NSTX-U Milestone R(18-3) Q3 update

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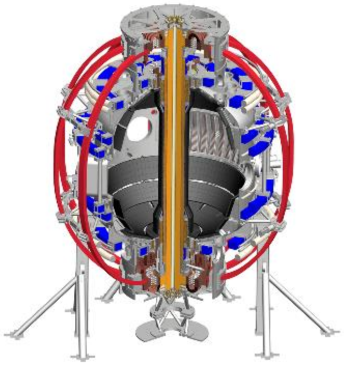
August 6, 2018



R18-3: “Validate and further develop reduced transport models for electron thermal transport in ST plasmas”

- **Focus of the milestone is on core electron thermal transport (ρ~0.4-0.9)**
  - **Main goal is to predict Te profiles from pedestal top inwards**
  - Not modeling the H-mode pedestal
  - Not modeling GAE/CAE-KAW mechanisms near-axis
  - Not focusing on turbulence measurement/validation

- ~~Three~~ **Two complementary parts of milestone activities**
  1. **Model validation (how well does model predict experimental Te)**
  2. **Model qualification (how well does model recover GK predictions)**
  3. ~~Analysis (Revisit profile fitting & mapping, EFIT reconstructions → Uncertainty Quantification)~~

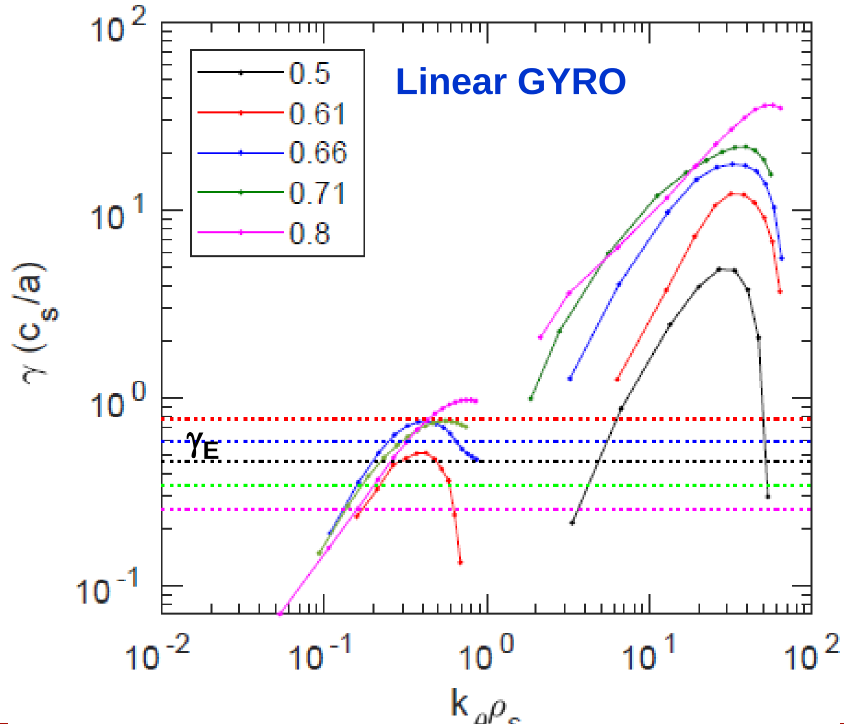
- **Considering multiple theoretical mechanisms in multiple regions of operating space**
  1. High-β, high-ν → MTM thought important
  2. High-β, low-ν → does NC + KBM set the limit on T_i & T_e?
  3. Low-β → expecting traditional electrostatic ITG/TEM at low aspect ratio
  4. When and where does ETG (electron-scale) fit in for all the above?

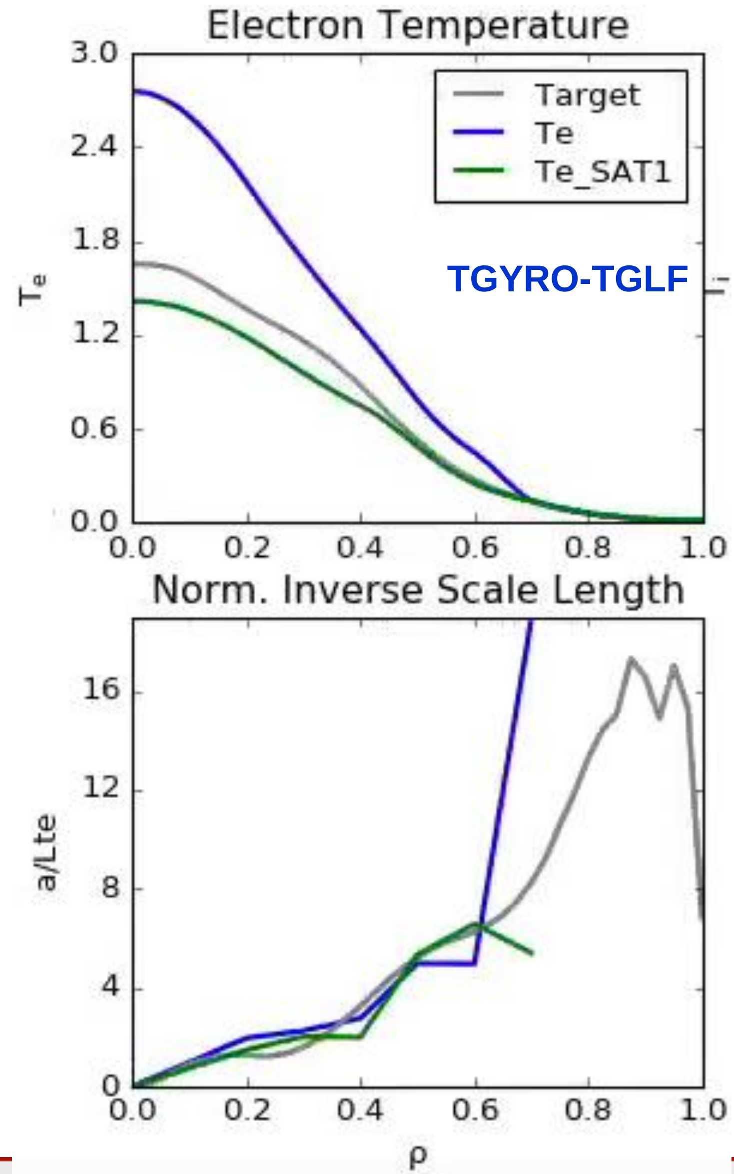
Q3 updates

- TGYRO-TGLF L-mode predictions
- Update on H-mode predictions (TGLF, NN)
- MMM-MTM development progress
- High β_{pol} gyrokinetic/MHD ballooning analysis

TGLF L-mode predictions imply electron-scale/multi-scale effects important

- “SAT1” saturation model accounts for multi-scale effects, gives much better prediction of T_e profile
  - Using TGLF + NEO, solved by TGYRO
- Linear GK analysis illustrates $\max(\gamma/k_y)_{ETG} \geq \max(\gamma/k_y)_{ion}$ at many radii, fits Staebler (2017) criteria for importance of multi-scale effects

