NSTX

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Gyrokinetic analysis of thermal transport scaling in NSTX and MAST

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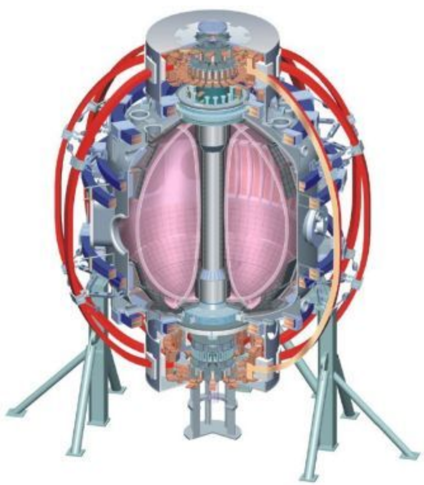


Overview

- Favourable $\tau_{E,th} \sim \nu_*^{-(0.7-0.9)}$ dependence in STs
  - Physical origin unclear, could influence design of next-generation device at low ν_*
- Microtearing modes found to be unstable in experimental ν_* scans
  - Scaling of linear growth rates $\gamma_{lin} \sim \nu_e$ – potential candidate to explain experimental confinement trend
  - Linear thresholds exist in ν_e, β_e, a/L_{Te}

⇒ **First <u>non-linear</u> microtearing simulations in NSTX**

  - Require relatively fine radial resolution ($\Delta x \approx 0.2\rho_s$, nx=400) to capture physics
  - Significant transport predicted without E×B shear
  - Dominated by electromagnetic contribution ($\delta A_{||}$) → stochastic field lines
- ETG also a possible transport mechanism
  - Unstable in some regions, can drive significant transport
  - Transport from nonlinear ETG simulations decreases with increasing ν_e – opposite to experimental trend

Experimental motivation - strong collisionality scaling in STs

- Next generation ST (high heat flux, CTF, …) likely to be at lower ν_*
- Present ST confinement scaling with ν_* favorable $\Rightarrow$ will it hold at lower ν_*?

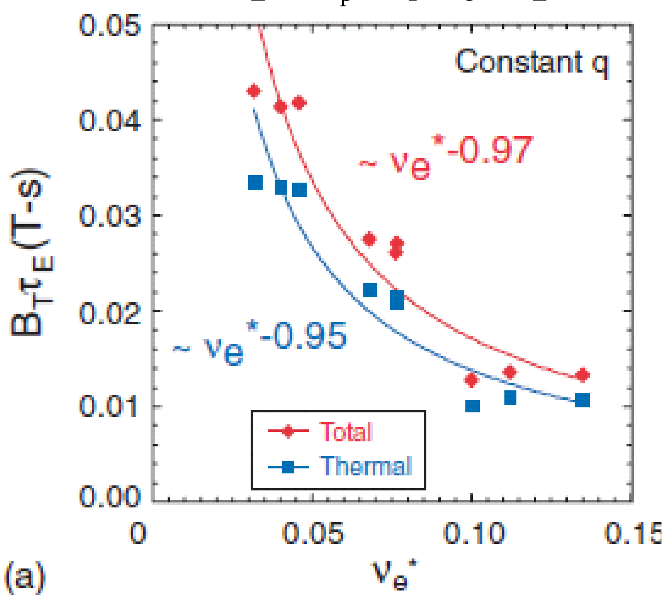
- Large (I_p+B_T) scaling related to strong ν_* scaling (assuming gyroBohm ρ_*^{-3})

$\Rightarrow$ What physical mechanisms are important?

$$\alpha_B + \alpha_I = \frac{(2-2x_\beta)}{(5/2 - x_\beta + 2x_\nu)}$$

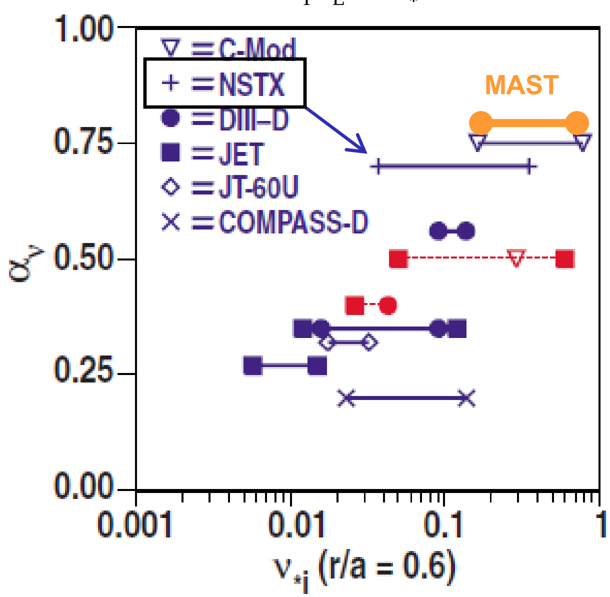
Kaye et al. (2007)

$$\tau_E^{th} \sim I_p^{0.6} B_T^{1.0} n_e^{0.35} P_L^{-0.6}$$

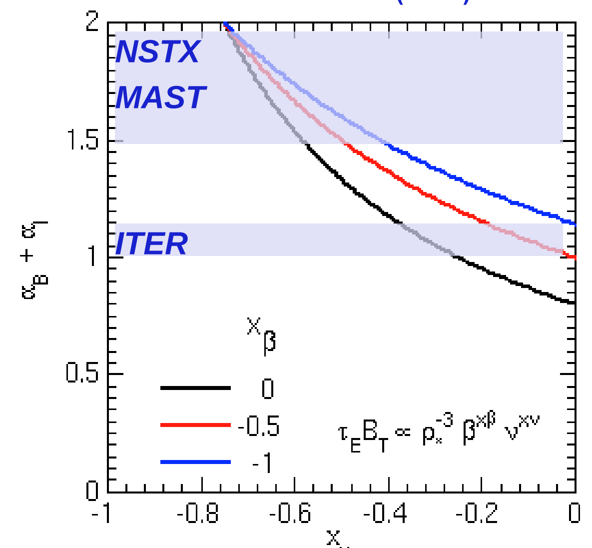


Petty (2008)

$$B_T \tau_E^{th} \sim \nu_*^{-\alpha_\nu}$$



Valovič et al. (2010)



Dimensionless ν^* scans – basis of microstability analysis

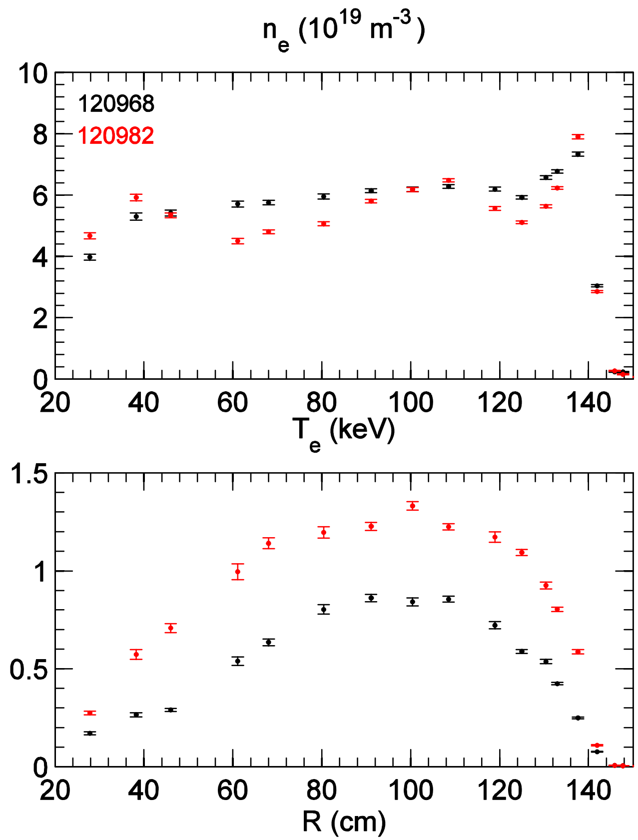
$$q \sim I_p / B \qquad \rho_* \sim T^{1/2} / B \qquad \beta \sim nT / B^2 \quad \Rightarrow \quad I_p \sim B \qquad T \sim B^2 \qquad n \sim B^0$$

