Simulation of DIII-D Shot #132707
Using Hybrid-MHD-Gyrokinetic Code (HMGC)

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DIII-D shot #132707 was dedicated to the SciDAC GSEP project focusing on energetic particle turbulence and transport. The shot is intended to serve as a reference case for global codes used to study Alfvén eigenmodes (AE).

We report and discuss first global nonlinear simulation results obtained with Hybrid MHD-Gyrokinetic Code (HMGC) [1] for this case.

[1] Briguglio S, Vlad G, Zonca F and Kar C, Phys. Plasmas 2, 3711 (1995)

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OUTLINE

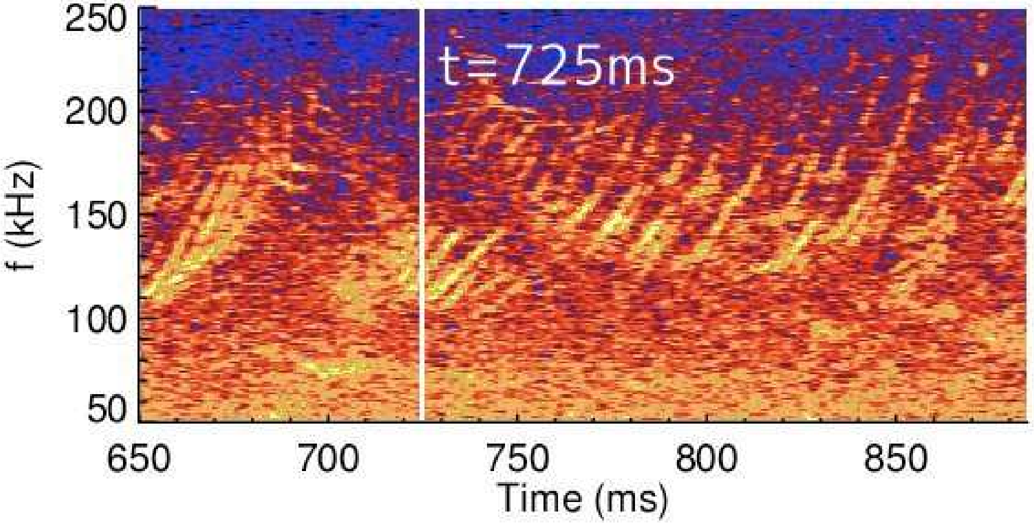
1. **Motivation and setting**
2. **HMGC**
3. **Profiles and parameters**
4. **MHD stability**
5. **Simulations with fast ions**
6. **Summary**
7. **Outlook**

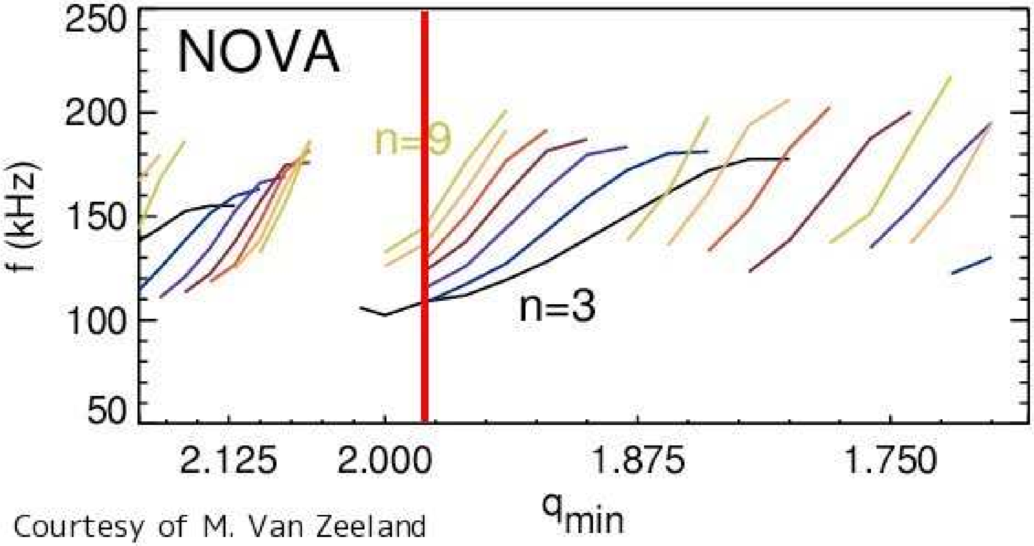
Note: The work summarized here was done 5–10 August 2008 using the updated fast-ion profile from 24 July 2008. A summary of earlier results obtained with a preliminary profile is given in a separate report. The preliminary fast ion density was too high and led to disruptive ballooning instability.

1. Motivation and Setting

Comparison between experiment and numerical simulation.

