Gyrokinetic Calculations of Microturbulence and Transport for NSTX and Alcator C-MOD H-modes

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MOTIVATION: Investigate turbulent microinstabilities in NSTX and CMOD H-mode plasmas exhibiting unusual plasma transport

- Remarkably good ion confinement and Resilient Te profiles on NSTX
- ITB formation on CMOD
- Identify underlying key plasma parameters for control of plasma performance

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METHOD- GS2 and GYRO flux tube simulations

- Complete electron dynamics. 3 radii, 4 species.
- Linear electromagnetic; nonlinear, electrostatic calculations (CMOD)

Gyrokinetic Model Equations

Perturbed electrostatic potential:

$$\tilde{\square}(r,\square,\square,t) = \exp[in\square \square inq(r)\square] \mathop{\square}\limits_{p=\square}^{p=} \tilde{\square}(\square \square 2\square p,r,t)\exp[inq(r)2\square p]$$

Linearized gyrokinetic equation, ballooning representation, “s-□” MHD equilibrium:

$$\frac{\partial}{\partial t}\tilde{g}_s + \frac{v_{//}}{qR}\frac{\partial}{\partial \square}\tilde{g}_s + i\square_{ds}\tilde{g}_s + C(\tilde{g}_s) =$$

$$\frac{e_s}{T_s}F_{ms}J_0\left(\frac{\partial}{\partial t} + i\square^T_{*s}\right)\left[\tilde{\square}(\square) \square \frac{v_{//}}{c}\tilde{A}_{//}(\square)\right] + [\square B_{//} terms]$$

Where $\tilde{g}_s \equiv \tilde{f}_s + \left(\frac{e_s}{T_s}\right)F_{ms}\tilde{\square}(\square), \square_{*s} = (k_{\square}T_s/Z_sB)(d\ln N_s/dr)$

$$\square_{ds} = \square_{*s}(L_{ns}/R)(E/T_s)(1+v_{//}^2/v^2)\{\cos\square + [\tilde{s}\square\square\square\cos\square]\sin\square\}$$

$$k_{\square} = \square nq/r, k_{\square} = k_{\square}\{1+[\tilde{s}\square\square\square\sin\square]^2\}^{1/2}$$

$$\tilde{s} \equiv (r/q)(dq/dr), \square \equiv \square q^2R(d\square/dr)$$

$$\square^T_{*s} \equiv \square_{*s}\{[1+\square_s[E/T_s)\square 3/2]\}, J_0 \equiv J_0(k_{\square}v_{\square}/\square_s),$$

Kotschenreuther, et al Comp. Phys. Comm. 88 128 (1995)

