# Initial transport validation studies using NSTX-U L-mode plasmas

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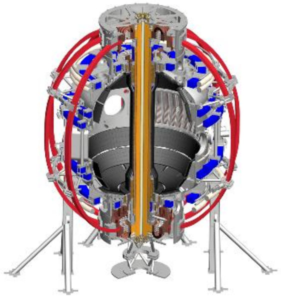


# Spherical tokamaks (STs) provide extended range of $\beta$, R/a and $\rho_*$ over which to validate theory and simulation

- Previous NSTX L-mode analysis using local and non-local gyrokinetic codes predict different results from relatively large $\rho_*=\rho_i/a\sim1/120$
  - Local GYRO ion-scale ($k_\perp\rho_s<1$) simulations predict wide variation of fluxes with radius compared to exp. *(Ren, Nucl. Fusion 2013)*
  - Global GTS ion-scale simulations get close to predicting $Q_{i,sim}\approx Q_{i,exp}$ but $Q_{e,sim}$ remains far too small *(Wang, Phys. Plasmas 2015; Ren, IAEA FEC 2016, EX/P4-35)*
  - Limited fluctuation data available

- **GOAL**: develop NSTX-U L-mode discharges for code benchmarking & validating finite-$\rho_*$/non-local effects at low A=R/a using global gyrokinetic simulations (GTS, GENE, XGC, GYRO…)
  - Ultimately want to do this for high-$\beta$ H-modes but electromagnetic simulations are very challenging
  
  $\Rightarrow$ Start with low-$\beta$ L-mode for electrostatic simulations

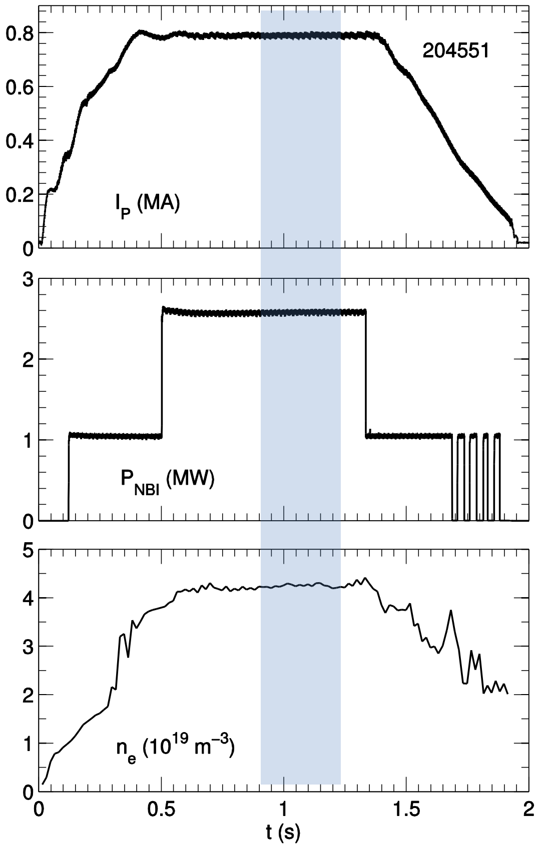
# Using stationary, sawtoothing L-modes established during NSTX-U commissioning for validation study

- Focus here is on $I_P$=0.8 MA, $4\times10^{19}$ $m^{-3}$, $P_{NBI}$=2.6 MW discharge
  - Used HFS fueling to raise density and avoid L-H transition

