Sensitivity of core transport to finite beta and rotation in DIII-D H-modes

by

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NERSC National Energy Research Scientific Computing Center

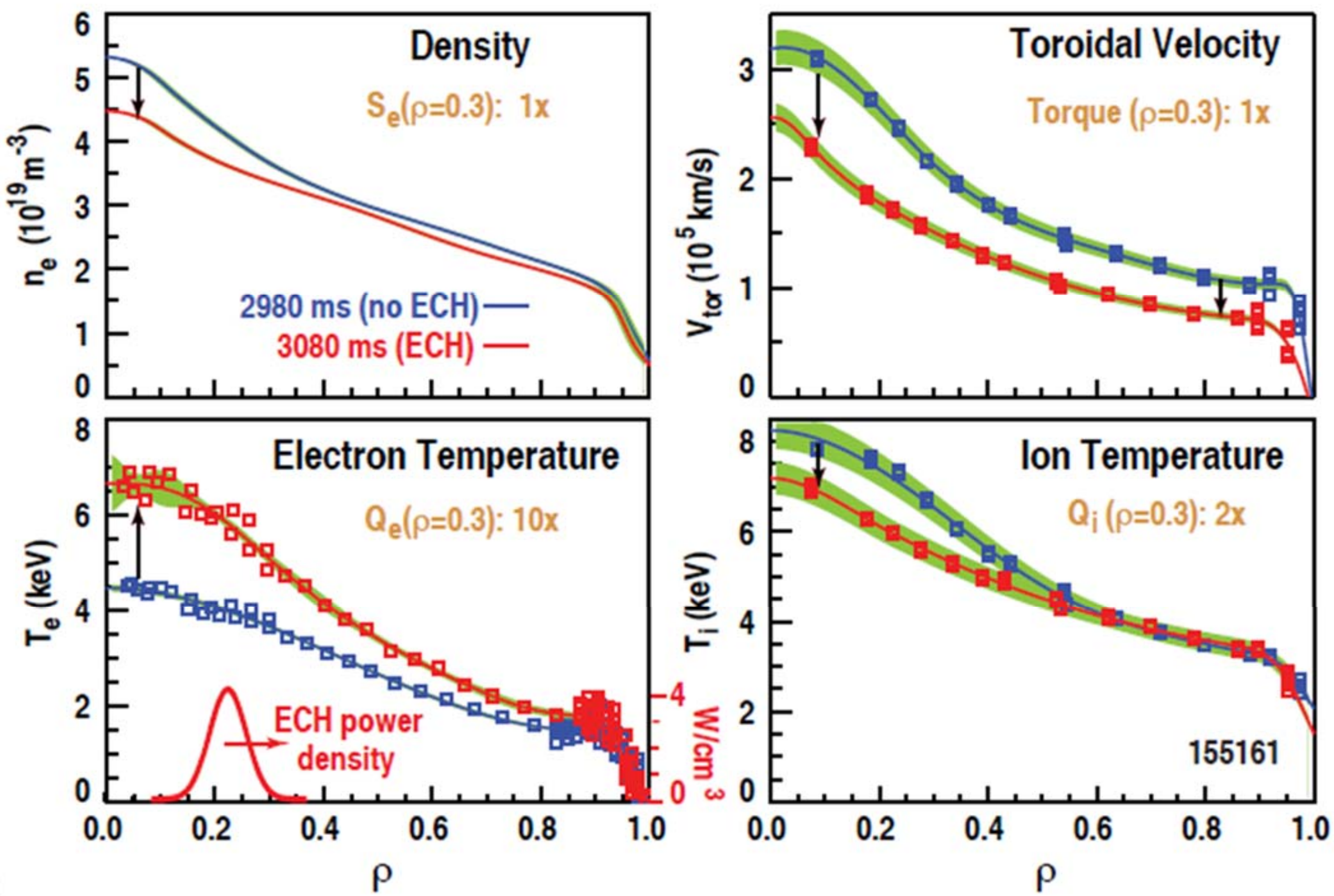
Overview/Summary

- Analysis of QH-mode from National Campaign experiment (Ernst, 2013)
- **Shear in equilibrium parallel flow (or parallel velocity gradient, PVG) enhances TEM transport in core (ρ=0.3) of QH-mode with NBI-only heating**
  - Reduces nonlinear threshold density gradient ~25%
  - *Critical* to match experimental fluxes
- **With additional ECH, density peaking, rotation and rotation shear reduced**
  - Influence of PVG becomes negligible
- **β is sufficiently high that EM stabilization is crucial to match exp. fluxes**
  - Impact of kinetic fast ions (n_{beam}/n_e=10%) is negligible

- Analysis of high-β_{pol} discharge with ITB (Garofalo, 2014)
- **PVG enhances linear instability inside ITB (ρ<0.6) where thermal gradients are weak**
- **In the deep core (ρ=0.3), profile appears to sit at balance between ITG-PVG and KBM instabilities**

Experimental background

- **QH mode with NBI heating (DIII-D National Campaign experiment, Ernst 2013)**
- **Addition of ECH reduces density peaking and rotation**
- **Nonlinear density-gradient-driven TEM sims reproduce transport and DBS spectra using synthetic diagnostic, without & with ECH [Ernst et al., IAEA-FEC EX/2-3 (2014)]**
  - Matching case without ECH was more complicated due to rotation shear…



For more details see:
Ernst et al.,
IAEA-FEC EX/2-3 (2014)
TTF (2015)

Three linear flow terms in the local, strong flow limit (e.g., from GYRO Technical Guide, https://fusion.gat.com/theory/Gyro)

$$\frac{\partial h_a}{\partial t} + (v_\parallel \mathrm{b} + \mathrm{v}_d) \cdot \nabla H_a + \mathrm{v}_{E0} \cdot \nabla h_a + \delta \mathrm{v}_a \cdot \nabla h_a + \delta \mathrm{v}_a \cdot \left(\nabla f_{a0} + \frac{m_a v_\parallel f_{a0}}{T_a} \frac{I}{B} \nabla \omega_0 \right) = C_a^{GL}\left[H_a\right] . \quad (3.29)$$

E×B (perpendicular) flow shear $\gamma_E \doteq -\frac{r}{q}\frac{\partial \omega_0}{\partial r}$,

Parallel flow shear

$$\gamma_p \doteq -R_0 \frac{\partial \omega_0}{\partial r} .$$

$$\mathrm{v}_d \doteq \frac{v_\parallel^2 + \mu B}{\Omega_{ca} B} \mathrm{b} \times \nabla B + \frac{2 v_\parallel \omega_0}{\Omega_{ca}} \mathrm{b} \times \mathrm{s} + \frac{4\pi v_\parallel^2}{\Omega_{ca} B^2} \mathrm{b} \times \nabla p$$

Toroidal flow

$$\omega_0 \doteq -c \frac{\partial \phi_{-1}}{\partial \psi}$$

$$M \doteq \frac{\omega_0 R_0}{c_s} ,$$

- Toroidal flow can lead to momentum pinch (e.g., Coriolis [Peeters, 2007], TEP+thermoelectric [Hahm, 2007])
- Parallel flow shear (or parallel velocity gradient, PVG) is a thermodynamic drive gradient, can drive instability [Catto, 1973] and momentum transport [Mattor & Diamond, 1988]
- E×B (perpendicular) flow shear can suppress instability and turbulent transport [BDT, 1990], can also cause momentum transport [Dominguez & Staebler, 1993].
- For theoretical insight, can vary each term independently, but if toroidal flow dominates: $\gamma_E=(r/qR)\gamma_P$
- Have ignored centrifugal effects, but has been included in gyrokinetic codes recently (e.g. Casson, 2010)

Reference parameters at ρ=0.3, prior to ECH (2980 ms) & w/ ECH (3080 ms)

Shot	time	ρ	n_e	T_e (kev)	n_{beam}/n_e	ρ_s/a (10^{-3})	T_e/T_i	a/L_{ne}	a/L_{Ti}	a/L_{Te}	Z_{eff}	ν_{ei} (10^{-3} c_s/a)	β_e (%)	Mach	γ_E (c_s/a)	u'	qR/r
155161	2980	0.3	3.68	3.58	0.10	4.87	0.55	1.23	1.27	1.22	3.21	15.4	0.57	0.51	0.077	3.40	15.2
155161	3080	0.3	3.39	5.13	0.15	6.05	0.93	0.77	0.94	1.67	3.08	7.06	0.81	0.30	0.049	1.97	13.7
160710	4750	0.28	6.58	2.81	0.04	3.88	0.69	0.68	0.80	0.22	2.34	44.3	0.68	0.57	0.025	3.66	46.8