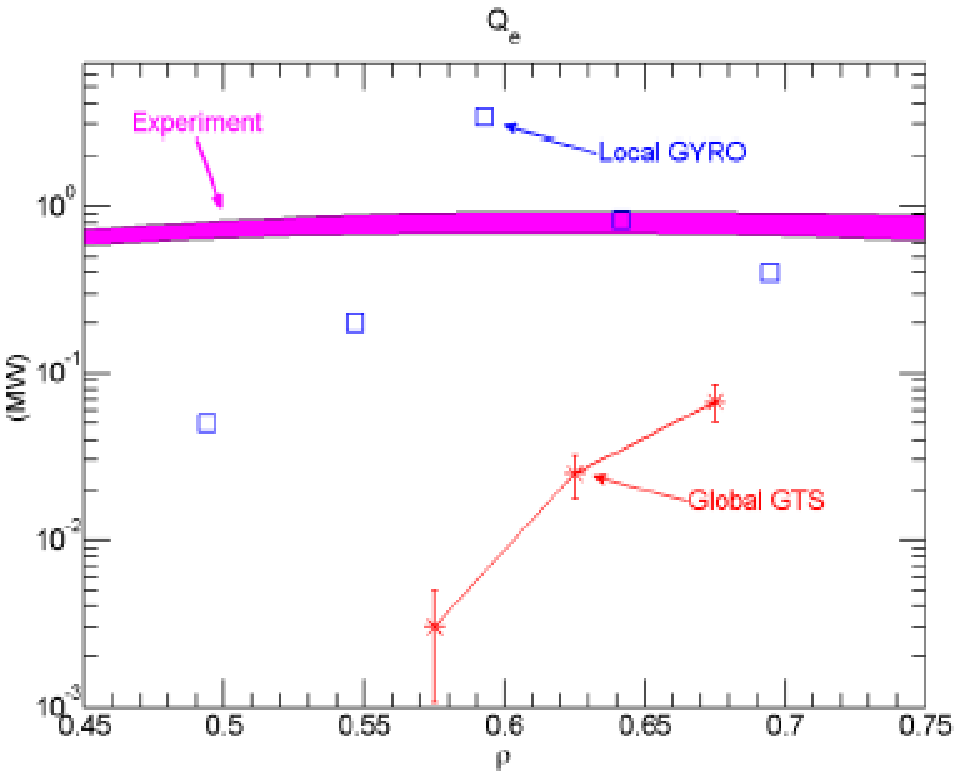




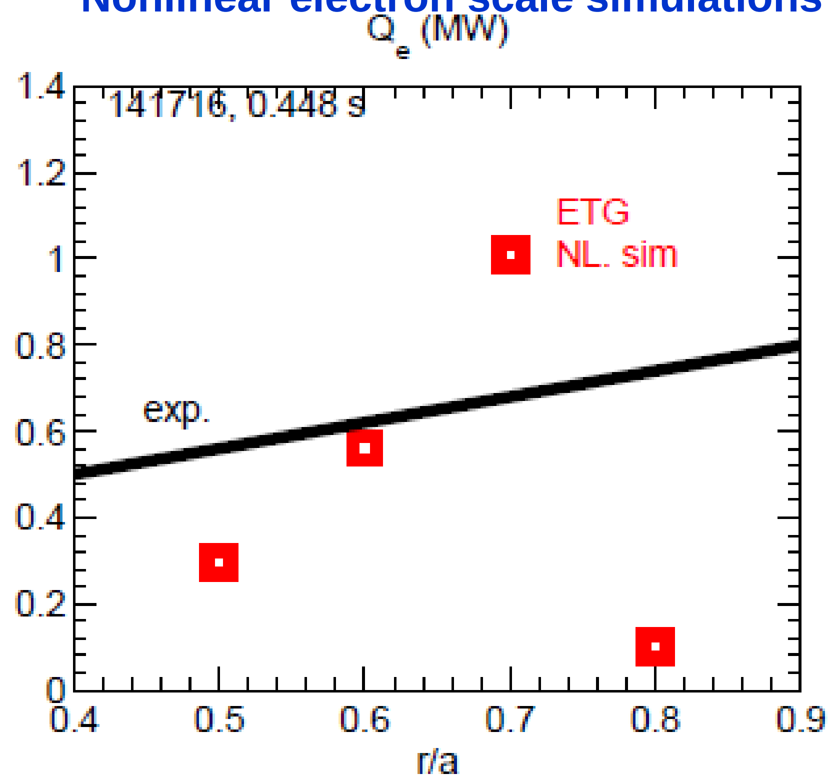
Supported by nonlinear ETG simulations that predict substantial transport (comparable to ion scale)

➢ Should try on NSTX-U L-modes (similar gyrokinetic analysis)
➢ Plan to separate TGLF low-k/high-k transport contributions to clarify roles of each

Nonlinear ion scale simulations



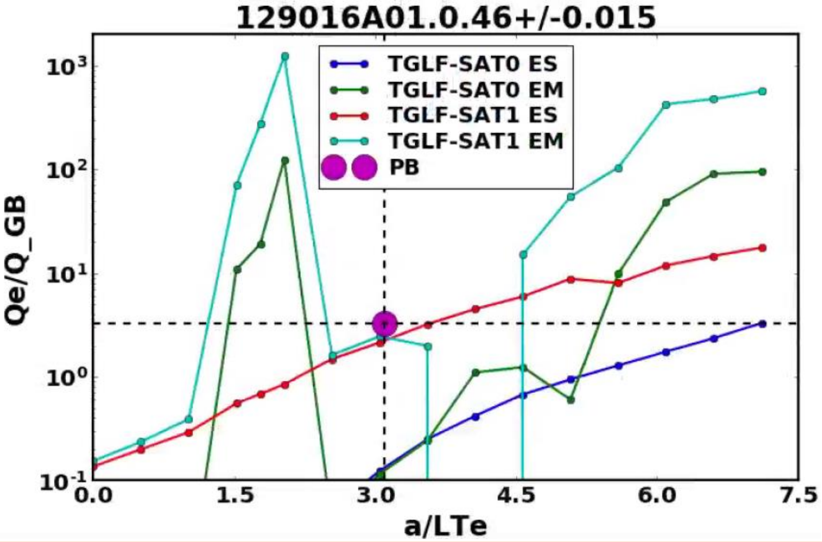
Nonlinear electron scale simulations



- Potentially a good target for (future) multi-scale nonlinear gyrokinetic simulations
- However, global effects important for ion-scales → need for global & multiscale?
  - Has been attempted before for high-ρ_* TCV discharges [Jenko, NF 2013]

Update on H-mode model predictions

- Have had some success with using TGLF for H-mode (e.g. 129016, illustrated ETG/multiscale important, good match with NL GYRO ETG at one radius)
- However, robust converged solutions only obtained using electrostatic models
- Gary suggested updated defaults for TGLF-EM, but TRANSP/PT-SOLVER struggles to converge



