Recent Progress in Understanding Electron Thermal Transport in NSTX and NSTX-U

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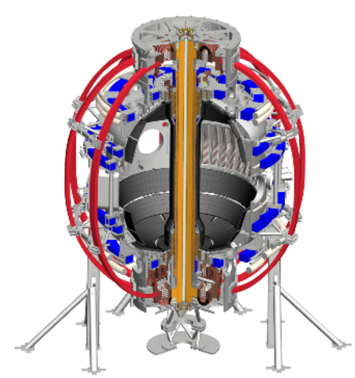
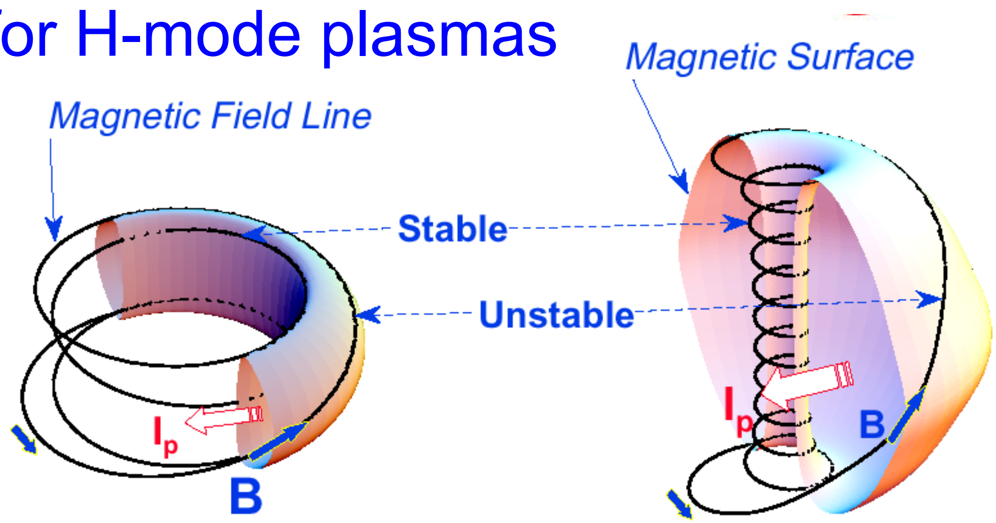


Outline

- Introduction
- Recent results on electron thermal transport in NSTX
  - Micro-tearing turbulence in NSTX high-beta and high-collisionality H-mode plasmas
  - ETG turbulence in NSTX L and H-mode plasmas
  - Fast-ion-driven Alfven eigenmodes in the core region of NSTX high-power H-mode plasmas
- NSTX-U Plans for electron thermal transport
- Summary

Spherical Tokamaks Have Some Significant Advantages over Conventional Tokamak

- The low aspect ratio of spherical tokamaks leads to improved ¯ limit than conventional tokamaks
  - More compact and lower-cost future devices, e.g. Fusion Nuclear Science Facility (FNSF) and power plant
- The effective shaping and/or strong ExB shear from low aspect ratio lead to reduced ion-scale turbulence
  - Neoclassical ion thermal transport and different confinement scaling for H-mode plasmas



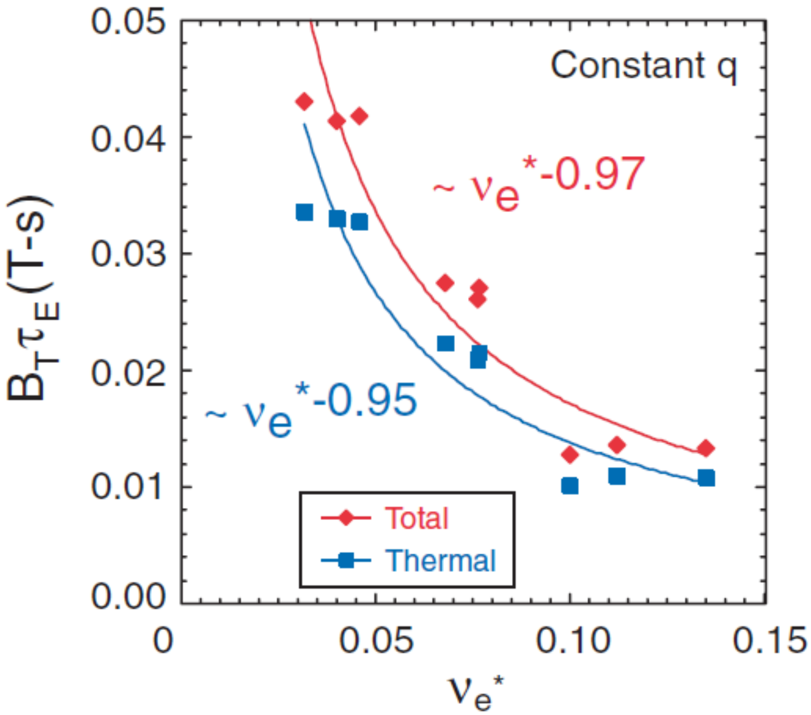
NSTX Thermal Confinement Has Strong Collisionality Scaling in H-mode Plasmas

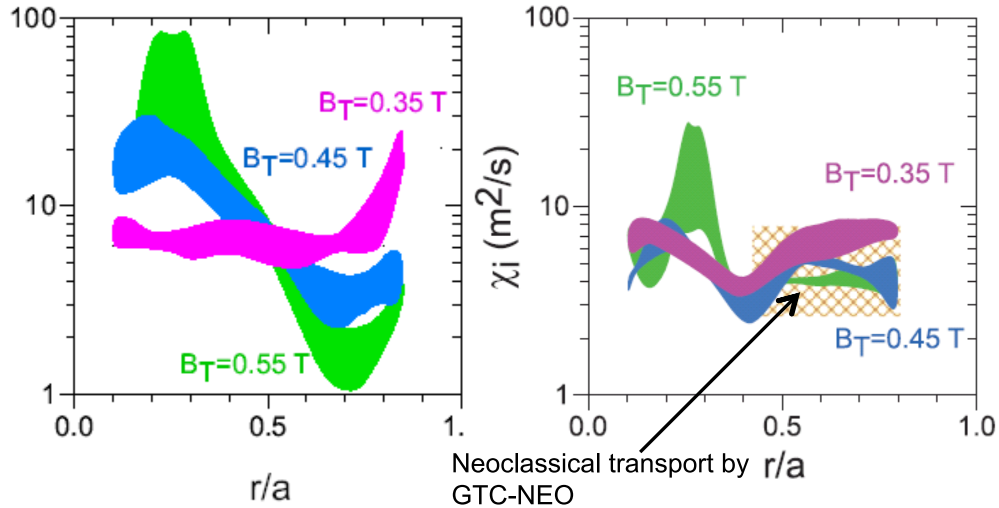
NSTX $\Omega\tau_E^{th} \sim \nu_{*e}^{-0.95}$

MAST $\Omega\tau_E^{th} \sim \nu_{*e}^{-0.82}$

ITER $\Omega\tau_E^{th,04(2)} \sim \nu_{*e}^{-0.2}$

Kaye et al., Nucl. Fusion, 2007
Valovič et al.,Nucl. Fusion, 2013
Doyle et al., Nucl.Fusion 2007

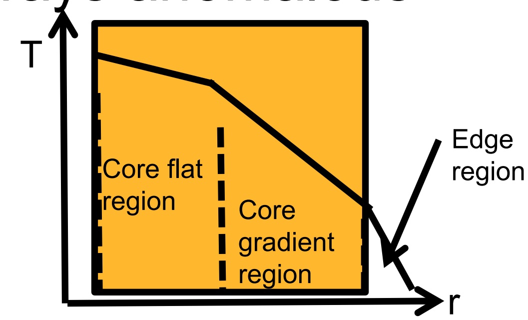




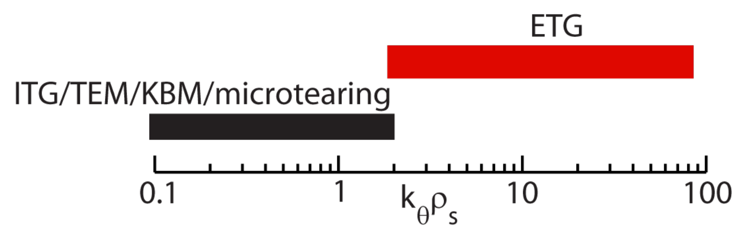
- Ion transport is neoclassical, consistent with strong flow shear and strong shaping
- The confinement scaling is determined by electron thermal transport

Multiple Mechanisms should be Responsible for Anomalous Electron Thermal Transport

- Different mechanisms needed to account for the always anomalous electron thermal transport
  - Different radial regions
    - Core flat region (small gradient drive)
    - Core gradient region (large gradient drive)
    - Edge region (steepest gradient, connection to SOL, e.g. H-mode pedestal)
  - Different parametric regimes
    - Large/small plasma beta/collisionality, magnetic shear, ExB shear, etc.