Shot	time	ρ	r/a	R/a	q	s	κ	δ	dR/dr
155161	2980	0.3	0.33	2.95	1.70	0.15	1.48	0.038	-0.057
155161	3080	0.3	0.33	2.97	1.52	0.21	1.43	0.034	-0.062
160710	4750	0.28	0.30	3.08	4.56	0.74	1.74	0.19	-0.44

$$\text{Mach} = R\Omega/c_s$$
$$u' = -R^2\nabla\Omega/c_s = (R/a)\cdot\gamma_{P,GYRO}$$
$$\gamma_{E,GYRO} = (r/qR)\cdot u'\cdot(a/R)\cdot(c_s/a)$$

Simulation model choices and resolutions

- **Simulations include:**
  - 3 kinetic species (D, C , e; beam dilution)
  - shear electromagnetic effects ($A_{||}$)
  - collisions (ν_{ei}, ν_{ii})

- **Spot checks of increased radial resolution, including kinetic fast ions (as a model for beam species), and compressional magnetic perturbations ($B_{||}$) made little difference**

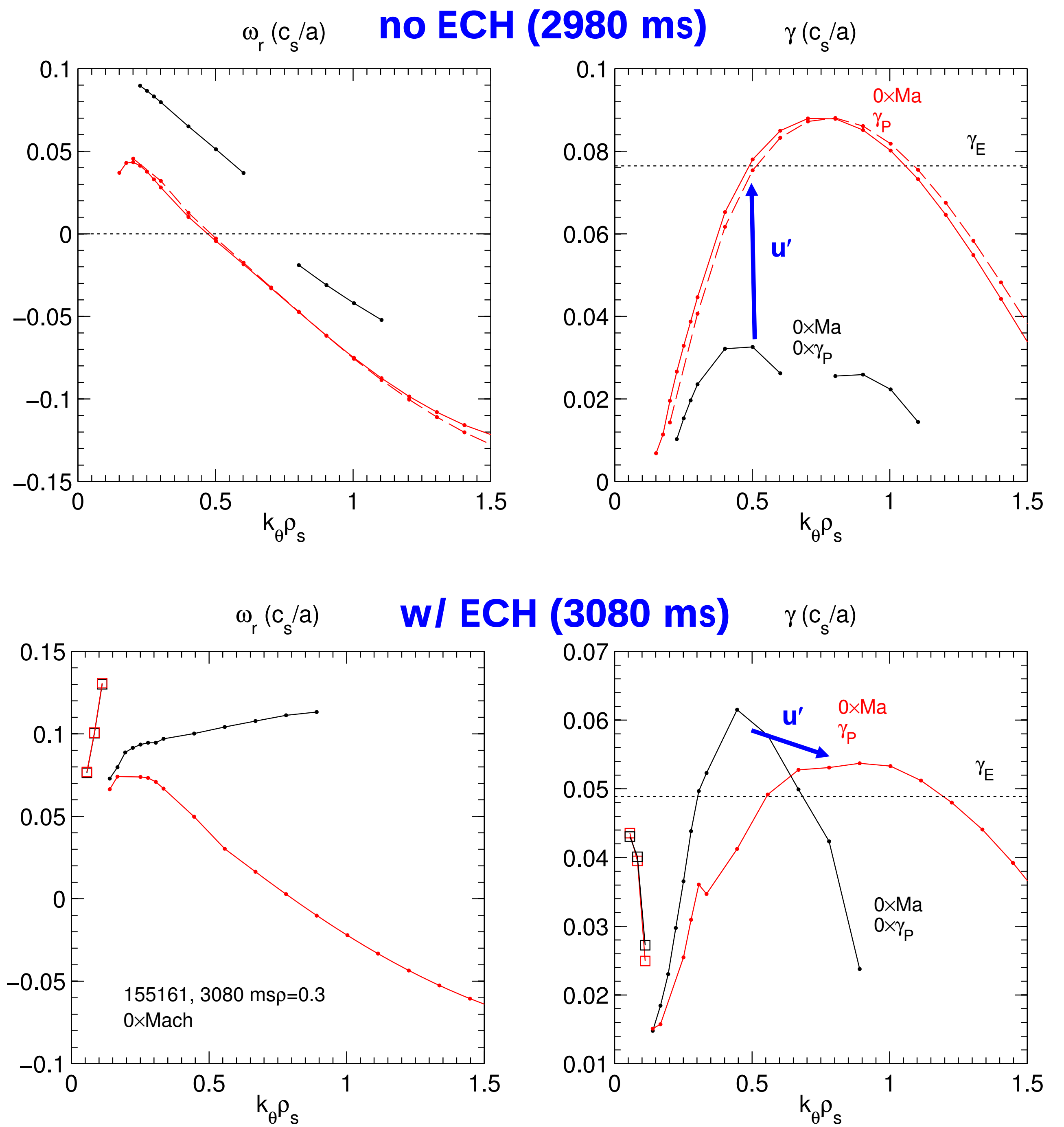
- **Following simulations run in the zero flow limit (Mach=0), even when flow gradients (u', γ_E) are retained**

Nonlinear GYRO grids

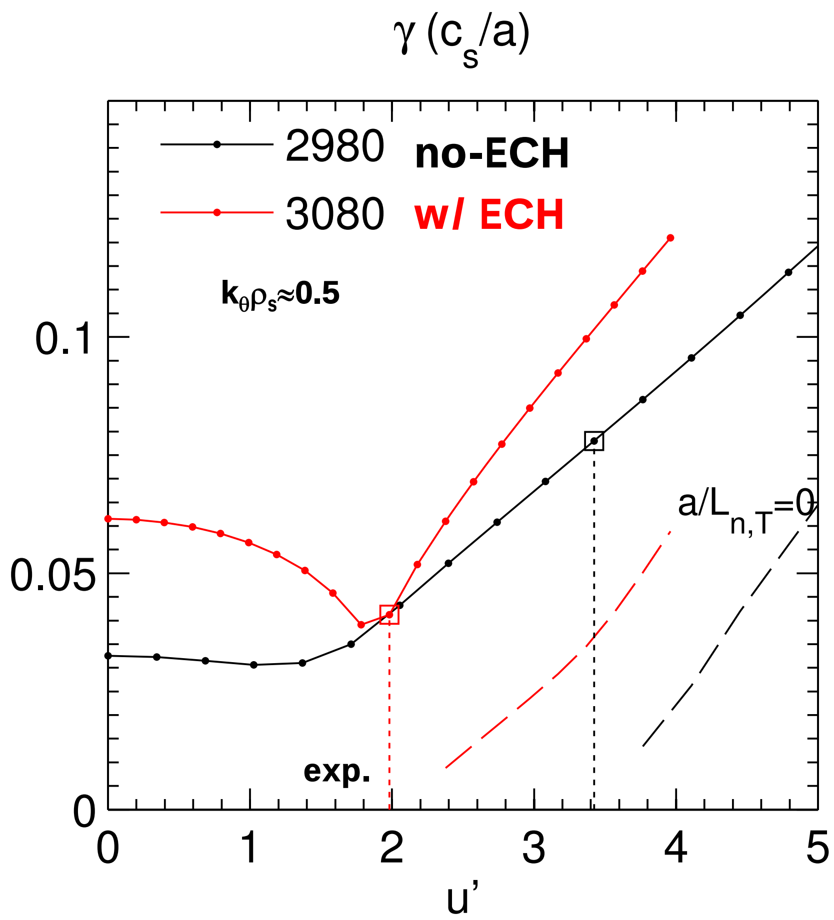
Case	**2980 ms**	**3080 ms**
ρ	0.3	0.3
r/a	0.33	0.33
$L_x \times L_y$	136×126	109×114
Δ**n**	2	2
nx×ny	128×32	128×32
min kx **max kx**	0.046 1.48	0.058 1.84
min ky **max ky**	0.050 1.542	0.055 1.71
[nθ,nλ,ne]	[14×2,8,8]	[14×2,8,8]
species	D,C,e; beam dilution	D,C,e; beam dilution

Without ECH, parallel velocity gradient (PVG) from rotation shear contributes substantially to linear instability at ρ=0.3

- **Maximum growth rate surpasses E×B shearing rate *only* when including instability drive from rotation shear, $u'=-R^2\nabla\Omega/c_s$**
  - Referred to as **parallel velocity gradient (PVG)** drive, similar to Kelvin-Helmholtz instability
  - As axis is approached, PVG drive can overcome ⊥ shear suppression as relative strength of E×B shearing rate weakened, $\gamma_E=(r/qR)\cdot u'$ (for purely toroidal flow)
- **Addition of ECH reduces rotation shear (u'=3.4→2.0)**
  - Broadens growth rate spectra, but maximum slightly reduced