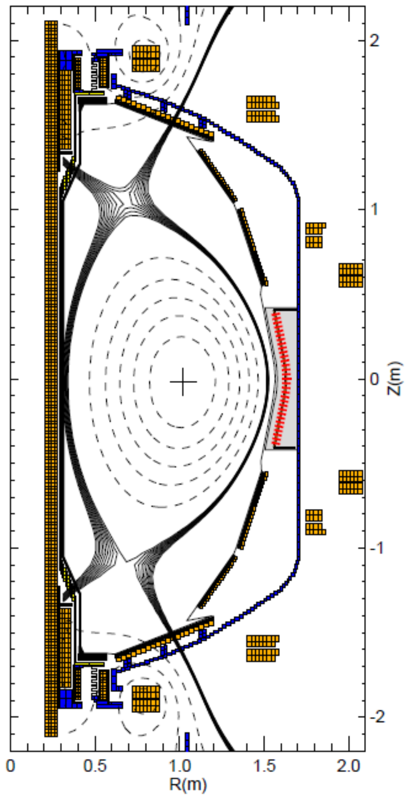
- EFIT reconstruction gives

$$\kappa = 1.7, \ell_i = 1.3, q_{95} = 4.8$$
$$\beta_N = 2.0, \beta_T = 4.1\%$$

- Using time-average between 0.9-1.2 s for transport analysis and simulations

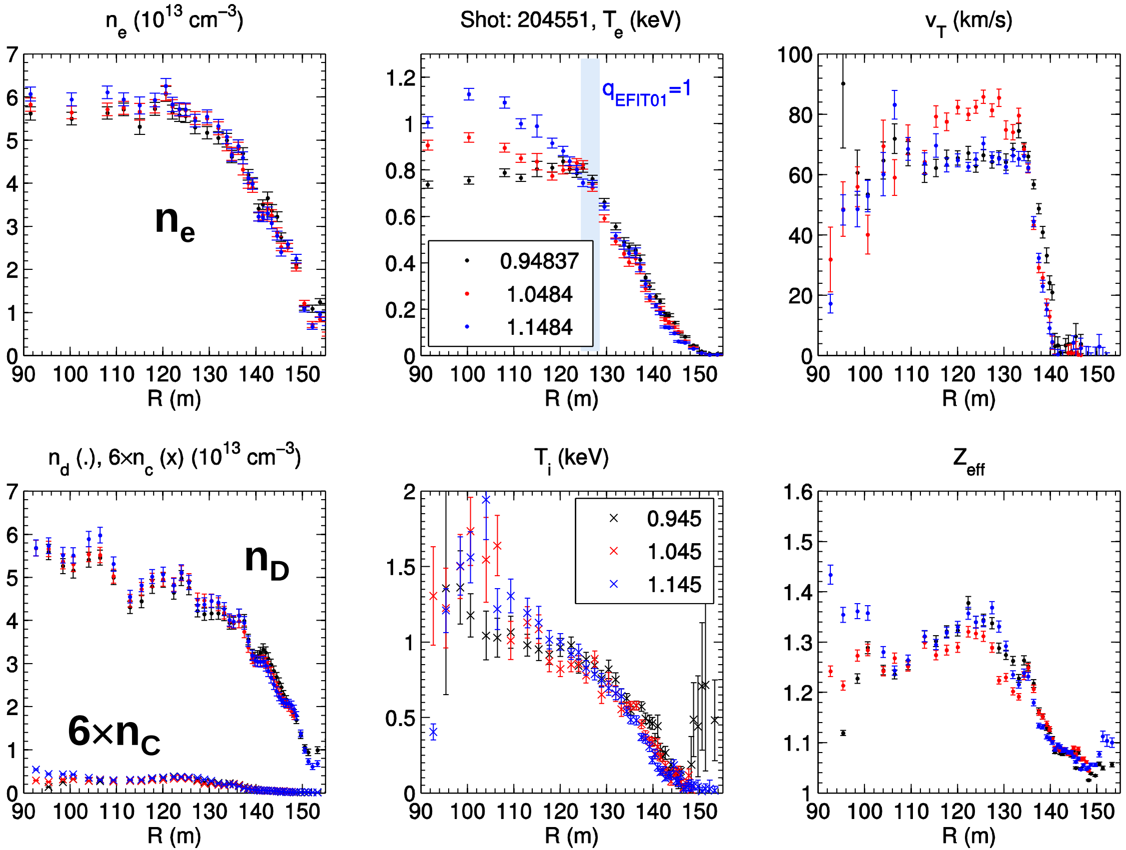



EFIT reconstruction



# Kinetic profiles illustrate sawteeth, low carbon impurity, and strong local flow shear in region of interest

- Sawtooth inversion radius R≈125 cm, $\psi_N$≈0.27 consistent with EFIT (no MSE measurements)
- Rotation locked outside 140 cm (likely from 2/1 mode)