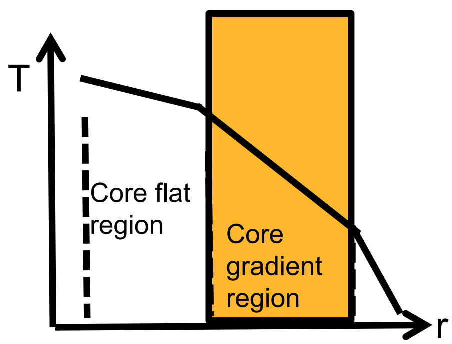


- Evidence exists for gradient driven electrostatic and electromagnetic ballooning drift instabilities:
  - Low-k (ion-scale): ITG/TEM/KBM/microtearing modes
  - High-k (electron-scale): ETG modes
  - Turbulent ExB drift and magnetic flutter effects



- Fast ion driven Alfvenic eigenmodes found relevant
  - GAE and/or CAE modes
  - Alfvenic eigenmode induced electron drift orbit stochasticity

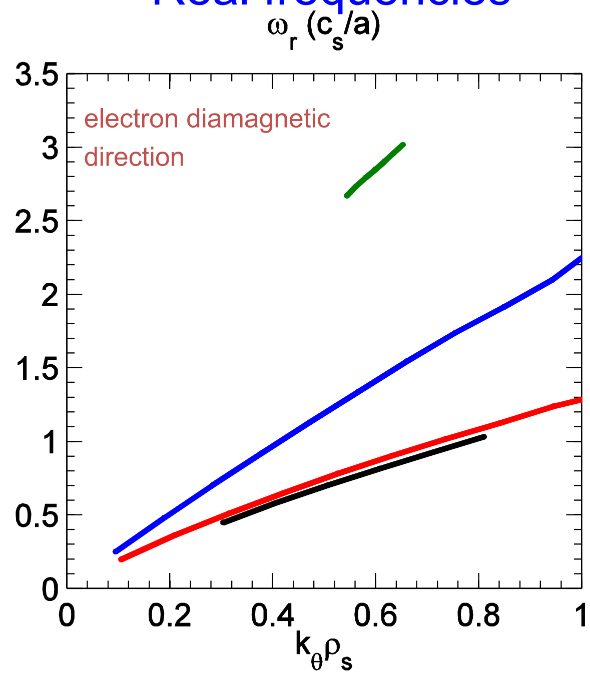
First nonlinear gyrokinetic simulation of micro-tearing turbulence in high-collisionality and high-beta H-mode plasmas

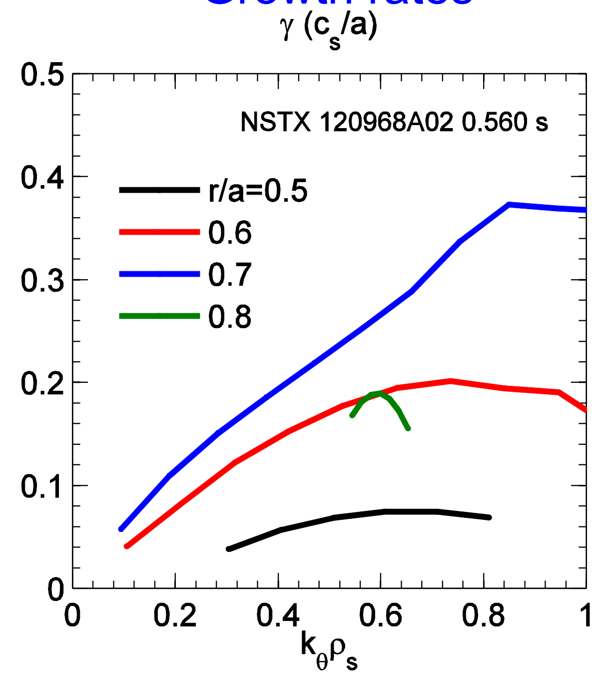


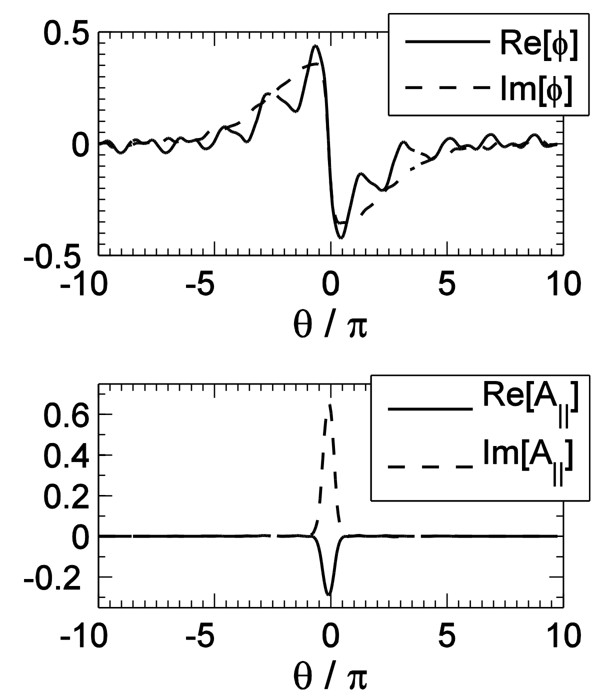
Microtearing Modes are Found to be Unstable in Many High n* H-mode Discharges

- Microtearing dominates over r/a=0.5-0.8, $k_q r_s<1$ ($n\sim5$-70)
- Real frequencies in electron diamagnetic direction, $w \sim w_{*e} = (k_q r_s)\cdot(a/L_n+a/L_{Te})\cdot(c_s/a)$
- ETG mostly stable due to larger $Z_{eff}\sim3$, $(R/L_{Te})_{crit,ETG}\sim(1+Z_{eff}T_e/T_i)$

B_T=0.35 T, I_p=700 kA, P_{NBI}=4 MW

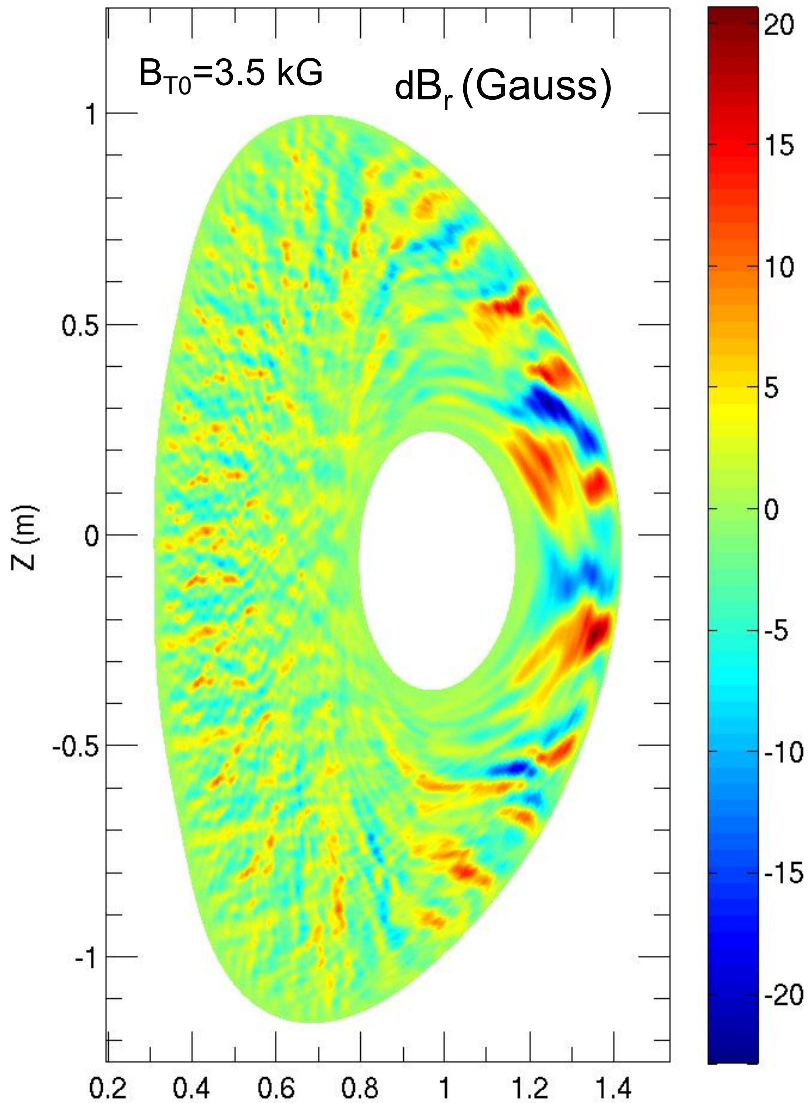




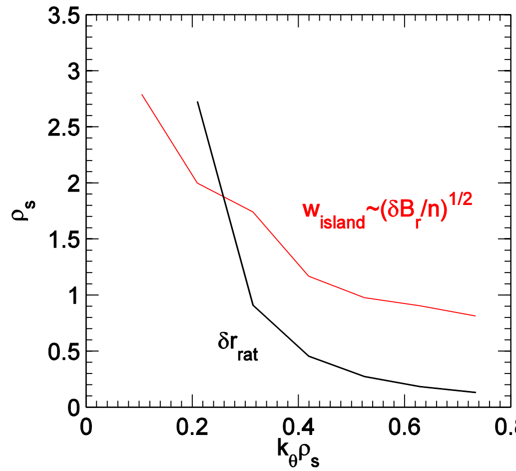


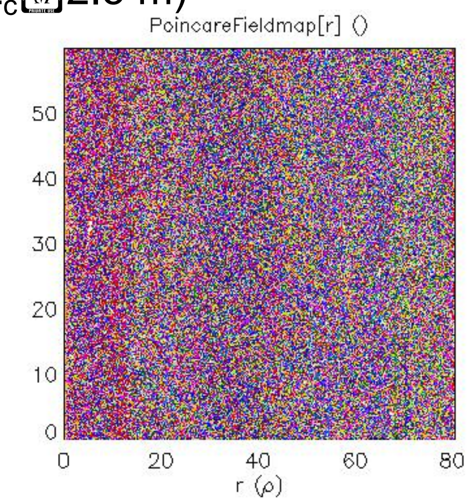
Linear GYRO simulations [Candy & Waltz, Phys. Rev. Lett. (2003); https://fusion.gat.com/theory/Gyro] using local general equilibrium, kinetic ions (D+C) and electrons, collisions, fully electromagnetic

First Successful Nonlinear Microtearing Simulations for NSTX



- ~98% of transport due to magnetic “flutter” contribution
- $w_{island}(n) > dr_{rat}(n)$, island overlap ⊠ perturbed field line trajectories are stochastic*
- $c_{e,EM} = 1.25\, r_s c_s^2/a$ close to *collisionless* Rechester-Rosenbluth** (l_{mfp}=12 m, L_c⊠2.5 m)





