*EFFECTS OF MICROTEARING MODES ON THE EVOLUTION OF ELECTRON TEMPERATURE PROFILES IN HIGH COLLISIONALITY NSTX DISCHARGES**

T. RAFIQ[1], S. KAYE[2], W. GUTTENFELDER[2], J. WEILAND[3], and J. ANDERSON[3]

[1]Lehigh University, Bethlehem, PA, USA

[2]Princeton Plasma Physics Laboratory, Princeton, NJ, USA

[3]Chalmers University of Technology, Gothenburg, Sweden

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Motivation

- **Microtearing modes (MTMs) can provide a significant contribution to the electron thermal transport in low-aspect ratio tokamaks**
  - **In plasmas where β_e and collisionality are sufficiently high, MTMs can become the dominant instability** [W. Guttenfelder *et al.*, PRL. 106, 155004 (2011)]
  - **MTMs may be unstable even when collisionality is negligible with the role of collisionality taken by particle inertia** [I. Predebon *et al.*, PoP 20(4), 040701 (2013)]
  - **In a GS2 gyrokinetic stability analysis, MTMs are found to be the most unstable modes in the core region** [K. Wong *et al.*, PRL 99, 135003 (2007)]
    - **Due to the somewhat low B, low electron temperature and high density**
- **Apart from the plasma core region, MTMs may be relevant in the plasma edge region regulating heat transport and, possibly, pedestal evolution** [D. Dickinson *et al.*, PRL 108, 135002 (2012)]
- **Non-linear GYRO calculations have shown that MTMs in high β H-mode NSTX plasmas can drive electron thermal transport at levels that match those inferred from experiment** [W. Guttenfelder *et al.*, PoP 19(5), 056119 (2012)]
- **Important to develop a reduced transport model for MTMs in order to understand how MTMs affect electron thermal transport and consequently the evolution of temperatures in tokamak plasmas**

Microtearing Modes (MTMs)

- **MTMs are short-wavelength $\left(k_y L_n \gg 1\right)$ ion scale (low k) electromagnetic instabilities driven by electron temperature gradients**
  - **Propagate in the electron diamagnetic drift frequency (ω_{*e}) direction, and have electron collisionality, $\nu_e/\omega \sim O(1)$**
  - **Frequency is generally greater than ω_{*e} and the mode structure is extended along the magnetic field lines**
  - **Nonlinear MTMs produce magnetic islands which saturate by transferring energy to stable long wavelength modes**
- **MTMs drive electron thermal transport through $\delta A_{\parallel}$ (magnetic potential fluctuations, with even parity), while other transport channels and contributions from $\delta B_{\parallel}$ (compressional magnetic perturbations) may be significantly smaller**
  - **Ion thermal and particle transport resulting from MTMs are negligible**
- **A unified fluid/kinetic approach is used in the development of a model for the transport driven by MTMs**
  - **Derivation includes the effects of $\delta\phi$ and $\delta A_{\parallel}$ fluctuations, collisionality, electron temperature and density gradients, $k_{\parallel}$ and magnetic curvature**

Outline

- Derivation of the microtearing mode model starts with the use of the gyrokinetic equation with collisions included
  - Finite Larmor radius effects for electrons are ignored
- Parallel current is calculated using nonlinear fluid equations of electron momentum, electron density, Maxwell equations, Ampere's law and quasi-neutrality condition
- Iterative nonlinear approach is used to calculate δf, which is used to calculate nonlinear parallel current and nonlinear dispersion relation
  - Collision dominant case of nonlinear microtearing dispersion relation is compared with the corresponding case of Drake *et al.*, PRL 44, 994 (1980)
- Dependence of the microtearing mode real frequency, growth rate, magnetic fluctuation strength as well as electron thermal diffusivity on plasma parameters and on NSTX like plasma profiles is examined
  - Magnetic fluctuation strength as well as electron thermal diffusivity due to microtearing modes is computed utilizing numerically determined microtearing mode eigenvalues

Calculation of MTM Magnetic Fluctuation and Thermal Diffusivity

- The MTM derivation yields the nonlinear dispersion relation which is solved for the fastest growing mode

- $\omega + \frac{k_\perp^2 c^2}{\omega_{pe}^2}(\omega - \omega_{De} + i\nu_{th}) =$

$$\omega_{*e}(1+\eta_e) - \frac{3}{8}\Gamma\left(\frac{9}{2}\right)\frac{\eta_e\omega_{*e}(\omega-\omega_{De})}{\omega - \omega_{De} + i\nu_{th}} - \frac{\omega_{*e} - \omega_{De}}{\omega-\omega_{De}+i\nu_{th}}\frac{k_\parallel^2 u_A^2}{\omega} -$$

$$\frac{5}{12}\Gamma\left(\frac{11}{2}\right)\eta_e\frac{u_{th}^2}{\nu_{th}}\sum_{k'}\frac{\omega_{*e}-\omega'_{*e}}{(\omega_k - \omega_{Dek} + \omega_{k'} - \omega_{Dek'})}\frac{\frac{1}{2}\left|\frac{\delta\mathbf{B}_{k'}}{B}\cdot\mathbf{k}\, u_{th}\right|^2}{(\omega_{k'} - \omega_{Dek'} + \omega_{k-k'} - \omega_{Dek-k'} + i\nu_{th})}$$

- The strength of the magnetic field fluctuations is obtained:

- $\frac{\partial\hat{A}}{\partial t} =$

$$\frac{3}{8}\Gamma\left(\frac{9}{2}\right)\frac{\eta_e\omega_{*e}(\omega-\omega_{De})}{\nu_{th}}\hat{A} - \frac{5}{12}\Gamma\left(\frac{11}{2}\right)\eta_e\frac{u_{th}^2}{\nu_{th}}\sum\left|\frac{\delta\mathbf{B}_{k'}}{B}\cdot\mathbf{k}\right|^2\frac{\omega_{*e}-\omega'_{*e}}{(\omega_k - \omega_{Dek} + \omega_{k'} - \omega_{Dek'})}\hat{A}$$

- $|\delta B|^2/B^2$ can be computed using the most unstable eigenvalue and as well as on its sidebands in the k_y spectrum