- DIII-D shot #132707: well-diagnosed AEs and fast ions, near-circular x-section
- HMGC code: nonlinear, MHD + fast ion orbits, global, circular cross-section





Courtesy of M. Van Zeeland
[adapted]

Simulation setting:

- Focus on time slice around $t = 725$ms.
- Prominent AE activity: reversed-shear Alfvén eigenmodes (RSAE).
- Vary toroidal mode number n and $q_{\min}$.

Figure:

- *top:* CO_2 interferometer data
- *bottom:* NOVA analysis of RSAE (Doppler shift: $\Delta f = n \times 5.6$kHz)

2. Hybrid MHD-Gyrokinetic Code (HMGC)

Briguglio *et al.*
PoP'95

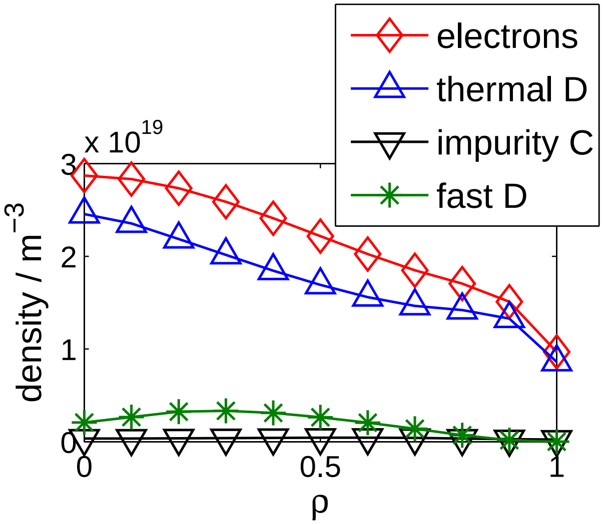
- $\mathcal{O}(\varepsilon^3)$ ideal MHD with zero bulk pressure ($\beta_{\mathrm{i}} = \beta_{\mathrm{e}} = 0$)
- Resistive and viscous dissipation (for numerical stability)
- Fast ("hot") ions enter MHD momentum equation as ⊥ component of divergence of pressure tensor $\mathbf{\Pi}_{\mathrm{H}} = \frac{1}{m_{\mathrm{H}}^2} \left\langle F_{\mathrm{H}}(t, \boldsymbol{R}_{\mathrm{gc}}, \mu, v_\parallel) \times \left[\frac{\mu B}{m_{\mathrm{H}}} \hat{\boldsymbol{I}} + \hat{\boldsymbol{b}}\hat{\boldsymbol{b}} \left(v_\parallel^2 - \frac{\mu B}{m_{\mathrm{H}}} \right) \right] \right\rangle$
- Formal ordering: $\frac{n_{\mathrm{H}}}{n_{\mathrm{i}}} \sim \mathcal{O}(\varepsilon^3)$, $\frac{T_{\mathrm{H}}}{T_{\mathrm{i}}} \sim \mathcal{O}(\varepsilon^{-2}) \quad \Rightarrow \quad \frac{\beta_{\mathrm{H}}}{\beta_{\mathrm{i}}} \sim \mathcal{O}(\varepsilon)$.

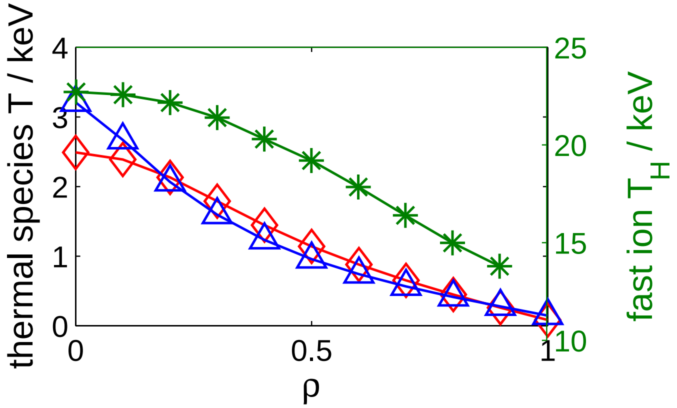
$$\frac{\partial \psi}{\partial t} = -\frac{cR^2}{R_0 B_0} (\boldsymbol{\nabla}\psi \times \boldsymbol{\nabla}\varphi) \cdot \boldsymbol{\nabla}\phi - \frac{c}{R_0} \frac{\partial \phi}{\partial \varphi} + \eta \frac{c^2}{4\pi} \Delta^* (\psi - \psi^{\mathrm{eq}}) + \mathcal{O}(\varepsilon^4 v_{\mathrm{A}} B_\varphi) \tag{1}$$

