Studies of NSTX L and H-mode Plasmas with Global Gyrokinetic Simulation

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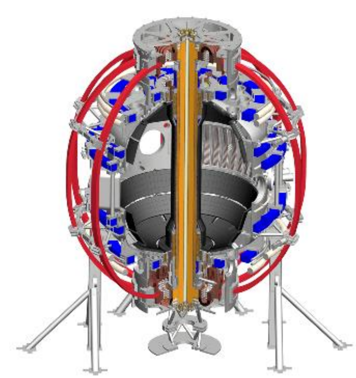


Why are Global Effects Important?

- Global effects are considered to be important for STs
  - Local assumption of flux tube simulations based on ρ^*->0
  - Large ρ^* of STs due to weaker toroidal field compared to conventional tokamaks (ρ^* ~ 0.01 for NSTX)
  - Global effects, e.g. profile variation, requiring global GK codes
- Study of global effects are important for achieving predictive capability for future STs
  - Need to validate first principle model for developing reduced transport model with global effects
- Serious validation efforts, applying global GK codes to ST plasmas, are still lacking

Outline

- GYROKINETIC TOKAMAK SIMULATION (GTS) code
- Global GTS simulations of NSTX L and H-mode plasmas
  - NSTX RF-heated L-mode plasmas
    - Fast response of electron-scale turbulence to RF cessation
  - NSTX H-mode plasmas
    - Density gradient stabilization of electron-scale turbulence

GTS - a Global Gyrokinetic Code with Robust Capability to Simulate Turbulence & Transport for Tokamak Experiments

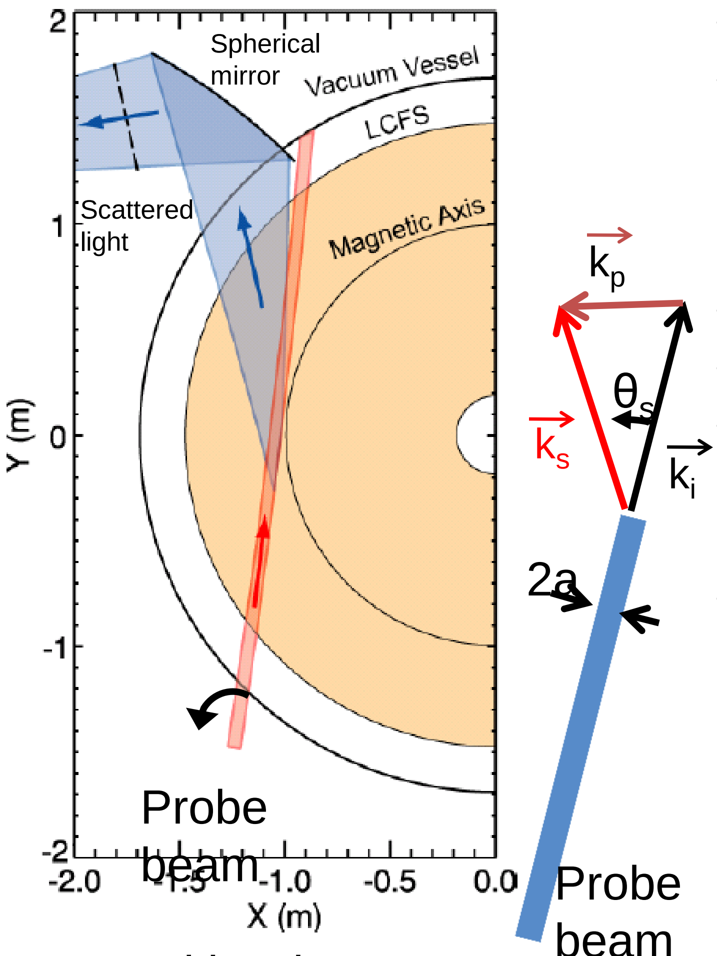
- δf PIC code solving modern GK equation in conservative form

$$\frac{\partial f_a}{\partial t} + \frac{1}{B^*}\nabla_Z \cdot (\dot{\vec{Z}} B^* f_a) = \sum_b C[f_a, f_b]$$

- New, improved weight scheme ensuring phase space incompressibility
- Full geometry, global simulation (without local ballooning approximation)
  - Real space field solvers with field-line-following mesh
  - Retains all toroidal modes allowed by resolution and full channels of nonlinear energy couplings
  - Enable to treat modes with low-n, with finite $k_{||}$, (e.g., shear flow mode)
- Fully kinetic electrons (both trapped and untrapped electron dynamics)
- Linearized Fokker-Plank operator with particle, momentum and energy conservation for i-i and e-e collisions; Lorentz operator for e-i collisions
- Include neoclassical physics self-consistently in turbulence simulations
  - Significant impact on some important transport & confinement issues (bootstrap current, poloidal flow, GAMs and particle transport, etc.)
- Applied to wide experiments for various physics studies: NSTX/U, DIII-D, C-MOD, KSTAR and ASDEX-U

NSTX RF-heated L-mode plasmas with fast response of electron-scale turbulence to RF cessation

High-k Microwave Scattering System is Used to Measure High-k Turbulence



D.R. Smith, PhD thesis, 2009

- 280 GHz microwave is launched as the probe beam.
- Coherent scattering by plasma density fluctuations occurs when the three-wave coupling condition is satisfied:

$$\vec{k}_s = \vec{k}_p + \vec{k}_i$$

- Bragg condition determines k_p:
- $$k_p=2k_i\sin(\theta_s/2)$$
- The scattered light has a frequency of:

$$\omega_s=\omega_p+\omega_i$$

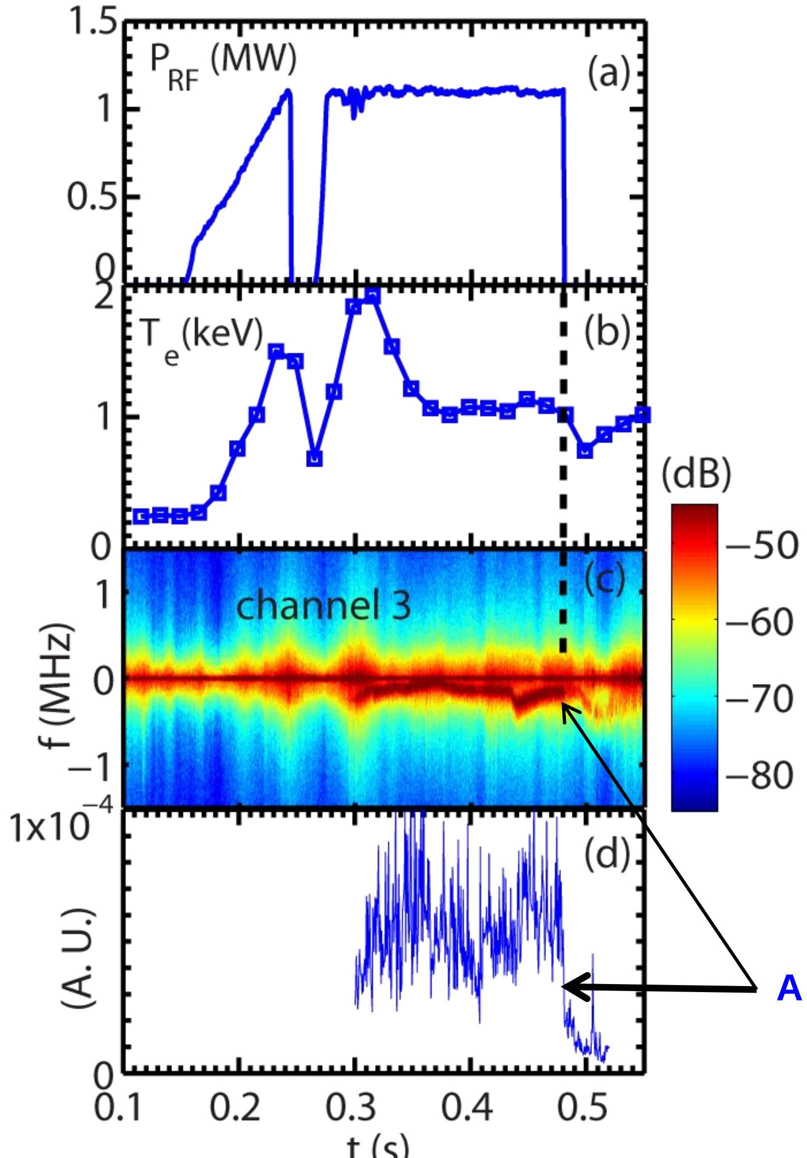
with ω_s and $\omega_i >> \omega_p$

- The scattering system characteristics are:
  - Frequency bandwidth: 5 MHz
  - Heterodyne receiver: Wave propagation direction resolved
  - Measurement: k_r spectrum
  - Wavenumber resolution: 0.7 cm^{-1} (2/a with a ≈ 3 cm)
  - Wavenumber range (k_r): 5-30 cm^{-1} (~5-30 ρ_s^{-1})
  - Radial resolution: $\pm$2 cm
  - Tangential resolution: 5-15 cm
  - Radial range: R=106 – 144 cm
  - Minimal detectable density fluctuation: $|\delta n_e(k)/n_e|^2 \approx 2\times10^{-11}$

Measured Turbulence Frequency Spectral Power Shows a Significant Drop Following the RF Cessation