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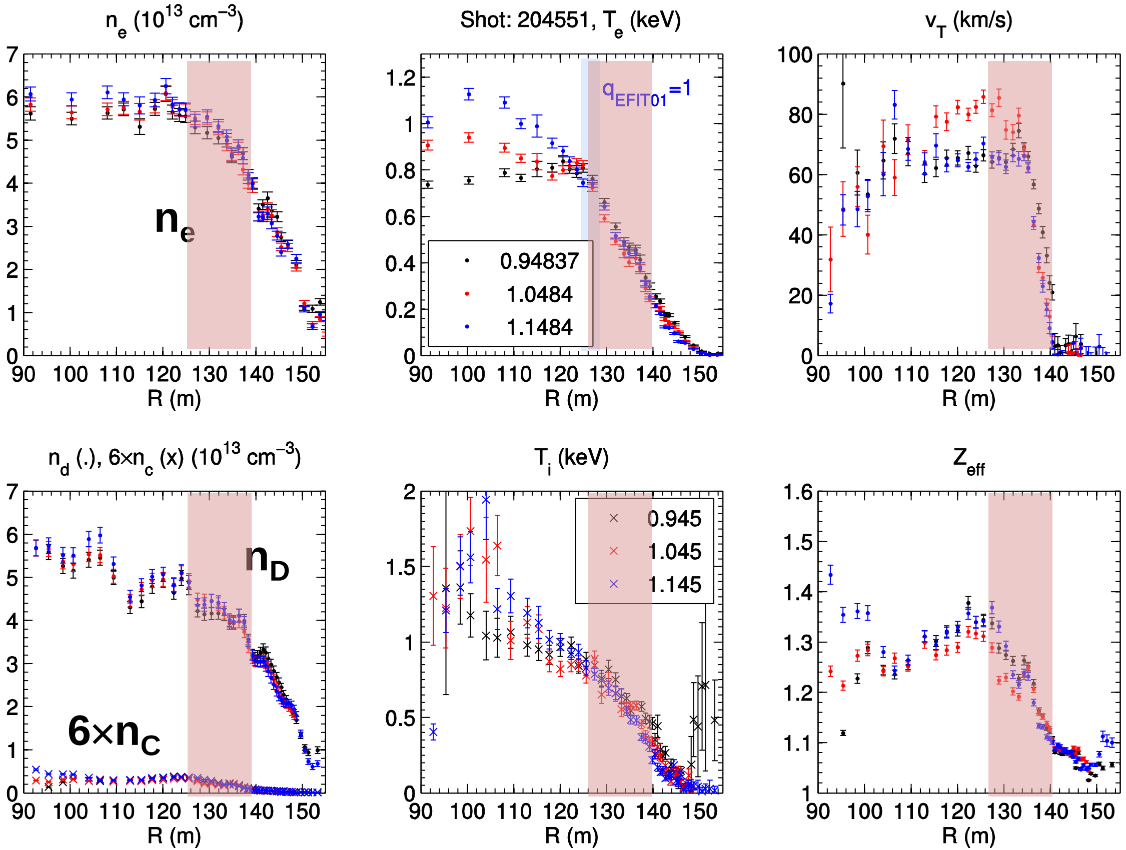
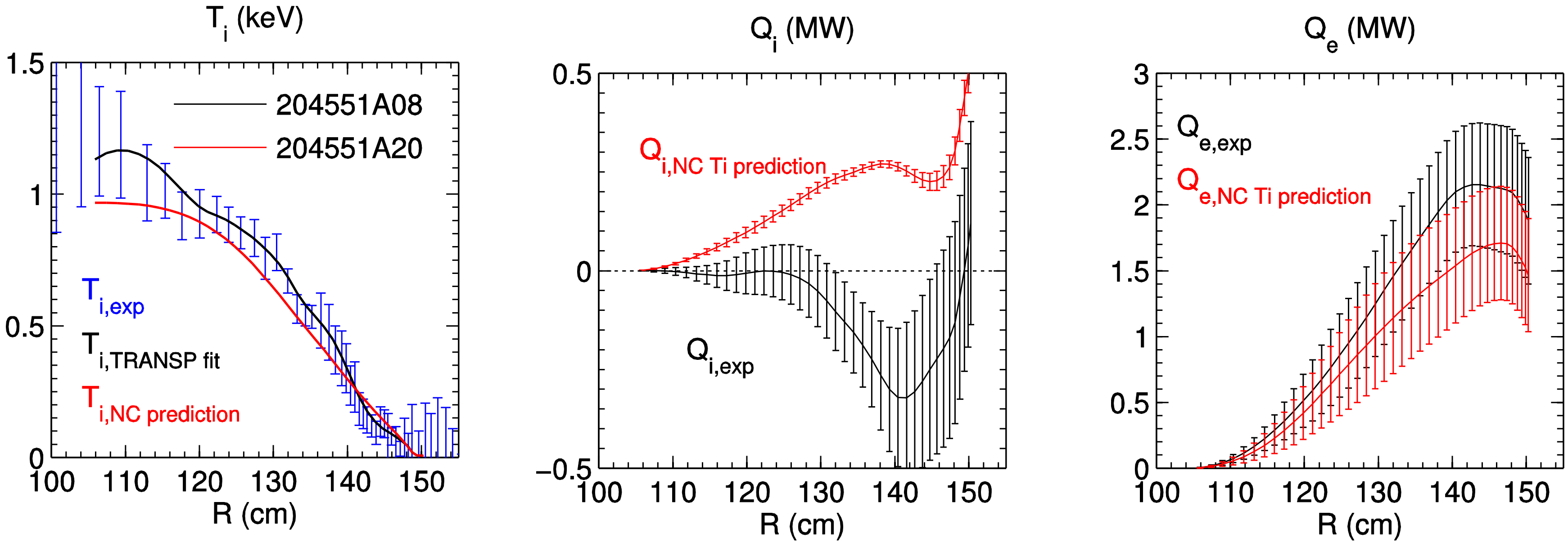
⇒ Very strong local flow shear in region of interest (R=125-140 cm, $\psi_N$=0.27-0.73, ρ=0.37-0.68)

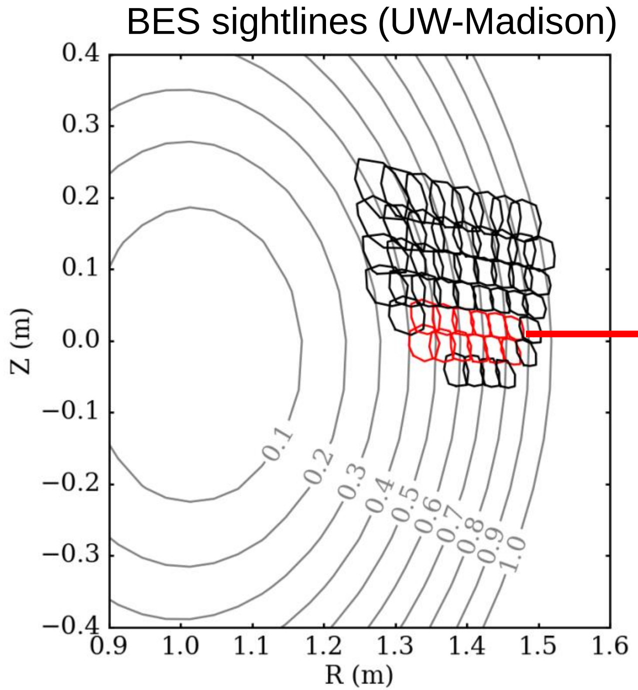


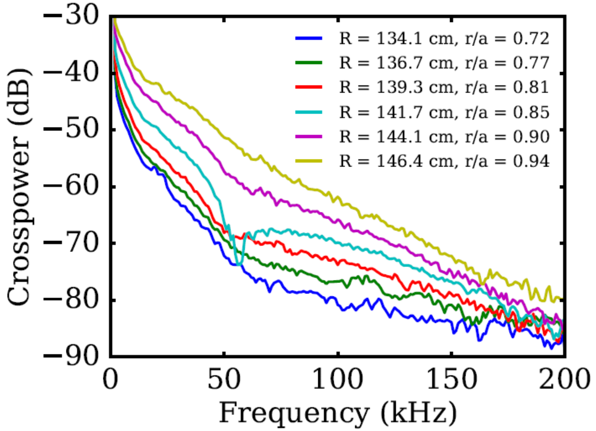
# Ion transport ~ neoclassical, ~0.5 MW uncertainty in heat fluxes from collisional coupling