NSTX H-mode:
Electron Temperature Profile Resiliency

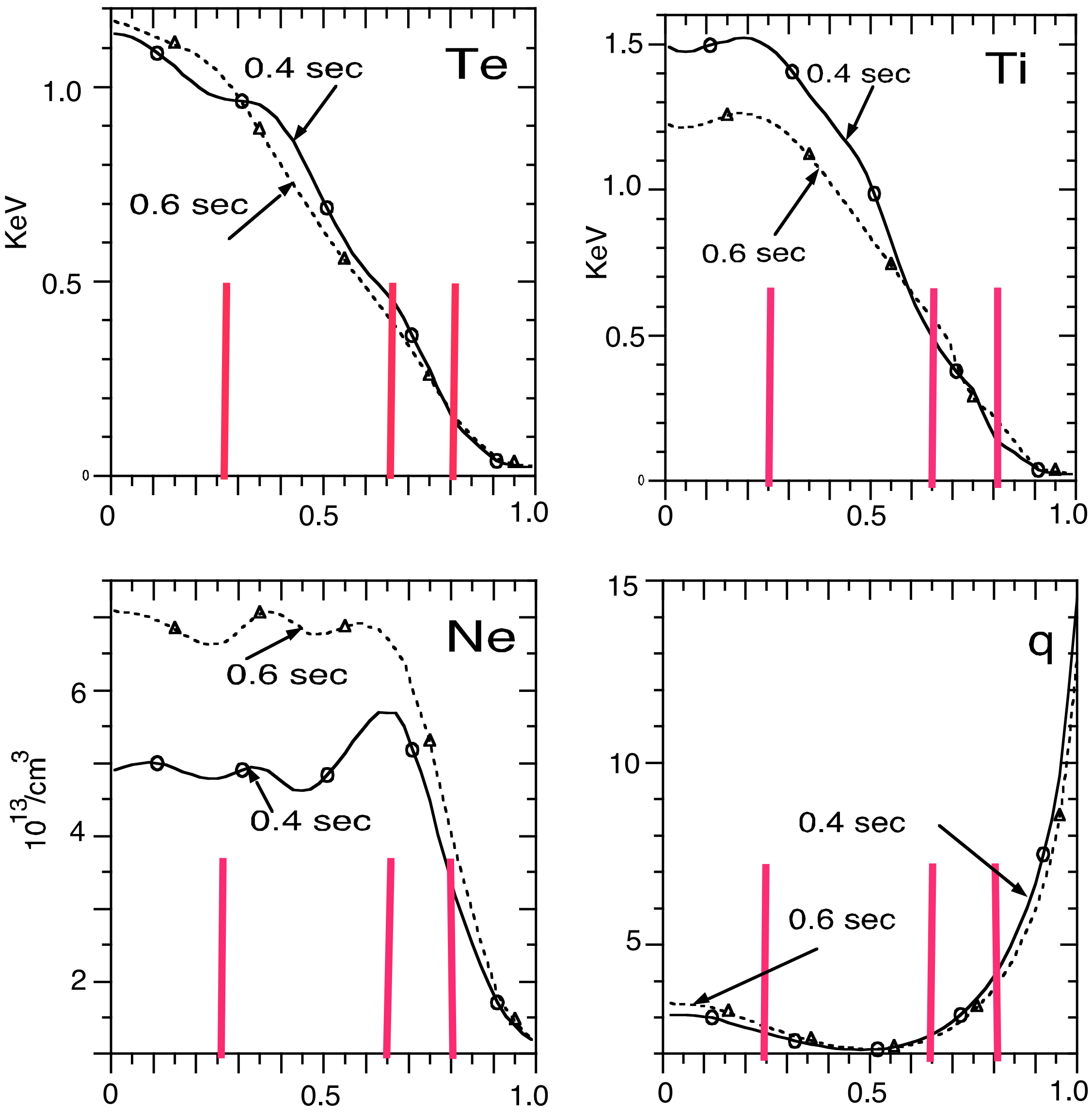
During H-mode

Te(r) remains resilient
electron density increases
ion temperature decreases

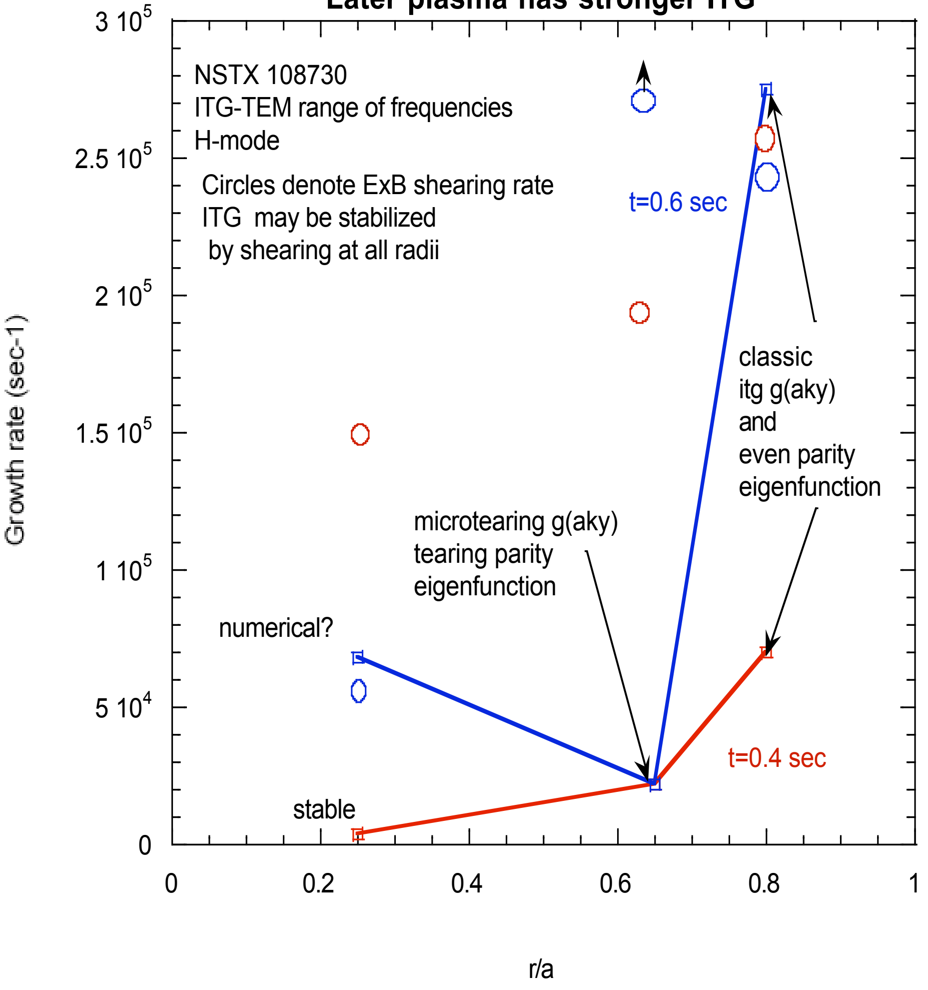
What clamps
Electron temperature profile?

Examine microinstability
Growth rates at 3 zones

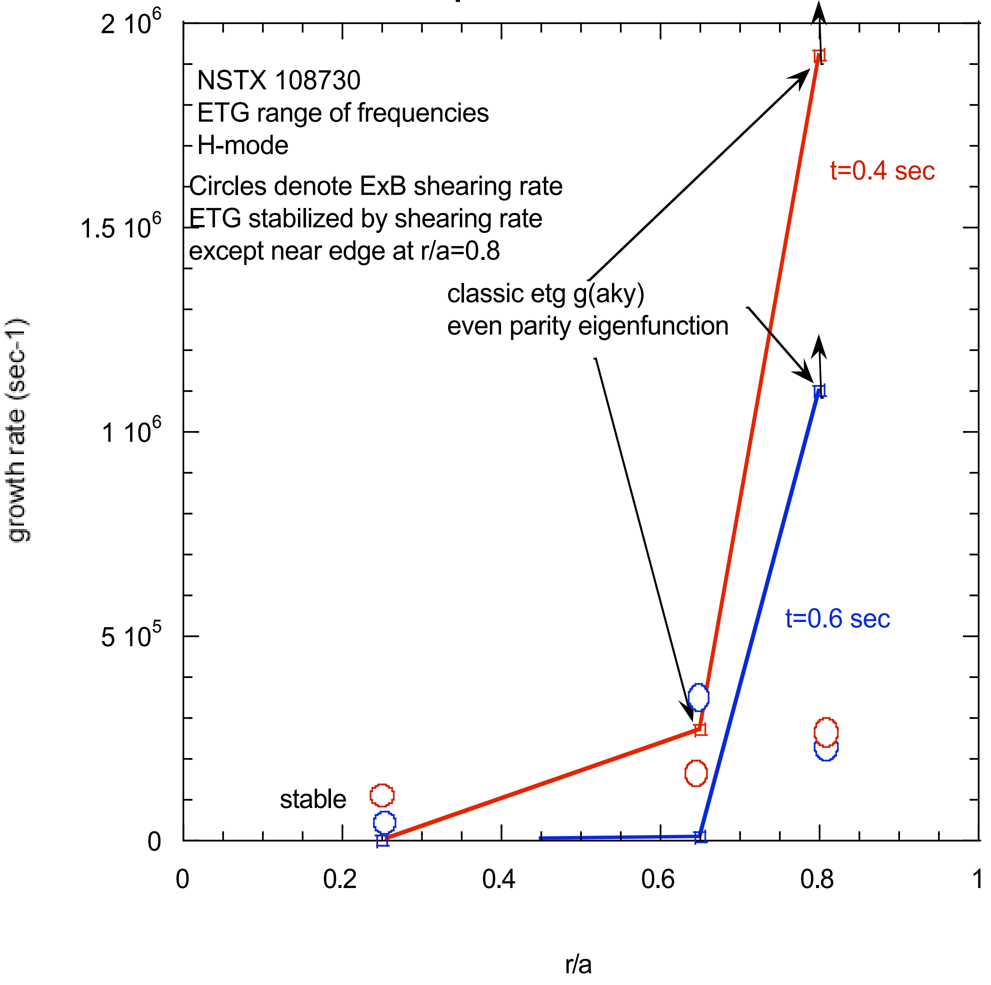
q profile: partial kinetic EFIT



NSTX: Examine Microinstability Growth Rates at 3 Zones



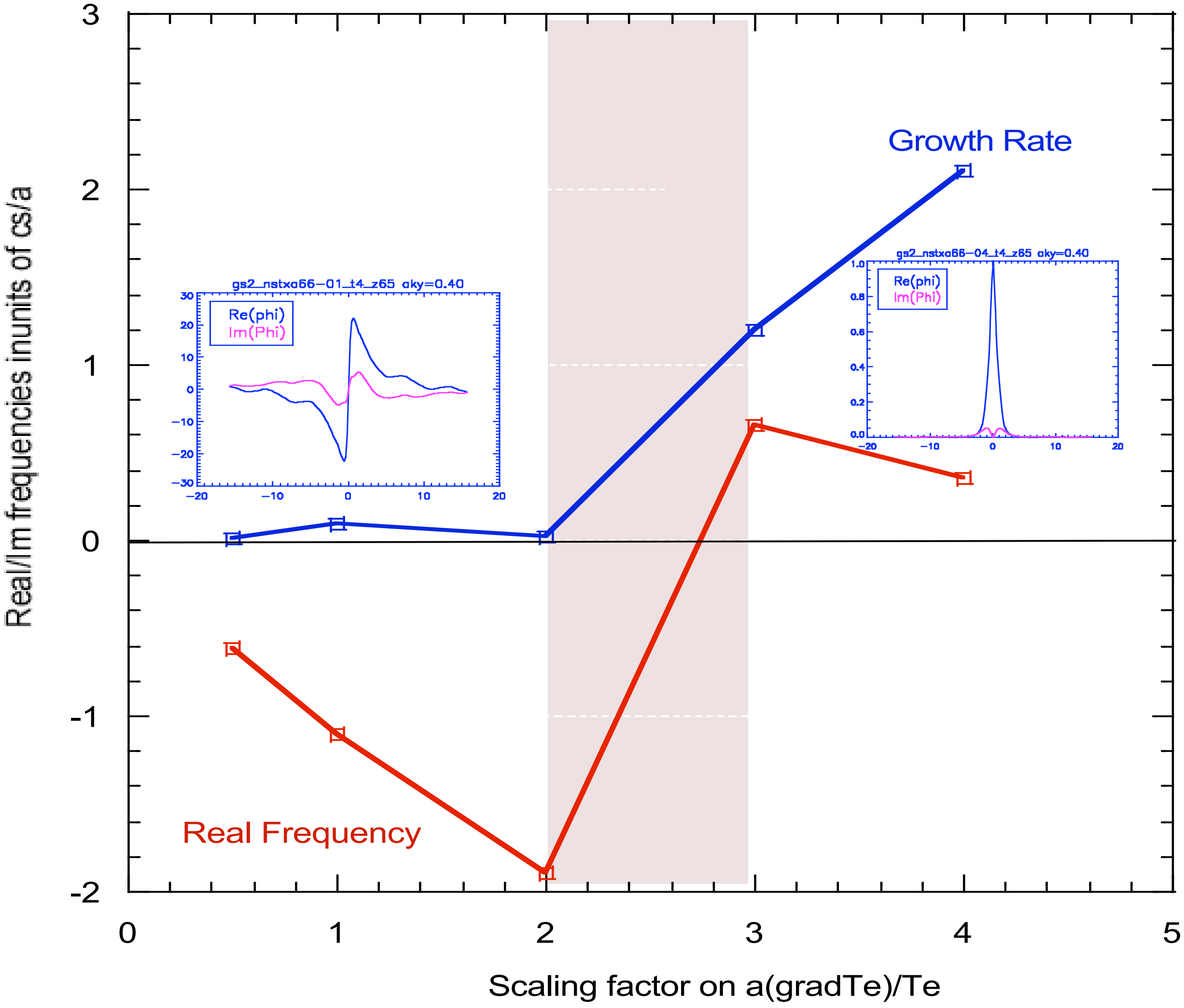
ITG Range of Wavelengths
Stronger growth near plasma edge
Weak instabilities inside
Microtearing modes observed
Later plasma has stronger ITG