Shot=140301

RF-heated L-mode plasma with B_T =5.5 kG and I_p=300 kA

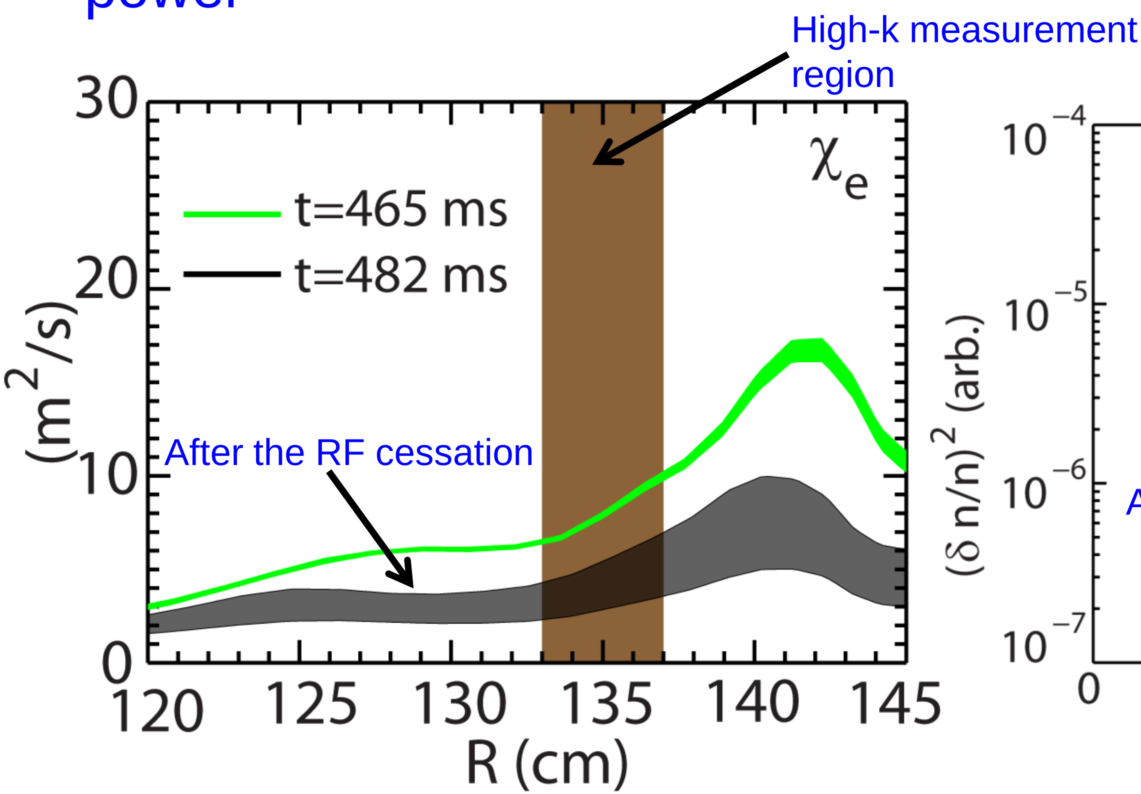


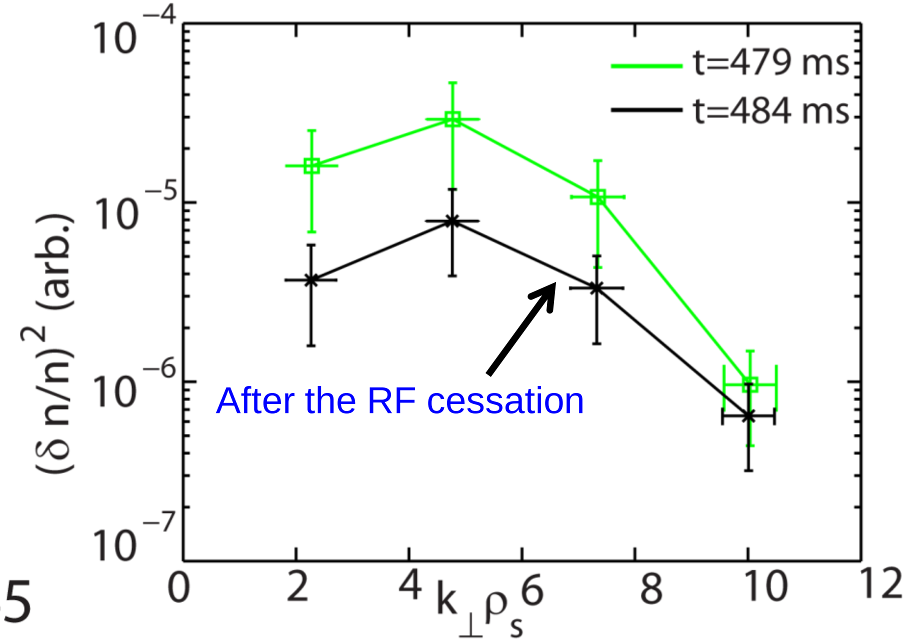
- Drop in turbulence frequency spectral power at the time of RF cessation
  - The drop happens in 0.5 to 1 ms
- High-k measurement region r/a~ 0.57-0.63

Ren et al., PoP, 2015

Turbulence Wavenumber Spectral Power is Correlated with Electron Thermal Diffusivity

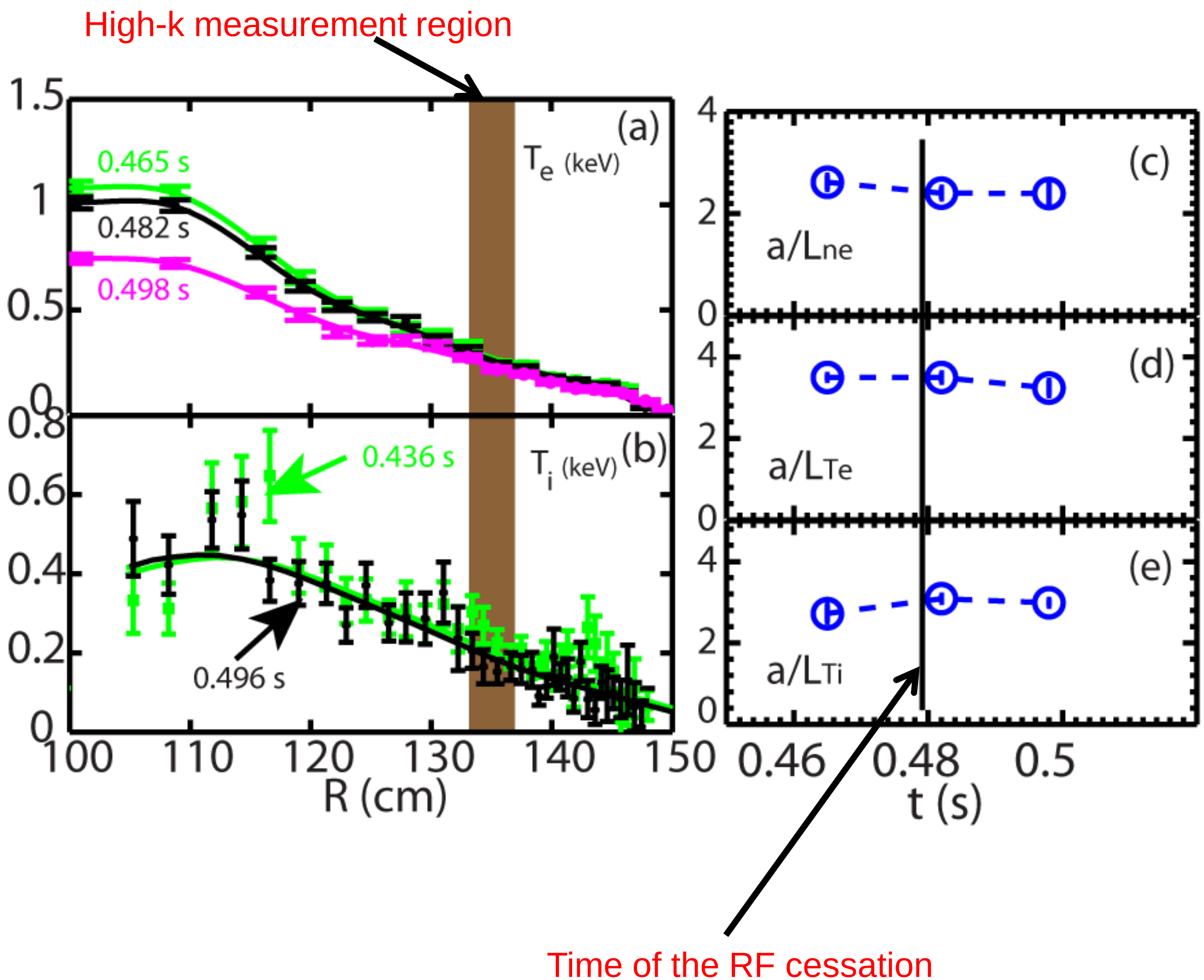
- About a factor of 2 decrease in electron thermal diffusivity after the RF cessation
  - Correlated with the decrease in turbulence wavenumber spectral power