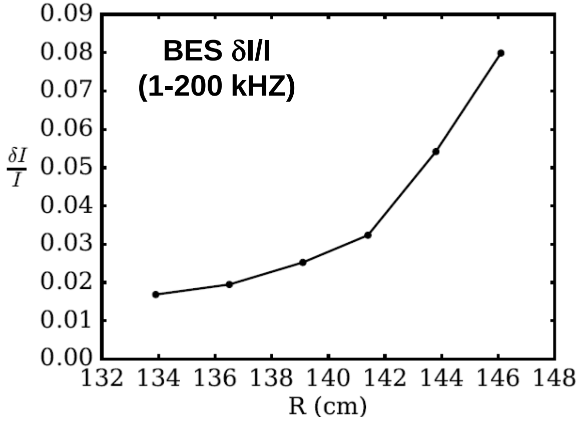



S.M. Kaye, NP10.01 (Wed AM)

# 48 channel BES system shows broadband (f<200 kHz), large amplitude (2-8%) ion-scale density fluctuations



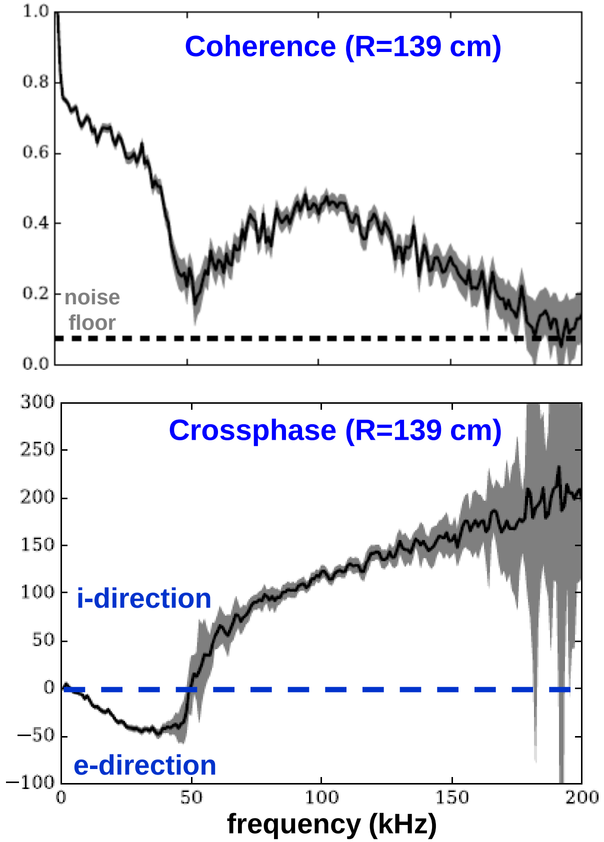




D.M. Kriete, NP10.14
(Wed AM)

# BES poloidal cross-phase shows dual-mode propagation

- Ion mode found R=134-144 cm
- Low frequency (f<50 kHz) electron mode found at all radii (R=134-146 cm)
  - Outer most radii has strong electron mode only
- Concern that electron mode could be due to shadowing from large amplitude edge fluctuations (see D.M Kriete poster NP10.14)



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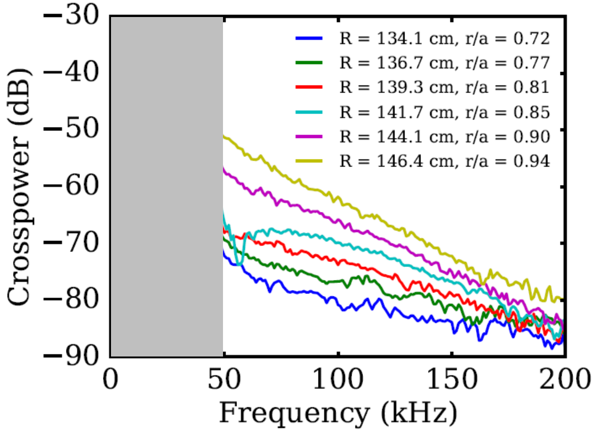
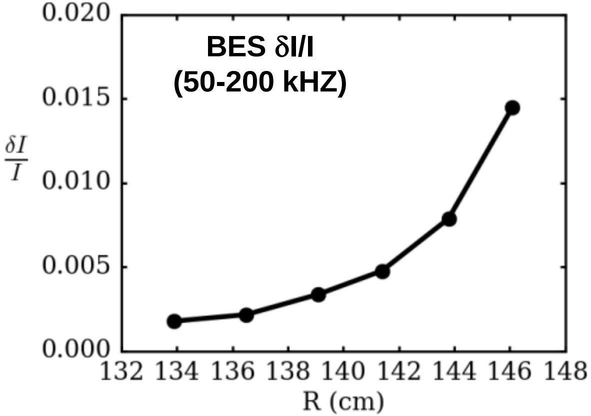
⇒ **Fluctuation amplitude of only ion-directed modes (50-200 kHz) much smaller (0.1-1.5%)**