- Electron thermal diffusivity is then given by $\chi_e = \frac{u_{th}^2}{\nu_{ei}}\frac{|\delta B|^2}{B^2}$

Plasma Parameters of NSTX Discharge 120968

R (m)	0.94
a (m)	0.62
r_{min} (m)	0.372
B_T (T)	0.35
β_e	0.09
q	1.7
s	1.7
$T_{i,e}$ (keV)	0.45

$k_y \rho_s$	0.67
k_y/k_x	0.2
ν_{ei} (s^{-1})	3.44×10^5
C_s (m/s)	1.47×10^5
$n_e(m^{-3})$	6.0×10^{19}
R/L_{Te}	4.1
R/L_{ne}	0

- **NSTX Discharge 120968:**
- **This shot is a part of ν_* and β dimensionless confinement scaling studies**

S.M. Kaye et al. Nucl. Fusion 47, 499 (2007)

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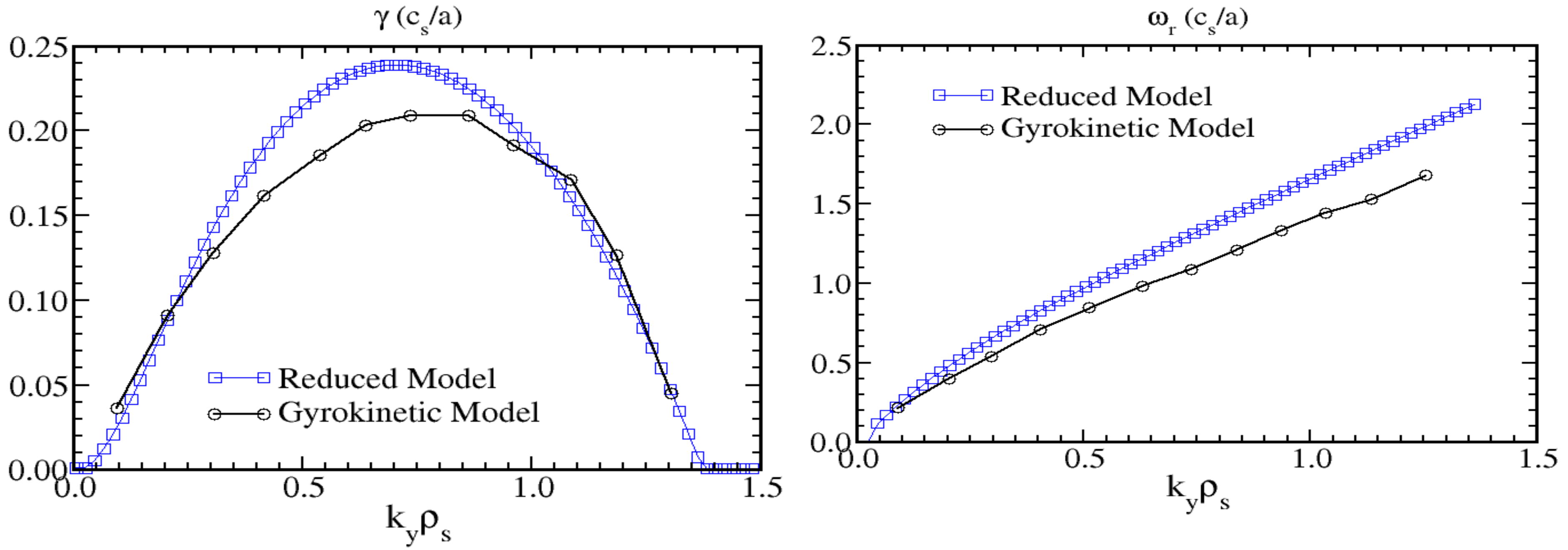
$k_y\rho_s$ Comparison Between Reduced Model and Gyrokinetic MTM Linear Growthrate and Frequency



- **MTM linear growthrate and real frequency as a function of $k_y\rho_s$ is compared with gyrokinetic code GYRO MTM linear growthrate and real frequency**

