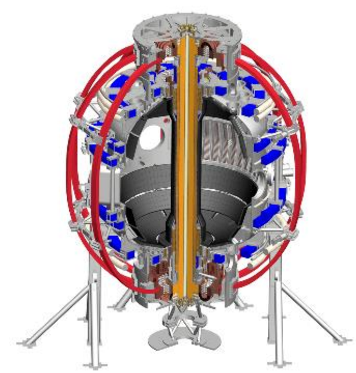
Kickoff meeting for NSTX-U Milestone R(18-3)

T&T TSG group meeting

November 6, 2017



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.

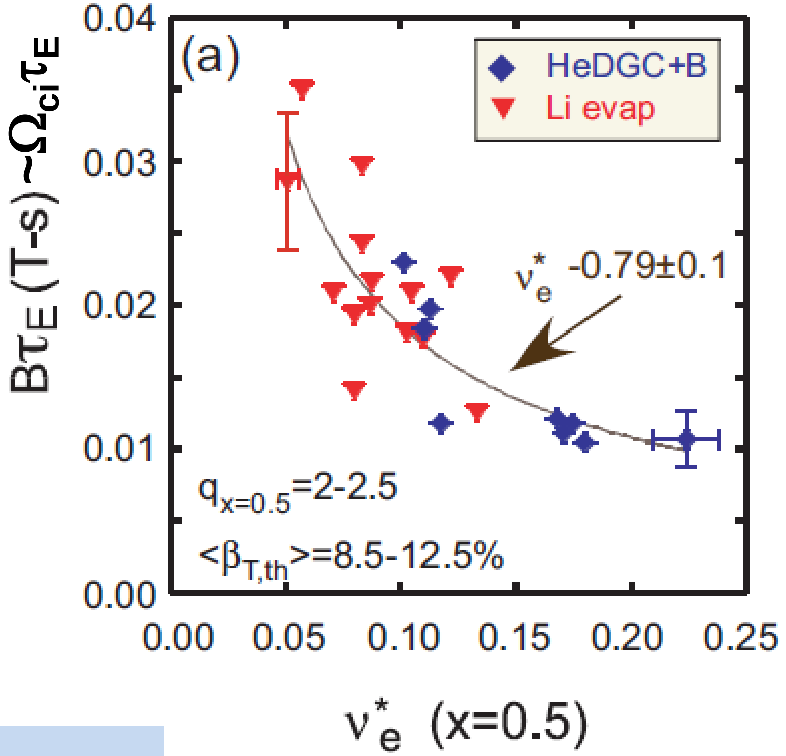
Highest T&T priority for NSTX-U: Measure & understand H-mode confinement scaling at higher B_T

NSTX H-modes

- In NSTX and MAST H-modes, dimensionless confinement time scales inversely with collisionality, $\mathbf{\Omega_{ci}\tau_E \sim \nu_*^{-0.8}}$

- *If* this holds at higher B_T & P_{NBI} (higher T_e, lower ν_*) $\rightarrow$ very favorable for future STs

$\Rightarrow$**What determines H-mode transport & confinement scaling?**



Kaye, NF (2013)

- We often consider three regions:

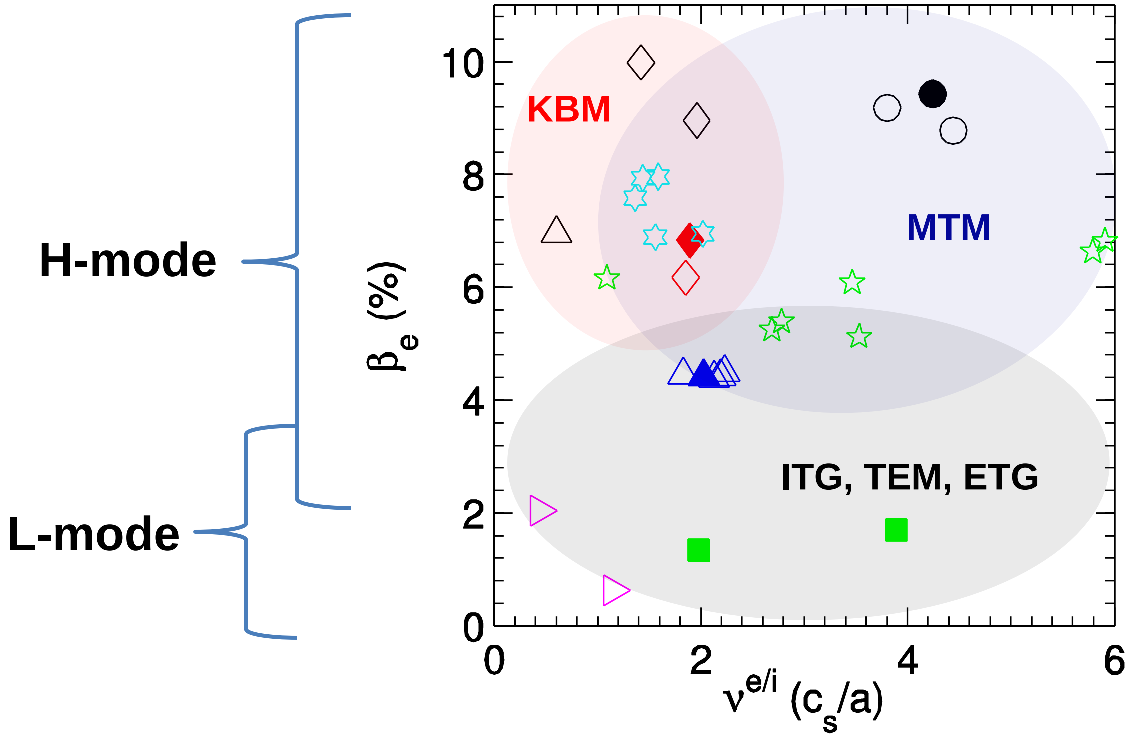
1. Pedestal, ρ>0.9
2. **Core, 0.4<ρ<0.9 (focus of R18-3)**
3. Near-axis, ρ<0.4, where T_e flattens (*AE effects?)

See Ren, NF (2017) for recent review

At high β, microtearing modes (MTM) and kinetic ballooning modes (KBM) are predicted unstable

- Predicted dominant core-gradient instability correlated with local β and ν
- Multiple instabilities usually predicted for a given experimental discharge

Local **gyrokinetic analyses at r/a~2/3**



Guttenfelder, NF (2013)

Milestone goals: (1) Identify ST conditions for which current core transport models work & fail, (2) Try to improve models

Focus on: Core transport in L-mode and H-mode (excluding pedestal), specifically:

- Electron thermal transport (+ ion thermal transport in L-modes)
- Drift wave (DW) based transport, i.e. not energetic particle mechanisms like GAE/CAE-KAW electron orbit stochastization/energy channeling
  - But need to consider this when judging whether DW models work or fail

Two complementary components of the milestone work:

1. Model validation → comparing profile predictions to experimental data
2. Model "qualification" → comparing reduced models to gyrokinetic simulations of linear stability, thresholds and nonlinear transport

- **A significant amount of transport modeling and gyrokinetic analysis has been done for MAST, NSTX, NSTX-U (see 4 reference slides)**

General comments & concerns

- Numerous theoretical drift wave mechanisms have been predicted in various NSTX discharges (ITG, TEM, DTEM, PVG, KBM, MTM, ETG, …)
- In my opinion, easiest to start in regions where few (hopefully one) mechanism expected dominant, then move in parameter space from there
  - One obvious distinguishing factor is β – focus on high-β H-mode & low-β L-mode
- Can any one model, or kluged combination of models, reproduce the ν_* scaling of ST H-mode confinement?
  - Neoclassical Ti + broadening Te (regardless of core flat-ness); will need pedestal BC scaling
- How do we distinguish "failure" of DW models vs. other unaccounted mechanisms (e.g. GAE/CAE-KAW)?