  - Analysis of UCLA 16 channel reflectometer ongoing

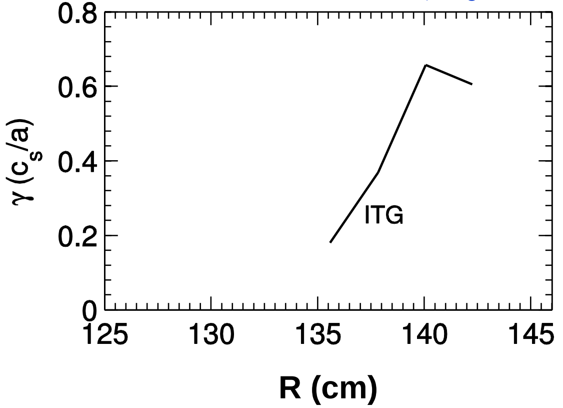


# At ion scales ($k_\theta \rho_s$<1), linear GYRO* simulations predict unstable ion temperature gradient (ITG)

- ITG modes propagates in ion direction
  - Propagation direction consistent with BES ion mode (need to consider Doppler shift, although also in ion direction)

**Linear growth rates, $\gamma$ ($c_s/a$)**




*GYRO (Candy, Waltz, 2003)

# At ion scales ($k_\theta \rho_s$<1), linear GYRO* simulations predict unstable ion temperature gradient (ITG) and microtearing modes (MTM)

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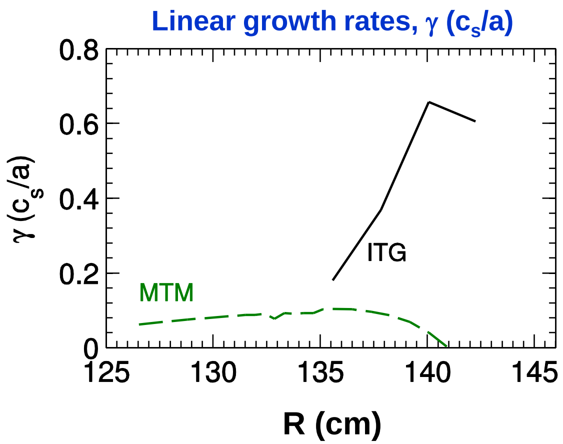
- MTM propagates in electron direction
  - Surprised to find MTM unstable ⇒ sufficient beta (4.1%) and large collisionality enhances MTM

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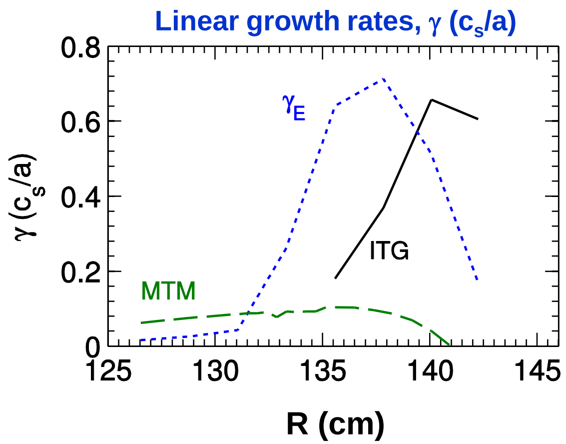
- Strong *local* E×B shearing rates ($\gamma_E > \gamma_{ITG}, \gamma_{MTM}$ at R=135 cm)
  - BES amplitudes increasing where $\gamma_{ITG} > \gamma_E$

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# Strong variation in turbulence, stability and E×B shear over ≤30 $\rho_s$ ⇒ *motivates the need for global simulations*

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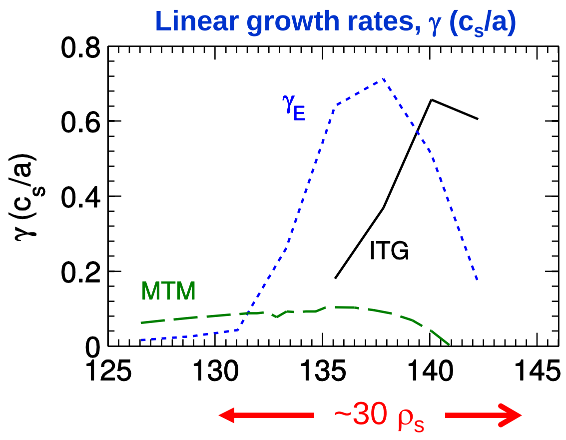


*GYRO (Candy, Waltz, 2003)

# Electron scale ($k_\perp \rho_s >> 1$) ETG also linearly unstable ($\gamma_{ETG} >> \gamma_E$) in region of strong E×B shear