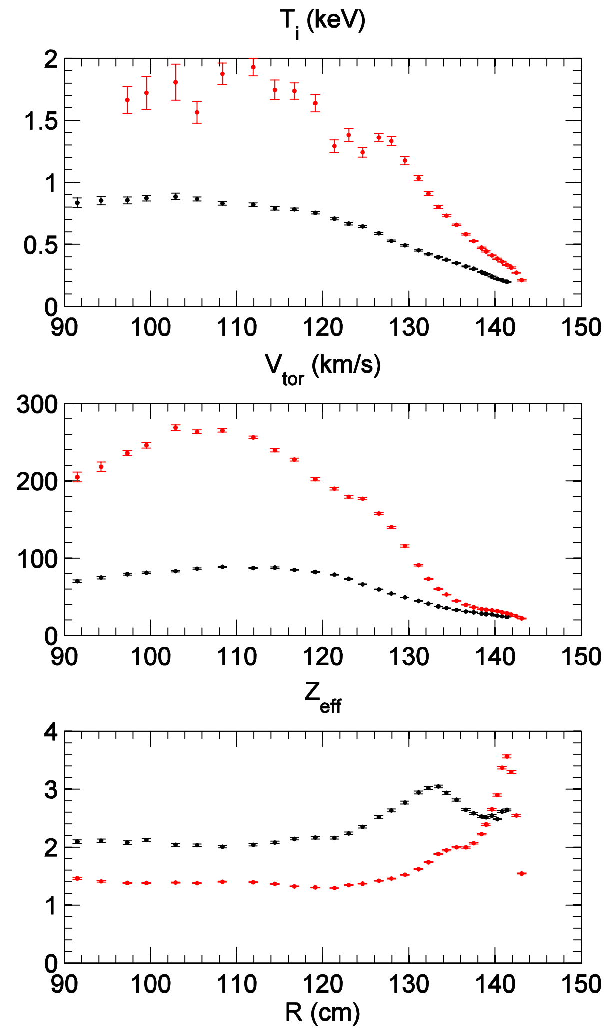
$$\boxed{\nu_* \sim B^{-4}}$$

NSTX 120968 I_p / B_T / P_{NBI} - 0.7 MA / 0.35 T / 4 MW
NSTX 120982 I_p / B_T / P_{NBI} - 1.1 MA / 0.55 T / 4 MW

Strong rotation and rotation shear

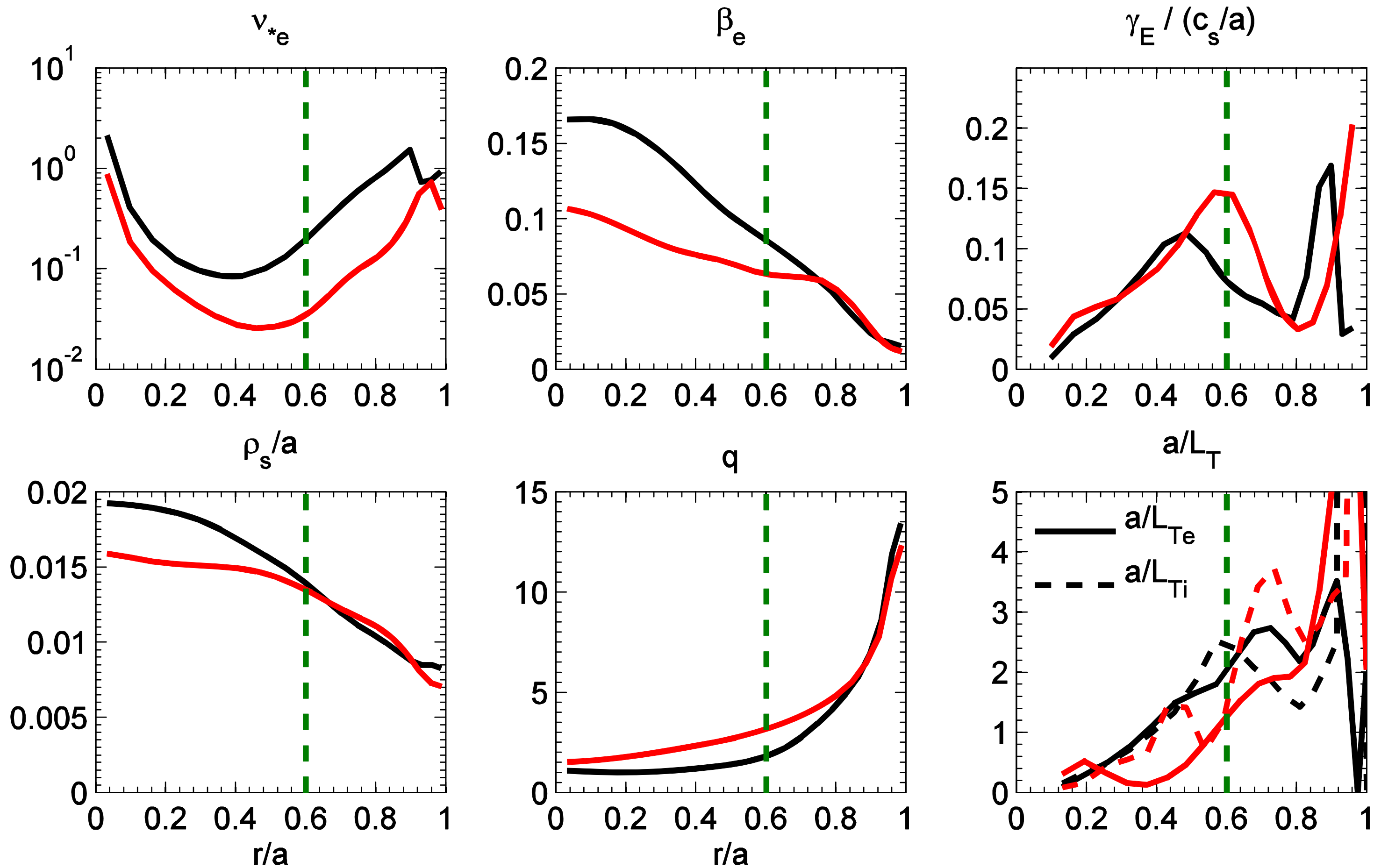
Ion transport well described by neoclassical (NCLASS)





Experimental profiles of dimensionless parameters

Factor ~5 variation in ν_*, additional (non-ideal) variation in other dimensionless parameters



The following simulations are based on high ν_* NSTX discharge 120968 (mostly r/a=0.6)

Calculations were also performed for MAST discharges with similar results (not shown)

Scaling of linear microtearing instability

GYRO* used for gyrokinetic simulations

- Eulerian solver of gyrokinetic-Maxwell equations
- Can use experimental profile variations, T(r), n(r), q(r), etc… (likely important in ST, ρ_s/a~1/100-1/50)
- Fully collisional & electromagnetic (both important in NBI heated ST)
- Freedom to include toroidal flow and flow shear (important in NBI heated ST)
- Substantial user-friendly documentation*
- Can be run in the local flux-tube limit ($\rho/a \rightarrow 0$, flat profiles, similar to FULL, GS2, GENE, GKW, etc…) for
  - Code benchmarking
  - Comparing “local” limit (flat profiles, $\rho_* \rightarrow 0$) with “global” (experimental profiles)

- *Following linear calculations performed in the local, flux-tube limit*

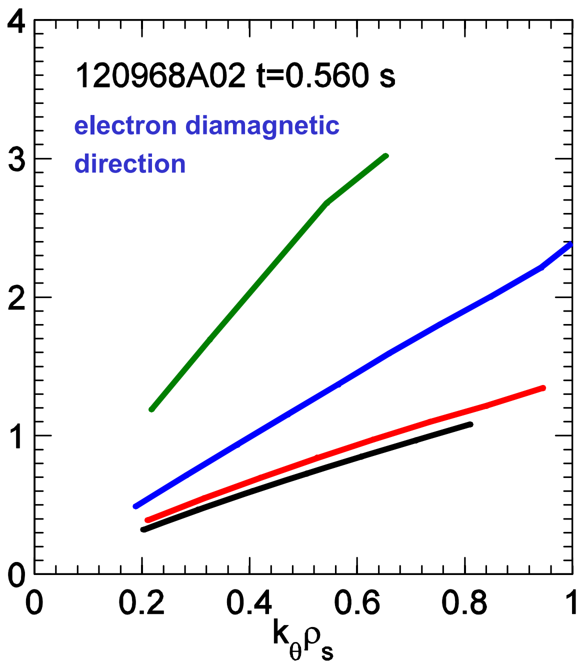
*J. Candy & R.E. Waltz, Phys. Rev. Lett **91**, 045001 (2003); J. Comp. Physics **186**, 545 (2003); https://fusion.gat.com/theory/Gyro

Microtearing modes found to be unstable in high ν_* discharge

- Microtearing dominates $k_\theta\rho_s$<1 in outer half-radius (r/a=0.5-0.8)
  - Resonant tearing parity in $A_{||}$ ($\delta B_r=-ik_\theta A_{||}$)
  - Extended potential eigenfunctions in ballooning space
  - Real frequencies in electron diamagnetic direction
- ETG becomes unstable at outermost locations (r/a=0.7-0.8, not shown)

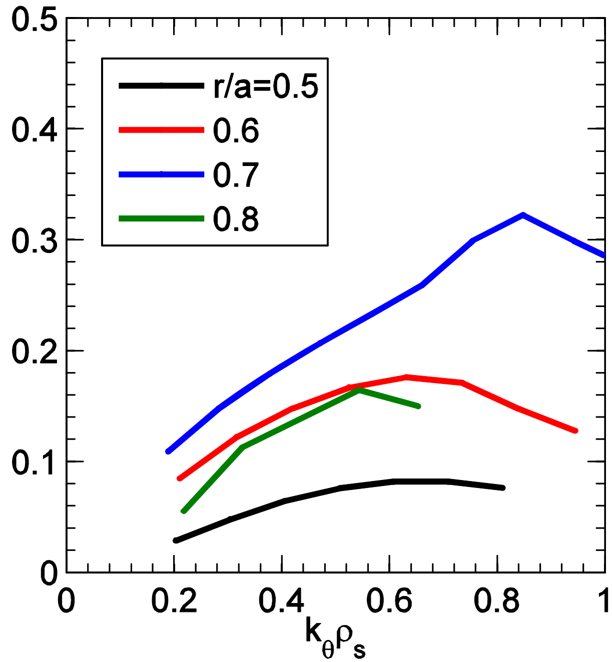
real frequencies

ω_r (c_s/a)

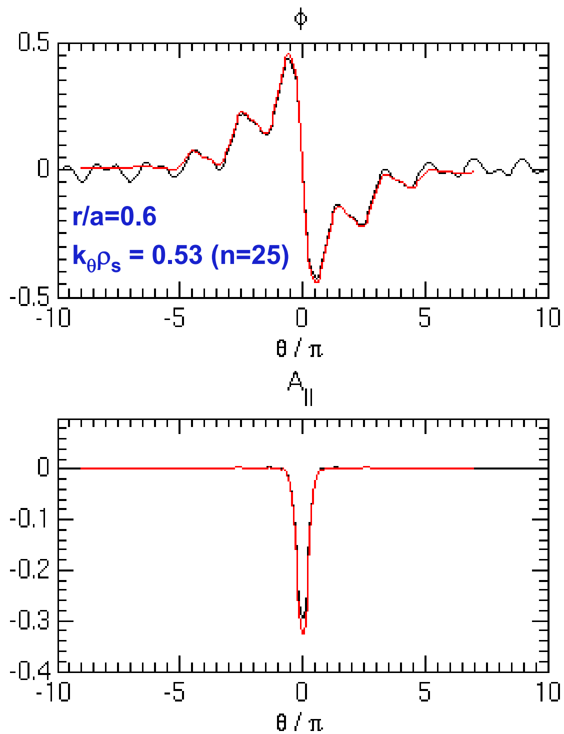


growth rates

γ (c_s/a)



Eigenfunctions in "ballooning" space



Linear microtearing instability

- High-m tearing mode around a rational $q(r_0)$=m/n surface ($k_{||}(r_0)=0$)
- Driven by ∇T_e with parallel thermal force, *requires collisionality* (Classical tearing mode stable for large m, $\Delta' \approx -2m/r<0$)

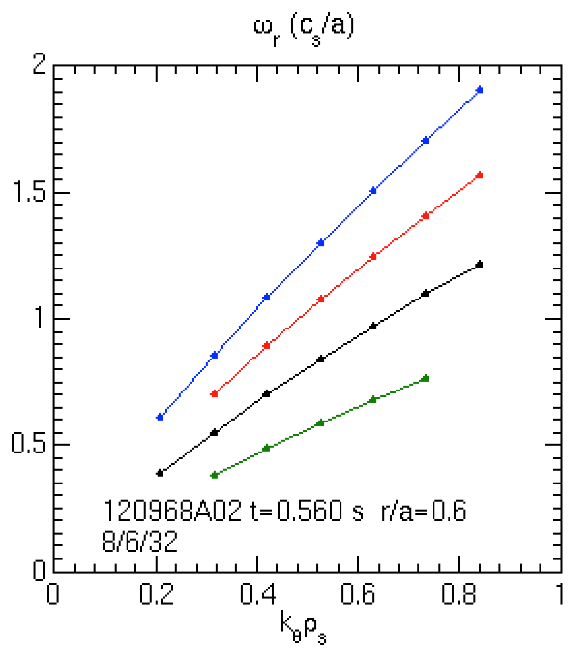
- Imagine helically resonant (q=m/n) δB_r perturbation $\delta B_r \sim \cos(m\theta - n\varphi)$
- δB_r leads to radially perturbed field line, finite island width $w = 4\left(\frac{\delta B_r}{B}\frac{Rq^2}{mq'}\right)^{1/2}$
- ∇T_e projected onto field line gives parallel gradient $\nabla_{||} T_{e0} = \frac{\vec{B} \cdot \nabla T_{e0}}{B} = \frac{\delta B_r}{B} \nabla T_{e0}$
- Parallel thermal force ($R_{T||} \approx -n_e \nabla_{||} T_e$) drives parallel electron current that reinforces $\delta B_r \rightarrow$ instability