From TRANSP analysis with

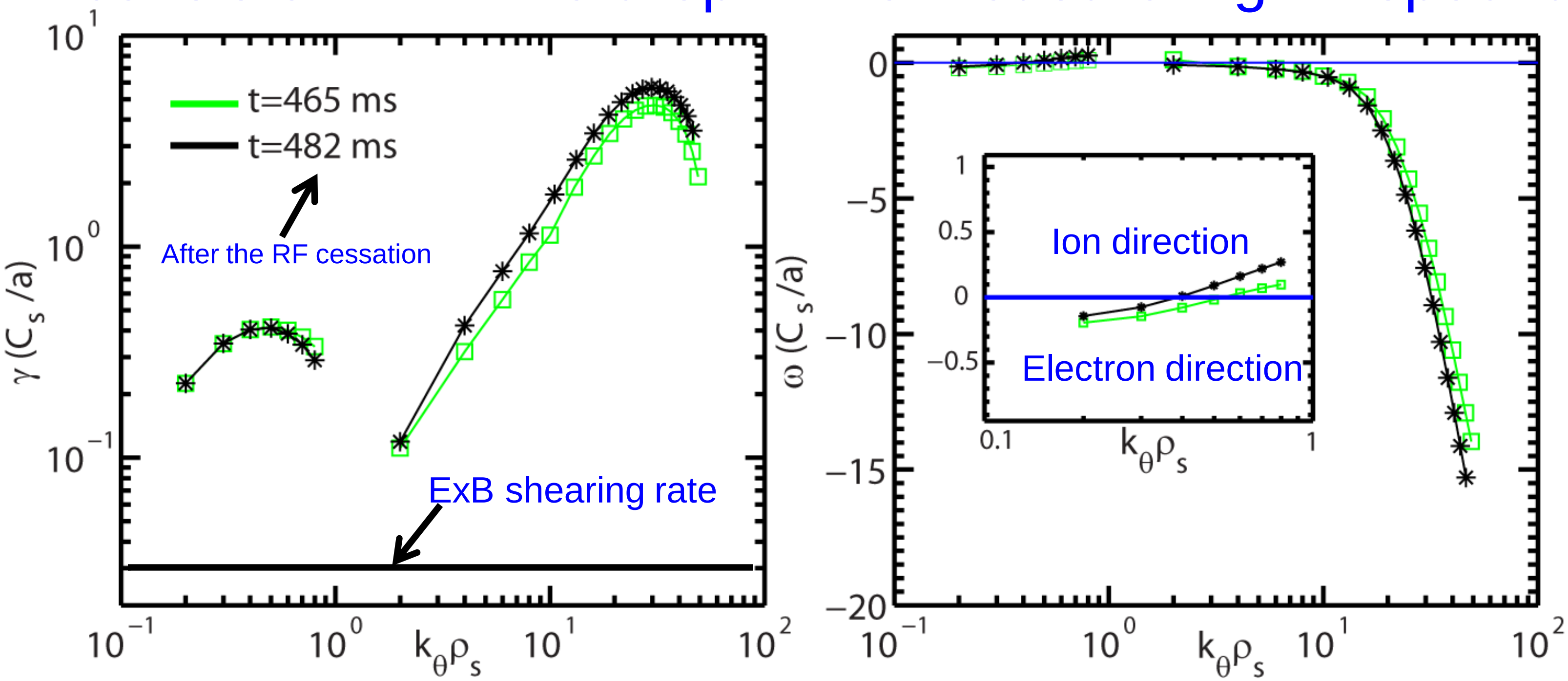
What Causes the Sudden Drop of Electron-scale Turbulence?



- <15% variation in equilibrium quantities in the high-k measurement region before and right after the RF cessation (over 17 ms)
- Equilibrium quantities not expected to change significantly on the time scale on which the turbulence changes (0.5-1 ms)
  - Energy confinement time~ 10 ms

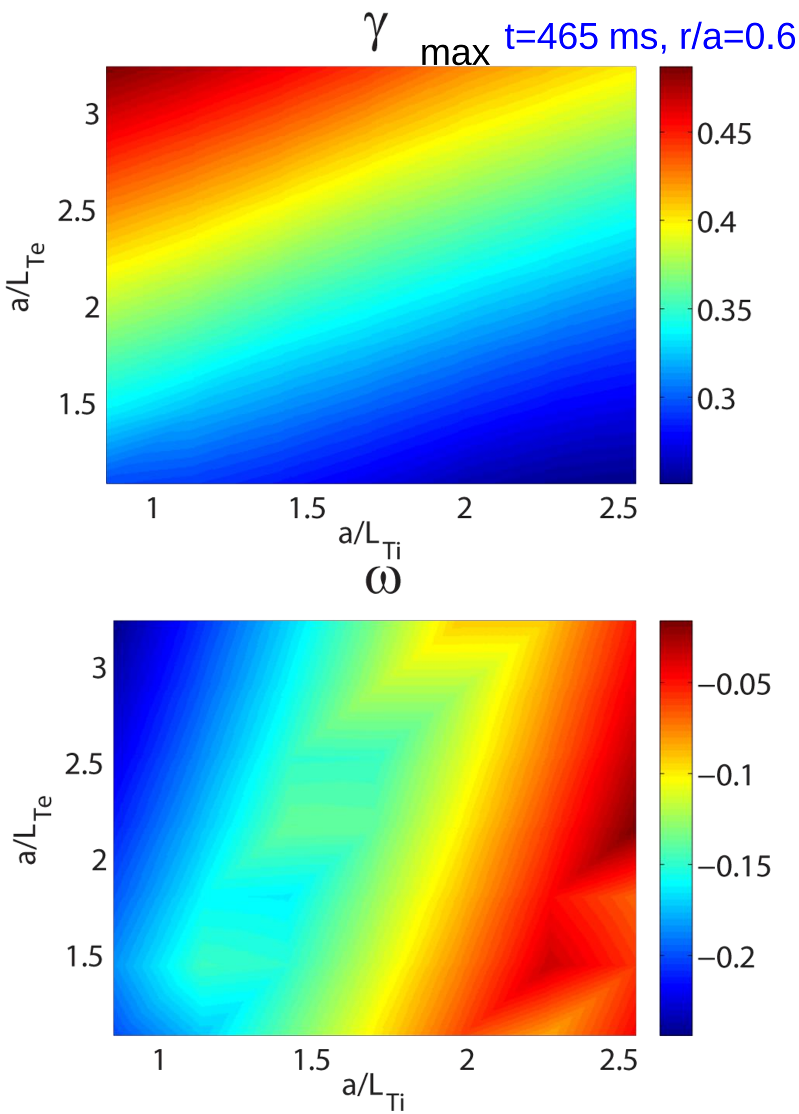
Changes in Linear Growth Rate Cannot Explain the Observed Significant Drop in High-k Turbulence

- Ion scale modes are ITG/TEM hybrid
  - Growth rate similar between t=465 and 482 ms
- ETG mode maximum growth rates show small increase from t=465 to 482 ms
  - Inconsistent with the drop in the measure high-k spectral power



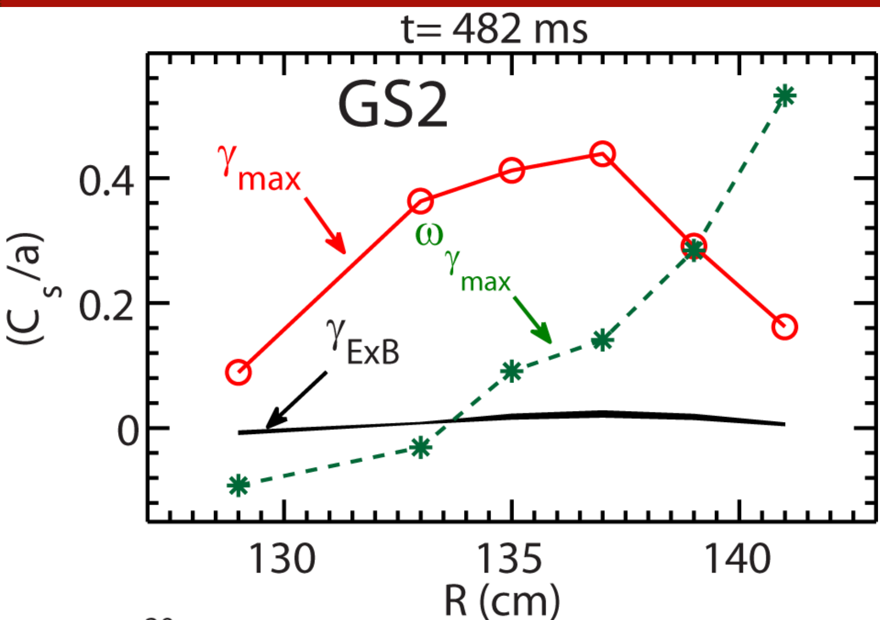
Stability Analysis was performed with the GS2 code (Kotschenreuther et al., 1995)

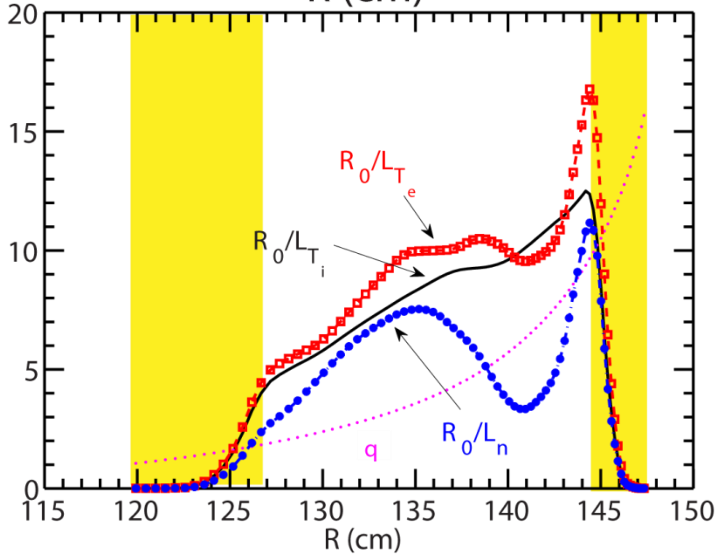
ITG/TEM and ETG Modes are Robustly Unstable



- T_e and T_i gradients are scanned with β' fixed
- The ion-scale modes are driven by both electron and ion temperature gradients
  - $a/L_{Te,exp}$=3.6
  - $a/L_{Ti,exp}$= 2.83
- ETG modes critical a/L_{Te} is determined to be 2.1 ($a/L_{Te,exp}$=3.6) from T_e gradient scan

Are Global Effects Able to Explain the Observation?

