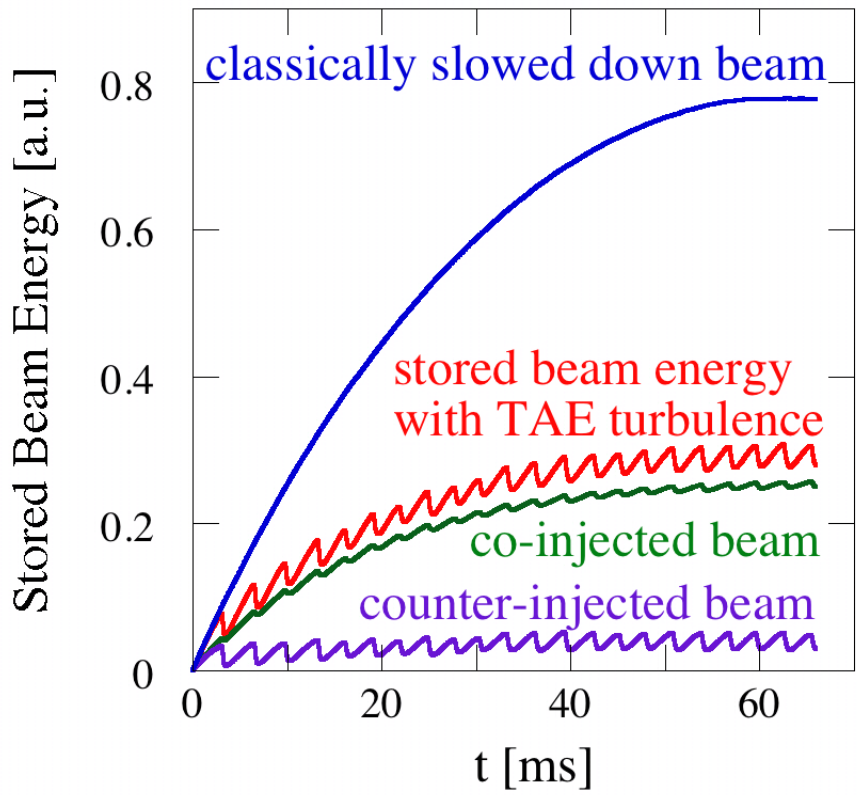


Time evolution of energetic-ion density profile.



Time evolution of TAE mode amplitude and stored beam energy





Synchronization of multiple modes due to resonance overlap with time interval 2ms (left).

Stored beam energy is reduced to 40% of the classically expected level due to the 10% drop at each burst (right).

Saturation amplitude of AE mode

- inferred from the plasma displacement [Durst et al., (1992)]
  - at the edge region (ρ~0.8): δB/B~10^-3
  - at the core region (ρ≤0.6): plasma displacement is not available
- simulation
  - δB/B~2×10^-2 at the mode peak location

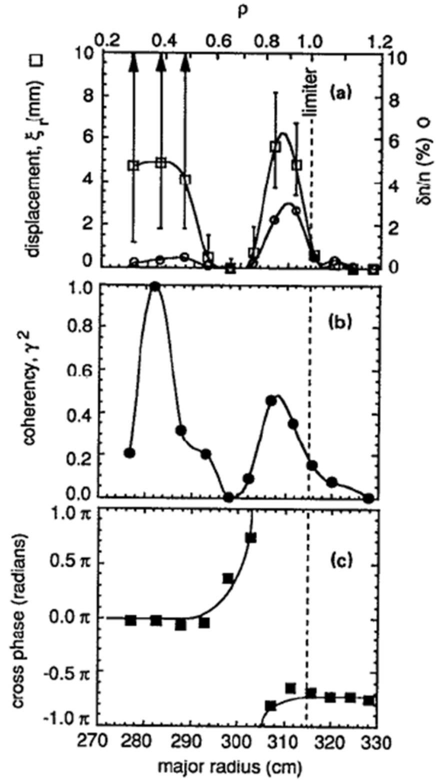


FIG. 4. The radial structure of the TAE mode. (a) The radial profile of the fluctuation amplitude (circles) and the radial component of the displacement vector (squares). The errors bars for the displacement are primarily due to uncertainties in the electron density profile (from microwave interferometry). Inside of $\rho=0.5$ the error bars become infinitely large. (b) The radial cross coherency profile. (c) The radial cross-phase profile ($B_T=1.0$ T, $I_p=420$ kA, $\bar{n}_e=2.6\times10^{19}$ m^{-3}).

[Durst et al., PoF B **4**, 3707 (1992)]

The problem is …

- The significant particle losses take place at $\delta B/B=6\times10$^-3 in the reduced simulation.
- The resonance overlap leads to the rapid growth of the mode amplitude up to 2×10^-2.
- => Needs some nonlinear mechanism that suppresses the growth. *MHD nonlinearity?*

Comparison between linear and NL MHD runs (j_h' is restricted to n=4)

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

$$\rho_{\rm eq}\frac{\partial}{\partial t}\mathbf{v} = -\nabla p + (\mathbf{j}_{\rm eq} - \mathbf{j}'_{heq})\times\delta\mathbf{B} + (\delta\mathbf{j} - \delta\mathbf{j}'_h)\times\mathbf{B}_{\rm eq}$$

$$+\frac{4}{3}\nabla(\nu\rho_{\rm eq}\nabla\cdot\mathbf{v}) - \nabla\times(\nu\rho_{\rm eq}\omega)$$

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

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

$$+\eta\delta\mathbf{j}\cdot\mathbf{j}_{\rm eq}$$

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

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

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

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

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

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

EP effects

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

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

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

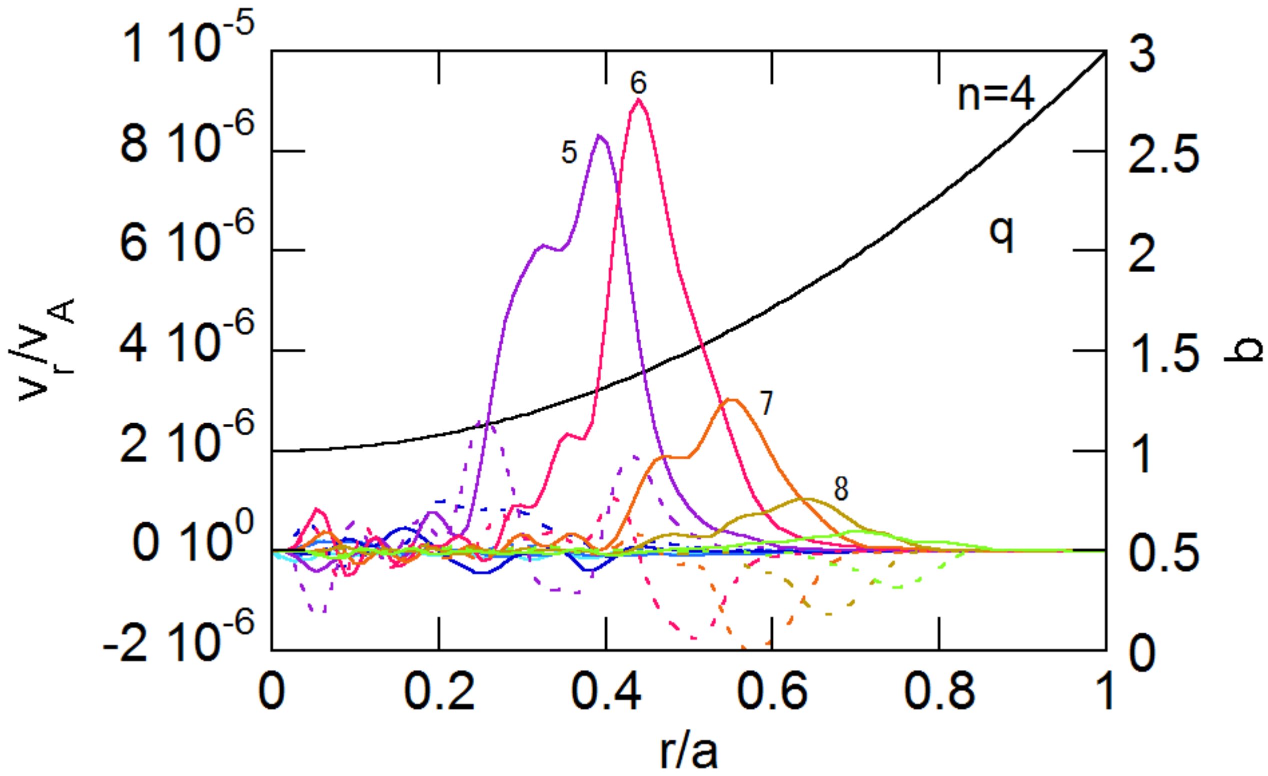
$$\mathbf{E} = -\mathbf{v}\times\mathbf{B} + \eta(\mathbf{j} - \mathbf{j}_{\rm eq})$$