- Flux-gradient scans illustrate erratic behavior of TGLF-EM model

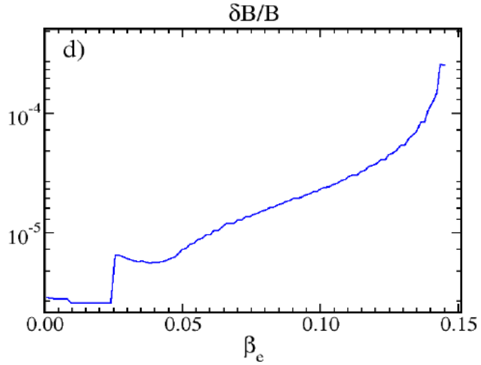
➢ Need to confirm path forward (if any) with Gary
  - Expansion of TGLF planned, not available for FY18 milestone

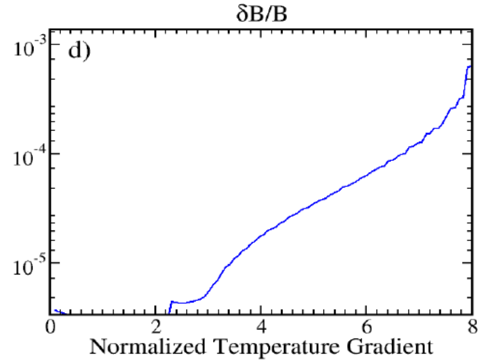
- Have also tried implementing in TRANSP the neutral net χ_e model trained on data (Y.-S. Na, 2017), but behavior indicates overfitting
- Re-training a new deep neural net to provide better conditioned model behavior

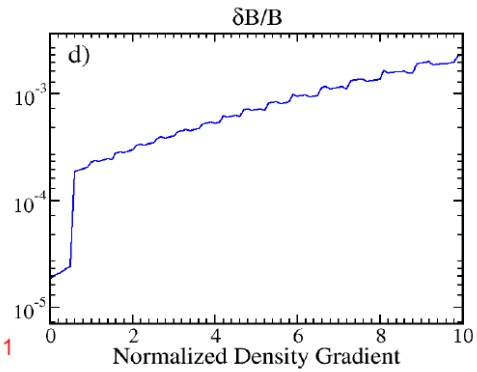
Update on MMM-MTM development

- MMM-MTM gives good profile predictions for high-ν_* discharge, but underpredicts low-ν_* (i.e. too much transport)
- Model recovers many NL GYRO dependencies, but not with ν_*

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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Identified modification to transport expression in MMM-MTM model to better treat ν_* scaling

- Eq. 57 from Rafiq PoP (2016) is based on 'collisional' R-R $\chi_e = \frac{u_{th}^2}{\nu_{ei}} \frac{|\delta B|^2}{B^2}$.

- Fundamental R-R theory uses: $\chi_e^{RR} \approx D_m v_{Te} = |\delta B/B|^2 L_c v_{Te}$

- Where L_c represents a decorrelation length in two limits:
  - Collisionless: $L_c = qR$ $(\lambda_{MFP} > qR)$
  - Collisional: $L_c = \lambda_{MFP}$ $(\lambda_{MFP} < qR)$ → gives transport expression used in present MTM model, but in the low collisionality limit will give unphysically large $\chi_e \sim 1/\nu_{*e}$
  - The distinction in collisionality is $(qR/\lambda_{MFP}) = qR \cdot \nu_e / v_{Te} = \varepsilon^{3/2} \cdot \nu_{*e}$ (plateau vs. Pfirsch-Schleuter, in terms of neoclassical regimes)

➢ Modifying MTM transport model as follows (two forms are equivalent, ν_{*e} is defined as in TRANSP):

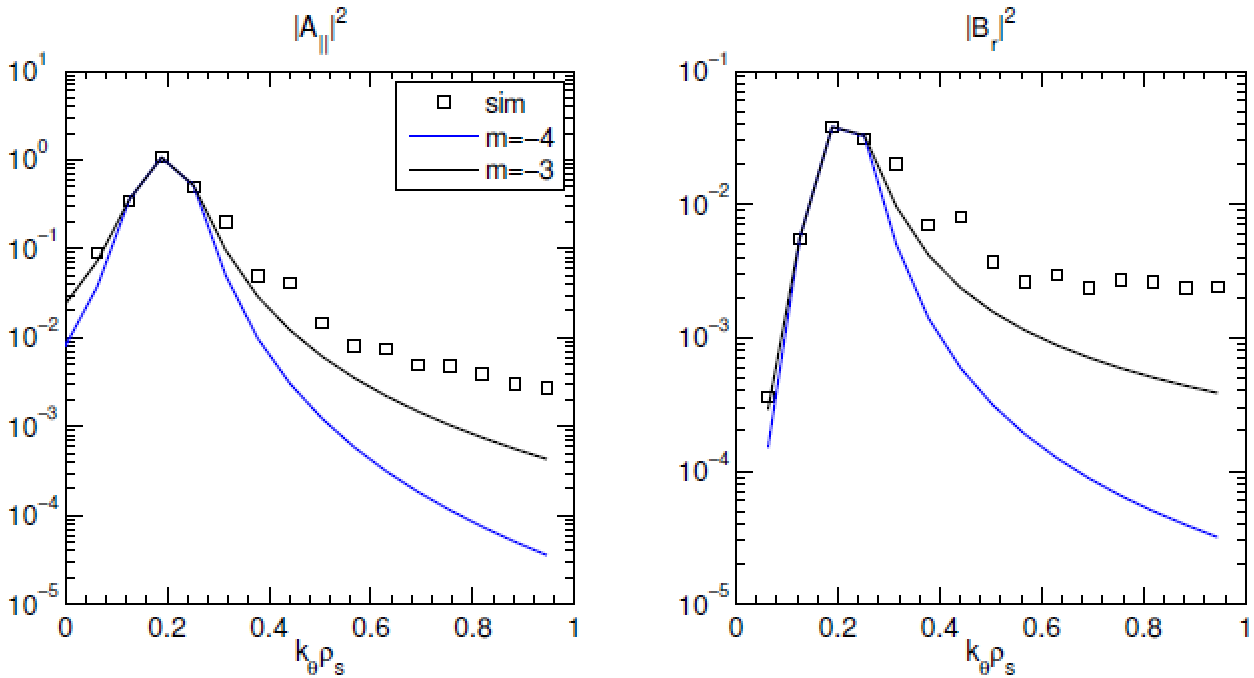
$$\chi_{e,MTM} = min\left[1, \varepsilon^{3/2}\nu_{*e}\right]\left(\frac{{v_{Te}}^2}{\nu_e}\left|\frac{\delta B^2}{B^2}\right|\right) \qquad \chi_{e,MTM} = min\left[1, \frac{1}{\varepsilon^{3/2}\nu_{*e}}\right] qR v_{Te}\left|\frac{\delta B^2}{B^2}\right|$$