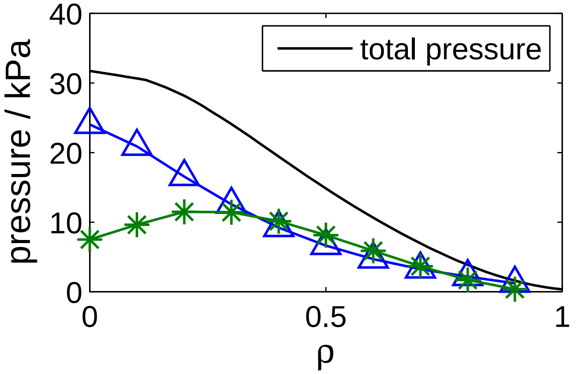
$$\hat{\rho} \left(\frac{\mathrm{D}}{\mathrm{D}t} - \frac{2c}{R_0 B_0} \frac{\partial \phi}{\partial Z} \right) \nabla_\perp^2 \phi + (\boldsymbol{\nabla}\hat{\rho}) \cdot \left(\frac{\mathrm{D}}{\mathrm{D}t} - \frac{c}{R_0 B_0} \frac{\partial \phi}{\partial Z} \right) \boldsymbol{\nabla}\phi = -\frac{B_0}{4\pi c} \boldsymbol{B} \cdot \boldsymbol{\nabla}(\Delta^* \psi) - \frac{B_0}{c R_0} \boldsymbol{\nabla} \cdot \left[R^2 (\boldsymbol{\nabla} \cdot \mathbf{\Pi}_{\mathrm{H}}) \times \boldsymbol{\nabla}\varphi \right] + \nu \hat{\rho} \nabla_\perp^4 \phi + \mathcal{O}\left(\varepsilon^4 \rho v_{\mathrm{A}}^2 B_\varphi / a^2 c \right) \tag{2}$$

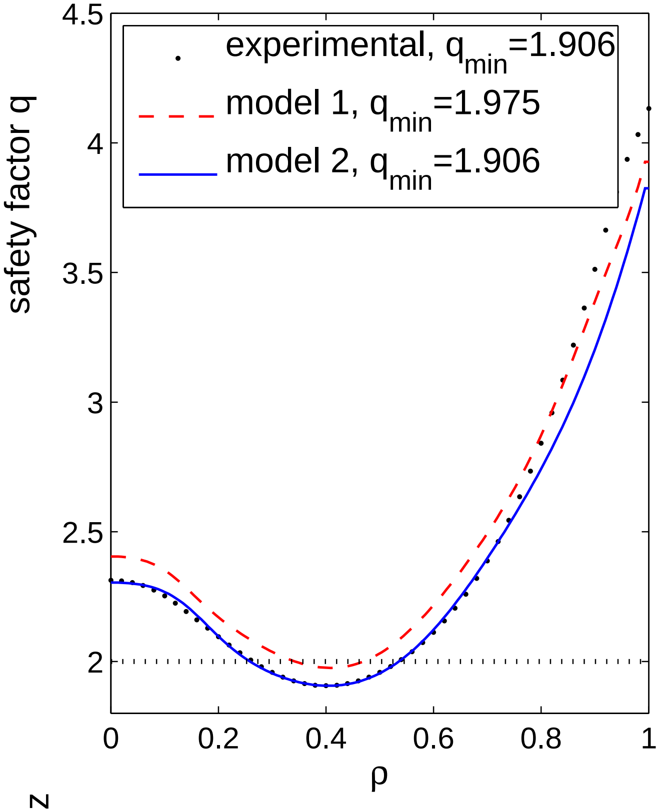
$$\hat{\rho} = \frac{R^2}{R_0^2} \rho, \quad \frac{\mathrm{D}}{\mathrm{D}t} = \frac{\partial}{\partial t} + \boldsymbol{v}_\perp \cdot \boldsymbol{\nabla}, \quad \nabla_\perp^2 = \frac{1}{R} \frac{\partial}{\partial R} R \frac{\partial}{\partial R} + \frac{\partial^2}{\partial Z^2}, \quad \Delta^* \psi = R \frac{\partial}{\partial R} \left(\frac{1}{R} \frac{\partial \psi}{\partial R} \right) + \frac{\partial^2 \psi}{\partial Z^2}.$$

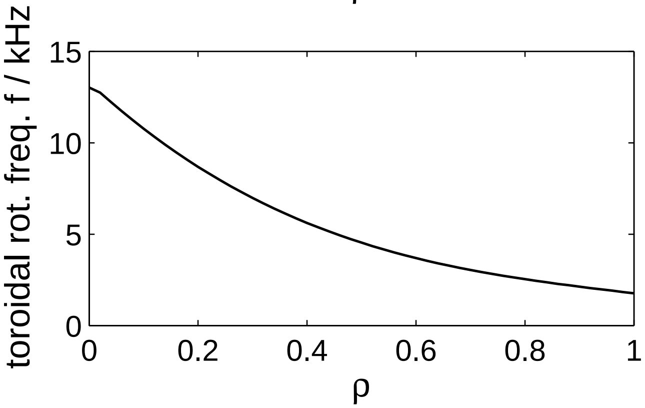
3. PROFILES AND PARAMETERS











Parameters:

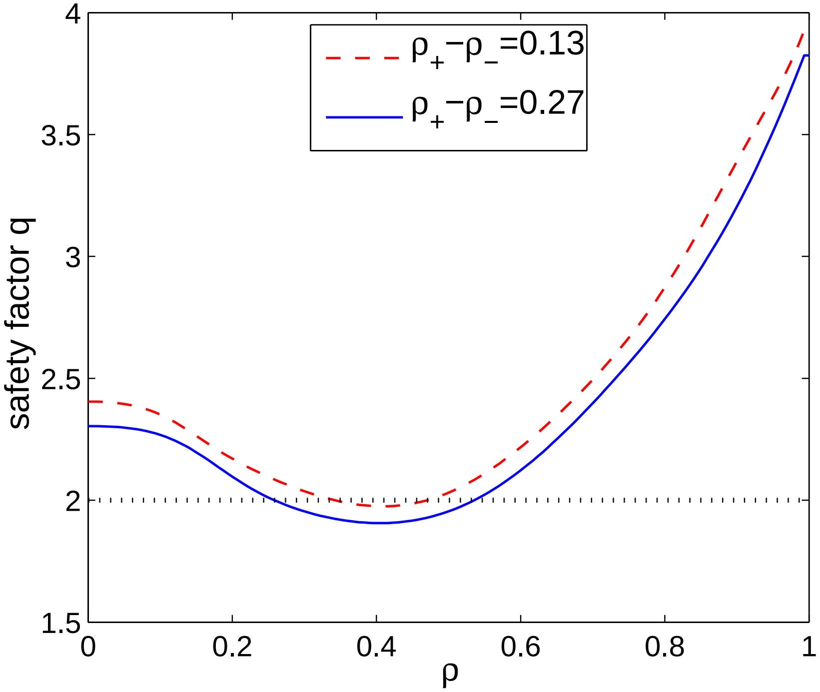
- $a/R_0 = 0.43$
- $\beta_\mathrm{i} = \beta_\mathrm{e} = 0$
- $\rho_{H0}/a = \frac{1}{36} = 0.028$
- $v_\mathrm{H0}/v_\mathrm{A0} = 0.32$
- $P_\parallel/P_\perp = 1.44$
- $E_0/E_\mathrm{crit,0} = 2.04$
- $n_\mathrm{H0}/\sum_i n_\mathrm{i0} = 8.3\%$
- slowing-down distribution
- $S_\mathrm{A} = 10^5$
- $Re_\mathrm{A} = 10^8$

Conversion:

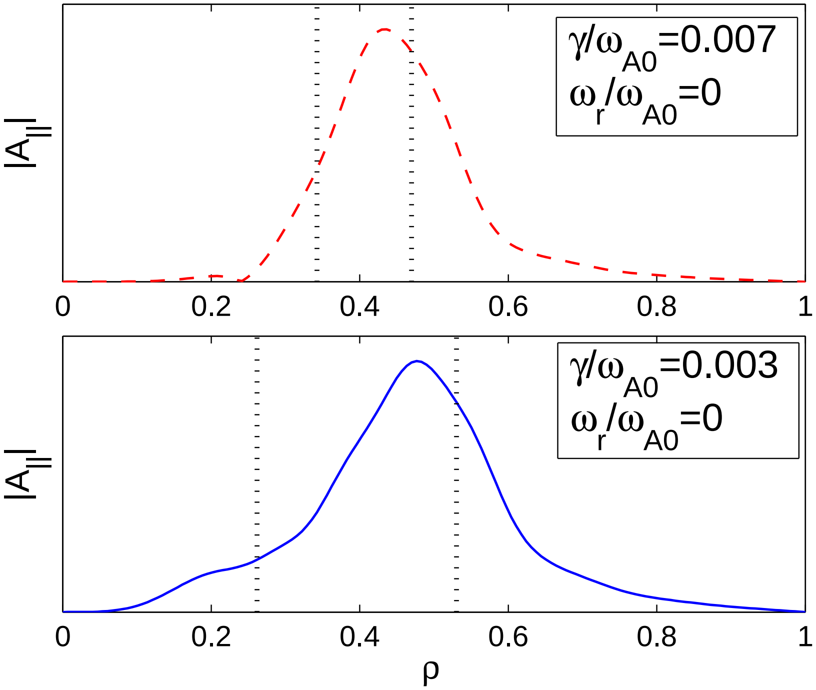
- normalization $f = \frac{\omega}{\omega_\mathrm{A0}} \times 583\mathrm{kHz}$
- Doppler shift at q_min $\Delta f = n \times 5.6\mathrm{kHz}$

