M3D-K simulation of beam-driven Alfvén modes in DIIID

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In collaboration with

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PPPL THEORY COMPUTATION

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Outline

- Motivation
- Benchmark M3D-K with NOVA using model equilibrium in mhd limit
- Comparison of mode structure between M3D-K and NOVA with DIIID equilibrium in mhd limit
- The effect of energetic particles on mode structure and frequency in M3D-K simulations
- Comparison with DIIID measurement

Main equations for M3D-K code

- **Momentum equation:** $\rho \dfrac{d\mathbf{v}}{dt} = -\nabla \mathrm{p} - \nabla \cdot \mathbf{p_h} + \mathbf{J} \times \mathbf{B}$

- **Ohm's law:** $\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$

- **Continuity equation for plasma mass density:** $d\rho/dt = -\rho \nabla \cdot \mathbf{v}$

- **Pressure equation for thermal plasmas:** $dP/dt = -\gamma P \nabla \cdot \mathbf{v}$

- **The particle pressure is calculated from particle distribution:**

$$P_{||}(\mathbf{x}) = \int M v_{||}^2 \delta(\mathbf{x} - \mathbf{X} - \boldsymbol{\rho}_\mathbf{h}) F(\mathbf{X}, v_{||}, \mu) d^3\mathbf{X} dv_{||} d\mu d\theta$$

$$P_{\perp}(\mathbf{x}) = \int M v_{\perp}^2 \delta(\mathbf{x} - \mathbf{X} - \boldsymbol{\rho}_\mathbf{h}) F(\mathbf{X}, v_{||}, \mu) d^3\mathbf{X} dv_{||} d\mu d\theta$$

Introduction to M3D-K (continued)

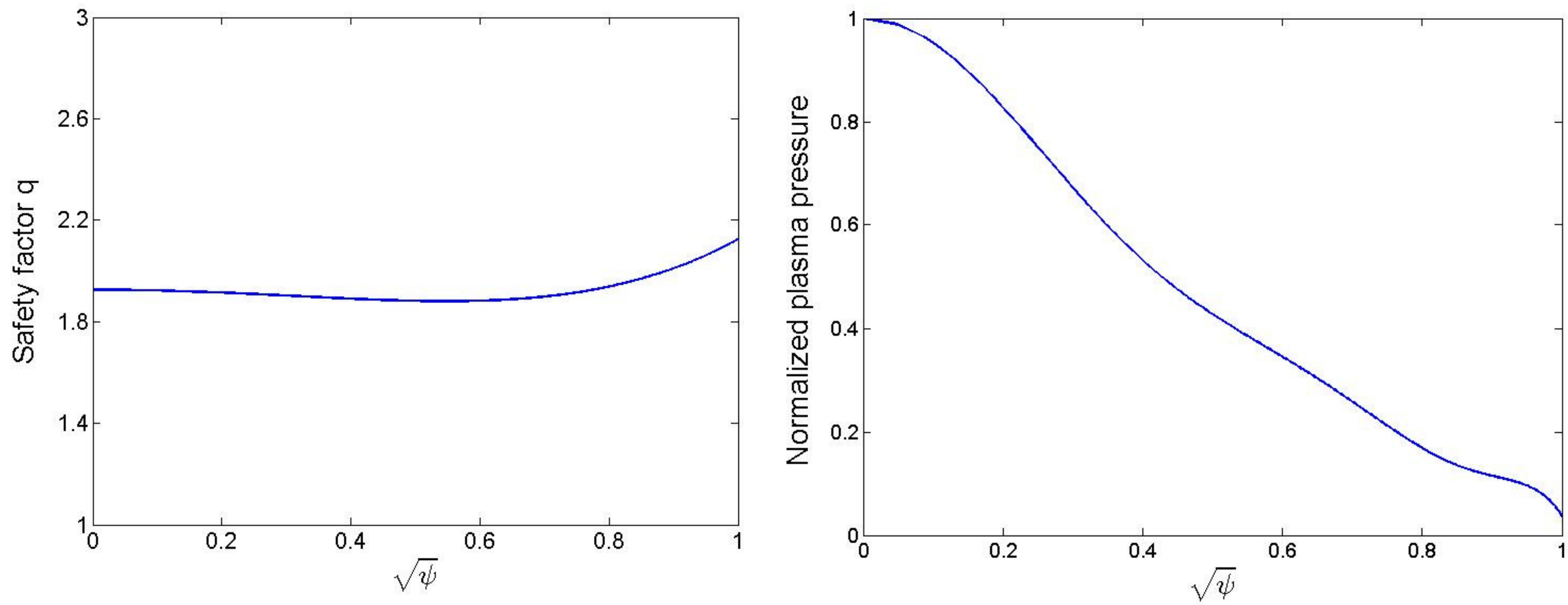
- Drift kinetic model is used to describe energetic particles and single fluid model is used to describe thermal plasmas. The model is fully nonlinear.

- The code uses numerically-calculated equilibrium including finite beta, finite aspect ratio and shaping.

- Energetic particle collision, source and sink are included.

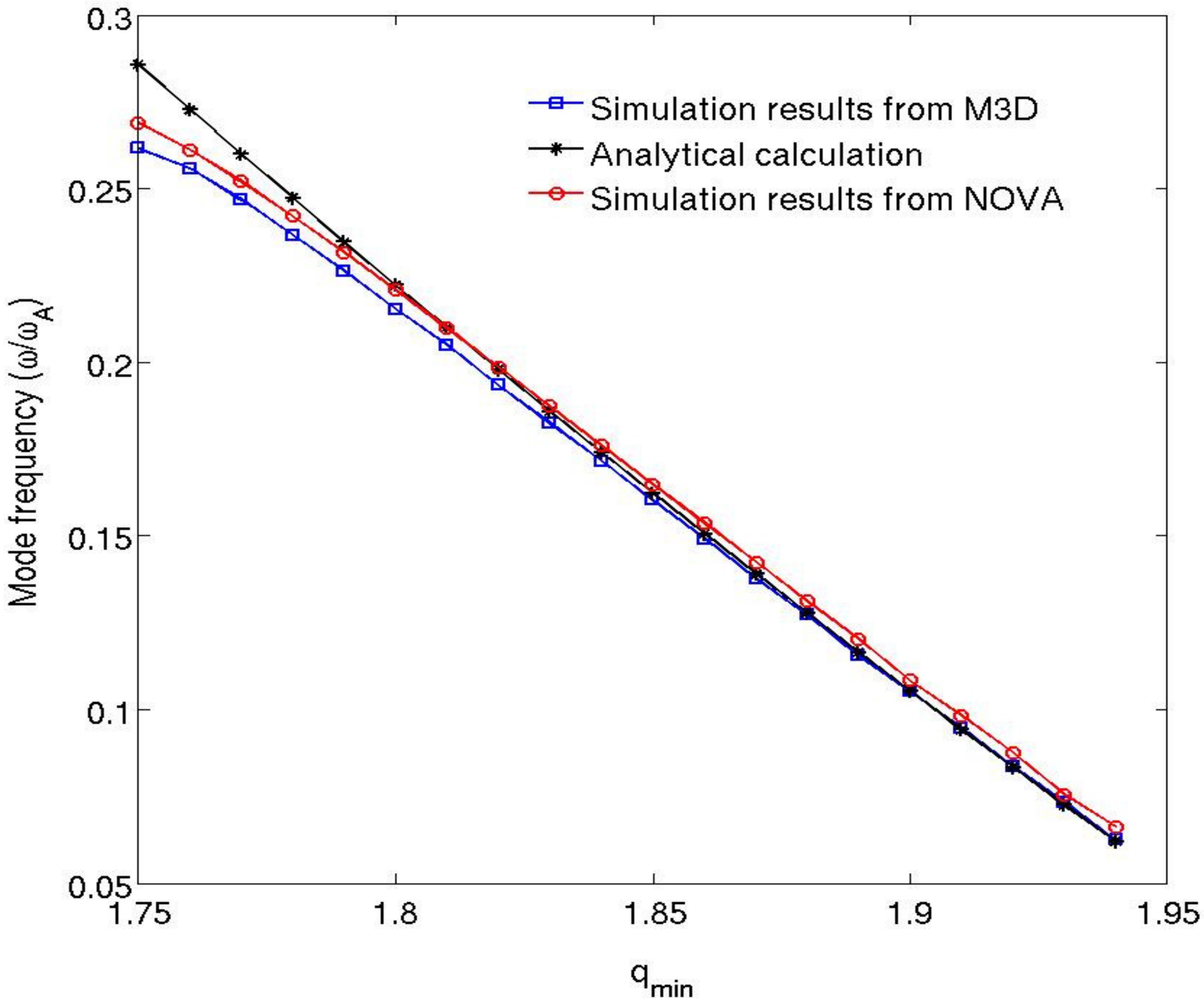
- Turbulence-induced energetic particle radial diffusion is included

Model equilibrium for n=2, m=4 RSAE



β=0 and uniform plasma density are applied in this model.

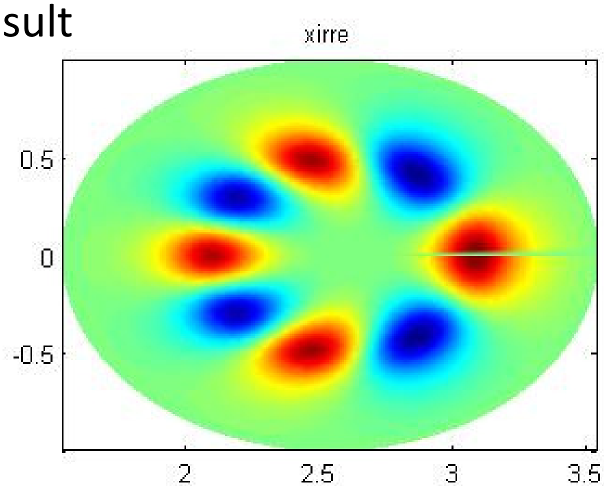
n=2, m=4 RSAE model equilibrium is used to benchmark M3D-K and NOVA with analytical theory



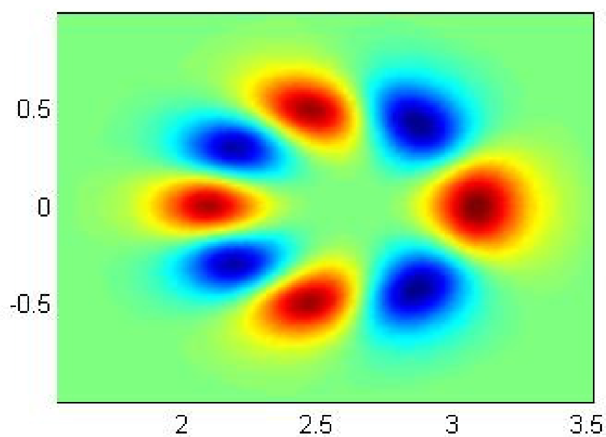
At low q_{min}, simulation shows mode transits from RSAE to TAE.