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- MTM propagates in electron direction
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- Strong *local* E×B shearing rates ($\gamma_E > \gamma_{ITG}, \gamma_{MTM}$ at R=135 cm)
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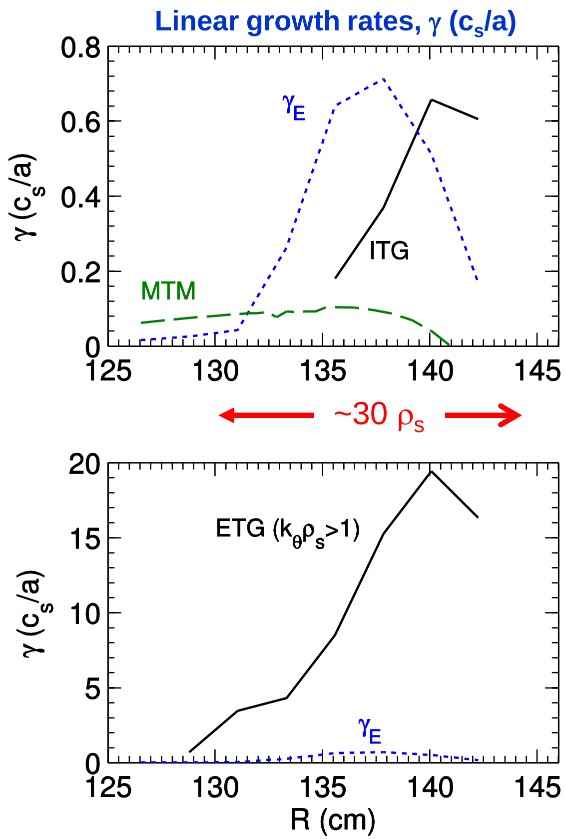
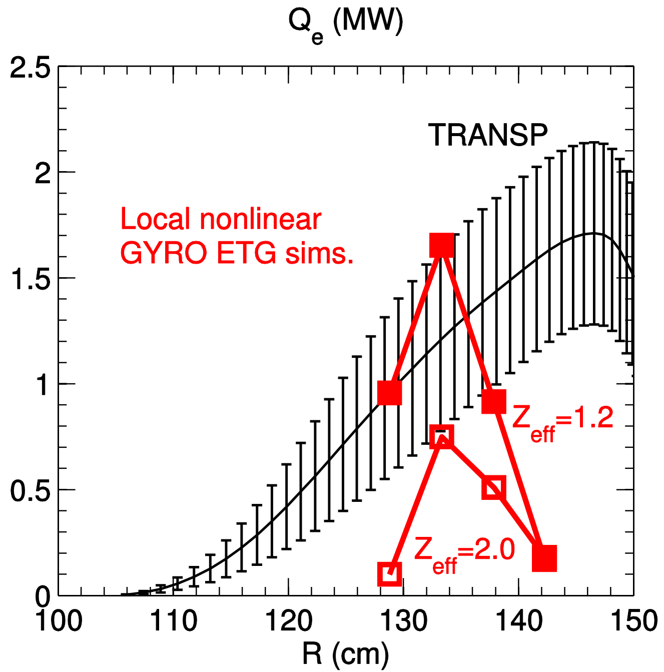



*GYRO (Candy, Waltz, 2003)

# Nonlinear ETG simulations give significant transport around mid-radius (R=129-140 cm, ρ=0.47-0.67)

- $Q_{e,etg}$ large enough to account for $Q_{e,exp}$ if $Z_{eff}=Z_{eff,c}\approx 1.2$
  - Larger $Z_{eff}$ (VB $Z_{eff}\leq 2$) would lower $Q_{e,etg}$
- New high-k microwave scattering diagnostic will be ideal for probing region of ETG turbulence
- *May require multiscale simulations for validation*



ρ ≈ 0.45 0.55 0.65 0.75

# Summary: L-modes established during NSTX-U commissioning being used for transport validation

**_Experiment_**

- Electrons carry majority of heat flux, ion transport ~ neoclassical
- BES measures strong, broadband ($f \leq 200$ kHz) ion-scale turbulence with bi-modal propagation (caveat of possible edge shadowing)

**_Simulation_**

- ITG & MTM are unstable at ion scales ($k_\theta \rho_s < 1$), $E \times B$ shearing is strong with significant radial variation $\rightarrow$ motivates global GK benchmarking and validation
- Significant electron-scale ($k_\theta \rho_s > 1$) ETG transport predicted at midradius where $\gamma_E > (\gamma_{ITG}, \gamma_{MTM}) \rightarrow$ may also require multiscale simulations

- *Acknowledgements: This research used resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.*

# At ion scales ($k_\theta\rho_s$<1), linear GYRO* simulations predict unstable spectra of ITG and microtearing modes (MTM)