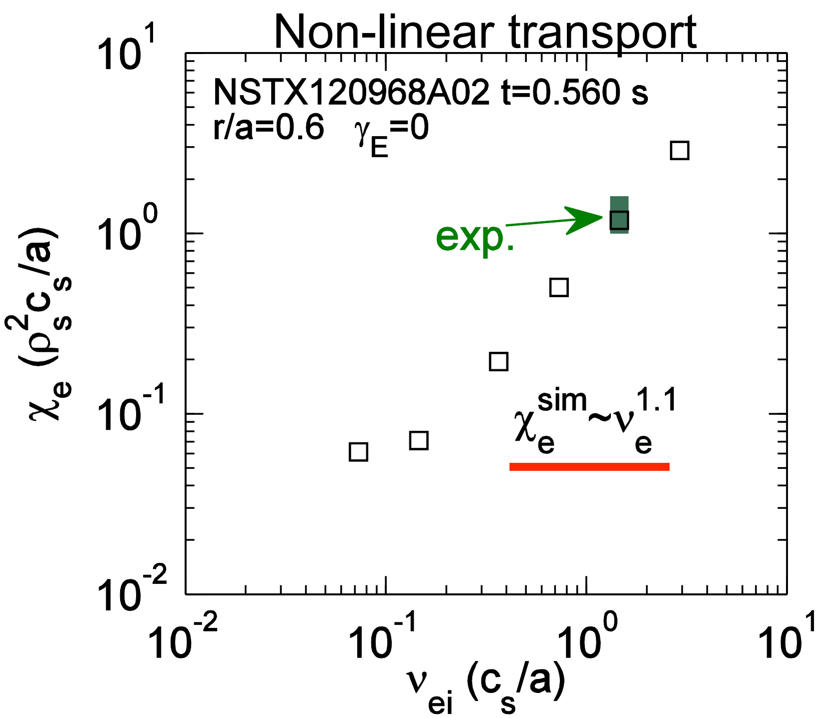
*E. Wang et al., PoP (2011).

**A.B. Rechester & M.N. Rosenbluth, PRL (1978)

Movies at http://www.pppl.gov/~wgutten/

W. Guttenfelder et al., PRL (2011)

Near Linear Scaling of Transport with n_e Consistent with Experimental Scaling

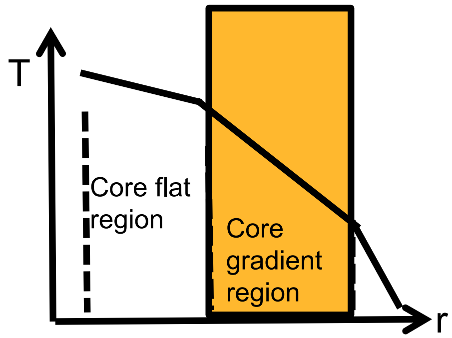


NSTX experimental scaling (Kaye et al., 2007)

$W_i t_E \sim n_*^{-0.95}$

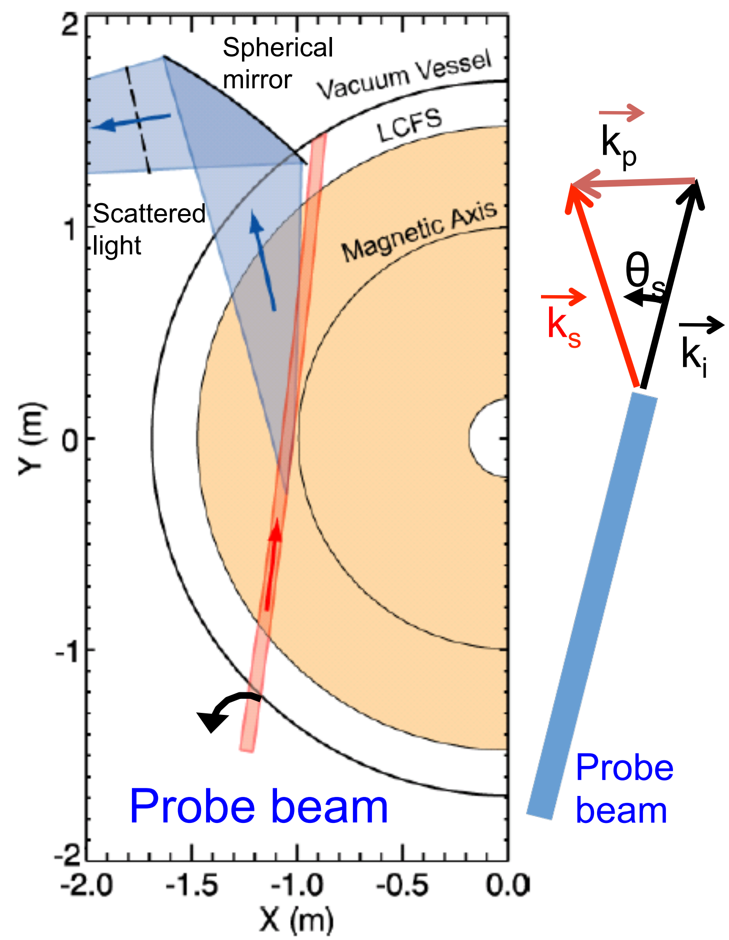
- As transport drops, a/L_{Te} will increase (for fixed heat flux), at some point ETG (TEM/KBM?) should become important
- This transition likely to determine limit of “favorable” n_* scaling

ETG turbulence in NSTX L and H-mode plasmas



A High-k Microwave Scattering System was Used to Measure Electron-scale Turbulence in NSTX

High-k turbulence measurement			
	r/a	Measured quantity	Spatial & temporal resolution
280 GHz microwave scattering system	~0.2-1 from core to edge	Density fluctuation	$3 \leq k_\perp \rho_s \leq 12$ $\Delta R \sim \pm 2$ cm f~ 5 MHz

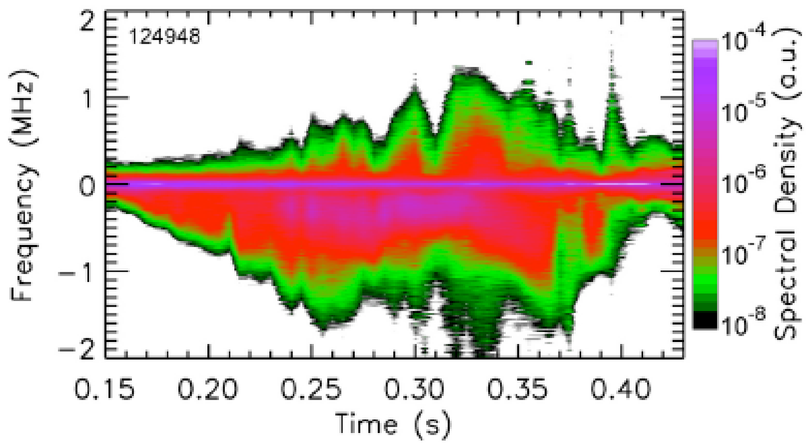


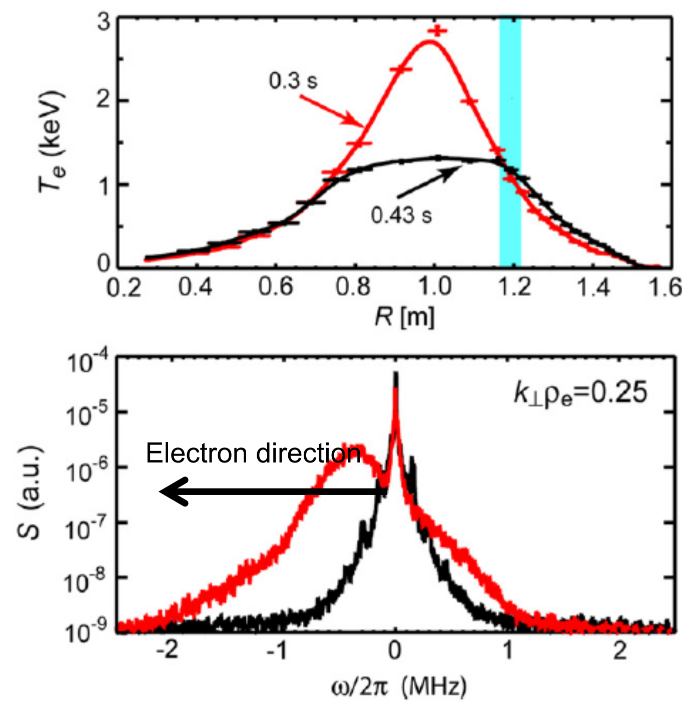
D.R. Smith, PhD thesis, 2009

First Identification of ETG Turbulence in NSTX RF-heated L-mode Plasmas

- The measured high-k turbulence is shown to be driven by electron temperature gradient (Mazzucato et al., PRL 2008, NF 2009).
  - In RF-heated helium L-mode plasma (1.2 MW, 5.5 kG, 700 kA)
  - Fluctuation propagates in the electron diamagnetic direction
  - Clear reduction in turbulence spectral power at lower electron temperature gradient