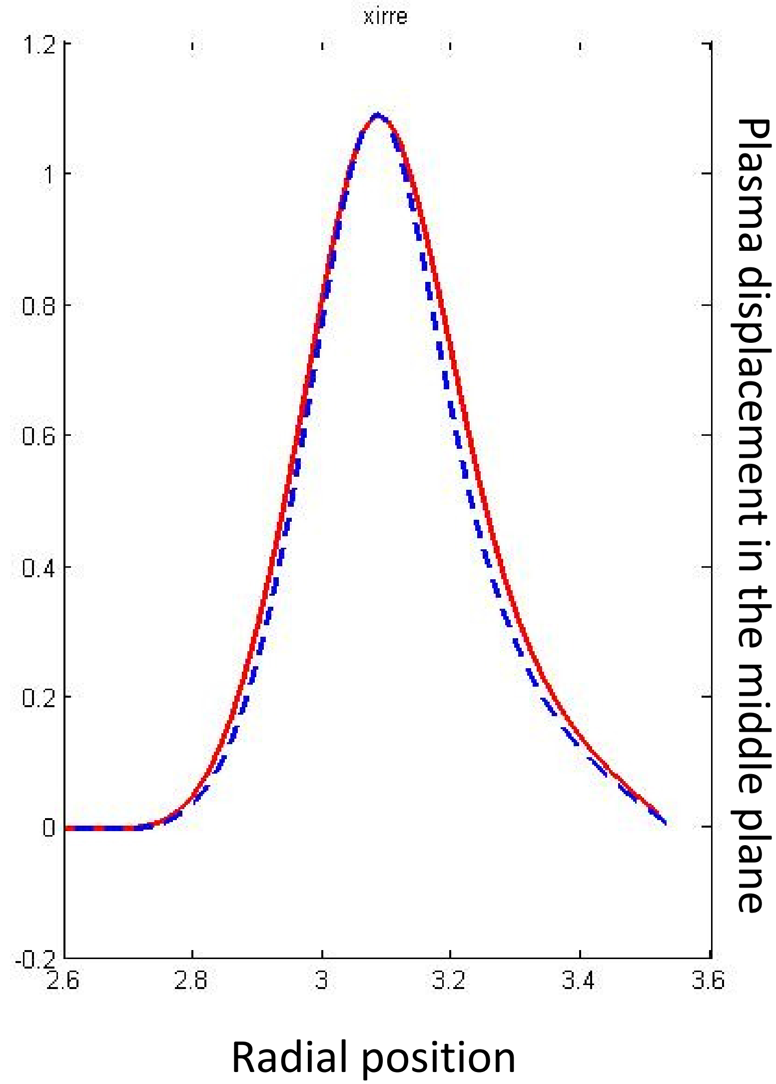
Mode structure of n=2, m=4 RSAE agrees well between NOVA and M3D-K with model equilibrium

NOVA result



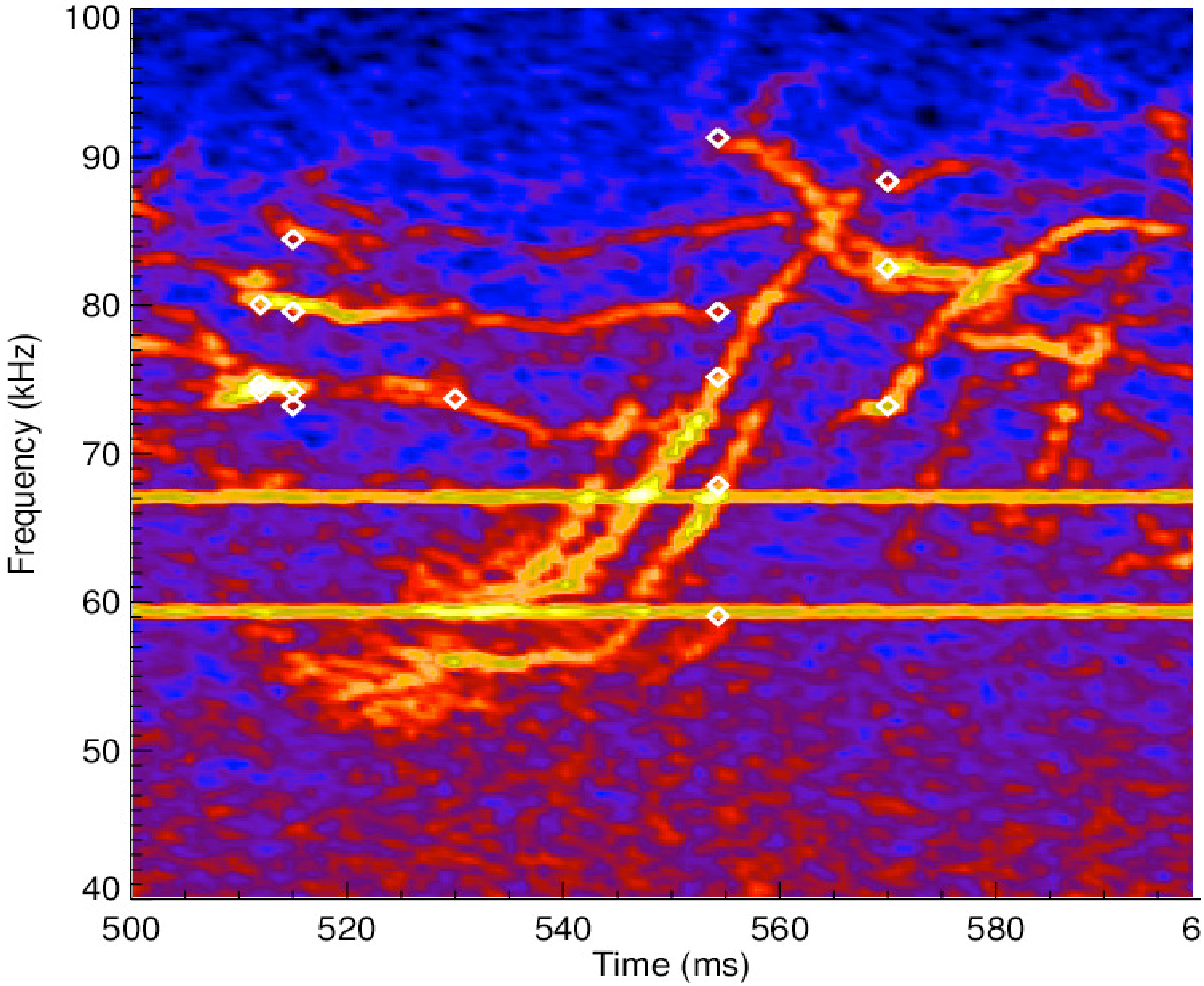
M3D-K result



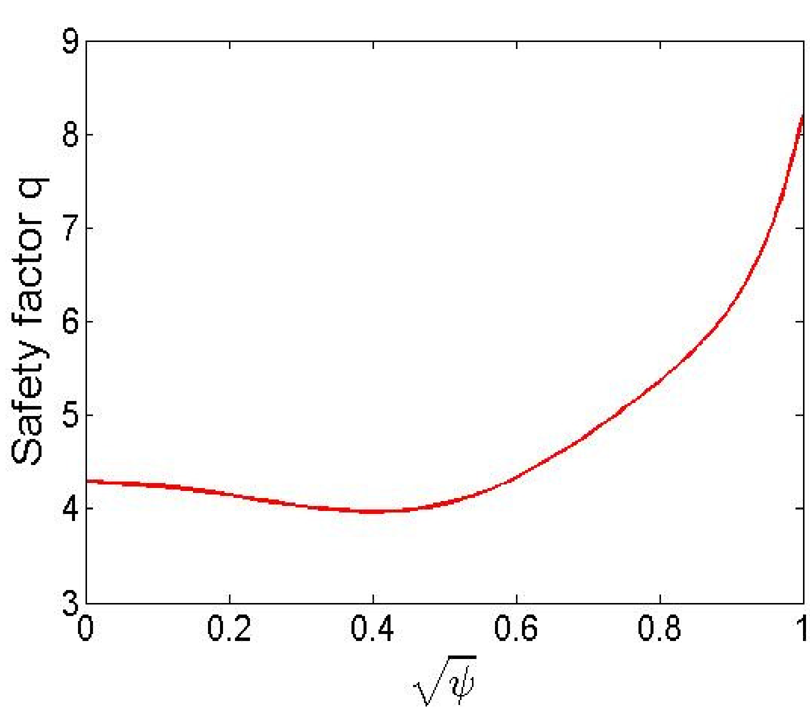


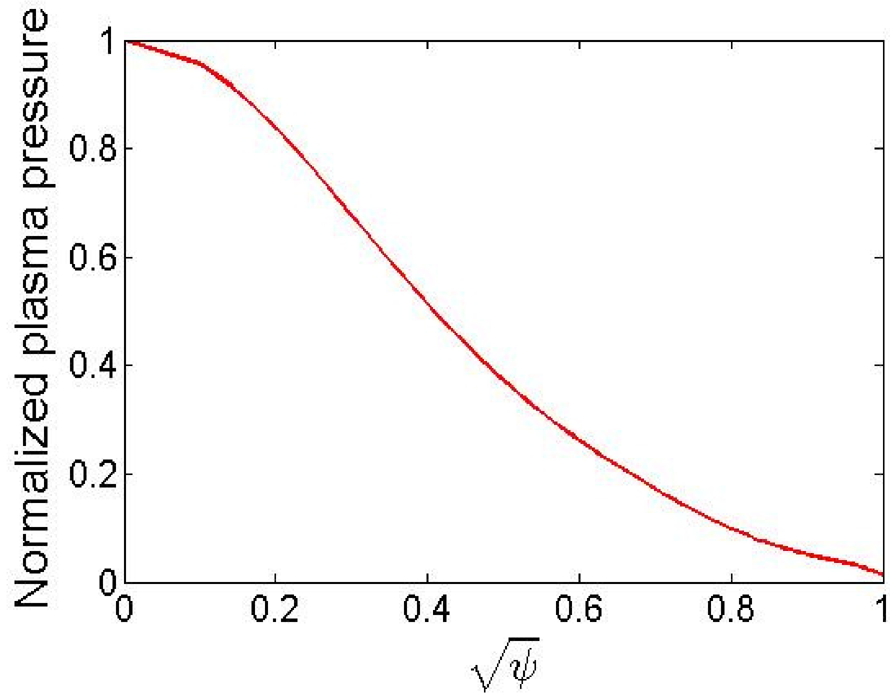
Simulation results at q_{min}=1.84

DIIID discharge #142111



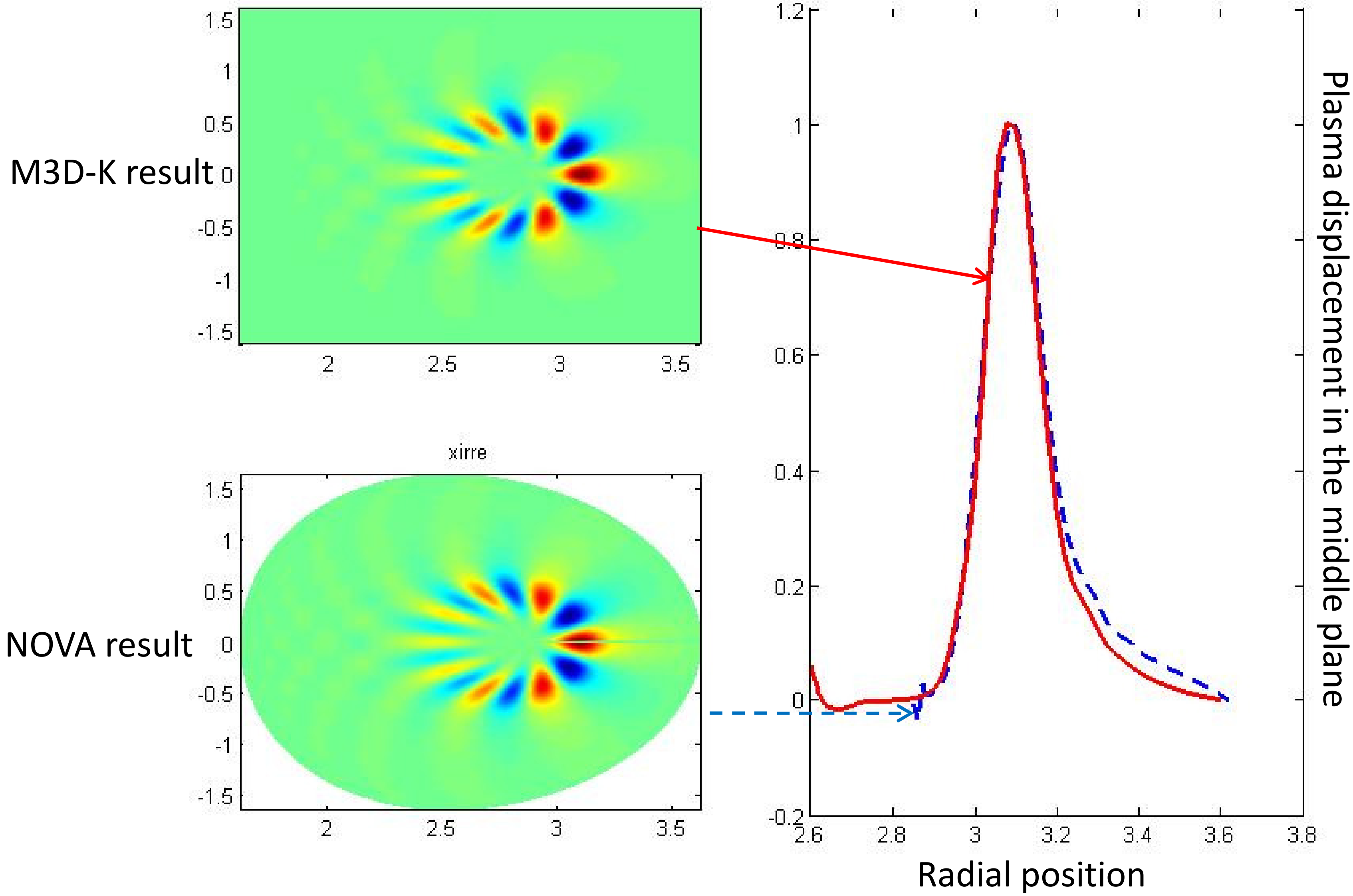
Equilibrium of DIIID discharge #142111 at time slice T~ 540ms