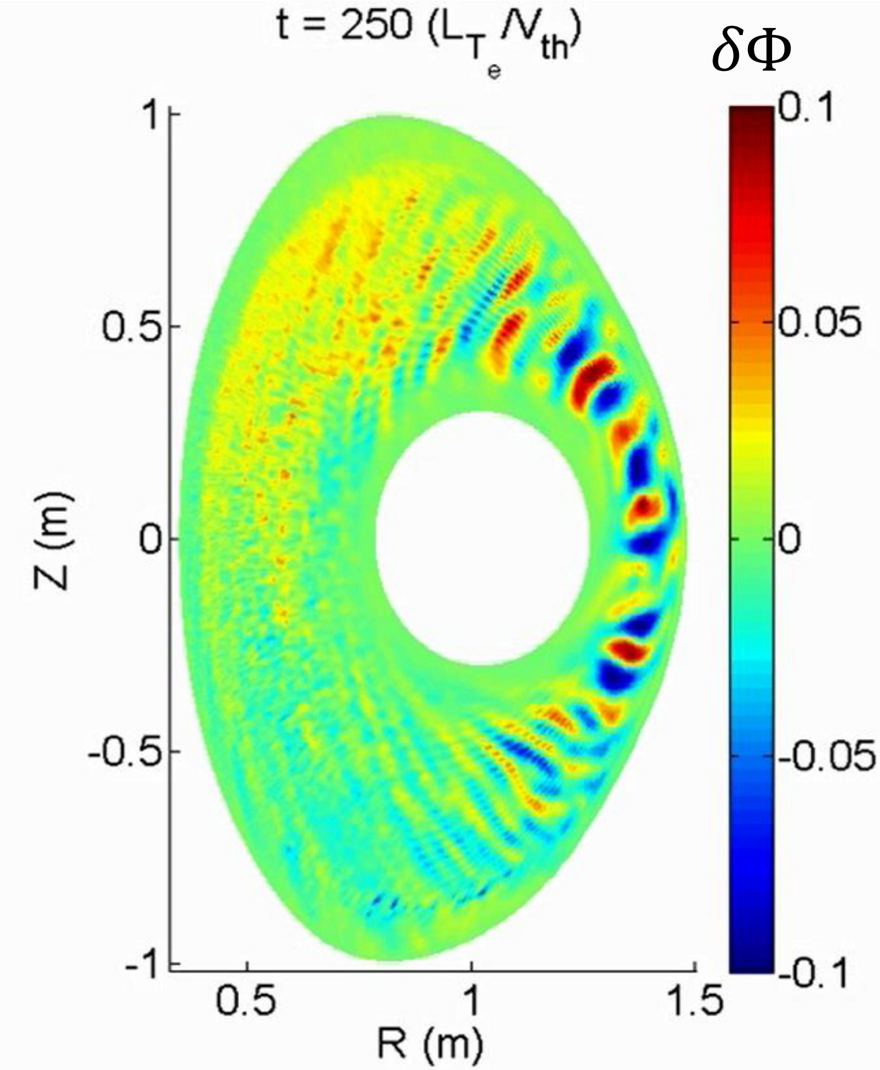




- Global effects, e.g. profile variation, may be important
  - –Turbulence can spread from one region to another
- GTS simulations are carried out with experimental equilibria
  - –Linear local GS2 simulations help determine the radial domain for GTS simulations
  - –Focus on ion-scale turbulence

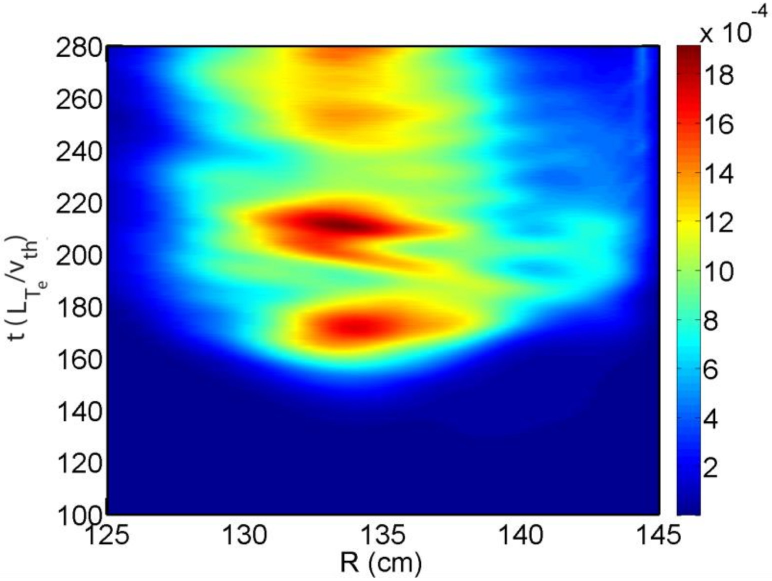
Robust Ion-scale Turbulence is Seen

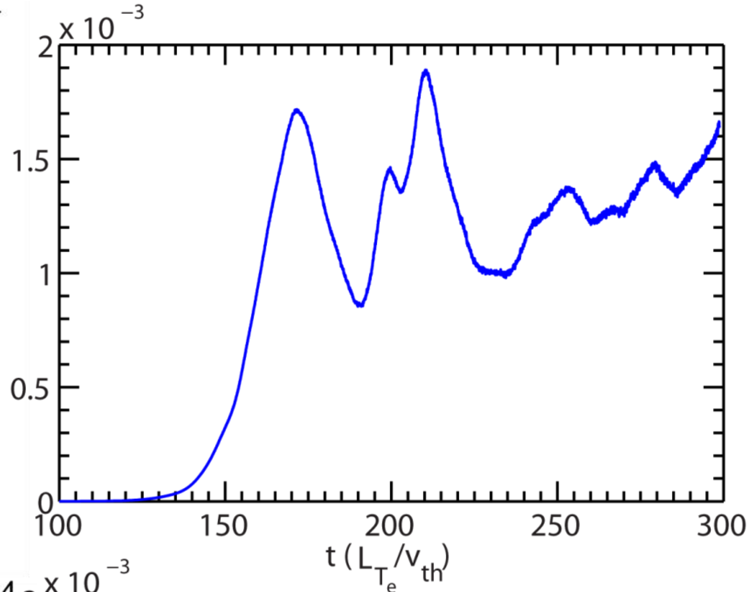
t=465 ms



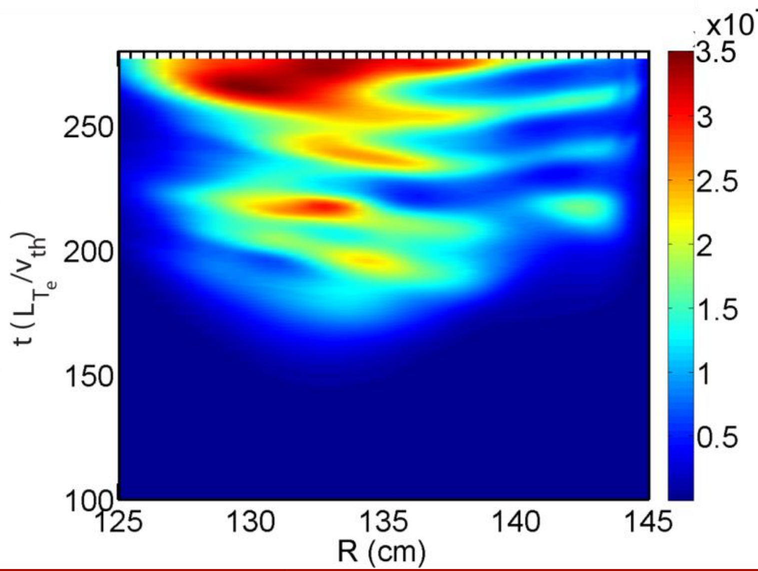
- Strong ion-scale turbulence generated
  - ExB shear is weak without strong NBI
- Turbulence propagates in the electron diamagnetic direction

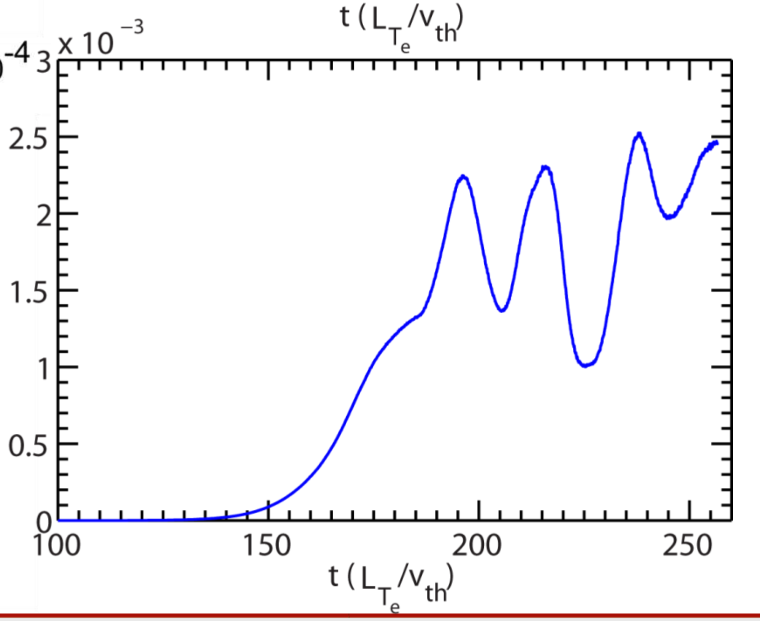
Similar Turbulence Intensity is Found before and after the RF Cessation





Before RF cessation (t=465 ms)