Some physics comments (MTM)

- Local NL GYRO scaling of MTM with ν_* reproduces NSTX H-mode scaling
  - But sensitive to suppression by experimental E×B shear
- RLW works amazingly well for high collisionality, high beta
  - Need to clarify physics scaling of RLW model

- **Model validation questions:**
  - Do Rafiq-MTM model & TGLF predict T_e profiles as well as RLW?
  - What criteria determines when each model fails to predict T_e?
    - Is it just collisionality? In what normalized form? What about beta? Etc…

- **Model qualification questions:**
  - Do Rafiq-MTM & TGLF recover GK linear threshold and NL transport scalings?
  - Is there a resolution to E×B suppression of NSTX 120968 r/a=0.6 MTM case?
    - I started working with CGYRO, suppression remains at r/a=0.6
    - I tried moving out (r/a=0.65, 0.7) where $\gamma_{lin,MTM} > \gamma_E$, but numerical saturation is elusive!
    - Initiate benchmark with GENE or GKW? (Probably outside scope of Milestone)
  - Will it be numerically feasible to simulate MTM globally due to excessive resolution requirements, $\Delta x<\Delta_{rat}(r)=1/nq'$?

Some physics comments (KBM)

- Numerous H-mode cases locally sit around or above α_{crit}
- Nonlinear GYRO simulation of KBM appears physically saturated
- Modes linearly transition from ITG/TEM to KBM ("hybrid modes")

- **Analysis & modeling questions:**
  - Do profiles really sit above α_{crit}? What is the sensitivity of $\alpha_{exp}>\alpha_{crit}$ to experimental uncertainties?
    - How does using equilibrium reconstruction with consistent P_{fast} influence this result? We've never done this routinely as far as I'm aware.
    - Revisit linear stability with updated TRANSP-kEFIT workflow (e.g. via OMFIT)
    - How sensitive is GK result to inclusion of kinetic fast ions?
  - Does TGLF recover KBM threshold compared to gyrokinetics?
  - If KBM is actually active, how do we reconcile $\chi_{e,anom}$ vs. $\chi_i \approx \chi_{i,NC}$?
    - Is it possible to have $T_i=T_{i,NC}$, and T_e self-organizes until $\alpha \sim \alpha_{crit}$?
  - Can we make a model prediction of T_e using the above recipe? (e.g. fixed n_e , P_{fast}, u' + neoclassical $T_i \Rightarrow$ predict T_e at marginal $\alpha=\alpha_{crit}$)
    - How do we do this using local KBM if regions are 2nd stable? Can we evolve kEFIT iteratively as part of the prediction?
  - How does KBM model profile prediction vary with nu? (e.g. KBM linearly stabilized by collisions)

Some physics comments (ETG)

- Numerous attempts to validate ETG transport with experiment
- Hundreds of nonlinear ETG simulations (NSTX, NSTX-U, MAST)
- Many experimental trends (with R/L_{Te}, R/L_n, s, γ_E) consistent with ETG
- But, predicted ETG transport often too small

- **Model validation questions:**
  - How well do MMM-ETG and TGLF predict T_e for regions of expected ETG dominance?
  - What fraction of Q_e comes from model ETG contributions in various discharges?

- **Model qualification questions :**
  - Does TGLF or Horton ETG model recover scalings predicted by nonlinear gyrokinetics?
  - When might multi-scale issues be important?
    - Tabulate $(\gamma/k_\theta)_{high\text{-}k}$ / $(\gamma/k_\theta)_{low\text{-}k}$ (incorporating γ_E) to identify potential importance

Some physics comments (ITG/TEM/PVG)

- Traditional ES DW (ITG, TEM) not often linearly unstable in high β H-mode
  - Due mostly to equilibrium configuration, *not* $E\times B$ shear
- Hoping that electrostatic ITG/TEM should be easiest to recover with models $\rightarrow$ pursue in low-β L-modes
- But non-local effects shown to be important
- GTS simulations of DTEM show favorable ν_* scaling

- **Model validation questions:**
  - How well does TGLF and MMM predict L-mode T_e and T_i?

