NSTX-U

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NSTX-U 5 Year Plan for Transport and Turbulence

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NSTX-U 5 Year Plan Review
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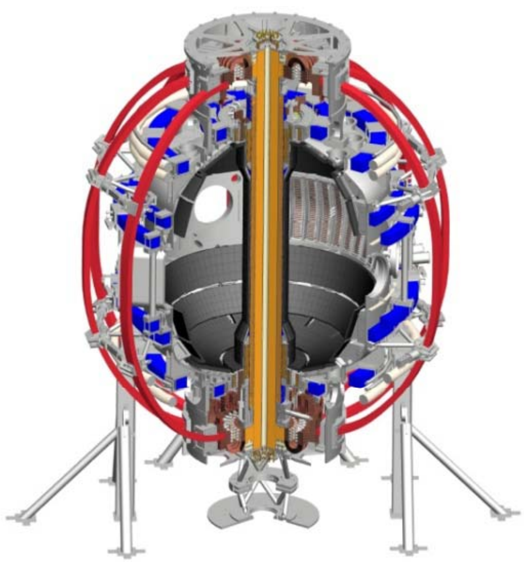

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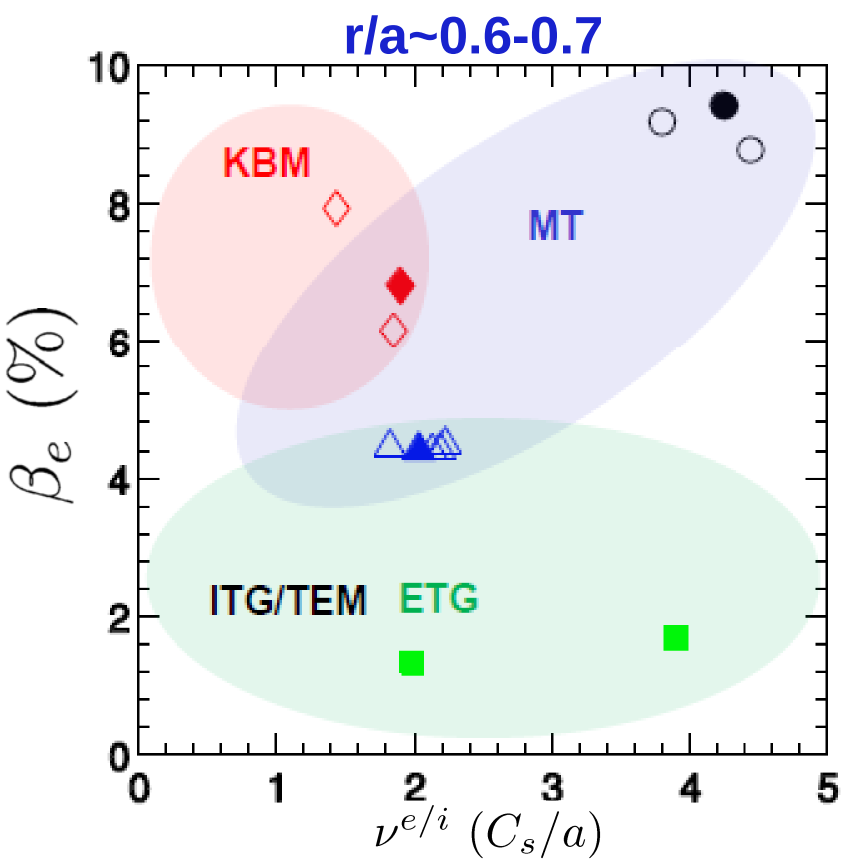
NSTX-U Transport and Turbulence (T&T) 5 Year Plan will Address Crucial Transport Issues of FNSF and ITER

- The goal of NSTX-U T&T research aims to establish predictive capability for the performance of FNSF and future devices
  - NSTX-U accesses a variety of transport mechanisms



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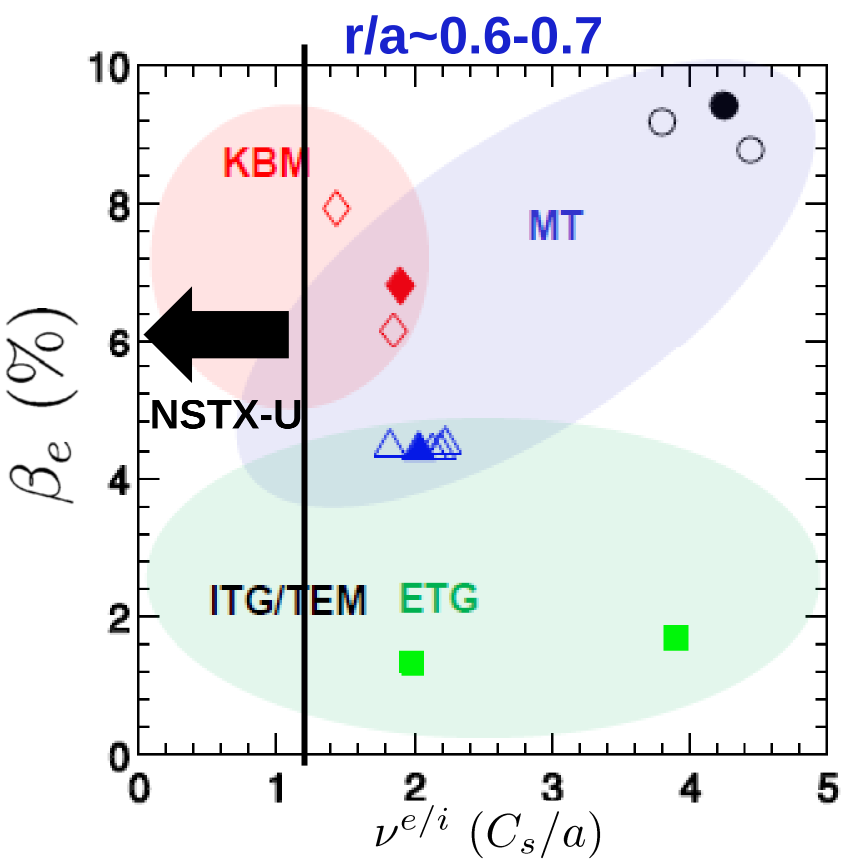

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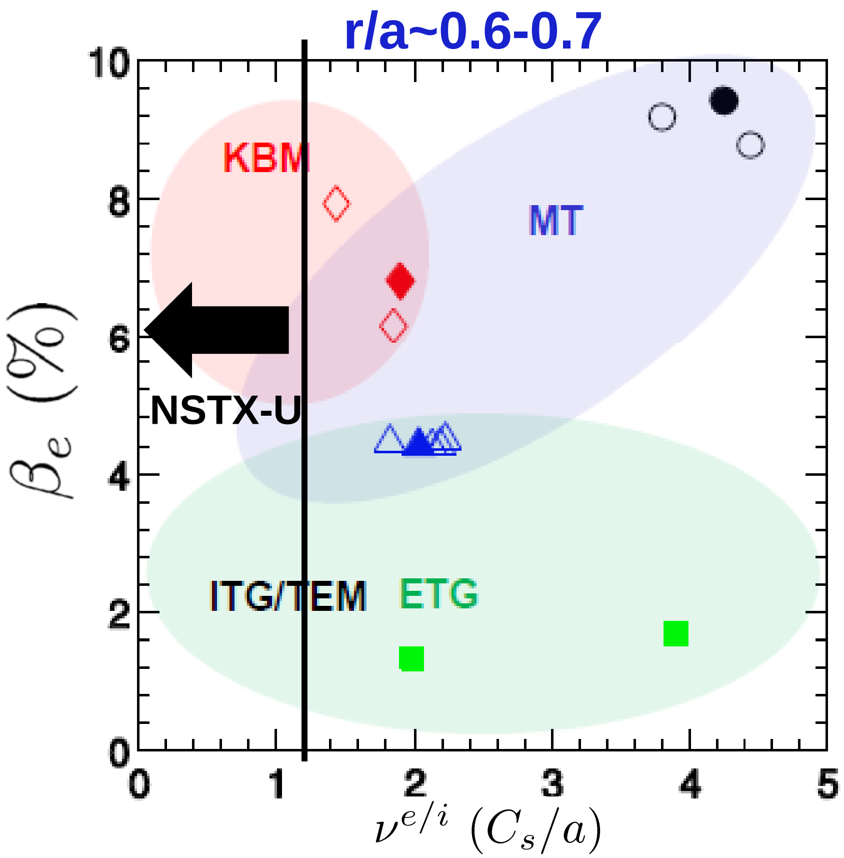

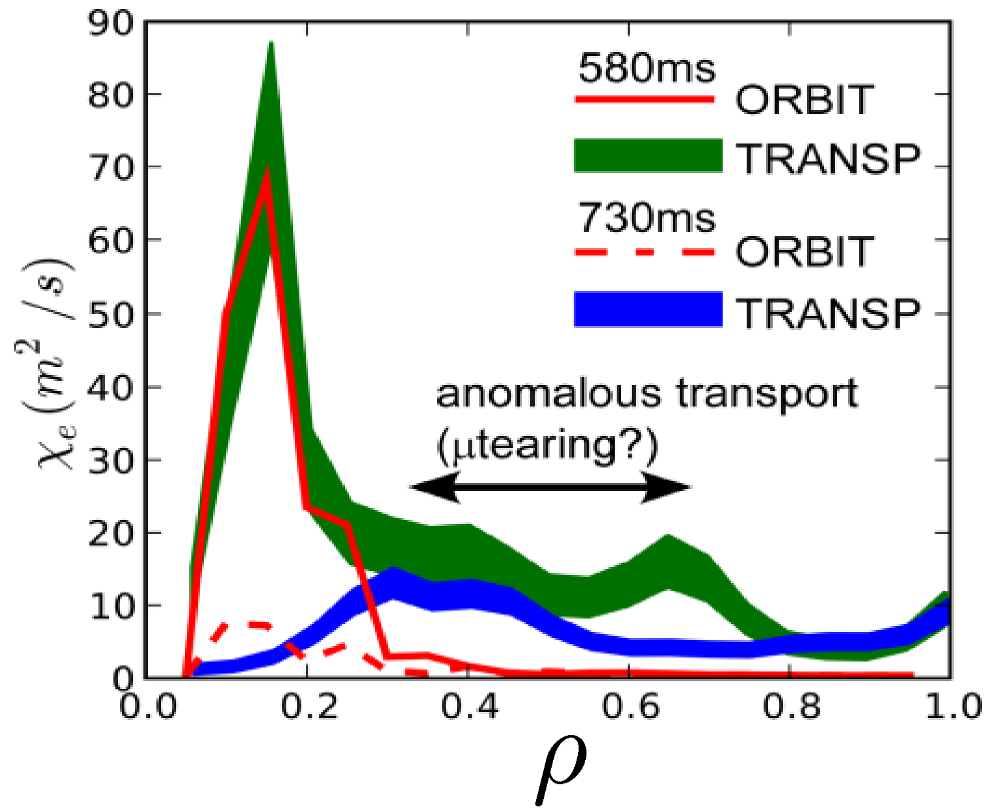

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- Thrust 2: Identify regime of validity for instabilities responsible for anomalous electron thermal, momentum, and particle/impurity transport in NSTX-U
  - Low-k modes ($k_\perp \rho_s \lesssim 1$): ITG/TEM/KBM, MT
  - High-k mode: ETG
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- Thrust 3: Establish and validate reduced transport models