- Requires ∇T_e, finite β, positive magnetic shear (dq/dr) & energy dependent collision operator

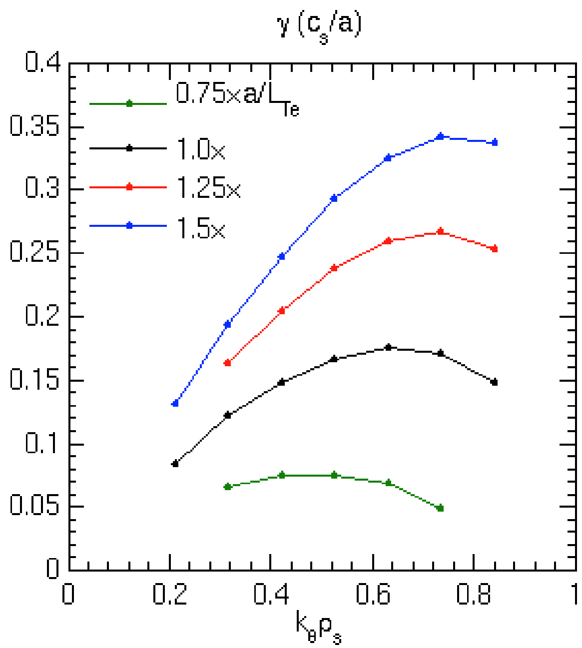
Microtearing instability exhibits a threshold in temperature gradient

- Growth rates increase with a/L_{Te}, apparent threshold $(a/L_{Te})_{threshold} \approx 1.3\text{-}1.5$
- $(a/L_{Te})_{threshold} \sim 0.5$ in Wong et *al*. (2008) (NSTX discharge 116313 r/a = 0.5)
- ω_r proportional with a/L_{Te} (and a/L_n) $\omega \approx \omega_{*e} = (k_\theta \rho_s) \cdot (a/L_n + a/L_{Te}) \cdot (c_s/a)$

real frequencies



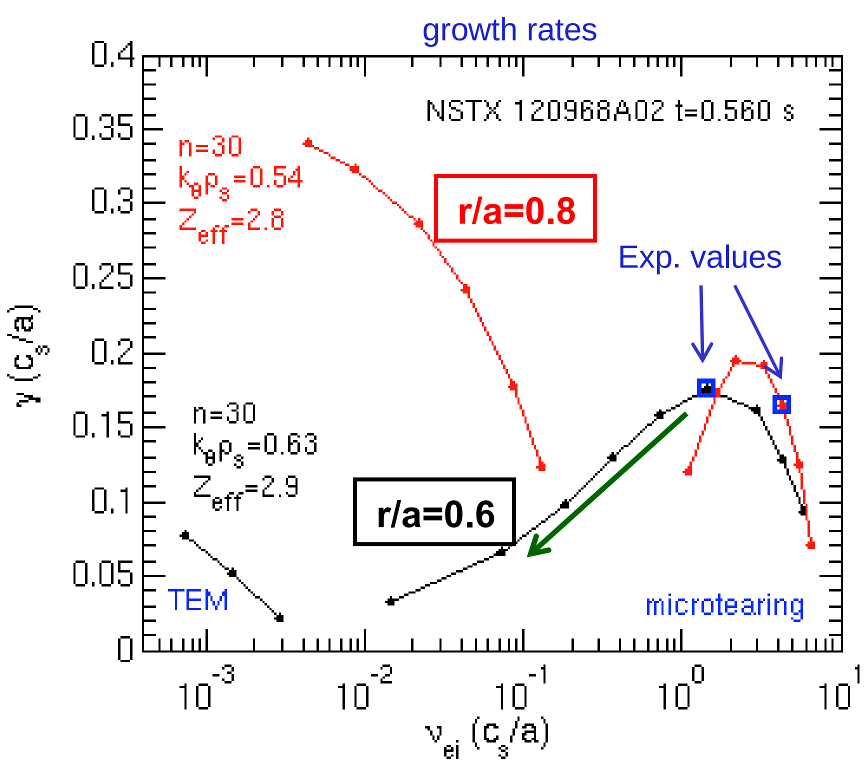
growth rates



$a/L_{Te,exp}$=2.7

At r/a=0.6, linear scaling with ν_e consistent with global τ_E scaling trend

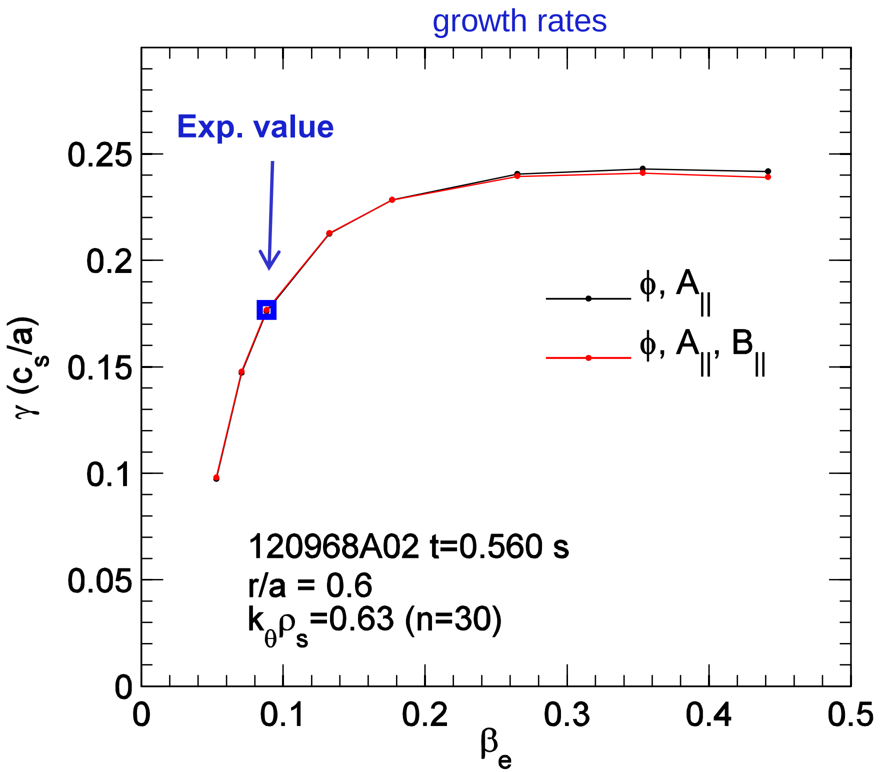
- Growth rates decrease with $\nu_e < \nu_{e,exp}$ (in the direction of the experimental ν_* scan)
- Scaling with ν_e not simply monotonic – transition to TEM at very low ν_e
- Farther out (r/a=0.8) larger a/L_{Te}, a/L_n, and trapping (ε) leads to larger TEM growth rate at low collisionality
  – Transition to microtearing occurs at higher ν_e but still in experimental range



Similar scaling calculated for MAST 22769 r/a=0.6

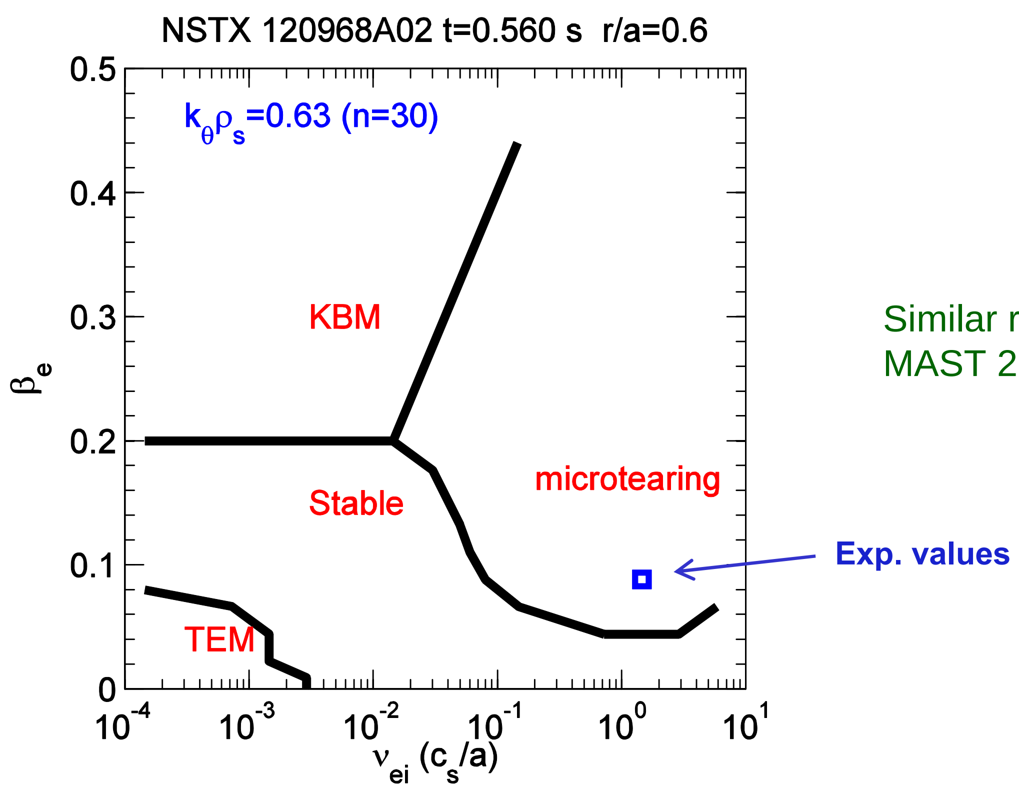
Finite beta critical to instability

- At experimental ν_e, lowering beta stabilizes microtearing → no instability remains
- KBM becomes unstable at much larger β_e (not shown)
- Microtearing dynamics insensitive to compressional magnetic perturbations ($\delta B_{||}$)