Influence of PVG on growth rate exhibits threshold-like behavior

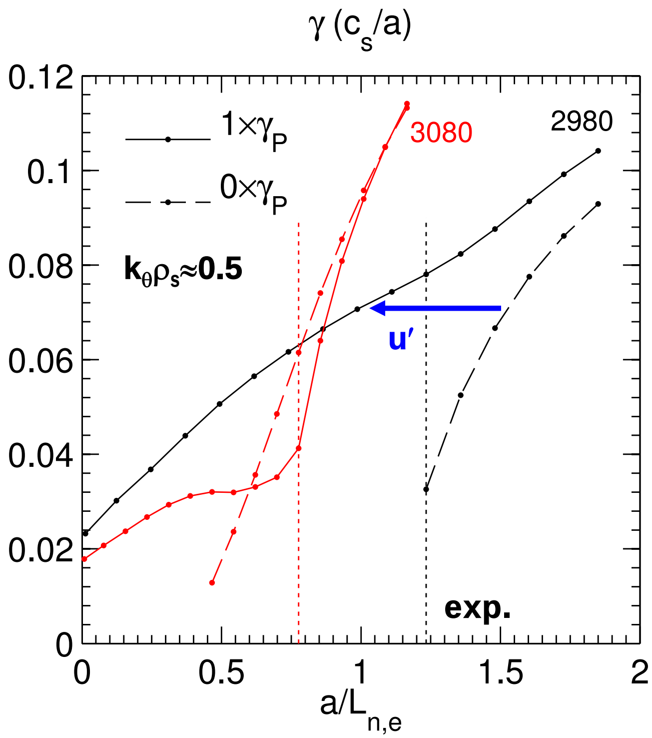


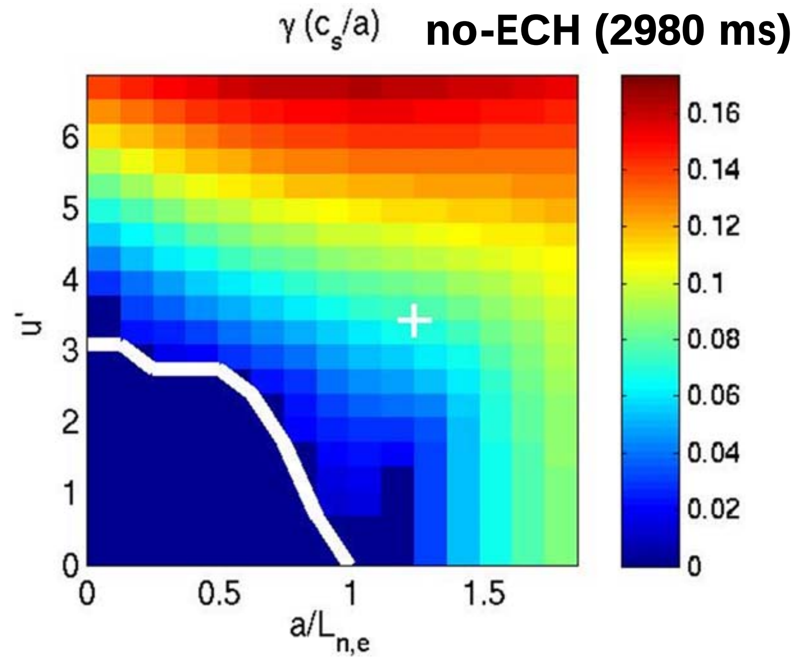
- **Case with no-ECH (2980 ms) strongly driven by large u′>2**
- **Case with ECH (3080 ms) sits just below transition to strong PVG drive**
- **In both cases, onset of pure PVG instability (with all other gradients set to zero, $a/L_n=a/L_T=0$) occurs just above experimental u′**
  - For reference, Catto (1973) slab threshold for PVG (∇T=∇n=0):

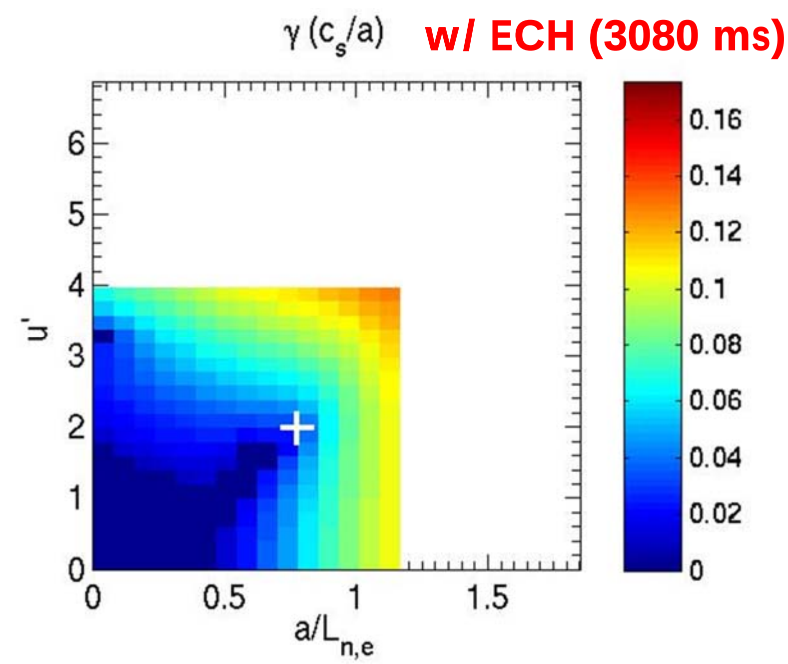
    $$u' > 1/q \cdot k_\theta \rho_s = 1.2$$

    (assuming $k_{||}=1/qR$)