Outline

- Plans for NSTX-U T&T TSG activities in FY14
- FY15-18 operational plans for thrusts 1-3
- Summary

A summary of acronyms used in presentation can be found in the backup slides

NSTX-U T&T TSG Activities in FY14 will Focus on Preparation for NSTX-U Operation

- Continue analyzing existing data, coupled with GK simulations
  - BES, k_r backscattering, high-k scattering, reflectometry, multi-energy SXR
  - Identifying experiments for NSTX-U and preparing data analysis tools (BES, high-k scattering, neural network for fast T_e profile analysis using ME-SXR data)
- Continue simulation and modeling for NSTX and NSTX-U
  - Testing of transport models (TGLF, MMM08, etc...) in transport solvers (TRANSP, TGYRO) for T_e and T_i predictions in a variety of NSTX scenarios
    - Validating model growth rates and fluxes with linear and nonlinear gyrokinetics
  - First attempt in predicting core electron thermal transport in NSTX-U by coupling ORBIT code with HYM CAE/GAE mode calculations
  - Further gyrokinetic simulations for NSTX-U, e.g. GTS with kinetic electrons
- Prepare turbulence and transport diagnostics
  - Integrated bench testing of high-k scattering system
  - BES system with additional channels
  - One channel μ-wave polarimetry system (NSTX/DIII-D, back to NSTX-U)
  - ME-SXR diagnostic design optimization for NSTX-U and collaboration with EAST
  - High-Z impurity transport with FTU using TGIS

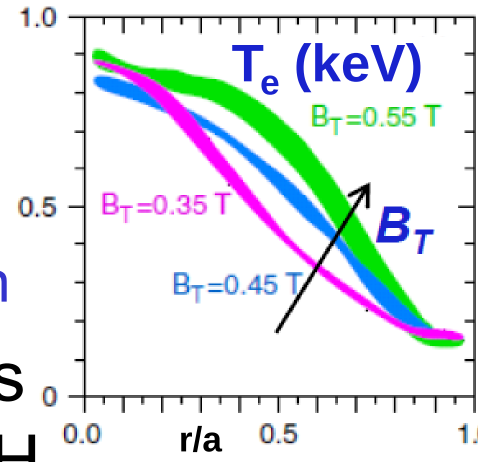
T&T Plans for FY15-18 will Exploit the Enhanced Capabilities of NSTX-U to Substantially Advance Physics Basis for Future Devices

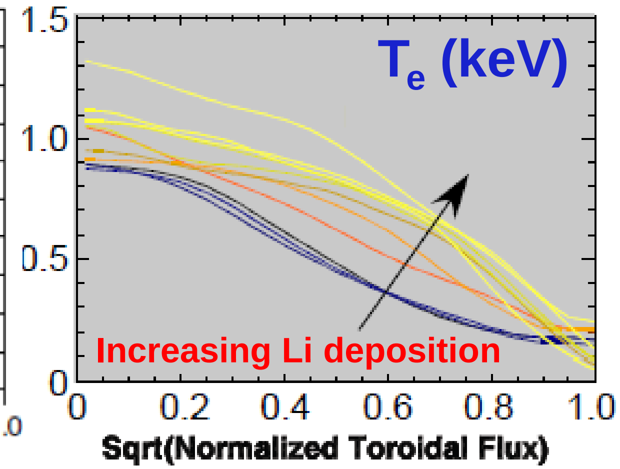
- Expanded operational capabilities of NSTX-U
  - Double B_T, I_p and NBI heating power and cryopump (lower collisionality)
  - More tangential 2^{nd} NBI and partial NCC (q and flow profile modification)
  - Fully relaxed plasmas and fully non-inductive scenario
- Turbulence diagnostics covering ion and electron gyro-scale
  - 48-channel BES for low-k and AE measurement ($r/a>\sim0.1$, $k_\theta \rho_s<\sim1.5$)
  - One channel polarimeter aiming to measure magnetic fluctuations
  - 16-channel reflectometer measuring density fluctuations ($k_r \rho_s <\sim 6$)
  - A FIR high-k scattering system for k_θ ($r/a>\sim0.1$, $k_\theta \rho_s \sim10\text{-}50$, $\rho_s\approx1$ cm)
- Couple with a variety of data analysis and modeling tools
  - Power balance analysis/Transport solver: TRANSP, TGYRO
  - Gyrokinetic (GK) codes: GENE, GS2, GTS, GYRO, XGC1
  - Neoclassical/reduced models: GTC-NEO, XGC0, NCLASS, NEO, TGLF
  - Impurity transport codes: MIST, STRAHL
  - Neutral transport code: DEGAS2

Thrust 1: Characterize H-mode global energy confinement scaling in the lower collisionality regime of NSTX-U

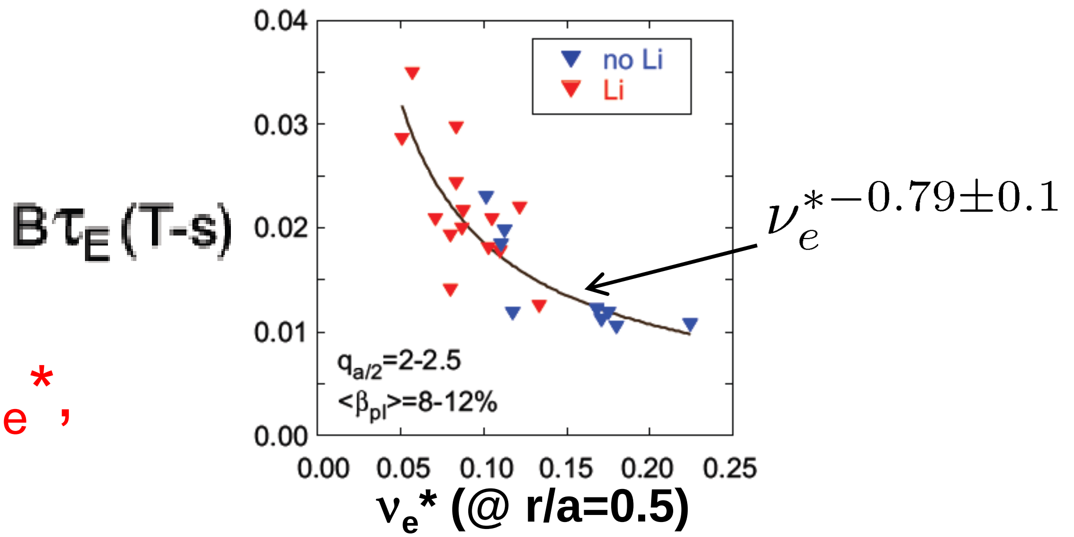
Inverse ν_e* Confinement Scaling is Found to Unify NSTX Boronized and Lithiated H-mode Confinement Results

- T_e broadening is an important element for ν_e* reduction
  - Correlated with B_T without Li
  - Correlated with Lithium deposition





- Observed ν_e* scaling reconciles NSTX boronized and lithiated H-mode plasma dimensional scalings
  - $\sim B_T^{0.85}$ and $\sim I_p^{0.38}$ without Li
  - $\sim B_T^{-0.09}$ and $\sim I_p^{0.94}$ with Li



- NSTX-U will investigate if this scaling extends to even lower ν_e*, i.e. a factor of 3-6 reduction
  - Lower ν_e* stabilizing for microtearing, destabilizing to TEM/KBM
  - ETG not sensitive to ν_e*

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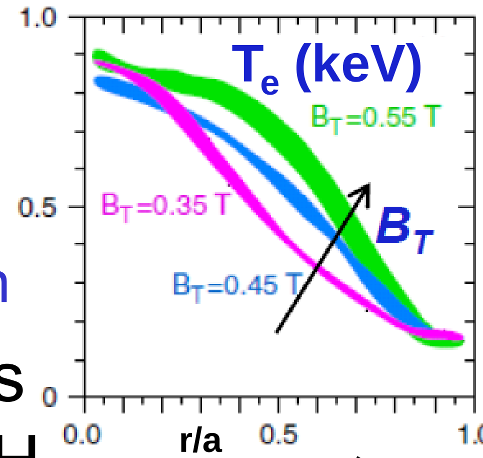
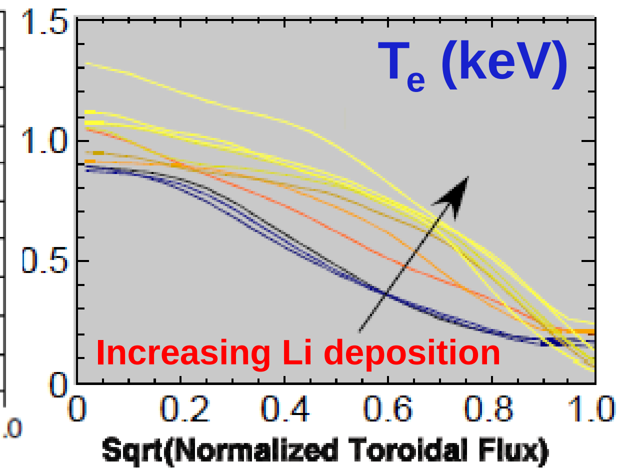
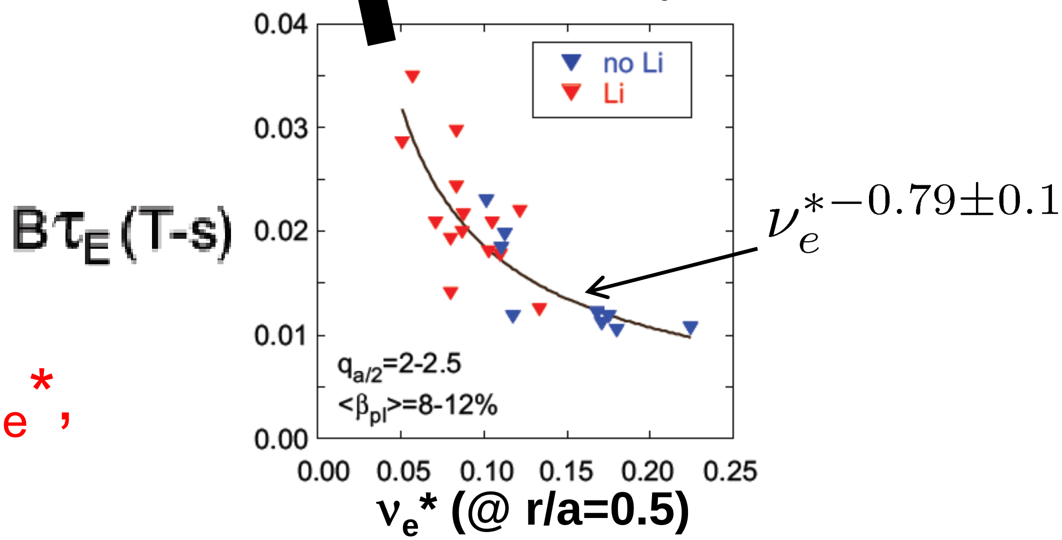