W. Guttenfelder et al Phys Plasmas 19, 022506 (2012)

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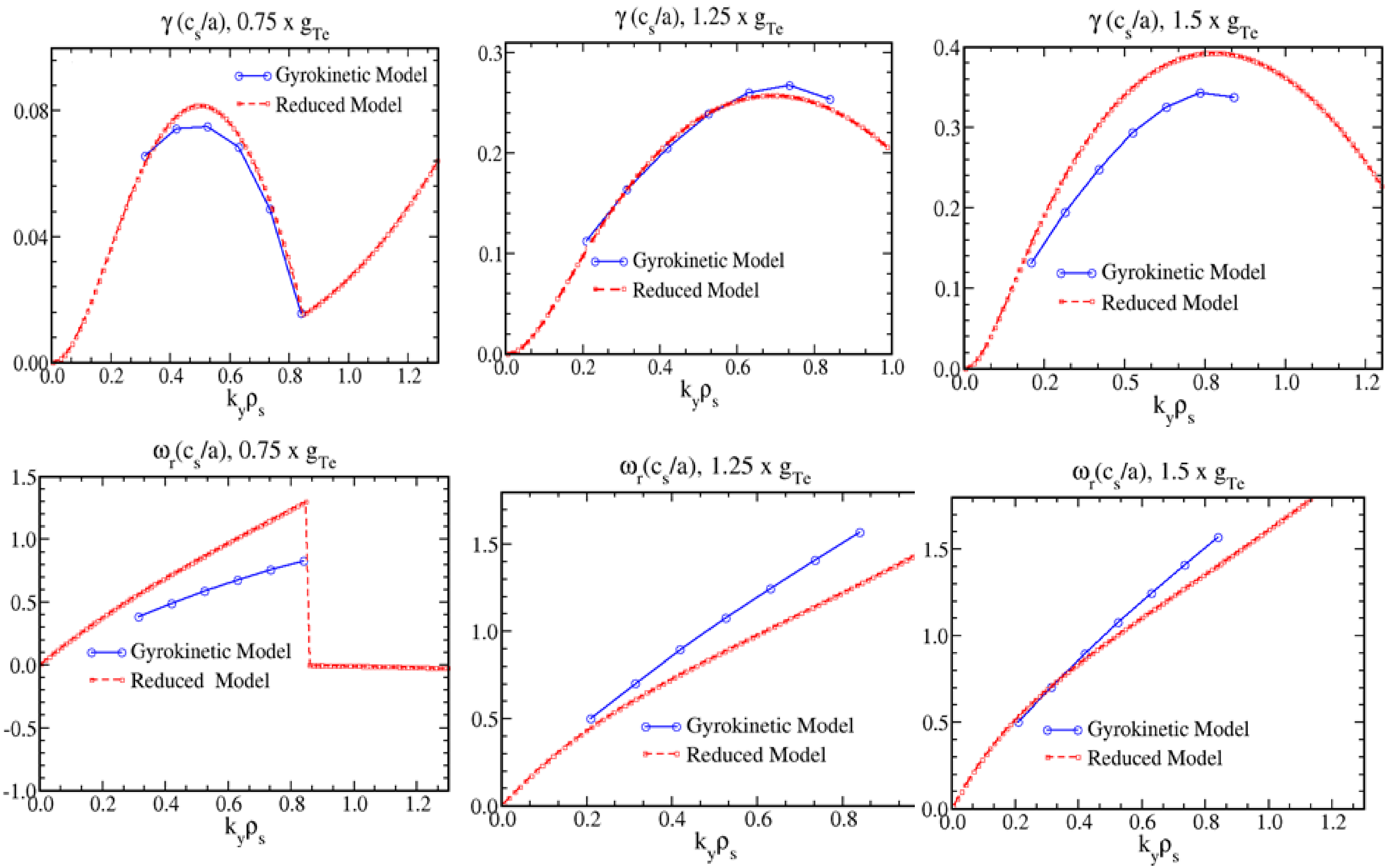
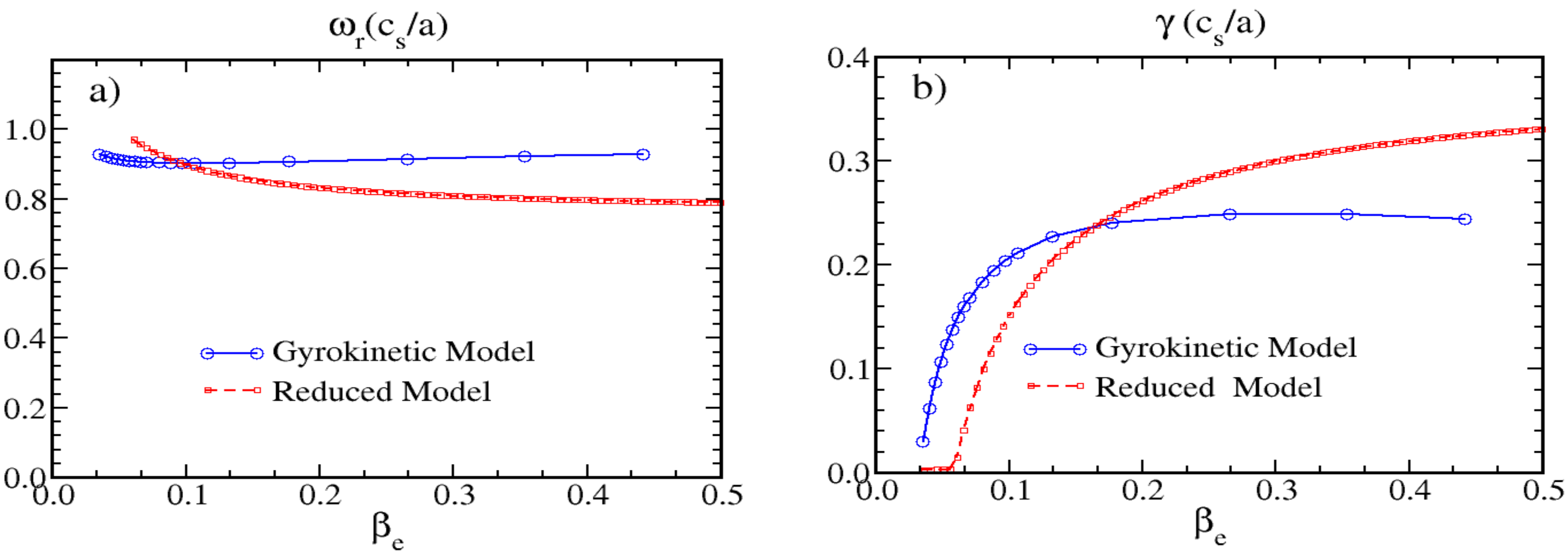
$k_y\rho_s$ Comparison Between Reduced Model and Gyrokinetic MTM Linear Growthrate and Frequency



β_e Comparison Between Reduced Model and Gyrokinetic MTM Linear Growthrate and Frequency



- The MTM instability threshold in electron beta is found to be $\beta_e \approx 5.0\%$
  - —Local experimental value of β_e is 9.0%
- For low values of β_e, γ increases with increasing values of β_e
- Real frequency is found to be almost independent of β_e in both the reduced and gyrokinetic model
- Moderate destabilization with β_e in experimental range is qualitatively consistent with the weak confinement scaling $\Omega\,\tau_E = \beta^{-0.1}$ observed in NSTX