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

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

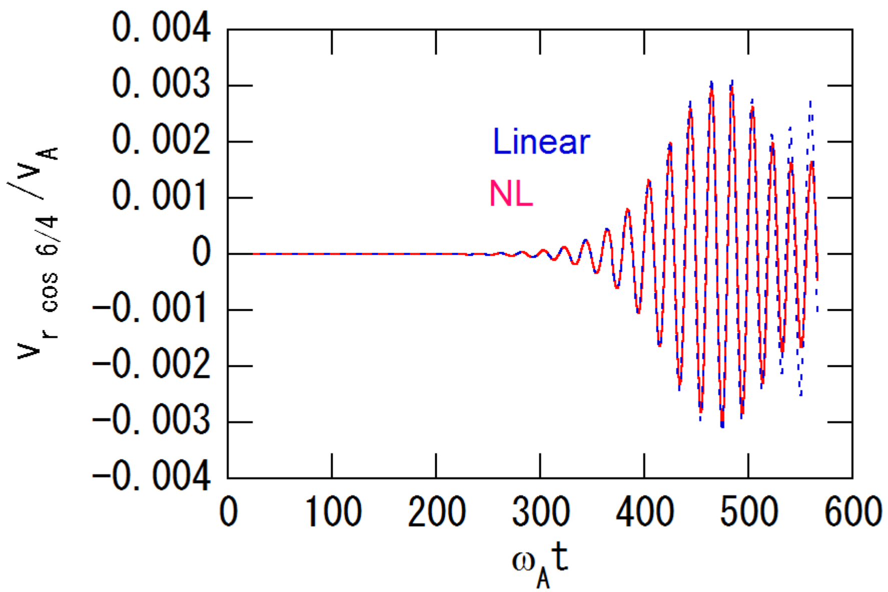
The viscosity and resistivity are $\nu=\nu_n=2\times10^{-7}v_A R_0$ and $\eta=2\times10^{-7}\mu_0 v_A R_0$. The numbers of grid points are (128, 64, 128) for (R, φ, z). The number of marker particles is 5.2×10^5.

TAE spatial profile (n=4)

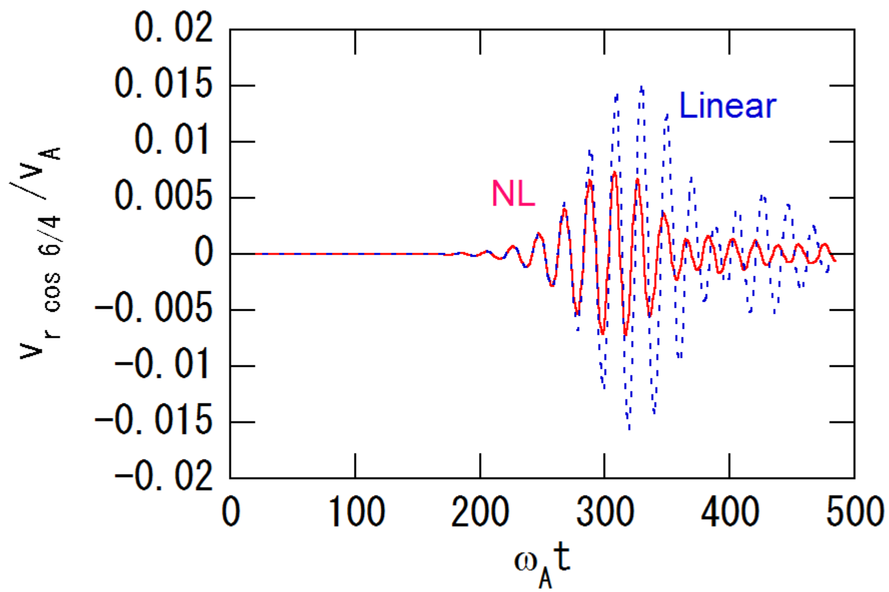


The main harmonics are m=5 and 6.

Comparison of linear MHD and NL MHD simulations



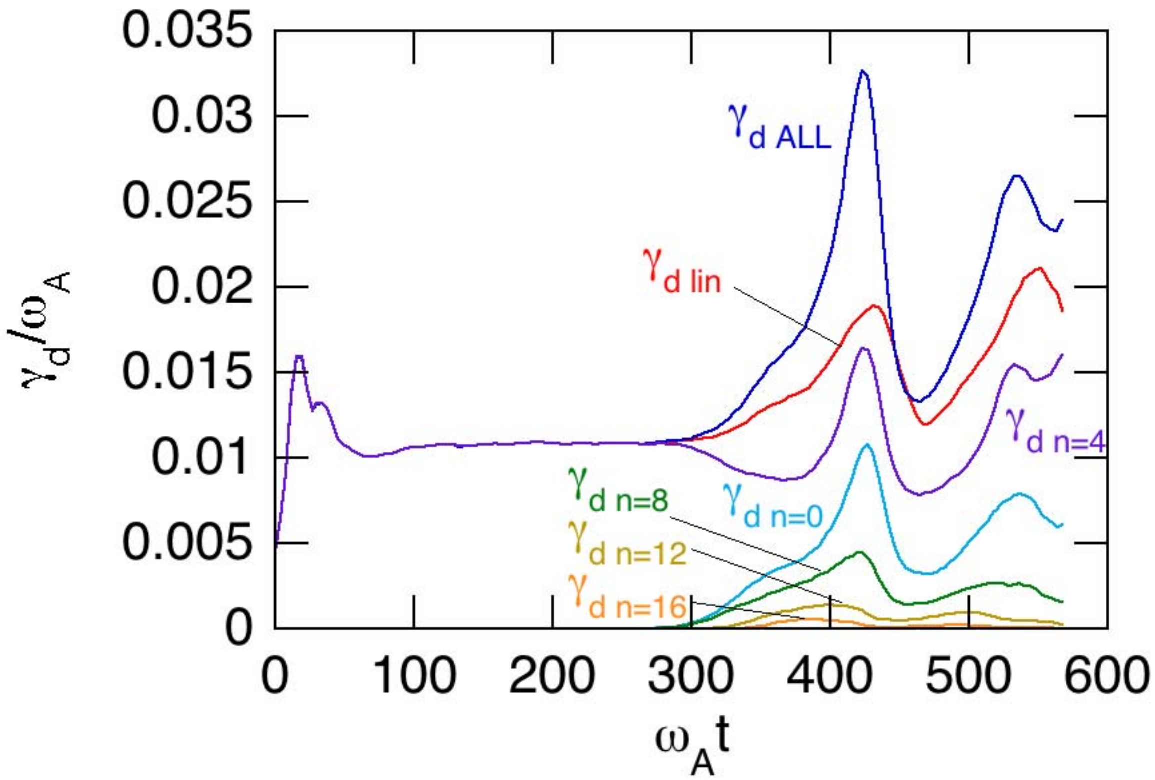
β_{h0}=1.5%
Sat. Level (linear) ~ 3×10^{-3}
Sat. Level (NL) ~ 3×10^{-3}



β_{h0}=2.0%
Sat. Level (linear) ~ 1.6×10^{-2}
Sat. Level (NL) ~ 8×10^{-3}

The saturation level is reduced to half in the nonlinear MHD simulation.