Have also fit nonlinear GYRO $\delta B(ky)/B$ spectra to implement in MMM-MTM transport model

|apar|^2 = x(1) / (1 + [abs(ky-x(2))/x(3)]^3)

with

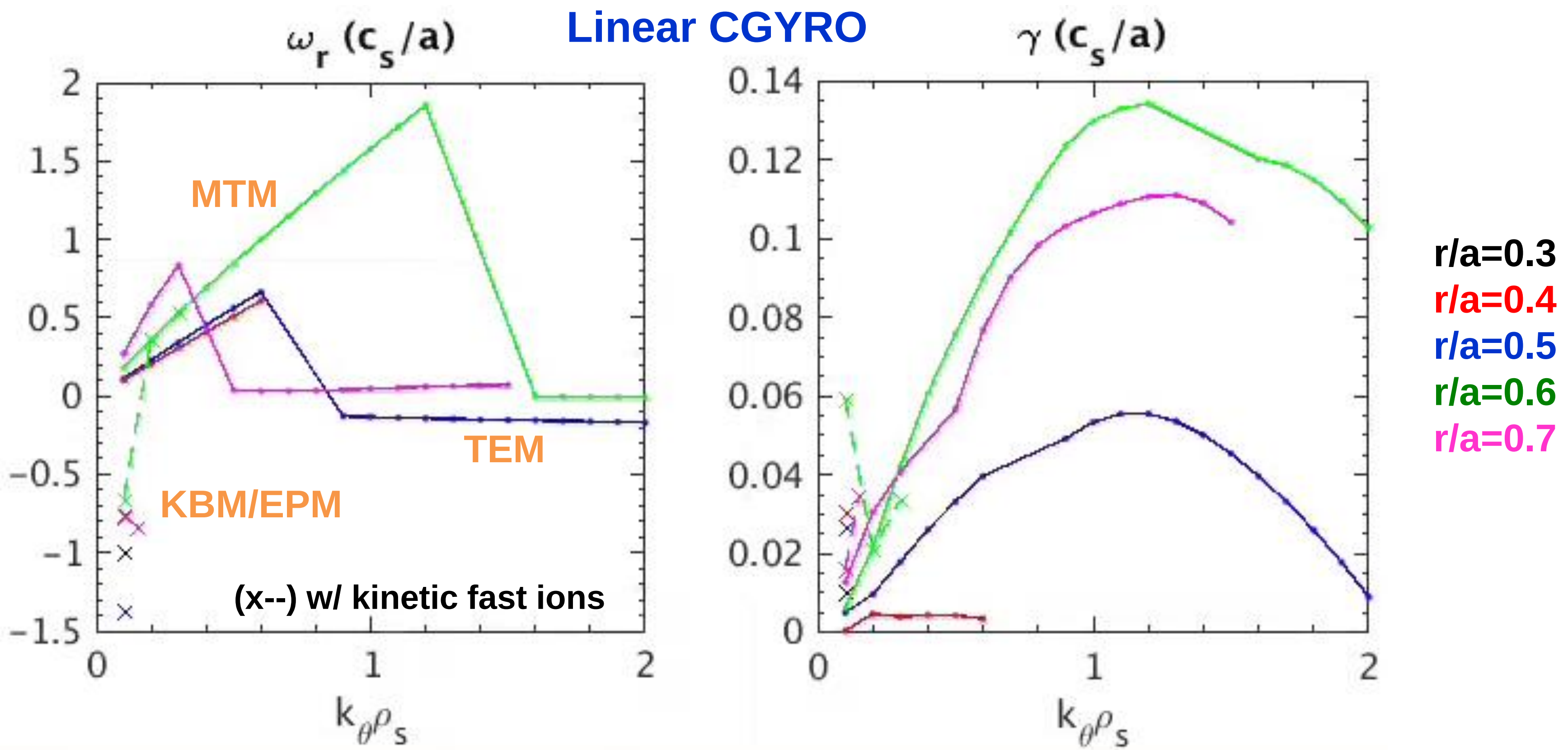
offset: x(2) = 0.19
width: x(3) = 0.056



- Will test whether more accurate spectral shape influences χ_e scaling with ν_*
- Then retest TRANSP profile predictions at low ν_*

Have begun analysis on high β_{pol} discharge (133964), target for high f_{NI} scenario (may expect KBM limit…)

- Discharge is unstable to MTM and TEM over mid-radius (r/a=0.4-0.7)
  – Surprised to see TEM; stabilized by collisions, not "DTEM" as found by GTS [W. Wang, PoP/NF 2015]
- KBM/EPM modes unstable at low-$k_\theta\rho_s$ when including kinetic fast ions

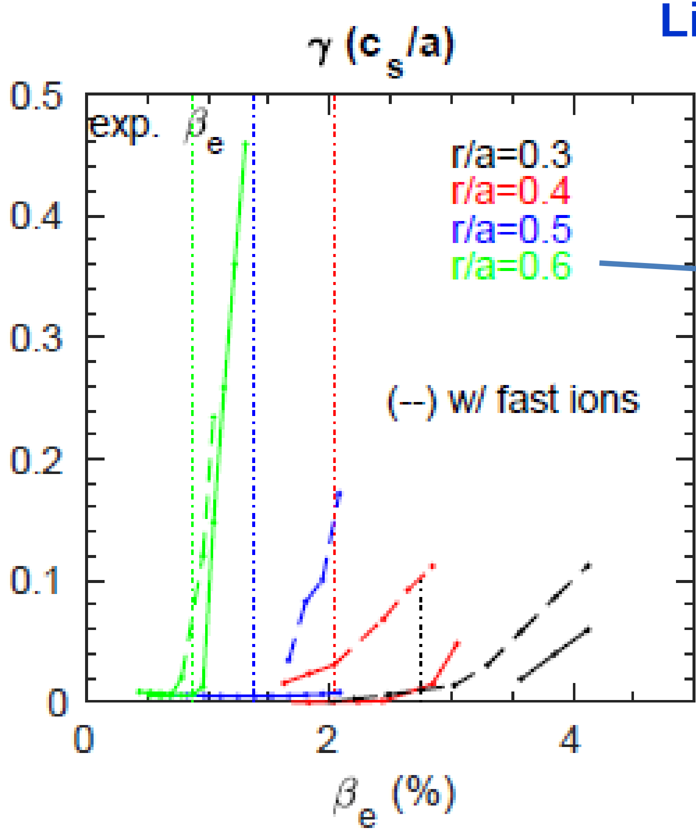


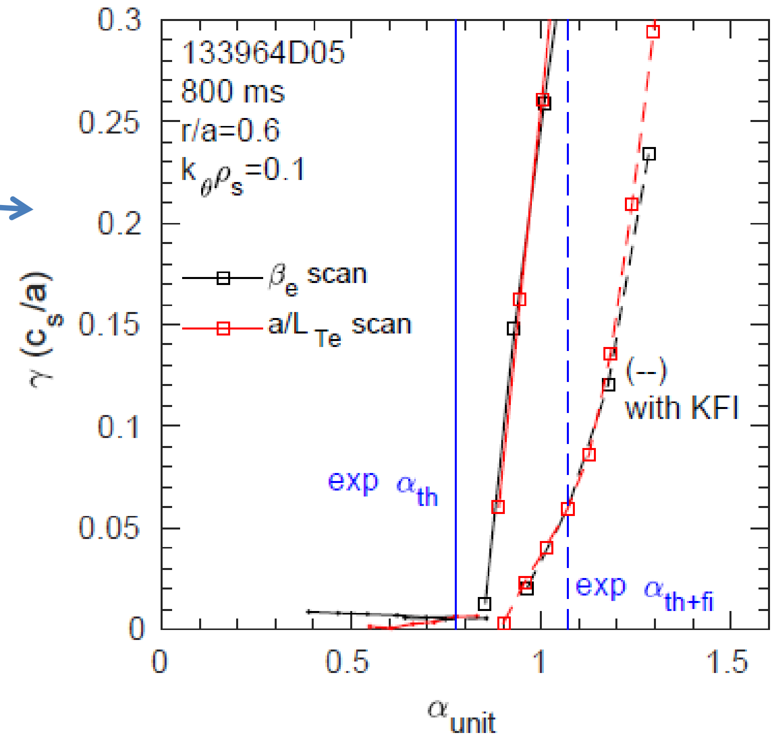
Linear CGYRO shows core near KBM/EPM threshold in high β_{pol} NSTX discharge