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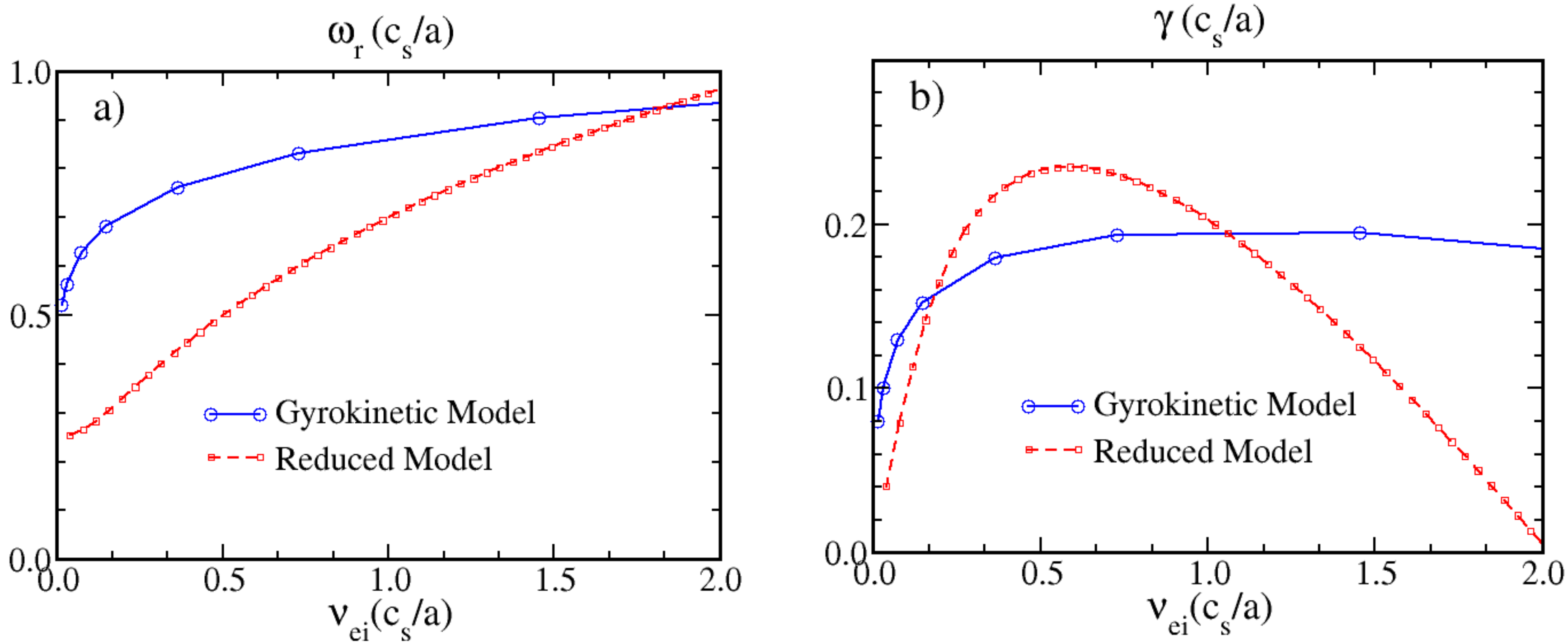
ν_{ei} Comparison Between Reduced Model and Gyrokinetic MTM Linear Growthrate and Frequency



- **Real frequency of MTM is found to be increasing with ν_{ei}**
- **Maximum γ is found for moderate values of ν_{ei}**
- **Nonmonotonic dependence of γ on ν_{ei} is consistent with gyrokinetic simulations**
- **Growthrate decreases with decreasing ν_{ei} is consistent with the dependence on collisionality is observed in the NSTX discharges**

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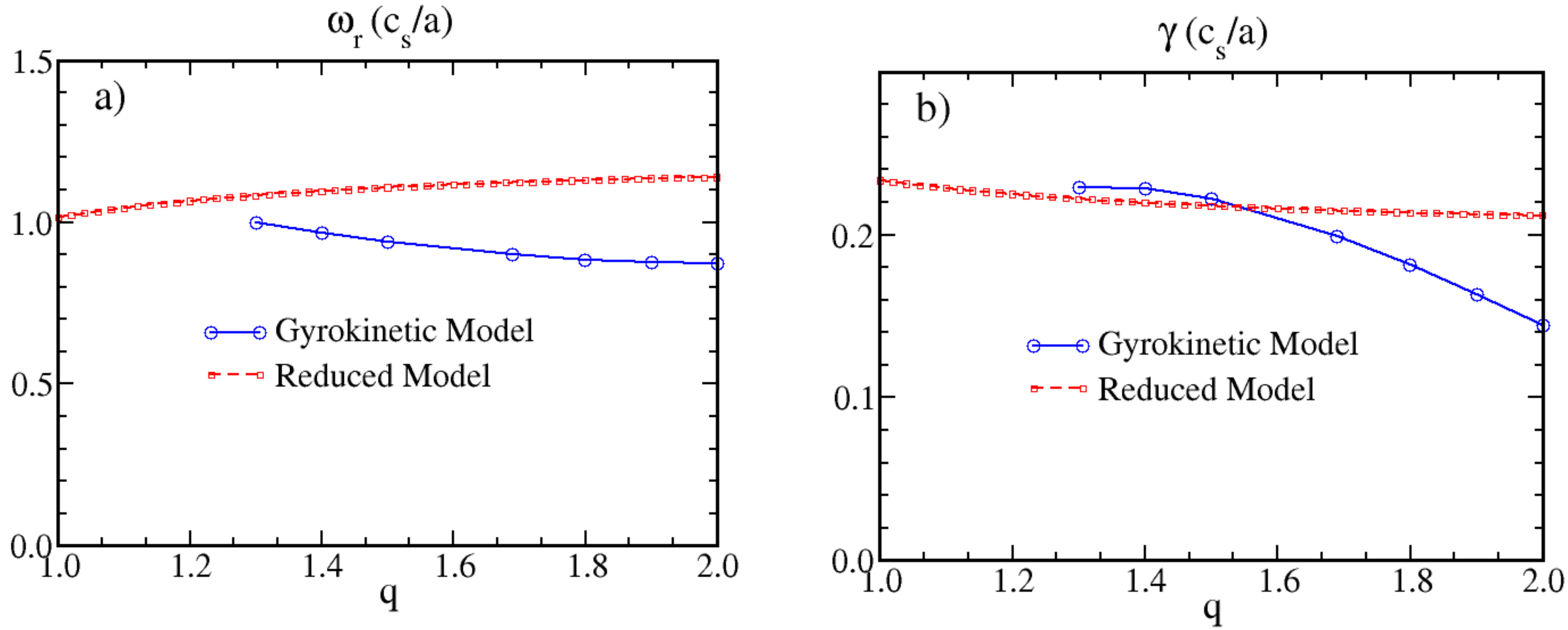
Magnetic-*q* Comparison Between Reduced Model and Gyrokinetic MTM Linear Growthrate and Frequency