4. MHD STABILITY

- First tentative runs done with relatively low radial resolution: $N_\rho = 150$
  $\longrightarrow$ need strong dissipation:
  Lundquist number $S_\mathrm{A} = 10^5$
- Results:
  - $n = 2$: unstable resistive double tearing mode (DTM)
  - $n = 4, 6$: stable
- Based on previous experience, expect that $n = 2$ DTM is stable for $S_\mathrm{A} \gtrsim 10^6$.

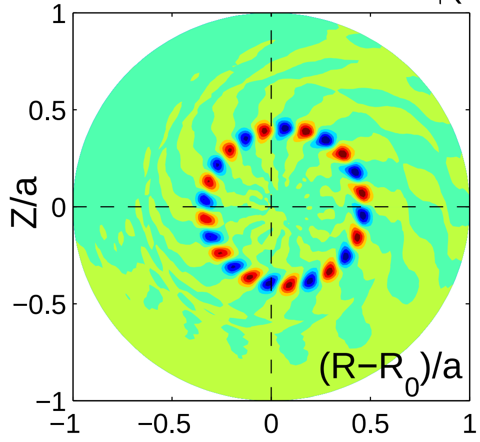


dominant component: (m,n)=(4,2)

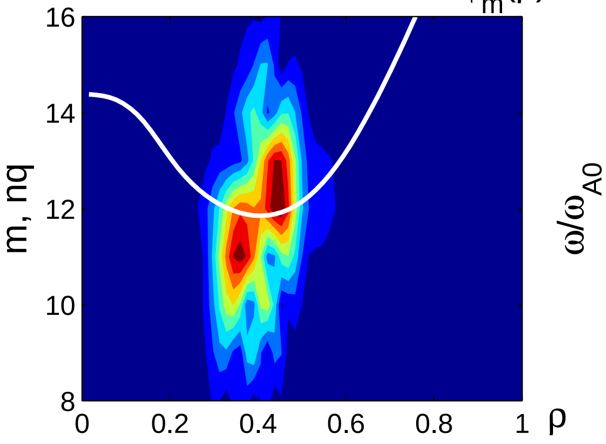