$k_\perp = 14\ cm^{-1}, k_\perp \rho_s = 8-10$

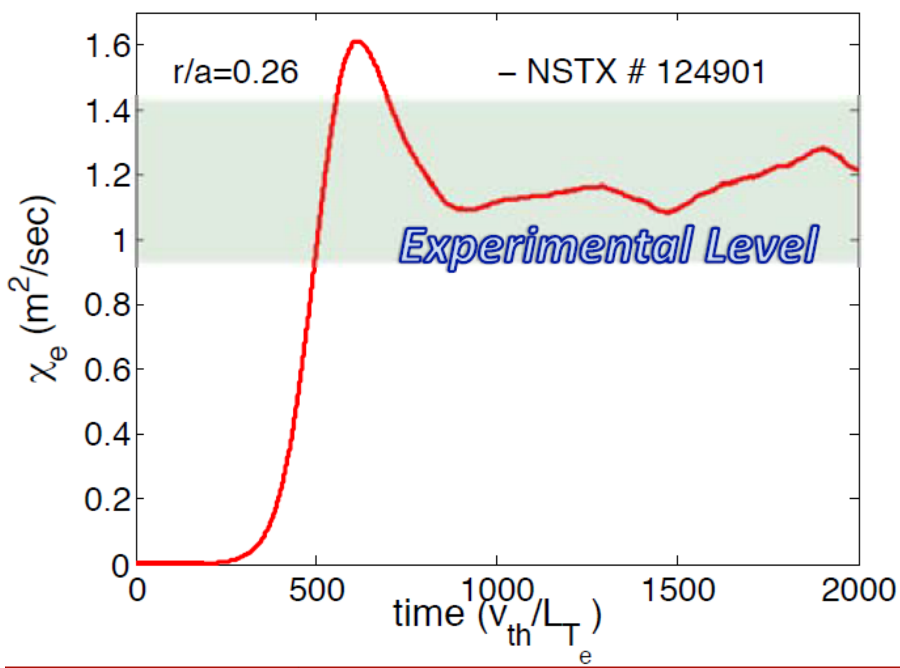


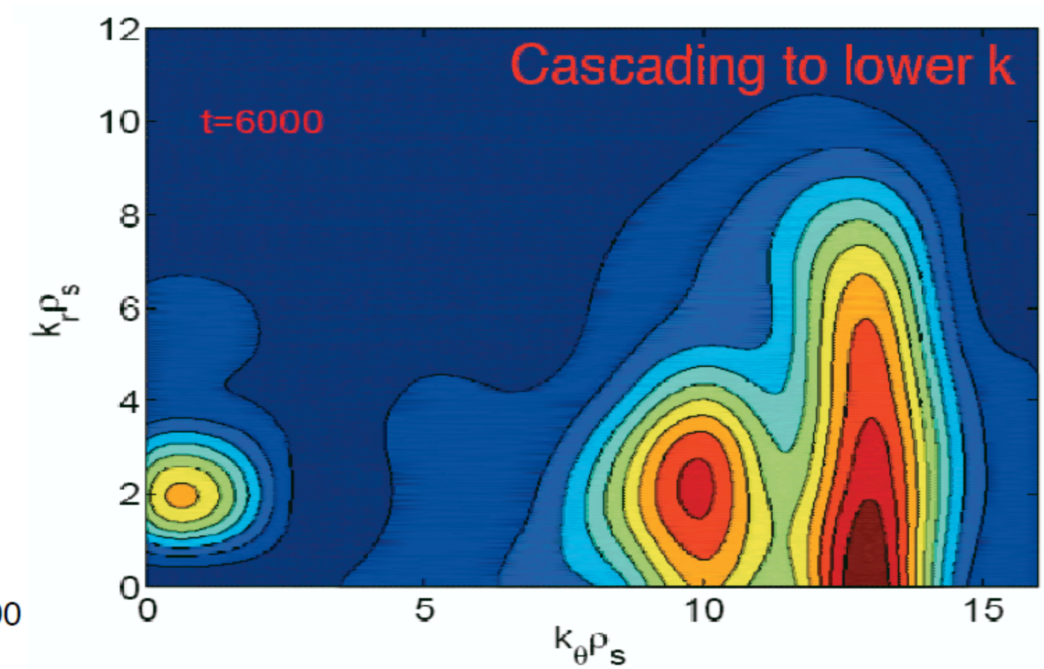


W.X. Wang et al., PoP (2015)

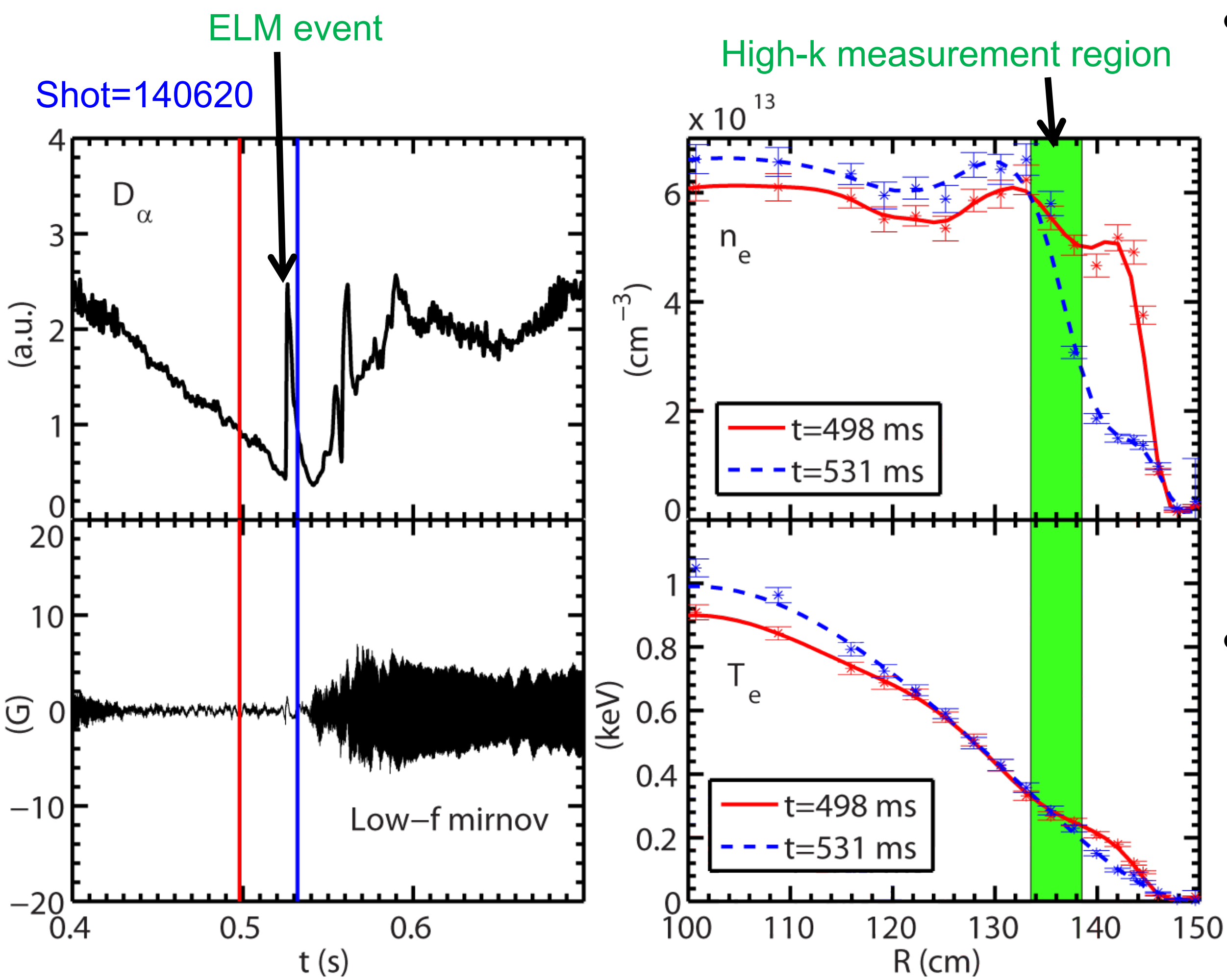
ETG Turbulence can Produce Experimentally Relevant Electron thermal Transport

- Significant ETG-induced contributions to anomalous Â$_e$ confirmed with global gyrokinetic code GTS
- Strong energy coupling to electron version of GAM (very high-ω ZF)





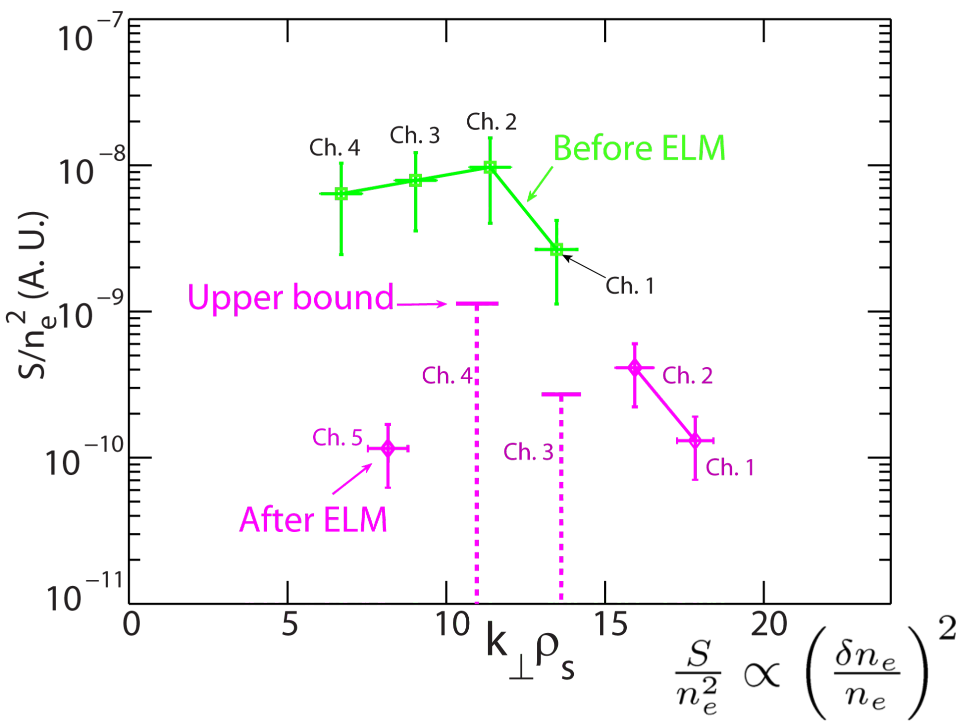
Large ELM Event induces Density Profile Steepening in the Core Region