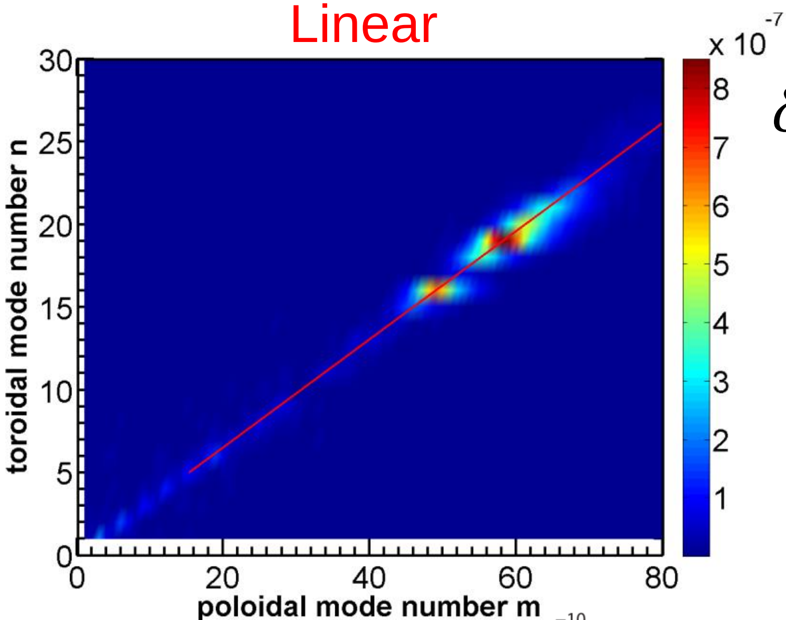




After the RF cessation (t=482 ms)

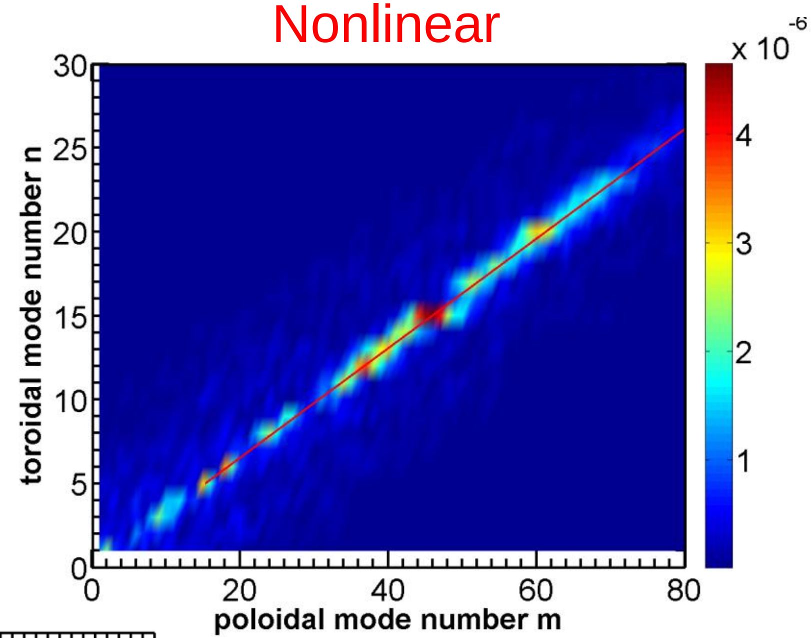
Simulation was Well Resolved Spectrally

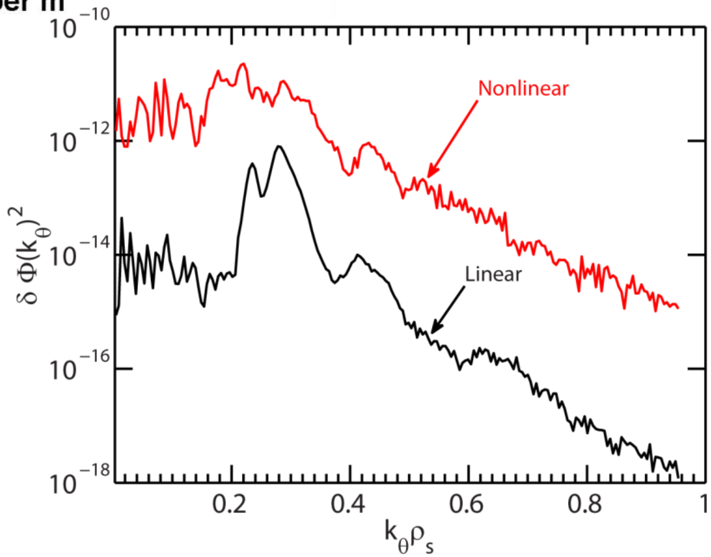
Linear



$\delta\Phi(m,n)$

Nonlinear





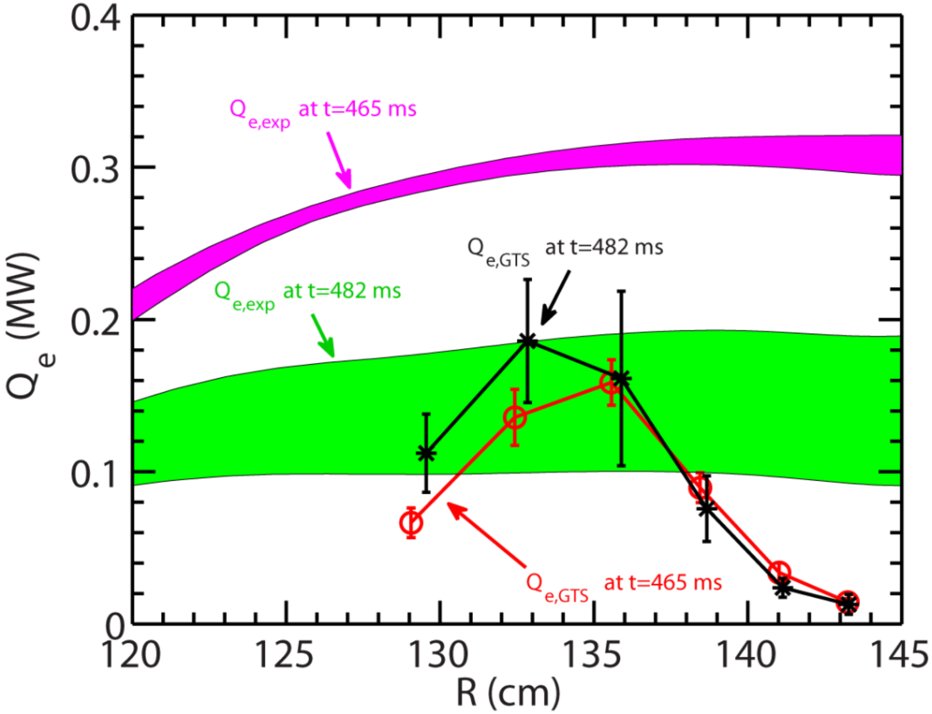
t=465 ms

R=134 cm

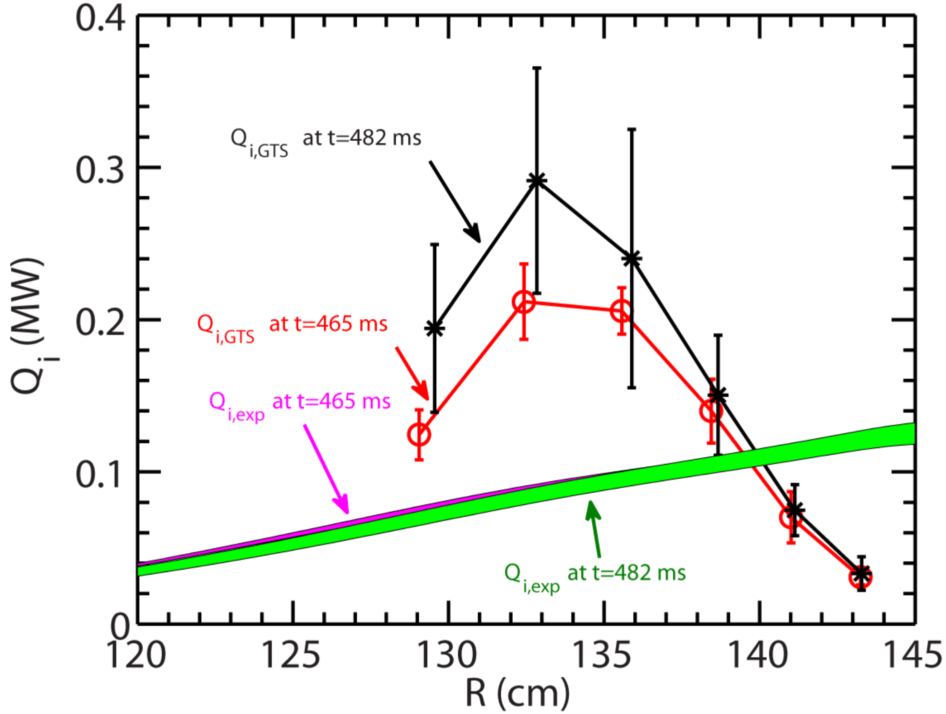
Similar Energy Fluxes from GTS are Seen before and after the RF cessation

- Electron energy flux matches experimental value after the RF cessation but not before
  - Experimental values from TRANSP+TORIC analysis
- Ion energy flux is over-predicted