- Profile very near KBM/EPM threshold (relatively lower threshold with $\nabla F_{fast,ion}$)

➢ Will test TGLF ability to predict KBM/EPM threshold [Staebler, APS 2017] → requires hand-tweaked (non-default) settings

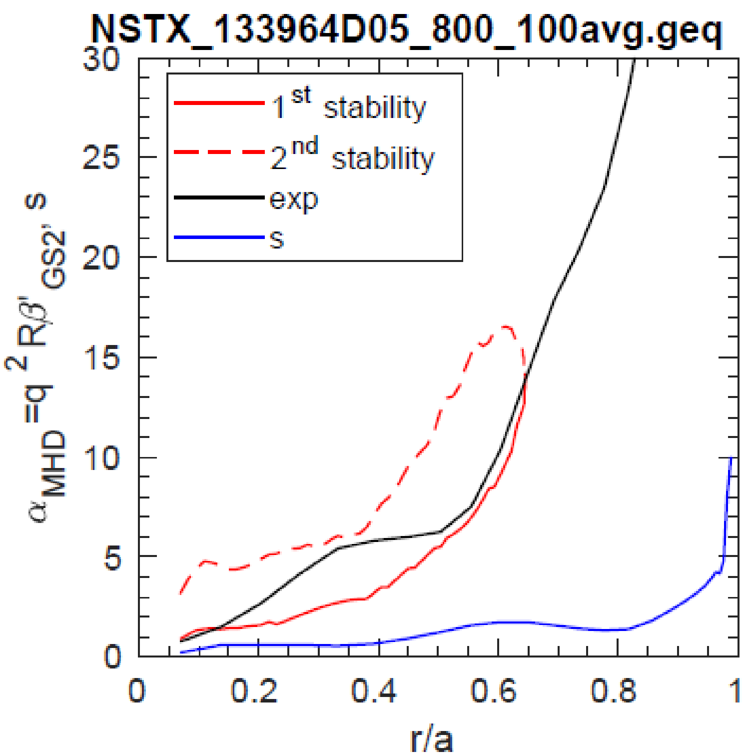
Linear CGYRO

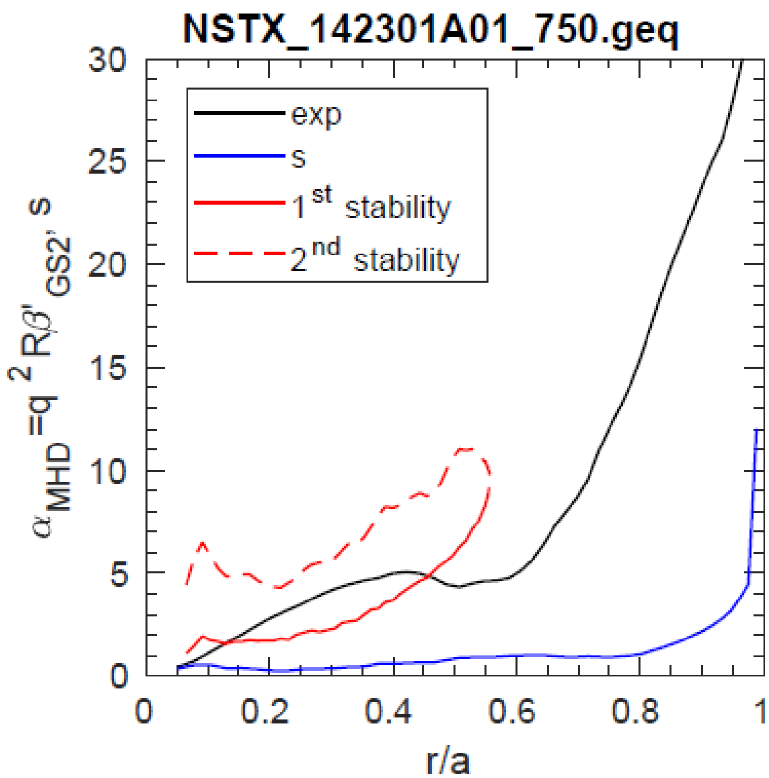




Presence of KBM/EPM consistent with ideal ballooning mode analysis

- Similar IBM result for high β_T discharge 142301 (basis for NSTX-U projections [Gerhardt NF 2012]





Priorities for closing out R18-3

- Finish updates to MMM-MTM and new TRANSP predictions
  - "Straightforward", but dependent on T. Rafiq's availability
- Summarize potential role of multi-scale in L-modes (→ will contribute to Kaye, IAEA)
- TGLF KBM/EPM threshold predictions → can sufficiently robust non-default TGLF settings be identified to enable profile prediction?
  - Is T_e profile truly limited by KBM/EPM? → Also map out MTM thresholds

BACKUP SLIDES

R18-3: “Validate and further develop reduced transport models for electron thermal transport in ST plasmas”

- http://nstx-u.pppl.gov/program/milestones/fy2018-research
- The design of next generation spherical tori (STs) will be influenced by the scaling of energy confinement. While ion thermal transport is often near neoclassical levels in H-modes in ST plasmas, gyro-kinetic simulations have indicated a number of potential drift wave turbulence mechanisms that can influence electron thermal transport. Reduced transport models that capture the key physics and scaling of the computationally expensive first-principles gyro-kinetic simulations are required to more thoroughly validate the modeling against experimental data, which can then be used to infer the key physics that determines the overall energy confinement. A variety of reduced transport models based on drift wave turbulence have been developed and tested extensively for conventional tokamaks. These models encompass much of the physics expected to be important in STs, although they have been tested much less rigorously for ST parameters (low aspect ratio, high beta, strong flow). **In order to improve the fidelity of reduced transport models (like TGLF, RLW and MMM), experimental NSTX, MAST and NSTX-U data will be used to examine predictions based on these models to assess their suitability for ST plasma. The physics accuracy of these fluid-based models will be also be qualified by comparing directly to first-principles gyro-kinetic simulations over a range of conditions.** The dependence of electrostatic ITG and TEM instabilities on aspect ratio will be evaluated by comparing **L-mode** cases to established conventional aspect ratio conditions. Validation with **high beta H-mode** data will push the limits of the available reduced models to recover electromagnetic instabilities like MTM and KBM. **A key outcome of this milestone will be to determine the ST physics regimes in which further model development is required.** The first-principles gyro-kinetic simulations based on ST parameters will form the basis for enhancements of the TGLF reduced model.