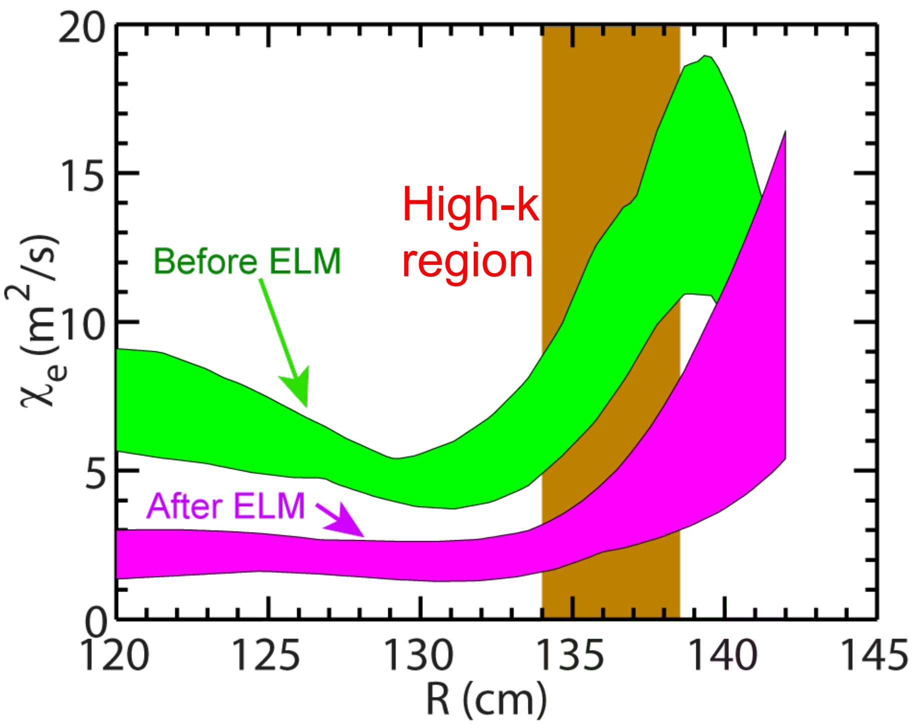
- After the ELM event:
  - Large density gradient developed in the high-k measurement region.
  - Electron temperature gradient also increases
  - Electron density has only a moderate decrease
  - Electron temperature remains essentially constant
- No large MHD mode appears before and right after the ELM event

Reduced ETG Turbulence Intensity and Electron Thermal Transport is Observed with Density Profile Steepening

- Significant decrease in spectral power in electron-scale observed for $k_\perp \rho_s \lesssim 10$



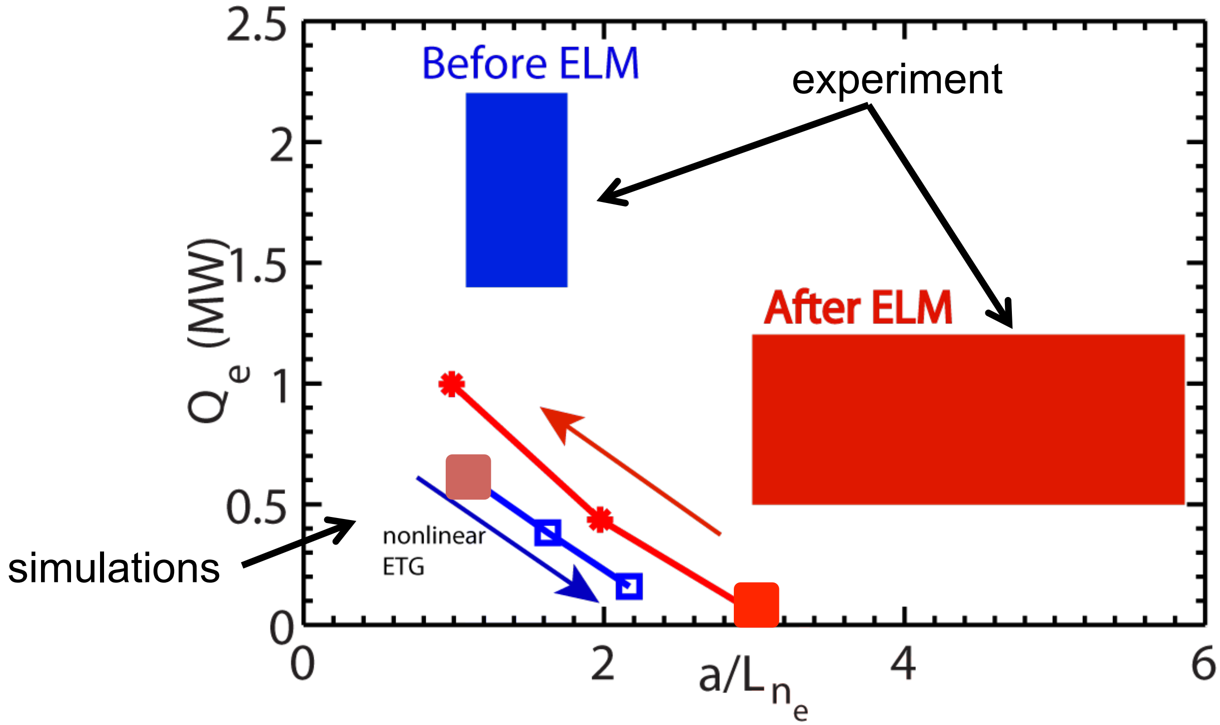
- Electron thermal diffusivity is decreased by a factor of ~2 after the ELM event



- **See Y. Ren et al., PRL 2011, PoP 2012**
- **Density gradient stabilization of high-k turbulence further confirmed in J. Ruiz-Ruiz et al., PoP 2015**

Nonlinear ETG Simulations Reproduce Observed Dependence of Electron Transport on Density Gradient

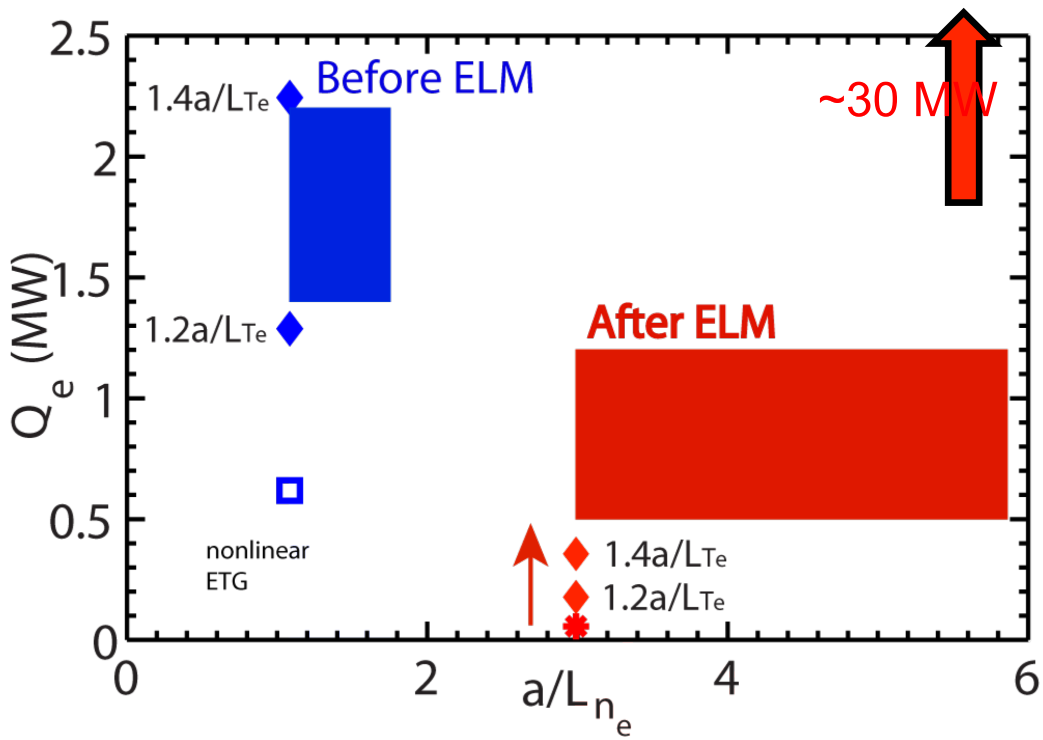
- Experimental Q_e is found to decrease after the ELM event with large density gradient
- The same trend is found from nonlinear ETG simulations, but does not agree quantitatively