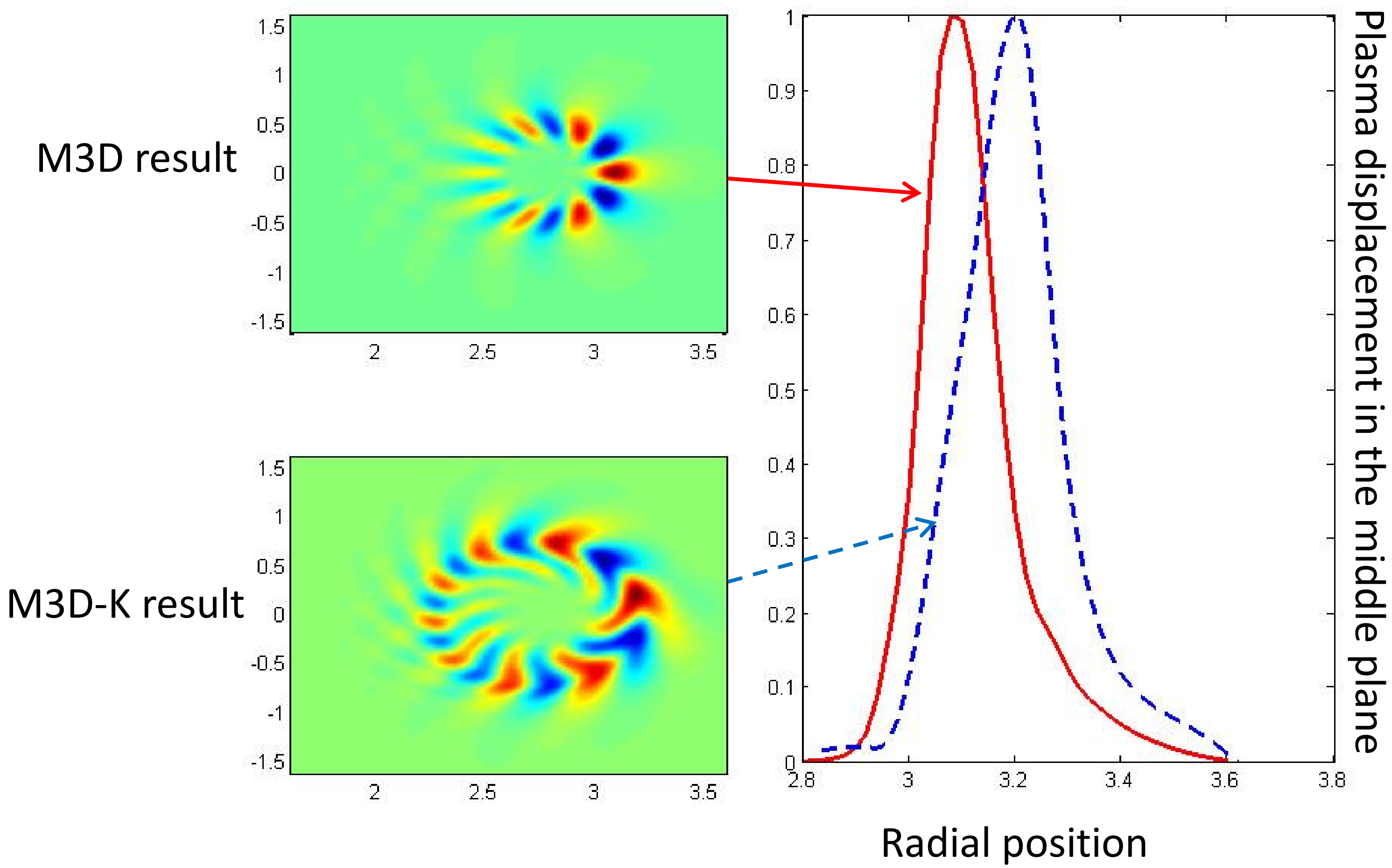


β_{tot}=1.84%, β_{hot}=0.4β_{tot}, and uniform plasma density are applied in this model.

Mode structure of n=2 at q_{min}=3.86 agrees well between NOVA and M3D-K with mhd limit

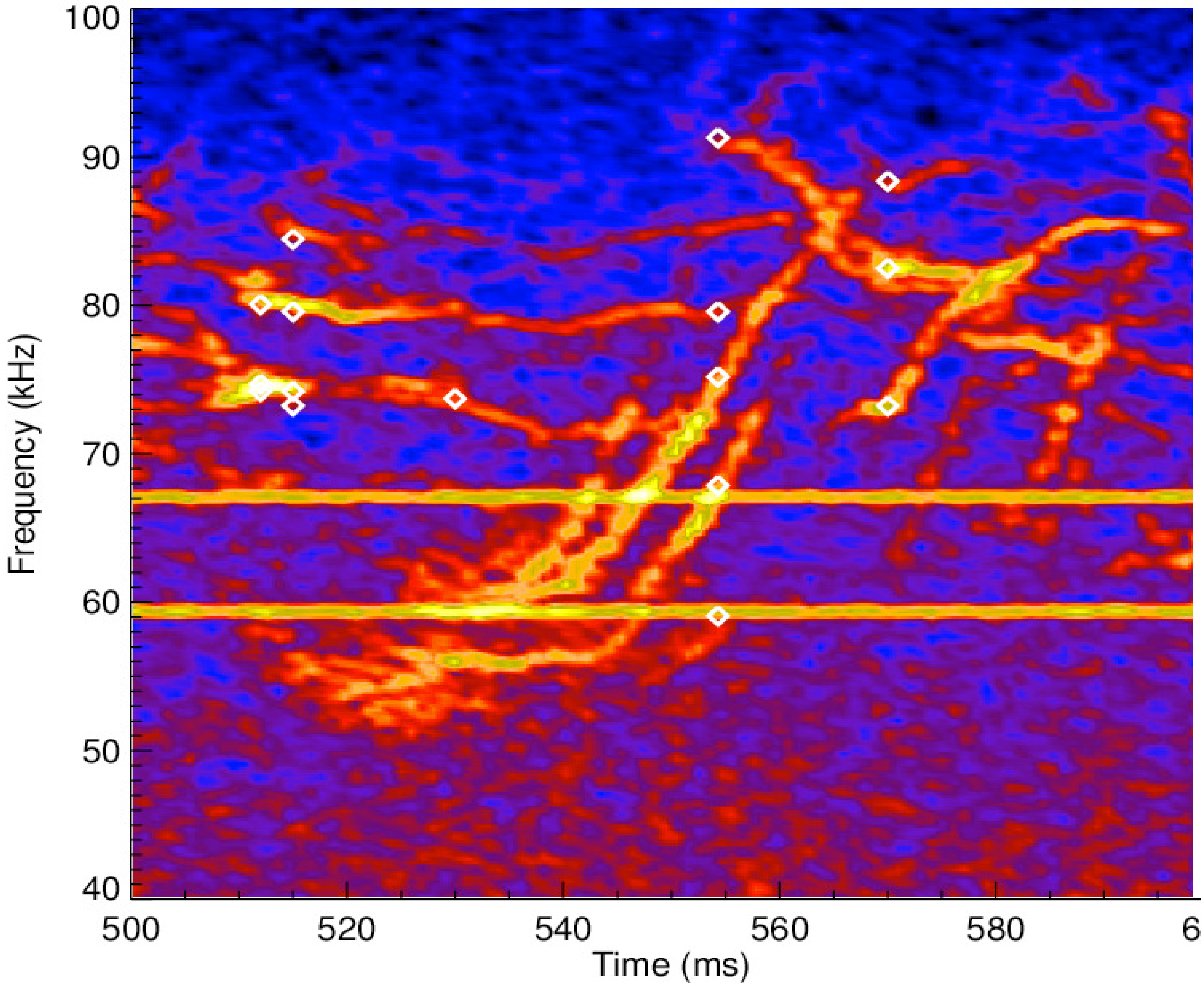


Energetic particles affect n=2 mode structure

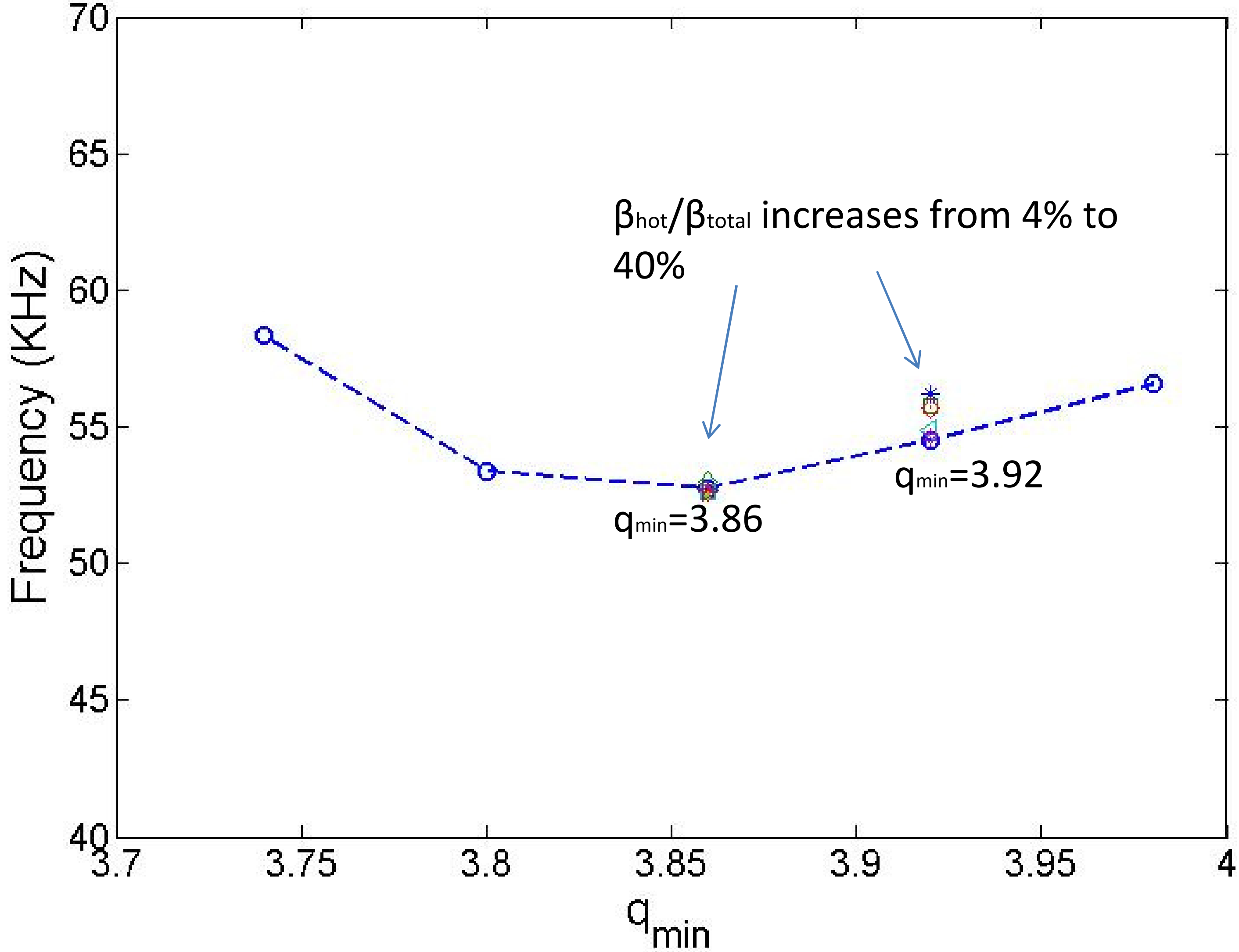


- ❑ Mode rotates along poloidal direction
- ❑ Mode peak shifts from q_{min} location to outside
- ❑ Mode width becomes broader