PVG reduces linear threshold density gradient for no-ECH case



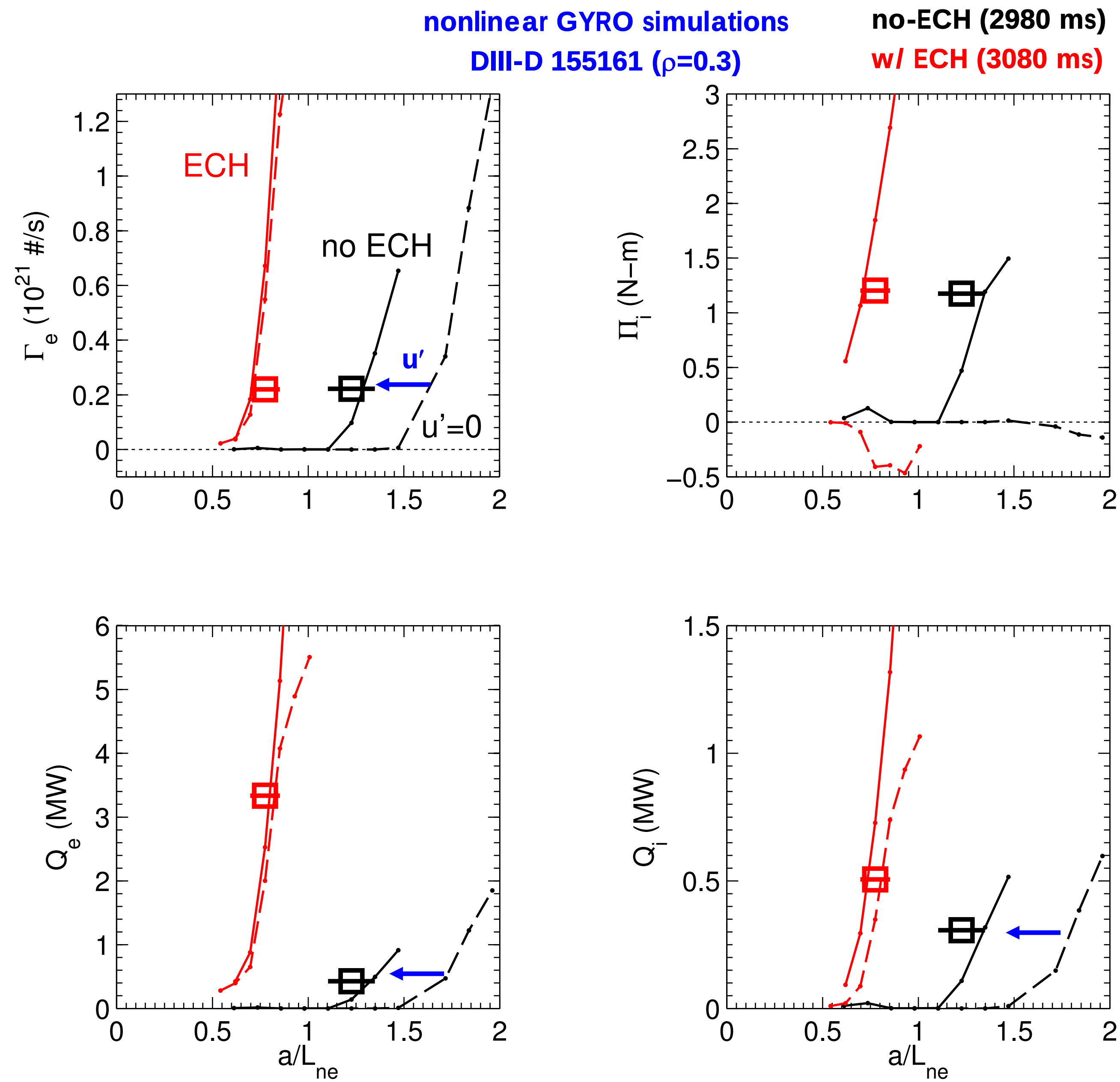




- **Same thing occurs for case with ECH (3080 ms), but stronger TEM drive overcomes effect at reduced u′**

PVG reduces nonlinear threshold density-gradient ~25% for no-ECH case

- **Crucial to include PVG to obtain good match with all experimental fluxes**
- **Addition of ECH reduces density peaking, rotation and rotation shear**
  - a/L_n TEM threshold reduced due to increased T_e/T_i & decreased ν_e
  - Influence of reduced u′ becomes negligible
- **Experimental fluxes from TRANSP (subtracted $Q_{i,NC}$ from NEO)**



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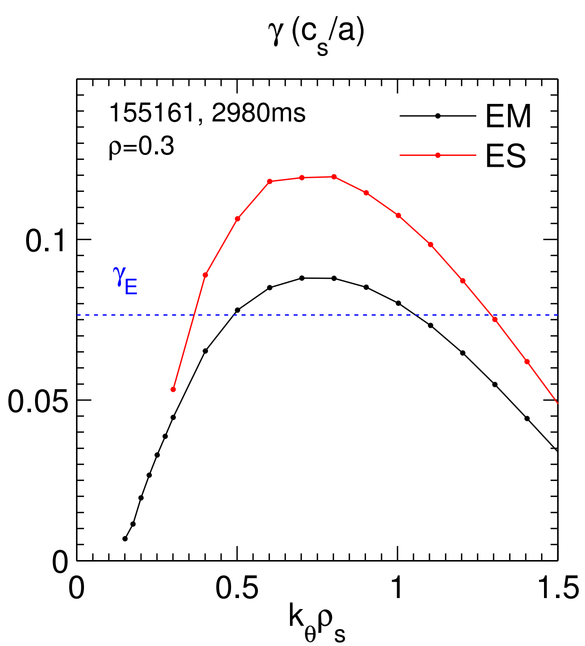
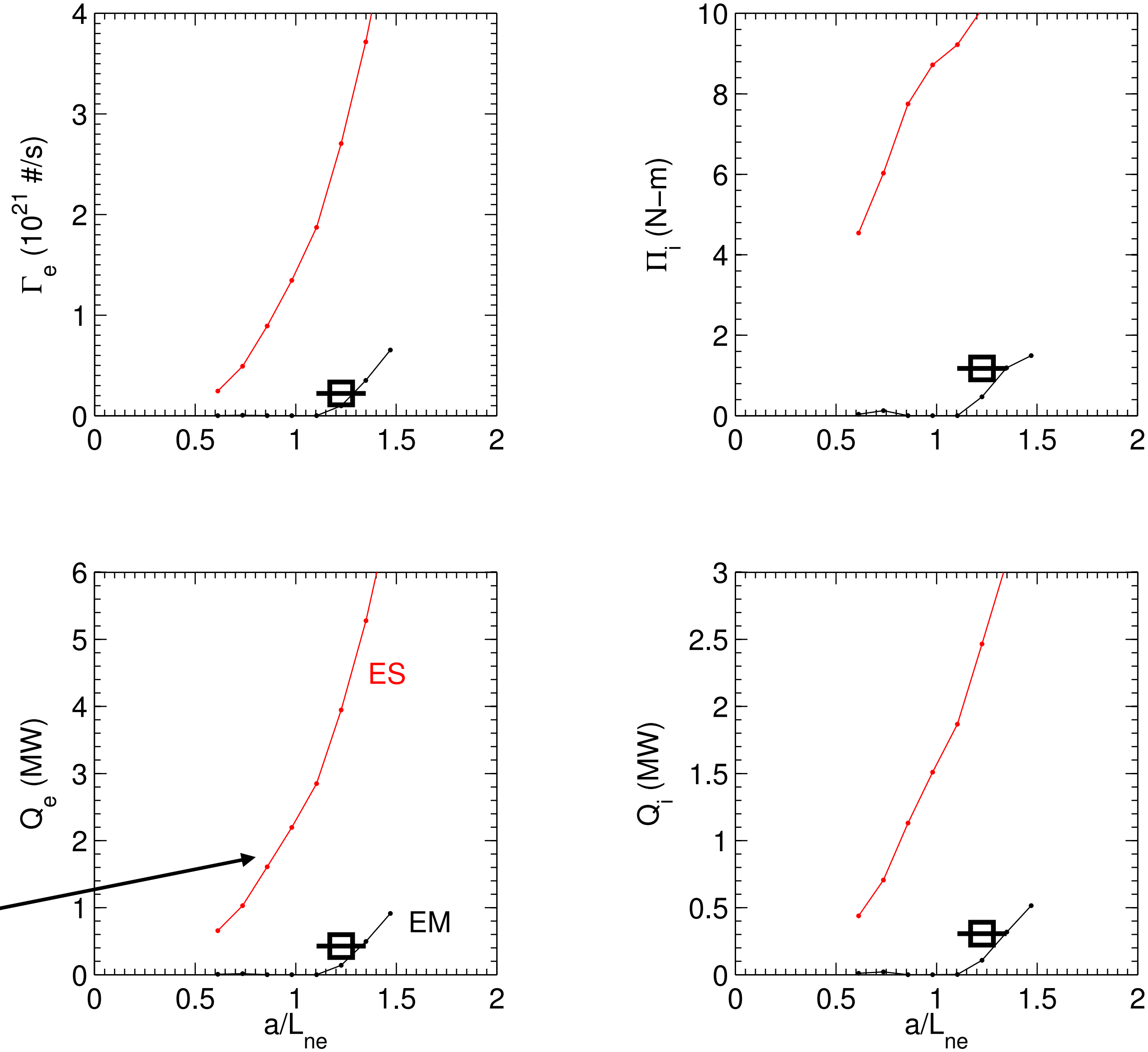
Finite beta stabilization is significant for no-ECH case

- **Max growth rates increased ~35% if electromagnetic effects ignored**



- **Resulting transport is increased significantly in the electrostatic (ES) limit**

nonlinear GYRO simulations
DIII-D 155161, 2980 ms (ρ=0.3)



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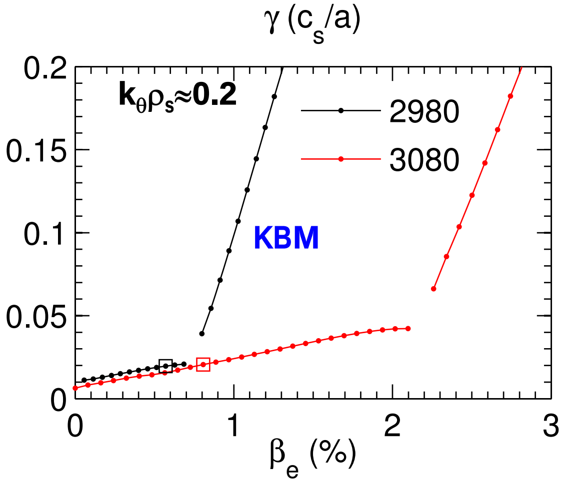
EM stabilization not surprising given proximity of no-ECH case to KBM threshold