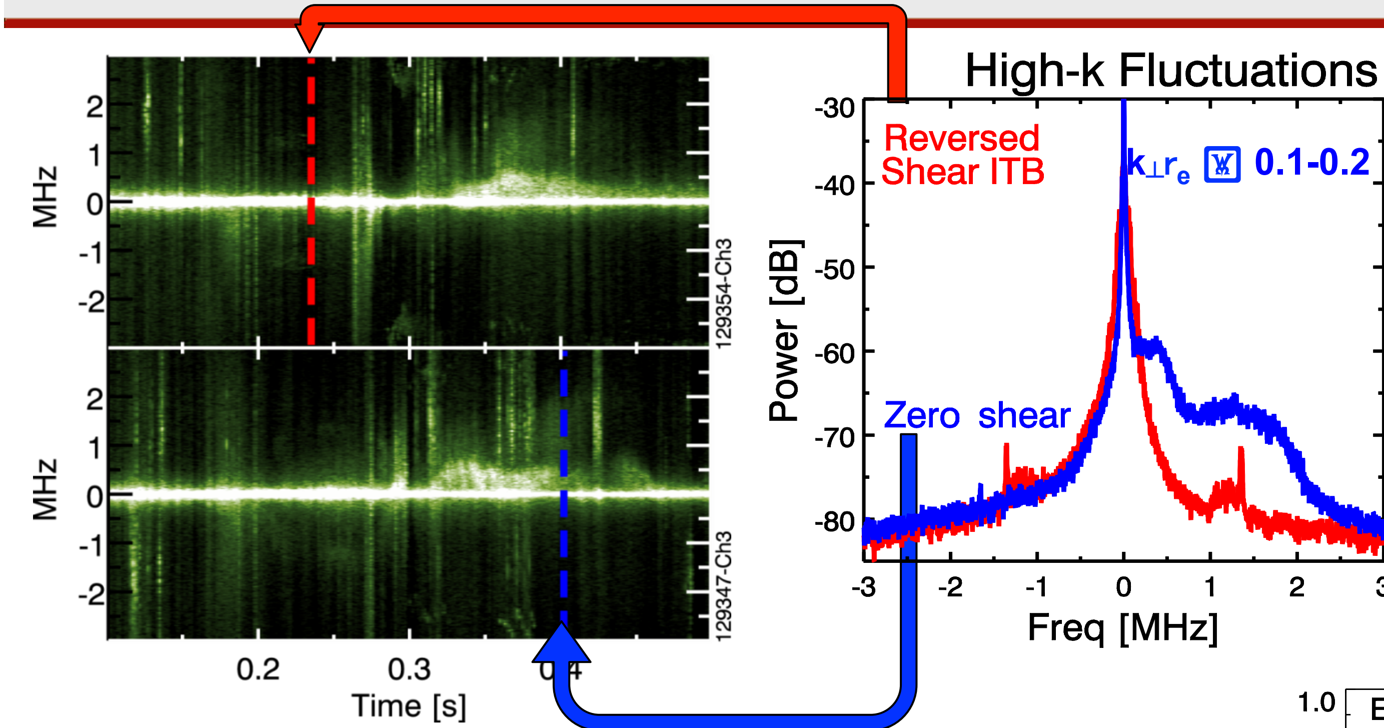
Nonlinear GYRO ETG simulations with: local general equilibrium, kinetic ions and electrons, collisions, electromagnetic, flow and flow shear

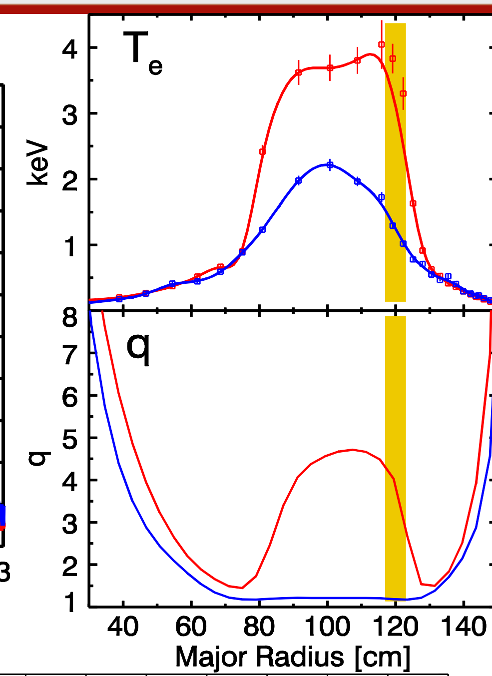
Trapped Electron Mode (TEM) Destabilized by Large Density Gradient may Contribute to Transport

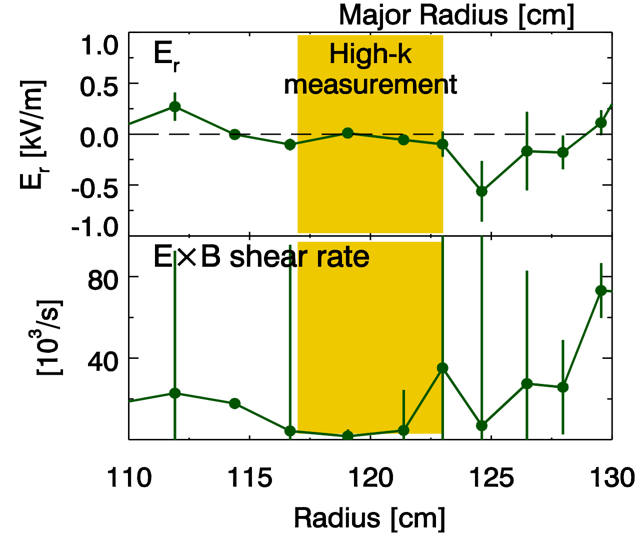
- Before ELM, a 20-30% increase in a/L_{Te} is able to match the experimental Q_e
- After ELM, increasing a/L_{Te} by 40% after still cannot match experimental Q_e
- Large TEM-induced transport (~30 MW) is predicted after ELM without E×B shear stabilization
- Using experimental E×B shear almost completely suppresses transport
  → does not require much residual transport to match experimental Q_e



ETG Turbulence Stabilization by Reversed Magnetic Shear is Responsible for ITB Formation



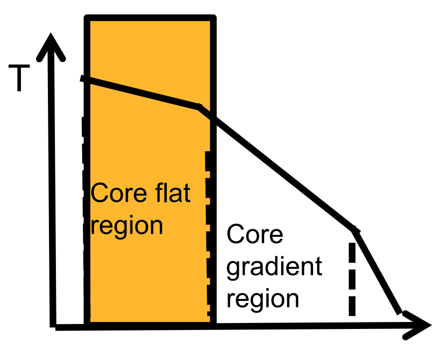




- HHFW only with beam blips
- Minimal ExB shearing rate due to cold ions with low toroidal rotation
- **Magnetic shear alone suppresses electron turbulence**

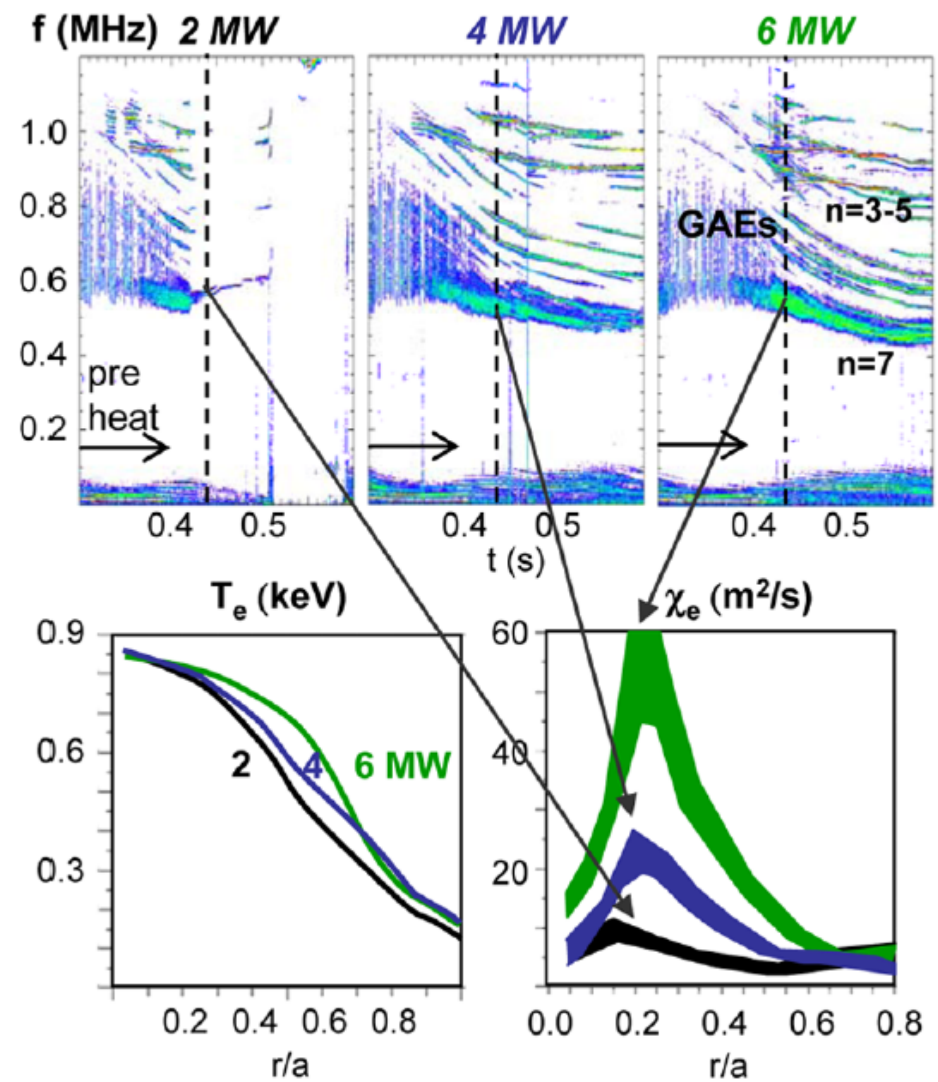
Yuh et al., NF 2009 and PRL 2011

Fast-ion-driven Alfven eigenmodes in the core region of NSTX high-power H-mode plasmas



Core T_e Flattening in High-power NBI H-mode plasmas is Observed to be Correlated with *AE Activities

- Core T_e flattening correlated with NBI power
  - No simultaneous increase in central T_e
- Almost a factor of 10 increase in core Â$_e$ (r/a~0.2)
  - Â$_e$ calculated with TRANSP power balance analysis
  - Calculated neutron rate with classical fast particle slowing-down in good agreement with measured neutron rate
- Increased *AE (GAE/CAE) activity observed from edge Mirnov measurement