Evolution of total damping rate



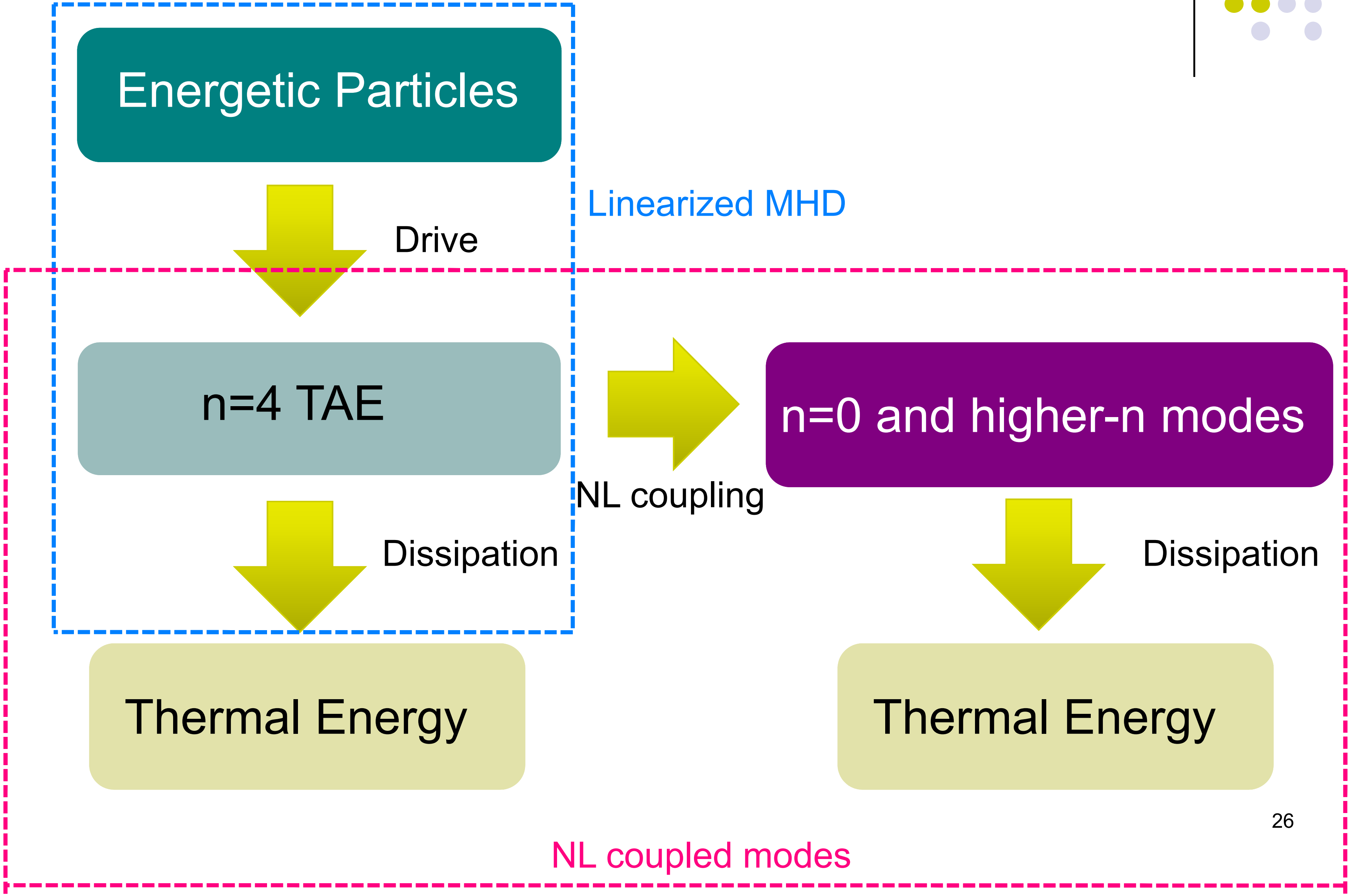
β_{h0}=1.7%

Sat. Level (linear) ~ 1.2×10^{-2}

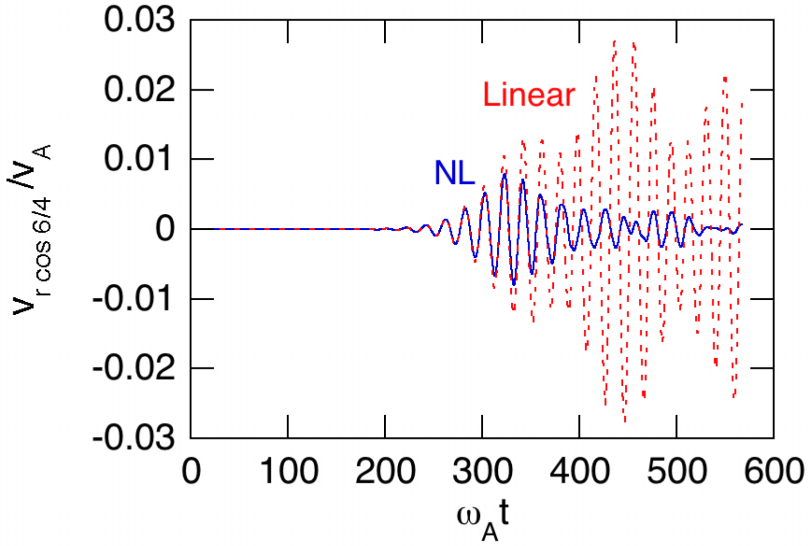
Sat. Level (NL) ~ 6×10^{-3}

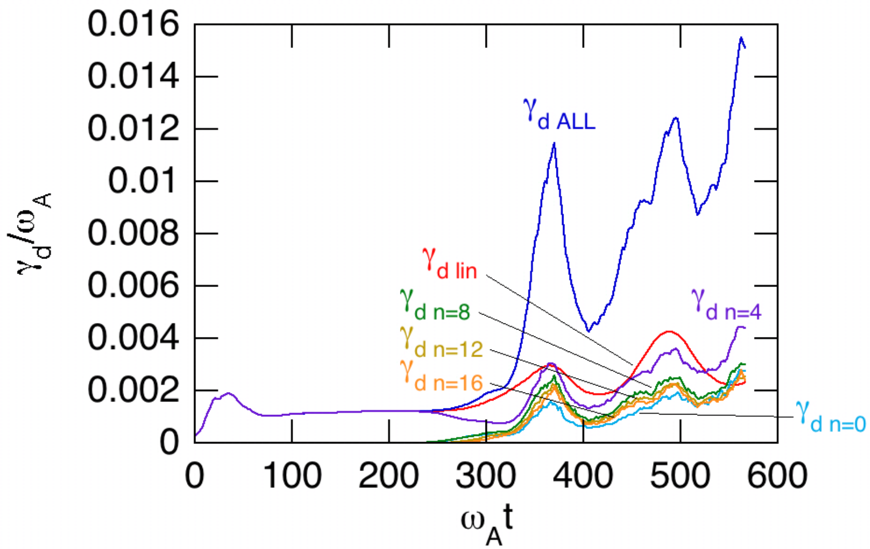
The total damping rate (γ_{dALL}) is greater than the damping rate in the linearized MHD simulation ($\gamma_{d\ lin}$).