ETG Range of Wavelengths
Stronger growth near plasma edge
Weak or stable modes inside
Later plasma has weaker ETG

What is the Instability at 0.65r/a on NSTX?
What Effect Does It Have on Transport?

Character of fastest growing mode changes to ITG/TEM.
This is an ETG-type microtearing mode, driven by (gradTe)/Te.
If a(gradNs)/Ns and a(gradTi)/Ti=0, mode ~unchanged.



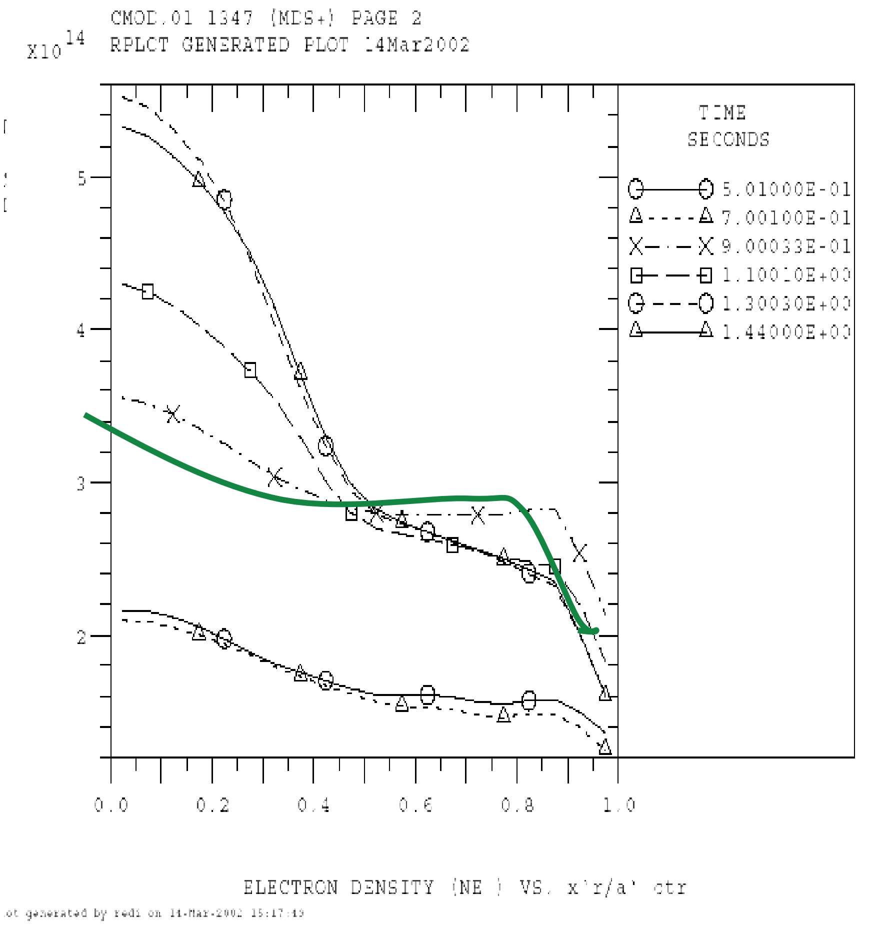
Summary: NSTX H-mode Gyrokinetic Results

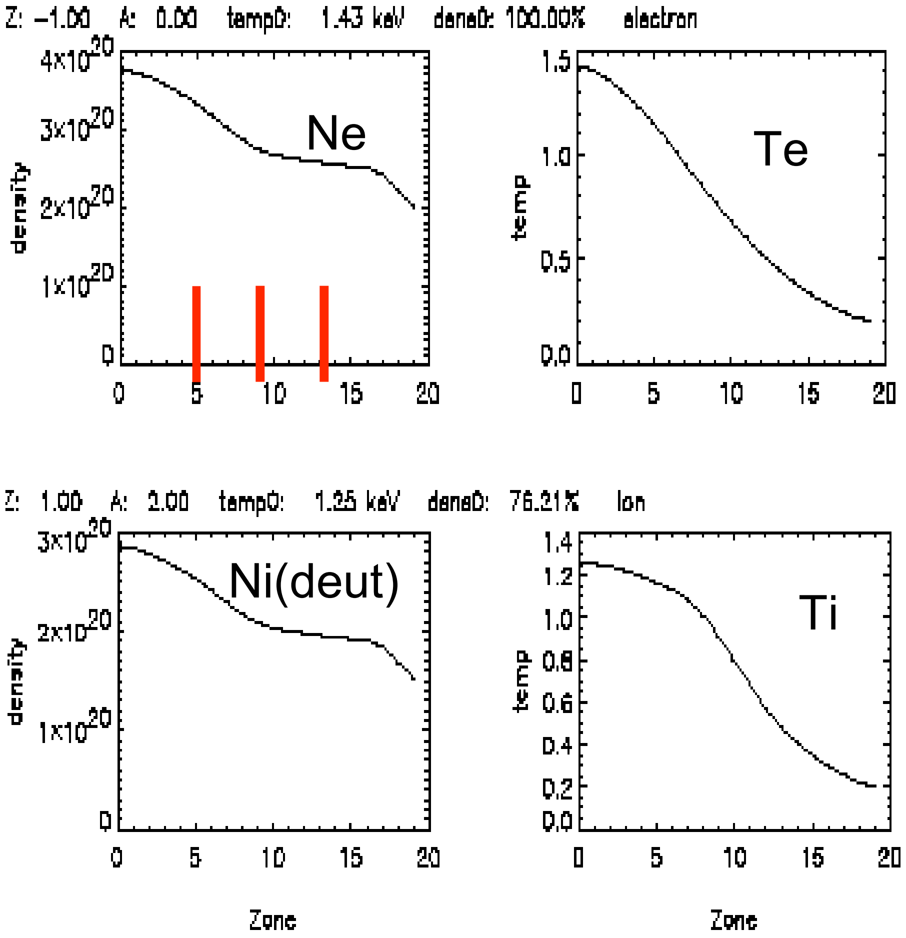
Good ion transport appears due to stabilized ITG
Poor electron transport and resilient Te profiles as yet unexplained

r/a		χ_i	χ_e	ITG	ETG
0.25	t=0.4s	$< \chi_{neo}$	$\gg \chi_i$	stable	stable
	t=0.6s			Likely ExB stabilized	stable
0.65	t=0.4s	$< \chi_{neo}$	$\gg \chi_i$	ExB stabilized	Likely ExB stabilized
	t=0.6s			ExB stabilized	stable
0.80	t=0.4s	$< \chi_{neo}$	$\gg \chi_i$	ExB stabilized	unstable
	t=0.6s			Likely ExB stabilized	unstable