- **Magnitude of real frequency and growthrate in reduced and gyrokinetic models are not very different, but the significant decreasing of growthrate for larger values of magnetic-*q* in the gyrokinetic model results is not captured by the reduced model**
  - **Simple estimation of $k_{\|}$, which does not depend on toroidal geometry, might be a reason of not capturing the decreasing trend of γ for large values of magnetic-*q***

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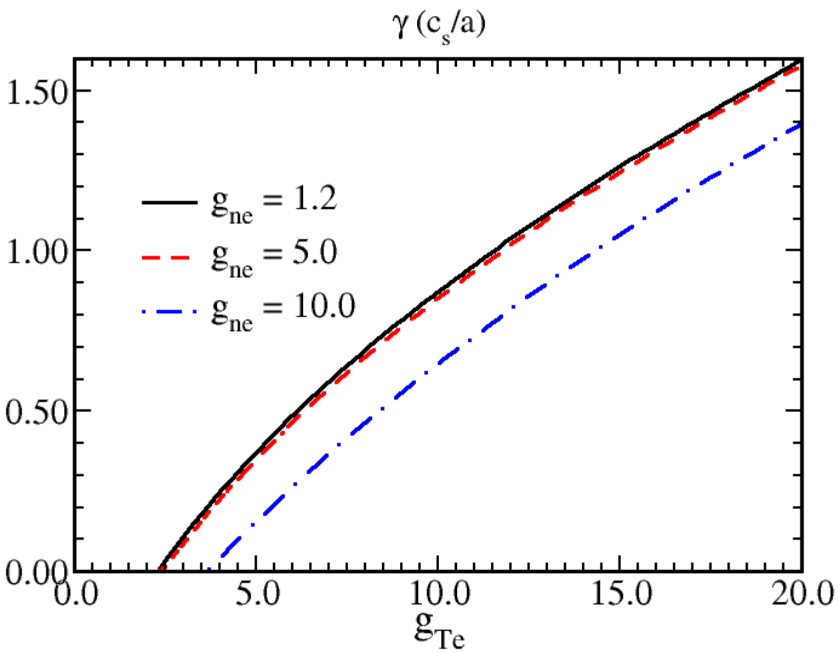
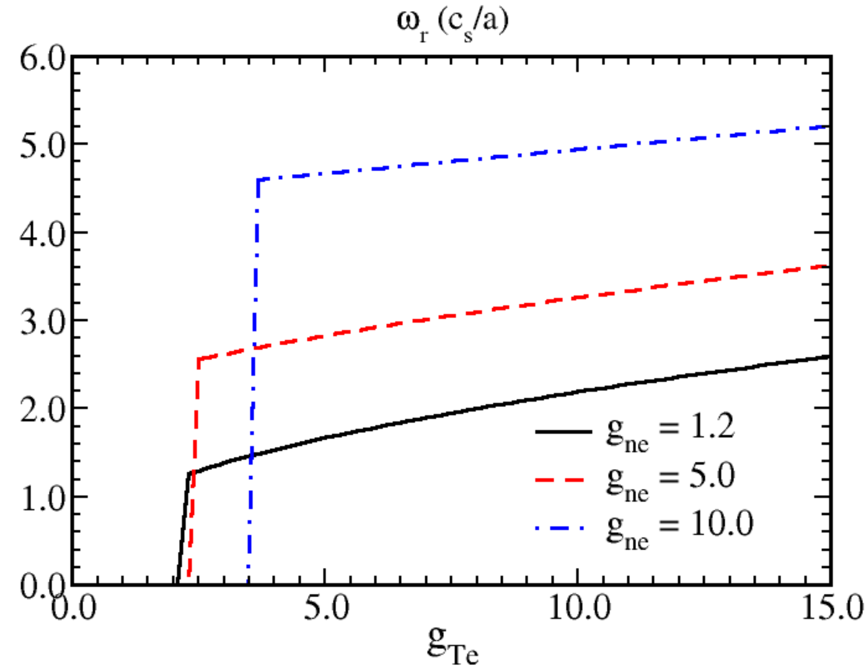
Temperature Gradient Dependence of MTM for Different Values of Density Gradients





- Destabilizing effect of increasing temperature gradient, g_{Te} is illustrated
  - MTM instability threshold in g_{Te} is found to be dependent on density gradient
    - Threshold is found to be increasing and growthrate is found to be decreasing with increasing density gradient, g_{ne}
- Experimental g_{Te} is larger than the inferred linear threshold in g_{Te}
- MTM growth rate increases rapidly above the g_{Te} threshold for small g_{ne}
- MTM real frequency increase with g_{Te} and with g_{ne}