Schematic Diagram of Energy Transfer



Effects of weak dissipation

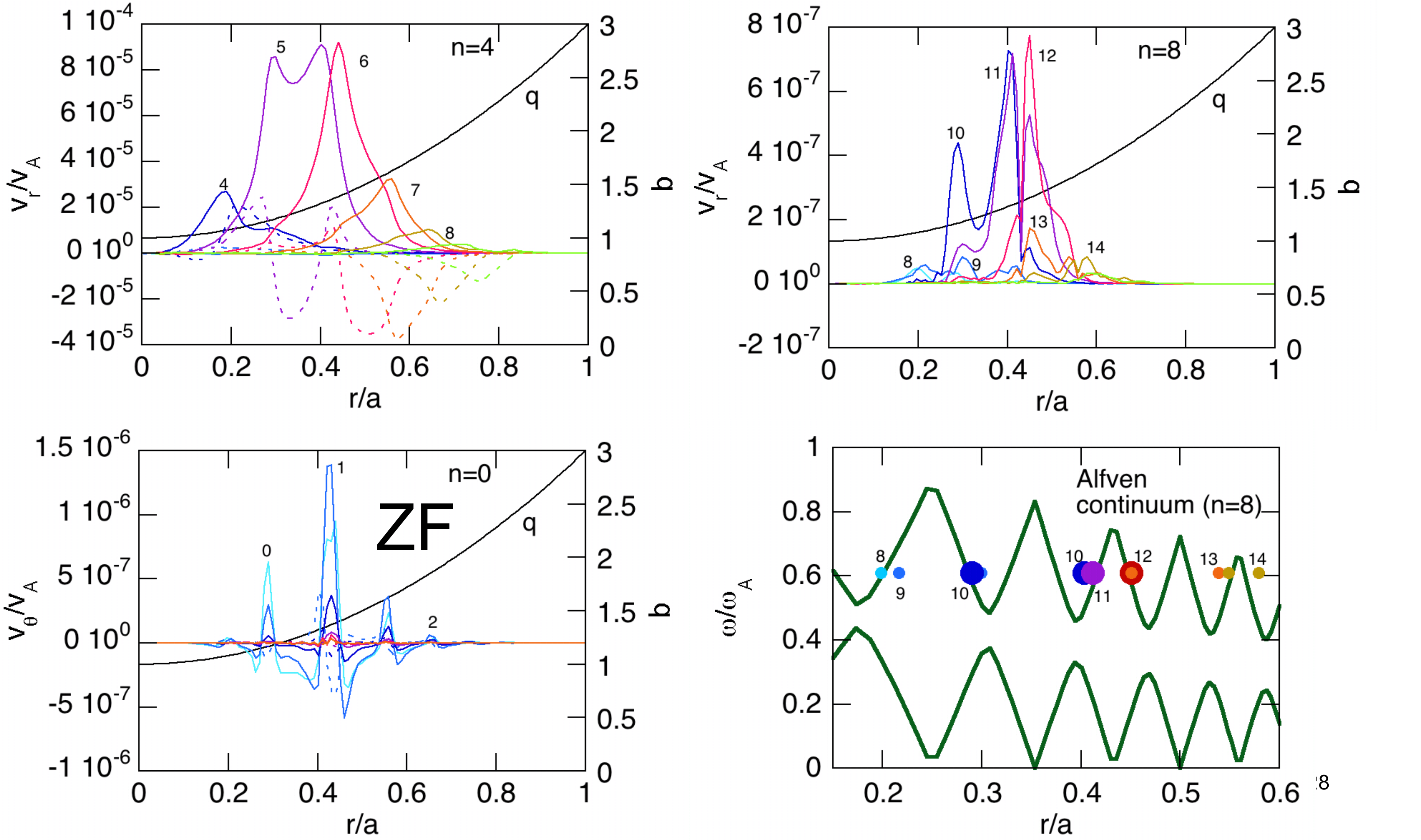




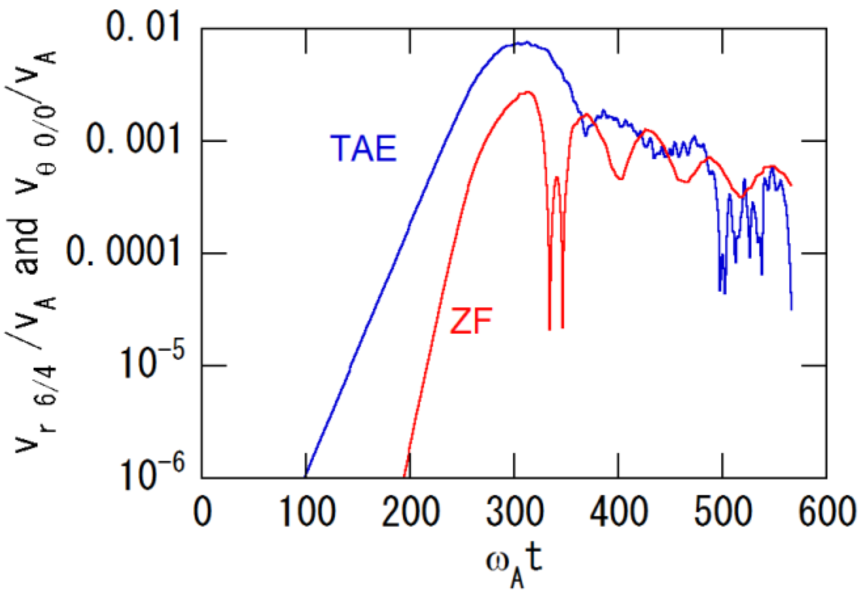
β_{h0}=1.7%
The viscosity and resistivity are reduced to 1/16,
$\nu=\nu_n=6.25\times10^{-8}v_AR_0$ and
$\eta=6.25\times10^{-8}\mu_0v_AR_0$
with the numbers of grids (512, 512, 128).

The nonlinear MHD effects reduce the saturation level also for weak dissipation.

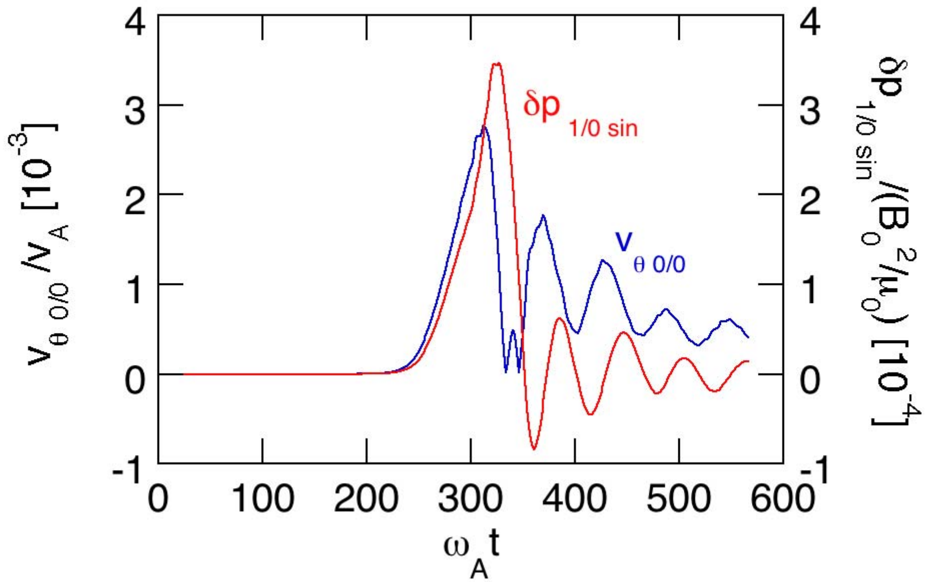
Spatial profiles of the TAE and NL modes: Evidence for continuum damping of the higher-n (n=8) mode