CMOD Internal Transport Barrier

TRIGGER time: Examine Microinstability Growth Rates at 3 Zones

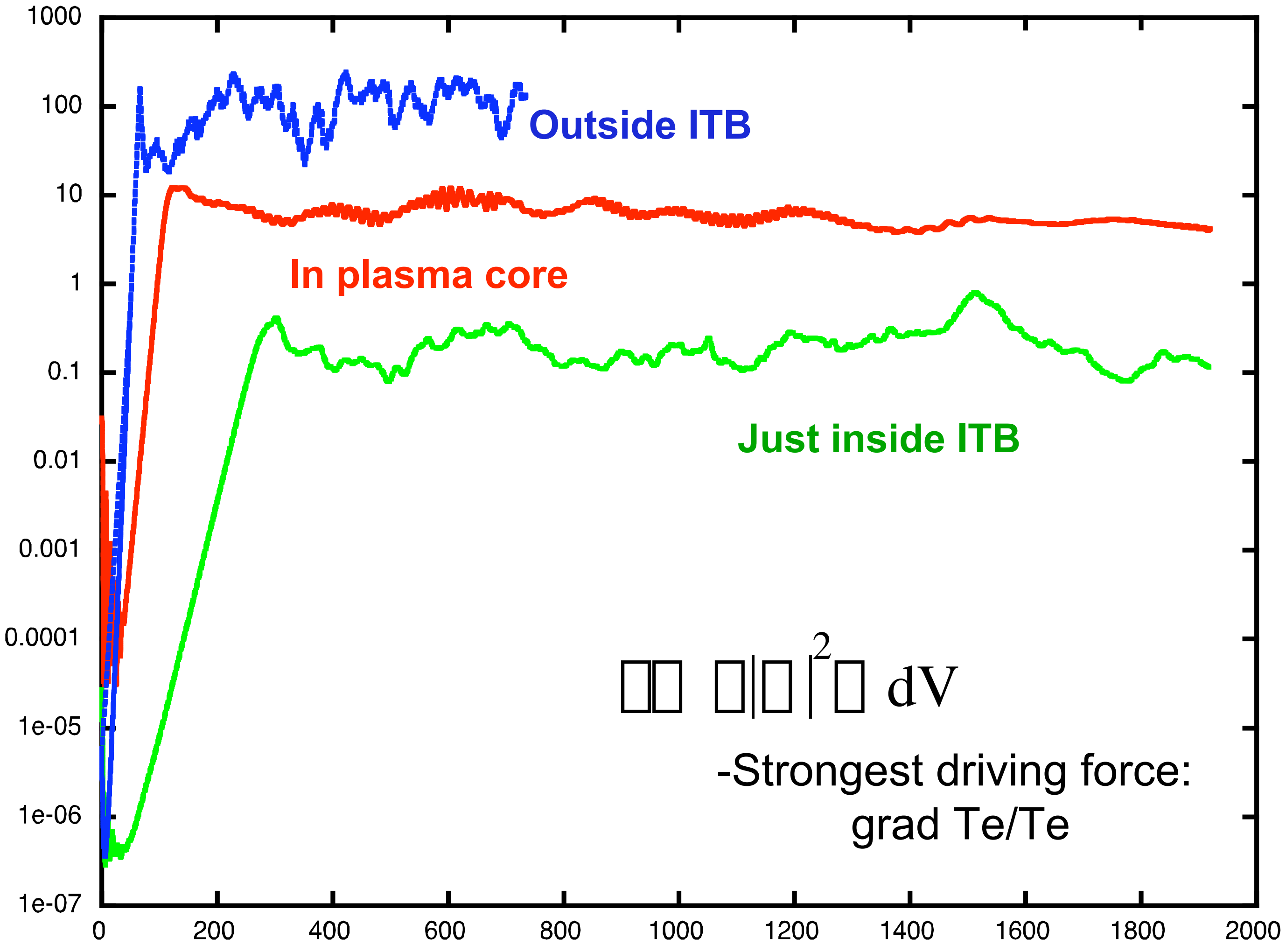




NONLINEAR GS2 Simulations reproduce linear result

ITB TRIGGER: Before n_e peaks, region of reduced transport and stable ITG microturbulence is established without ExB shear

Quiescent, microturbulence in ITB region
Moderate microturbulence in plasma core
High microturbulence level outside half-radius



-Strongest driving force:
grad Te/Te

SUMMARY:

Linear calculations of drift wave instabilities in the ion temperature gradient and electron temperature gradient range of frequencies

Roughly consistent with improved ion confinement in NSTX and improved confinement within and at ITB in CMOD H-mode plasmas

Remarkably good ion transport in NSTX H-mode (Gates, PoP 2002) would be expected from stable ITG throughout plasma

Profile effects (GYRO) may fully stabilize ITG everywhere.

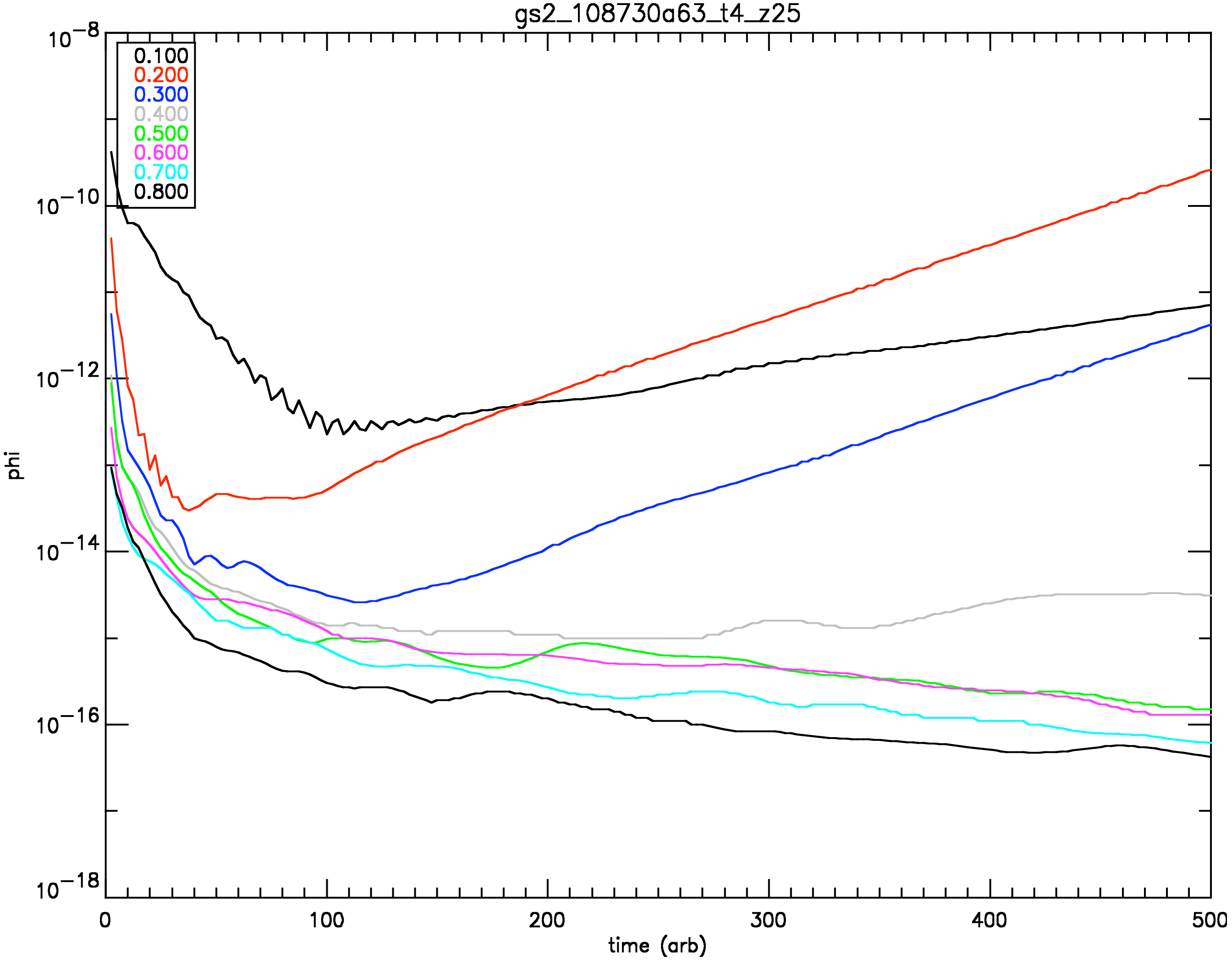
Electron transport => q monotonic so unstable ETG at all r…MSE?