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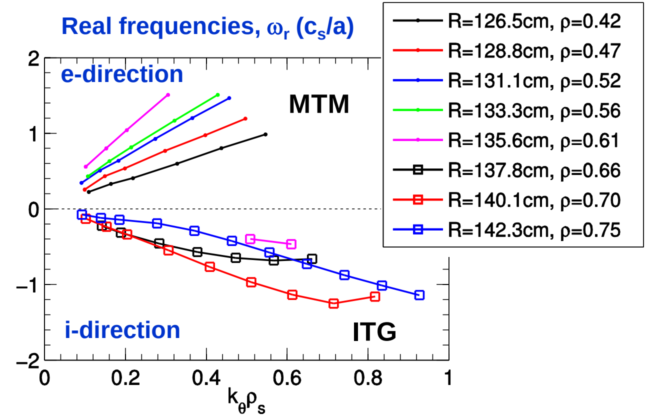
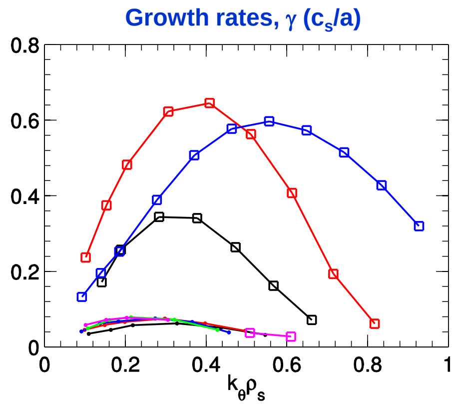
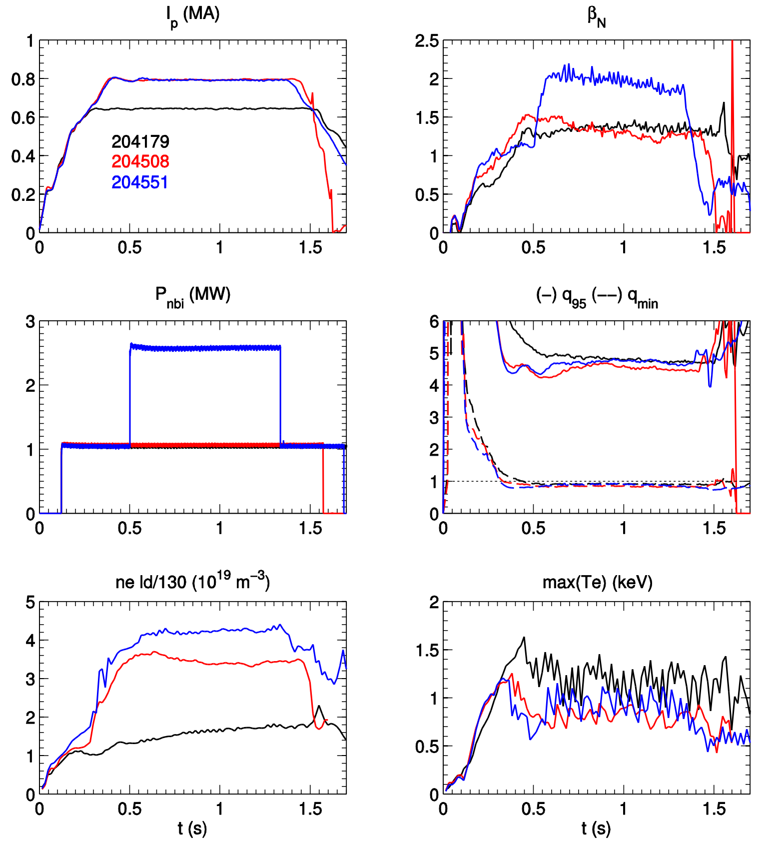


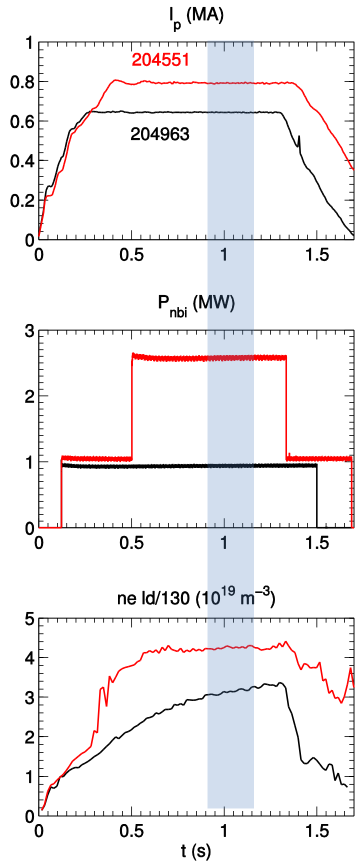

*GYRO (Candy, Waltz, 2003)

# NSTX-U L-modes established over range of density, plasma current, neutral beam power & tangency radii

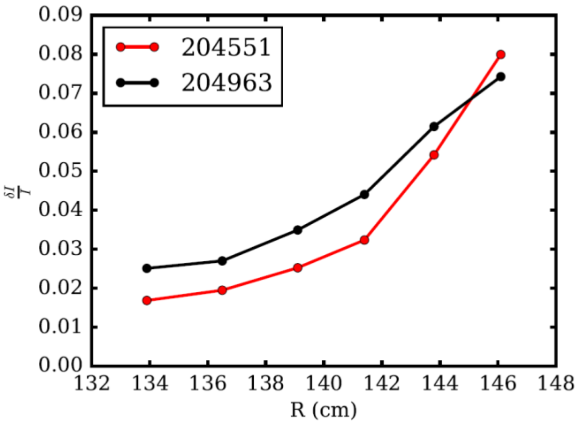
- Established stationary, stable L-modes during commissioning (spring 2016)
  - $\langle n_e \rangle$=1-4×10$^{19}$ m$^{-3}$
  - $I_p$=0.65-1.0 MA ($B_T$=0.65 T)
  - $P_{NBI}$=1-3 MW
  - 2$^{nd}$ NBI sources (bigger $R_{tan}$) had noticeable effect on rotation, tearing stability, locked modes
- Sustained shots up to 1.5 sec with 2.5-2.9 MW, $\beta_N \leq 2$ with different combination of beam sources
  - Used HFS fueling to raise density and avoid L-H transition
  - Tried up to 4.3 MW but H-mode or disruptions occur ($\beta_N$~2.5)
- All shots sawtoothing ($R_{inv}$~125 cm, $\Delta$t~25-35 ms depending on NBI source and plasma density)