Electron energy flux



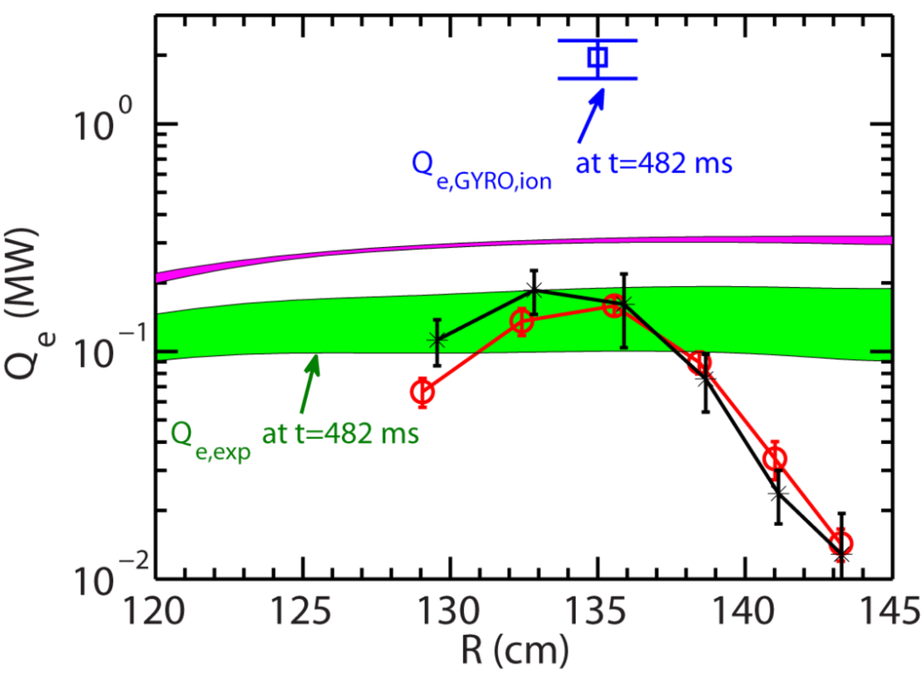
Ion energy flux



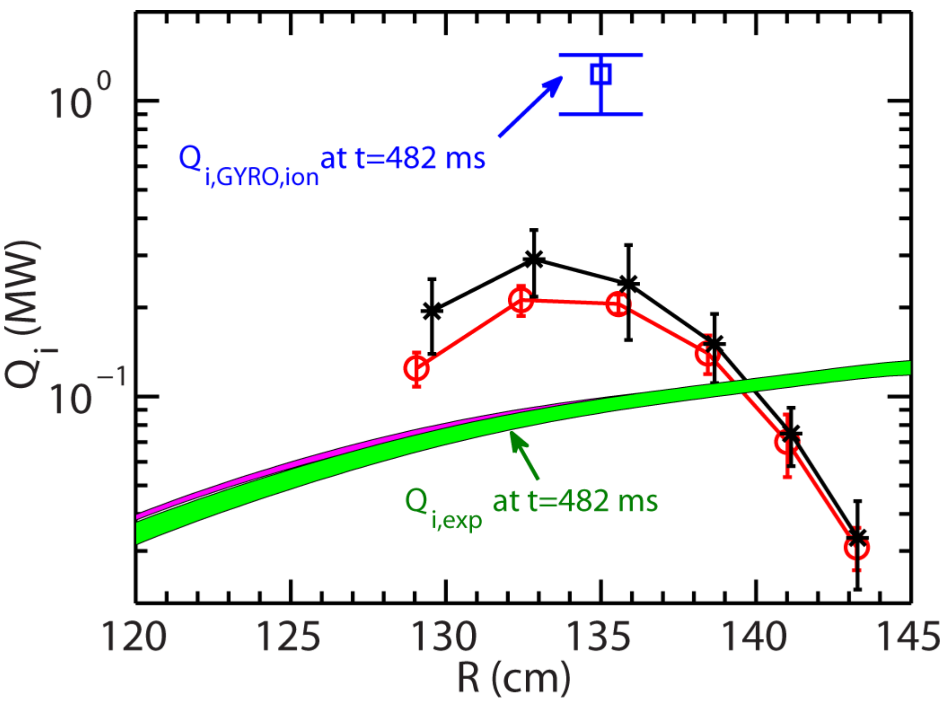
Energy Fluxes from Local Nonlinear Ion-scale GYRO Simulations are Significantly Higher

- Local nonlinear ion-scale GYRO simulations were carried out for R=135 cm
  - T_e and T_i gradients varied by $\pm$25% to assess profile stiffness

Electron energy flux



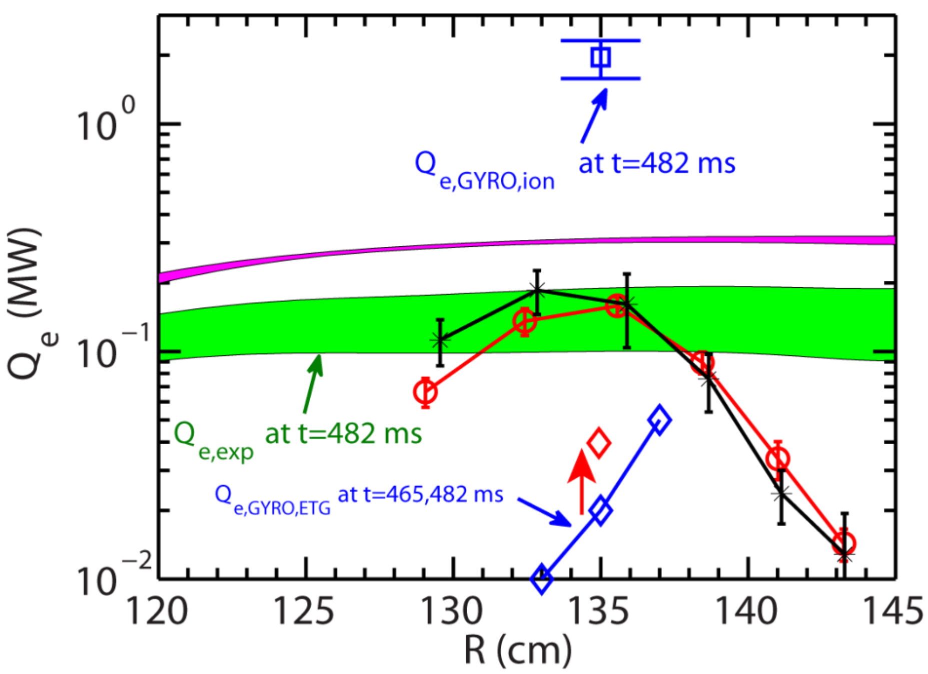
Ion energy flux



Electron Energy Fluxes from Local Nonlinear ETG GYRO Simulations are Smaller than Experiment

- Electron energy fluxes from ETG turbulence have large variation vs radial location
  - Energy flux from 0.02 MW to 0.04 MW with a 25% increase in T_e gradient

Electron energy flux



Gradient-driven Gyrokinetic Models have Difficulty Explaining Experimental Observations

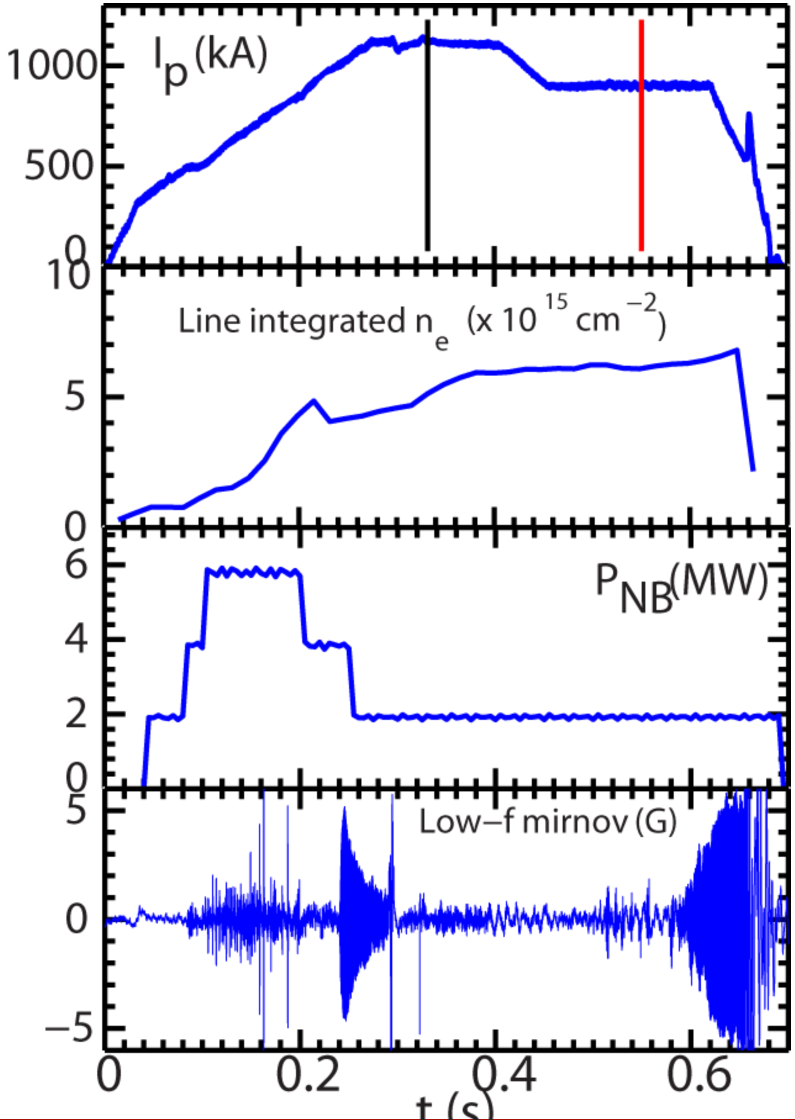
- Observed turbulence variation time scale is 0.5 -1 ms, much smaller than confinement time ~ 10 ms
  - Equilibrium profiles are not expected to vary significantly on 0.5 – 1 ms time scale
  - <15% variation in equilibrium quantities in the high-k measurement region are found before and right after the RF cessation (over 17 ms)
- Local and global gyrokinetic simulations are unable to explain observed change in turbulence and electron thermal transport before and after the RF cessation
- Nonlocal flux-driven mechanism may be important