Mapping out stability space via ν_e-β_e regime diagram

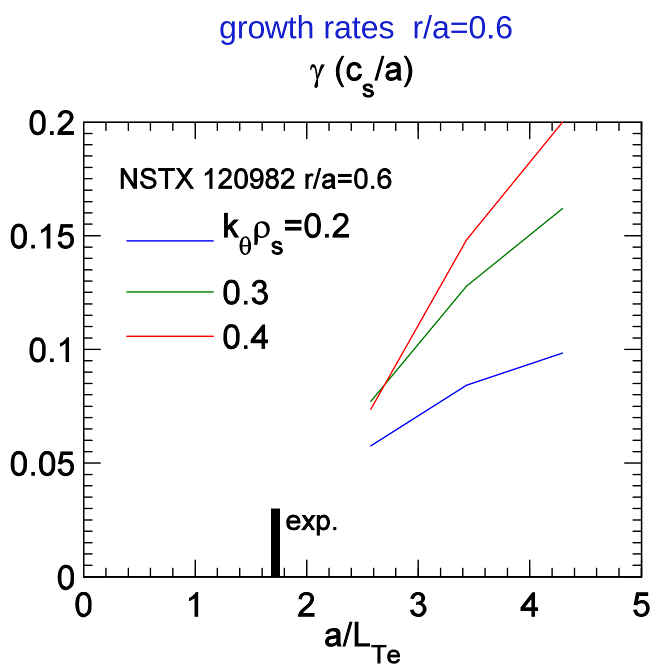
- Artificially varying ν_e and β_e (inconsistently holding $\nabla\beta_{eq}$ constant) for fixed $k_\theta\rho_s$=0.63 (n=30)
- At this location, microtearing mode dominates over wide range of ν_e and β_e
- There appears to be a broad stable region at much lower collisionality
- Onset of KBM is sensitive to $\delta B_{||}$ (included below)

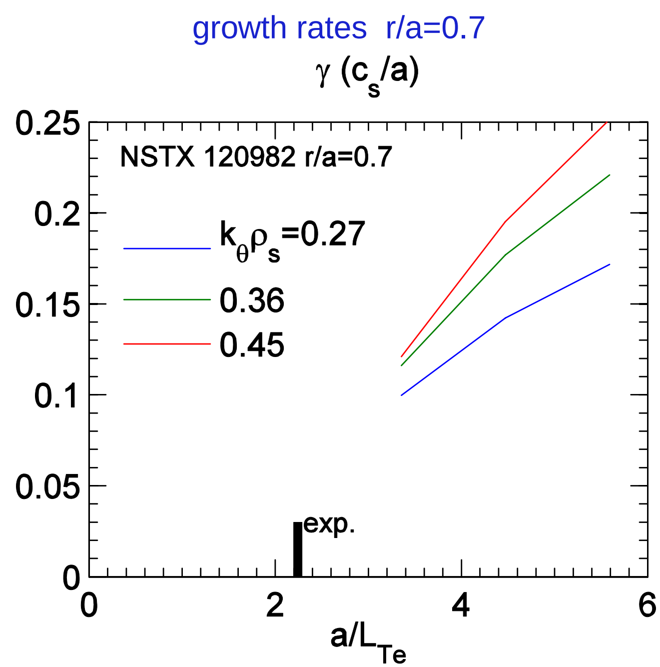


Similar regime diagram for MAST 22769 r/a=0.6

Low ν_* discharge near microtearing ∇T_e threshold

- Calculations for low ν_* discharge (NSTX 120982) are stable (r/a=0.5) or near marginal (r/a=0.6-0.8)
- Consistent with above ν_e-β_e regime diagram, but other parameters changing





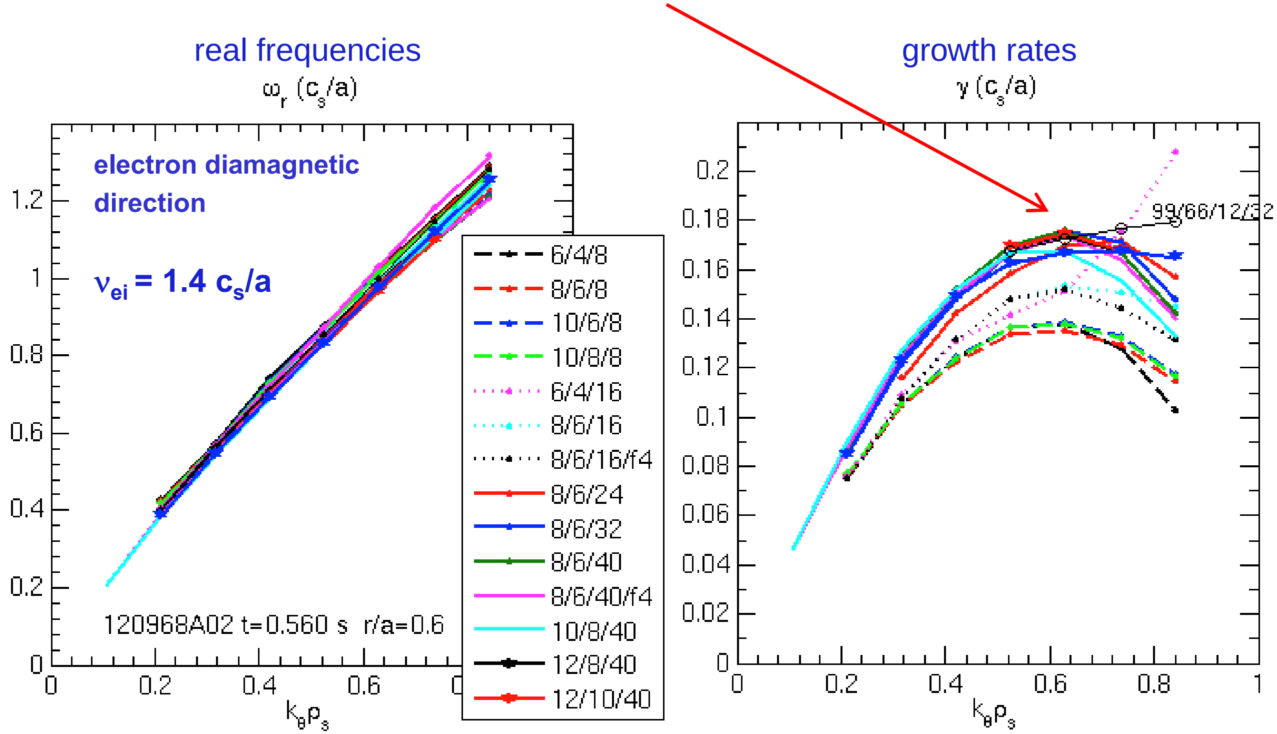
Structure of linear microtearing modes

Linear convergence sensitive to resolving narrow inner layer

- Growth rates most sensitive to radial resolution (Δx) at higher $k_\theta \rho_s$
- "Semi-collisional" regime of microtearing modes $\nu_{ei} \sim |\omega|$ (Drake & Lee, 1977)
  - Inner layer width Δ_d theoretically determined by balance of drift frequency ω_{*e} with Doppler shift due to parallel electron diffusion ω_d

    $\Rightarrow \omega_{*e} \sim \omega_d = (k_{||} v_{te})^2/\nu$, $k_{||} = k_y \Delta_d / L_s$ $\Rightarrow$ $\Delta_d \sim 0.07\ \rho_s$ (for $k_\theta \rho_s = 0.6$)

    Linear growth rate converged for $\Delta r \approx 0.03\ \rho_s$ (for $k_\theta \rho_s = 0.6$)



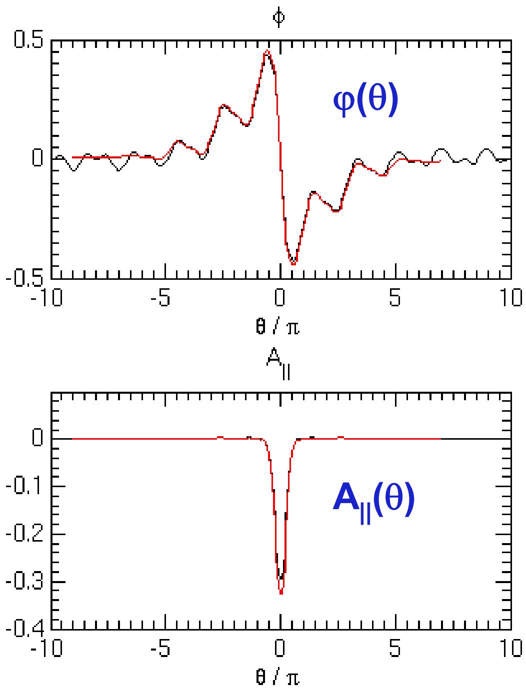
Linear mode structure in perpendicular (r,α) plane illustrates microtearing mode dynamics

- Narrow resonant current channel ($\approx 0.3\rho_s$) centered on rational surface (compare to simple slab $\Delta_d \sim 0.07\rho_s$ estimate above)
- "Constant ψ" ($A_{||}$), resonant tearing parity
- Nearly unmagnetized/adiabatic ion response $\Rightarrow \frac{\tilde{n}}{n_0} \approx -\left(\frac{e\tilde{\varphi}}{T_i}\right)$
- Narrow potential, density, T_e perturbations

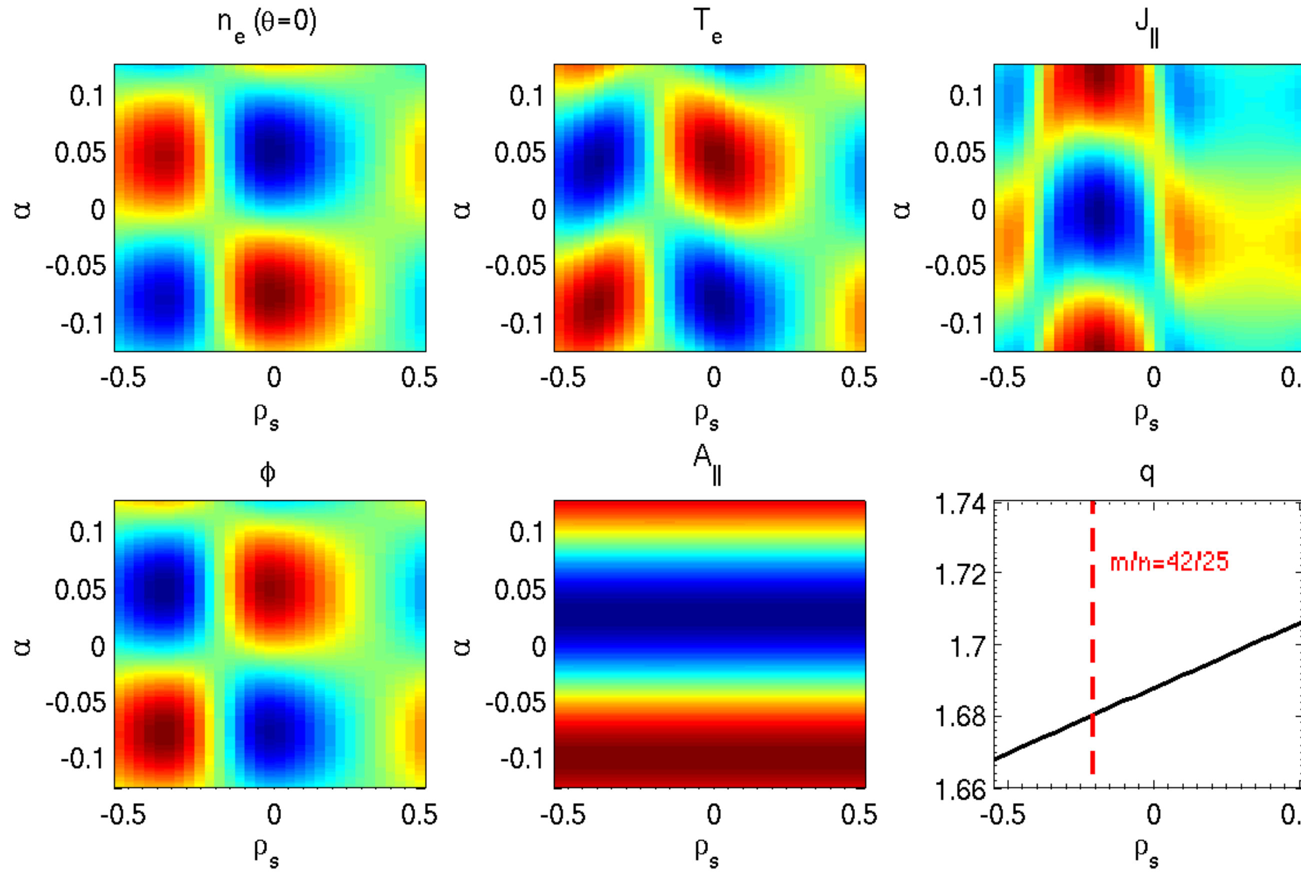
$\alpha = \varphi - q\theta$ for low β circular surfaces