Resilient temperature profiles on NSTX may be maintained through ETG instabilities, Nonlinear calculations needed. Tearing parity microturbulence found - in contrast to tokamaks - effects on transport to be determined.

Internal transport Barrier on CMOD appears after off-axis RF heating, where microstabilities quiescent. Nonlinear calculations in ~agreement with linear.

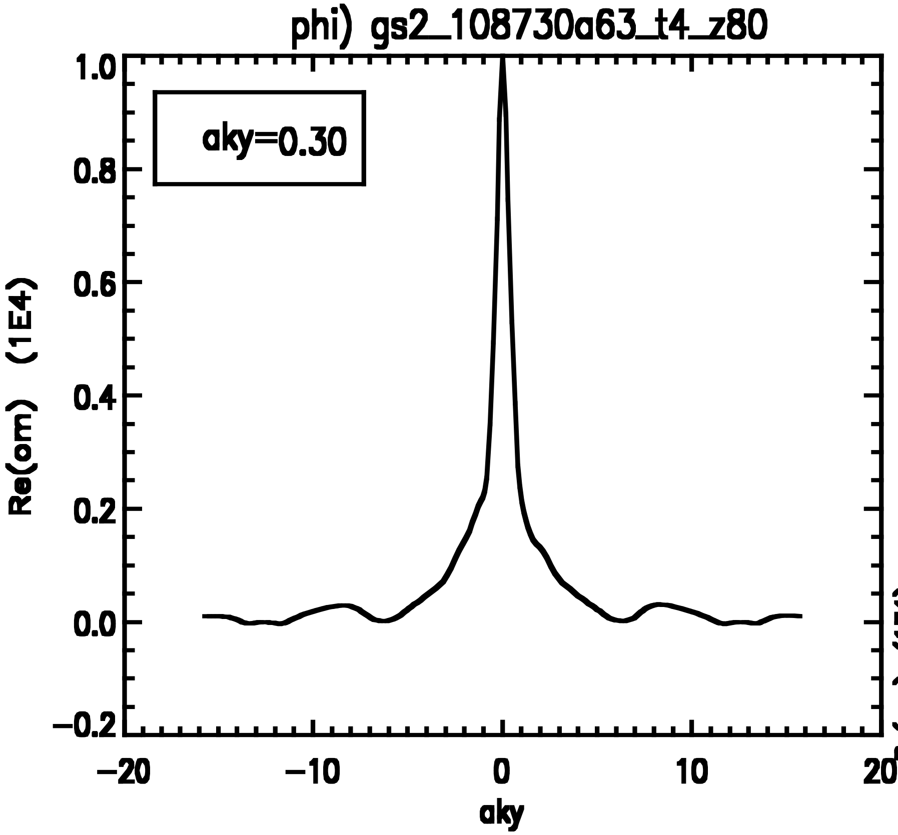
Sawtooth propagation measurements confirm low transport in the region at the trigger time (Wukitch, PoP, 2002).

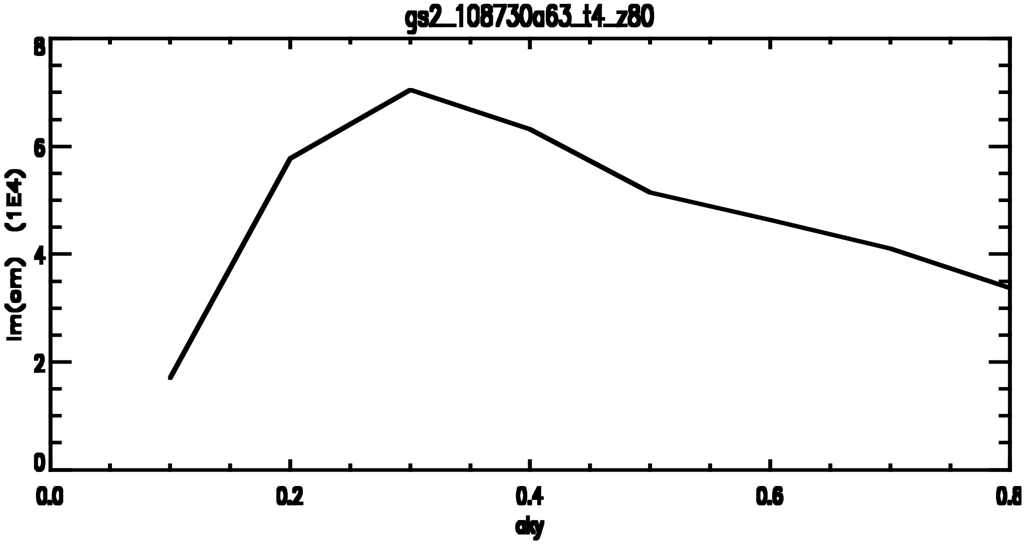
GS2 Evolution of Linear Growth Rates for $k_{\perp}\rho_i$ = 0.1 to 0.8
Some stable, some unstable

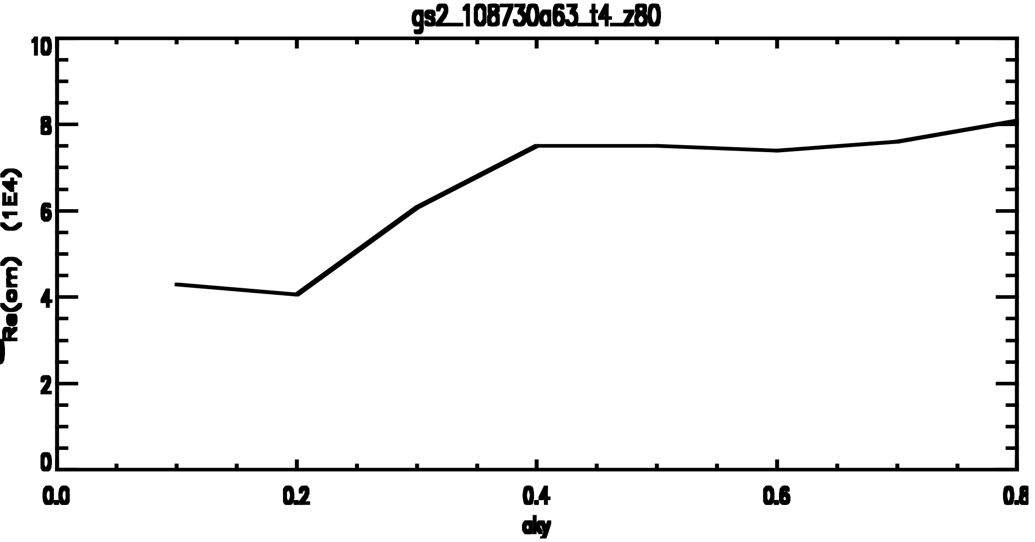


NSTX r/a=0.8: ITG Range of Frequencies

Outside Core, ITG Range of Frequencies
Growth Rates and Eigenfunction at Most Unstable Wavelength