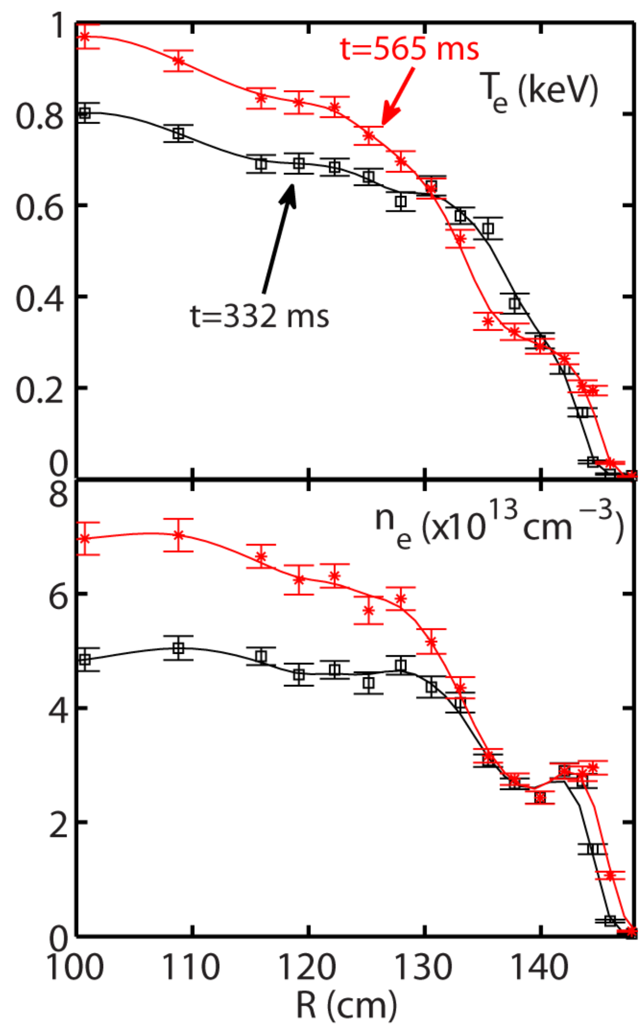
NSTX H-mode plasmas with density gradient stabilization of electron-scale turbulence

Current Ramp-down in NSTX H-mode Plasma Leads to Core Density Gradient Increase

Shot=141767

NBI-heated L-mode plasma with B_T =5.5 kG



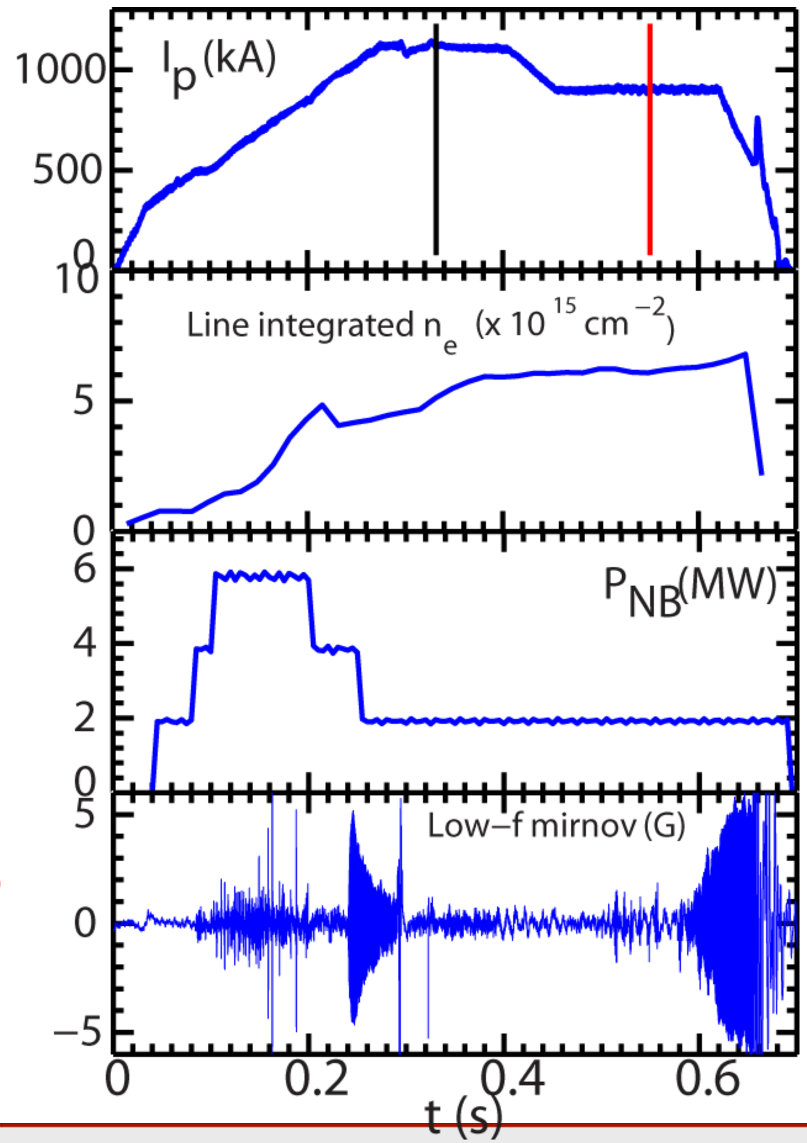


Ruiz-Ruiz et al., submitted to PoP and see poster P1-10

Current Ramp-down in NSTX H-mode Plasma Leads to Core Density Gradient Increase

Shot=141767

NBI-heated L-mode plasma with B_T =5.5 kG



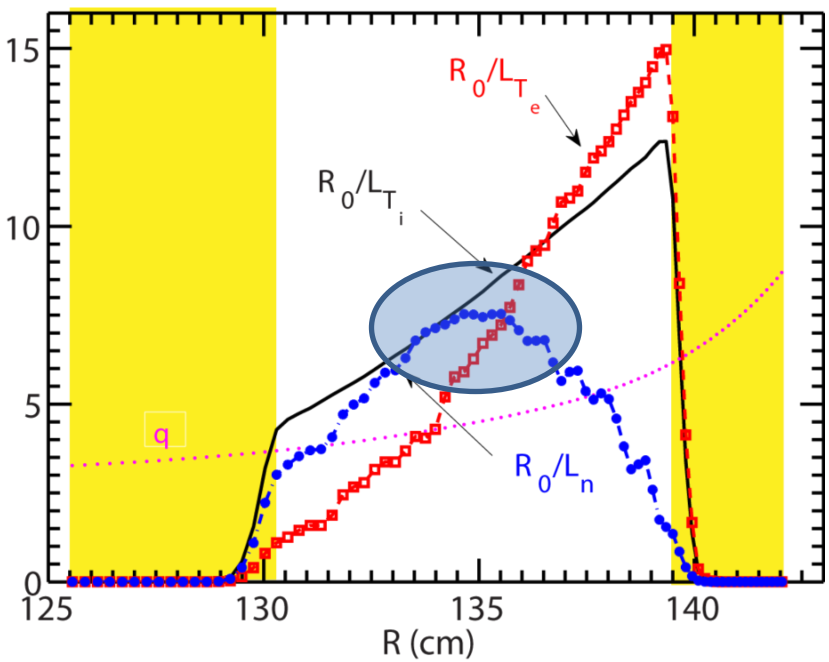
Ruiz-Ruiz et al., accepted by PoP

- ETG turbulence suppressed by large density gradient
  - See Ruiz-Ruiz's poster, GP12-61
- Is ion-scale turbulence driving thermal transport?
  - Here, we focus on ion-scale GTS simulations and thermal transport

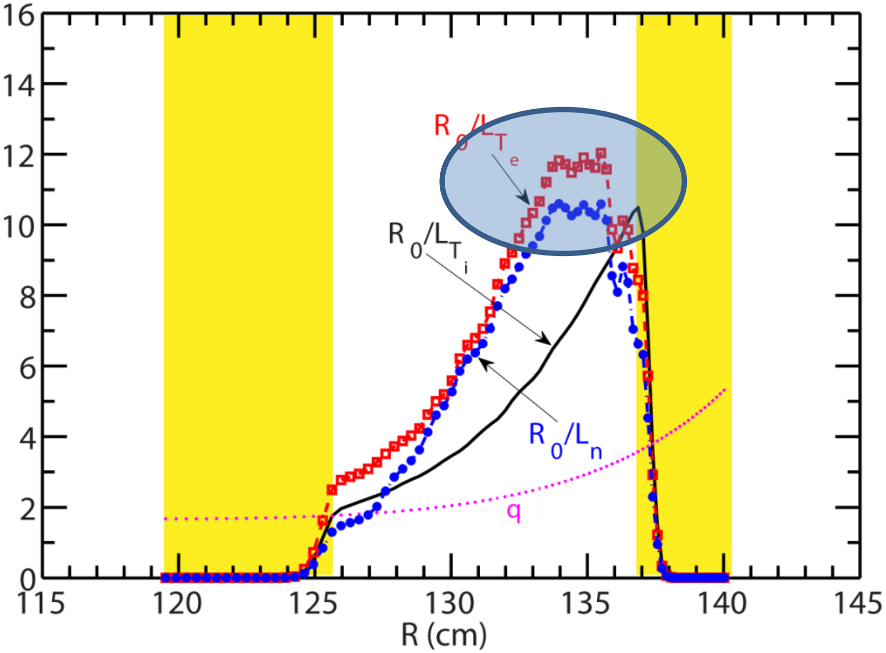
GTS Simulation Domains are Chosen to Have Significant Gradients