ZF Evolution and GAM Excitation

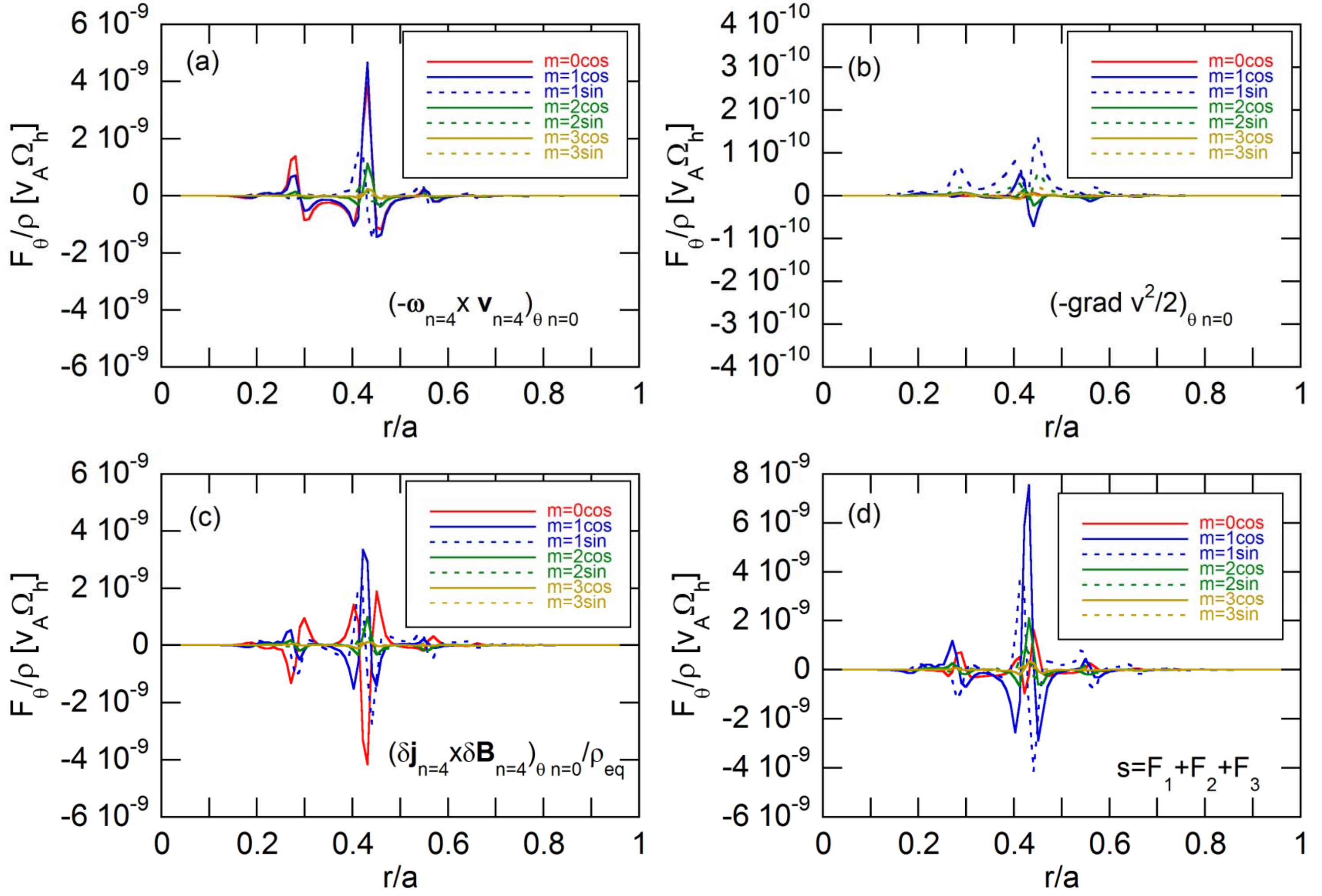


Evolution of TAE and zonal flow

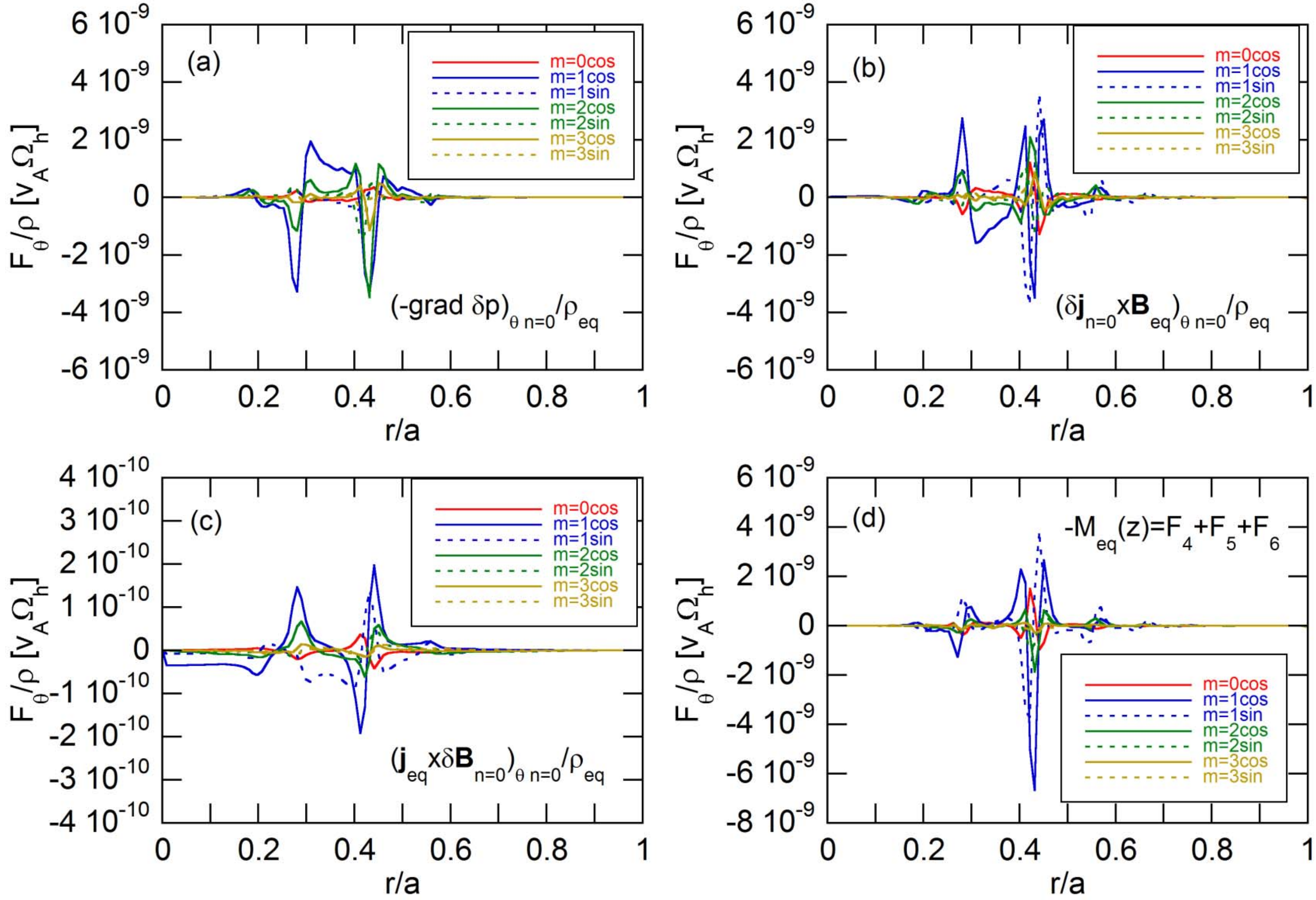


After the saturation of the TAE instability, a geodesic acoustic mode is excited.

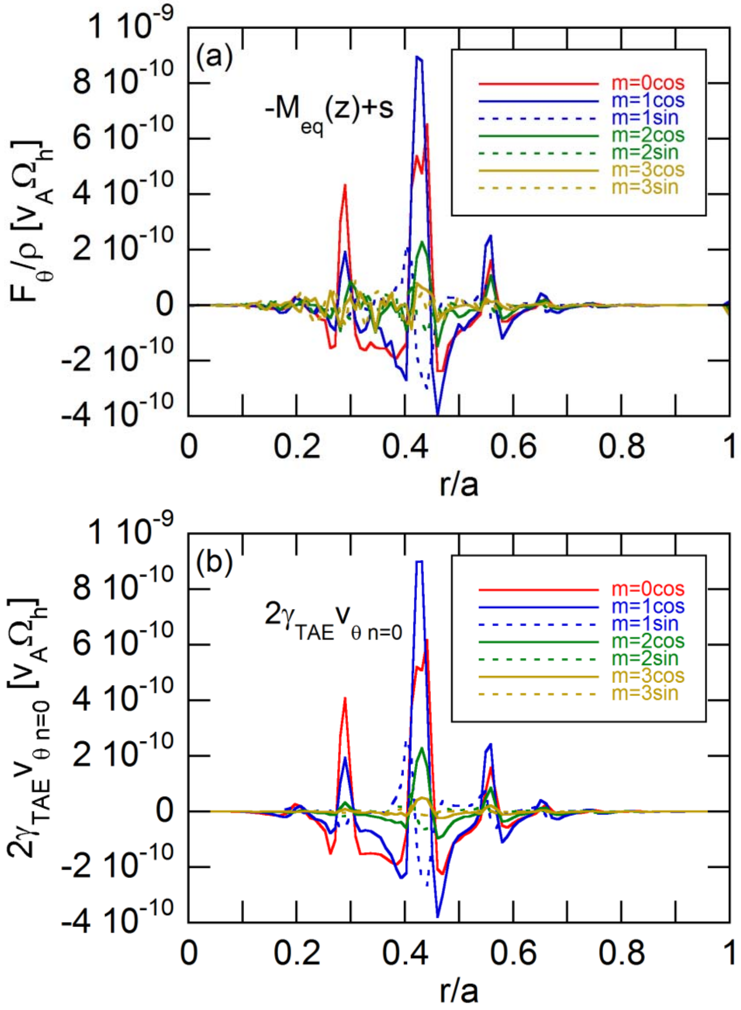
NL source for n=0 poloidal flow (s)



Equilibrium response to n=0 fluctuations for poloidal flow [$-M_{eq}(z)$]



$s-M_{eq}(z)=2\gamma_{TAE}{}^{*}z$ during the linearly growing phase of TAE



- The contributions from NL source (s) and equilibrium plasma response [-$M_{eq}(z)$] are comparable and cancel out each other.
- $s-M_{eq}(z)=2\gamma_{TAE}{}^{*}z$ holds.