$B\tau_E$ ~ 0.15 (T·s) with a factor of 6 reduction in ν_e^* in NSTX-U



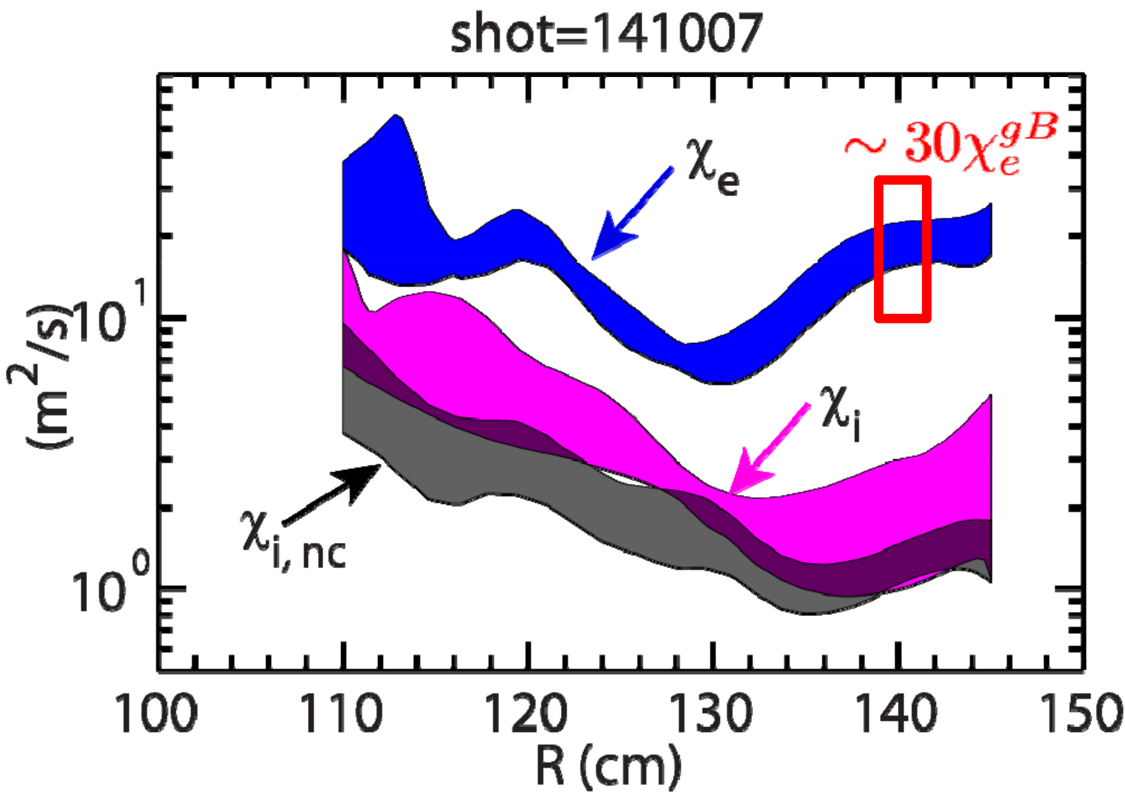
NSTX-U will Address ST Confinement Scaling in the Regime more Relevant to Future STs (Thrust 1)

- Near-term plan for FY15-16
  - Re-establish and extend confinement scaling to lower ν_e^* with higher B_T, I_P and NBI power
    - $B_T/I_P \leq$ 0.8 T/1.6 MA in FY15 and 1.0 T/2 MA in FY16
  - Compare I_p and B_T scaling to the different scalings found on NSTX
  - Characterize confinement scaling with different PFC materials
    - Carbon vs high-Z
  - Project 0D performance for future STs with expanded empirical confinement scaling
  - Assess H-mode energy confinement, pedestal and scrape off layer characteristics with higher B_T, I_P and NBI heating power (NSTX-U FY15 milestone)
- Long-term plan for FY17-18
  - Characterize confinement scaling for
    - Fully relaxed plasmas
    - Advanced scenarios, e.g. fully non-inductive discharges, as they are developed
  - Decouple ν_e^* and ρ^* dependence of global confinement with density control from cryopump

Thrust 2: Identify regime of validity for instabilities responsible for anomalous electron thermal, momentum, and particle/impurity transport in NSTX-U

T&T Research on NSTX has Gained Insight into Underlying Mechanisms behind Thermal Transport

- Ion thermal transport is close to neoclassical in NSTX H-mode plasmas
  - Anomalous in L-mode plasmas
- Electron channel dominates the thermal transport in most regimes
  - Also predict dominant electron heating in NSTX-U/FNSF/ITER



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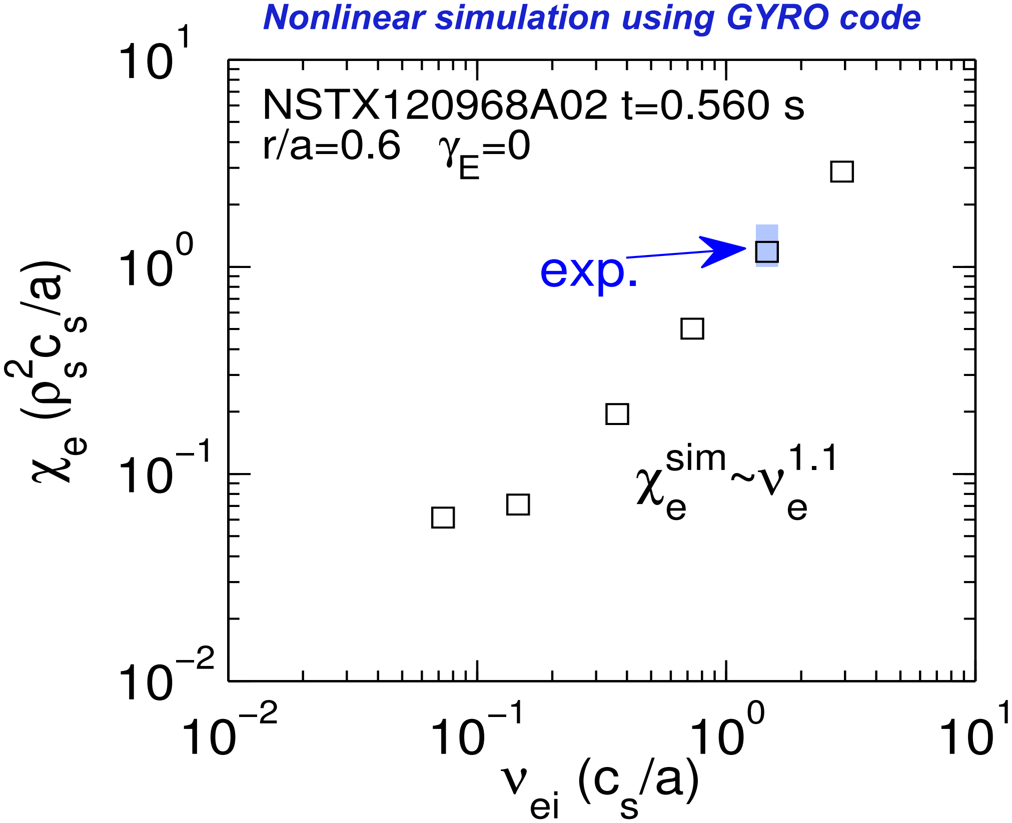
  - ITG and ETG in L-mode
  - KBM/microtearing/ETG/CAE/GAE in H-mode

Nonlinear simulation using GYRO code



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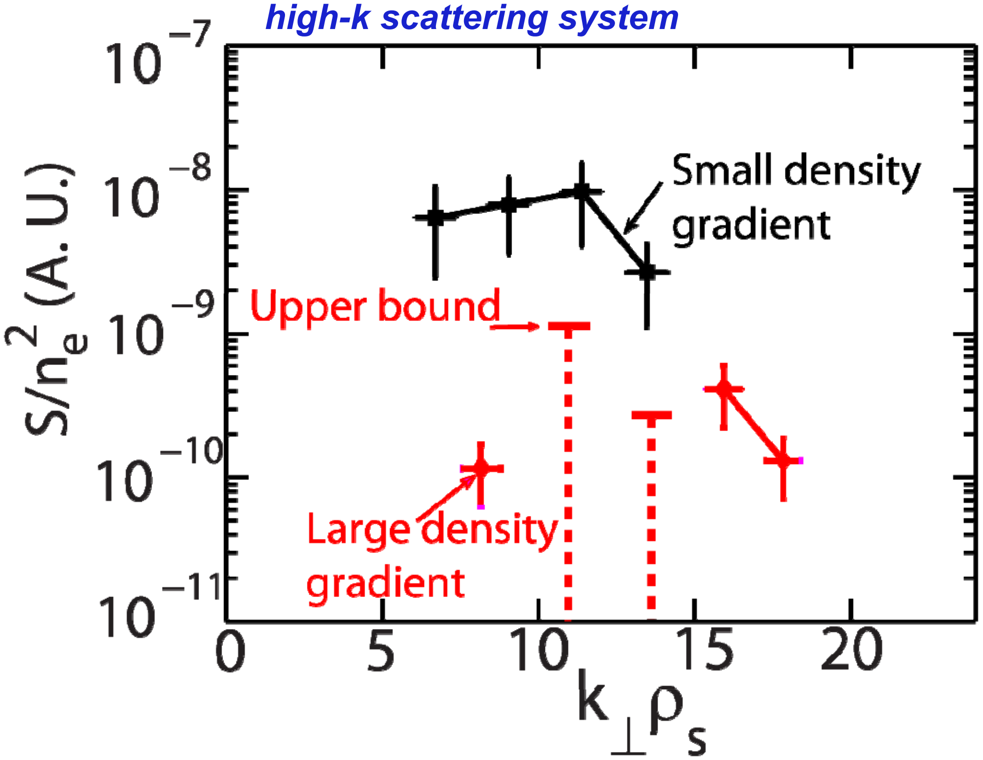
Electron-scale turbulence measured by a high-k scattering system



