NSTX

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Transport and Turbulence Physics Progress and Plans

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NSTX PAC-29
PPPL B318
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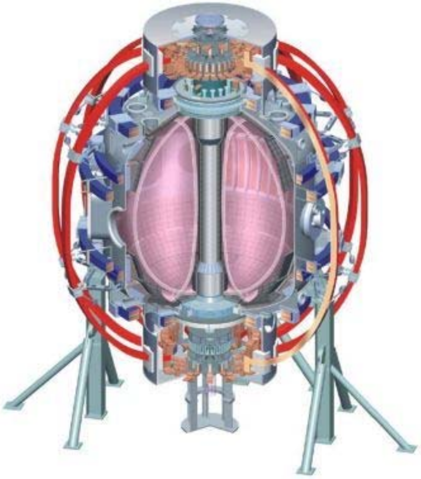

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Outline

- Motivations of NSTX Turbulence and Transport (T&T) research.
- Recent results and plans for FY11 and FY12
- Activities during NSTX upgrade period (FY13 and FY14)
- Summary

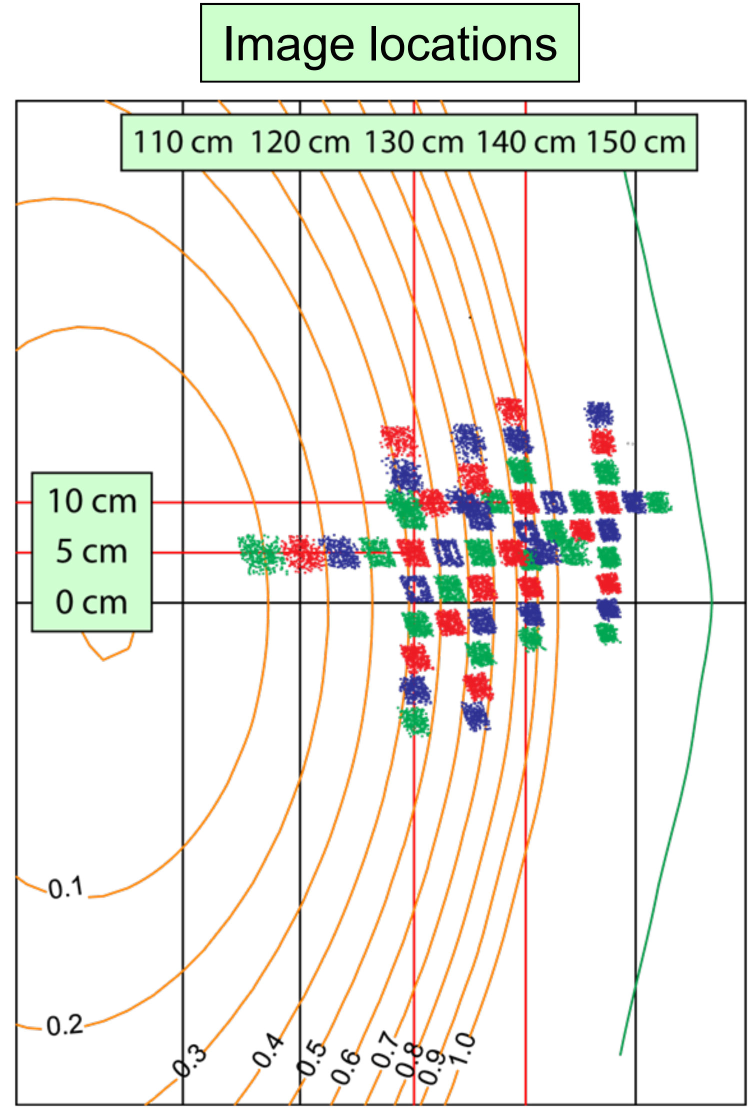
NSTX Accesses a Unique Parameter Regime to Address T&T Issues Crucial for Future ST and non-ST Devices

- Strong ExB flow shear: decoupling of the electron and ion channels (ions close to neoclassical in H-mode) to study electron thermal transport
- Achievable range of β_T can lead to significant EM contribution: Assessing magnetic flutter effect, *e.g.* micro-tearing turbulence
- Large ρ_e makes localized electron-scale measurement possible

- Validating physics models over a wide range of operating space (B_T, Ip, ν_e*, etc.) for NSTX-U and future devices
  - Validating gyro-kinetic models for electron transport by varying β_e and ν_e*: μ-tearing (high β_e, ν_e*) and ETG (low β_e, ν_e*) with both high and low k measurements
  - Validating GAE electron transport model by varying B_T and P_{NBI}

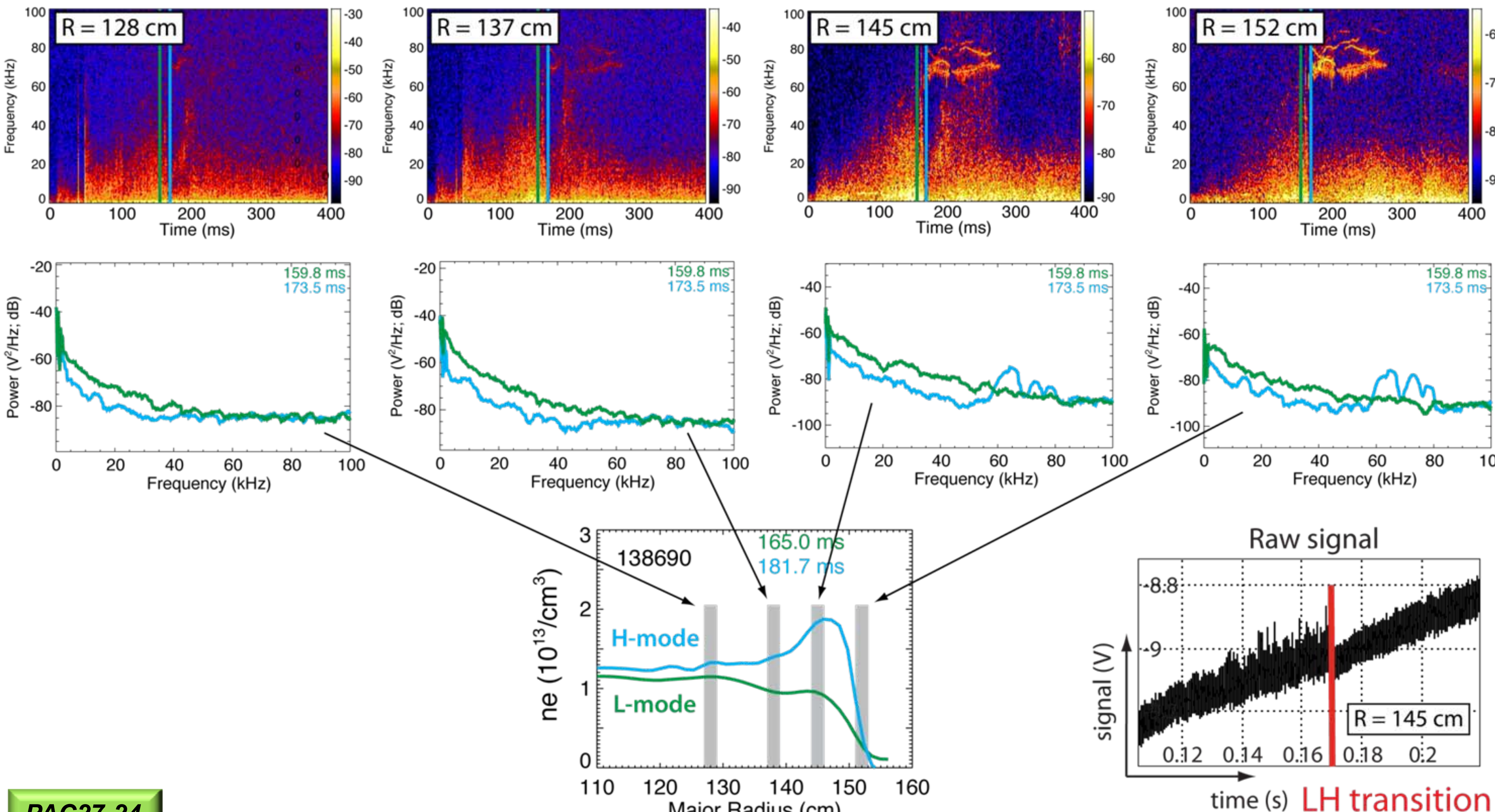
BES Diagnostic System Commissioned in 2010 with up to 24 Detection Channels

- Measures Doppler-shifted D_α emission from neutral beams
- Radial coverage from r/a~0.1 to beyond LCFS with 2-3 cm spot size
- 56 fiber views
- Fiber layout includes radial and poloidal arrays and 2D grids
- Digital anti-alias FIR filter eliminates photodetector e-noise > 1 MHz
- 32 detection channels planned for 2011



R. Fonck, G. McKee, D. Smith, and I. Uzun-Kaymak (UW-Madison) and B. Stratton (PPPL)

BES Observed Decrease in Fluctuations at L-H transition from Edge to Core Regions

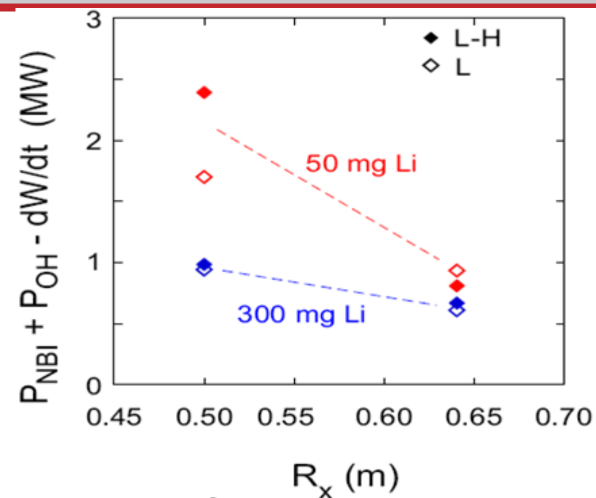


PAC27-24

R. Fonck, G. McKee, D. Smith, and I. Uzun-Kaymak (UW-Madison) and B. Stratton (PPPL)

L-H Transition Study on NSTX Characterizes both Power Threshold and Turbulence

- P_{LH} decreases with R_X and Li deposition
  - Consistent with XGC-0 predicted E_r well depth
  - B_T at X-point location is important in determining P_{LH}
  - Plan to study the effect of X-point height and to investigate P_{LH} dependence on B_{TX} with XGC-0



- k_r backscattering measurements from improved reflectometer show turbulence suppression at the Electron Transport Barrier (ETB) location (R≈146 cm) after L-H transition