Summary of NL MHD effects on a TAE instability [Y. Todo et al. NF 50, 084016 (2010), and submitted to NF]

- Linear and nonlinear simulation runs of a n=4 TAE evolution were compared. The saturation level is reduced by the nonlinear MHD effects.
- The total energy dissipation is significantly increased by the nonlinearly generated modes. The increase in the total energy dissipation reduces the TAE saturation level. The dissipation from higher-n modes can be attributed to the continuum damping.
- The zonal flow is generated during the linearly growing phase of the TAE instability. The geodesic acoustic mode (GAM) is excited after the saturation of the instability. The GAM is not directly excited by the energetic particles but excited through MHD nonlinearity.

Questions for AE bursts

- Is the mode amplitude reduced also for the AE bursts?

- Do the significant fast ion losses take place with the NL MHD effects?

-> EP-MHD hybrid code MEGA is extended to simulate with beam injection, collisions, and losses

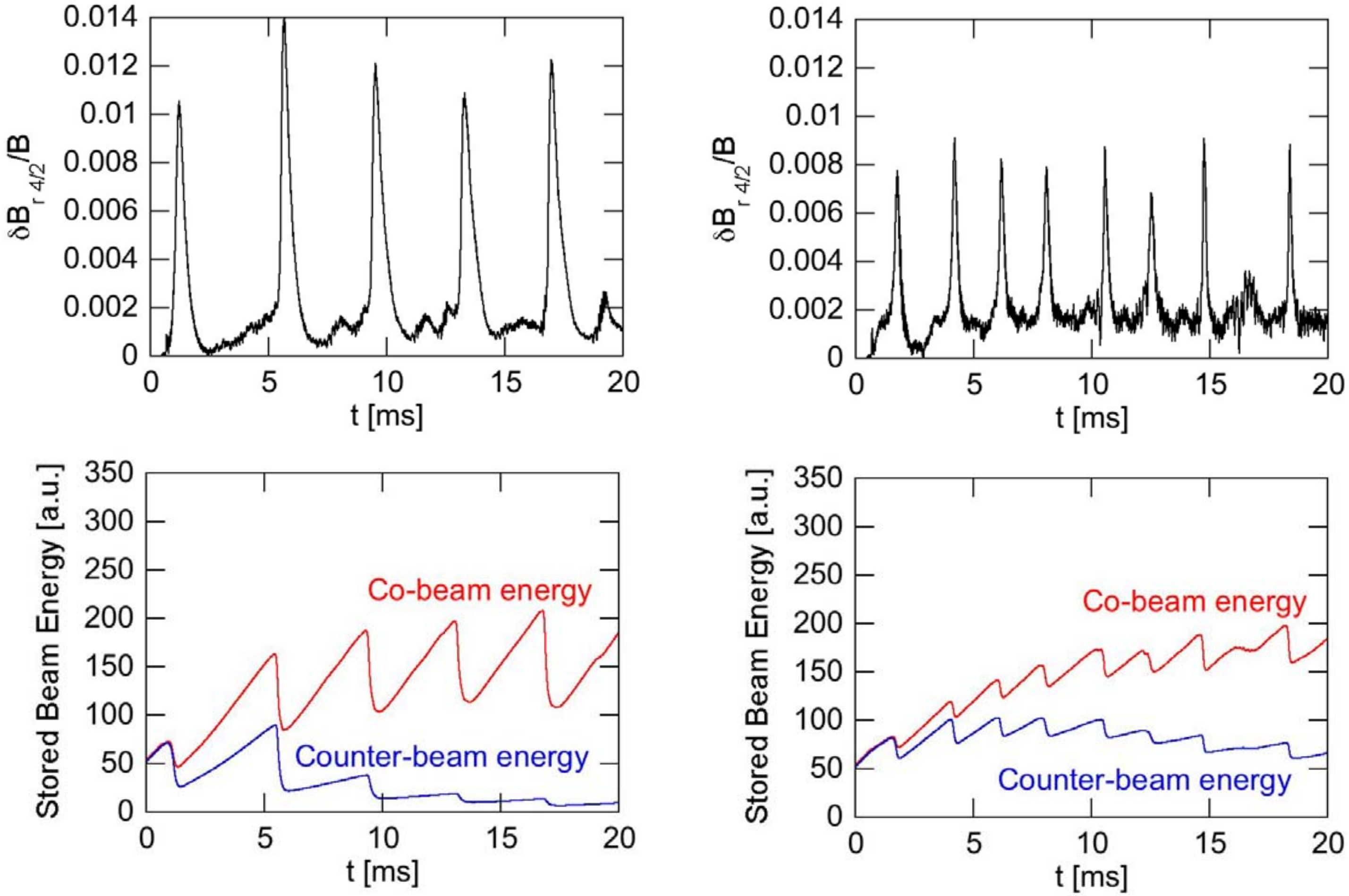
Physics condition

- similar to the reduced simulation of TAE bursts at the TFTR experiment
- parameters
  - a=0.75m, R_0=2.4m, B_0=1T, $q(r)=1.2+1.8(r/a)^2$
  - NBI power: 10MW
  - beam injection energy: 110keV (deuterium)
  - $v_b=1.1v_A$
  - slowing down time: 100ms
  - parallel injection ($v_{//}/v$=-1 or 1)
  - no pitch angle scattering
  - particle loss at r/a=0.8