- **Model qualification questions:**
  - Do MMM and TGLF recover NL GK predictions of ITG/TEM?
  - Can we include non-local effects in local QL models (e.g. Waltz PoP 2004)
  - Do fluid models recover DTEM? Can we benchmark DTEM in other GK codes?
  - How robust is DTEM in ST H-mode plasmas?

Comments on deep-core ($\rho<0.5$) transport

- T_e is very flat in the inner half radius of high power H-modes
- We often assume thermal gradient are too weak to drive drift wave instability
- Theory and observation suggest stochastic electron orbits from GAE/CAE modes and/or energy-channeling from GAE/CAE to KAW can influence T_e
- BUT, we should revisit DW stability thresholds including kinetic fast ions + parallel flow shear (with self-consistent kEFIT)

Initial thoughts on milestone tasks

- **Analysis**
  - Revisit self-consistent kEFIT + TRANSP/NUBEAM for some high-β H-mode cases
- **Model validation (how well do profile predictions recover exp.)**
  1. H-mode profile predictions using TGLF & Rafiq-MTM for same discharges used by Kaye with RLW model
  2. Develop and implement algorithm for locally constrained KBM profiles (e.g. fixed n_e, NC T_i, fixed P_{fast}, fixed u′, predict T_e using $\alpha=\alpha_{crit}$)
  3. L-mode profile predictions using TGLF, MMM
  4. Identify model cases where ETG provides non-negligible Q_e (L & H mode)
- **Model qualification (how well do models recover linear & nonlinear GK)**
  1. MTM: Document TGLF and Rafiq-MTM linear and nonlinear comparison with gyrokinetics
  2. KBM: Document TGLF α_{crit} with linear GK
  3. ITG/TEM: Document linear stability, nonlinear saturation dependencies with aspect ratio
  4. ETG: Do TGLF and MMM recover GK NL ETG dependencies? Tabulate $(\gamma/k_\theta)_{high\text{-}k}$ / $(\gamma/k_\theta)_{low\text{-}k}$ (incorporating γ_E) as proxy for possible multi-scale effects
  - ITG/TEM: Document non-local deviations from local GK, use to inform local models
  - DTEM: Benchmark local GK codes with global GK for DTEM conditions; Is there a transport model available for profile predictions?

Immediate action items for November

- Identify and tabulate targeted shots and TRANSP IDs (H & L mode) to focus model-experiment validation

- Identify targeted shots/parameter sets (H & L mode) to focus model-GK comparisons

- Begin documenting initial profile predictions using TGLF & Rafiq-MTM

- …

- Plan to have ~monthly meetings for group updates
  - Will meet more frequently as needed for task-specific actions

A number of transport solvers, transport models & gyrokinetic codes are available

- Transport solvers
  - TRANSP
  - PT-SOLVER
  - XPTOR
  - TGYRO
- Drift wave microturbulence transport models
  - TGLF
  - MMM (Weiland ITG/TEM + Horton ETG + Rafiq DRIBM)
  - Rafiq-MTM
  - RLW
- GK codes
  - GYRO
  - CGYRO
  - GS2/GKS
  - GTS
  - XGC1
  - GENE, GKW, GEM, GTC, ...
- Modeling frameworks
  - OMFIT

References

Previous ST transport modeling using reduced models (not gyrokinetic predictions)

- Kaye NF (2007), Horton ETG transport model comparison
- Wong PRL (2008), PoP (2008) MTM R-R transport modeling
- Staebler IAEA-FEC (2008), MAST TGLF profile prediction
- Akers IAEA-FEC (2008), MAST ETG χ_e model; GLF23 profile predictions
- Guttenfelder, Staebler (2011), TGLF-GYRO tests of MTM (NSTX H-mode)
- Guttenfelder, Staebler (2013), TGLF-GYRO tests of ITG/TEM, linear and nonlinear (NSTX L-mode)
- Kaye, PoP (2014) NSTX RLW MTM profile predictions
- Rafiq, PoP (2015), MTM model development
- Rafiq, APS (2016), NSTX MTM model comparison to GYRO
- Guttenfelder, Staebler (2017), TGLF-GYRO linear aspect ratio scan
- Rafiq, Pankin (?), MMM ETG-Horton model presentations for NSTX