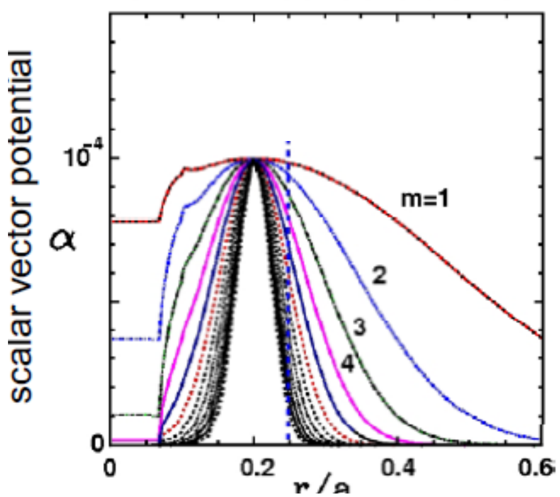


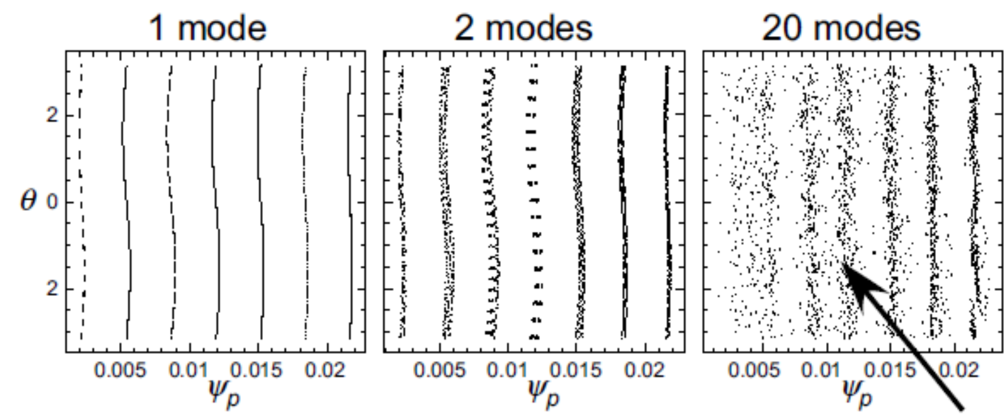
D. Stutman et al., PRL (2009)

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

N. Gorelenkov Nucl. Fus. 2010

GAE Model used in ORBIT calculations

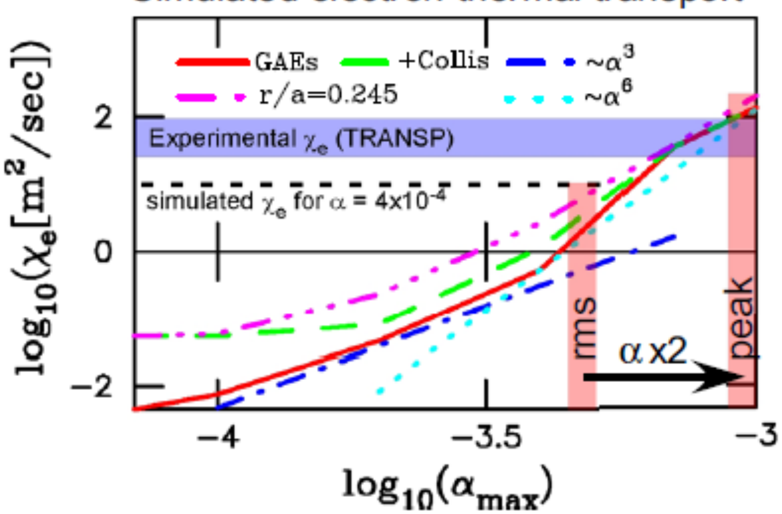




Poincaré plot of electron trajectory

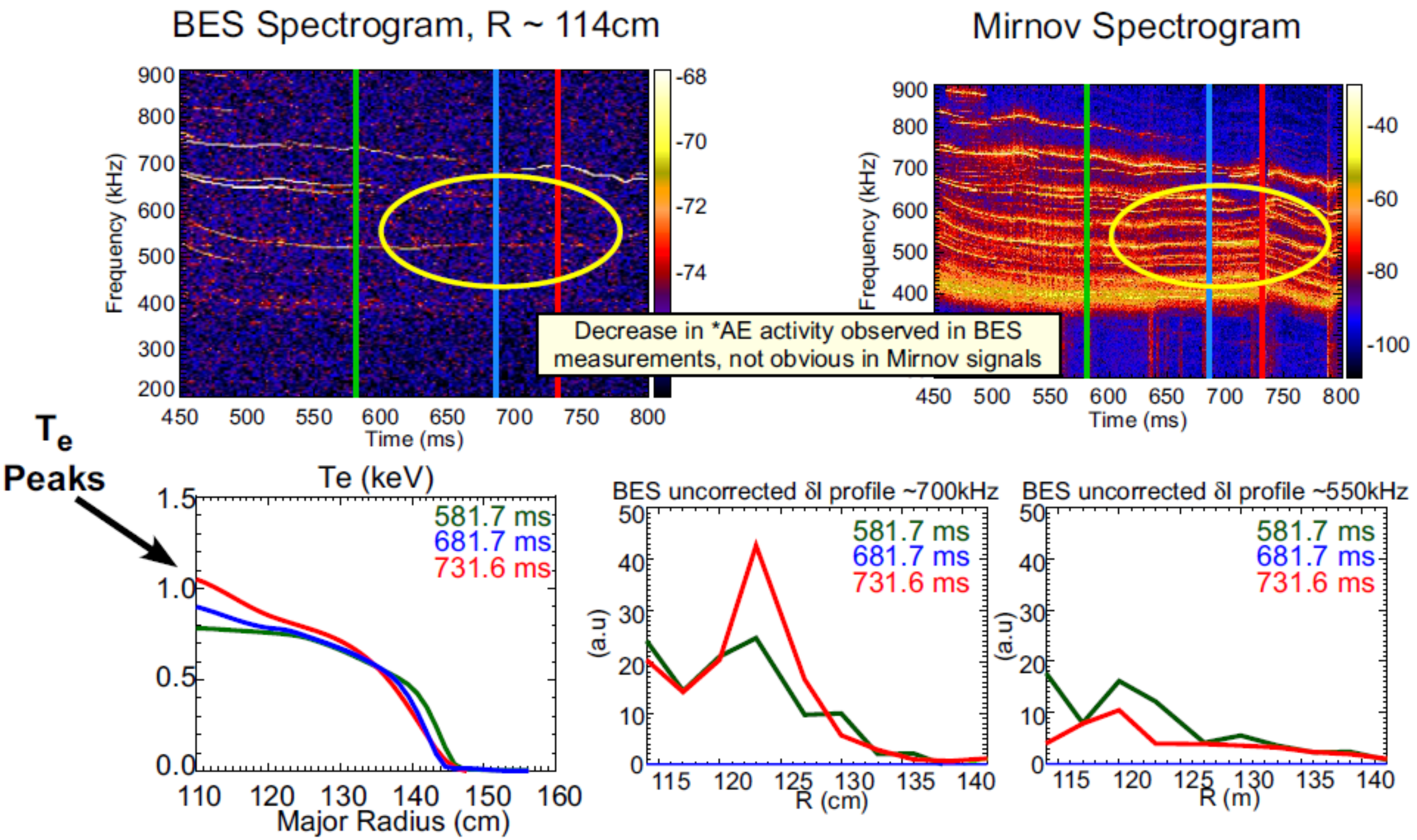
stochastic particle trajectories

Simulated electron thermal transport



- Ad-hoc model used to study transport vs. mode amplitude and number
- χ_e > 10m^2/s for GAE mode amplitude: α > 4x10^{-4}, number: N > 16
- 'stochastic' transport sensitive to mode structure and amplitude (~^{3}-^{6})

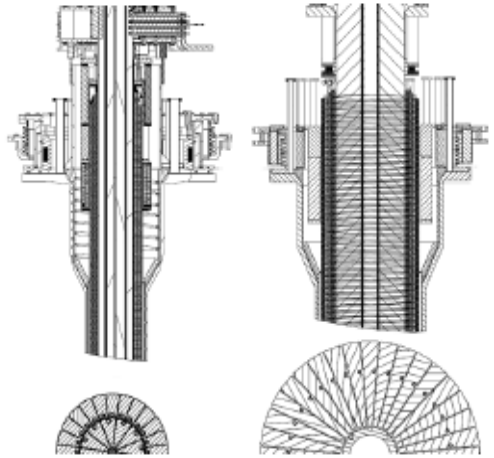
Decrease in *AE Activity Measured by BES Corresponds with Peaking of Central Electron Temperature



- T_e remains peaked even with large single mode (bulk *AEs still largely supressed)
- BES sensitivity to *AEs marginal at later times, density rise limits reflectometer data
- Need high-k core data to determine if high-k turbulence limits central T_e gradient

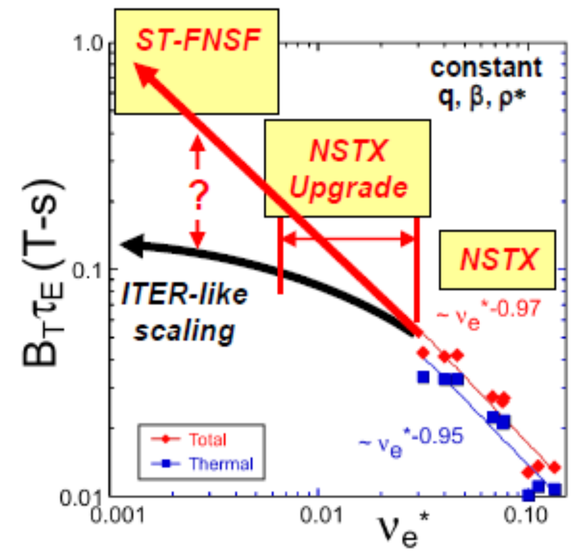
Study of Electron Thermal Transport will Benefit from Two New Capabilities of NSTX-U