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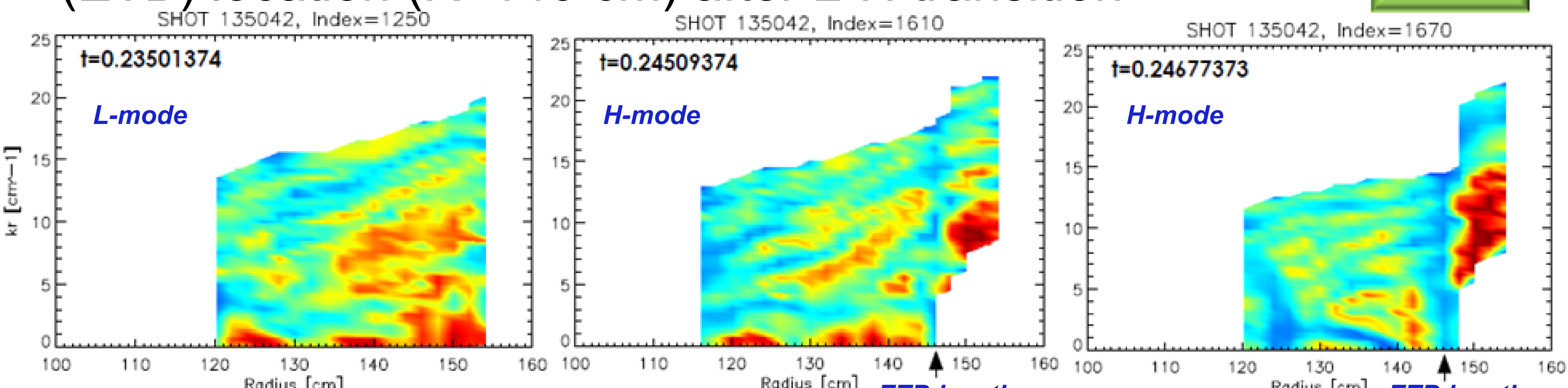
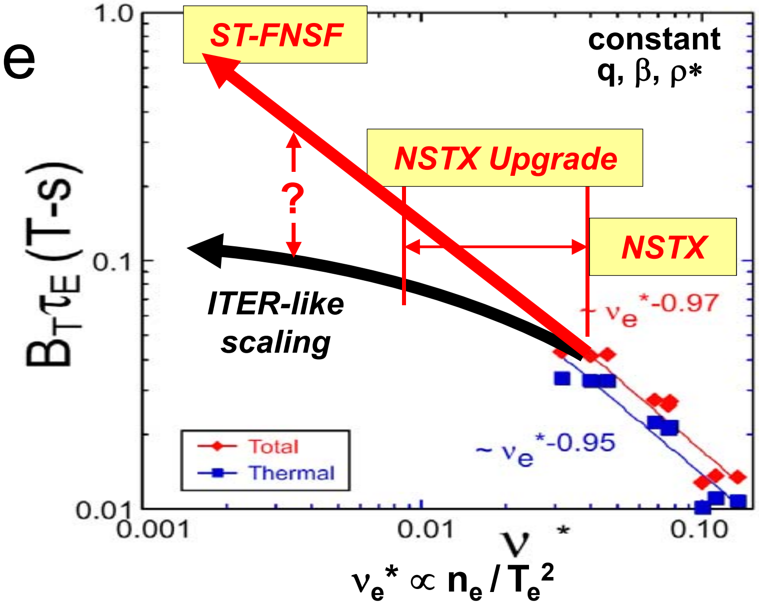
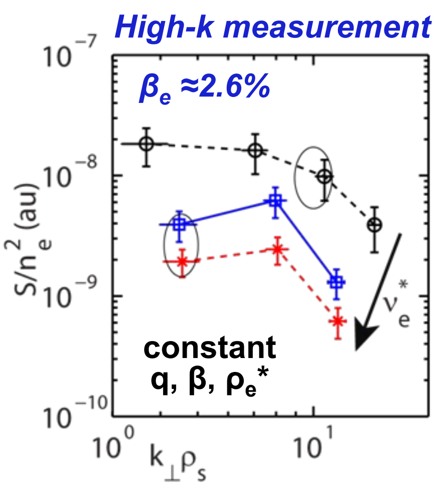
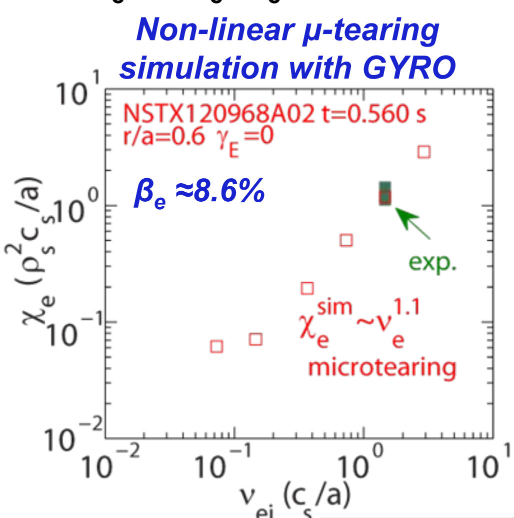


Coupling of Measurement and Simulations is Improving Understanding of NSTX ν_e^* Confinement Scaling

- $B_T \tau_E \propto \nu_e^{*-1}$ observed in NSTX H-mode
- Non-linear μ-tearing simulations indicate $\chi_e^{sim} \propto \nu_e^*$
- High-k measured fluctuation power decreases with ν_e^* (R11-1, TC-10)
  - ETG linearly unstable, high-k scaling consistent with ETG predictions
  - Unclear how sensitive high-k scattering is to μ-tearing
- μ-tearing (high β_e, ν_e^*) and ETG (low β_e, ν_e^*)
  - BES, high-k and/or k_r back-scattering
  - R11-1, TC-10, 2012 JRT



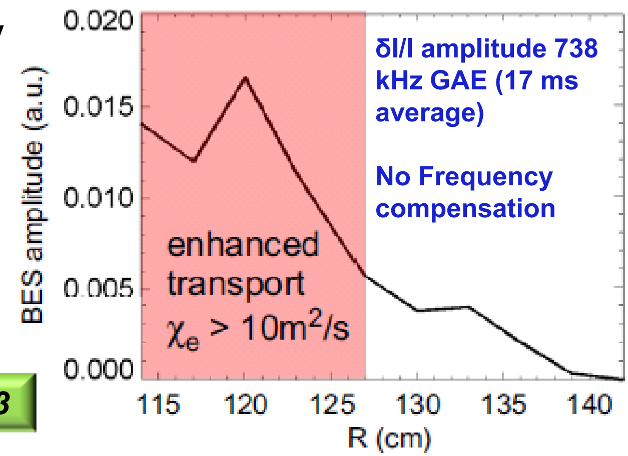




PAC27-23

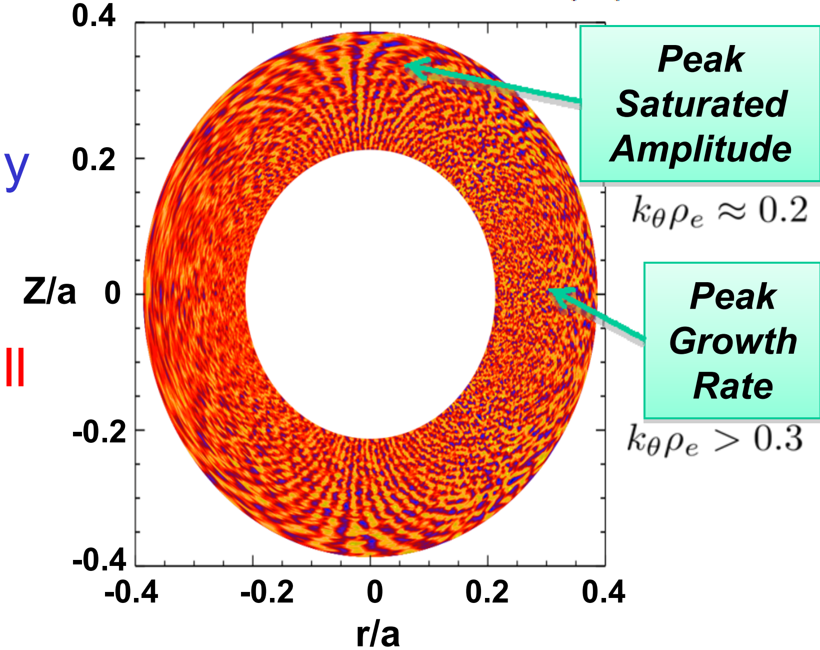
NSTX is also Exploring Other Mechanisms of Electron Thermal Transport (R11-1, TC-10, 2012 JRT)

- BES measured Global Alfvén Eigenmode (GAE) peak amplitudes consistent with numerically simulated electron thermal transport
  - BES calibrated mode structures and amplitudes for future ORBIT simulations
  - To investigate robustness of physics with constant-q B field scan and P_{NBI} scan



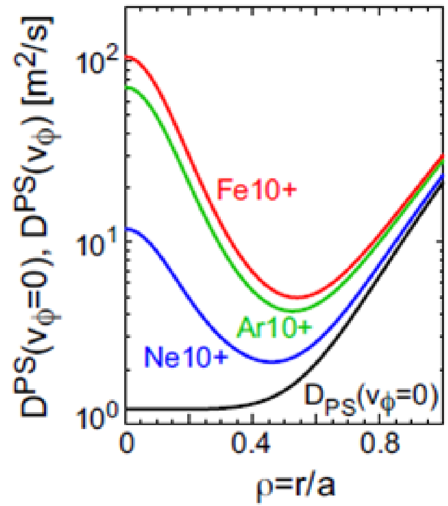
PAC27-23

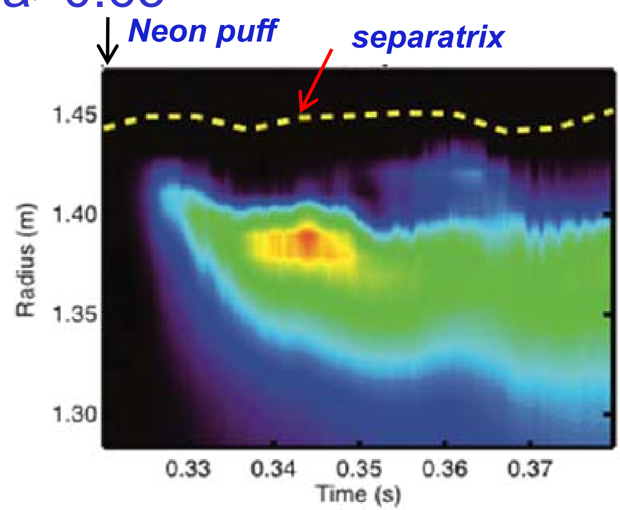
- ETG is identified in NSTX reversed shear plasmas
  - Off-mid-plane ETG streamers nonlinearly driven by mid-plane unstable ETG with steep T_e profile (nonlinear GYRO)
  - High-k measurement at off-mid-plane will be conducted
    - High-k scattering at Z/a≈-0.3 possible
    - Shifting magnetic axis will be tried.