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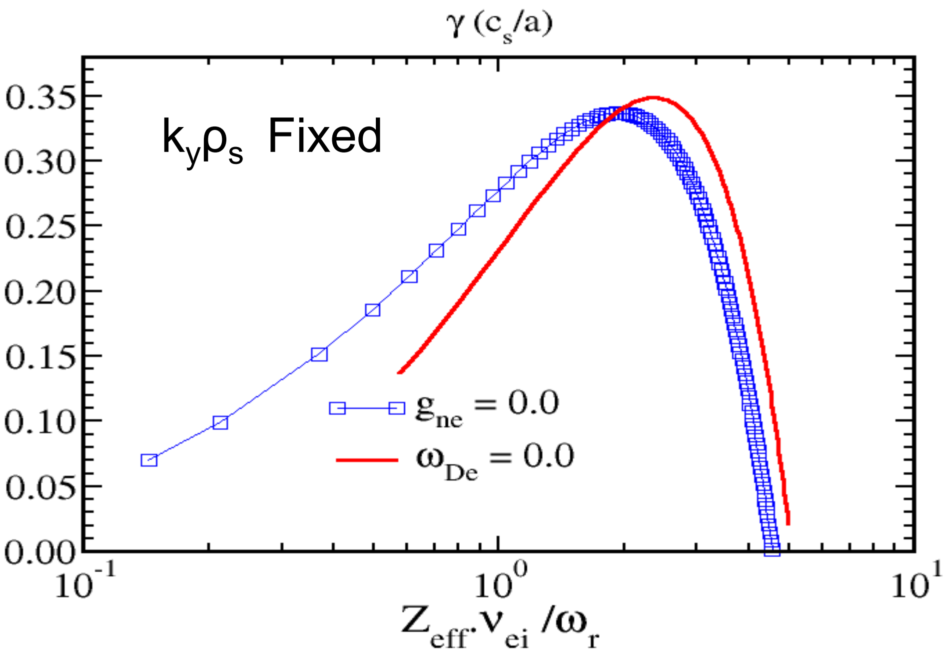
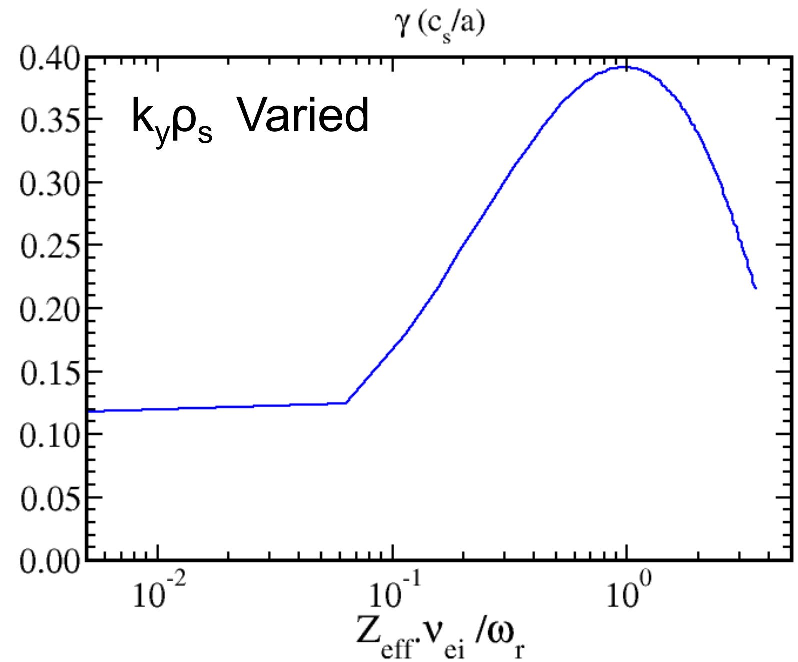
Collisionality Dependence of MTM





- **As ν_{ei} is reduced, MTM growth rate is reduced**
  - **This scaling trend is qualitatively consistent with the global energy confinement trend, $\Omega\tau_E = \nu_*^{-0.95}$ observed in NSTX analysis**
  - **This behavior is opposite to the drift waves instabilities where collisionality tends to provide a stabilizing influence to TEM which otherwise enhance the ITG and ETG instability in the collisionless limit**
- **Peak MTM growth rate occurs around $\frac{Z_{\mathrm{eff}}\,\nu_{ei}}{\omega} \approx 2$**

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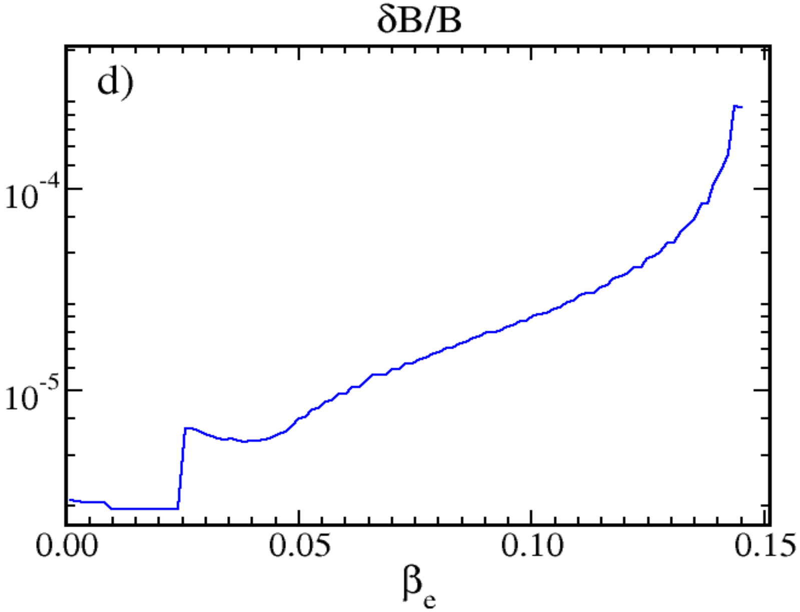
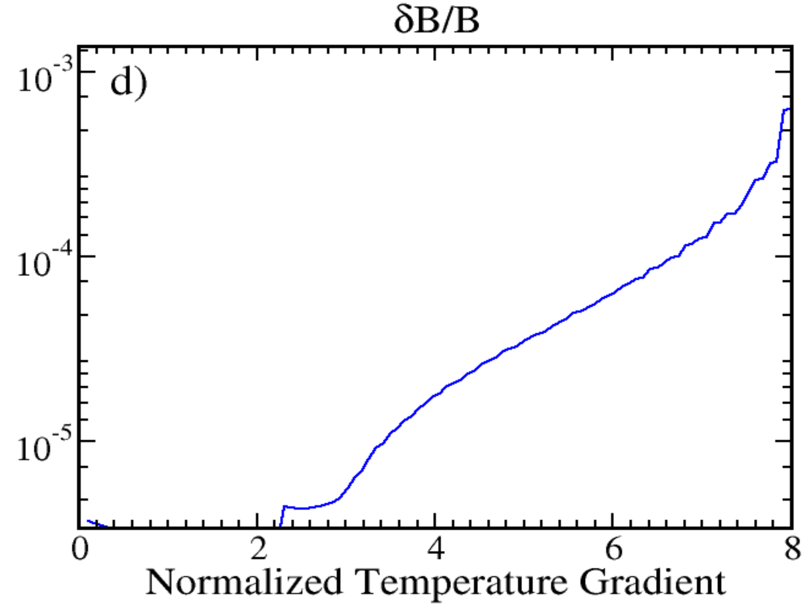
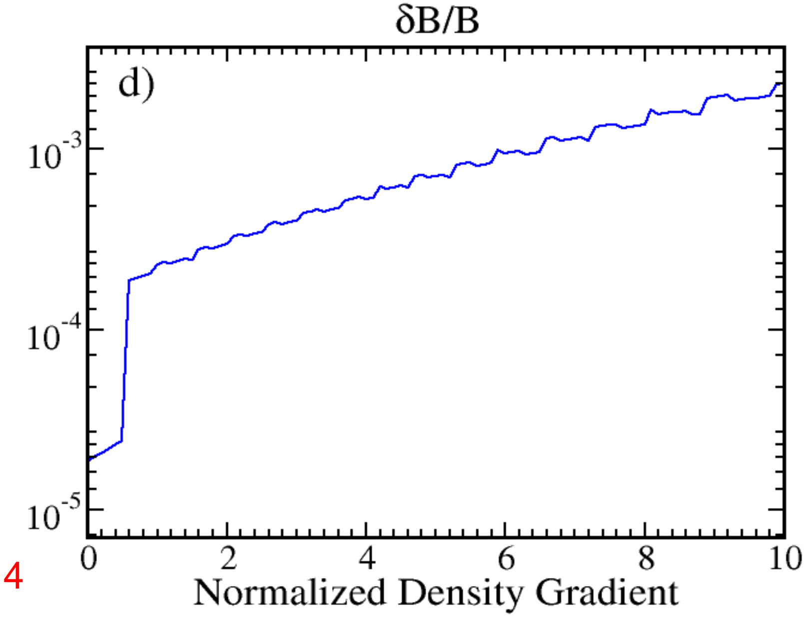
Magnetic Fluctuation Dependence on β_e, Temperature Gradient and Density Gradient