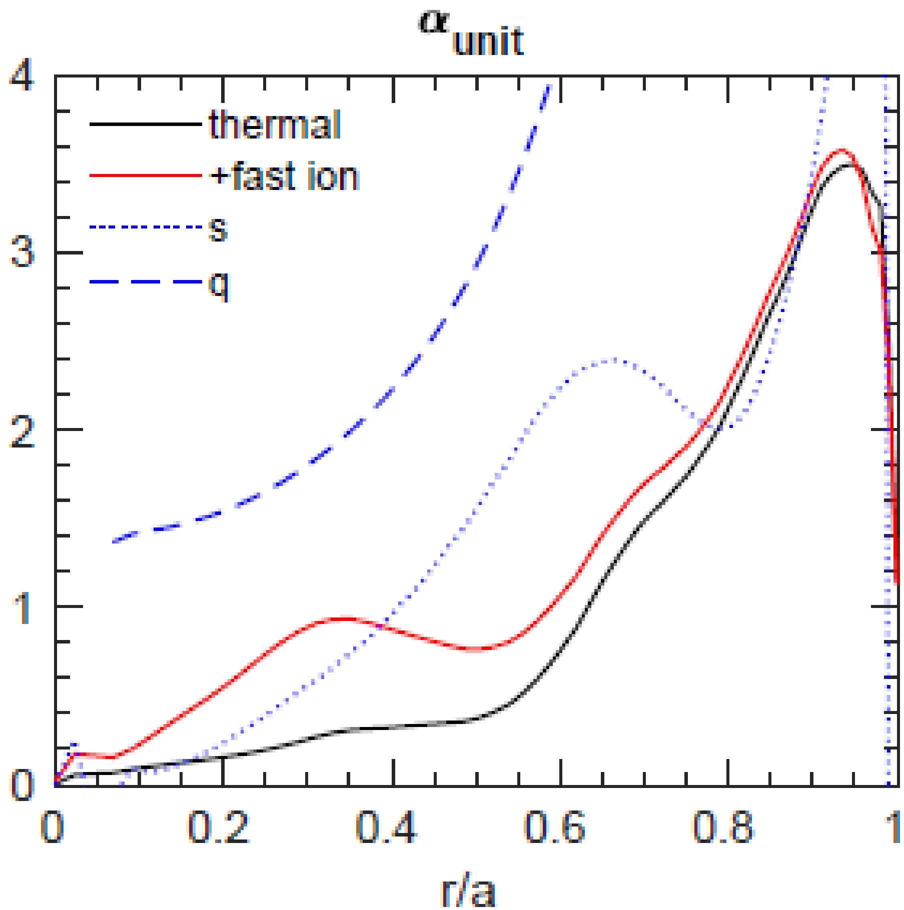
Outline of milestone tasks & estimated quarterly timeline (Q1-Q2, Q2-Q3, Q3-Q4)

- **Model validation (how well do profile predictions recover exp.)**
  - **[MV1]** H-mode profile predictions using TGLF, Rafiq-MTM, RLW
  - **[MV2]** L-mode profile predictions using TGLF, MMM
  - **[MV3]** Identify cases where ETG provides non-negligible Q_e (L & H mode)
  - **[MV4]** Develop and implement algorithm for locally constrained KBM profiles

- **Model qualification (how well do models recover linear & nonlinear GK)**
  - **[MQ1]** MTM: Document TGLF & Rafiq-MTM linear & nonlinear with gyrokinetics
  - **[MQ2]** ITG/TEM: Document linear stability, nonlinear saturation dependencies with aspect ratio
  - **[MQ3]** ETG: Do TGLF and MMM recover GK NL ETG predictions?
  - **[MQ4]** KBM: Document TGLF α_{crit} with linear GK
  - **[MQ5]** ITG/TEM: Document non-local deviations from local GK, use to inform local models
  - **[MQ6]** DTEM: Benchmark local GK codes with global GK for DTEM conditions

- **Analysis (profile fitting & mapping, EFIT reconstructions)**
  - **[A1]** Revisit EFIT w/ Pfast, rotation… influence on GK stability, thresholds

133964 α profile (without and with fast ions)

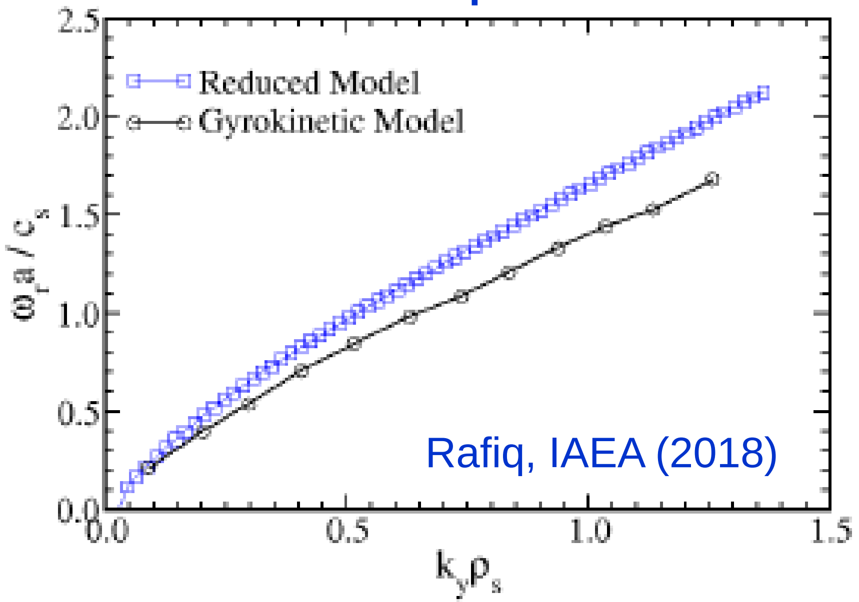


OLD STUFF

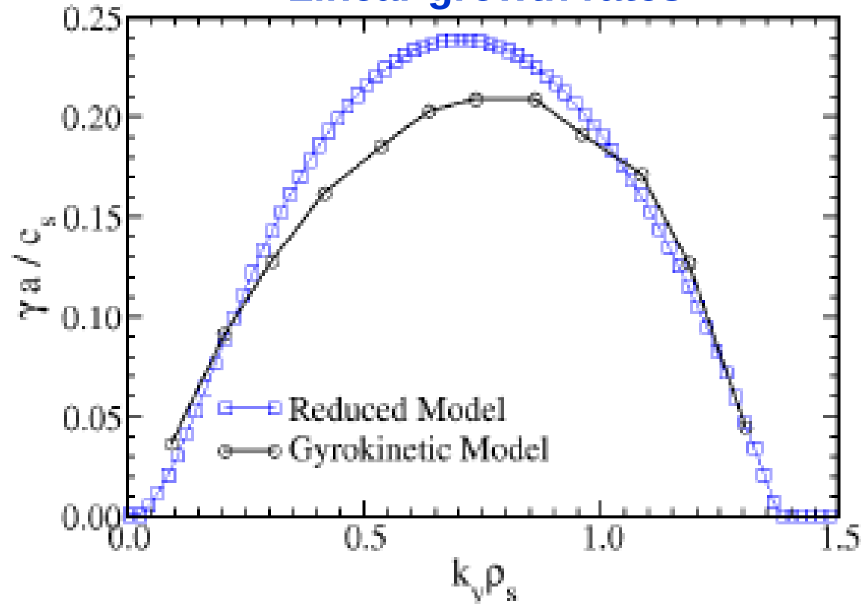
[MQ1] Qualifying new MTM model with gyrokinetics for high-β NSTX discharges