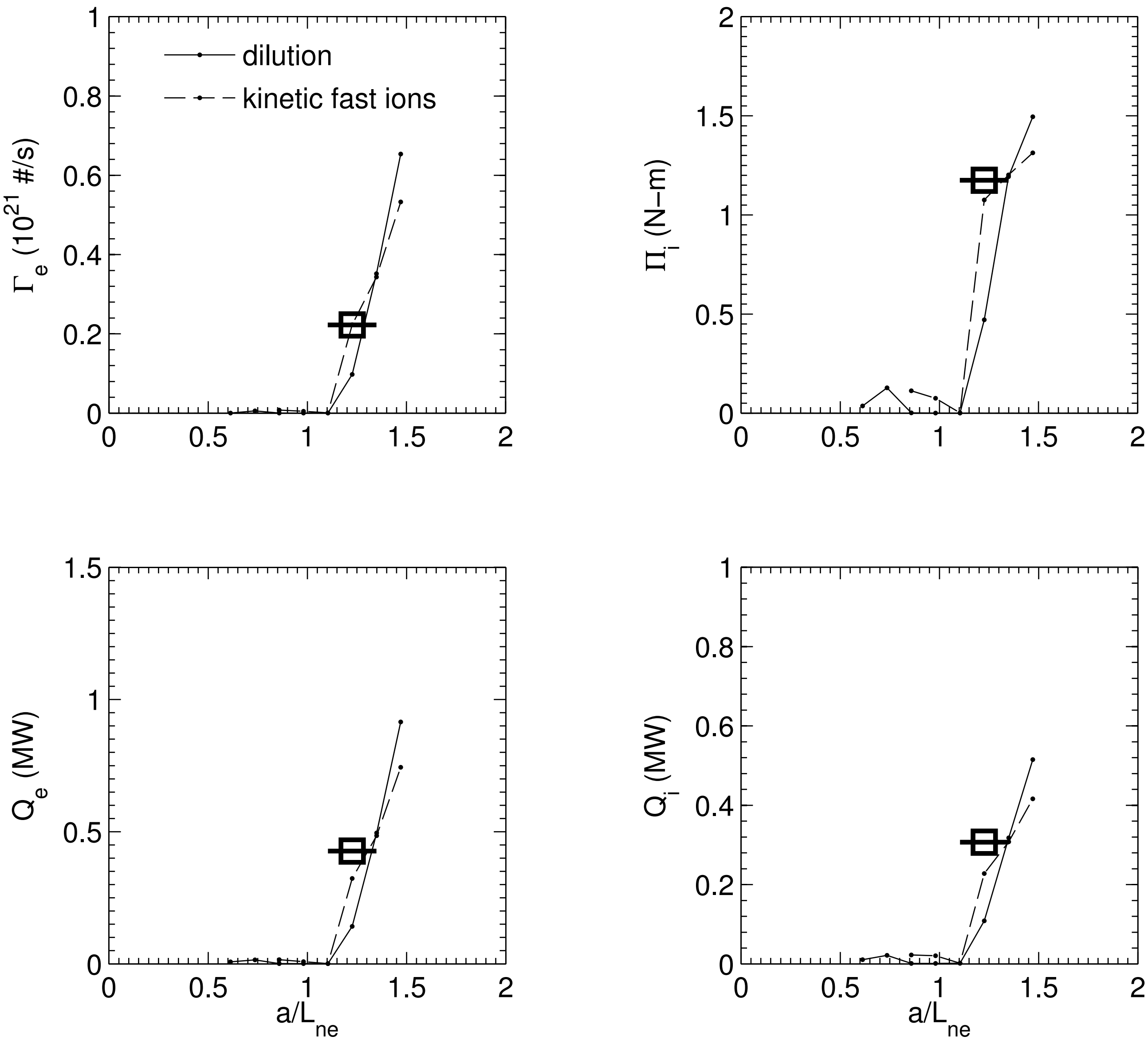


- $\beta_e / \beta_{e,KBM}$~[80%,40%] for [2980,3080]

- **Negligible influence on transport when including kinetic fast ions (n_{beam}/n_e=10%)**
- Near-axis simulations in DIII-D [Holland, 2012] and JET [Citrin, 2013] have indicate kinetic fast ions + EM effects can have significant effect on transport, especially as β_e approaches $\beta_{e,KBM}$

nonlinear GYRO simulations

DIII-D 155161, 2980 ms (ρ=0.3)



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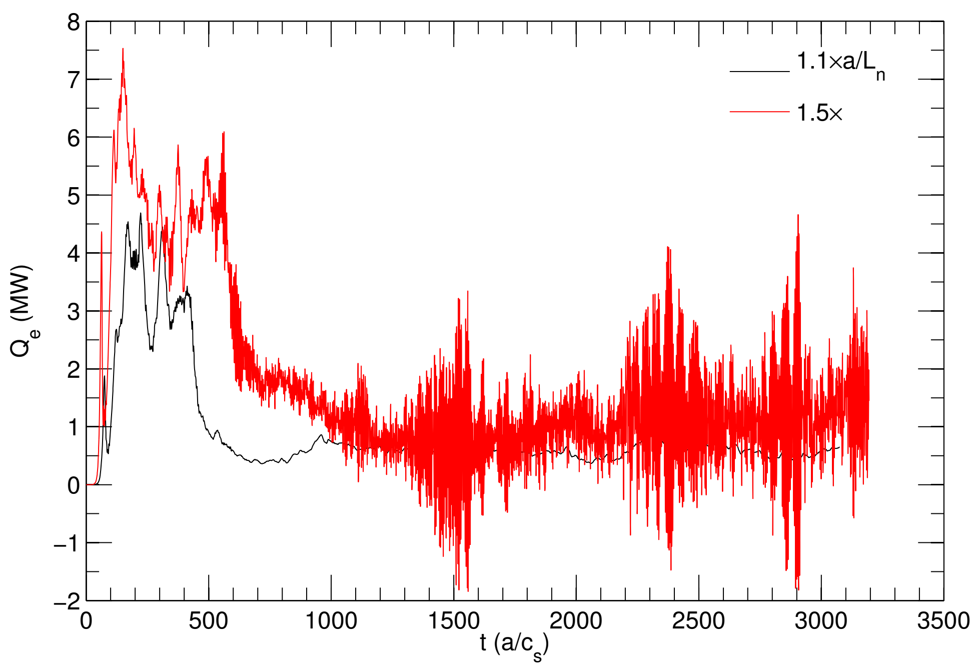
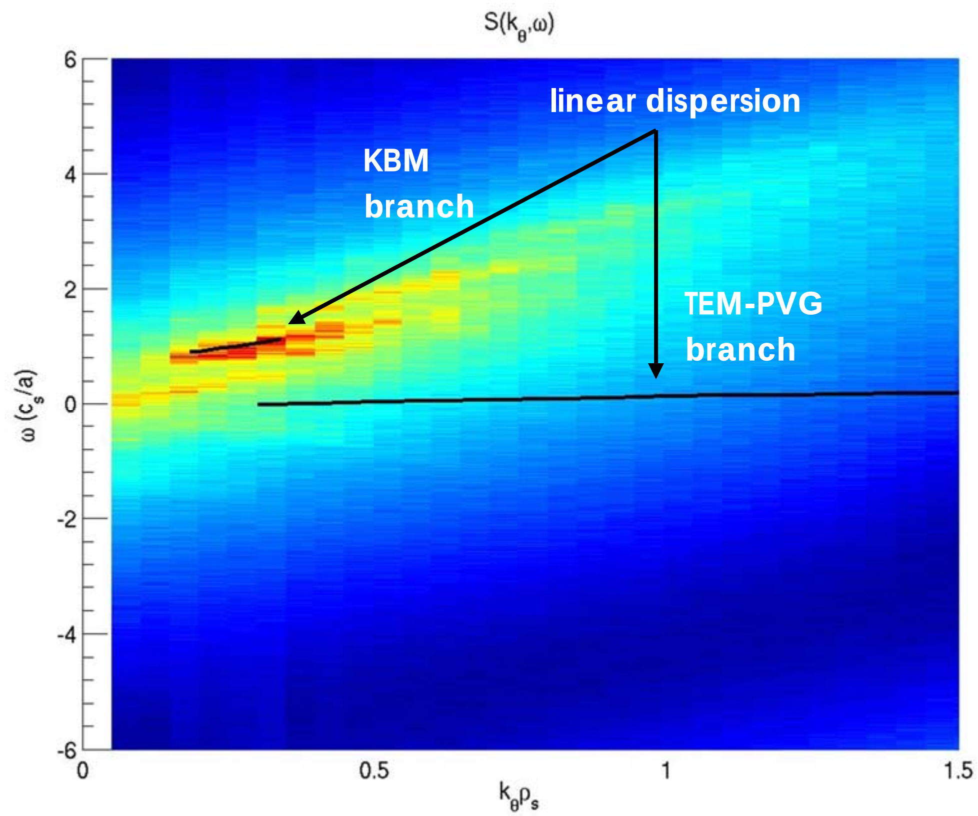
In running density gradient scans, high frequency oscillations develop for no-ECH case at increased a/L_n