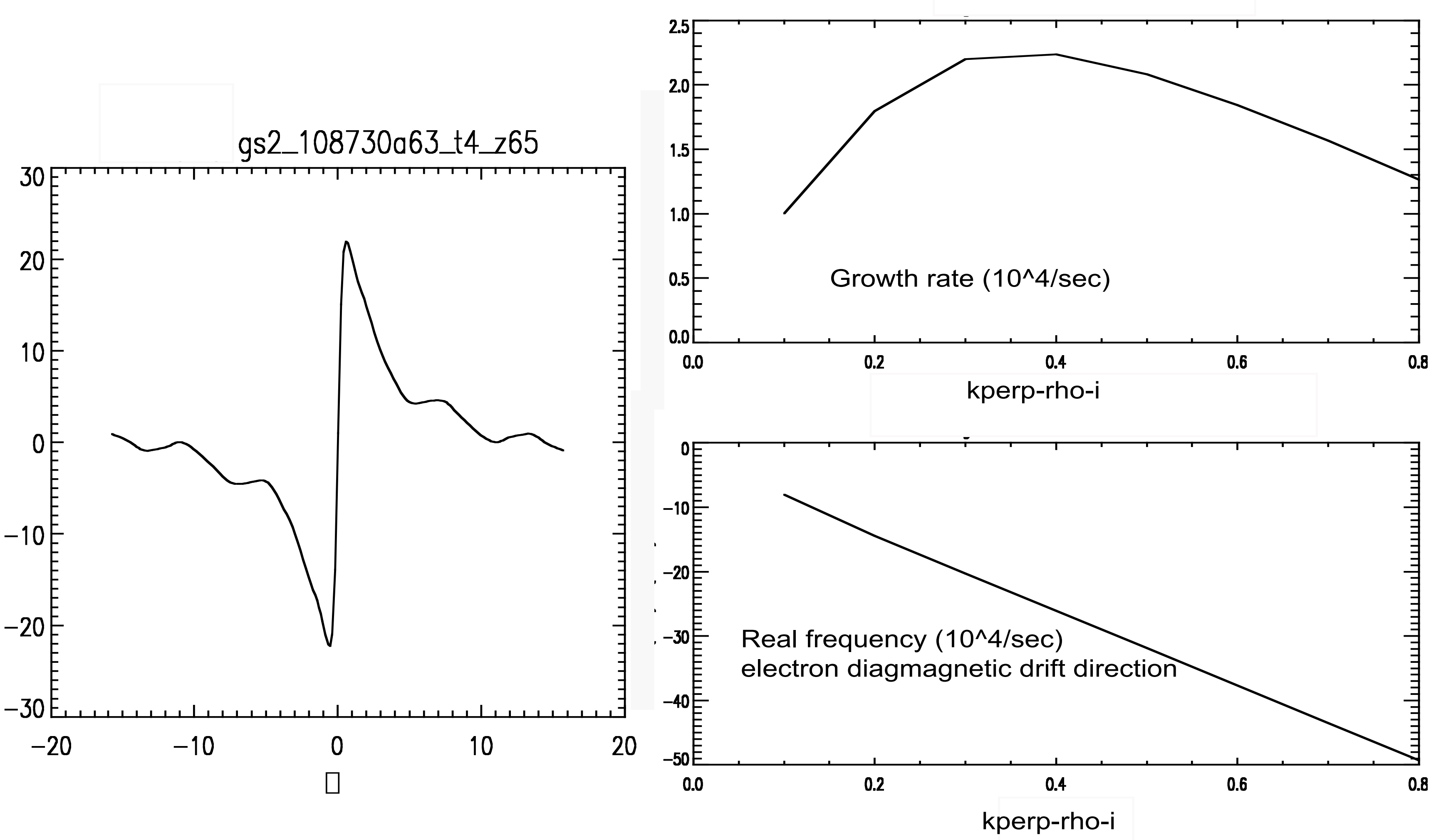






NSTX r/a=0.65: ITG Range of Frequencies

Growth Rates and Eigenfunction of Most Unstable Mode
- Tearing Parity



GS2 criterion H-mode plasmas:

- GS2: Linear, fully electromagnetic, 4 species
- Criteria: $\rho/L \ll 1$ for GS2,

  but profile effects can mix different wavelengths

  => ρ^* stabilization (GYRO)

•NSTX zone,	rho-star,	# ion gyroradii across plasma
0.25r/a	$\rho^*=0.0185/0.6=$ 0.031	32
0.65r/a	0.014	71
0.80r/a	0.0064	157
CMOD		
0.25r/a	0.008	122
0.45r/a	0.008	122
0.65r/a	0.006	167

Very Preliminary Results from GYRO Code for CMOD: ITG Range of Frequencies

GYRO: (R. Waltz, J. Candy, General Atomics)

Large software project for solution of gyrokinetic Maxwell eqns

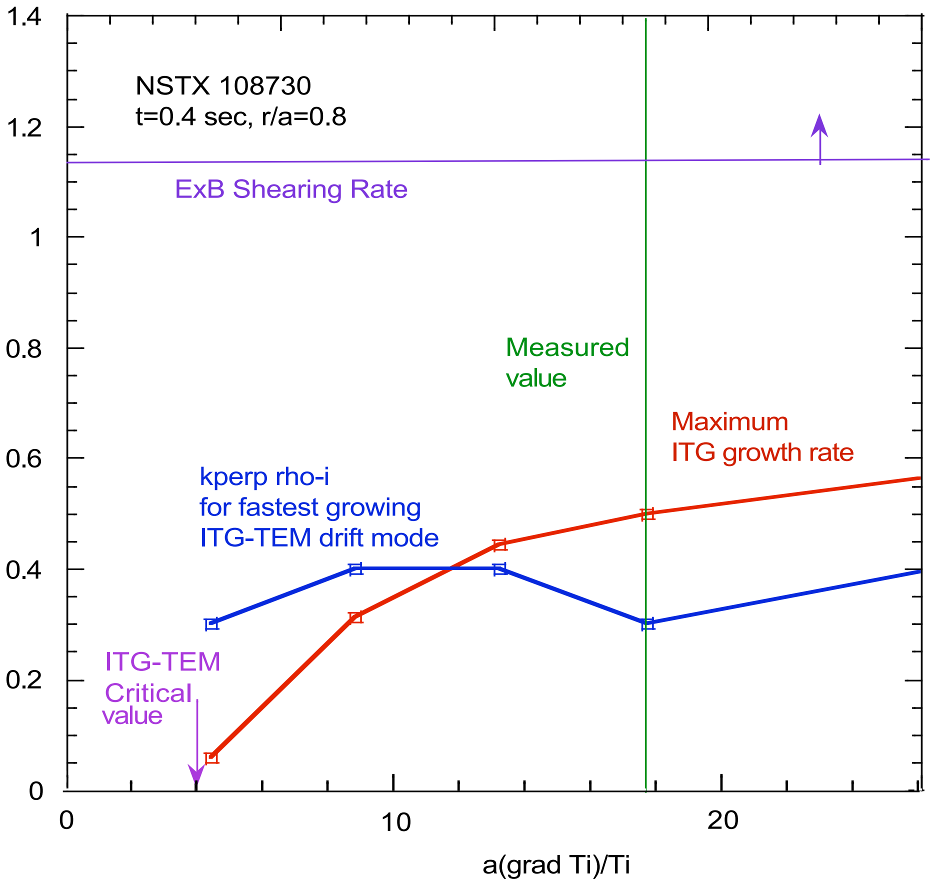
Simultaneous solution of electromagnetic physics
(with kinetic electrons)
and global radial profile variations