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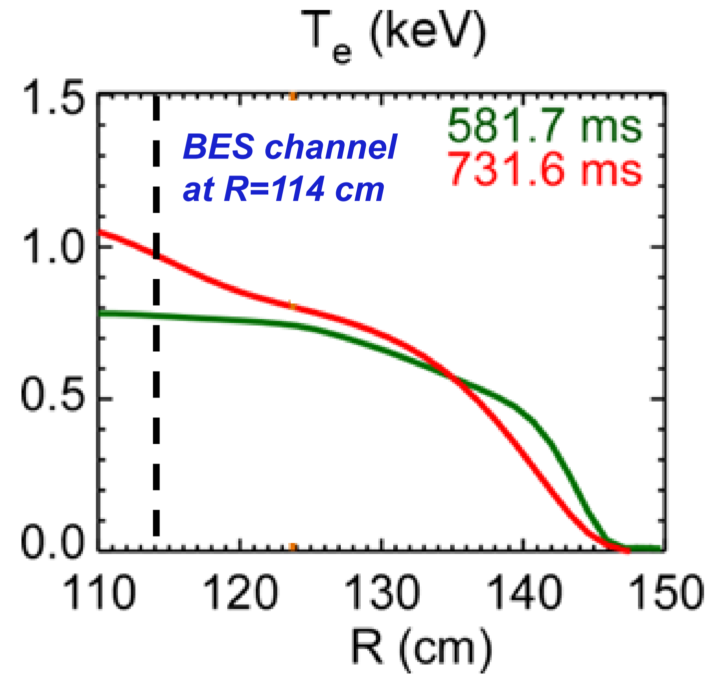
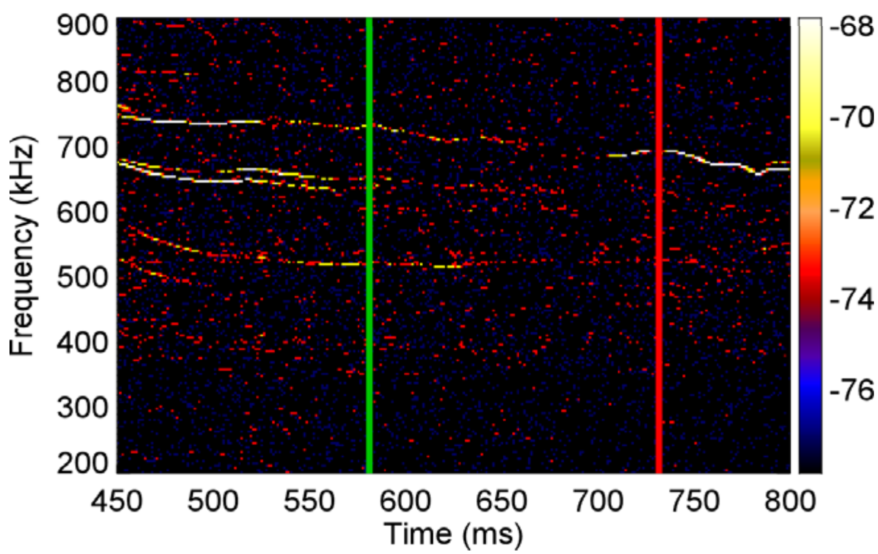


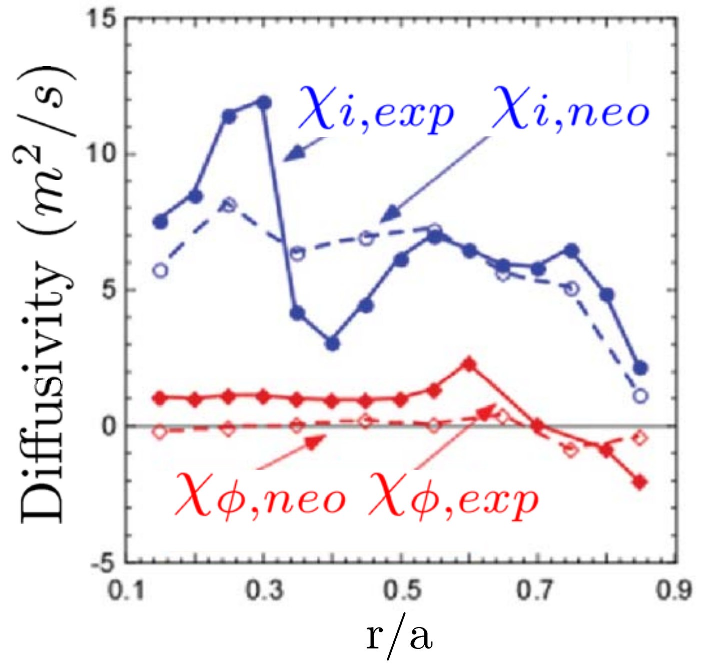


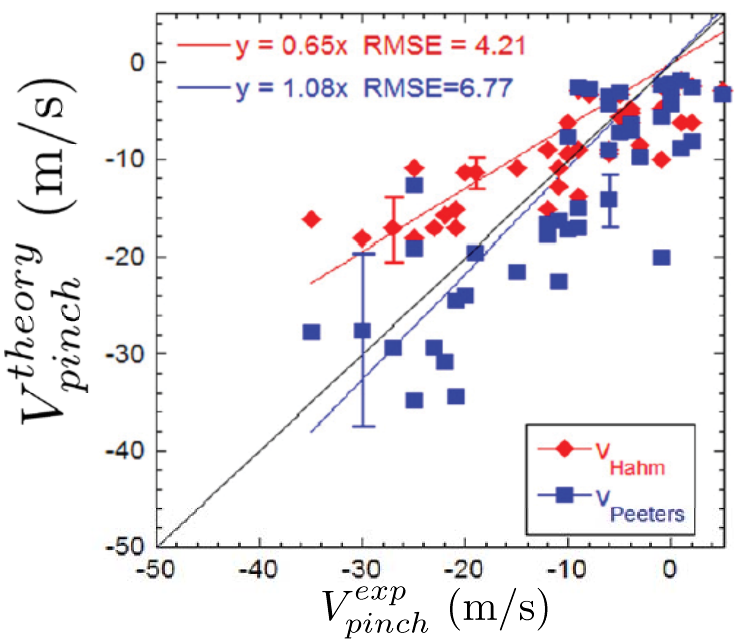
NSTX-U T&T Plan will Address Important Issues in Electron and Ion Thermal Transport (Near-term FY15-16)

- Identify dominant modes in lower ν_e^* H-mode plasmas of NSTX-U and determine $\chi_i/\chi_{i,neo}$ vs ν_e^* (coordinated with thrust 1)
  - Characterize low/high-k turbulence as global confinement is varied
- Characterize low/high-k turbulence and thermal transport in isolated regimes of micro-instabilities guided by GK simulations
  - MT/ETG (high/low β and ν_e^* H-mode); ITG/TEM (low β & lower ExB shear L-mode)
- BES/reflectometry/polarimetry for CAE/GAE measurements with a range of B_T, I_p, ν_e^* and P_{NBI}, coupled with ORBIT code
- Cold pulse propagation (LBO and ME-SXR) for profile stiffness
- Couple with turbulence diagnostics, GK simulations and experimental tools
  - k_θ spectrum (high-k scattering); B fluctuations (polarimeter); zonal flow (BES)
  - Global/local transport trend and turbulence characteristics with GK simulations
  - Profile variations (q and flow) for turbulence and neoclassical transport modification

NSTX Results for Momentum Transport and Intrinsic Torque/Rotation Stimulate Research Plan for NSTX-U

- Effective χ_ϕ from transport analysis found to be anomalous in NSTX H-mode plasmas
- Momentum pinch consistent with some theoretical models involving low-k turbulence
  - Measured by magnetic braking and NBI pulses
  - Nonlinear GK simulation to be carried out
- Edge intrinsic torque/rotation showing correlation with pressure/T_i gradient
- 2nd NBI pulses to be used in perturbative experiments for pinch and intrinsic torque measurements
- Need to couple with low-k turbulence measurements and GK simulations



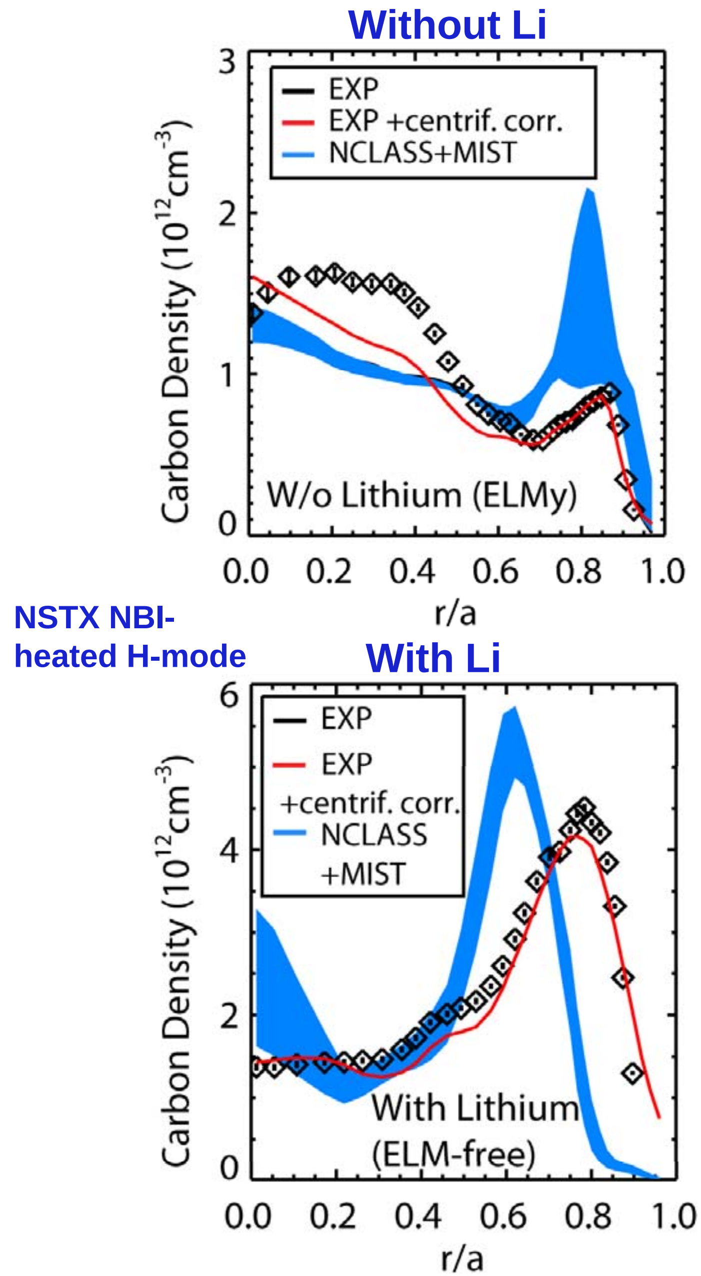


Momentum Transport and Intrinsic Torque/Rotation Studies will have Increased Emphasis in NSTX-U T&T Plan (Near-term FY15-16)

- Characterize χ_ϕ as a function of ν_e^*, B_T and I_P
  - Compare with trends in $\chi_i/\chi_{i,neo}$ and low-k turbulence
- NBI and existing external coils pulses for momentum diffusivity, pinch and intrinsic torque measurements in a variety of regimes
  - Microtearing/ETG regimes, e.g. high/low β and ν_e^* H-mode
  - ITG/TEM regimes, e.g. NBI-heated L-mode
- Vary q and flow profiles ($\hat{s}$, ExB shear) to explore the parametric dependence of χ_ϕ, pinch and intrinsic torque and the correlation with low-k turbulence
  - Use 2^{nd} NBI and existing external coils
- Intrinsic rotation study with passive CHERS in scenarios with negligible external momentum input (RF-heated and ohmic)
- Compare momentum measurements and low-k turbulence with GK simulation predictions

Impurity Transport is often Consistent with Neoclassical Transport in Core, more Uncertain at Edge

- Core C^{6+} profile shape consistent with local neoclassical calculation (NCLASS and NEO)
  - Larger departure from neoclassical at edge with Li than w/o Li
  - Global neoclassical in future (GTC-neo/XGC0)