- **Near KBM threshold → nonlinear spectra becomes dominated by high-frequency KBM mode at low-k**
  - Similar complications arise when including finite rotation (Ma~0.5)
  - Investigating (i) numerical resolution, and (ii) centrifugal effects



Nonlinear density fluctuation spectrum, $S(k_\theta,\omega)$



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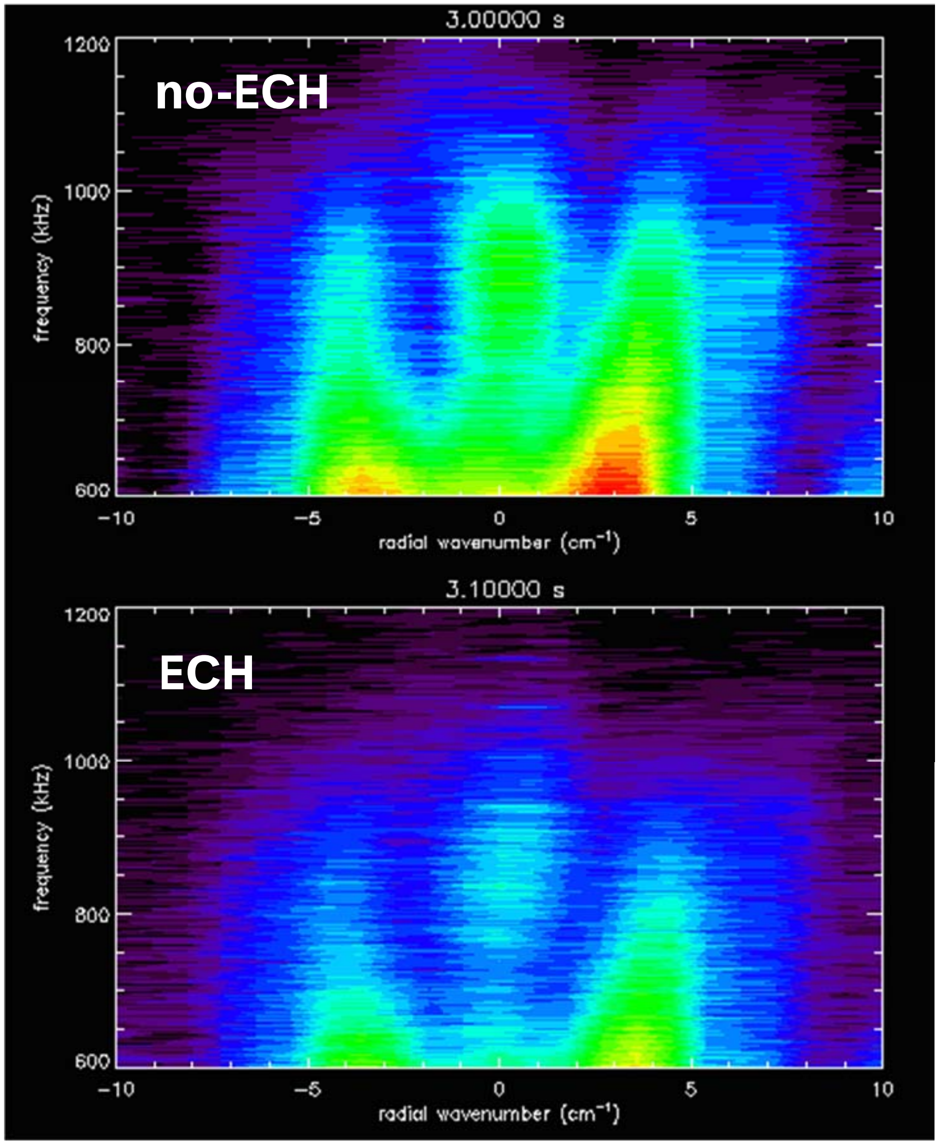
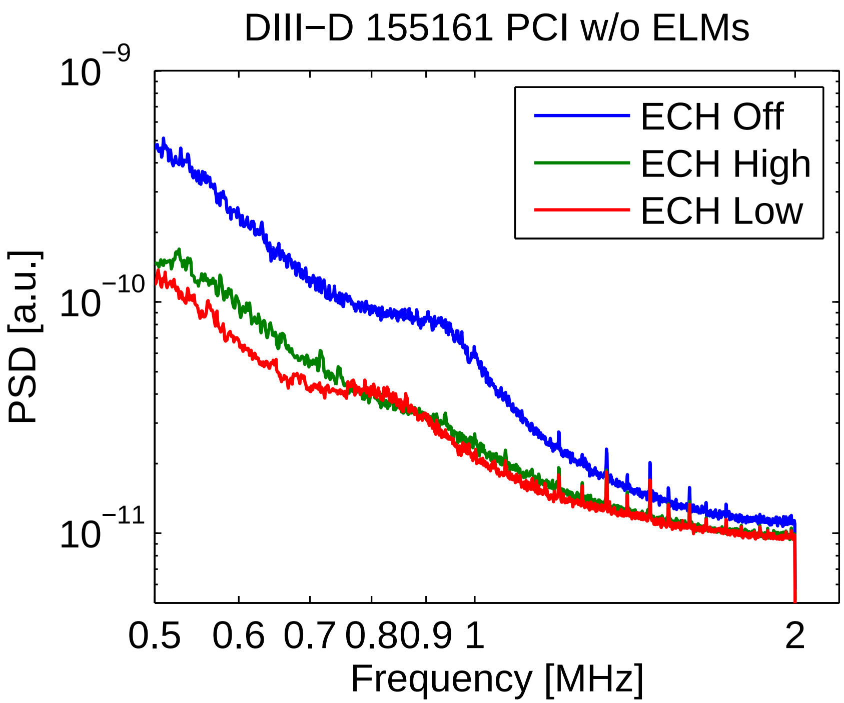
PCI measurements shows high frequency fluctuation at low k_R in the no-ECH case