Few initial runs with GYRO in fluxtube, circular mode only:
three radii at trigger time as for GS2 studies

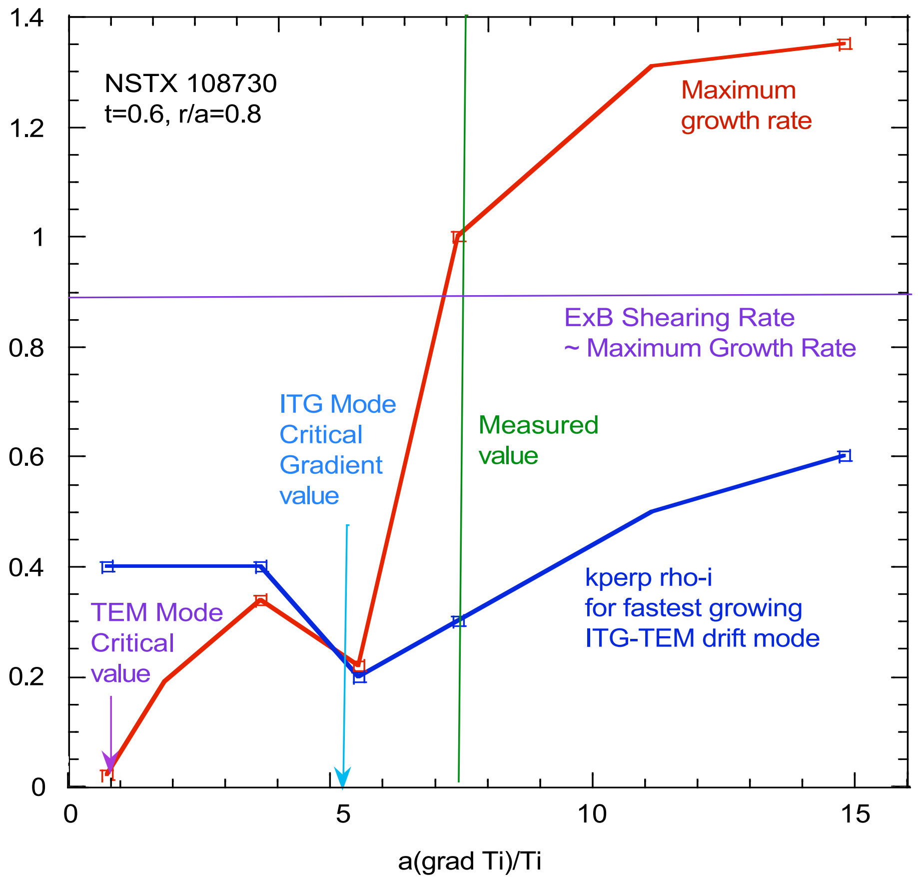
Core:	damped ITG mode
Outside ITB region:	converged ITG mode
In ITB region:	in progress

NSTX: Critical Gradient Below or At Marginal Stability for ITG

Experimental Temperature Gradient for ITG-TEM Drift Modes far below Marginal Stability when ExB Shearing Rate Subtracted Hybrid root changes from ITG to TEM character below experimental a(grad Ti)/Ti. Fastest Growing ITG Drift Mode Wavelengths Change little as grad Ti/Ti is reduced