"ballooning" space

$$k_r(\theta) = \hat{s} k_\theta (\theta - \theta_0)$$



r-α perpendicular plan (θ=0)



Field line integration used to map island

- δB_r in linear run (arbitrary) determines $w_{island} \sim 0.4\ \rho_s$
- Slab/cylindrical island width estimate does not work well (δB_r strongly ballooning)

$$\left|\frac{\delta B_{r,mn}}{B}\right| = 1.8\cdot 10^{-7}$$

$$w = 4\cdot\left[\frac{\delta B_{r,mn}}{B}\frac{rR}{n\hat{s}}\right]^{1/2} = 0.03\rho_s$$

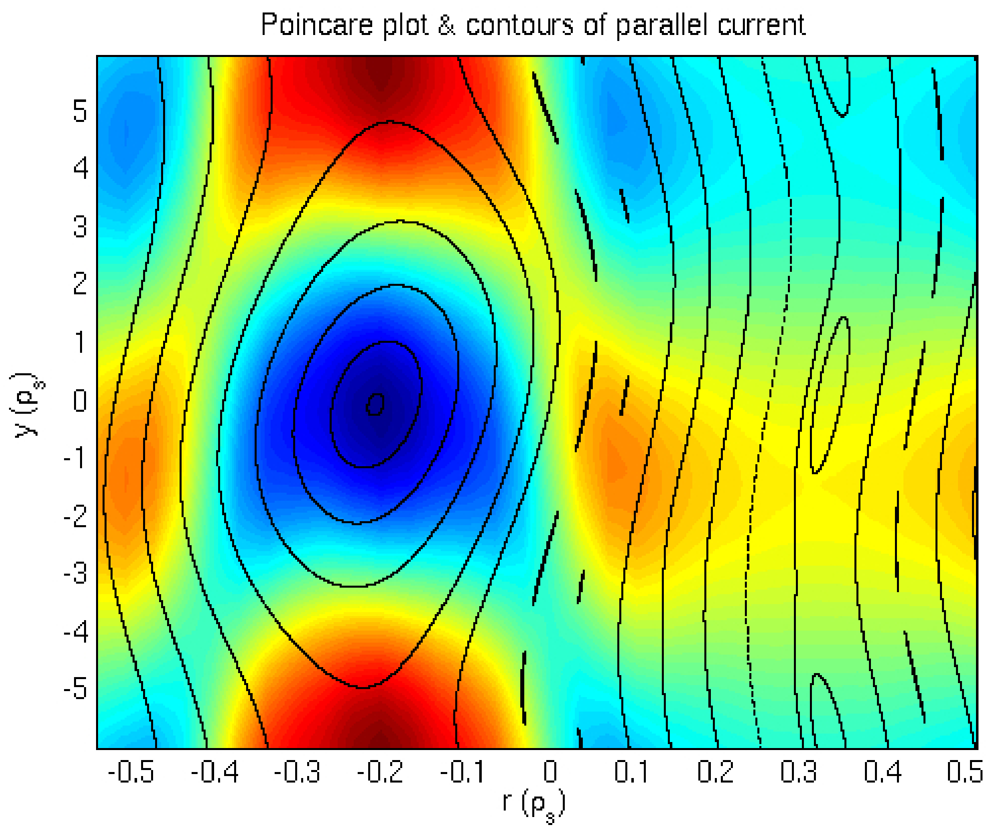
- Estimate using rms δB_r gets closer

$$\left|\left\langle\frac{\delta B_r^2}{B^2}\right\rangle_{\alpha,\theta}\right|^{1/2} = 2.5\cdot 10^{-5}$$

$$w = 4\cdot\left[\left(\frac{\delta B_r}{B}\right)_{rms}\frac{rR}{n\hat{s}}\right]^{1/2} = 0.39\rho_s$$

- $w_{island}/L_{Te} \approx 8\cdot 10^{-3}$ but $\max(\delta T_e/T_e) \approx 4.5\cdot 10^{-4}$

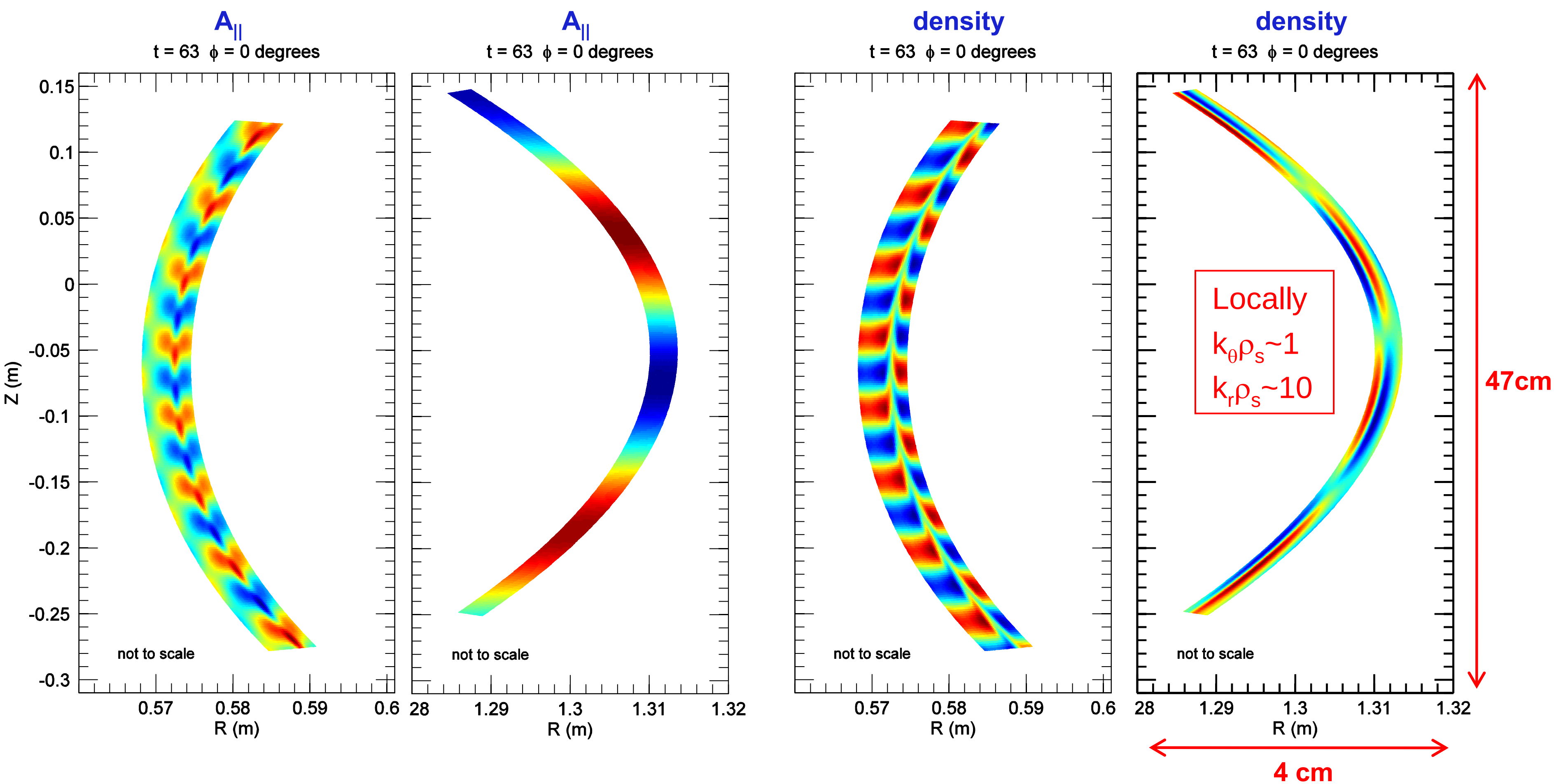
$\Rightarrow$ Influence of perpendicular drift dynamics



Linear mode structure in toroidal (R,Z) plane

- Nonuniform poloidal structure (comparing inboard and outboard perturbations)
- Density perturbations radially narrow, extended vertically on outboard side

$\Rightarrow$ "High-k" scattering diagnostic (see adjacent poster by Y. Ren) well suited for $k_r >> k_\theta$



First ***nonlinear*** microtearing mode simulations in NSTX

Summary of first nonlinear microtearing simulations in NSTX

- Local, flux-tube simulations (flat profiles) at r/a=0.6 (NSTX 120968) where only microtearing unstable (no ETG)
  - Electromagnetic (φ, $A_{||}$) and collisional (ν_e)
  - Varying E$\times$B shear

$L_x \times L_y = 80 \times 60 \rho_s$
$n_x \times n_y = 400 \times 8$ ($\Delta x = 0.2\ \rho_s$)
$n_\theta = 14$ (parallel orbits)
$n_\lambda = 12$, $n_E = 8$ (velocity space)

- Significant transport predicted, depending on γ_E/γ_{lin}
  - Fine radial resolution required ($\Delta x \leq 0.2 \rho_s$)
  - Transport dominated by electromagnetic component
  - Field lines are stochastic
  - Transport reduced with significant E$\times$B shear