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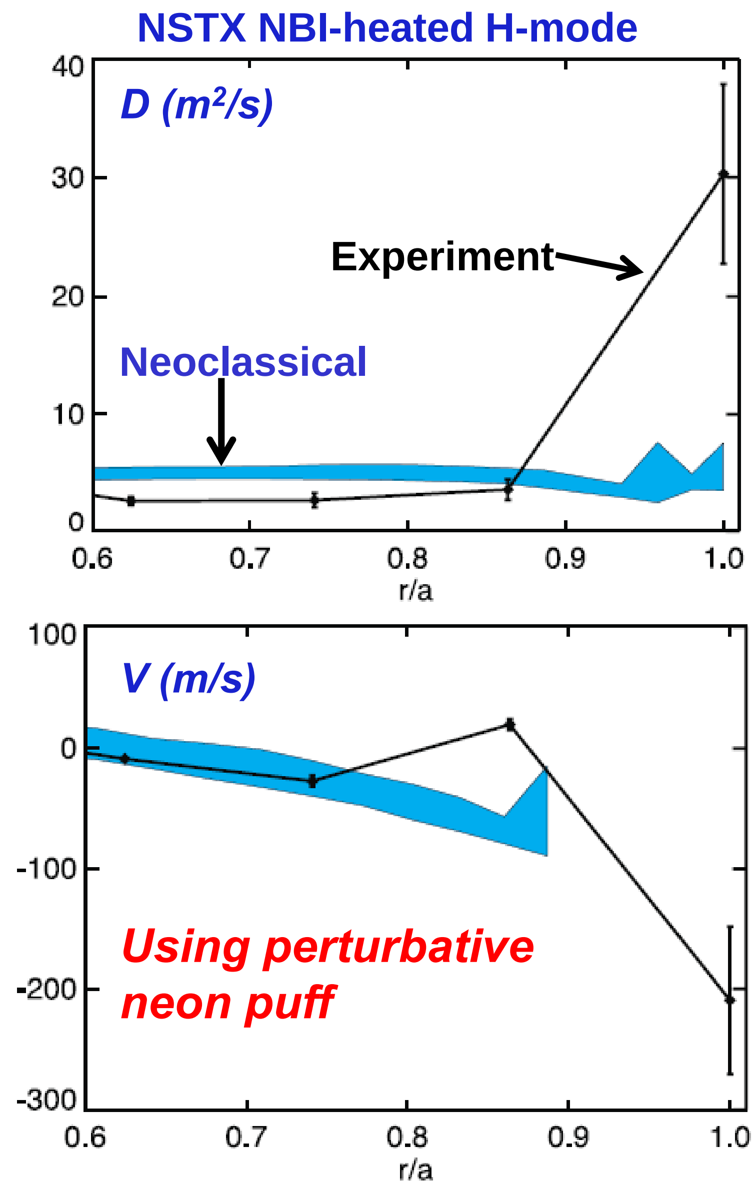
- Neon transport close to neoclassical calculations in core
  - Deviation from neoclassical diffusion in the edge possibly due to edge turbulence (w/ BP TSG)



Particle/Impurity Transport Studies will be Explored in the Lower Neoclassical Transport Regime of NSTX-U (Near-term FY15-16)

- Compare particle/impurity transport with neoclassical transport as NSTX-U reaches lower ν_e^* with increased B_T, I_P and P_{NBI}
  - Trace-impurity V and D with perturbative neon puff
  - Carbon/lithium with CHERS measurements
  - High-Z impurity with the laser blow-off system and metal PFC
  - Coupled with impurity transport codes
  - Main ion transport studies through steady-state analysis, coupled with modeling (DEGAS2) and measurements of edge neutral source
- Similar experiments in isolated regimes of micro-instabilities
- Vary q, $\hat{s}$ and ExB shear to alter neoclassical transport and low-k turbulence and to explore parametric dependence of particle/impurity transport
- Assess the effect of HHFW heating on core high-Z impurity transport
- Compare anomalous particle/impurity transport with GK calculations and correlate it with low-k turbulence measurements

Long-term (FY17-18) NSTX-U T&T Plan to Address Thrust 2

- Identify operational regimes of ETG, microtearing, CAE/GAE and ITG/TEM/KBM modes for thermal transport
- Identify low-k turbulence responsible for momentum transport/ intrinsic torque and particle/impurity transport and its operational regimes
- Facilitated by further NSTX-U facility enhancements
  - Lowest ν_e^* with highest B_T, I_p and lowest density (with cryopump)
  - Impact of increased high-Z tile coverage in divertor
  - Effects of RF heating (HHFW, possibly EBW) on high-Z impurity transport
  - Decouple ν_e^* and ρ^* dependence with density control from cryopump
  - Better inter-machine experiments for R/a scaling from B_T enhancement
  - Partial NCC for varying flow profile/shear and for 3D effects (w/ external 3D coils) on intrinsic torque coupled with global gyrokinetic codes, e.g. GTS and XGC1
- Expanding turbulence and transport parametric dependence
  - β, ρ^* (density control from cryopump), T_i/T_e (RF heating) and Z_{eff} (impurity control techniques), using full field and current capability of NSTX-U
- Explore long pulse fully relaxed and fully non-inductive scenarios
- Move towards an integrated understanding of all transport channels

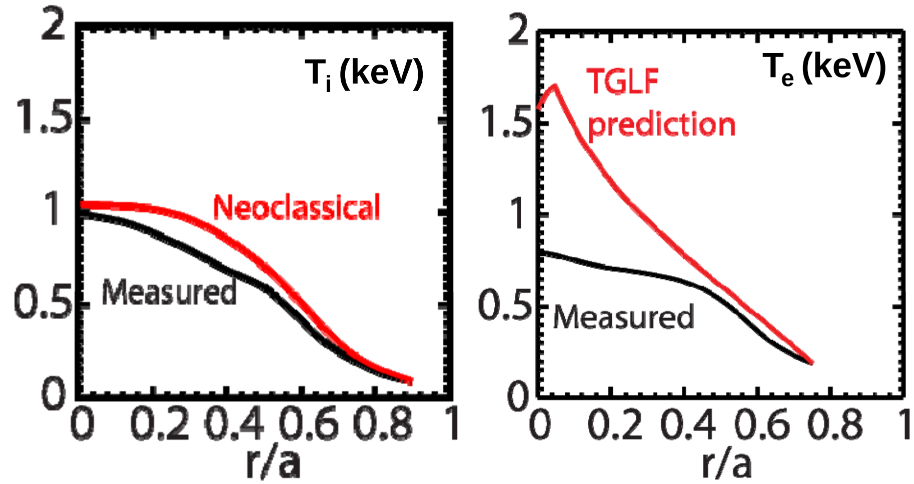
Thrust 3: Establish and Validate Reduced Transport Models

NSTX-U T&T 5 Year Plan Aims to Deliver Reduced Transport Models

- Reduced transport models are required deliverables to meet the goal of achieving predictive capability for performance of next generation STs and ITER
- NSTX-U will allow validation of transport models over a broad range of parameters, e.g. ExB shear, β, ν
  - Wide range of theoretical mechanisms to consider
  - More comprehensive validation of physics models being used for conventional aspect ratio tokamaks and ITER
- Emphasis throughout 5 years will be on predictive transport simulations using TRANSP and TGYRO coupled with core transport models:
  - Neoclassical (NC) (Chang-Hinton model, NCLASS, NEO)
  - Drift wave (DW) (TGLF, MMM08, …)
  - Energetic particle (EP) driven χ_e (stochastic ORBIT model)
- Additional emphasis on validating NC, DW & EP models with first principles simulations (GTC-neo, gyrokinetics & HYM, respectively)

FY15-16 Modeling will Focus on Ion and Electron Thermal Transport at Expanded I_p, B_T and P_{NBI}

- Predict T_e & T_i profiles using neoclassical and drift wave models and compare with NSTX-U profiles
  - Will ion thermal transport remain neoclassical in NSTX-U?
  - TGLF overpredicts core T_e, possible missing physics: CAE/GAE modes, turbulence spreading, sensitivity to ExB shear



- Validate drift wave models with linear and nonlinear GK, focusing on:
  - Linear instability regimes, e.g. TEM/MT/KBM, scaling and thresholds
  - Nonlinear electron & ion heat flux scaling for the different mechanisms
- Consider developing semi-empirical or analytic models based directly on GK simulations
  - Depending on quantitative success of available DW models
- Develop model $\chi_{e,EP}$ based on ORBIT simulations using measured CAE/GAE mode structures (w/ EP TSG)

FY17-18 Long Term Plans will Focus on Complete T_e Profile Prediction for Low Collisionality & Advanced Scenarios

- Validate predictions at lowest collisionality accessible with cryopump and advanced scenario development
  - Integrate analytic $\chi_{e,EP}$ model into TRANSP predictions for core T_e profile
  - Non-linear HYM simulations for first principles GAE/CAE spectra for ORBIT $\chi_{e,EP}$ modeling

- Investigate non-local core effects using global gyrokinetics
  - Relatively large ρ^* in NSTX-U, possible turbulence spreading into near-axis region
  - Pursue heuristic model to incorporate non-local effects

- When feasible move to core/pedestal full-F simulations, e.g. XGC1 to investigate possible non-local influence from pedestal to core region (w/ BP TSG)

- Depending on success of T_e, T_i predictions for NSTX-U:
  - T_e, T_i, τ_E predictions for future device, e.g. ST-FNSF, Pilot
  - Integrated scenario predictions (consistent equilibrium & q profile evolution) for fully relaxed and fully non-inductive scenarios
  - Predict density and rotation profile (n, Ω) (need to predict particle source, torque from MHD)

Summary: NSTX-U T&T Research will Provide Physics Basis Leading to Predictive Capability for Transport in Future ST/AT Devices

- Motivated by the results from NSTX, the proposed T&T research thrusts for NSTX-U aim to address
  - H-mode global energy confinement
  - Transport mechanisms and their operational regimes
  - Establishment and validation of reduced transport models
- A set of turbulence diagnostics coupled with a comprehensive set of data analysis and simulation/modeling tools will greatly facilitate achieving the research goals
  - BES, reflectometry, polarimetry and high-k_θ scattering system
  - TRANSP, GYRO, GTS, XGC0/XGC1, NEO, GTC-NEO etc.