- Multi-Mode Model (MMM) (Rafiq, PoP 2014) has been updated to included new hybrid-kinetic/fluid microtearing mode (MTM) transport model (Rafiq, PoP 2016)
- Captures many trends predicted by linear gyrokinetics (GYRO) in high-β NSTX H-mode (Guttenfelder, PoP 2012)

Real frequencies



Linear growth rates

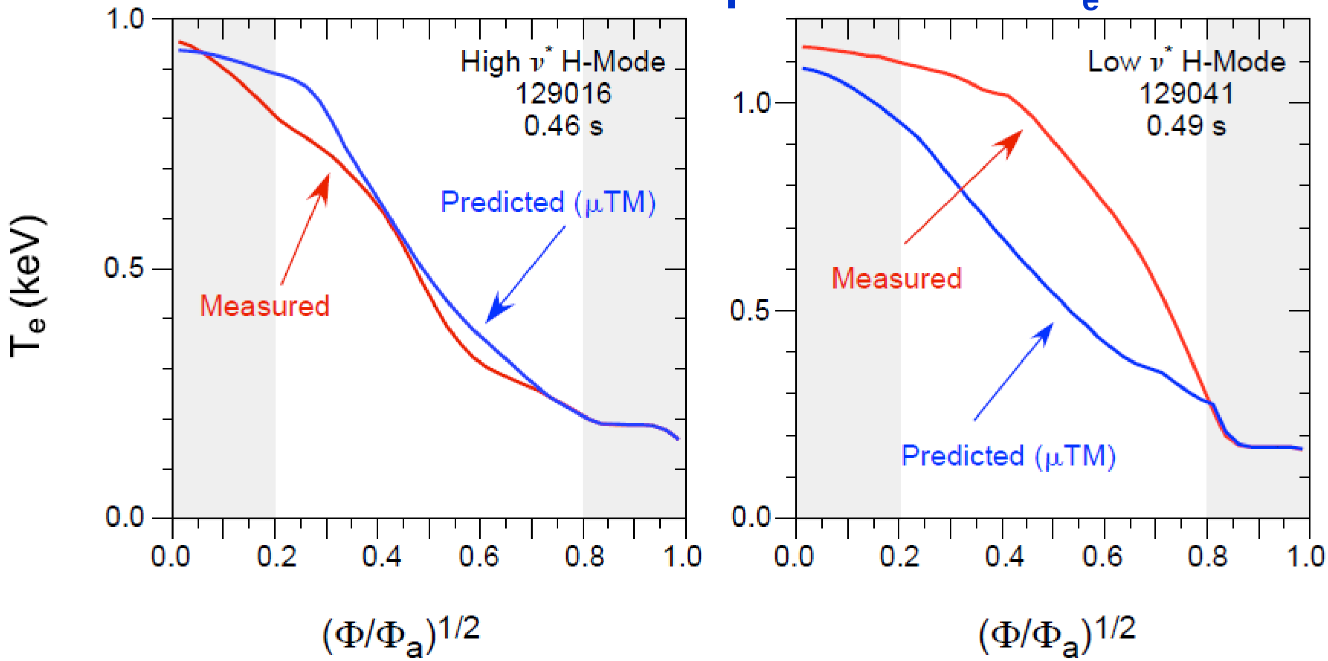


- Also reproduces scaling with ν_e, β_e, a/L_{Te}
- Does not capture complete scaling with magnetic shear

[MV1] MMM-MTM model can successfully predict T_e in high-β, high-ν_* NSTX H-mode discharges

- Fails to predict T_e at low-ν_* → will begin testing TGLF predictions of KBM expected at low-ν_* (Guttenfelder, NF 2013) in task [MQ4]

TRANSP + MMM predictions of T_e

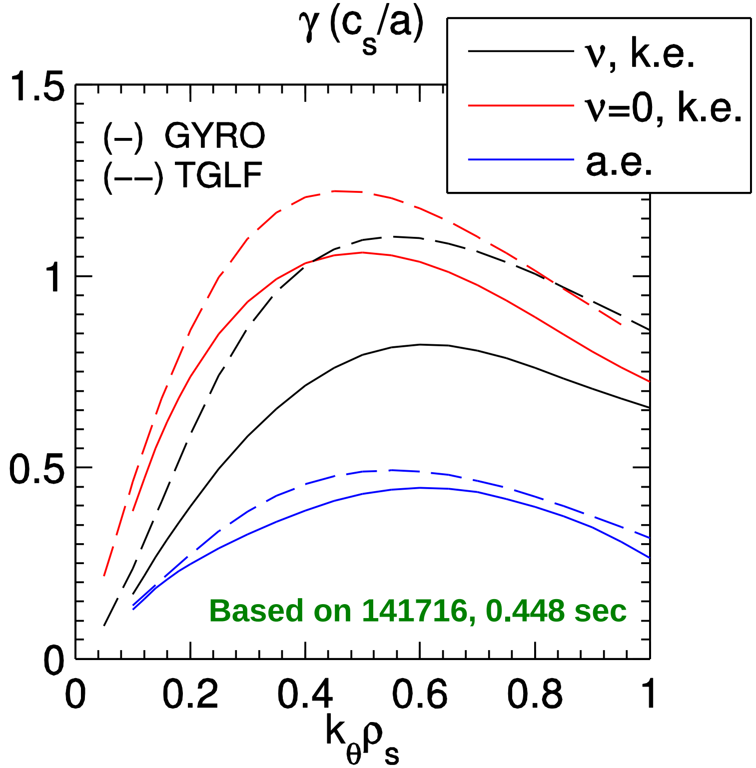


- A much wider comparison of TRANSP predictions (using RLW, MMM, TGLF) over a database of discharges has already been initiated (S. Kaye)
  - Repeating using updated TGLF settings per G. Staebler recommendations
  - Have also started TRANSP-TGYRO verification/benchmark