Previous center-stack | New center-stack

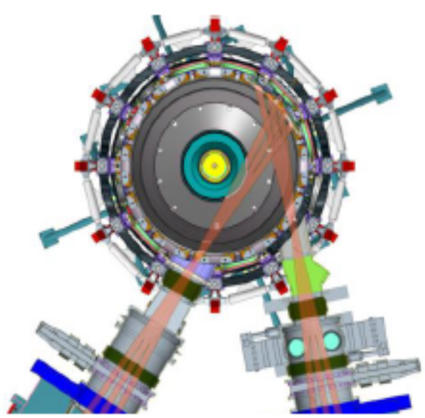


TF OD = 20cm | TF OD = 40cm

- ➢ Reduces ν^* → ST-FNSF values to understand ST confinement
  - Expect 2x higher T by doubling B_T, I_P, and NBI heating power
- ➢ 5x longer pulse-length
  - q(r,t) profile equilibration
  - Test non-inductive ramp-up

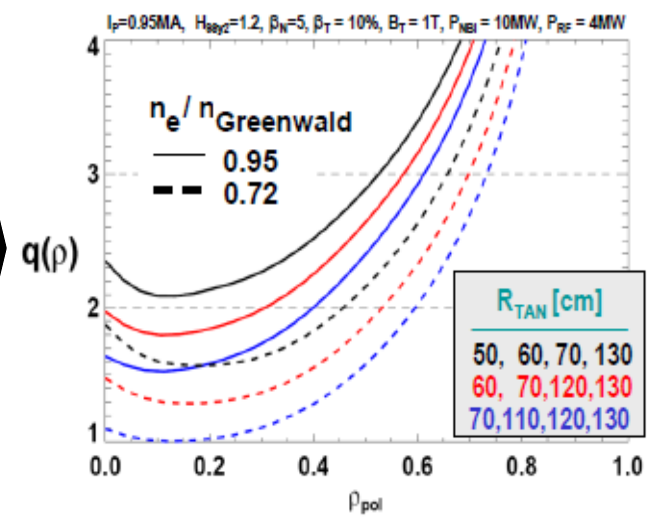


Normalized e-collisionality $\nu_e^* \propto n_e / T_e^2$



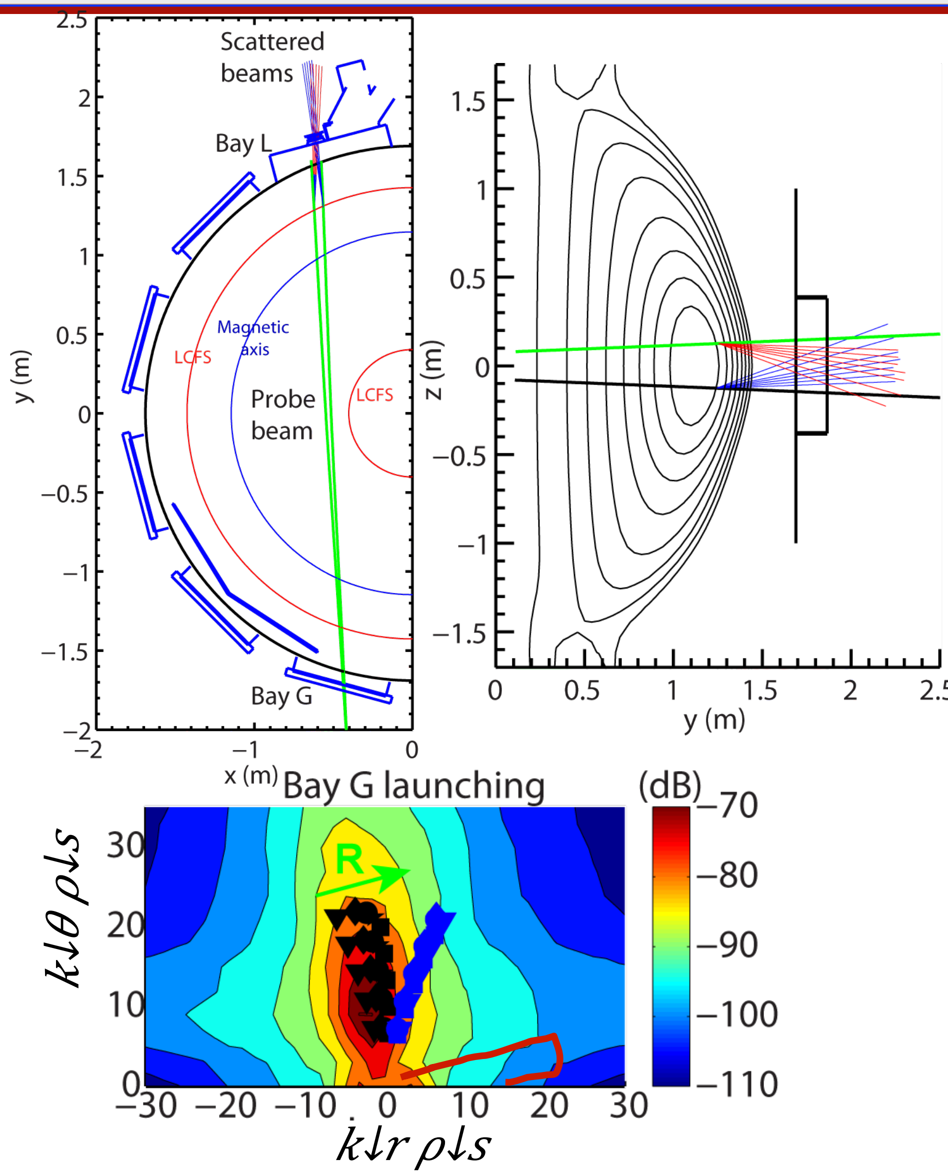
Present NBI | New 2[nd] NBI

- ➢ q and flow profile control from larger tangency radius R_{TAN} of 2[nd] NBI
  - •2x higher CD efficiency
- ➢ 100% non-inductive CD



Improved Diagnostics on NSTX-U will Strongly Support the Study of Electron Thermal Transport

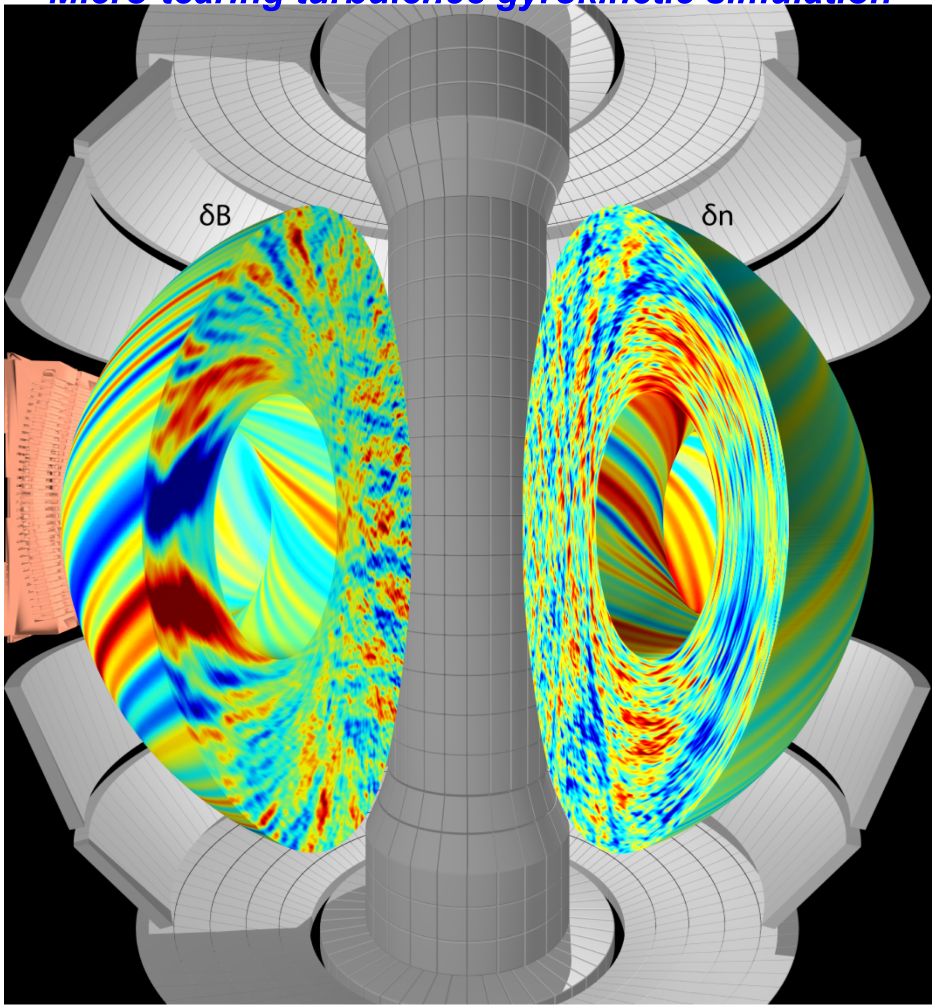
- A new FIR high-k_θ scattering system being designed at UC-Davis
  - To be installed for FY17 run campaign



Improved Diagnostics on NSTX-U will Strongly Support the Study of Electron Thermal Transport

- A new FIR high-k_θ scattering system being designed at UC-Davis
  - To be installed for FY17 run campaign
- A DBS/CPS system will be installed for FY17 run campaign
  - Measure ion-scale turbulence
  - Able to measure magnetic fluctuations (CPS)
- 48 BES channels are now available on NSTX-U
  - 16 more than NSTX

Micro-tearing turbulence gyrokinetic simulation



Summary

- NSTX has made significant progress towards understanding anomalous electron thermal transport
  - First nonlinear gyrokinetic simulation of microtearing turbulence to produce experimental confinement scaling and transport in NSTX H-mode plasmas
  - ETG turbulence driving electron thermal transport in L and H-mode plasmas, supported by linear and nonlinear gyrokinetic simulations
  - *AE-induced core Te flattening, consistent with electron stochastic transport from ORBIT simulations; Alternative mechanism of coupling CAE to KAW also presented
- Electron thermal transport will be the key part of the transport and turbulence research plan for NSTX-U
  - Ip ~2 MA, BT ~1 T, 2nd NBI (~12 MW), a suite of turbulence diagnostics, e.g. new high-k scattering system and DBS/CPS