Impurity Transport Studies will Exploit New Diagnostics and Modeling Capabilities (R11-1, 2012 JRT)

- Neon diffusivity neoclassical in the core accompanied by some anomalous convection
  - Under-resolved at the edge and suffered from low signal
- Plasma rotation enhancing core impurity transport without invoking low-k turbulence
- New Multi-Energy Soft X-Ray diagnostic in 2010
  - ~1 cm resolution; <100 μs response; high SNR; r/a>0.65
- STRAHL transport code being used
  - Neoclassical calculation embedded; Up-to-date atomic data
- Impurity transport study at plasma edge
  - Carbon build up in ELM-free discharges
  - Z dependence of impurity transport
  - Measure edge turbulence and its relation to impurity transport (BES, High-k, reflectometer etc.)



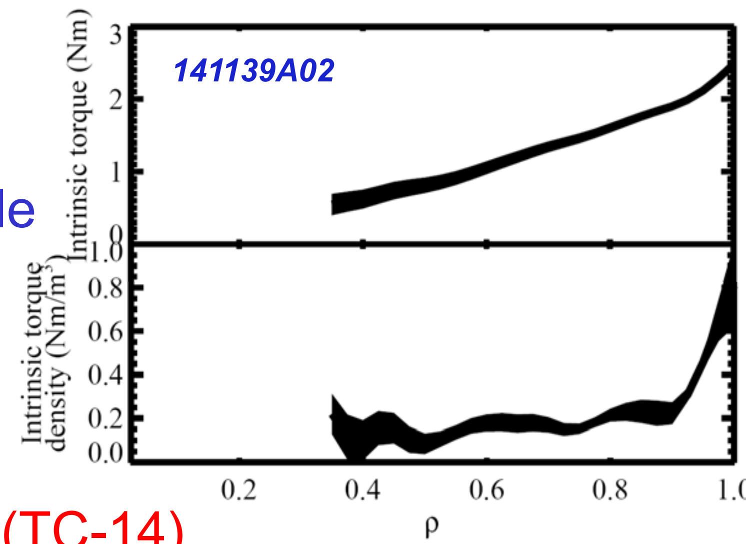


H-, He-like Neon

PAC27-25

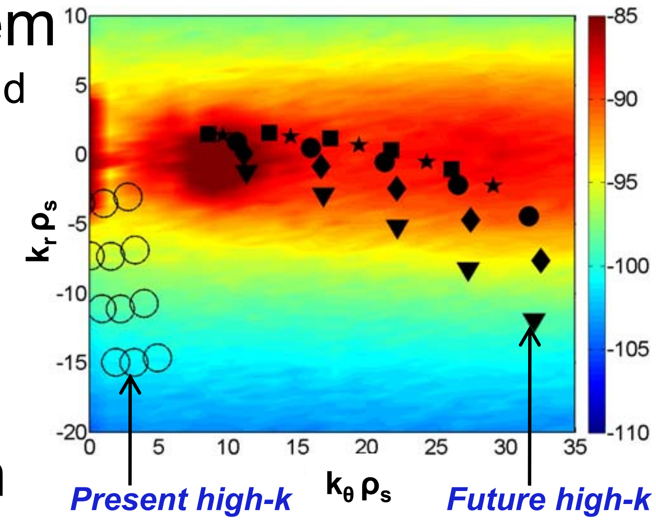
NSTX is Participating in ITPA JEX Studying Intrinsic Torque

- Preliminary results indicating higher and more edge-localized intrinsic torque in NSTX than in DIII-D (TC-9)
  - Qualitatively similar torque profile as observed on DIII-D
- Understanding the mechanism of intrinsic torque is important for ITER
  - Projection and optimization of rotation profile
- Plans for FY11 and FY 12:
  - Characterize role of turbulence in driving intrinsic rotation (R11-1)
  - Modification to intrinsic drive by RF/HHFW (TC-14)
  - Interaction of intrinsic drive with other torques (*e.g.* NTV)
  - Contribute data to ρ* scaling experiment (TC-17)
  - Look for signature of thermal ion orbit loss

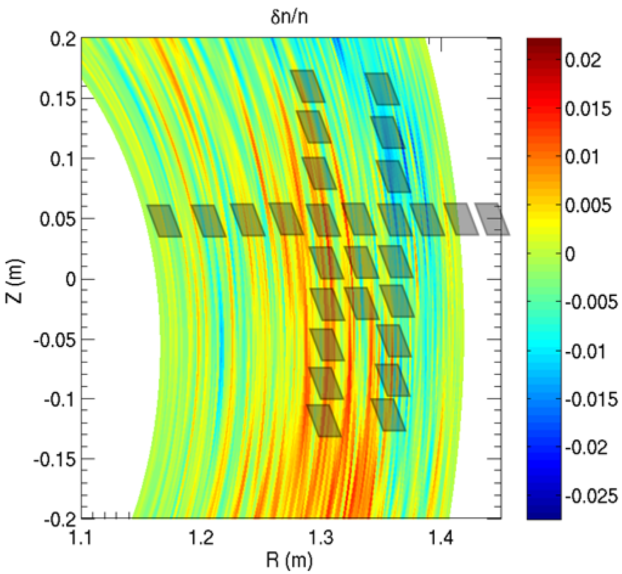


T&T TSG Activities for FY13 and FY14

- Current high-k_r scattering system will be removed to install the 2nd NB during upgrade
  - Design of a new high-k scattering system is in progress and will be completed during FY13 and FY14
- Extensive comparison between measurements and micro-instability calculations including GYRO, GTS, GS2, GTC-NEO
  - Use synthetic diagnostics to compare simulated and measured fluctuating quantities and their spectral characteristics



k space coverage for the present and future high-k scattering systems with ETG k spectrum (non-linear GYRO, NSTX L-mode)



BES views with micro-tearing density fluctuations (nonlinear GYRO NSTX H-mode)

NSTX will Provide Physics Basis Leading to Predictive Capability for Transport in Future ST/AT Devices

- Newly commissioned BES and ME-SXR diagnostics complement an extensive set of fluctuation instruments
  - High-k_r microwave scattering, GPI (gas-puff imaging), radial and poloidal correlation reflectometers, high bandwidth infrared interferometer (FIReTIP)
- Fluctuation measurements covering both high and low k coupled with nonlinear simulations will improve our understanding of:
  - Physics mechanisms influencing H-mode confinement at low aspect ratio
  - Processes that drive electron transport
  - L-H transition and changes in turbulence over the entire plasma profile
  - The role of turbulence on Intrinsic torque and momentum transport
  - Impurity transport studies
- FY11 T&T milestone well suited to the goal of providing an extensive set of fluctuation measurements to further understanding of thermal, momentum, particle, and impurity transport processes

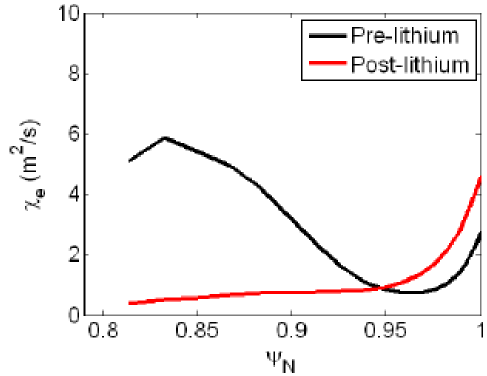
Backup Slides

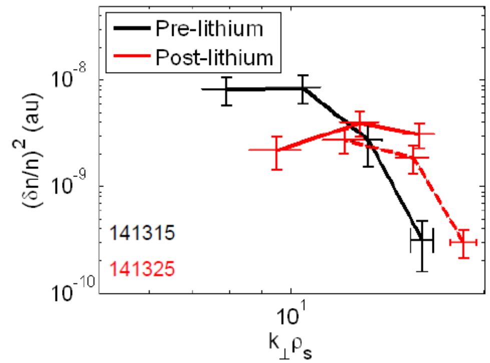
NSTX Efforts Towards PAC27 T&T Recommendations

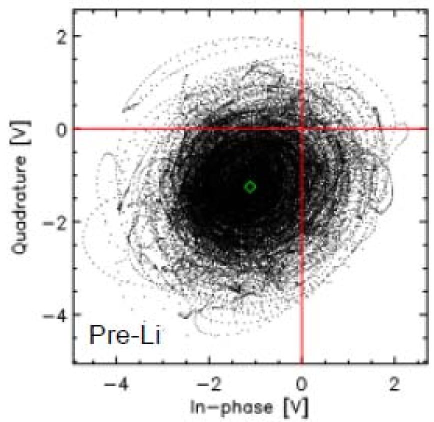
PAC27-22	It has been shown that the improvement of confinement with Lithium operation is due to a local decrease of the electron heat diffusivity. This clearly answers a PAC recommendation, though it would be interesting to know more about the reasons why this local improvement occurs.	Recent experiments has found a decrease in χ_e on the top of the pedestal as more Lithium is introduced. Reflectometer measurements have shown a ten-fold decrease in density fluctuation with Lithium. High-k measurement showed some decrease in fluctuation power at $k_\perp \rho_s$<10.
PAC27-23	The near-term program will continue to investigate the respective role of different candidates (ETG, micro-tearing modes, and GAEs) to explain electron turbulent transport. With respect to the planned upgrade, it would be interesting to see the parametric dependence of the observed ETGs and GAEs on Bt and Ip to see if the different confinement scaling can be related to the proposed transport mechanisms.	An investigation of high-k turbulence dependence on electron collisionality shows that the measured high-k turbulence power actually decreases with increasing collisonality, which seems to scale differently than NSTX H-mode scaling. However, recent nonlinear micro-tearing simulations using GYRO are able to reproduce the experimental scaling. Measurement of micro-tearing turbulence using BES, high-k scattering system and backscattering system will be conducted to identify micro-tearing instability. Study of the dependence of GAE on Bt and Ip will be conducted in FY11 and FY12.
PAC27-24	The work that has been done on the L-H transition is interesting, in particular regarding hysteresis and the parametric dependences of the power threshold. The experiments that are planned should bring more information, and the PAC looks forward seeing these results. It is of particular importance to go beyond threshold scaling experiments and characterize also the fluctuations in order to understand the triggering mechanism for the transport barrier.	Recent L-H threshold experiment has shown that the L-H power threshold decreases with increased R_x, which is consistent with XGC-0 predictions for the E_r well depth. Measurements by a backscattering diagnostic using FWCW reflectometer shows that high-k_r fluctuation power is suppressed at ETB location after L-H transition.
PAC27-25	Overall, it is certainly important to clarify the issues related to edge turbulence and its interplay with core turbulence, in view of the operation of NSTX with Li-coated PFCs. Regarding this point and the possible implementation of Molybdenum tiles, the PAC recommends intensifying the study of impurity transport and investigating possible solutions (e.g., external coils, RF heating) to prevent impurity accumulation.	The impurity transport study using Neon gas puff in 2009 found that the Neon diffusivity in the plasma core is neo-classical accompanied by some anomalous convection. However, it was unclear for the plasma edge due to poor radial resolution and low signal level of the SXR diagnostic used. A new ME-SXR diagnostics, commissioned in 2010, is capable to study impurity study at the plasma edge with ~ 1cm spatial resolution, >10 kHz frequency response and high SNR.