- **Saturated magnetic fluctuation, $\delta B/B$ clearly show dependence on β_e, temperature and density gradients**
  - **Use of mixing length estimate $\frac{\delta B}{B} \approx \rho_e/L_{\mathrm{Te}}$ in previous MTM related publications is incapable of capturing such dependencies**

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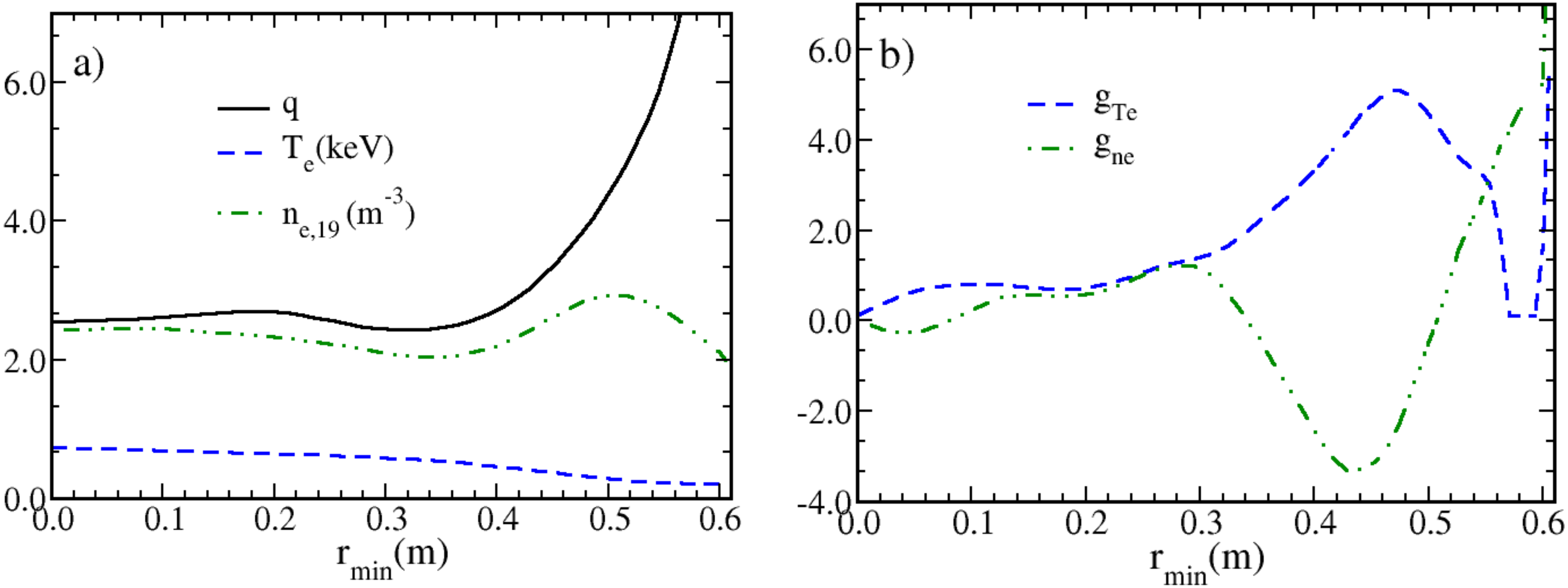
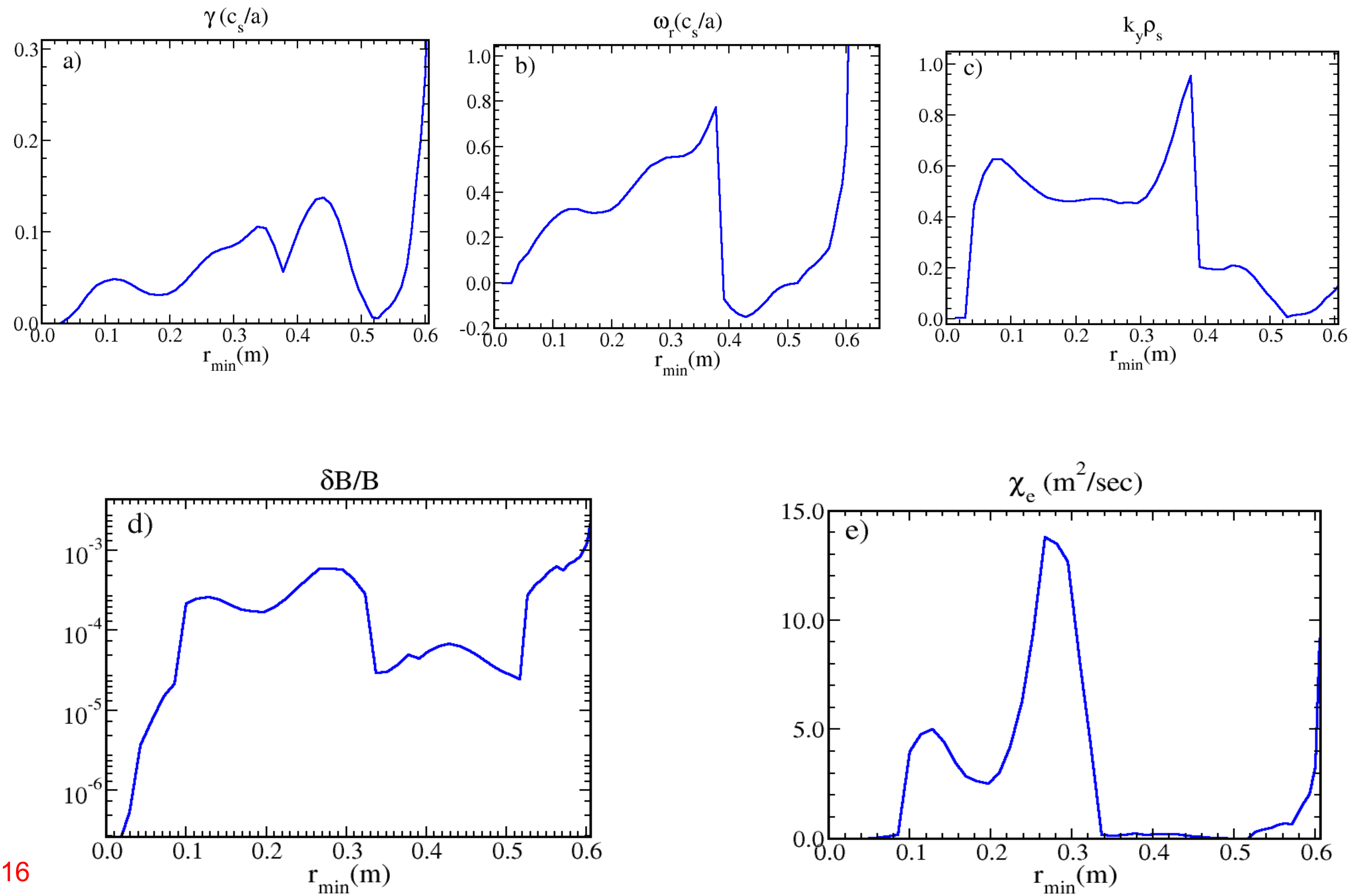
Magnetic q, Electron Temperature, Density and Gradient Profiles