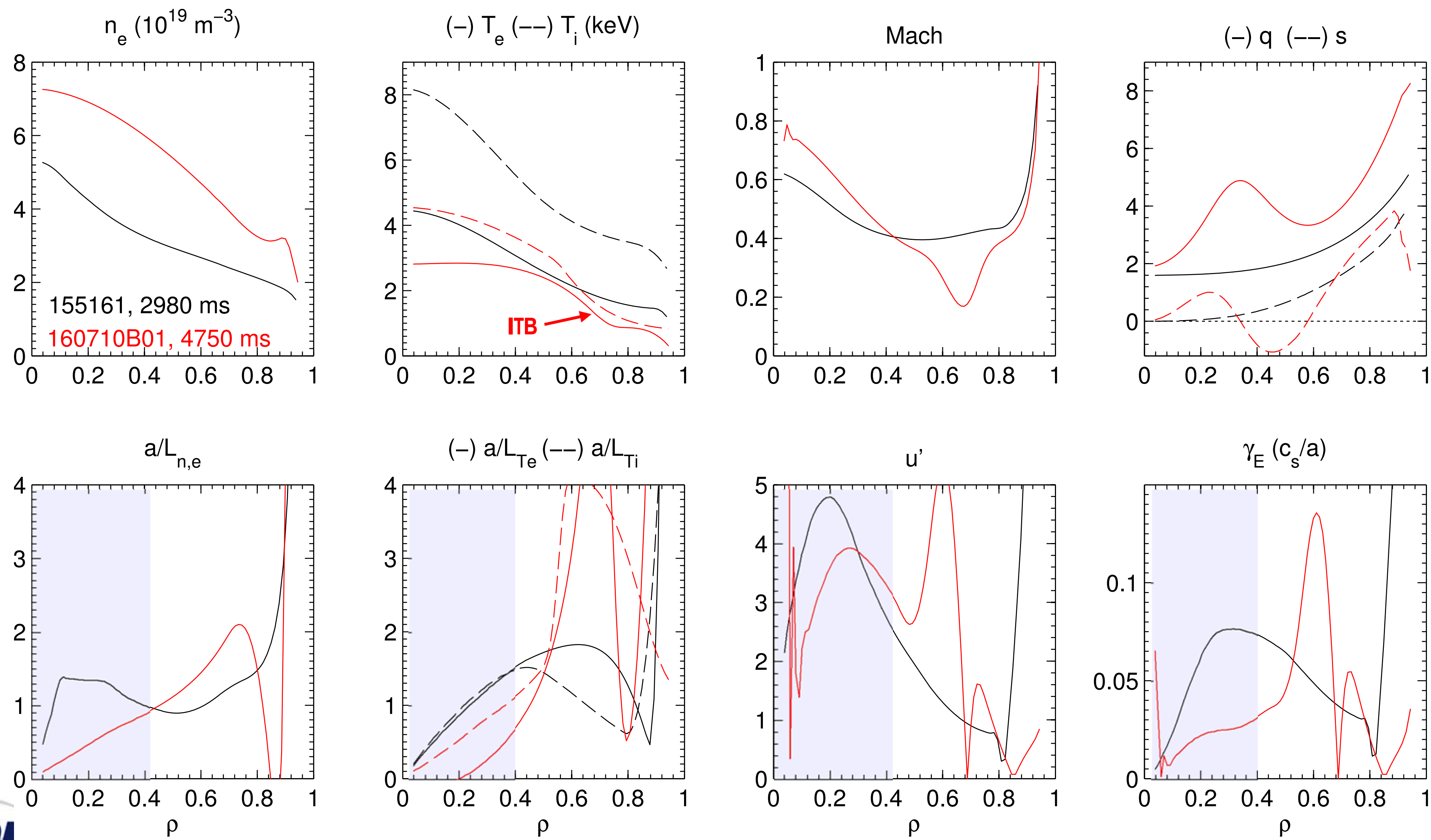


- **Possibility of nonlinear coupling between PVG-enhanced TEM and near-marginal KBM?**
  - Future: apply synthetic PCI diagnostic



Are there other cases where strong u′ contributes to core instability?

- **High-β_p experiment with ITB [Garofalo et al., IAEA PPC/P2-31 (2014)]**
- **160710, inside ITB (ρ<0.6):** Weak thermal gradients (a/L_n & a/L_T<1), strong flow shear (u′>3)



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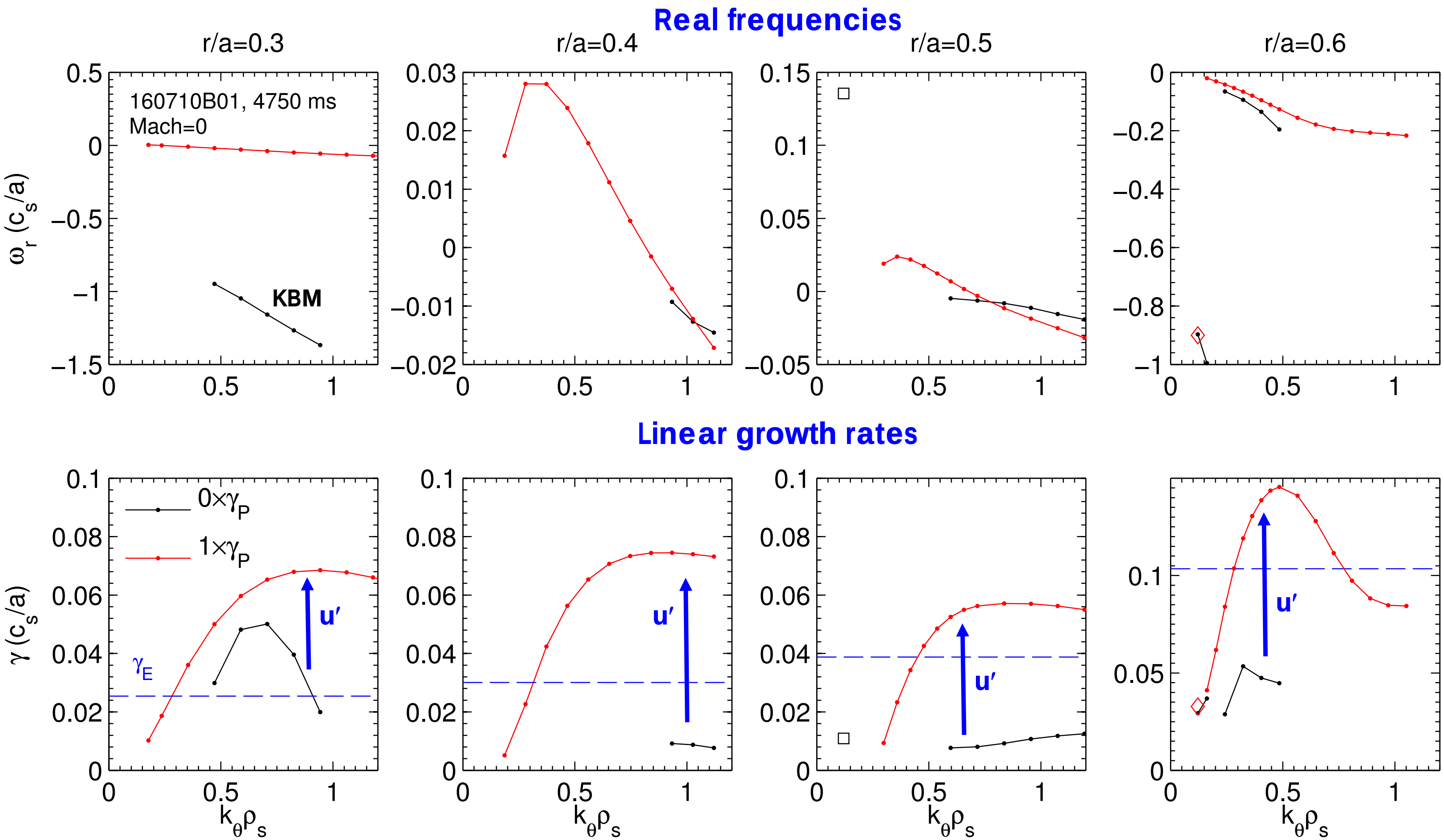
In high-β_{pol} discharge, large u′ enhances instability inside ITB (r/a<0.6) where thermal gradients are weak

- **PVG enhances ITG/TEM linear growth rates at multiple radii**
  - At r/a=0.3, KBM exists without rotation shear (u′=0)