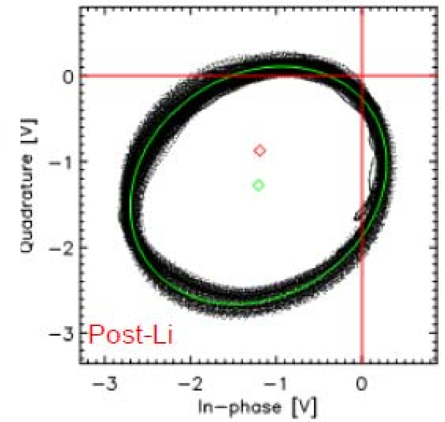
Electron Transport Reduced by Lithiated PFC

- Lithiated PFC leads to broadened T_e profile, corresponding to reduced pedestal-top χ_e
  - Reduction of turbulence at $k_\perp \rho_s$ <10 measured by high-k scattering
  - Turbulence level reduced from ~10% to ~1% with lithium measured by reflectometer
- Plan to investigate how fluctuation changes in the core







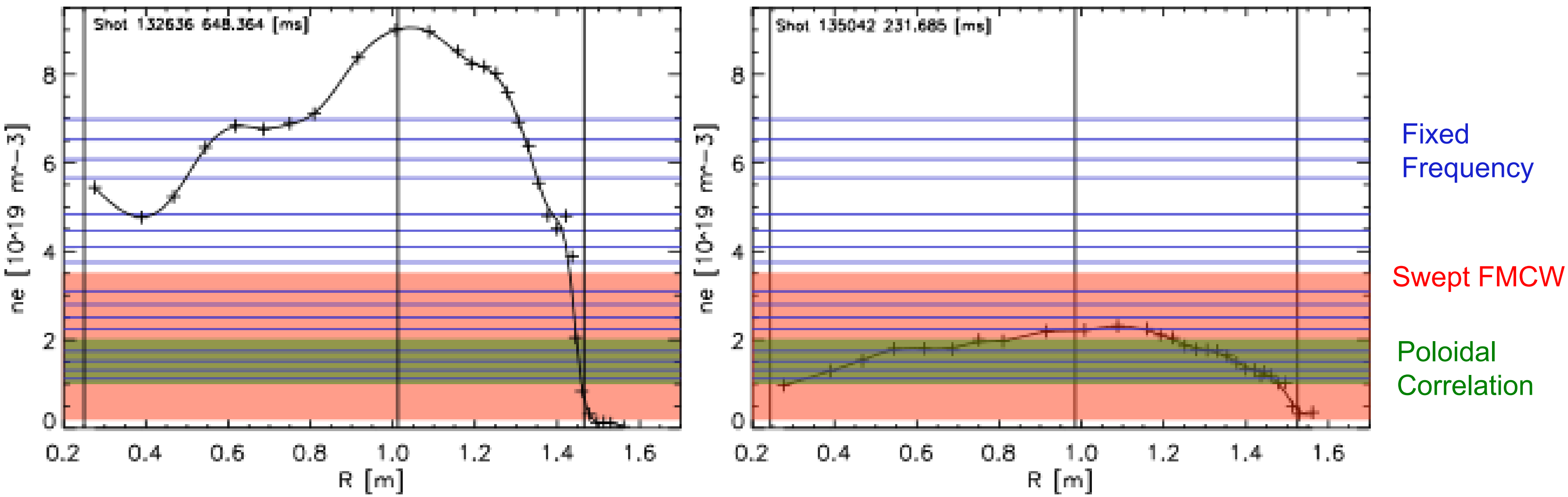


PAC27-22

UCLA Reflectometers on NSTX

Millimeter-wave reflectometers available for 2010 (Bay J mid-plane)

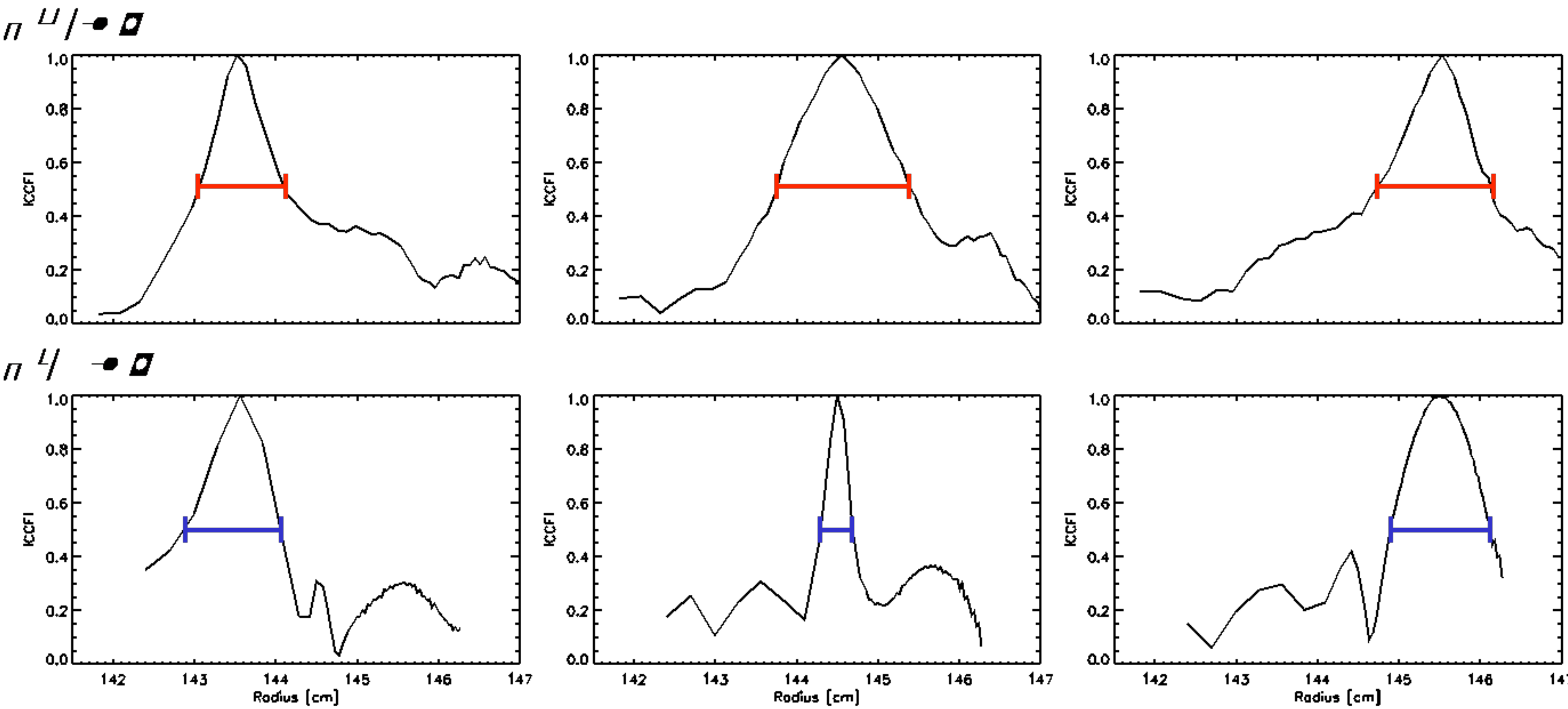
- Ultra-fast swept FMCW reflectometers coupled with new analysis techniques
  - Electron density profiles with ≥4 μs time resolution, 13-53 GHz
  - Sub-millisecond turbulence radial correlations
  - k_r back-scattering with radial resolution
- Poloidal correlation reflectometer (2 channel, 28.5-40 GHz)
  - Turbulence flow
  - Poloidal correlations
  - k_r back-scattering with radial resolution
- 16 channel fixed-frequency reflectometers (30 to 75 GHz)
  - Detailed profile of coherent and turbulent fluctuation levels (2.5 MHz bandwidth)



Ohmic L- to H-Mode Transition

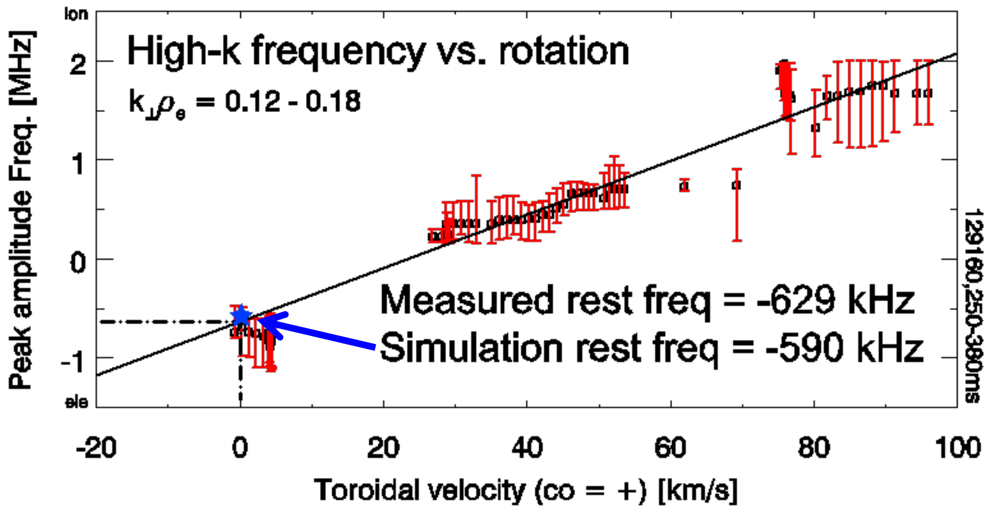
Turbulence radial correlation length decreases prior (<1 ms) to L- to H-mode transition

- Change only seen localized at ETB location R~144.5 cm
- Utilizes FMCW correlation reflectometer with <1 ms resolution
- Consistent with previous k_r backscattering measurements which show "all k_r" turbulence suppressed around ETB location