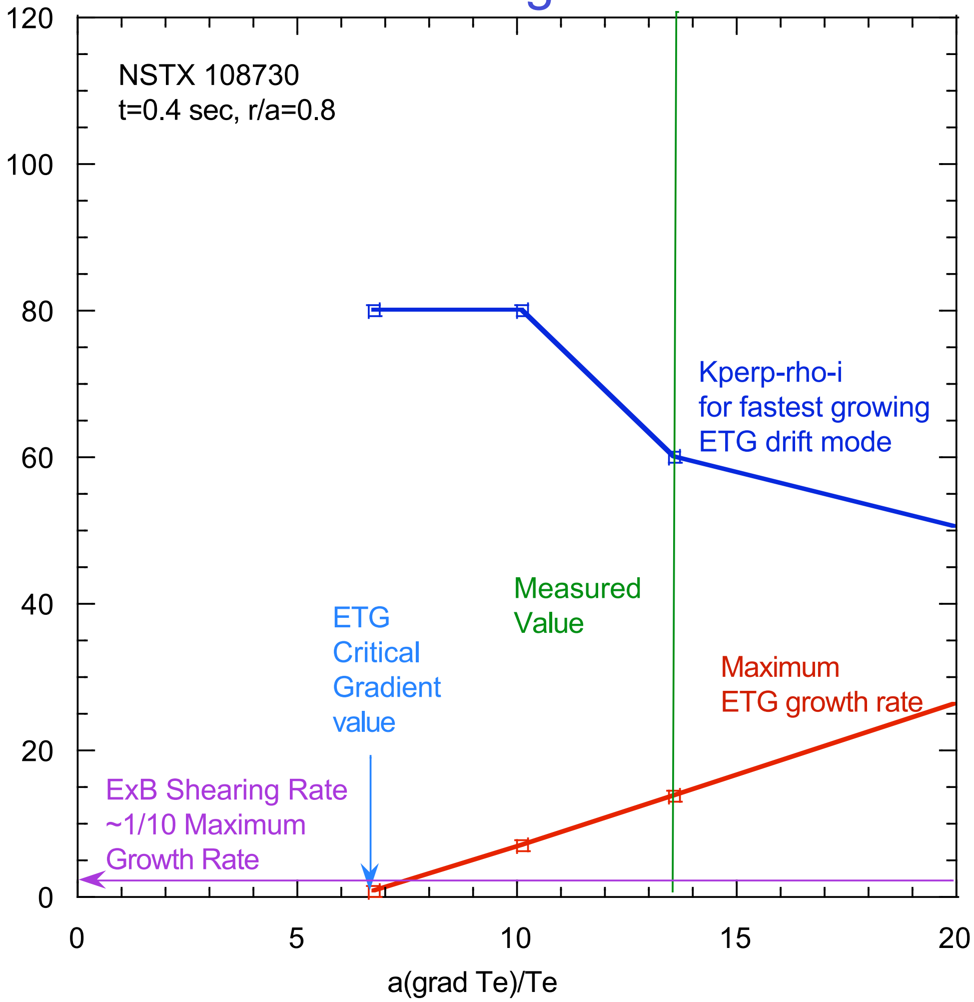


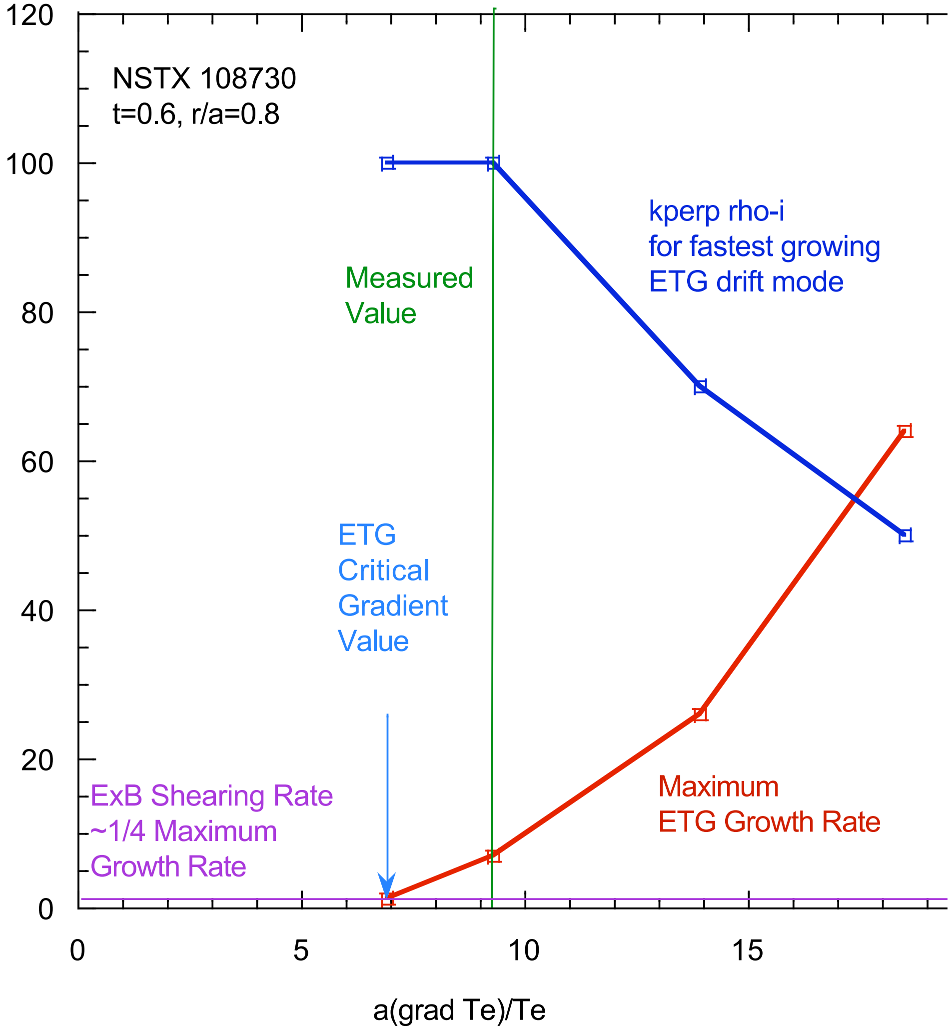
Experimental Temperature Gradient is near Marginal Stability for ITG and above Marginal Stability for TEM Drift Modes. Drift mode with maximum growth rate changes from ITG to TEM as grad Ti/a/Ti decreased. Find two critical gradients, for distinct ITG and TEM roots ExB shearing rate ~ maximum growth rate: ITG likely stable



NSTX: Far Above Critical Gradient for ETG Modes

ExB Shearing Rate<<Maximum Growth Rate
Fastest Growing ETG Drift Mode Wavelengths and Growth Rates Decrease as gradTe/Te is Reduced
Higher Critical Gradient for ETG than ITG





ITB Trigger Time:

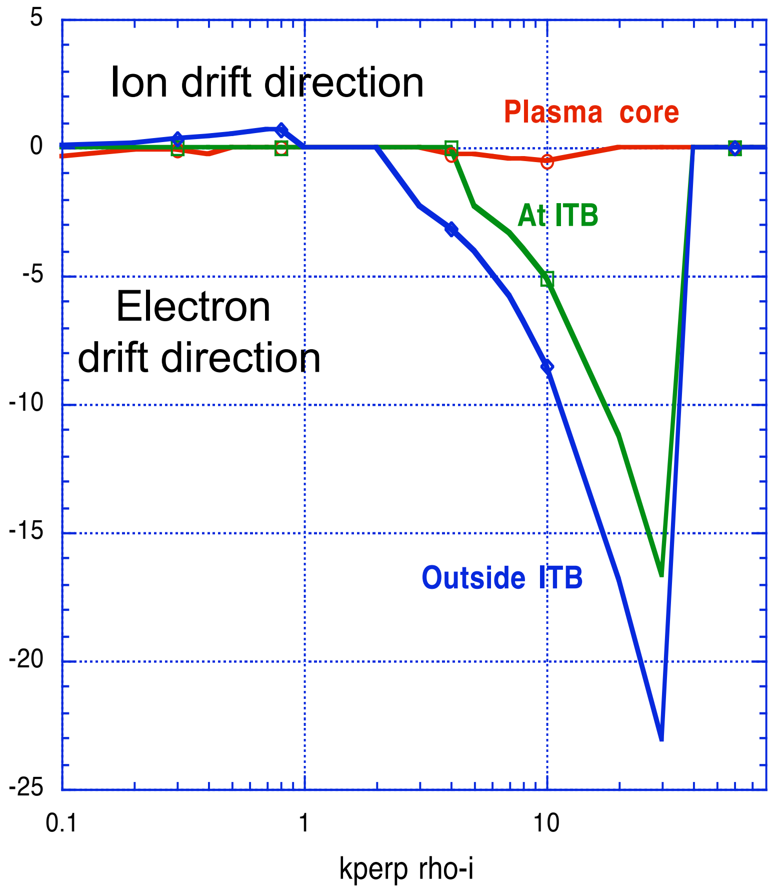
Linear, Electromagnetic Gyrokinetic Calculations with GS2:

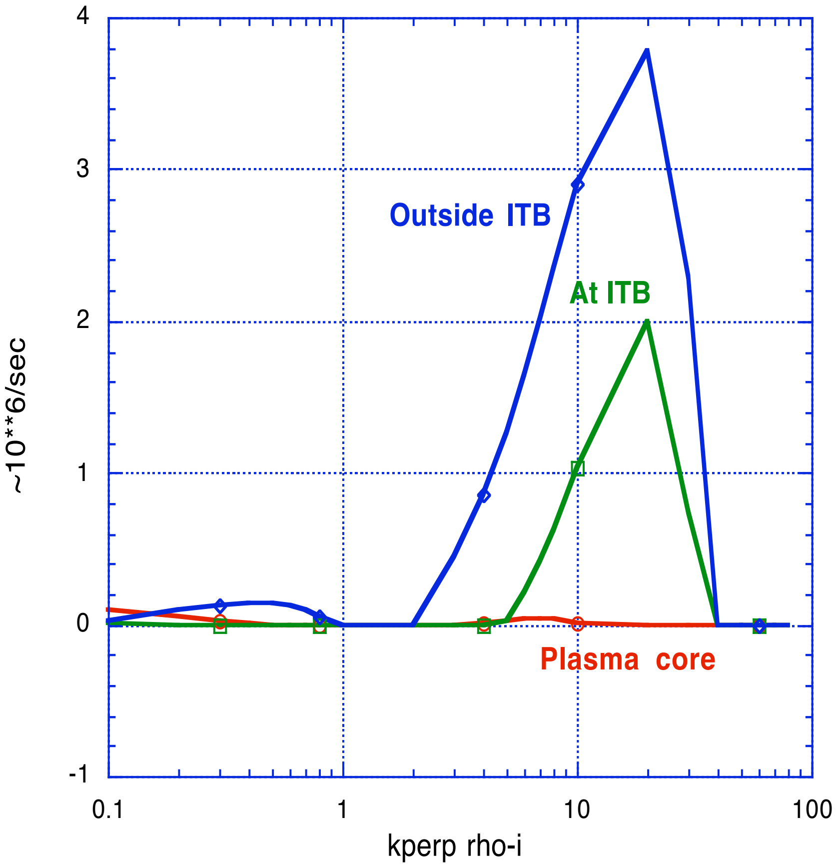
Drift wave Microturbulence at $k_{\perp}\rho_i$ = 0.1 to 80.

Low $k_{\perp}\rho_i$: ITG => $\chi_i^{anomalous}$ outside ITB

TEM and ITG: already stabilized at and within ITB

High $k_{\perp}\rho_i$: ETG driven by strong ∇T_e => $\chi_e^{anomalous}$ at and outside ITB


Real frequencies (~10**6/sec)
zones 5,9,13
kperp rho-i from 0.1 through 80


Growth rates at zones 5,9,13
for kperp rho-i from 0.1 to 80
ITG stabilized in plasma core and near ITB
eta-i small, TE drive weak; ITG and TEM stable