Fine radial resolution required to capture *linear* resonant layers

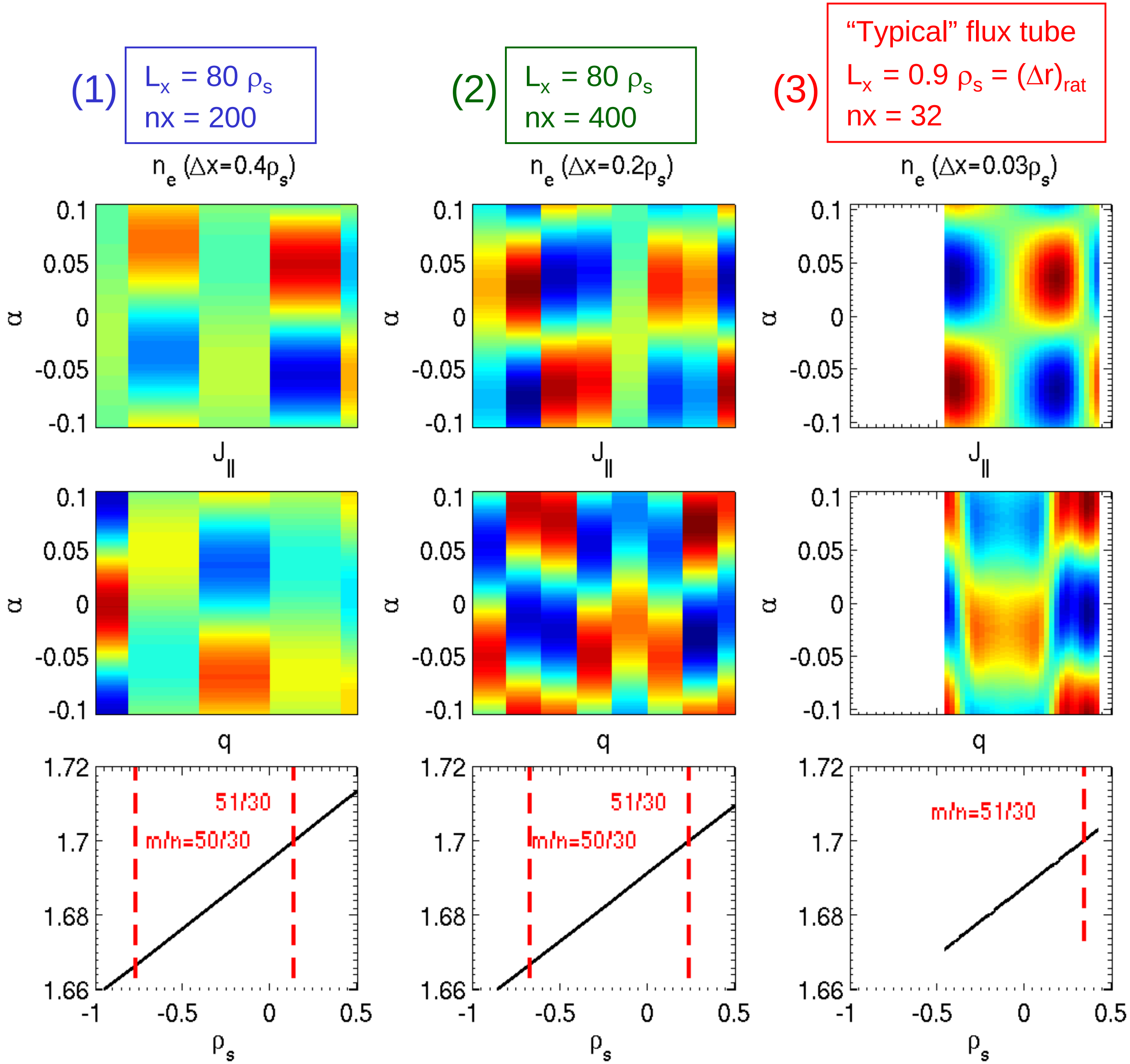
Calculating linear growth rate for single mode ($k_\theta \rho_s$=0.63, n=30) using box width and resolution of nonlinear simulations

L_x=80 ρ_s, Δx=0.4 & 0.2 ρ_s

(1) Δx=0.4 ρ_s is barely small enough to distinguish resonant layers

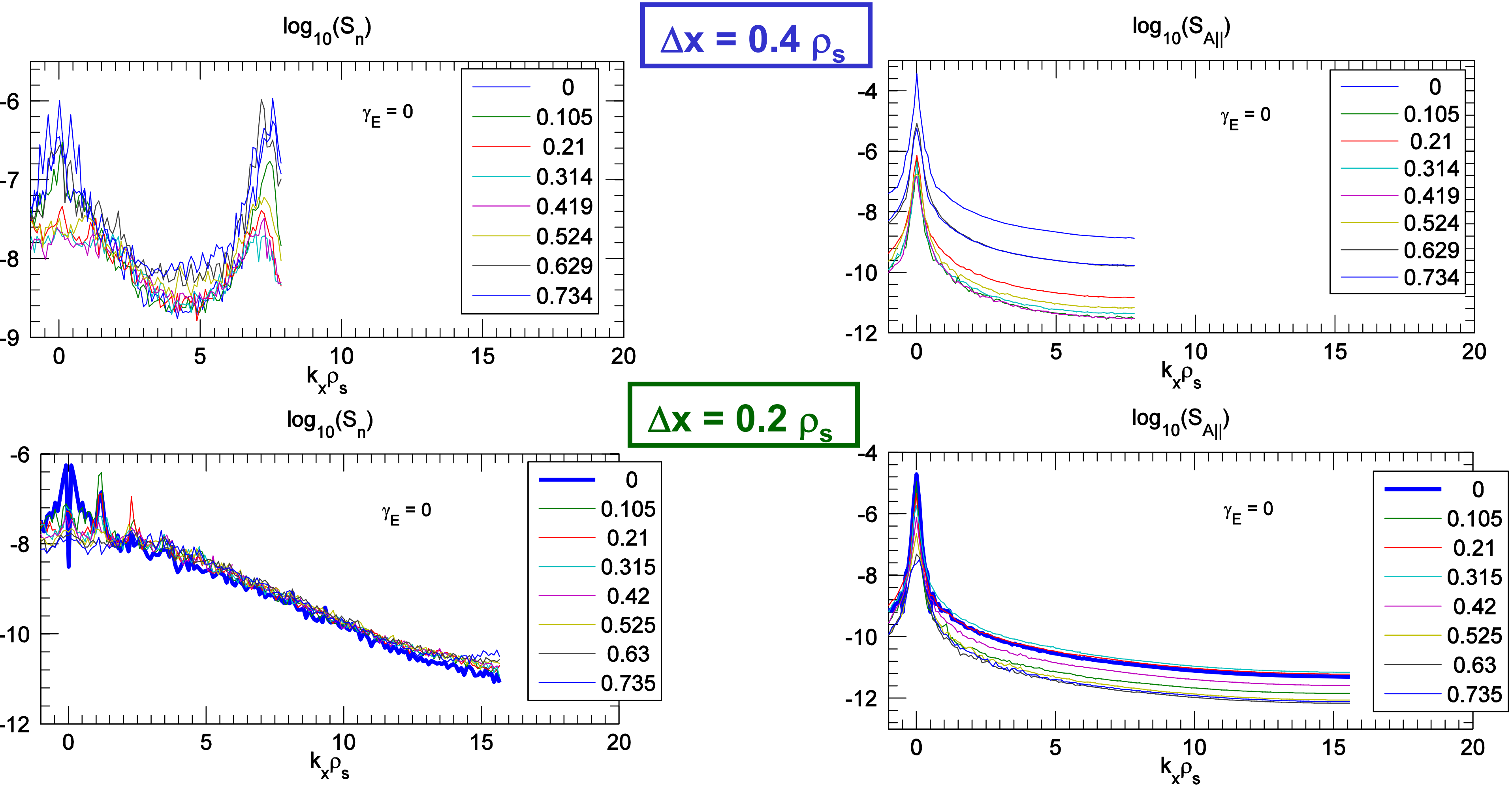
(2) Δx=0.2 ρ_s resembles the...

(3) high resolution flux-tube case



Fine radial resolution required for resolved *nonlinear* spectra

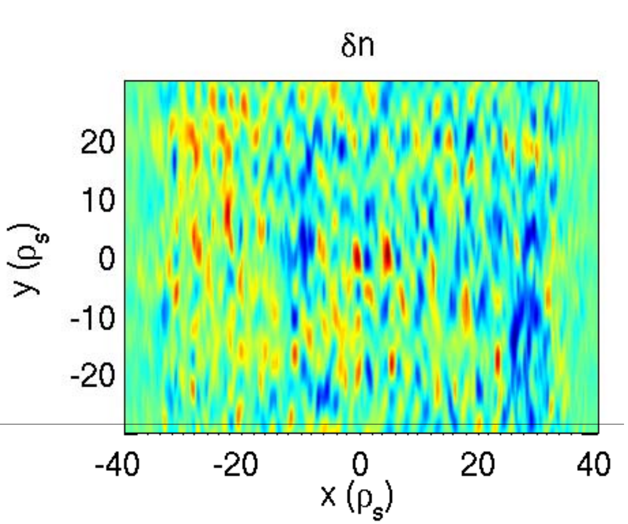
- k_x spectra completely different for Δx=0.4→0.2ρ_s
- Insufficient resolution leads to peaking at high k_x similar to GS2 simulations in Applegate Ph.D. thesis (2007, Imperial College London)



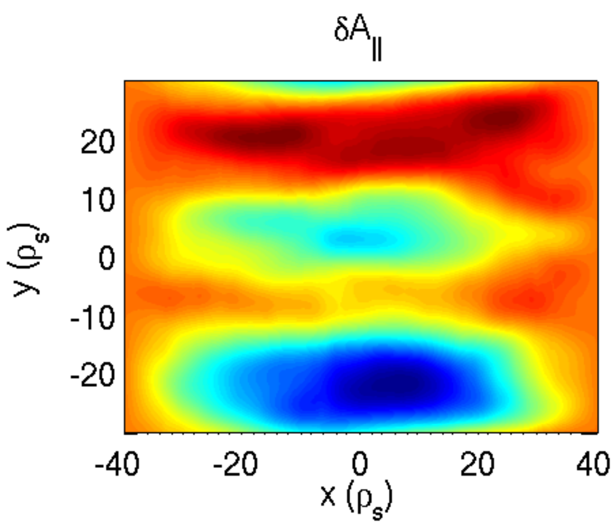
Narrow density perturbations remain in nonlinear simulations

- Narrow radial n, φ, $j_{||}$ structures need to be resolved but $A_{||}$ very broad
- $\delta B_r/B \sim 8.7\times10^{-4} \sim \rho_e/L_{Te} = 3.4\times10^{-4}$
- $\delta B_r/B \sim \rho_e/L_{Te}$ analytic approximation from Drake et al. PRL 1980; used for NSTX in Wong et al. PRL 2007

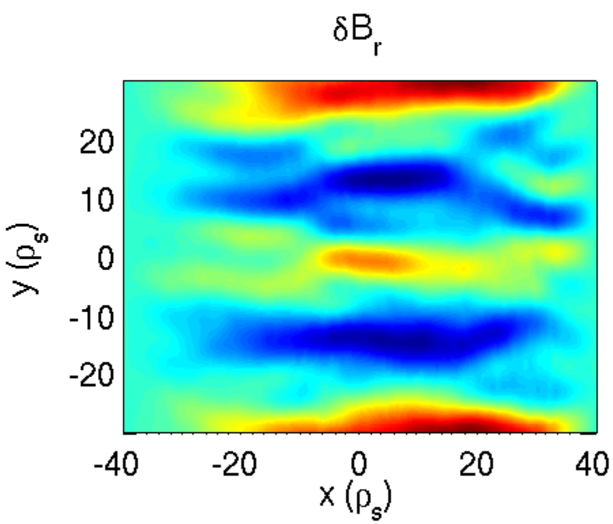
$\delta n/n \approx 0.5\%$



$\delta A_{||}/c_s T_e \approx 0.8\%$



$\delta B_r/B \approx 0.09\%$



$\delta T_e/T_e \approx 2\%$

$\delta v_{e,||}/c_s \approx 6\%$

Perturbed field lines are stochastic

- $w_{island}(n) > \Delta r_{rat}(n)$, island overlap → perturbed field line trajectories are stochastic