Backup Slides

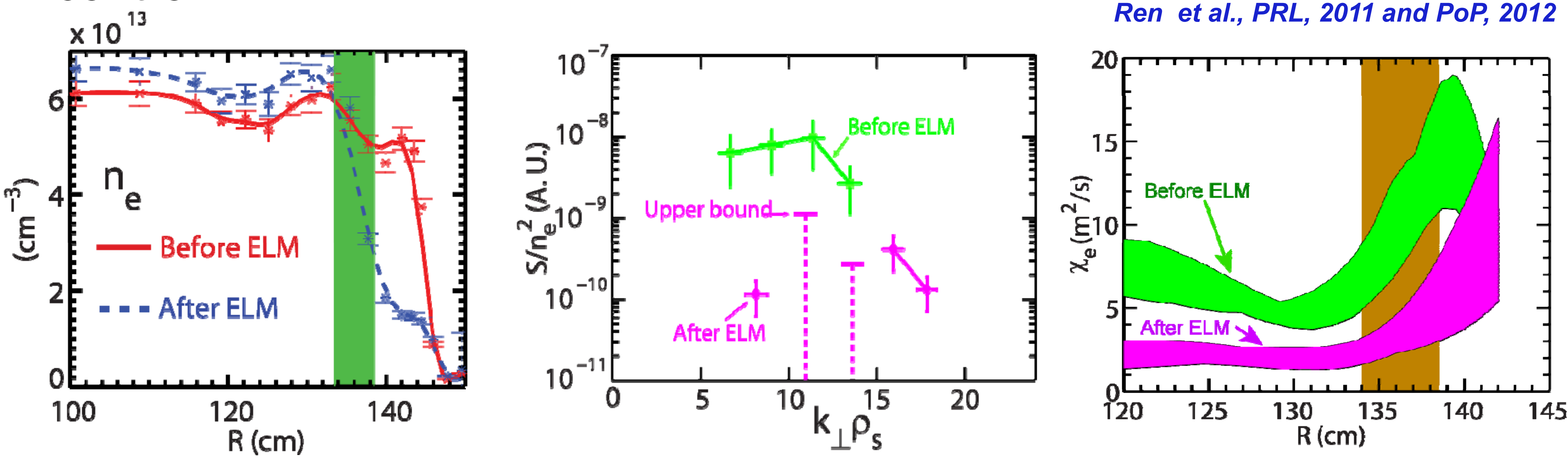
A Summary of Acronyms (SoA)

- Instabilities
  - ITG – ion temperature gradient, electrostatic
  - TEM – trapped electron mode, electrostatic
  - KBM – kinetic ballooning mode, electromagnetic
  - MT – microtearing, electromagnetic
  - ETG – electron temperature gradient, electrostatic
  - CAE – compressional Alfven eigenmode, electromagnetic
  - GAE – global Alfven eigenmode, electromagnetic
- Codes
  - GYRO – an eulerian gyrokinetic code
  - GS2 – an eulerian gyrokinetic code
  - GTS – global particle-in-cell Gyrokinetic Tokamak Simulation (GTS) code
  - GENE – Gyrokinetic Electromagnetic Numerical Experiment (GENE) code
  - XGC0/XGC1 –full-f global particle-in-cell gyrokinetic code
  - TGLF – an gyro-Landau-fluid code
  - MMM08 – multi-mode anomalous transport model
  - NCLASS – a local neoclassical transport code
  - NEO – a local eulerian neoclassical transport code
  - GTC-NEO –a global particle-in-cell neoclassical transport code
  - HYM – nonlinear 3-D HYbrid and MHD simulation code (HYM)
  - TRANSP – a time dependent tokamak transport and data analysis code with free boundary and multi-zone predictive capability
  - TGYRO – a transport solver
  - MIST – Multi-Ionic Species Transport (MIST) code
  - STRAHL – an impurity transport code
  - DEGAS2– a neutral transport code
  - ORBIT – A guiding center test particle code for tokamak geometry
- Diagnostics
  - BES – beam emission spectroscopy (BES)
  - CHERS – charge exchange recombination spectroscopy (CHERS)
  - ME-SXR – multi-energy soft X-ray (ME-SXR)
  - TGIS – Transmission Grating Imaging Spectrometer (TGIS)
  - LBO – Laser Blow-off system (LBO)

Density Gradient Stabilization of High-k Turbulence was Identified

- Provided the first experimental evidence of density gradient stabilization of high-k turbulence
- Correlated with a factor of about two decrease in electron thermal diffusivity
- Consistent with theoretically predicted increase in critical electron temperature gradient for ETG modes due to density gradient
- A possible way to stabilize/mitigate ETG turbulence by density profile control

Ren et al., PRL, 2011 and PoP, 2012



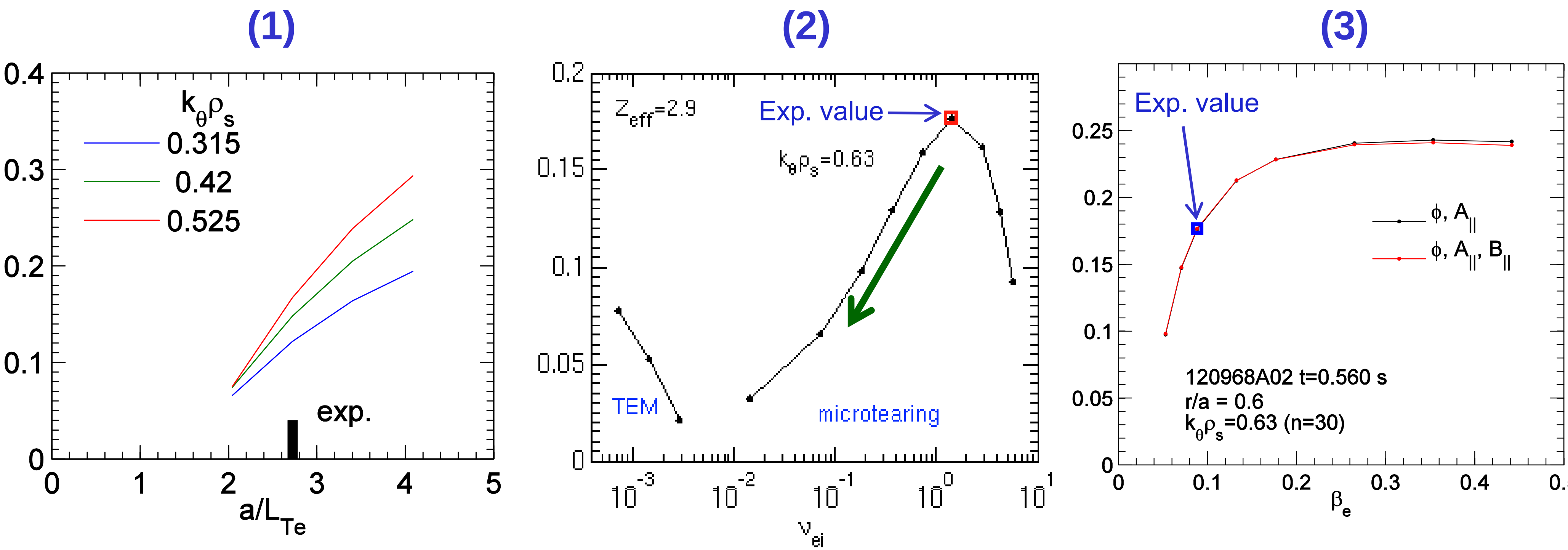
Microtearing Instability Exhibits Thresholds in Electron Temperature Gradient, Collisionality and Beta

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

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

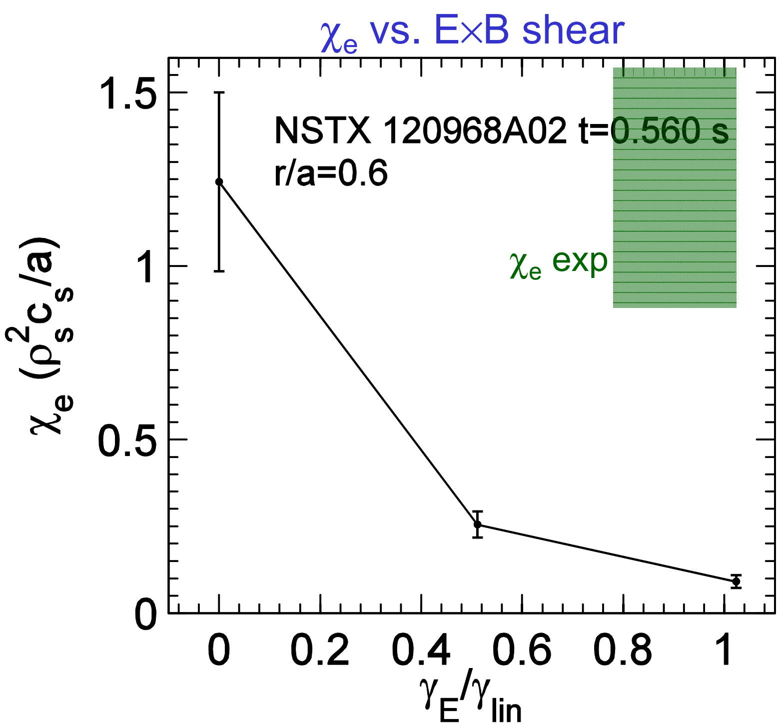
(3) Lowering beta stabilizes microtearing