DIIID discharge #142111

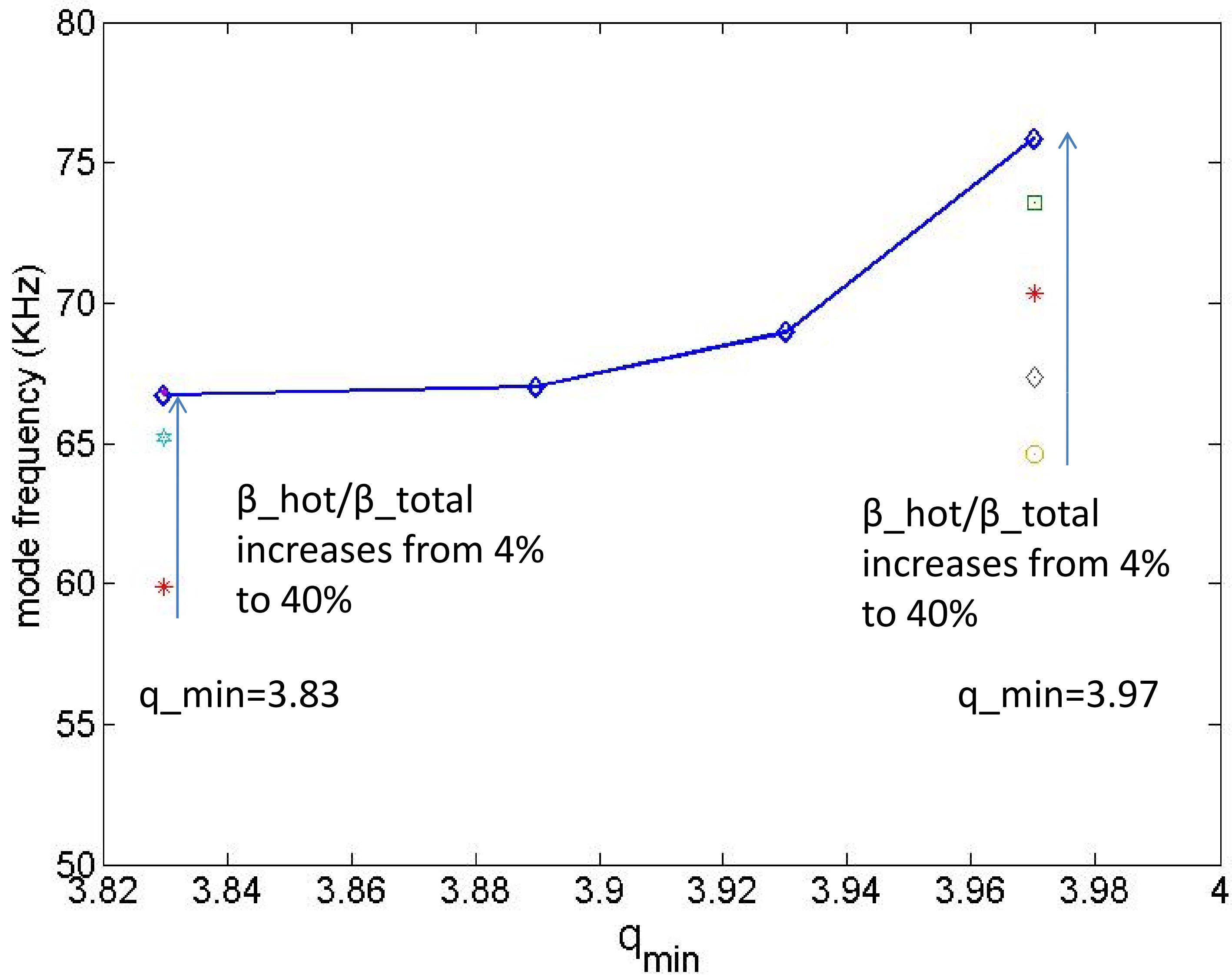


Linear mode frequency of n=2 mode is not sensitive to q_{min} or fast particle pressure

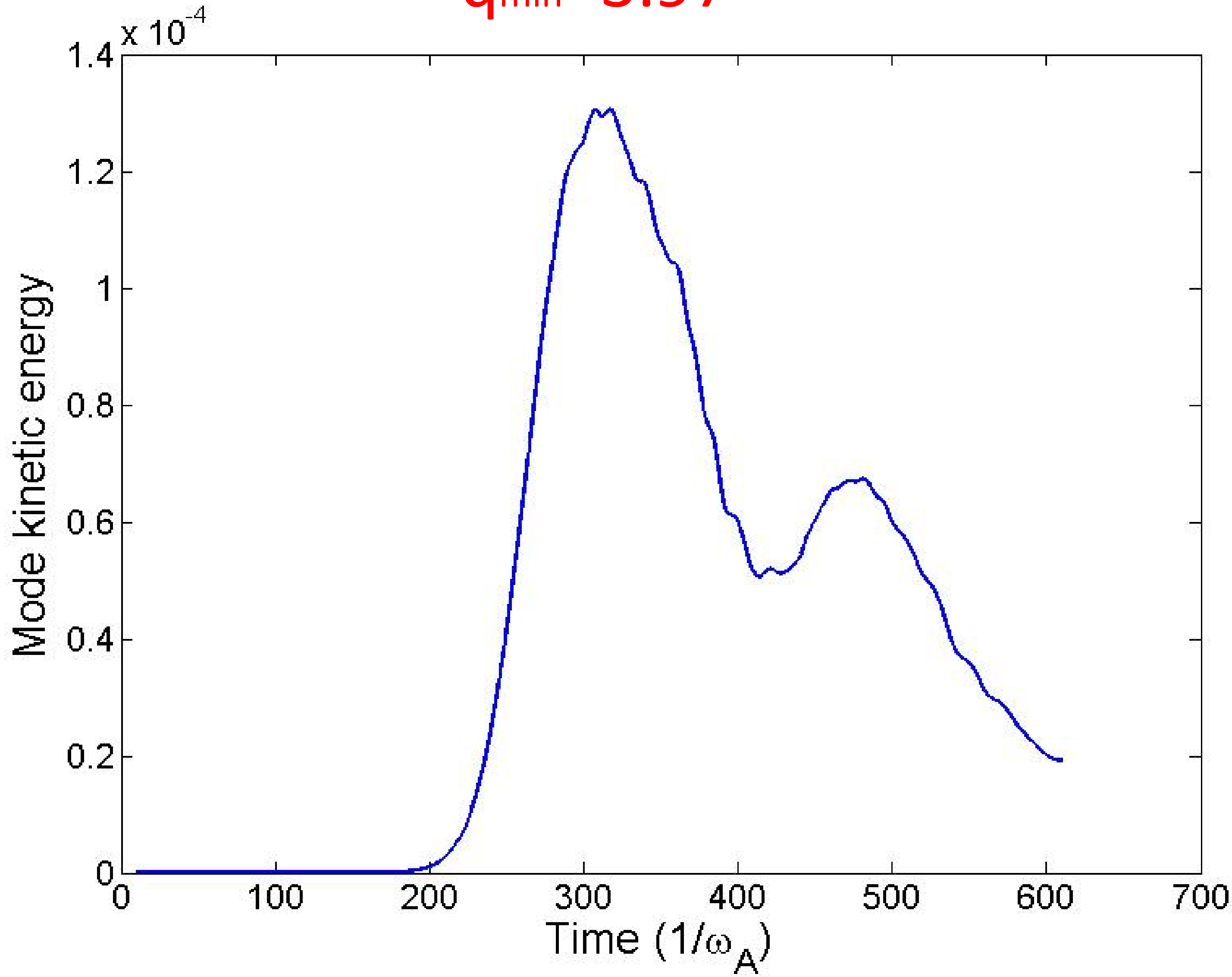


Linear mode frequency of n=3 mode is not sensitive to q_{min}

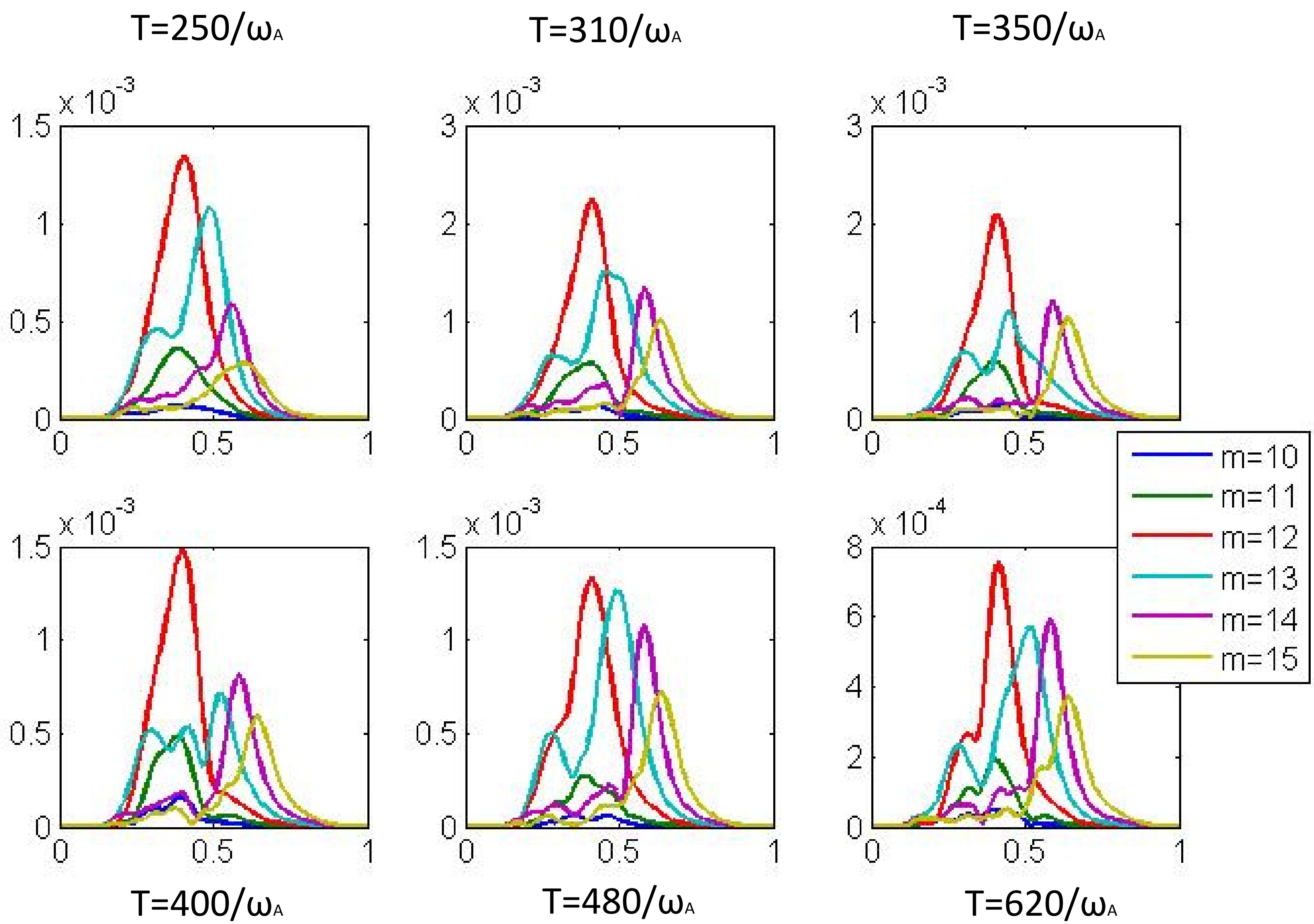
For T~540 ms DIIID equilibrium



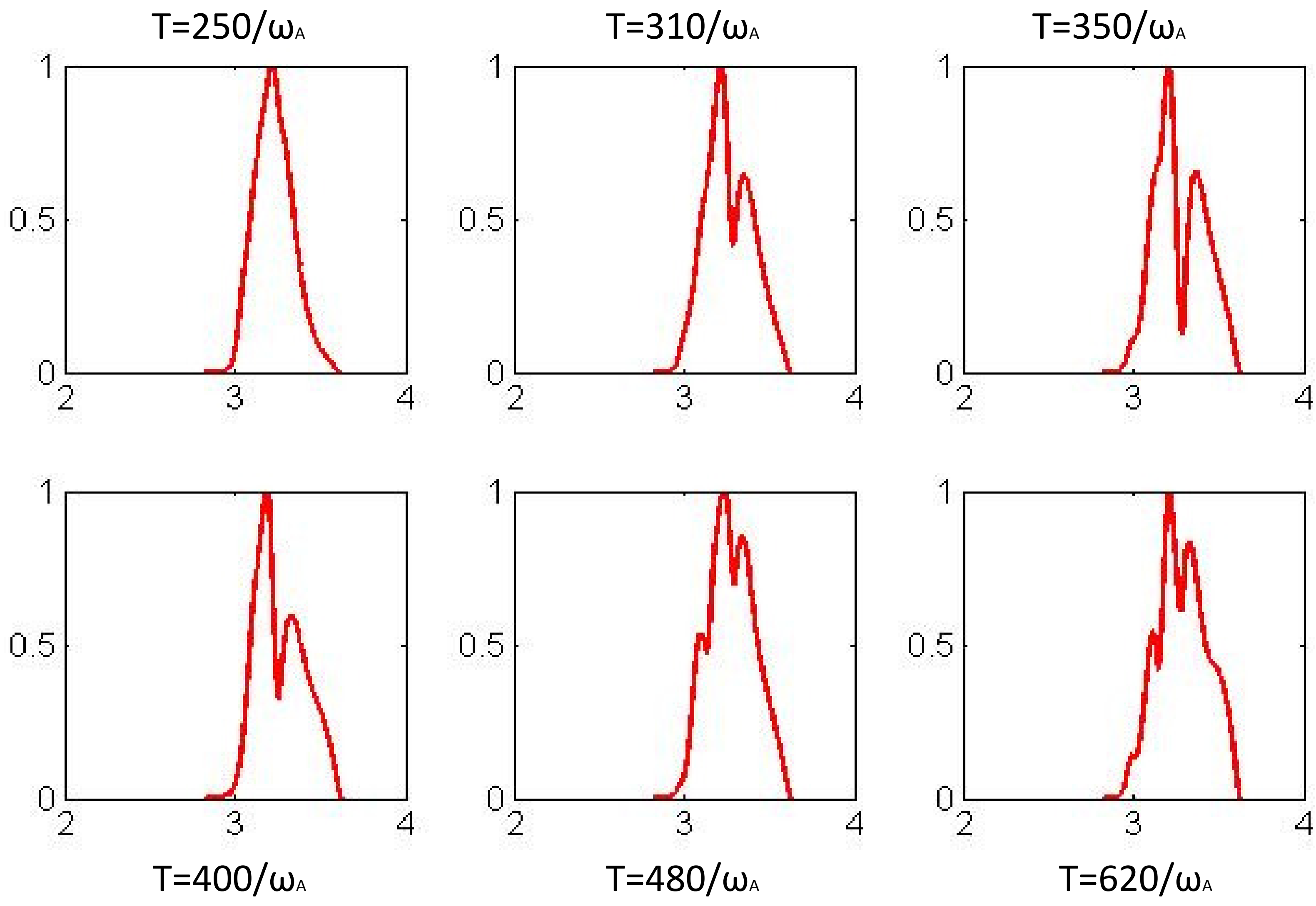
Nonlinear evolution of n=3 mode energy at q_{min}=3.97