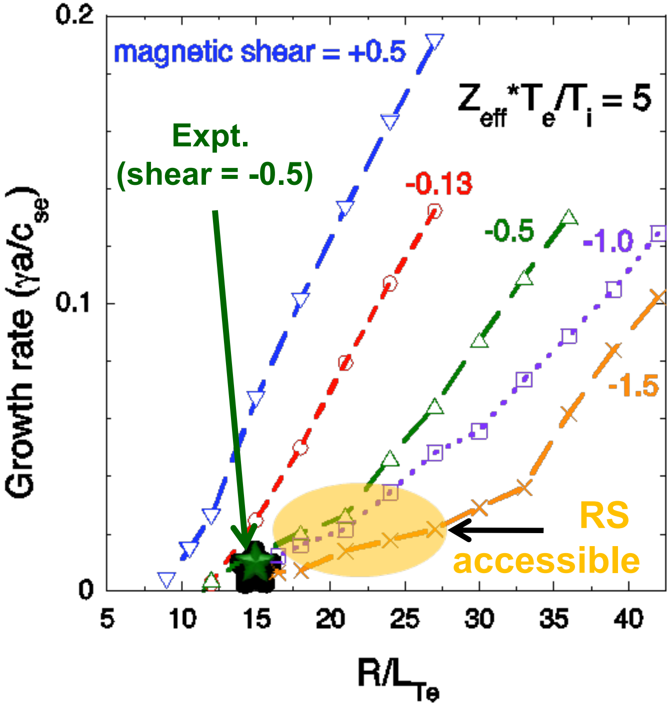


ETG believed to be important for driving anomalous electron transport

- ETG mode has been identified by comparing linear growth rate and rest frequency of measured fluctuations to linear GS2/GYRO calculations
- ETG in e-ITB found to be suppressed by reversed magnetic shear, allows access to supercritical electron temperature gradients



Rest frequency of peak amplitude mode measured by subtraction of Doppler shift due to plasma rotation

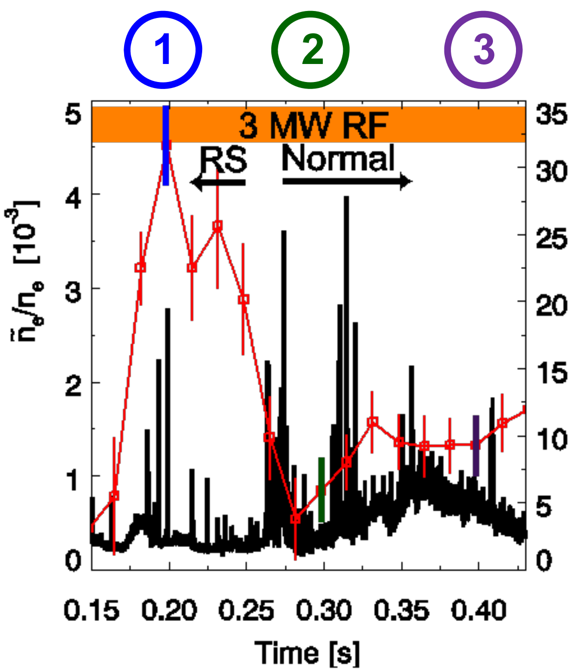


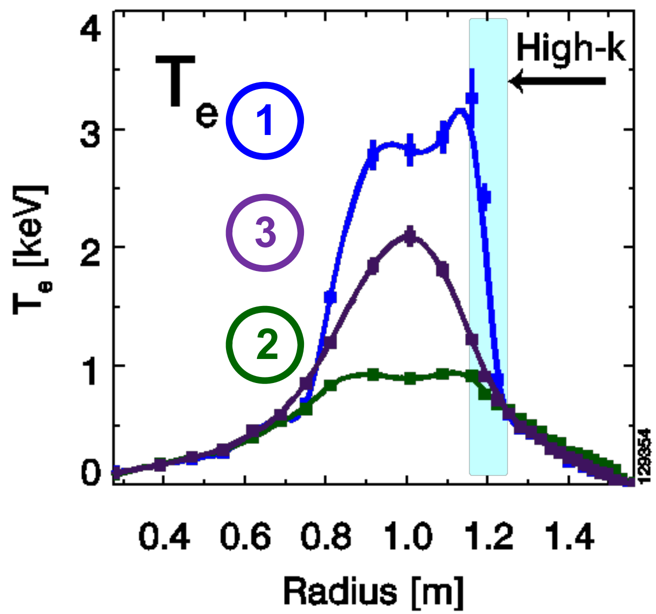
Linear GS2 / GYRO simulations of ETG mode growth rates are consistent with high-k measurements

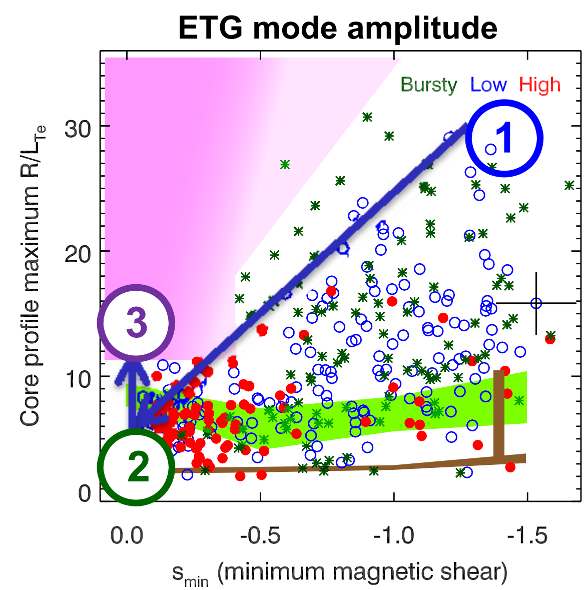
PAC25-22

Reversed shear suppresses mode growth even at supercritical ETG gradients during e-ITBs

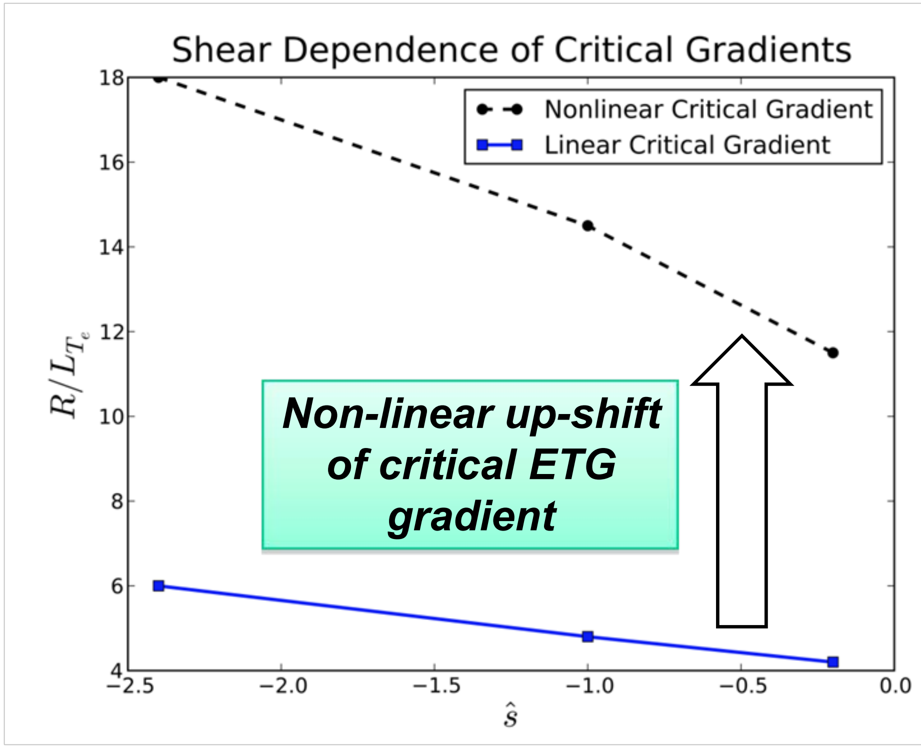
1. Intermittent, short duration bursts of ETG observed during RS phase
   - Average ETG mode amplitude low, T_e gradient well above ETG critical
2. A series of large amplitude, closely spaced in time bursts of ETG collapses Te profile
   - Magnetic shear becomes zero/positive due to anomalous current redistribution
3. T_e profile can only be reheated to ETG critical gradient at zero shear
   - ETG mode amplitude grows to a moderate continuous level