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

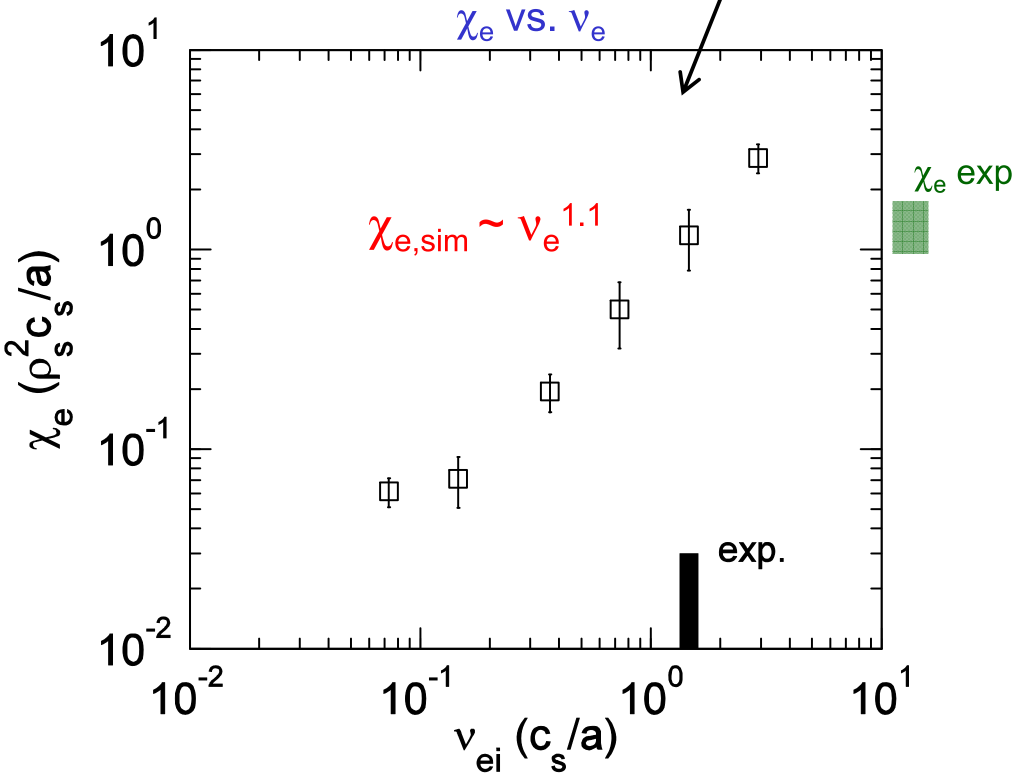


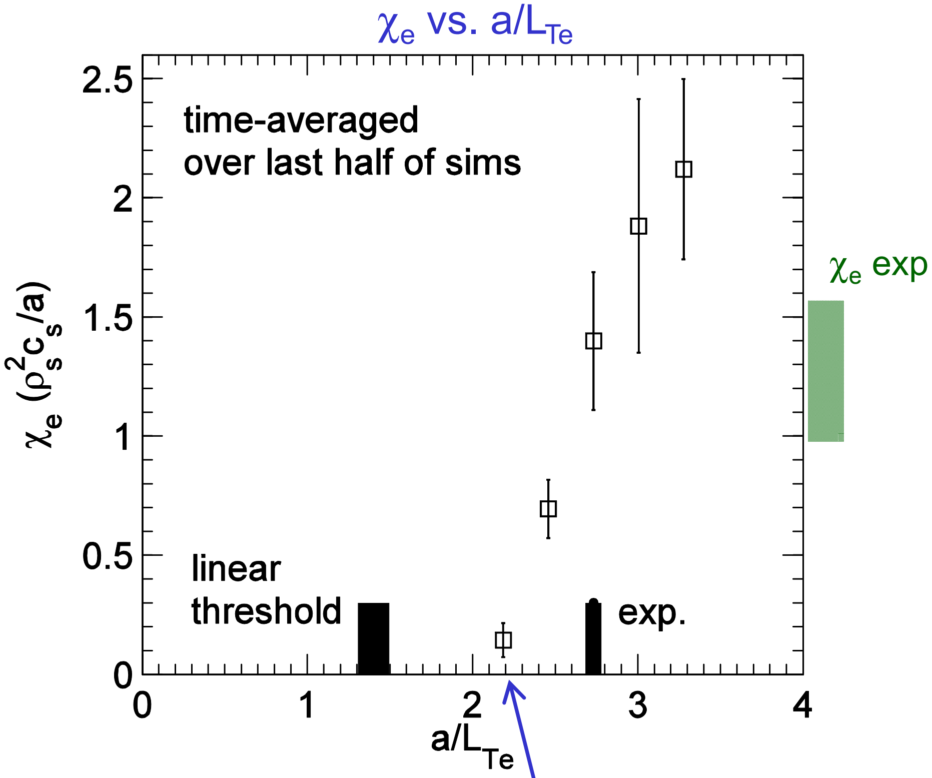
$\rho_s^2 c_s/a = 5\ m^2/s$

- What are the other important dependencies?

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

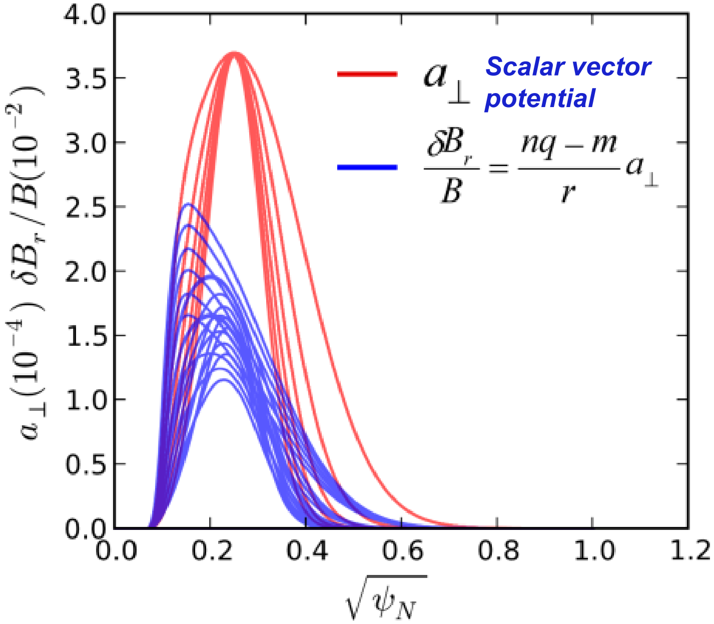
Predicted Non-linear Collisionality Dependence Consistent with Experimental Scaling

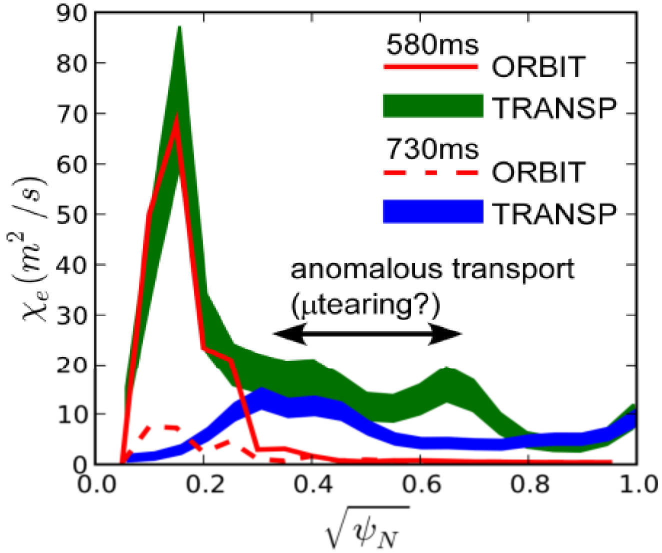


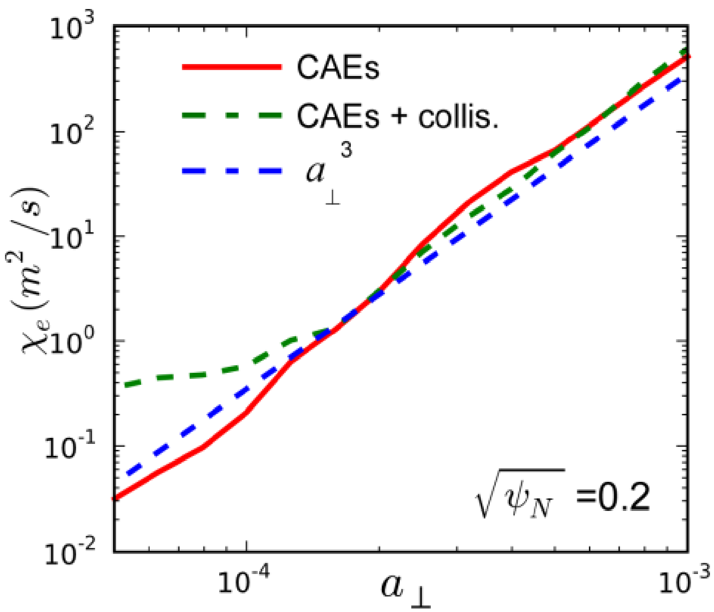


- Transport very sensitive to ∇T_e - may be more important to characterize scaling of effective threshold gradient, $(a/L_{Te})_{crit,microtearing}$
- Might help distinguish from expected ETG scaling, $(a/L_{Te})_{crit,ETG}$ – work in progress

ORBIT Guiding Center Code Used to Simulate CAE/GAE Effects on Electron Thermal Transport

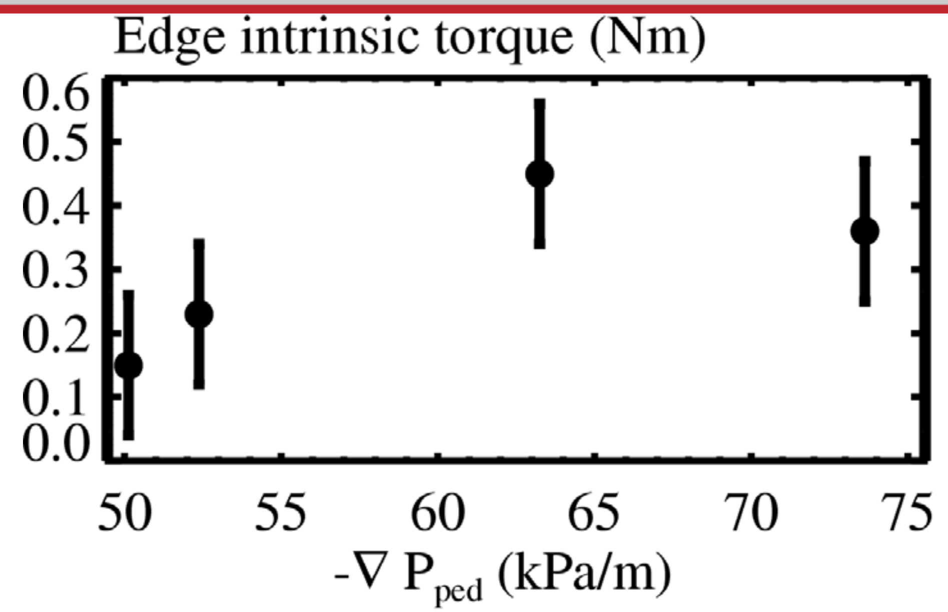




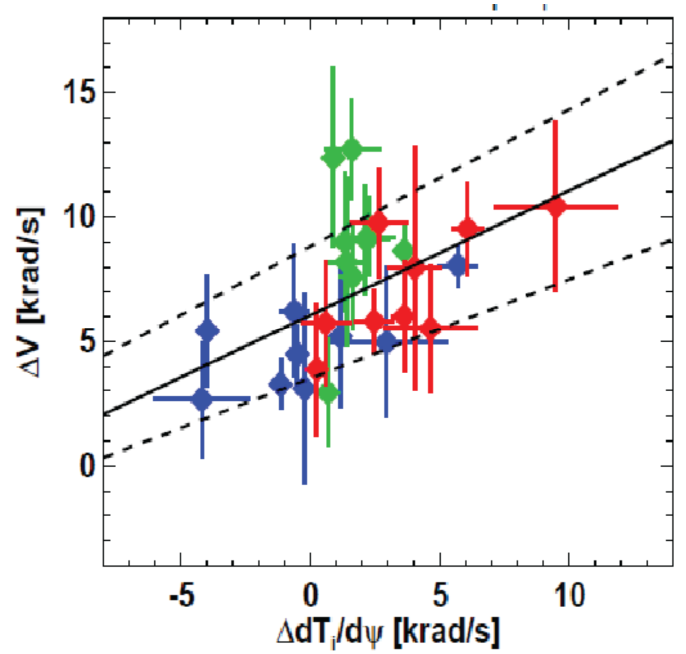


- A Gaussian radial structure for the CAE modes is chosen to match the experimentally measured mode peak location and width
- Frequencies and toroidal and poloidal mode numbers are determined using measurements and theoretical dispersion equations
- ORBIT simulations predict a strong scaling of transport with mode amplitude (~ a^{3-4})
- CAE & GAE modes combined can produce high levels of electron transport (~70 m^2/s) for r/a < 0.2 at t=580 ms
- Predicted transport is much lower at t=730 ms as the number of CAE modes appears to decrease

NSTX Edge Intrinsic Torque and Rotation Show Dependence on Pressure Gradient and T_i Gradient, Respectively



- Edge intrinsic torque shows some correlation with pressure gradient
  - Measured with NBI torque steps
  - Qualitatively similar dependence on pedestal gradients as DIII-D