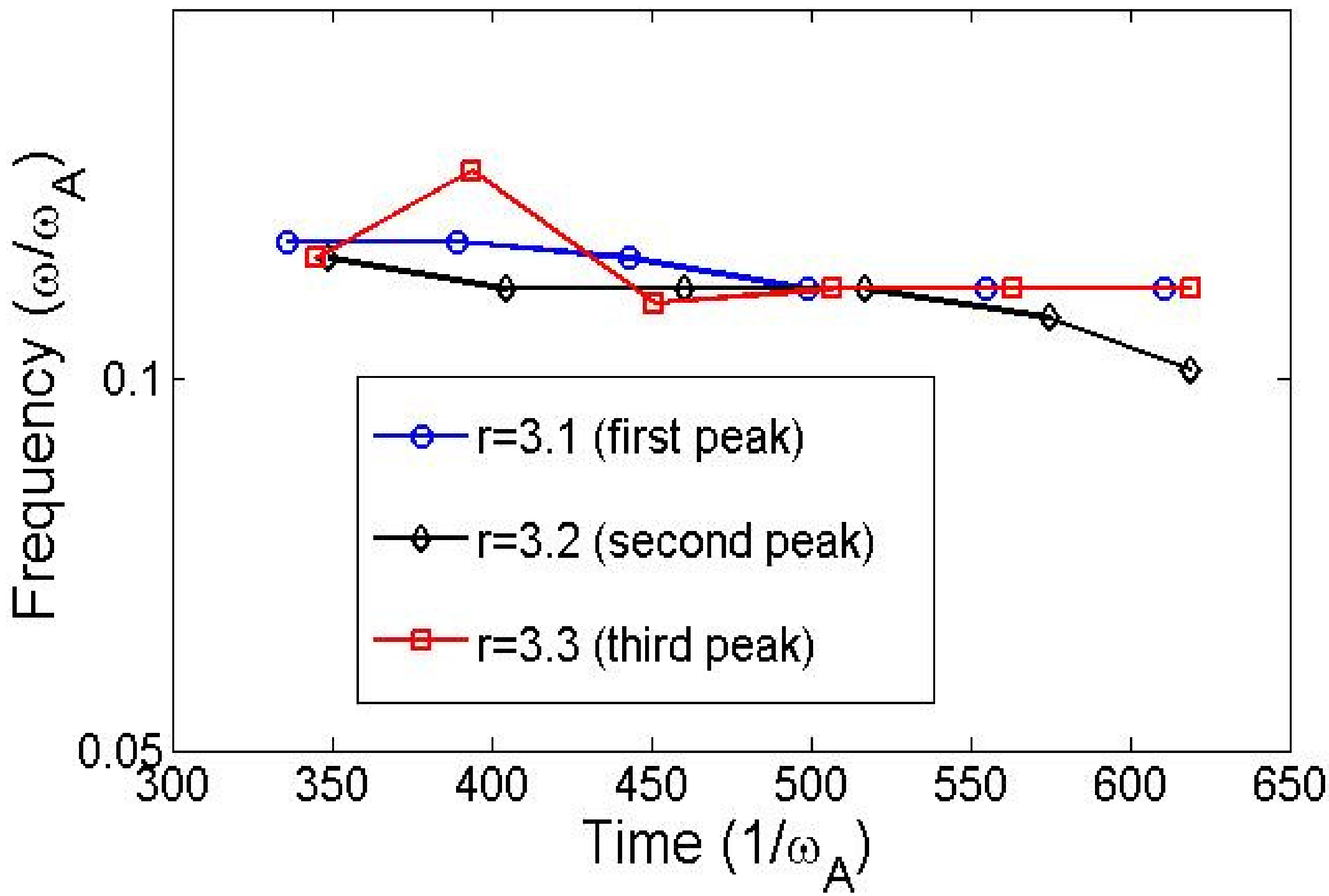
Poloidal harmonics of n=3 mode at q_{min}=3.97



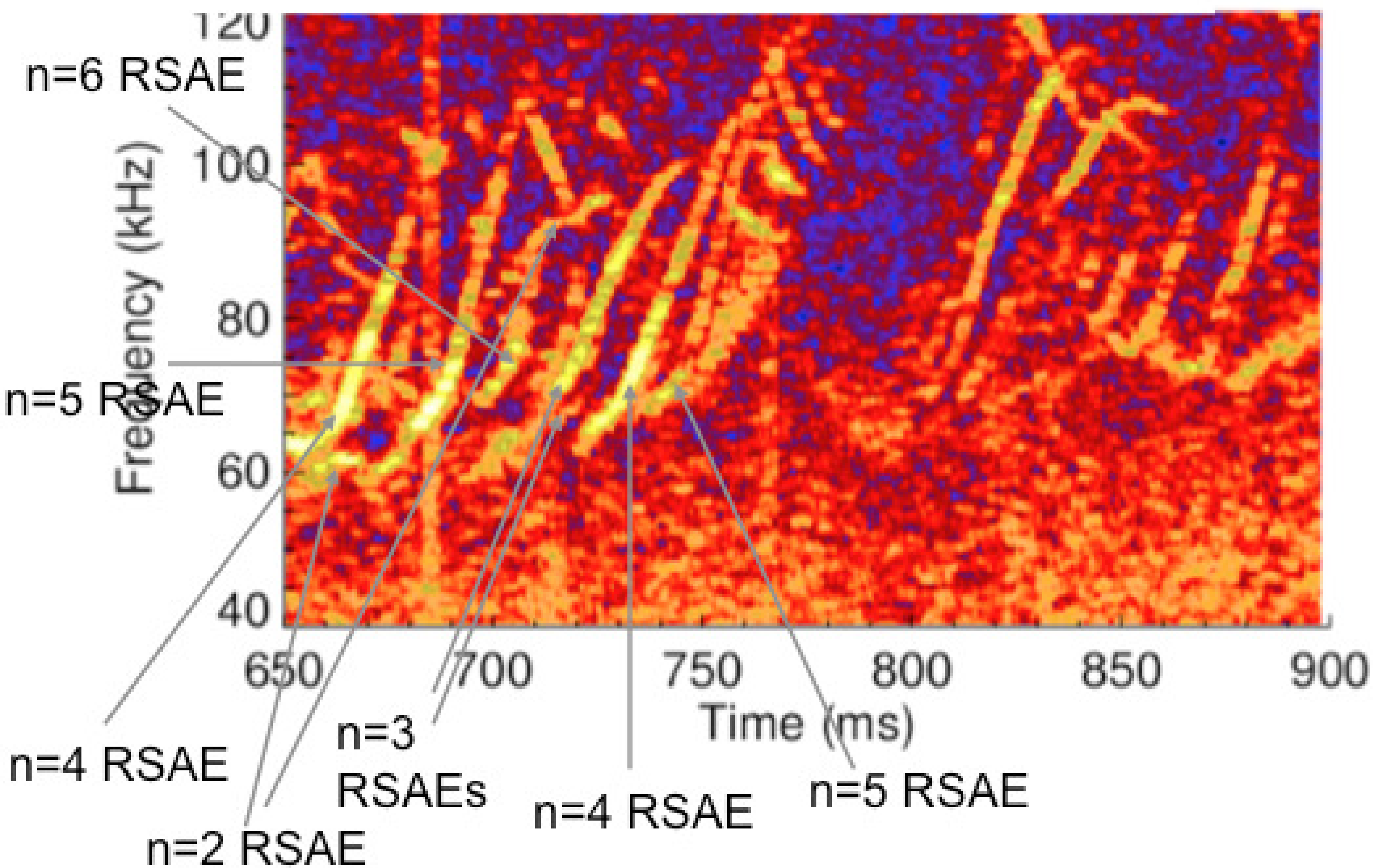
Middle plane mode amplitude of n=3 mode at q_{min}=3.97 of DIIID equilibrium



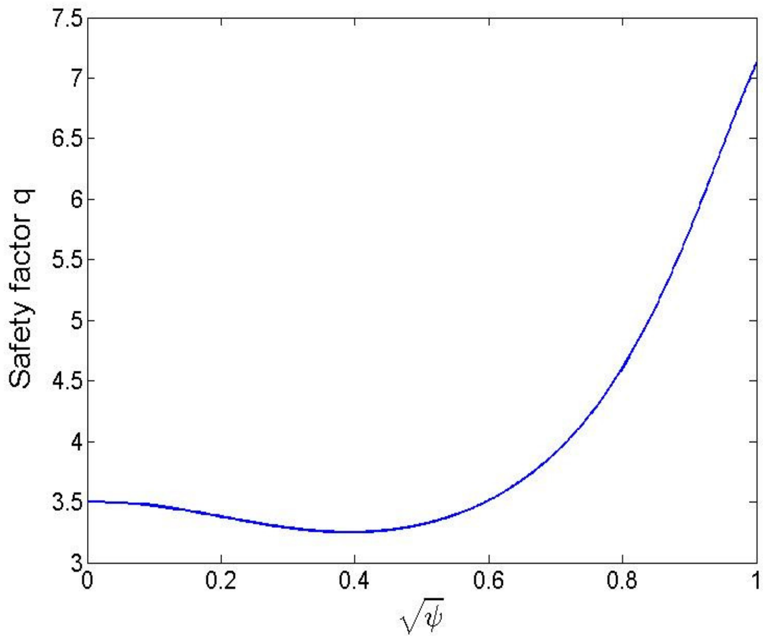
Nonlinear evolution of n=3 mode frequency at q_{min}=3.97 at different location