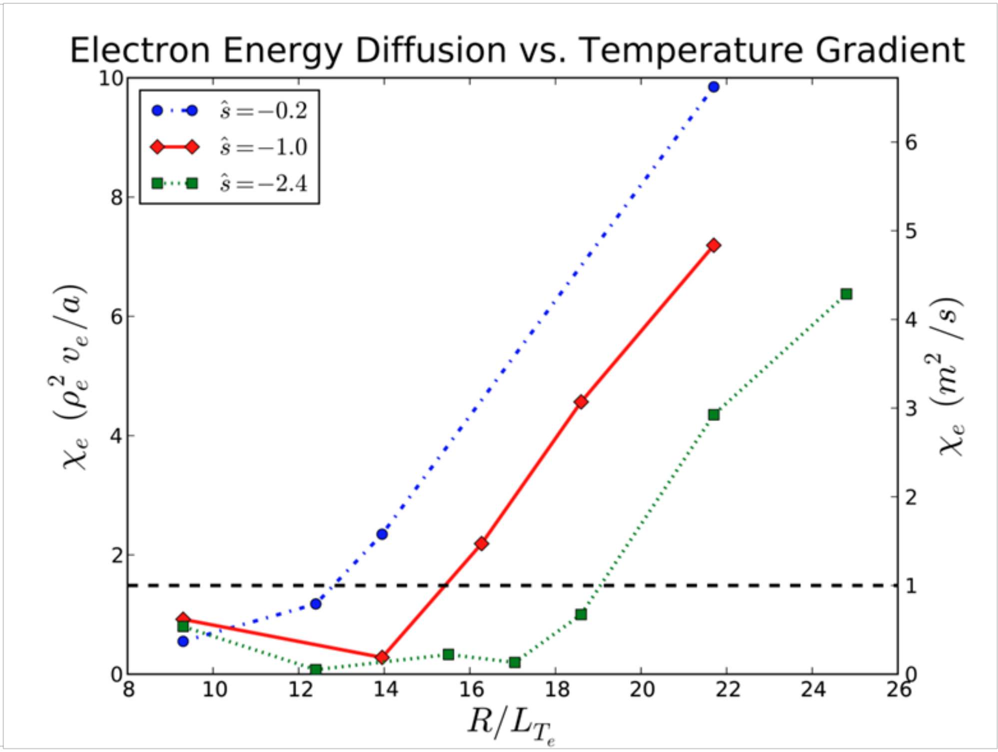






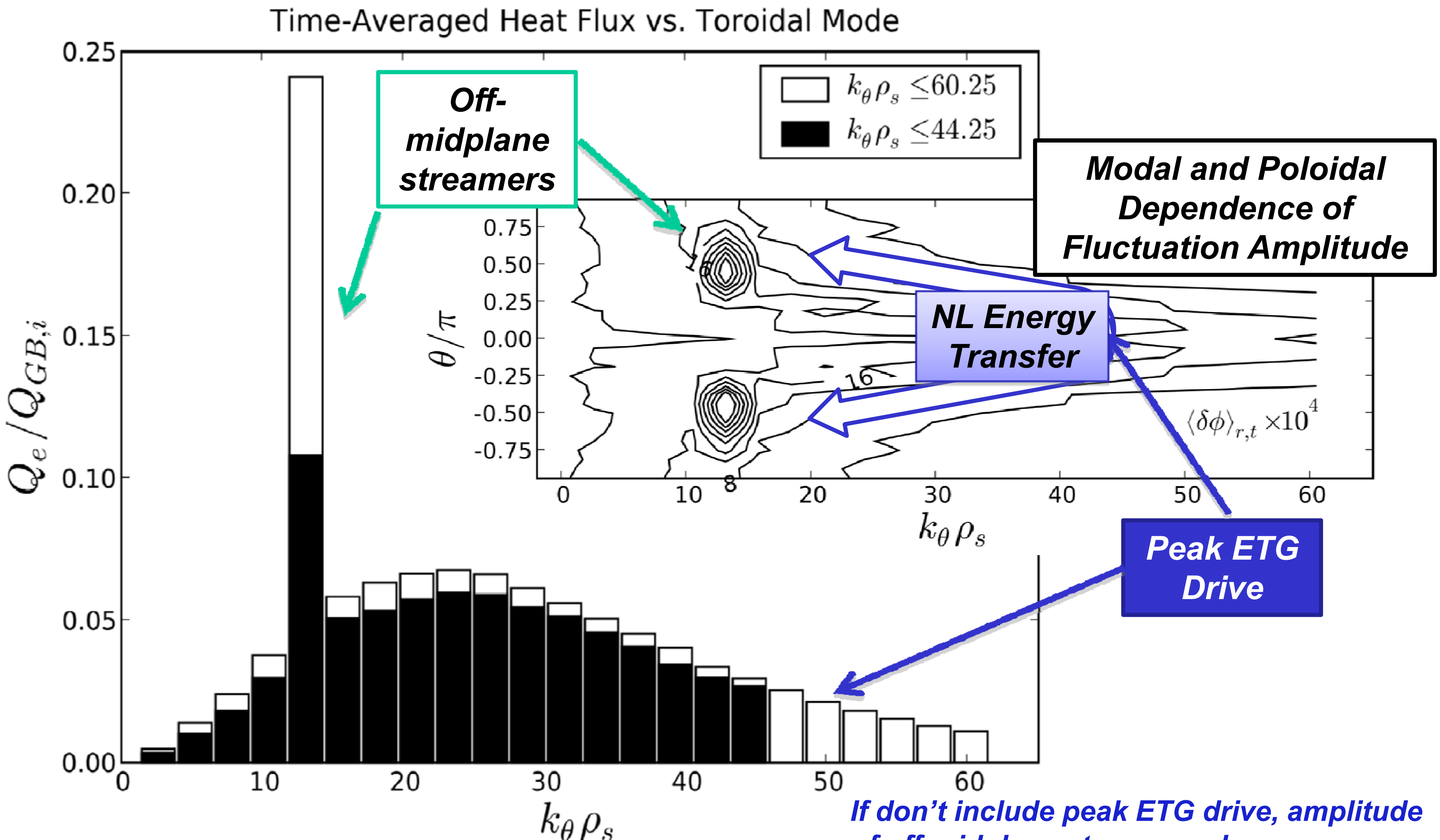
Nonlinear GYRO Simulations of NSTX Reversed Shear Show Strong Up-Shift of Critical Gradient for ETG Turbulence





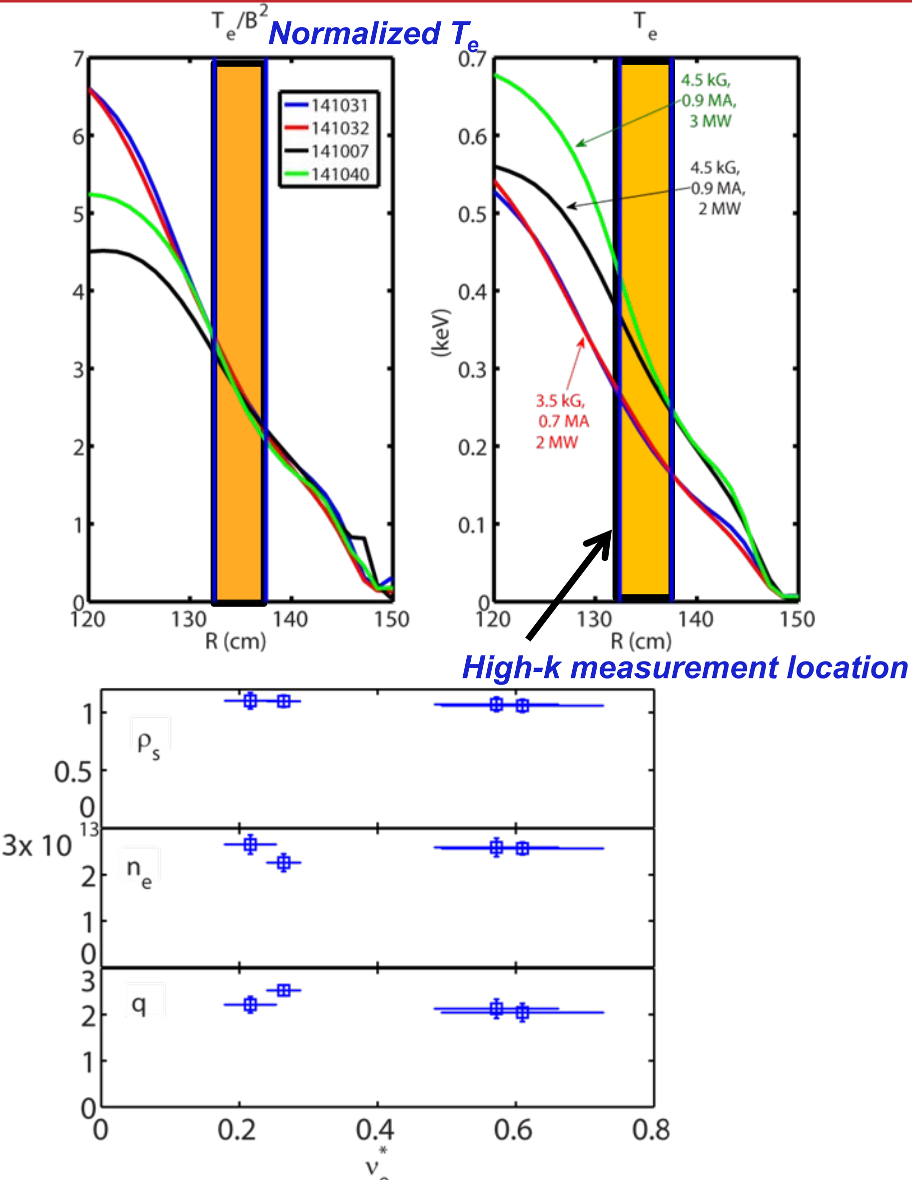
Scan in shear and electron temperature gradient for NSTX e-ITB baseline parameters
Nonlinear critical gradient for transport has large up-shift during reversed shear

Evidence of Energy Transfer to Off-Midplane Streamers



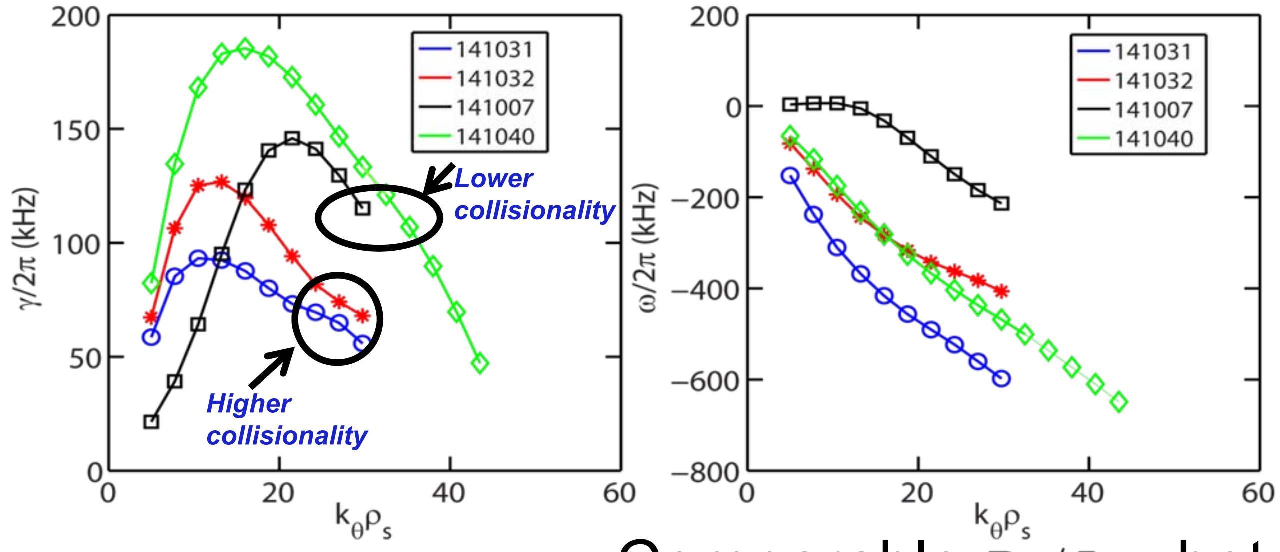
If don't include peak ETG drive, amplitude of off-midplane streamers drops.