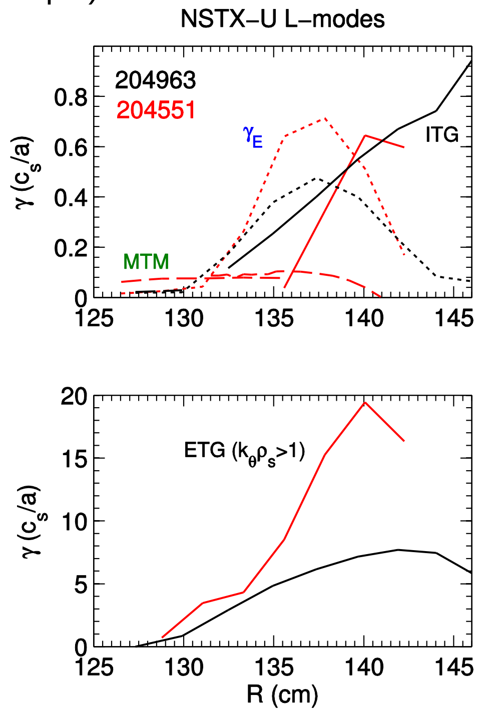


# Have repeated analysis on lower $I_p$, $n_e$, $P_{nbi}$ discharge 204963, Qualitative similarity ion scale fluctuations and microstability

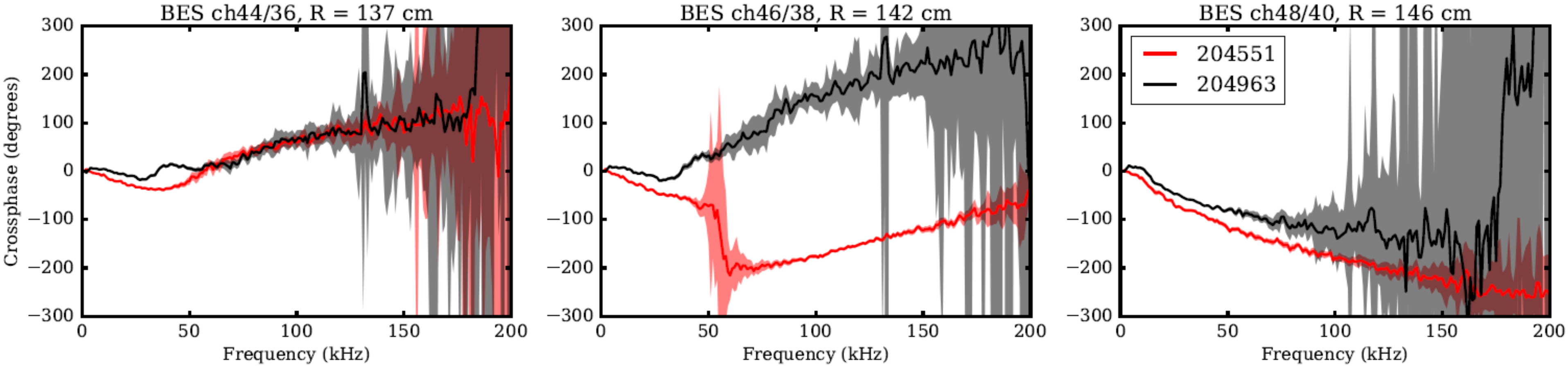



- Larger low-k fluctuation amplitudes in 204963, cross-phases similar to 204551
  - 16 channel UCLA reflectometer data also available for this shot
- $\gamma_{ITG}$ larger due to reduced $T_i/T_e$ & $\gamma_E$ reduced (less beam torque)
- $\gamma_{MTM}$ weaker (lower $\beta_e$)
- $\gamma_{ETG}$ weaker (reduced $T_i/T_e$, $R/L_{Te}$)



# Evidence for dual-modes found in multiple discharges



# Shot parameters

| Shot | Time (s) | $B_T$ (T) | $I_p$ (MA) | $P_{NBI}$ (MW) | $n_e$ | $W_{MHD}$ (kJ) | $q_{95}$ | $\beta_N$ | $\beta_T$ (%) | $\kappa$ | $l_i$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 204551 | 0.9-1.2 | 0.63 | 0.79 (0.8) | 2.6 (1A+1B) | 4.3 | 95 (105) | 4.8 (4.5) | 2.0 (2.1) | 4.1 (4.4) | 1.7 (1.8) | 1.3 (1.1) |
| 204651 | 0.9-1.1 | 0.63 | 0.64 (0.65) | 1.0 (1C) | 3.1 | 42 (63) | 5.1 (5.2) | 1.1 (1.6) | 1.9 (2.8) | 1.7 (1.7) | 1.5 (1.2) |
| 204963 | 0.9-1.1 | 0.63 | 0.64 (0.65) | 0.94 (1B) | 3.1 | 62 (80) | 5.5 (5.5) | 1.7 (2.1) | 2.8 (3.6) | 1.7 (1.7) | 1.3 (1.1) |

- EFIT01 (EFIT02)