5. Simulation with Fast Ions: Case with $q_{\min} = 1.975$

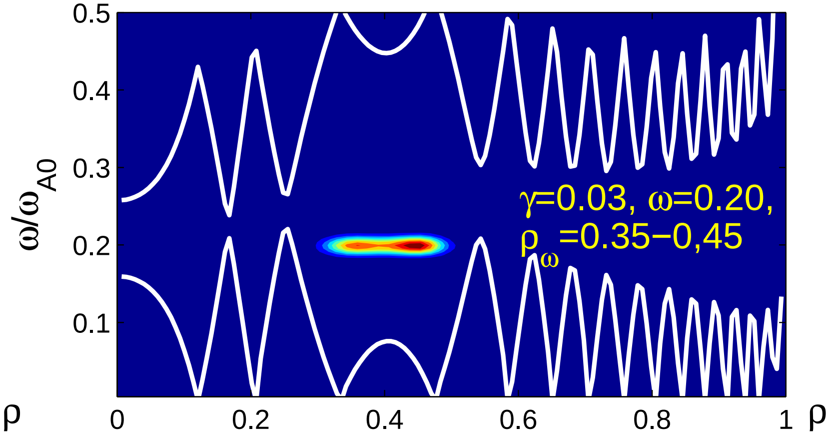
LINEAR: mode structure $\phi(R,Z)$



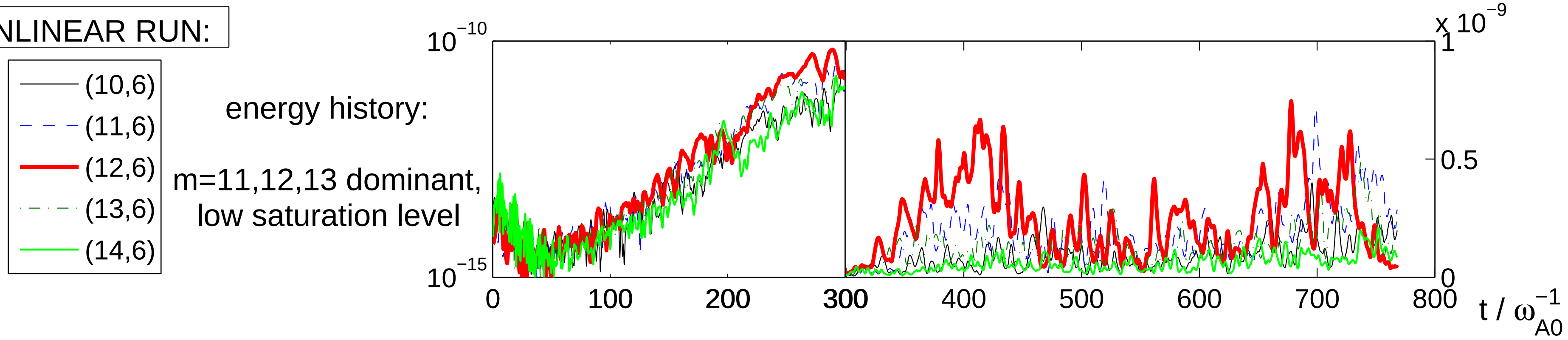
LINEAR: mode structure $\phi_m(\rho)$



LINEAR: power spectrum $P(\omega,\rho)$



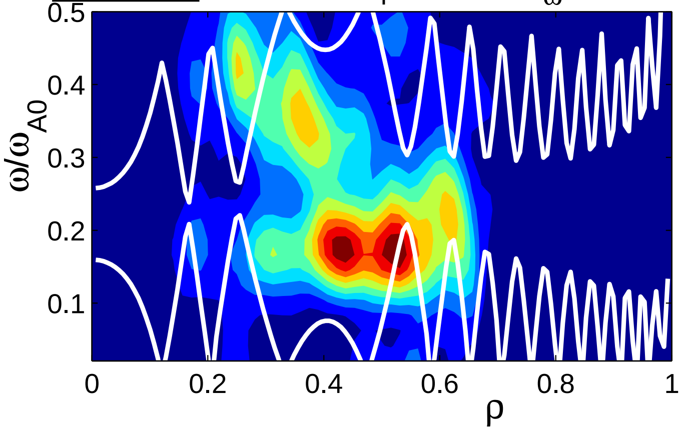
NONLINEAR RUN:



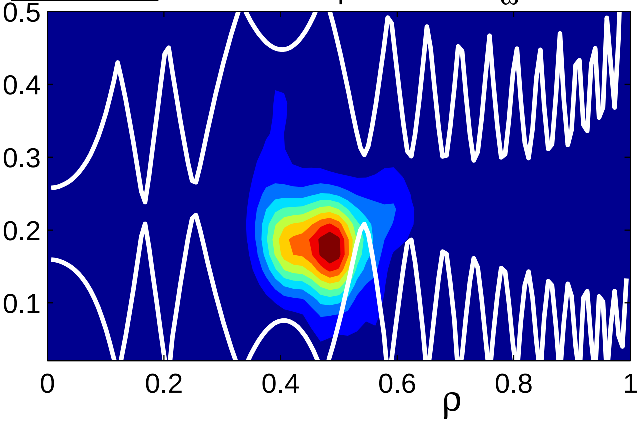
energy history:

m=11,12,13 dominant,
low saturation level

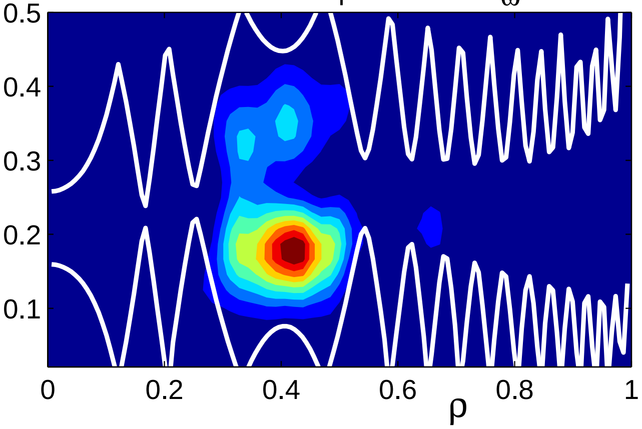
t=150 $\gamma=0.020$, $\omega_r=0.166$, $\rho_\omega=0.531$