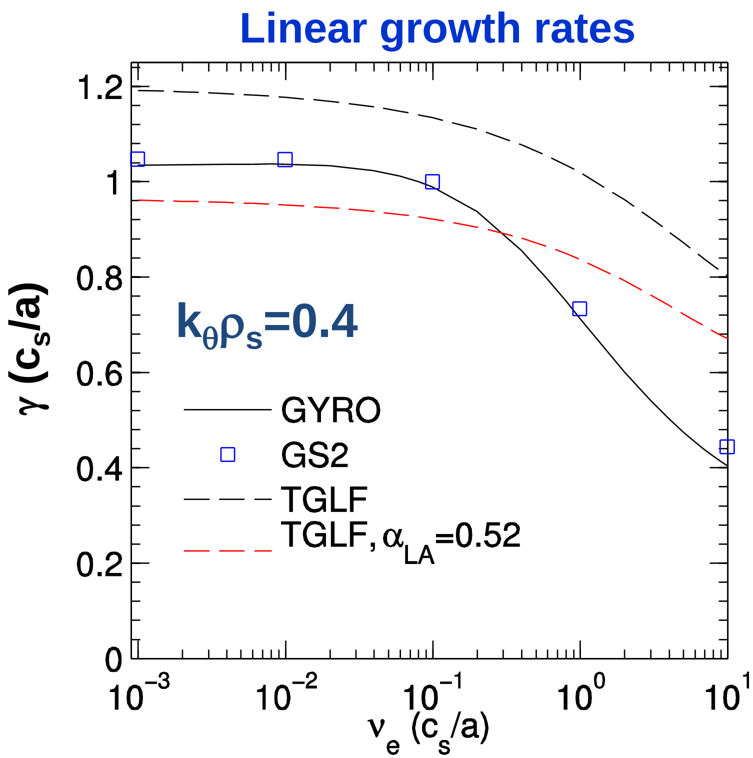
[MQ2] Have started qualifying TGLF for linear ITG/TEM based on NSTX L-mode

- Low beta (L-mode) experimental case (Ren, NF, 2013) to avoid EM effects

- Good agreement to GYRO in adiabatic electron limit (a.e.)
- Increasing discrepancy with kinetic electrons (collisionless & collisional)



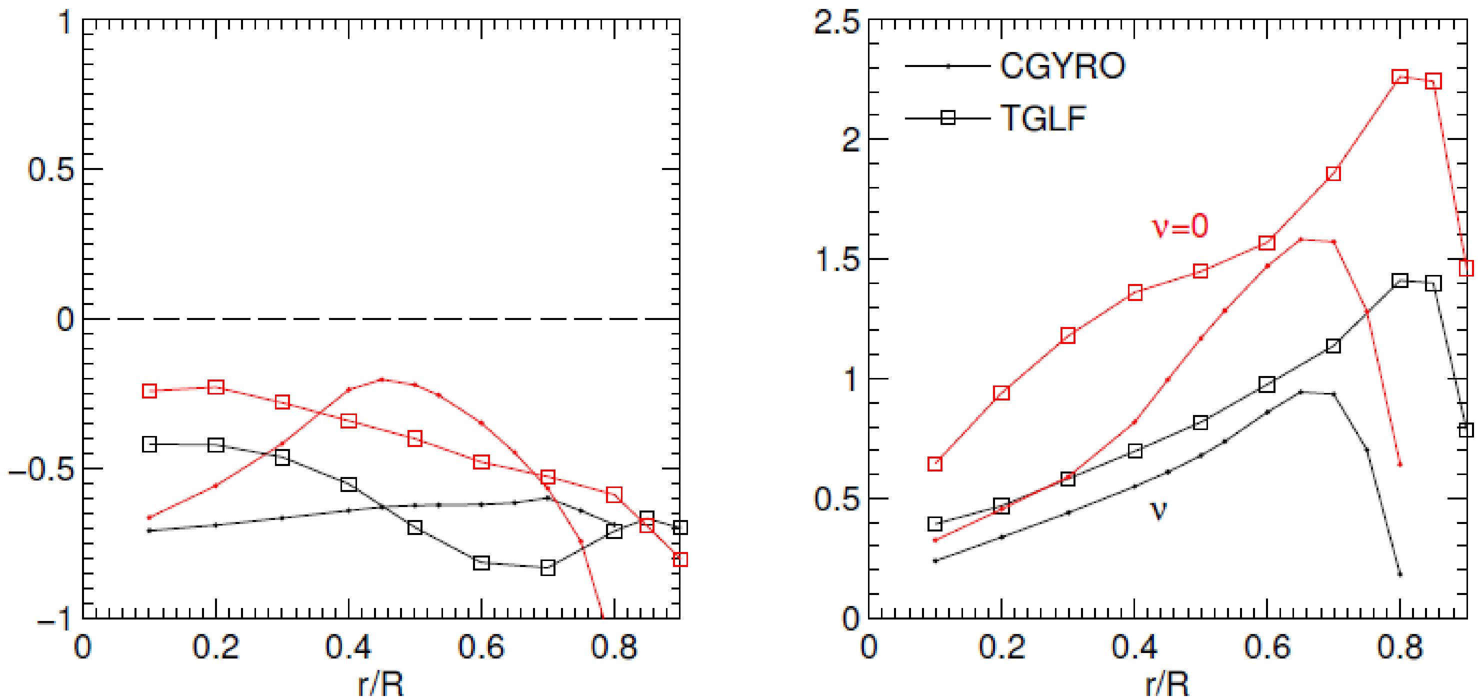
- TGLF stabilization with increasing collisionality not as strong as GYRO/GS2 → need to improve trapped electron response



[MQ2] Using aspect ratio scan to clarify TGLF trapped particle response

- Varying surface r/R using local equilibrium model (Miller, PoP 1998) with $\beta'_{eq}=0$ (not physically realistic but useful to isolate role of trapped particles)
- TGLF recovers GK trends → working towards modifications to improve quantitative agreement (Staebler, GA)
  - Also successfully benchmarked CGYRO & GYRO for NSTX parameters as part of this effort (not shown)

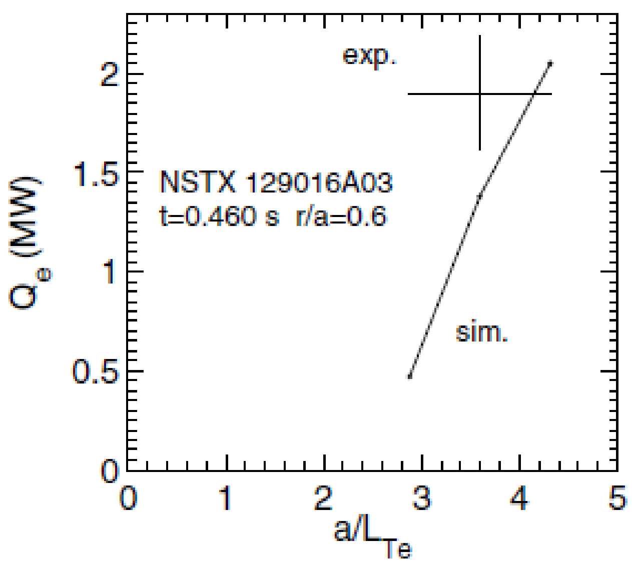
Real frequencies **Linear growth rates**



[MV3] Using previously published nonlinear ETG simulations to qualify TGLF-high k model

- Based on H-mode where ETG is significant, at least locally (Guttenfelder, NF 2013)
- TGLF reproduces comparable transport using “sat1” (updated ETG saturation rule based on multi-scale simulations)
  - To-do: compare saturated spectral shapes of $Q_e(k_\theta)$

Nonlinear GYRO sims



TGLF predictions