⇒ ~97% of transport from EM contribution $\chi_{e,EM}$

- $\chi_{e,EM}$ well described by *collisionless* Rechester-Rosenbluth (λ_{mfp}=25 m, qR=1.6 m)

  → see invited talk by Eric Wang, NI2:03 Wed. 10:30 am

$$w_{island} = 4\sqrt{\frac{\delta B_{r,n}}{B}\frac{rR}{n\hat{s}}} \qquad (\Delta r)_{rat} = \frac{1}{nq'} = \frac{1}{k_\theta \hat{s}}$$

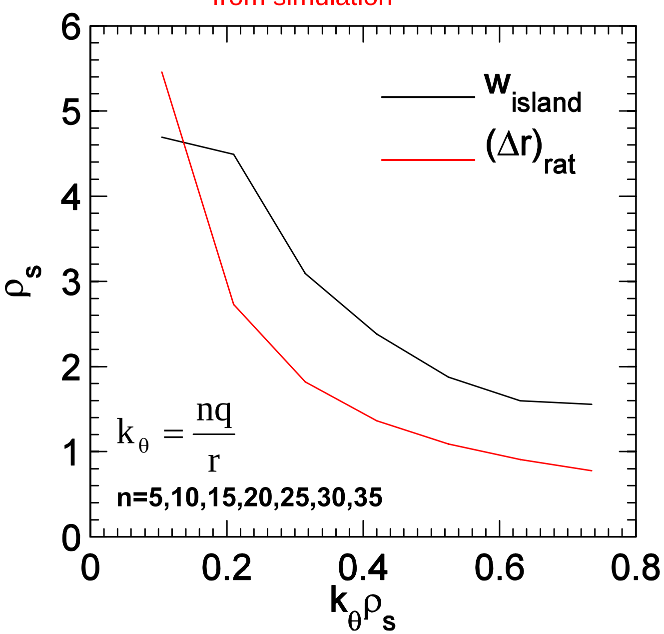
from simulation

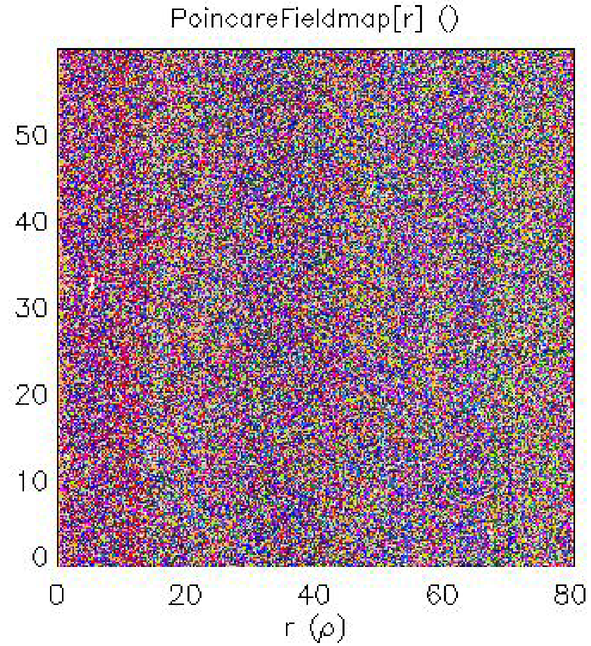
integrating dl/B
3000 transits for each
of 100 field lines

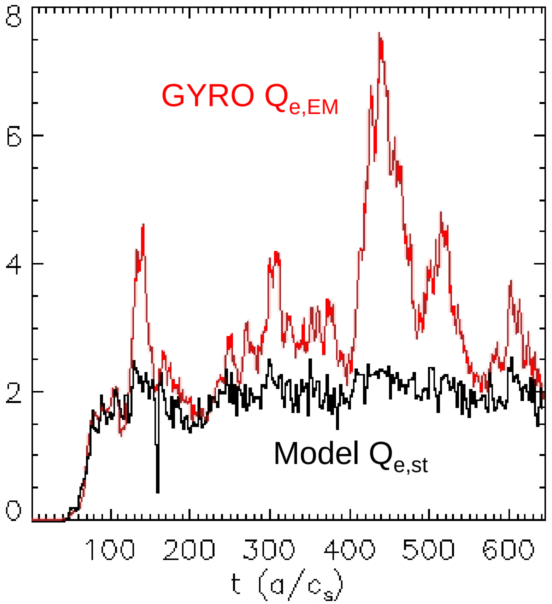
f_p≈50% passing particles

$$\chi_{st} \approx 2\left(\frac{2}{\pi}\right)^{1/2} D_{st} v_{te} f_p$$

$$D_{st} = \lim_{s\to\infty} \frac{\langle [r_i(s) - r_i(0)]^2 \rangle}{2s}$$

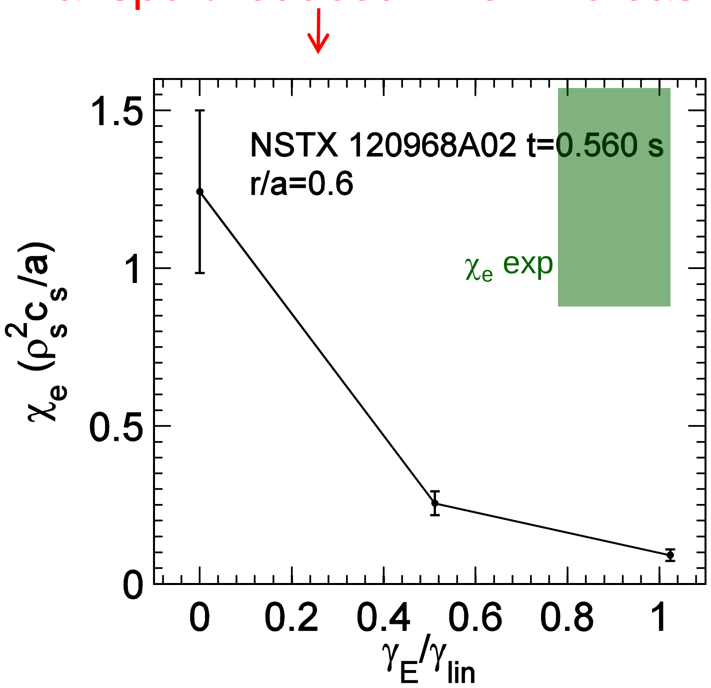


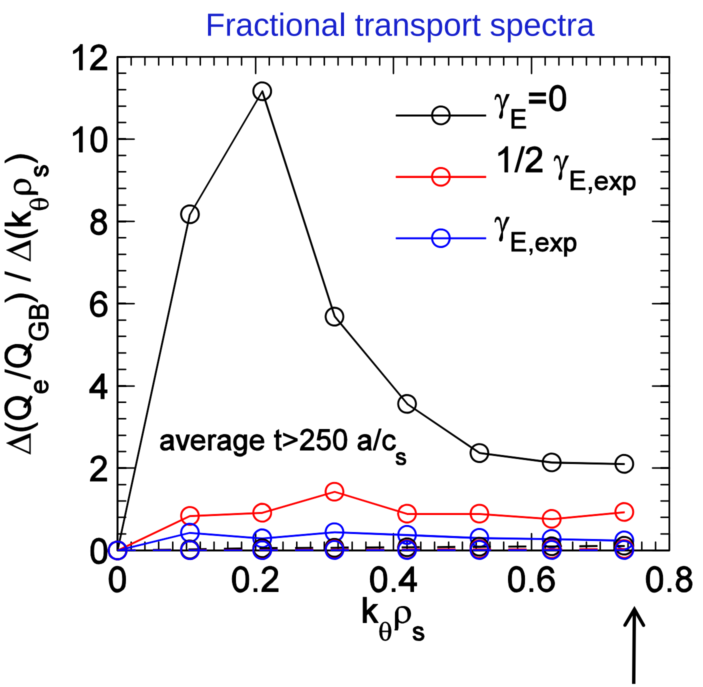




Nonlinear microtearing transport sensitive to γ_E/γ_{lin}

- With no E×B shear predicted transport (1.2 $\rho_s^2 c_s/a$) comparable to experimental transport (1.0-1.6 $\rho_s^2 c_s/a$)
- Transport reduced when increasing γ_E to local experimental value





- Simulations are underway to investigate (1) convergence with binormal resolution ($k_\theta\rho_{s,max}$) and (2) sensitivity to a/L_{Te}, β_e, ν_e
- Above are local simulations, but ρ_s/a=0.08 & physical domain r/a=0.3-0.9 → have not investigated influence of profile variations, e.g. $a/L_{Te}(r)$, $\gamma_E(r)$, q(r)

Unclear how χ_e will scale with ν_e

- Linear growth rate scaling $\gamma_{lin} \sim \nu_e$ may (or may not) influence saturated $\delta B_r/B$ and resulting D_{st}
- Similar trend may (or may not) hold from linear β_e scaling

$\Rightarrow$ Nonlinear simulations in progress

- *Collisional* R-R model used by Wong et al.* for NSTX 116313 :

$$\chi_{st}^{Wong} = D_{st}\frac{\chi_{e,\parallel}}{L_c} = \left(\left|\frac{\delta B_r}{B}\right|^2 R\right)\frac{v_{Te}\lambda_{mfp}}{qR} = \underline{\left(\frac{\rho_e}{L_{Te}}\right)^2 \frac{v_{Te}^2}{\nu_{ei} q}}$$