ST gyrokinetic simulations

Early scoping

- Rewoldt, PoP (1996), linear FULL
- Kotschenreuther, Dorland, NF (2000), linear GS2
- H. Wilson (2004), linear GS2

Early experimental analysis

- M. Redi, EPS (early 2000's), linear GS2 (NSTX)
- D. Mikkelsen, TTF (2004), linear, nonlinear GYRO (NSTX)
- Applegate, PPCF (2004), linear GS2 (MAST)
- Roach, PPCF (2005), linear GS2 (MAST)

ST gyrokinetic simulation work - ETG

- Joiner, PoP (2007), GS2 NL ETG (MAST H-mode)
- Kaye, NF (2007), GYRO NL ETG prediction
- Roach, PPCF (2009), GS2 NL ETG (MAST H-mode)
- Mazzucato (), GS2 linear ETG thresholds
- Smith, PRL (), thresholds, ExB shear
- Poli, PoP (2010), Ethier (APS?), GTS NL ETG
- Yuh, PRL (2011), GS2 linear ETG thresholds (reverse shear ITBs)
- Guttenfelder, PoP (2011) GYRO NL ETG
- Ren, PoP (2012) GYRO NL ETG
- Peterson, PoP (2012) GYRO NL ETG, reverse shear
- Guttenfelder, NF (2013) GYRO NL ETG
- Ruiz-Ruiz, PoP (2015) GS2 linear, GYRO NL
- Colyer, (2016) GS2 NL ETG, collisionality dependence
- J. Chowdhury, APS (2017), ETG benchmark with XGC-1, GYRO, GENE

ST gyrokinetic simulation work – ion scale

MTM
- Applegate, PPCF (2006), linear GS2 (MAST H-mode)
- Applegate, Thesis (2007) NL GS2 (MAST H-mode)
- Wong, PRL (2008), PoP (2008) linear GS2
- Smith, PPCF (2011) linear GS2, high-k MTM
- Guttenfelder, PoP (2012), linear GYRO
- Guttenfelder, PRL (2011), PoP (2012), NF (2013), NL GYRO
- Smith, APS (2017), linear GENE (Pegasus H-mode)

ITG/TEM/PVG
- Sareelma, PPCF (2012), nonlinear ORB5 (MAST L-mode)
- A. Field, NF (2014), nonlinear ORB5 (MAST L-mode)
- Diallo, NF (2013), linear XGC-1, GENE comparison at rho=0.7 (NSTX H-mode)
- Ren, NF (2013), linear GS2, nonlinear GYRO (NSTX L-mode)
- Ren, PoP (2015), nonlinear GTS (NSTX RF L-mode)
- Wang, NF (2015), PoP (2015), nonlinear GTS (NSTX L & H modes)
- Guttenfelder, NF (2017), linear & nonlinear GYRO (NSTX-U L-mode)

KBM
- Guttenfelder NF (2013), linear & nonlinear GYRO (NSTX H-mode)
- J. Liang, APS (2015), linear KBM comparison XGC1, GYRO (NSTX H-mode, Diallo case)

Extra slides

Action items (living document)

Q1 (Oct-Dec)	• Identify target shots for profile predictions (Kaye … • Identify target shots for detailed GYRO-TGLF comparisons (Guttenfelder, Staebler, …) • Compare Rafiq-MTM transport to previous GYRO NL (Rafiq …) • Initial linear TGLF-GYRO comparisons • Document initial TGLF profile predictions • Document initial Rafiq-MTM profile predictions
Q2 (Jan-Mar)	
Q3 (Apr-June)	
Q4 (July-Sept)	