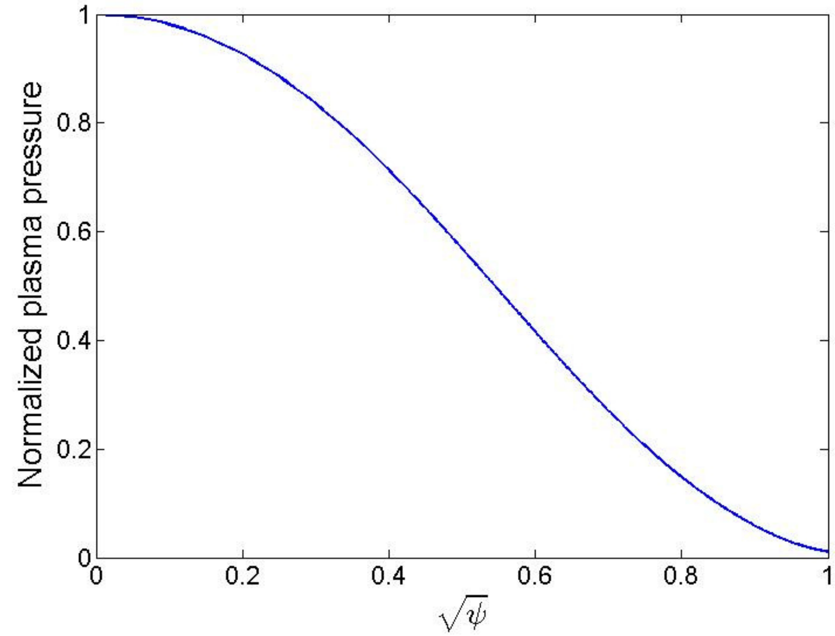


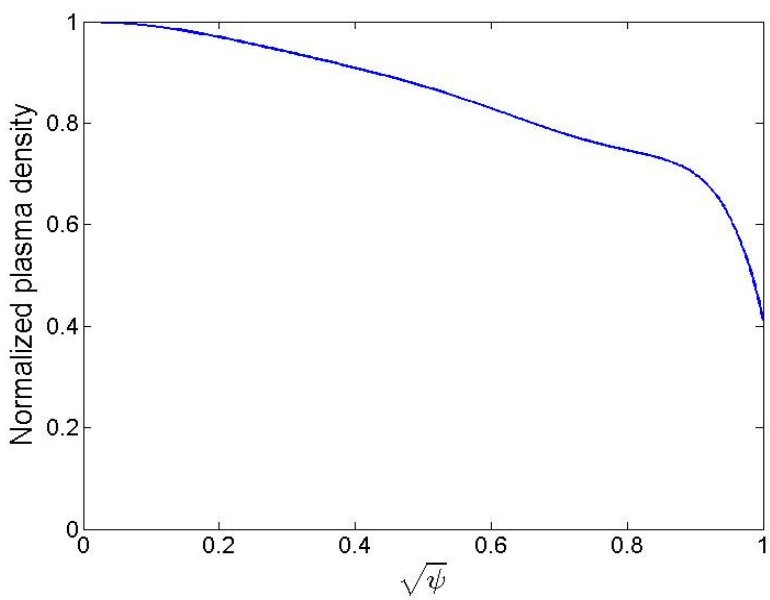
DIIID discharge #142111



DIIID equilibrium at time slice around T~ 725ms



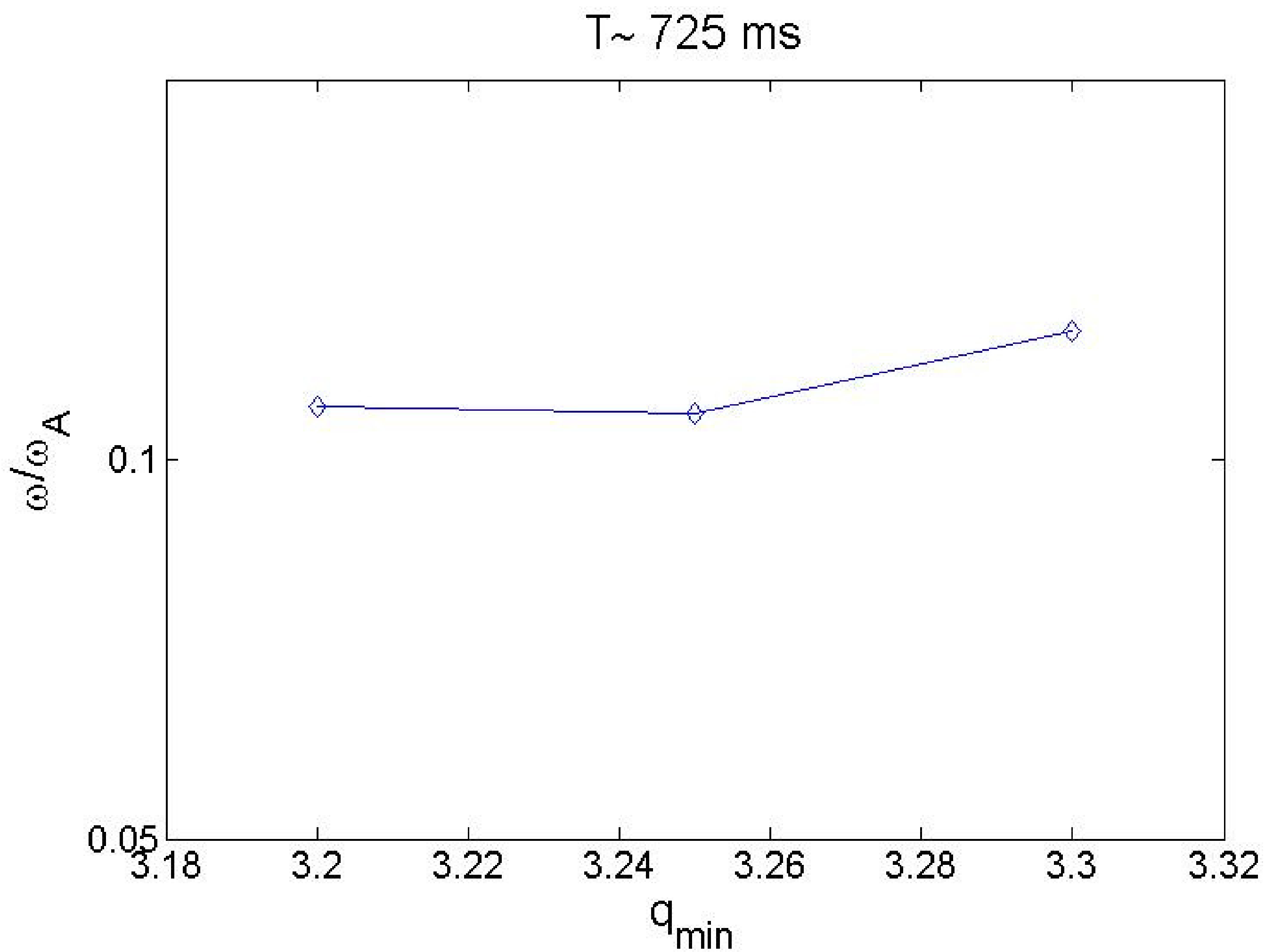




β_{tot}=1.84%, β_{hot}=0.4β_{tot}

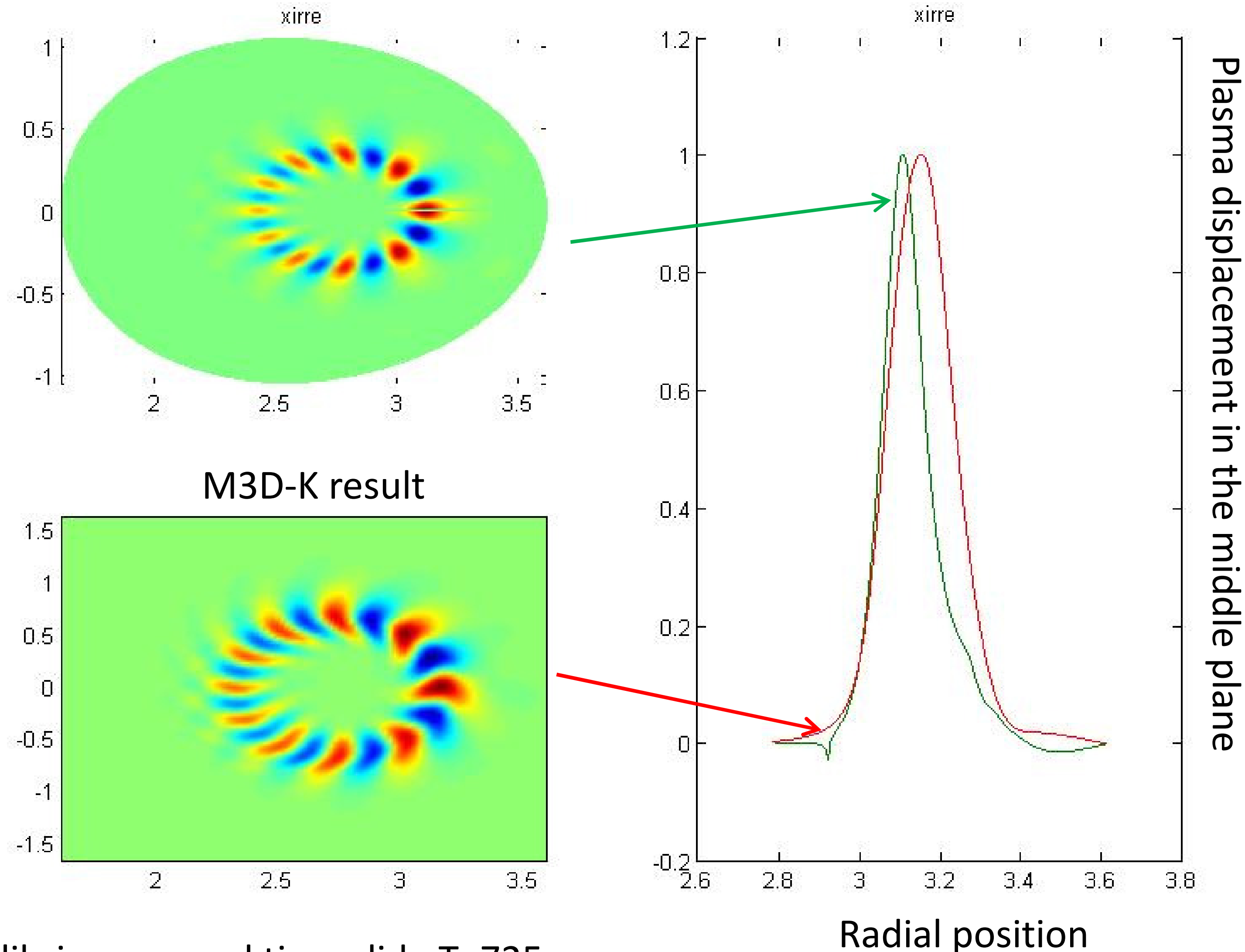
Theory indicates dominant RSAE being n=3, m=10.

Linear mode frequency of n=3 mode is not sensitive to q_{min}



Mode structure of n=3 at q_{min}=3.25 shifts outside in the presence of energetic particles compared to NOVA result

NOVA result



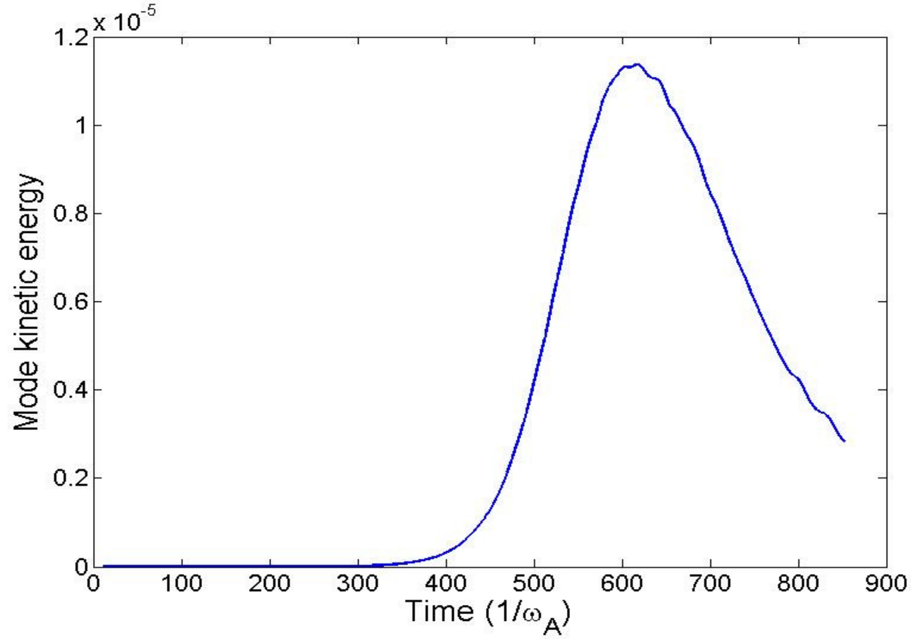
DIIID equilibrium around time slide T=725 ms

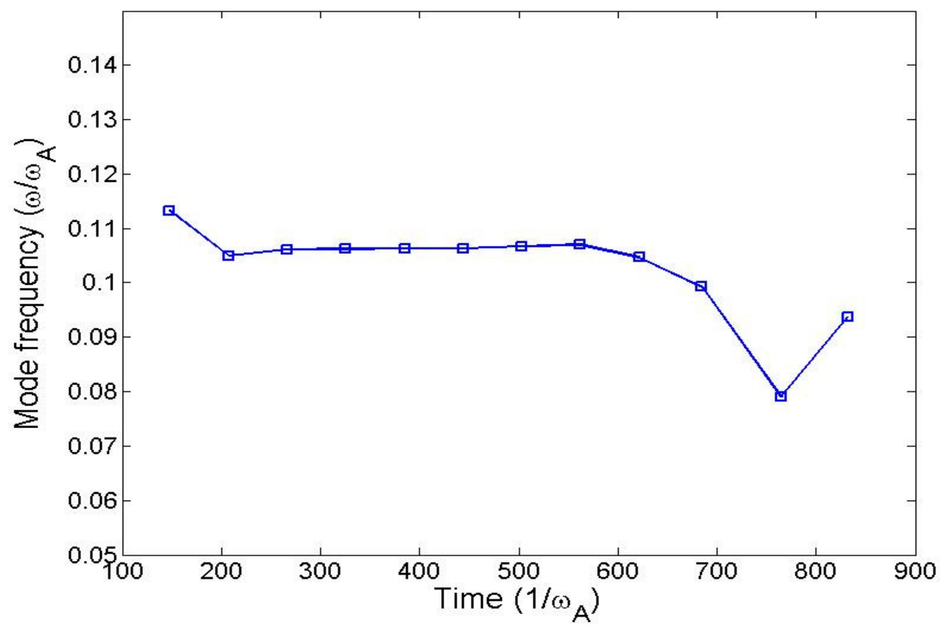
Nonlinear evolution of mode kinetic energy and mode frequency at q_{min}=3.25

Mode frequency is measured near q_{min} location.