NL MHD effects: reduction of TAE amplitude and beam ion losses

n=2 TAE peak amplitude

stored beam energy



Linear MHD

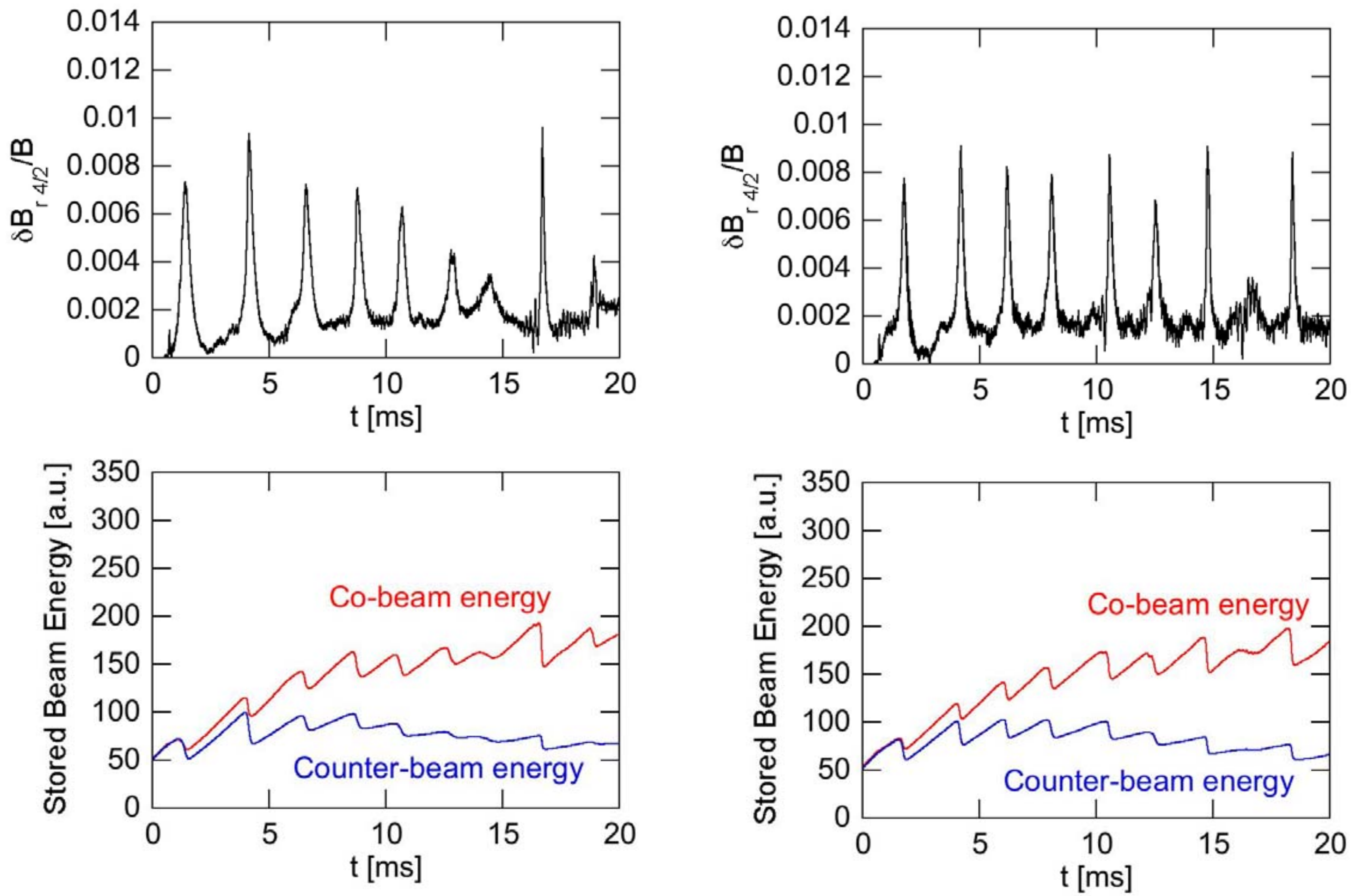
NL MHD

- $\nu = \eta/\mu_0 = \chi = 5 \times 10^{-7} v_A R_0$

Numerical convergence in numbers of particles and grid points

n=2 TAE peak amplitude

stored beam energy

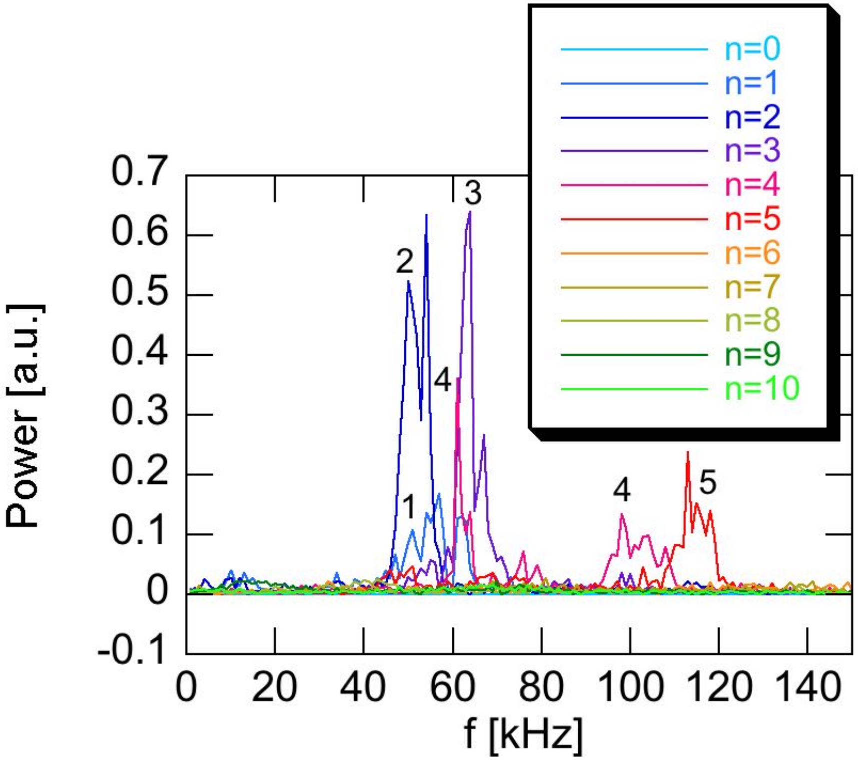


2^21 particles & (256×256×128) grids

2^19 particles & (128×128×64) grids

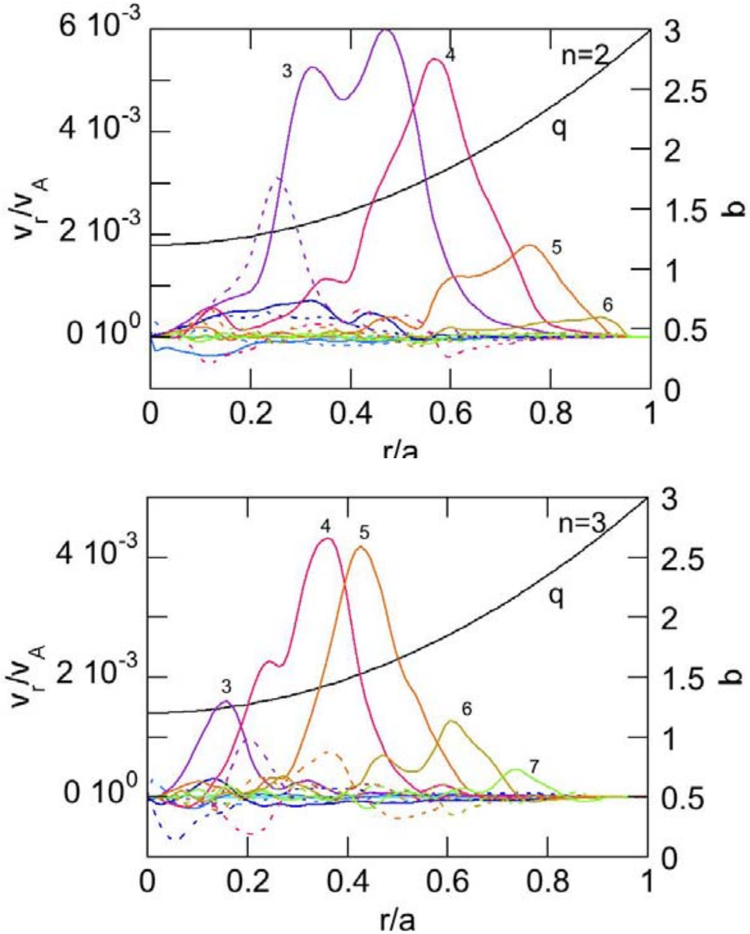
- $\nu=\eta/\mu_0=\chi=5\times10^{-7}v_A R_0$

Frequency spectra and TAE spatial profiles



■ Frequency spectra at r/a=0.41 (q=1.5) for 0≤t≤10ms

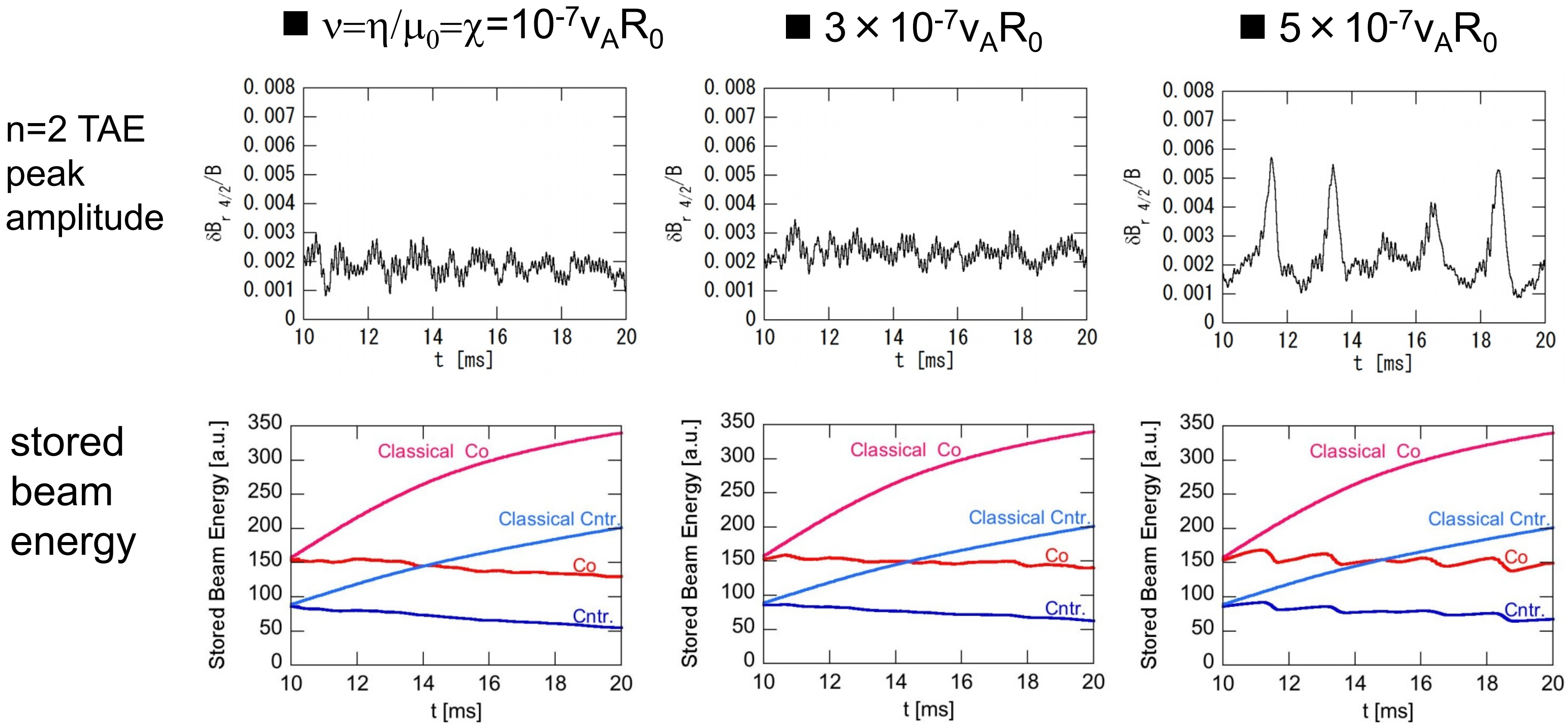
■ Nonlinear modes with n=4 and 5 at f=100-120kHz