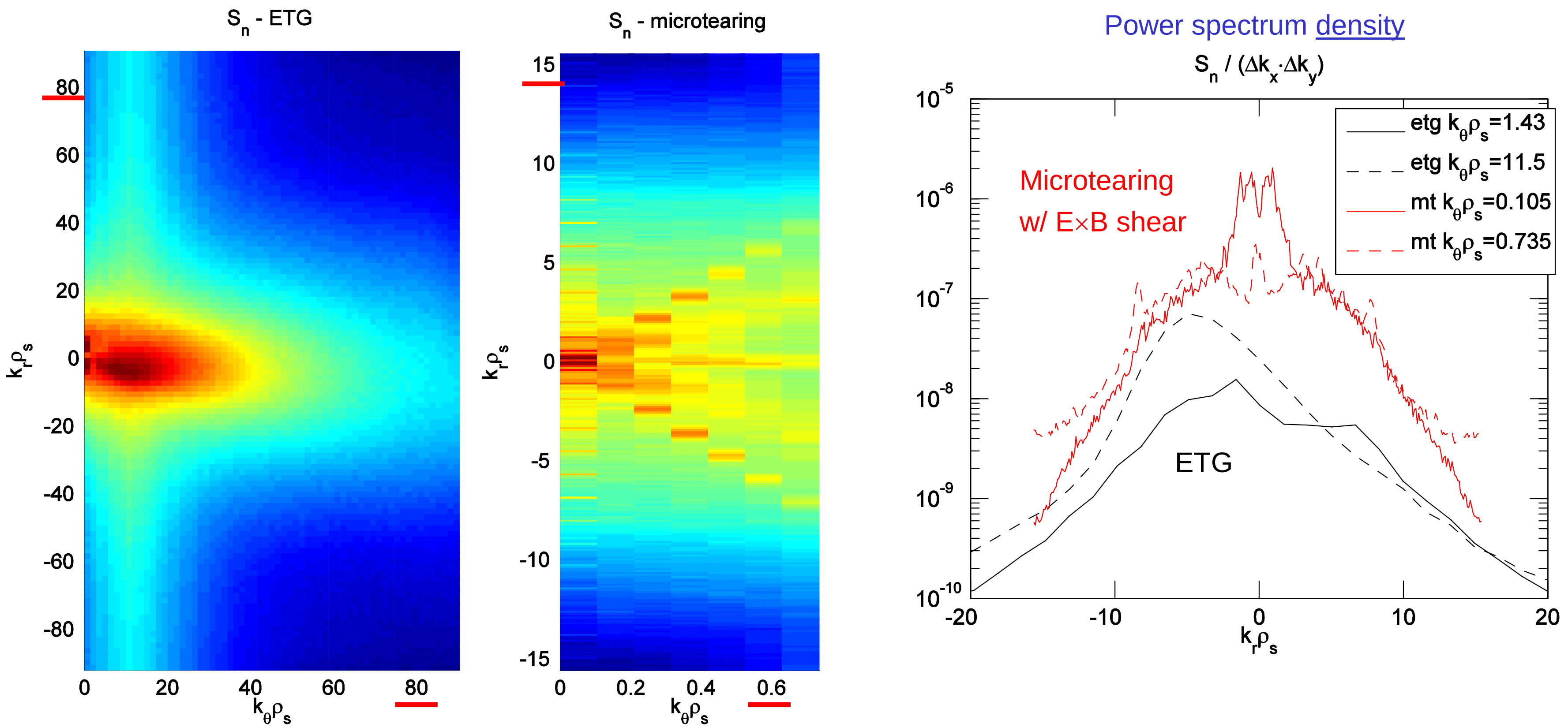
  - *inversely* dependent on ν_e
  - no explicit dependence on β_e
  - very sensitive to T_e and ∇T_e
  - "knows" nothing about linear thresholds

$$\chi_{st}^{Wong} \propto T_e^{3/2} \cdot (\nabla T_e)^2 = T_e^{7/2} \cdot \left(\frac{1}{L_{Te}}\right)^2$$

*K.L. Wong et al., Phys. Rev. Lett **99**, 135003 (2007); Phys. Plasmas **15**, 056108 (2008)

May expect significant intensity in high-k scattering from microtearing

- Comparable δn/n predicted for ETG (2.8×10^{-3}) and microtearing (1.7×10^{-3})
- But ETG spectrum much broader in $k_\theta\rho_s$ → less intensity per unit $\Delta k_x \cdot \Delta k_y$
- Application of synthetic "high-k" diagnostic to simulations beginning (see adjacent posters by F.M. Poli & Y. Ren)



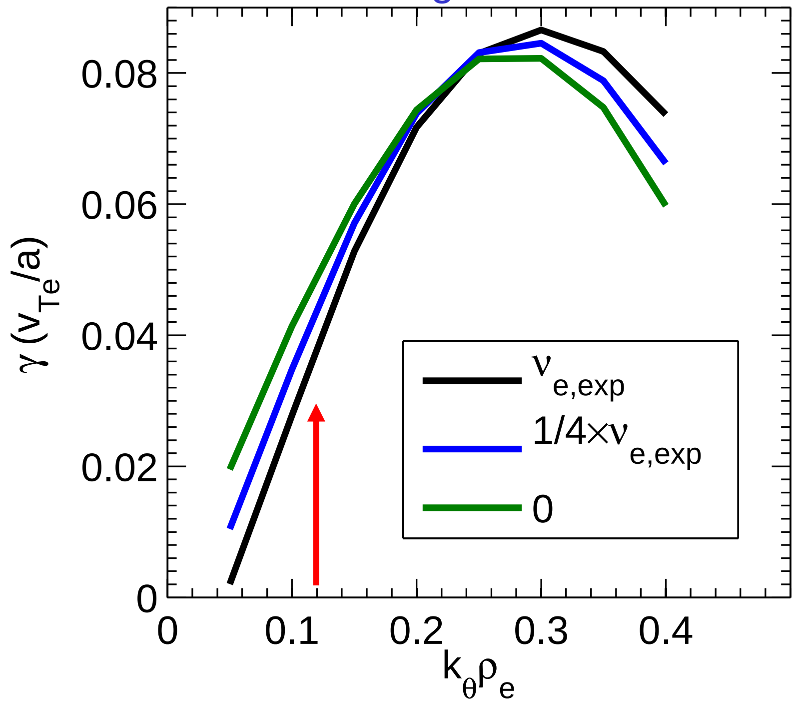
Nonlinear ETG simulations in MAST – ν_* scaling

Decreasing collisionality destabilizes lower $k_\theta\rho_e$ ETG modes where transport dominates

- Little change in peak growth rates when scaling only ν_e
- Lower $k_\theta\rho_e$ are destabilized (trapped electron contributions)
- Small increase in non-linear transport (~15% at ν_{ei}=0) → **inconsistent with experimental scaling**

MAST 22769 (hi ν)

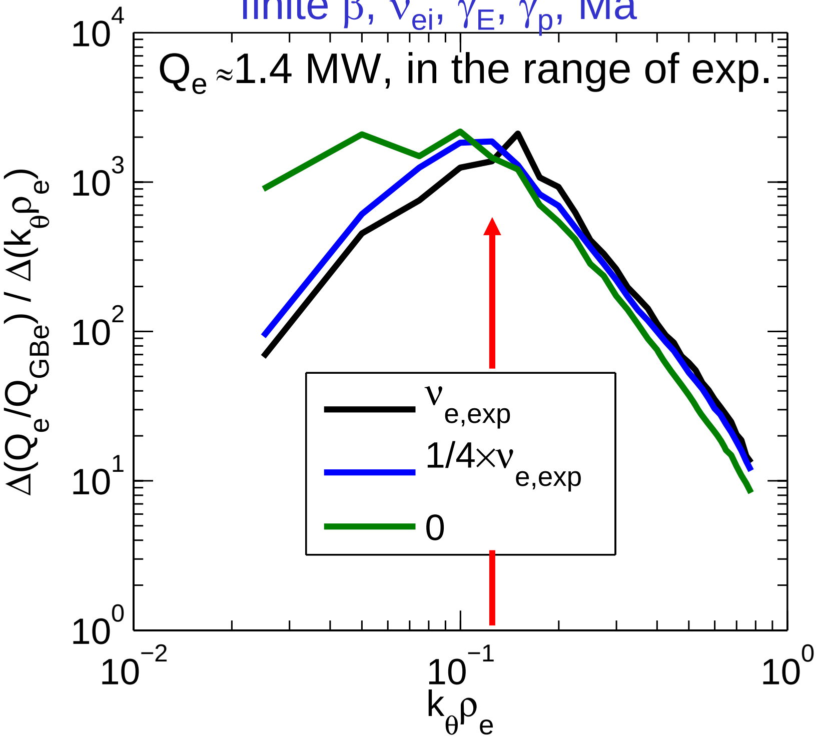
Linear growth rates



Non-linear transport spectra

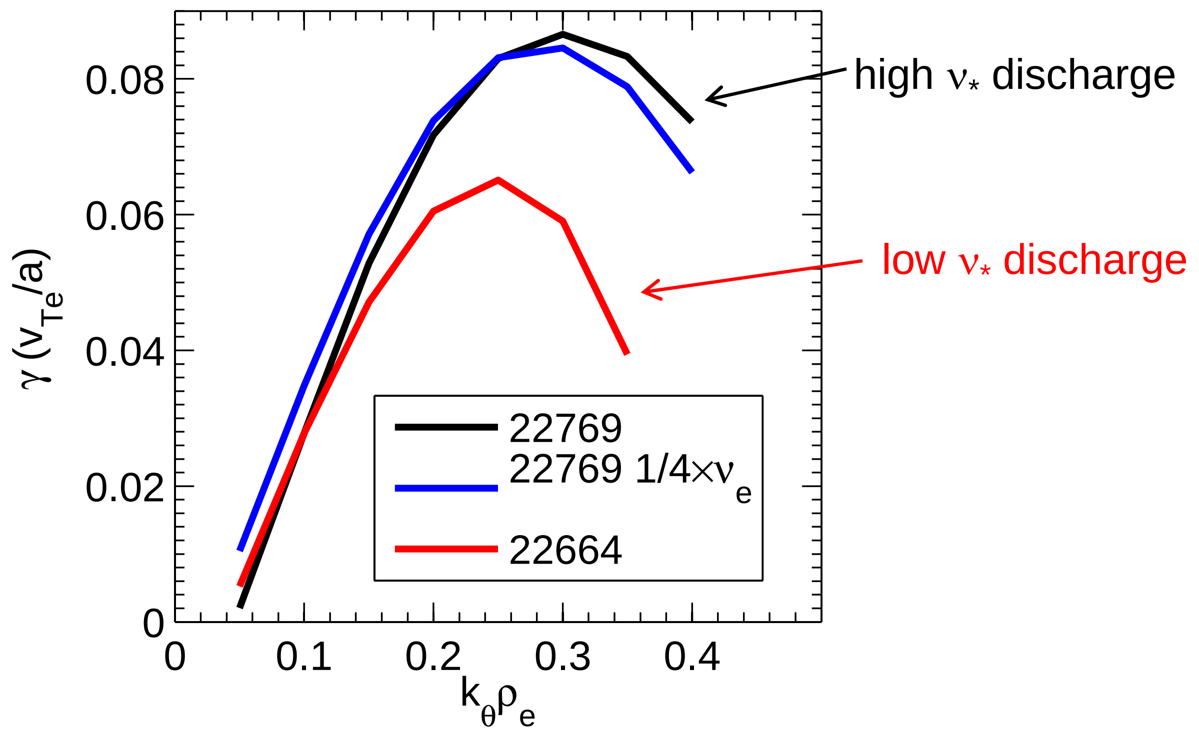
ETG-ki, m_i/m_e=3600

finite β, ν_{ei}, γ_E, γ_p, Ma



Peak growth rates reduced when directly comparing low ν_* discharge

- Small changes in other dimensionless parameters add up



- Pursuing integrated transport predictions (e.g. with TGLF+NEO) including all experimental variations (see adjacent poster by J.L. Peterson)