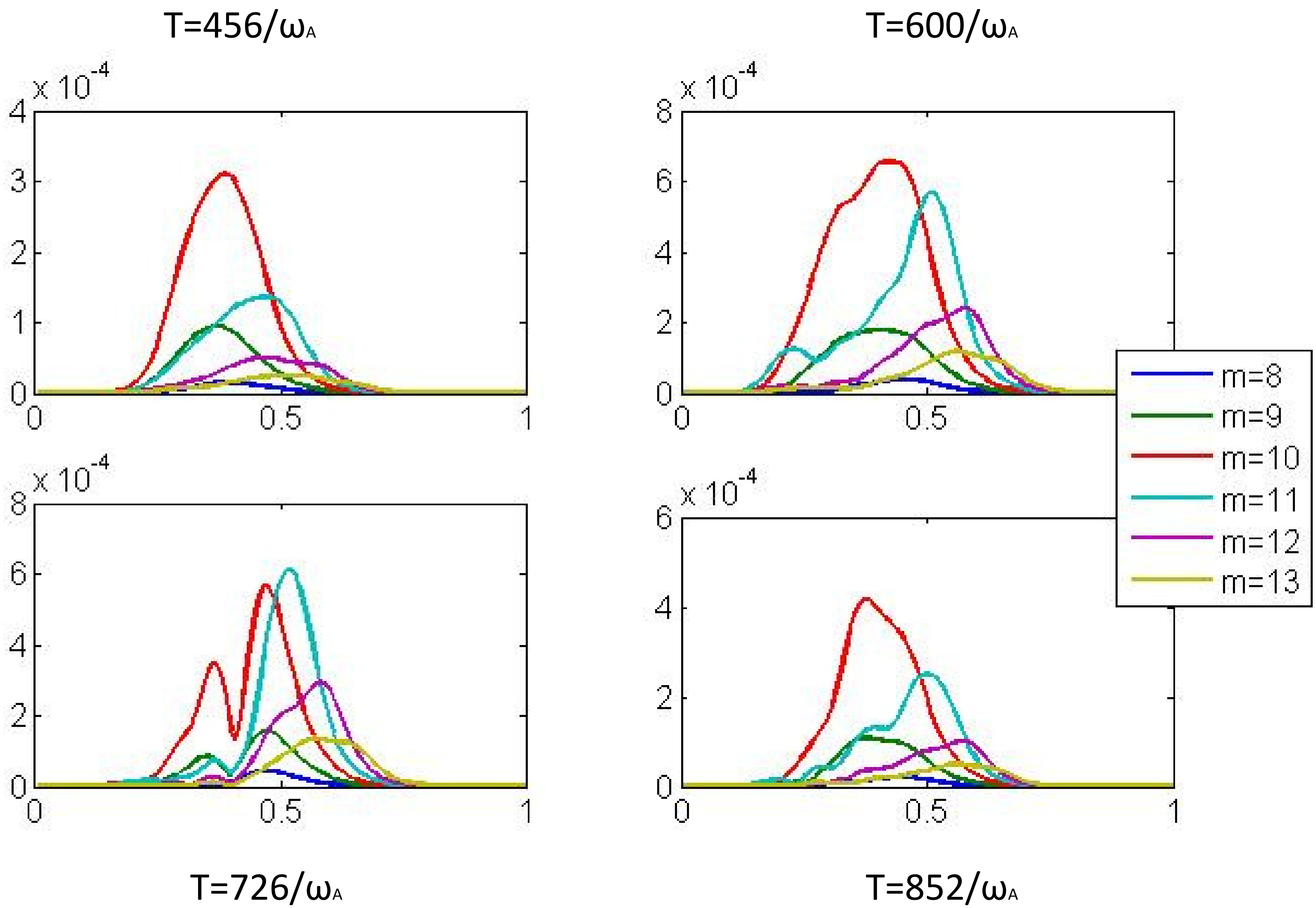
Frequency shifts in the nonlinear stage indicates the linear mode transits to a different one.

No source/sink



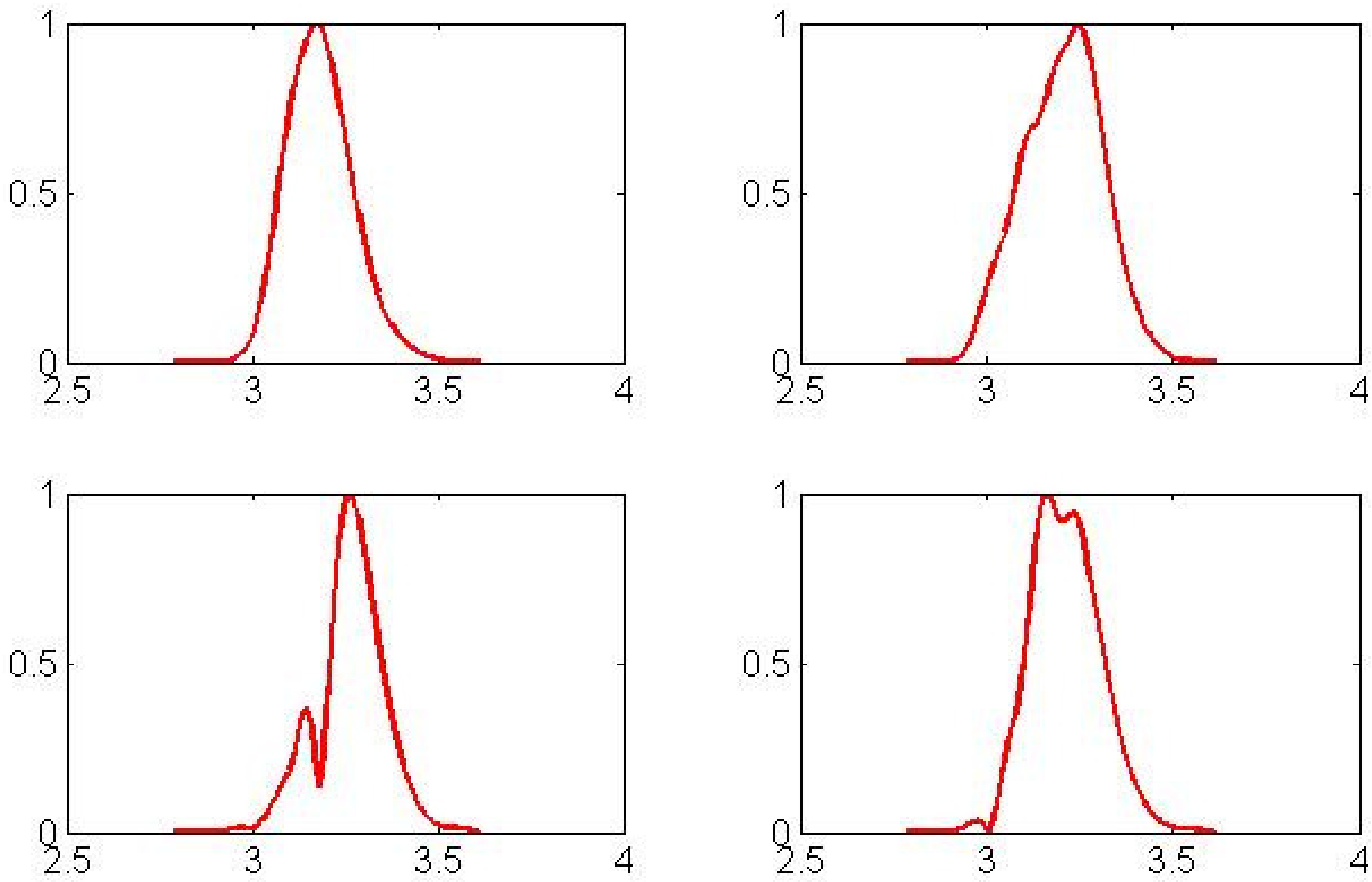


Poloidal harmonics of n=3 mode at q_{min}=3.25 of DIIID equilibrium



Middle plane mode amplitude of n=3 mode at q_{min}=3.25 of DIIID equilibrium

T=456/ω_A T=600/ω_A



T=726/ω_A T=852/ω_A

Conclusion

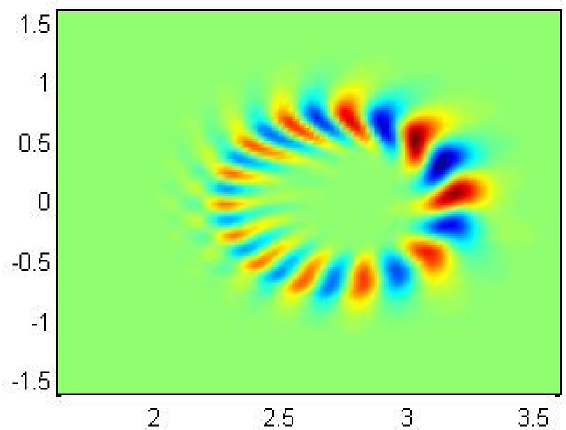
- M3d-K simulation results agree very well with NOVA in the MHD limit
- In the presence of energetic particles, both mode structure and mode frequency are different from the results in MHD limits
- The frequency of excited mode does not sweep as qmin varies, which indicates it is TAE-like mode
- Both mode structure and mode frequency change during nonlinear evolution

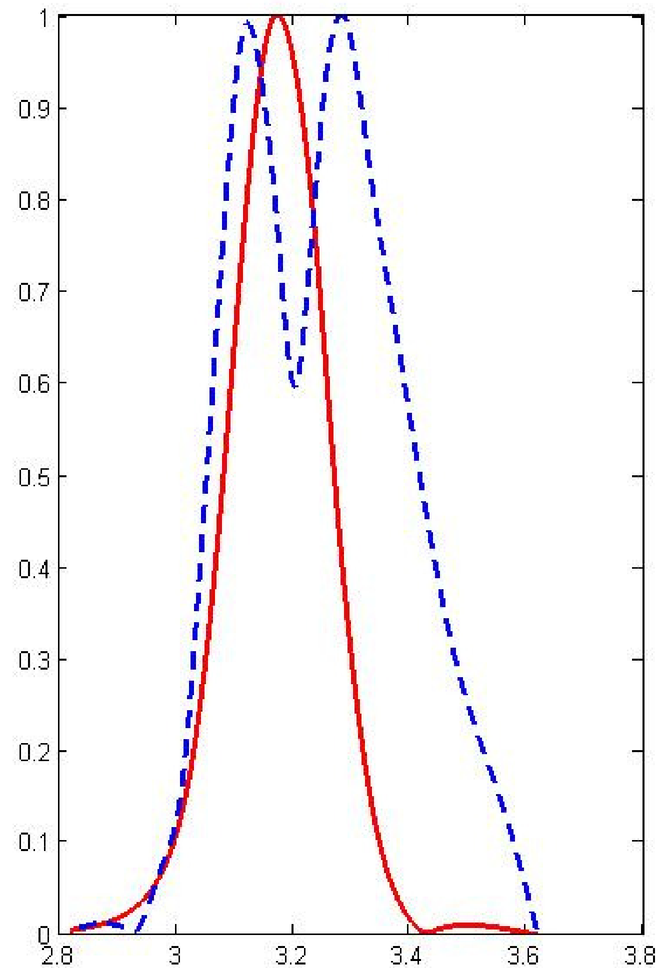
Future work

- Code benchmark with GEM
- To explore the effects from energetic particle profile including realistic beam distribution function
- Nonlinear evolution with source and sink