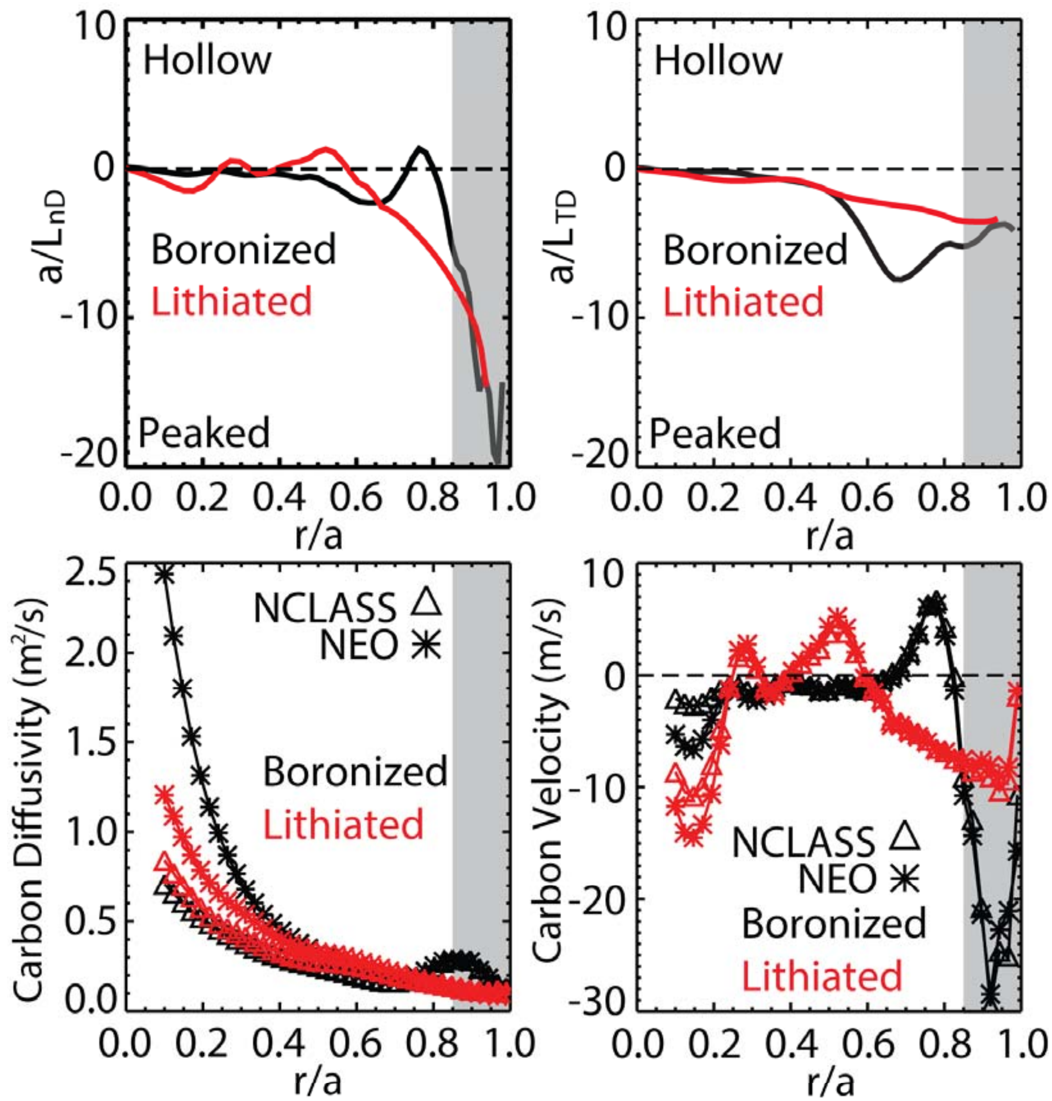


- Edge intrinsic rotation shows better correlation with T_i gradient (TC-9)
  - Measured on pedestal top through Ohmic L-H transition with passive CHERS
  - Zero input torque, small NTV torque and transport effect
  - No correlation found with T_e and n_e gradients

Changes in Main Ion Profiles with Lithium Conditioning Lead to Changes in Carbon Neoclassical Transport

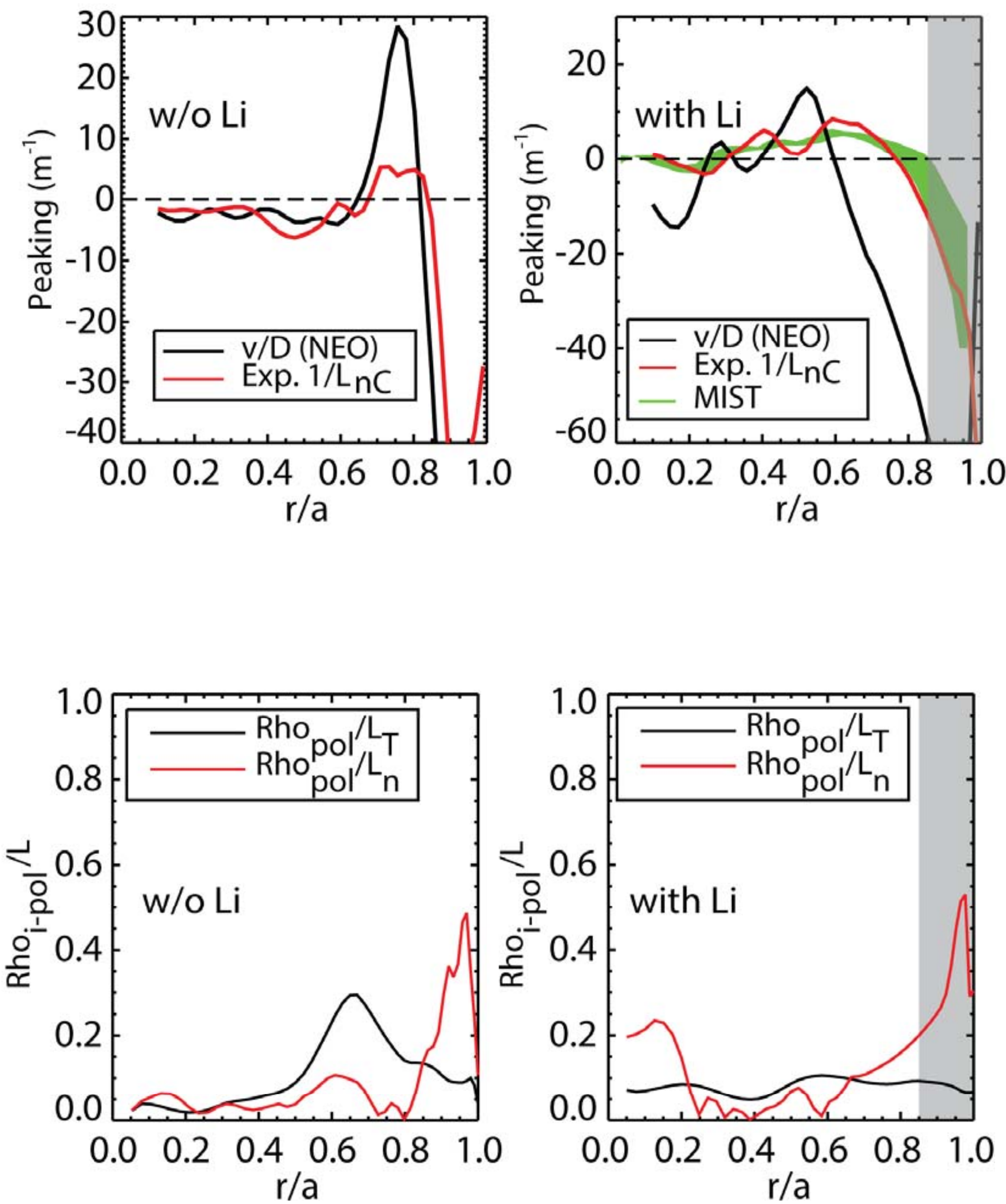
With lithium conditioning:

- Change in n_D and T_D profiles
  - Wider edge inward convection, 0.6 < r/a < 1.0
  - Increased core inward convection
  - Reduction in edge diffusivity
- Consistent results obtained using NCLASS and NEO:
  - Differences observed only in regions with large toroidal rotation
  - Comparable impurity peaking factors



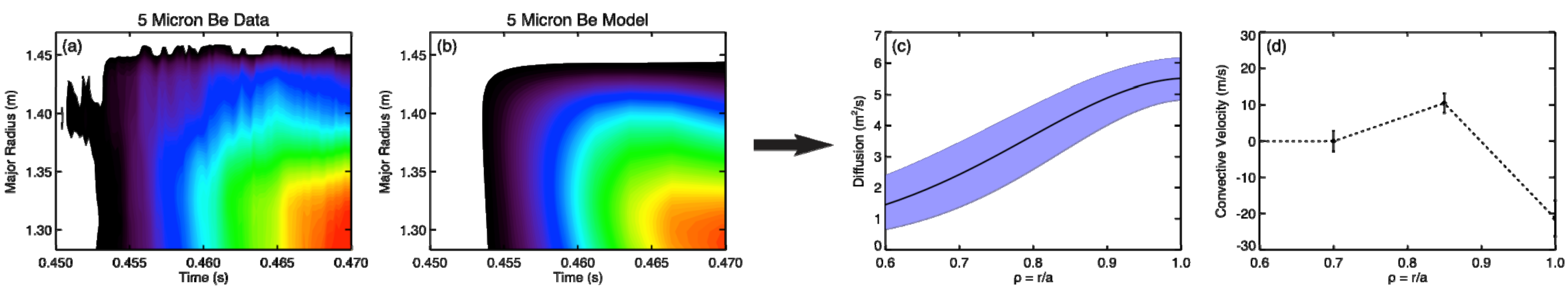
In lithium Conditioned Discharges Residual Anomalous Transport is Needed to Explain Carbon Profiles

- In steady state, source free, peaking $L_{nz}^{-1} \sim \frac{v_{exp}}{D_{exp}}$
- With boronized PFCs, carbon close to neoclassical predictions:
  - weaker edge peaking observed due to ELM flushing
- With lithium conditioned PFCs, qualitative agreement found:
  - outward convection region [0.2<r/a<0.6] and strong edge pinch
- Anomalous outward convective transport needed at pedestal top
  - Neoclassical ordering are only marginally applicable
- Consistent with deviations of ion thermal transport from neoclassical (Kaye, IAEA 2012)



Multi-Energy SXR Technique is Used to Determine Impurity Transport Profiles in the NSTX Plasma Edge

- Perturbative impurity transport measurements were performed using neon gas puffs in the plasma edge (non-perturbative to bulk plasma)
- ME-SXR arrays measure emission from many charge states of neon with high space and time resolution, coarse spectral resolution
  - Five 20-channel photodiode arrays with different filters (one with no filter for bolometry) provide tangential SXR emissivity measurements in five energy bands
  - 1 cm radial resolution (r/a ~ 0.6–1.0) and 10–100 kHz time resolution
  - Filtered ME-SXR arrays measure emission from highly-charged neon
  - Bolometer measures emission from lower charge states, thus providing the source term for higher charge states via ionization
- Impurity transport simulations (STRAHL) are coupled with a synthetic ME-SXR diagnostic and fit to data to obtain diffusion, convection profiles



5 μm Be Data ***5 μm Be Simulation*** ***Radial Diffusion*** ***Radial Convection***