t=250 $\gamma=0.015$, $\omega_r=0.166$, $\rho_\omega=0.484$

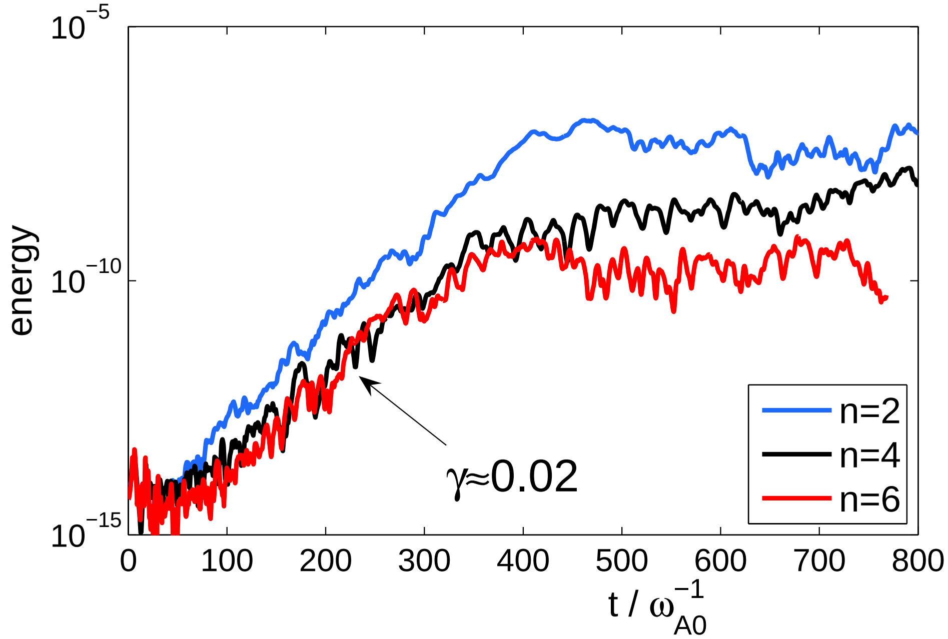


t=700 $\gamma=0.001$, $\omega_r=0.187$, $\rho_\omega=0.422$

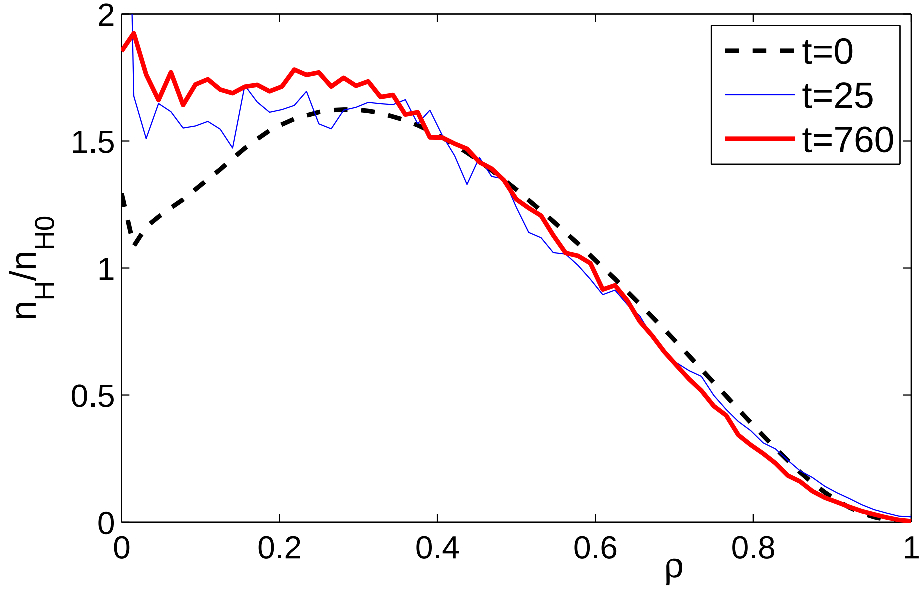


5. Simulation with Fast Ions: Comparisons

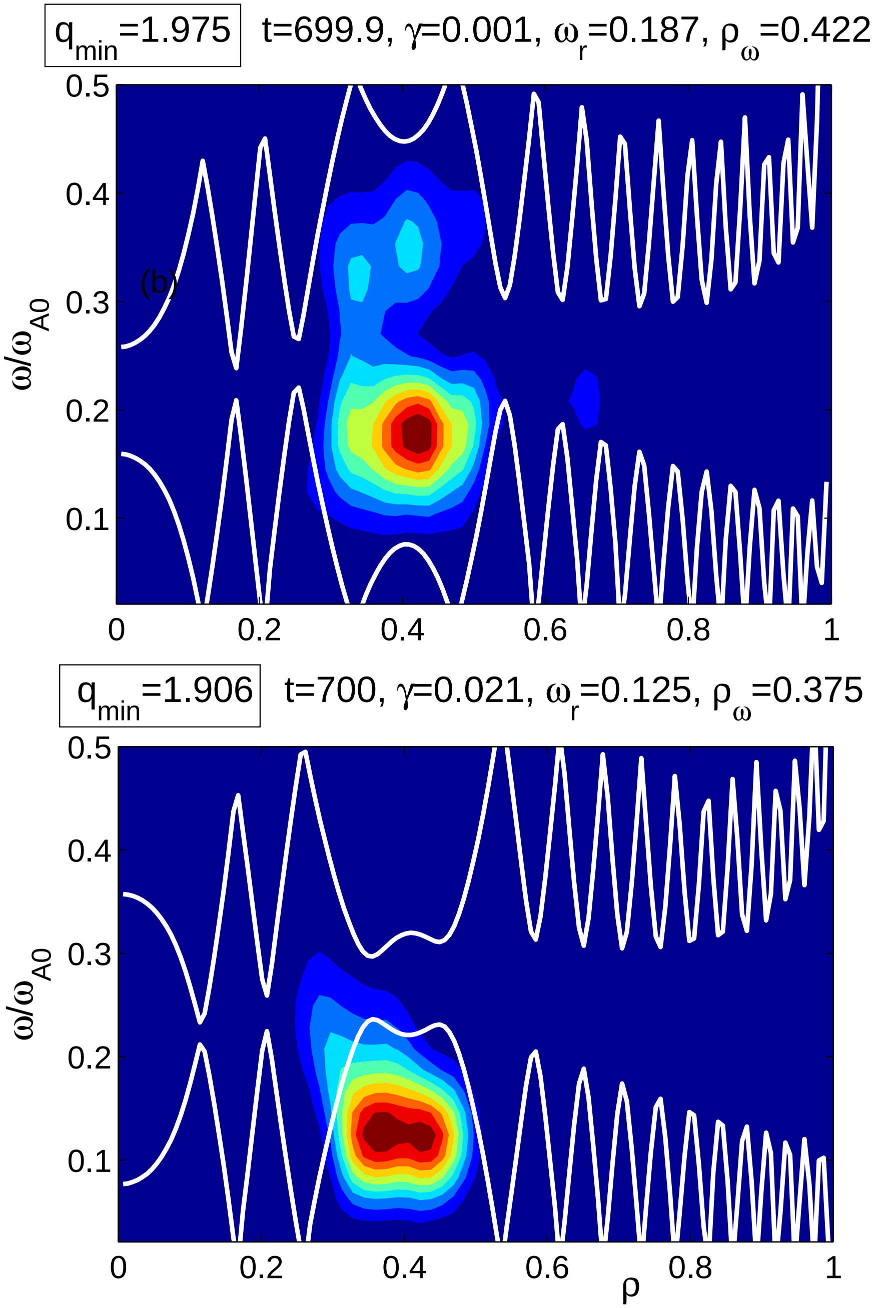
(a) q_{min}=1.975, evolutiion of (2×n,n) component



(b) typicel evolution of fast ion density profile



(c) power spectrum P(ω,ρ) in saturated phase



6. Summary of Preliminary Results

Instability characteristics:

- linear growth rate independent of n
- main mode localized at $q_{\min}$ ($\rho = 0.4$), often double-peaked
  occasional transient activity near TAE gaps and accumulation points
- dominant mode frequencies:

$$\begin{array}{lcccc}
\underline{n=2:} & \omega \sim 0.06 & (f \sim 35\text{kHz}) & (\Delta f = 11\text{kHz}) \\
\underline{n=4:} & 0.1 \lesssim \omega \lesssim 0.13 & (60\text{kHz} \lesssim f \lesssim 75\text{kHz}) & (\Delta f = 22\text{kHz}) \\
\underline{n=6:} & 0.1 \lesssim \omega \lesssim 0.2 & (60\text{kHz} \lesssim f \lesssim 120\text{kHz}) & (\Delta f = 34\text{kHz}) \\