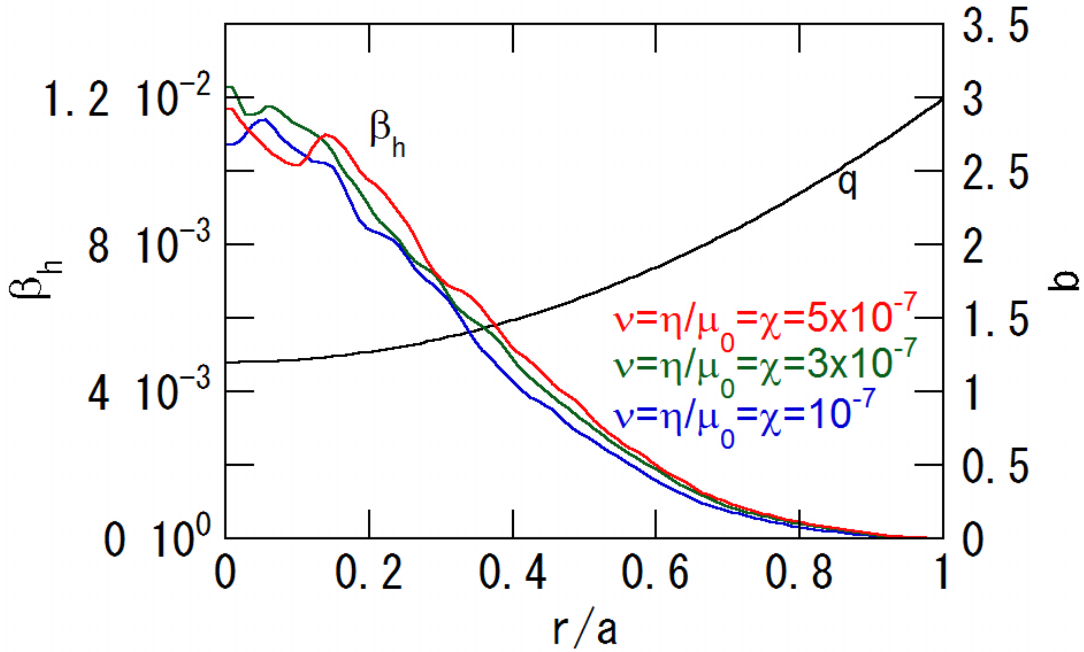
■ Spatial profiles of n=2 and 3TAE modes at t=1.41ms (first burst)

Effects of dissipation coefficients

- Starting from the same condition at t=10ms
- Lower dissipation: steady amplitude $\delta B/B=2\times 10$^-3 with significant loss
- Higher dissipation → bursts with $\delta B/B=5\times 10$^-3 with 10% loss



Comparison of EP pressure profiles for different dissipation



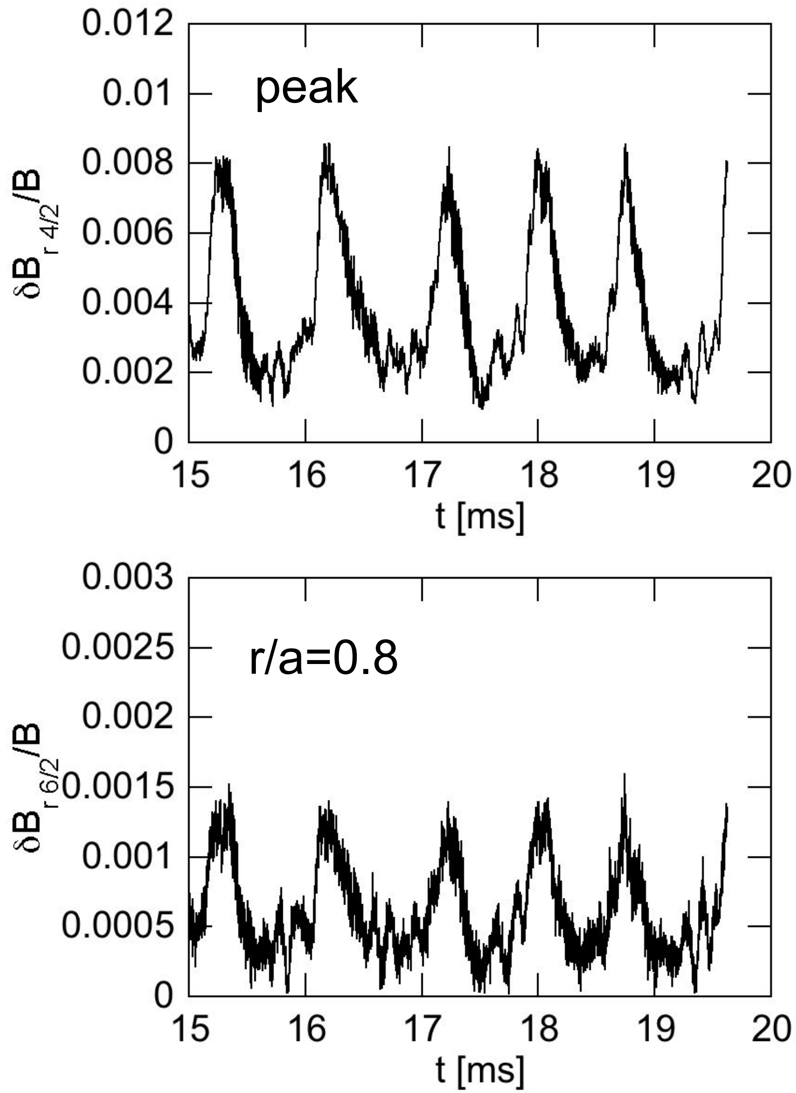
■ t=20.0 ms

■ EP pressure profiles are very similar among the different dissipation coefficients.

■ Higher dissipation leads to slightly higher EP pressure.

Amplitude at r/a=0.8 (particle loss at r/a=1)

- simulation:
  - $\delta B/B \sim 8 \times 10^{-3}$ at the mode peak location
  - $\delta B/B \sim 10^{-3}$ at r/a=0.8
- inferred from the plasma displacement [Durst et al., (1992)]
  - $\delta B/B \sim 10^{-3}$ at r/a~0.8



Summary of TAE burst simulation with NL MHD effects

[Y. Todo et al., NF 52, 033003 (2012)]

- TAE bursts are successfully simulated with NL MHD effects using time-dependent f_0.
  - saturation amplitude of the dominant harmonic with significant beam ion loss: $\delta B/B \sim 5\text{-}8 \times 10^{-3}$ at the mode peak location and 10^{-3} at r/a=0.8 (comparable to the TFTR experiment)
- Effects of dissipation
  - Low dissipation: steady amplitude with significant beam ion loss: $\delta B/B \sim 2 \times 10^{-3}$
  - High dissipation: bursts
  - Higher dissipation leads to higher stored beam energy