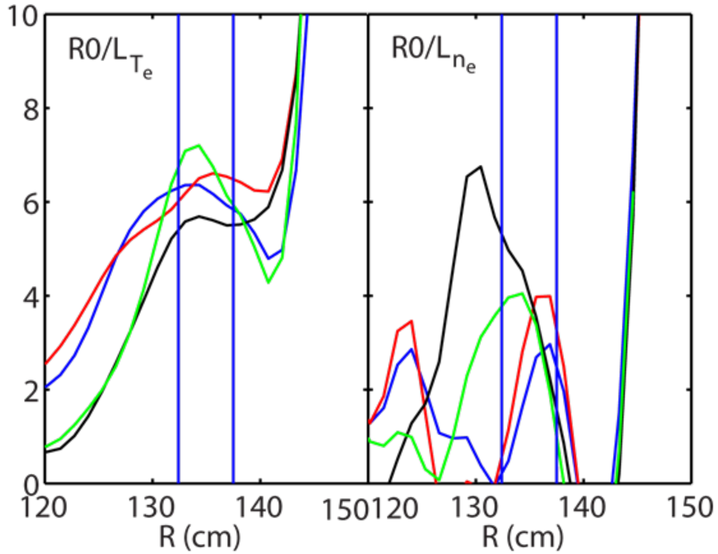
A Factor-of-Three Local Collisionality Scan Achieved



- **Time points chosen so that $T_e \propto B^2$ was well maintained from R=130-145 cm: local ν_{e*} was varied with constant ρ_e and β_e**
- **I_p and B_T were varied with a constant ratio to keep constant q**
- **Neutral beam power was adjusted to have a better match in T_e profile.**
- **The scan was carried out with (I_p(MA), B_T (kG))=(0.7,3.5), (0.9, 4.5) and (1.1, 5.5)**
- **(1.1 MA, 5.5 kG) shots have much high density and Z_{eff} and are not used.**
- **Factor of three change in ν_{e*} is achieved**
- **ρ_s , n_e and q have only small variations against ν_{e*}**

ETG Turbulence Linearly Unstable in all These Discharges





- Comparable R_0/L_{n_e} between these shots
- Maximum ETG growth rates are higher for the lower collisionality cases, the same trend as wavenumber spectral power
- Nonlinear simulations will be conducted

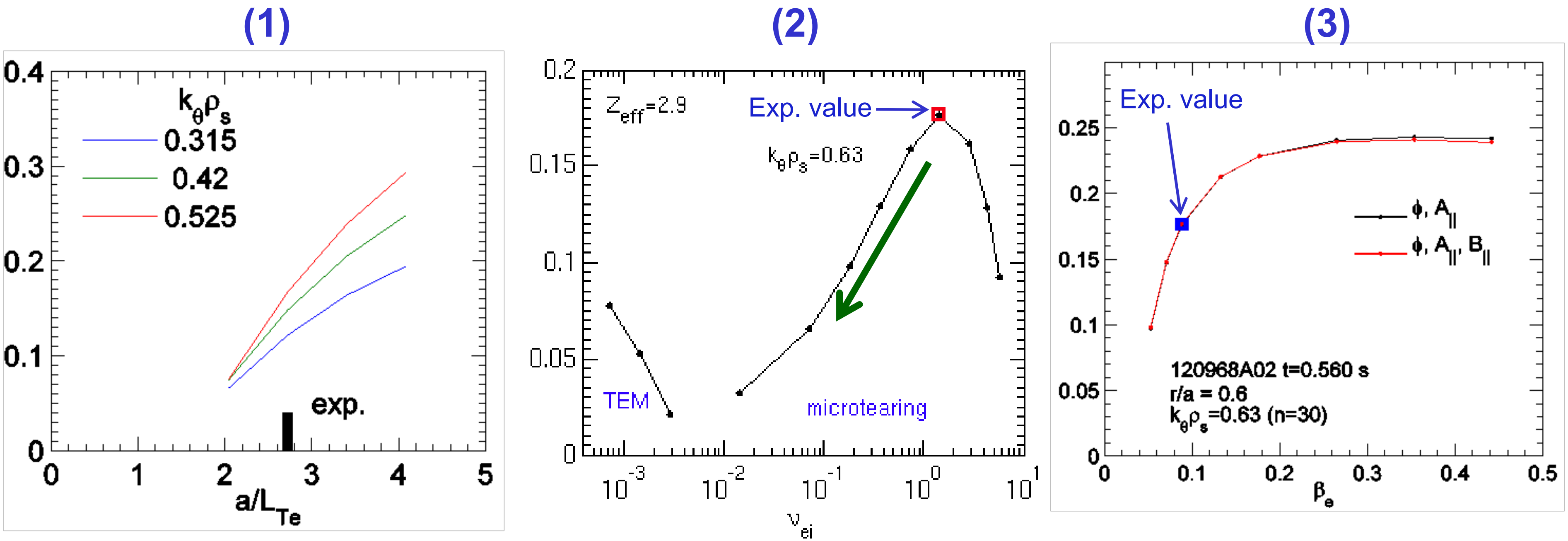
Microtearing instability exhibits thresholds in electron temperature gradient, collisionality and beta

(1) Apparent threshold in ∇T_e, $(a/L_{Te})_{crit} \approx 1.3\text{-}1.5$ $(a/L_{Te,exp}=2.7)$

(2) Growth rates decrease with $\nu_e < \nu_{e,exp}$ (consistent with experimental ν_* scan)

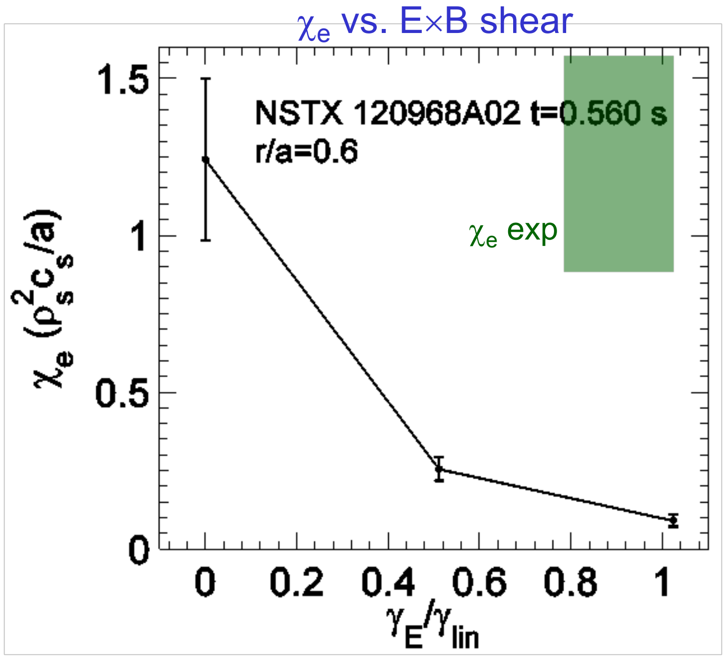
(3) Lowering beta stabilizes microtearing

Linear growth rates ($\gamma \cdot a/c_s$) for NSTX 120968 t=0.56 s r/a=0.6



Nonlinear microtearing transport comparable to experimental transport*

- 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

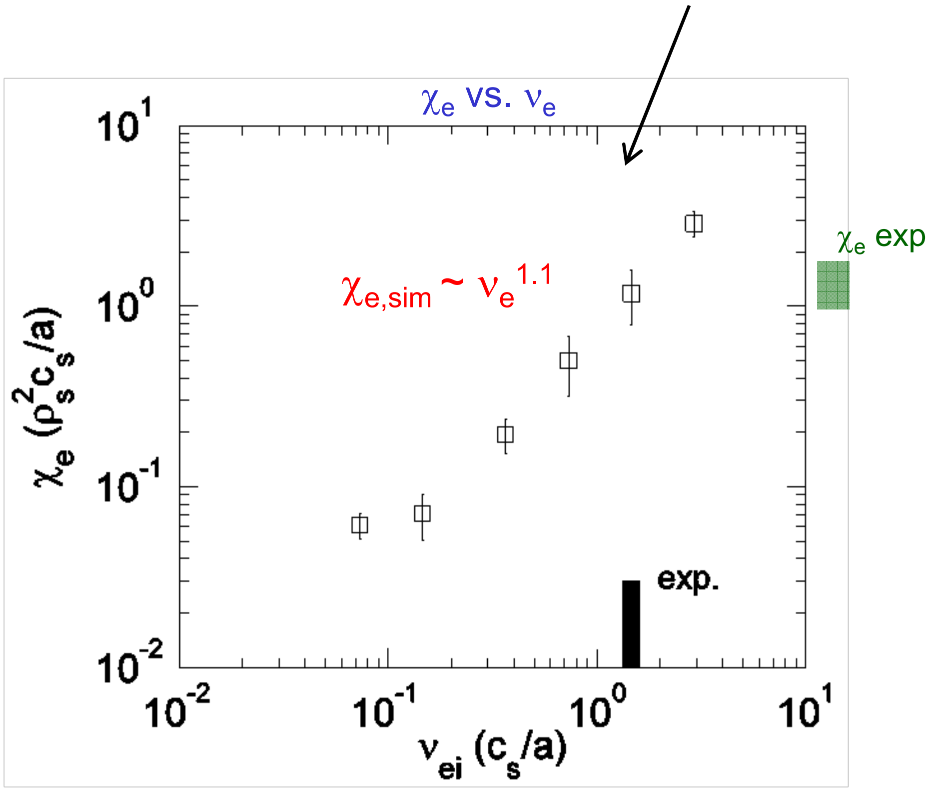


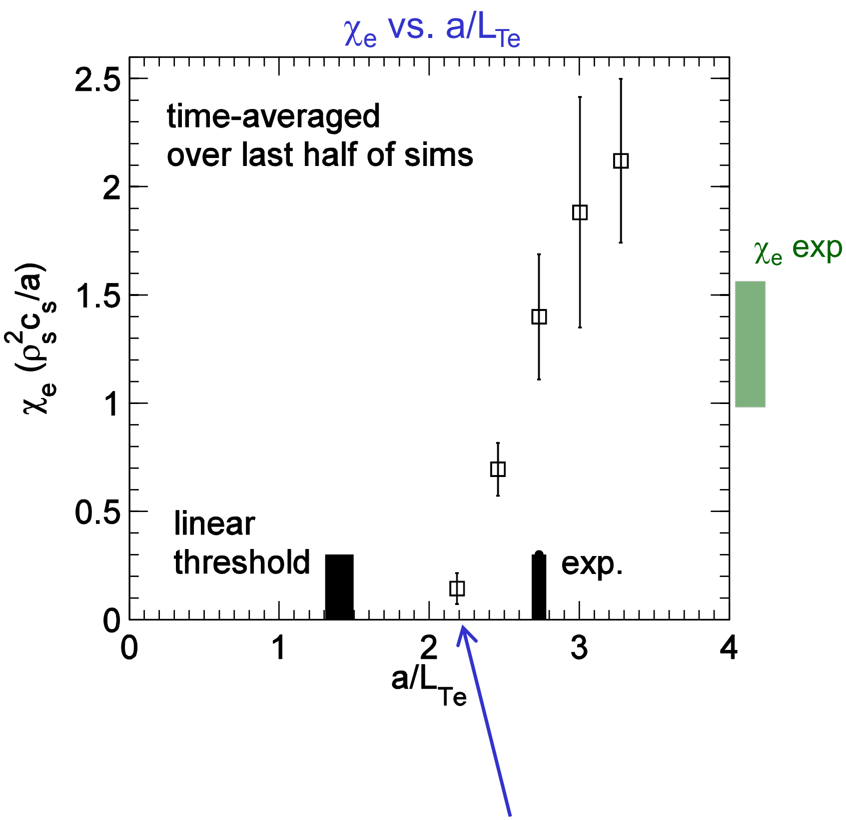
$\rho_s^2 c_s/a = 5\ m^2/s$

- What are the other important dependencies?