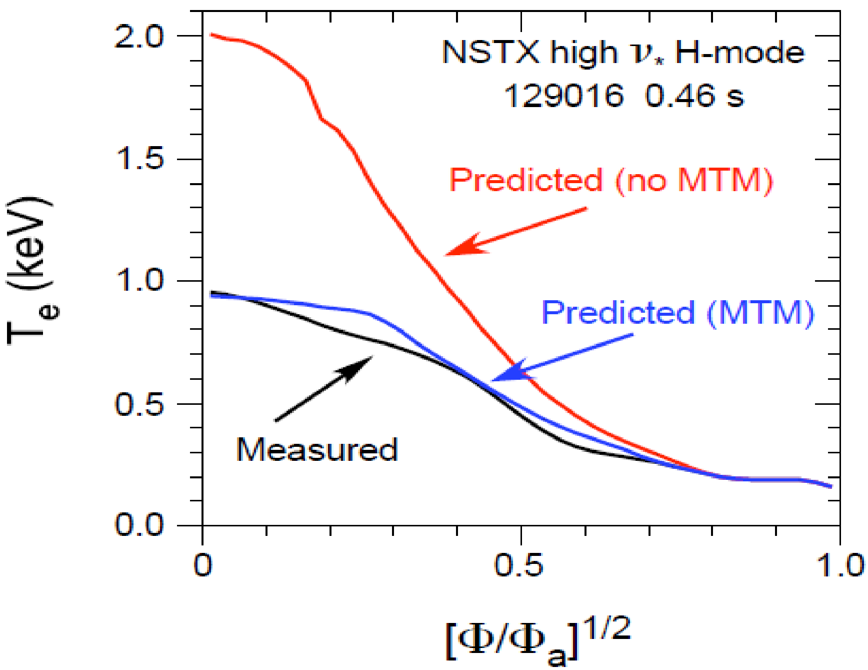


- **Magnetic q, electron temperature, and density profiles are specified**
  - **Normalized temperature gradient, g_{Te} and density gradients, g_{ne} are shown**

Behavior of the MTM Model for Prescribed Profiles



Predicted and Measured Electron Temperatures for High ν^* NSTX Discharge



Predicted and measured T_e profiles for the high ν^* NSTX discharge, 120916, with and without the contribution of transport associated with microtearing modes, as a function of the normalized square root of toroidal flux

- When the microtearing component in MM model is not included, an over-prediction of temperature occurs

– When the MM model, that includes transport associated with microtearing modes, is installed in the TRANSP code and is utilized in studying electron thermal transport in NSTX discharge, it is found that agreement with the experimental electron temperature profile is significantly improved in a high collisionality discharge

Summary

- Microtearing modes have been identified as a source of significant electron thermal transport in tokamak discharges
- Reduced model for nonlinear microtearing modes in integrated predictive modeling codes is developed
- Goal is to improve the prediction of electron thermal transport and, consequently, the prediction of the evolution of the plasma in devices in which microtearing modes have a significant role
- Dependence of MTM stability on plasma parameters appropriate for high collisionality NSTX discharges is investigated
  - Growth rate and real frequency obtained using the reduced transport model for MTM are compared and found to be consistent with MTM results obtained using the gyrokinetic code GYRO
- Saturated amplitude of the magnetic fluctuation strength, which depends upon the growth rate and real frequency of the most unstable mode and as well as on their sidebands in the k_y spectrum, is computed
- Agreement with experimental electron temperature profile is significantly improved in a high collisionality discharge when MTM model is included as a component in the MMM model

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