 & \text{and } \omega \sim 0.35 & (f \sim 200\text{kHz}) & (\Delta f = 34\text{kHz})
\end{array}$$

- frequency does not follow accumulation point upon variation of $q_{\min}$
- low saturation level
  → no significant radial redistribution of fast ions

Preliminary interpretation:

(a) EPM in all cases.

(b) RSAE for $q_{\min} = 1.975$, EPM for $q_{\min} = 1.906$

Further parameter scans necessary to distinguish EPM and RSAE.

7. OUTLOOK

Comparison with experiment

- DIII-D shot #132707:
  - more detailed linear and nonlinear simulations
  - use higher resolution, lower resistivity (avoid DTM, reduce noise)
  - identify mode type (EPM, RSAE) and saturation mechanism
  - analysis of velocity space dynamics
  - comparison with other codes and experimental data

Benchmark between nonlinear global codes

- TAE test case:
  - compare HMGC results with those from GTC, GYRO

HMGC development:

- ENEA/Frascati team (Briguglio, Fogaccia, Vlad, Zonca) and IFTS (Wang):
  - realistic flux surface geometry (MARS)
  - kinetic treatment of plasma compressibility via kinetic thermal ions
- UCI (Bierwage):
  - port new MPI+OpenMP version of HMGC to machines in U.S.