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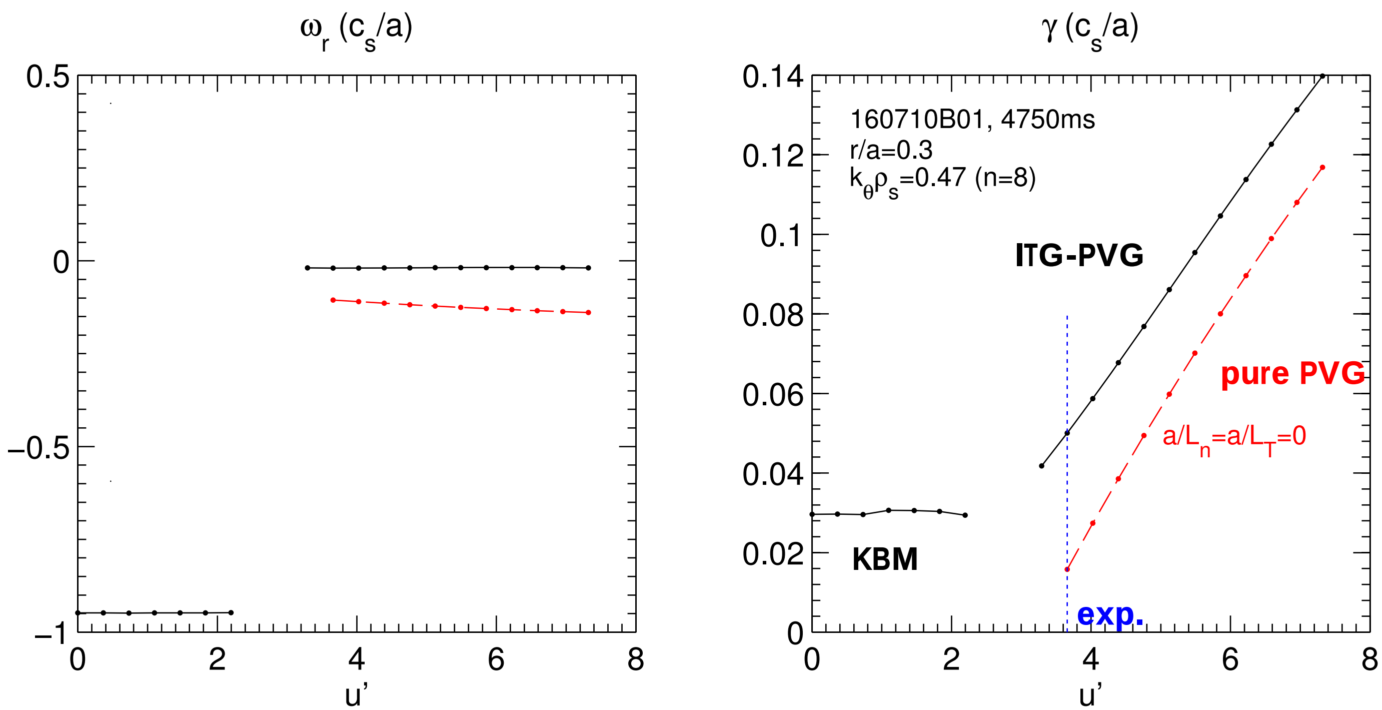
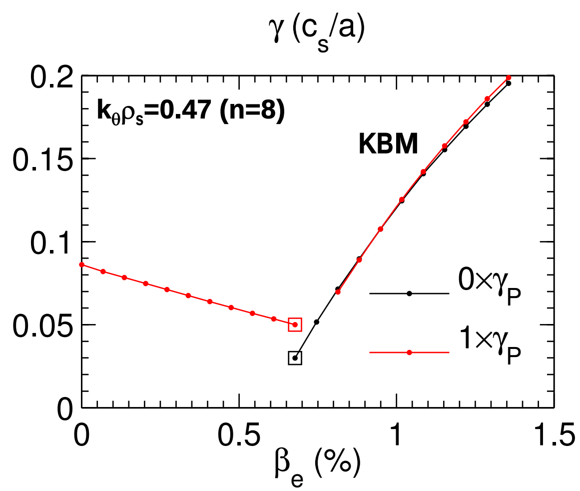
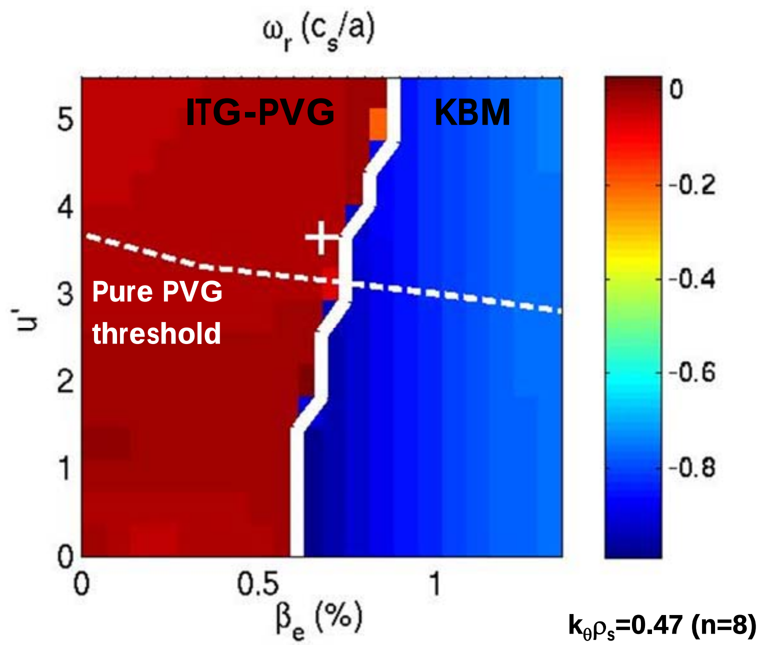
At r/a=0.3, u′ sufficiently large to push ITG-PVG growth rates above KBM

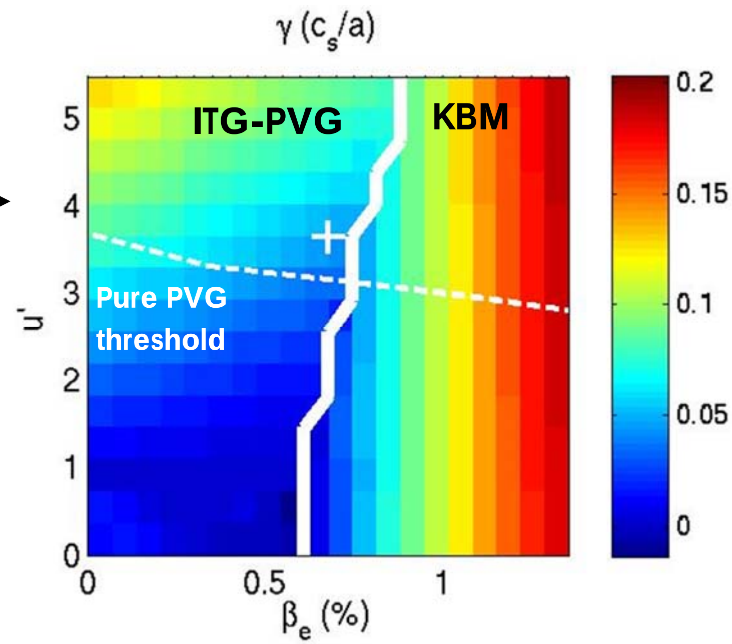
- **KBM insensitive to u′**
- **Pure PVG threshold (a/L_n=0, a/L_T=0) occurs near experimental u′**



Profiles at r/a=0.3 also near KBM threshold







- **Ideal MHD ballooning modes unstable for ρ=0.1-25**
  - second-stable outside ρ>0.25

- **Balance between ITG-PVG and KBM depends sensitively on variations of β_e and u′** →

- **Have begun nonlinear simulations**

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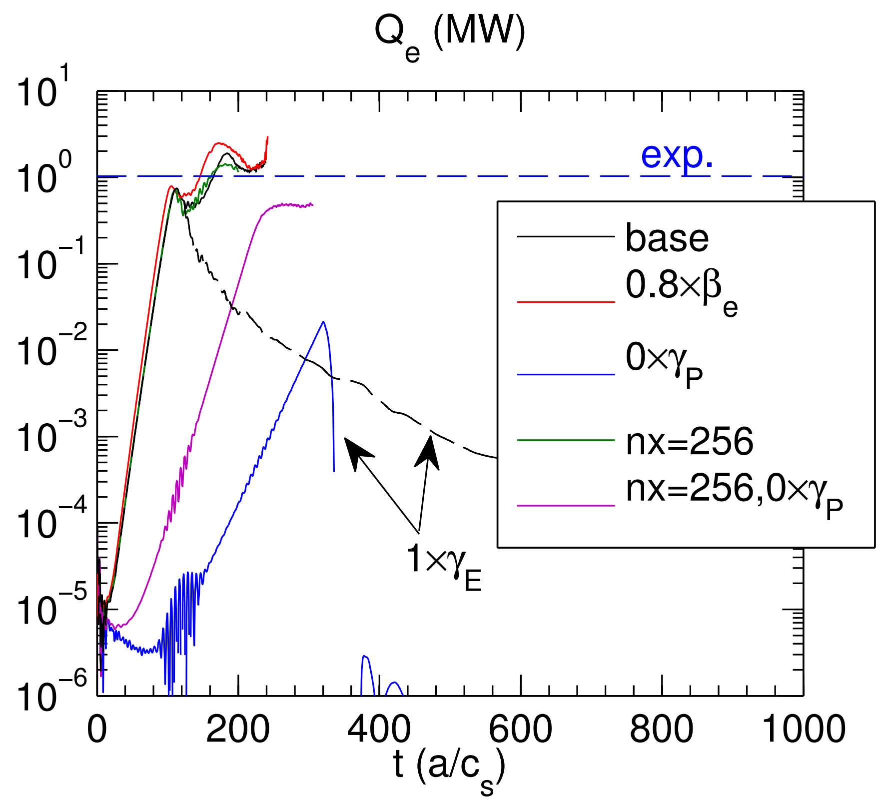
Summary

- **Analysis in deep core (ρ=0.3) of DIII-D QH-modes & high-β_{pol} H-mode illustrate importance of strong rotation shear and finite beta on microinstability and transport**

- **While rotation shear and it's effects expected to be weaker in ITER or future burning plasmas, finite beta effects still critical to consider, see other recent work:**
  - C. Holland (2012); J. Citrin (2013-2015); S. Moradi (2014); J. Garcia (2015)

Initial attempts at nonlinear runs met with numerical challenge

- **Without E×B shear, simulations hit numerical instability after initial transient**
  - Also with $0.8\times\beta_e$
- **Tried running without E×B shear into linear growth phase (just into initial transient), then restarted with E×B shear → turbulence suppressed**
- **Running with u′=0 (γ_P=0) eliminates problem, but produces negligible transport (with finite γ_E)**
- **Higher radial resolution hasn't helped so far**



- **Simulations ongoing**

IBM unstable ρ=0.1-0.25, second stable outside

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