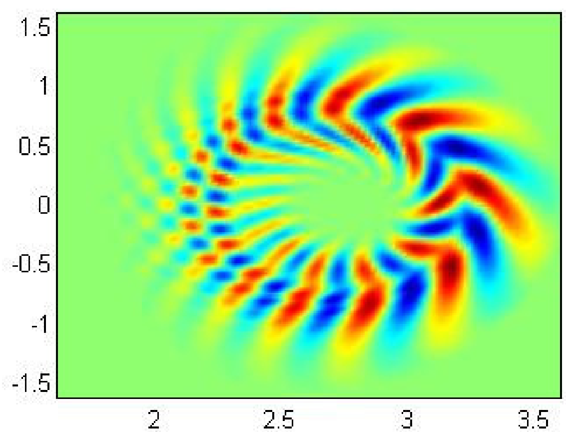
n=3, m=12 at q_min =3.83 from M3D-K for the same DIIID equilibrium

Linear mode structure





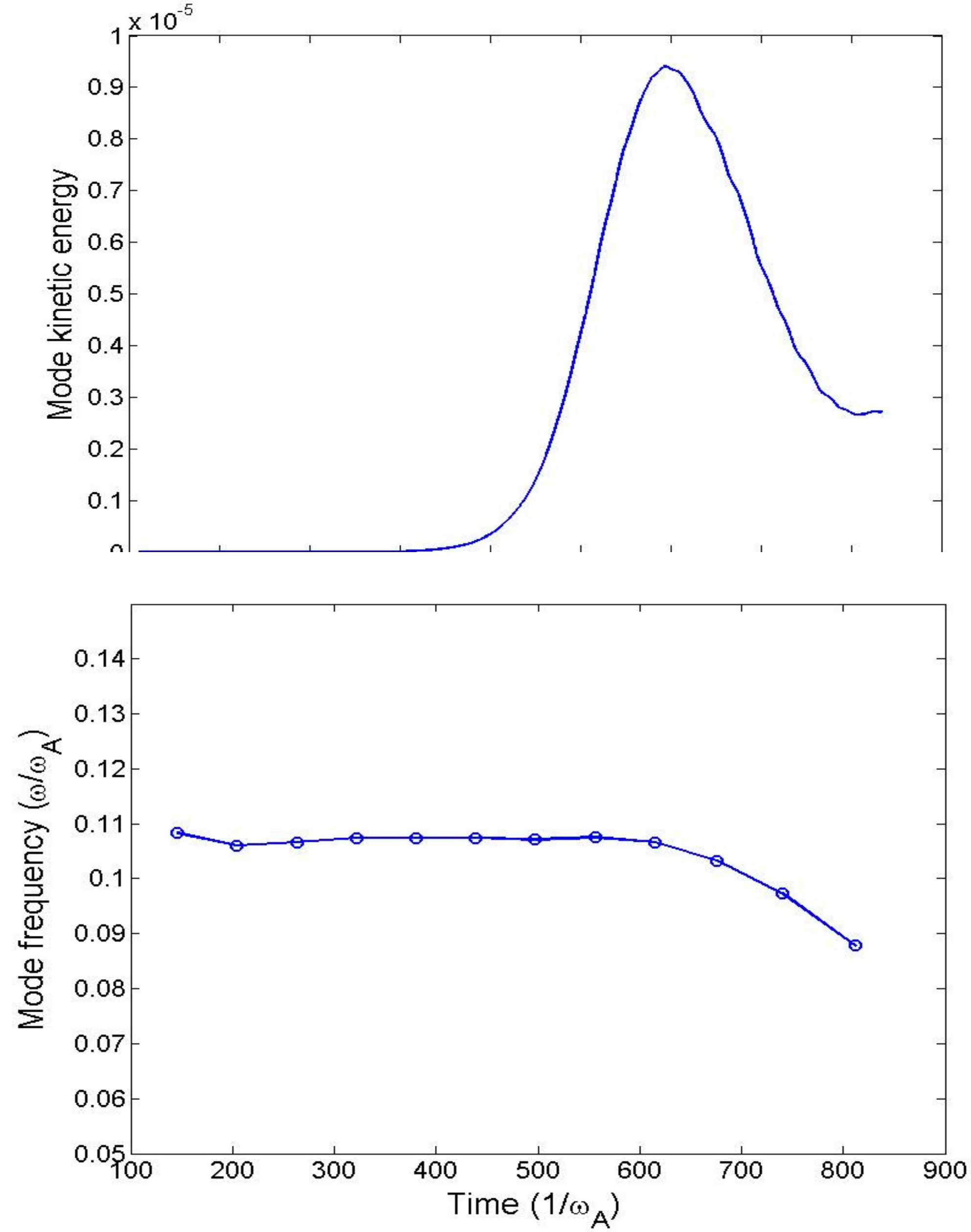
Nonlinear mode structure



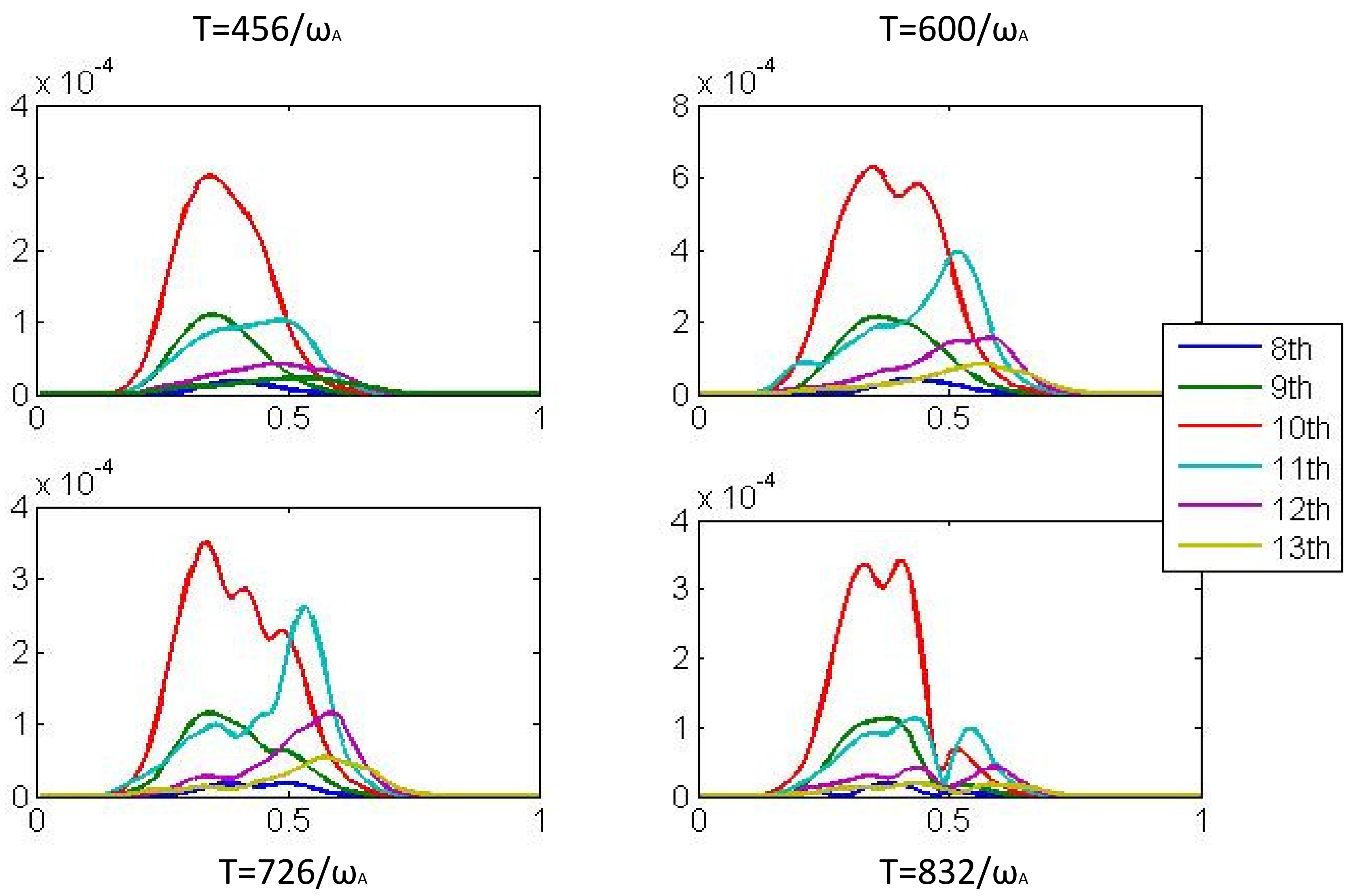
The time evolution of mode kinetic energy and mode frequency at q_{min}=3.20

Mode frequency is measured near q_{min} location.

Frequency shifts in the nonlinear stage indicates the linear mode transits to a different one.

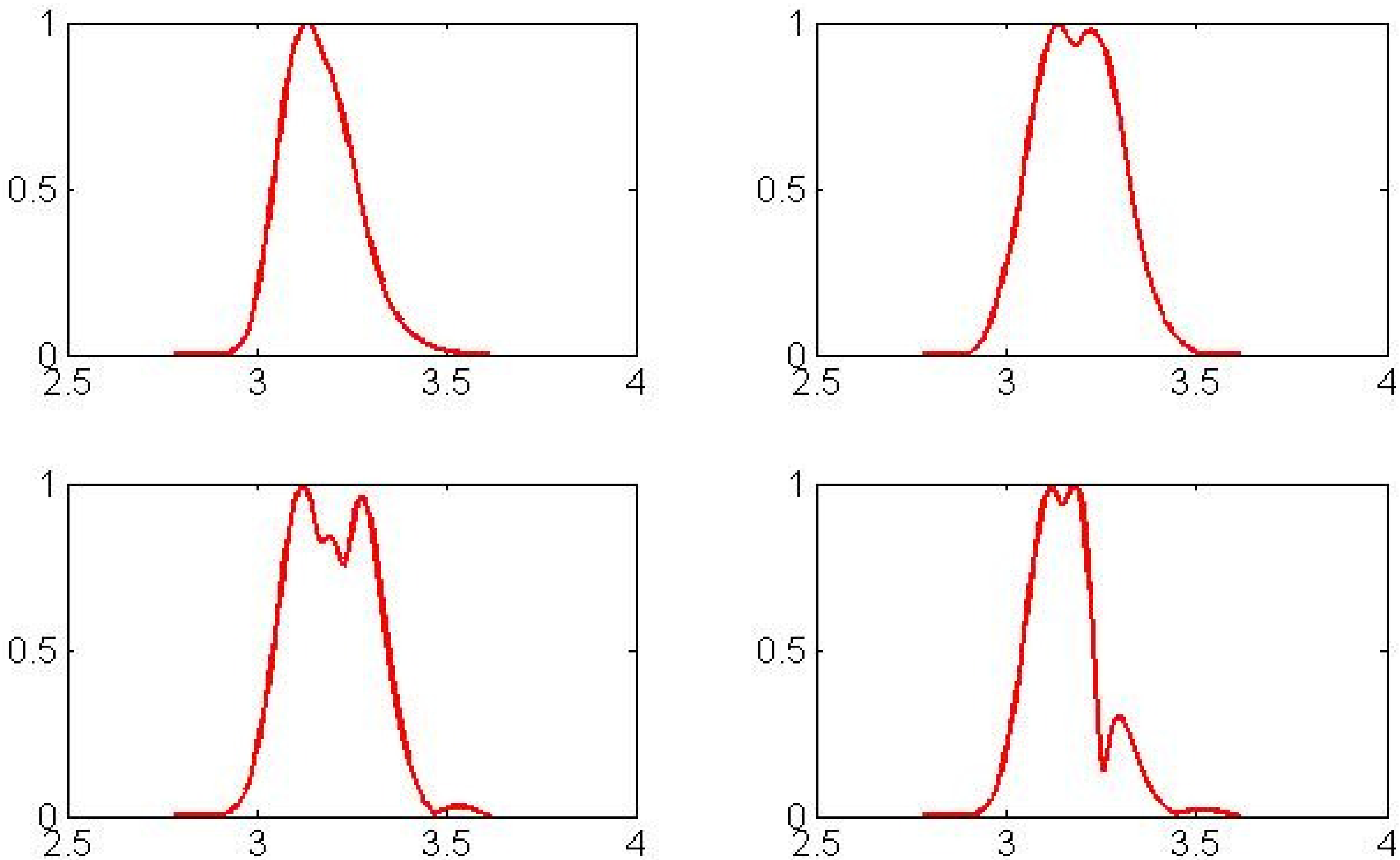


Poloidal harmonics of n=3, m=10 modes at q_{min}=3.20 of DIIID equilibrium



Middle plane mode amplitude of n=3, m=10 modes at q_{min}=3.20 of DIIID equilibrium

T=456/ω_A T=600/ω_A



T=726/ω_A T=832/ω_A