*Guttenfelder et al., submitted to PRL (2010)

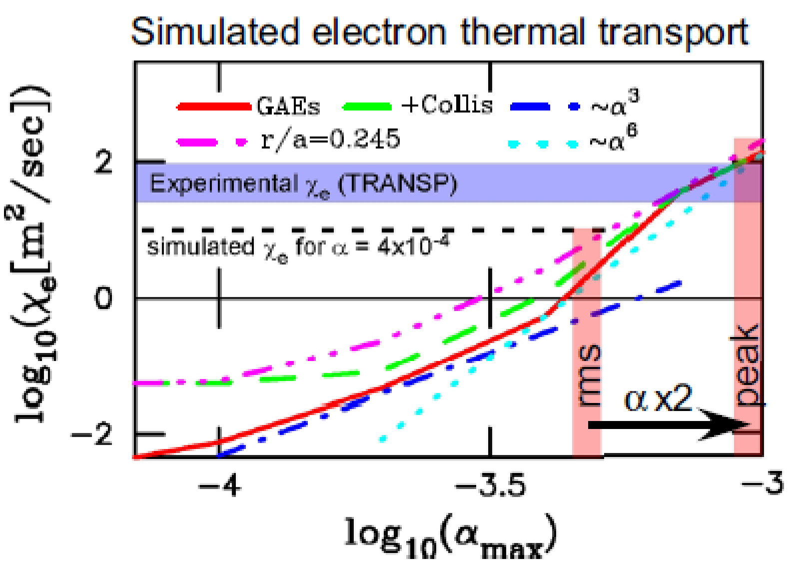
Predicted non-linear collisionality dependence consistent with experimental scaling





- Transport very sensitive to ∇T_e - may be more important to characterize scaling of effective threshold gradient, $(a/L_{Te})_{crit,microtearing}$
- Might help distinguish from expected ETG scaling, $(a/L_{Te})_{crit,ETG}$ – work in progress

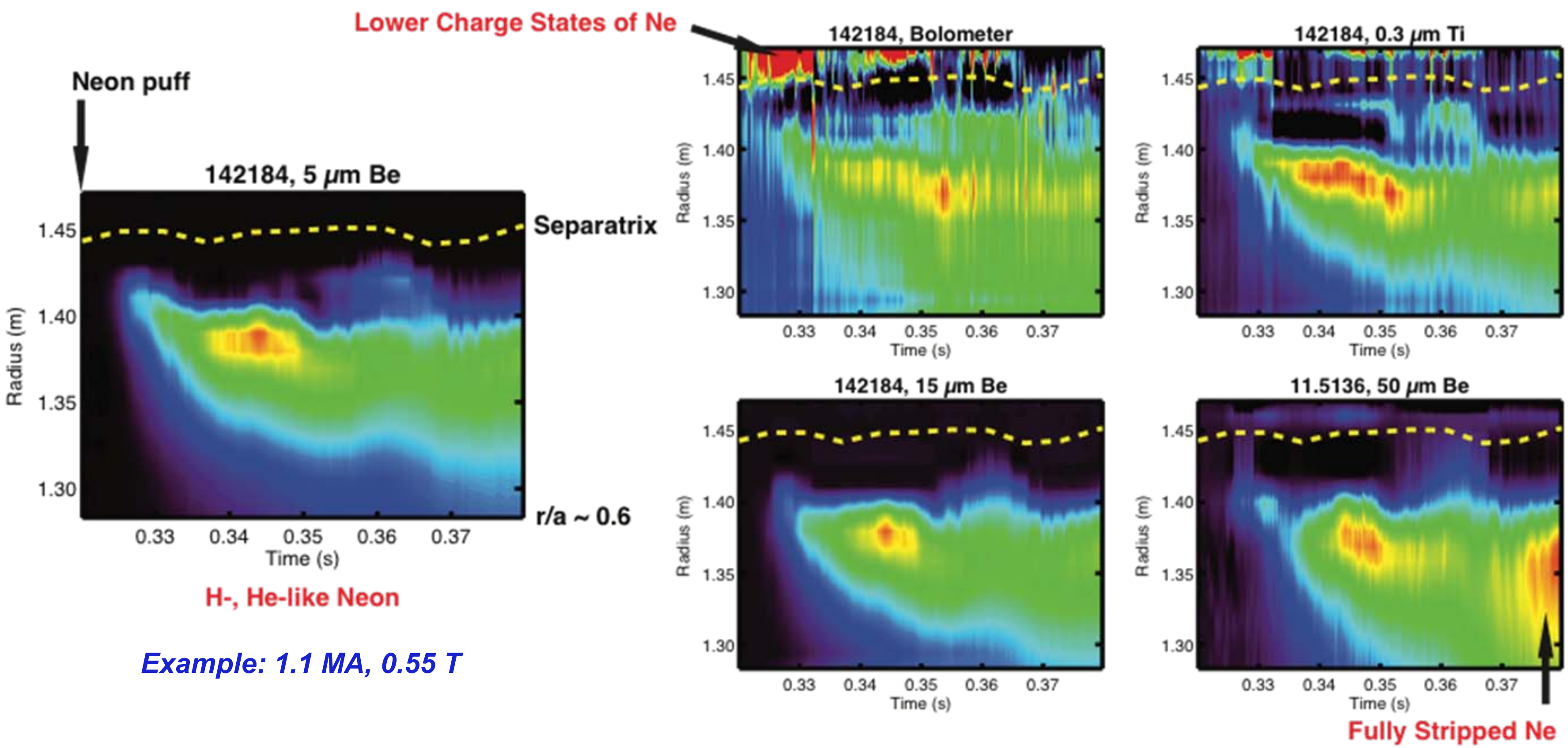
BES Measured GAE Peak Amplitudes Consistent with Numerically Simulated Electron Thermal Transport



- Strong scaling of transport with α indicates mode amplitude peak values dominate χ_e
- Peak amplitudes ~ x2 to x3 higher than time-averaged, rms values from BES and magnetics
- Future numerical simulations will use calibrated mode structures and amplitudes to calculate and compare χ_e
- FY11/12 XPs planned to investigate robustness of physics with constant-q B field scan and P_{NBI} scan (need shot repeatability)

Inverted Data from Five Arrays Provide X-Ray Emissivity Profiles Used for Transport Modeling

- Five arrays are used to distinguish different charge states
- STRAHL impurity transport code is now being implemented to calculate radial transport coefficients $D_r(r)$, $v_r(r)$

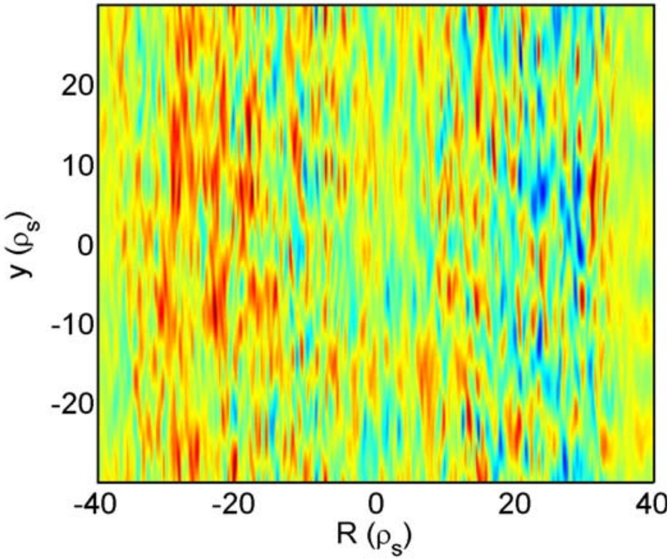


Example: 1.1 MA, 0.55 T

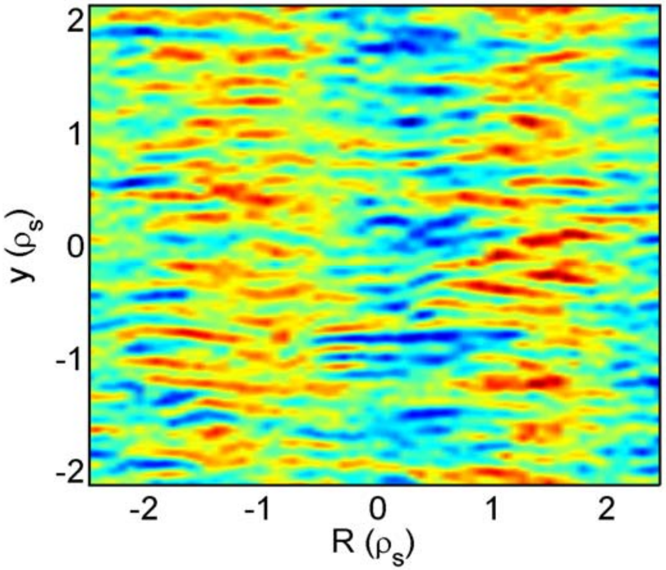
Measuring Micro-tearing Turbulence with High-k Scattering System

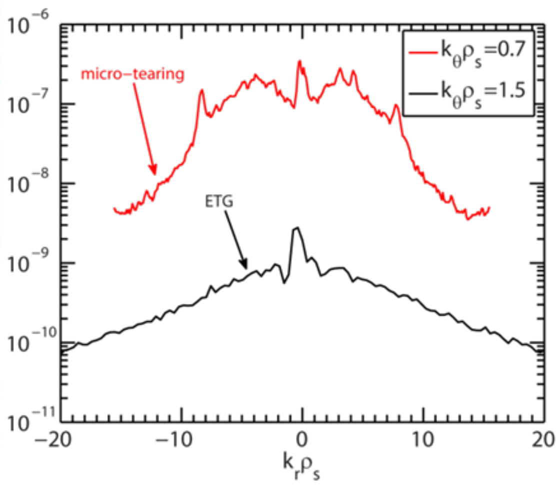
- Micro-tearing turbulence has significant density fluctuations
  - Very Different 2D k spectrum anisotropy than ETG
  - Significant spectral power in large k_r (electron-scale) is expected for micro-tearing turbulence
- The present high-k system measures mostly k_r spectrum and is able to distinguish the different anisotropies

Micor-tearing density fluctuation, NSTX H-mode



ETG density fluctuations, NSTX L-mode





Preliminary Design of the New High-k Scattering System for NSTX-Upgrade

- The design utilizes the launching port of the present high-k_r system and its microwave hardware
- Two scattering configurations of the system allow it to measure 2D k spectrum