- Both electron and density gradients are significantly larger at t=565 ms than at t=332 ms

t= 332 ms

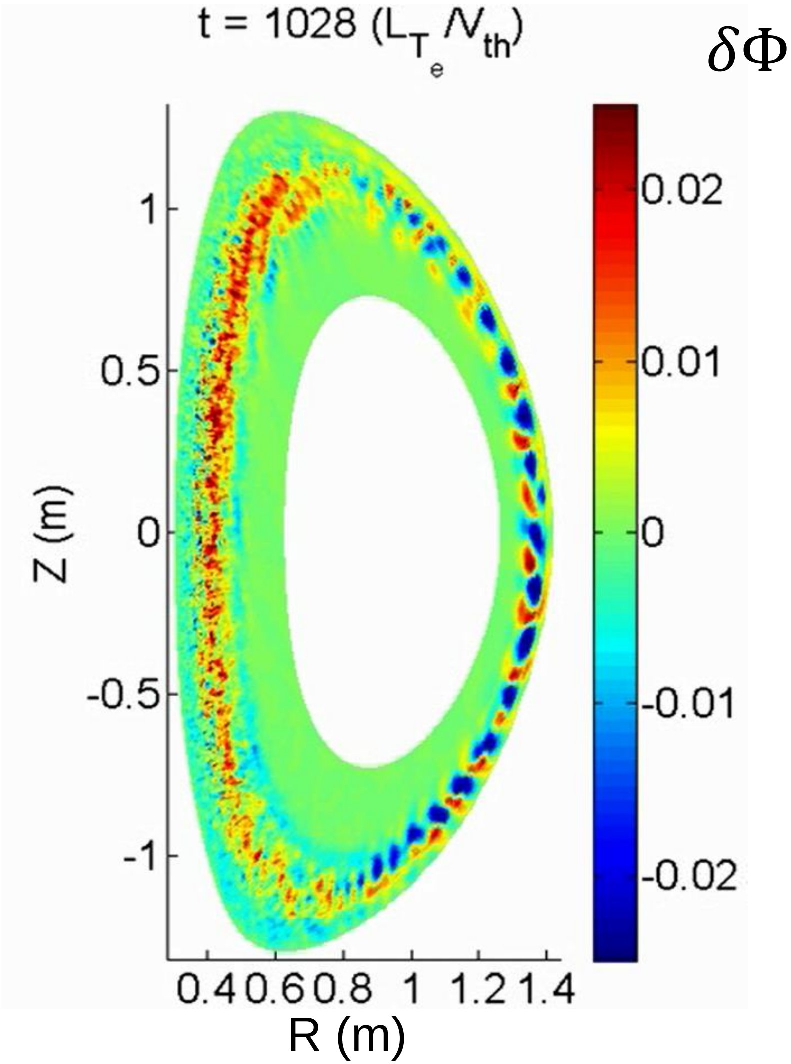


t= 565 ms



Robust Ion-scale Turbulence is Seen at t=332 ms

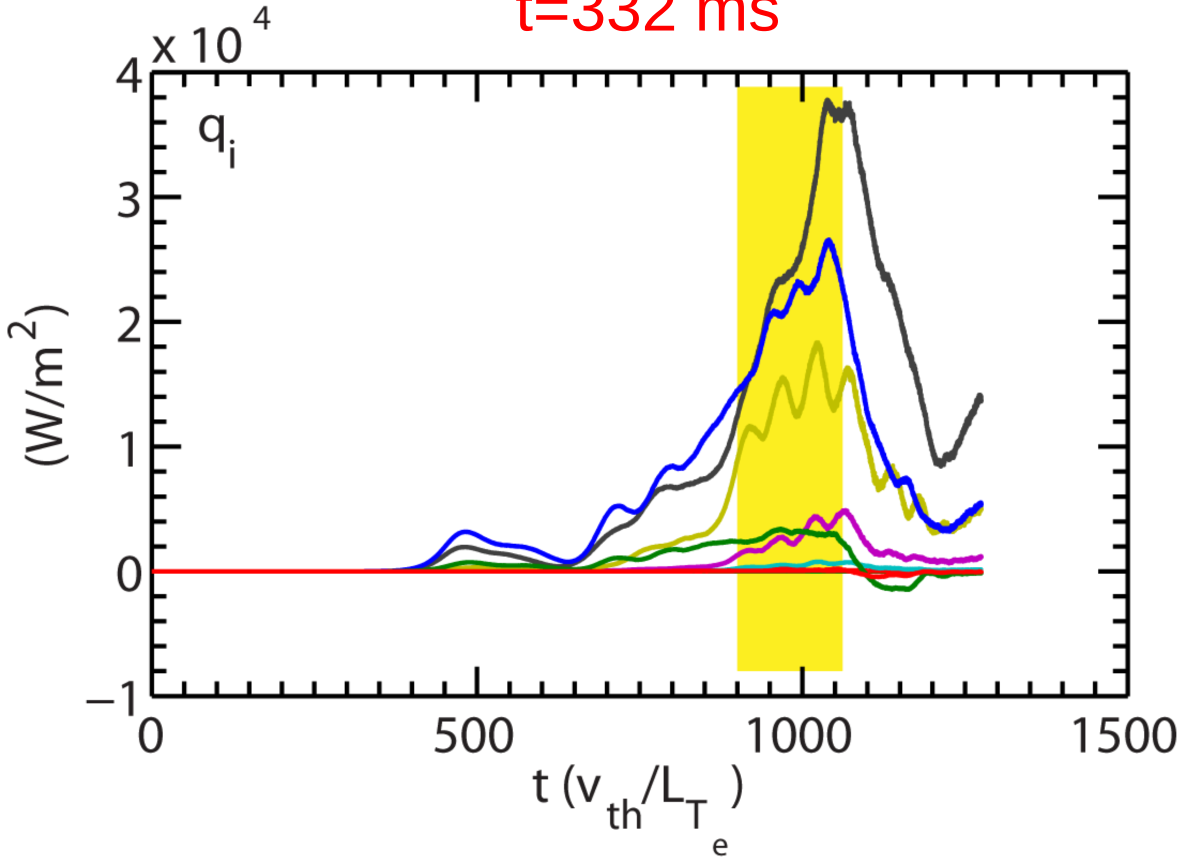
t=332 ms



- Strong ion-scale turbulence generated
  - ExB shear is turned on from the beginning of the simulation
- Turbulence propagates in the ion diamagnetic direction, due to toroidal rotation

Simulation Quantities are Averaged Over a Quasi-steady Period

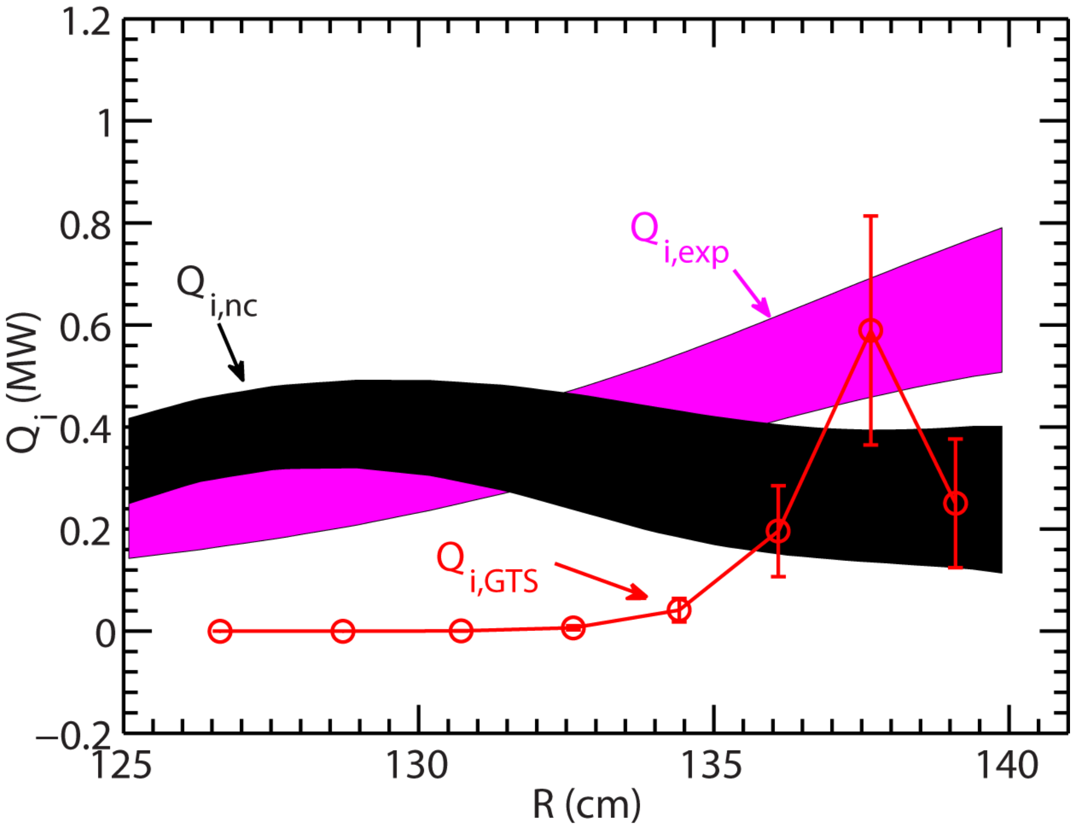
t=332 ms



- Energy flux drops after significant interaction with boundary in the simulation

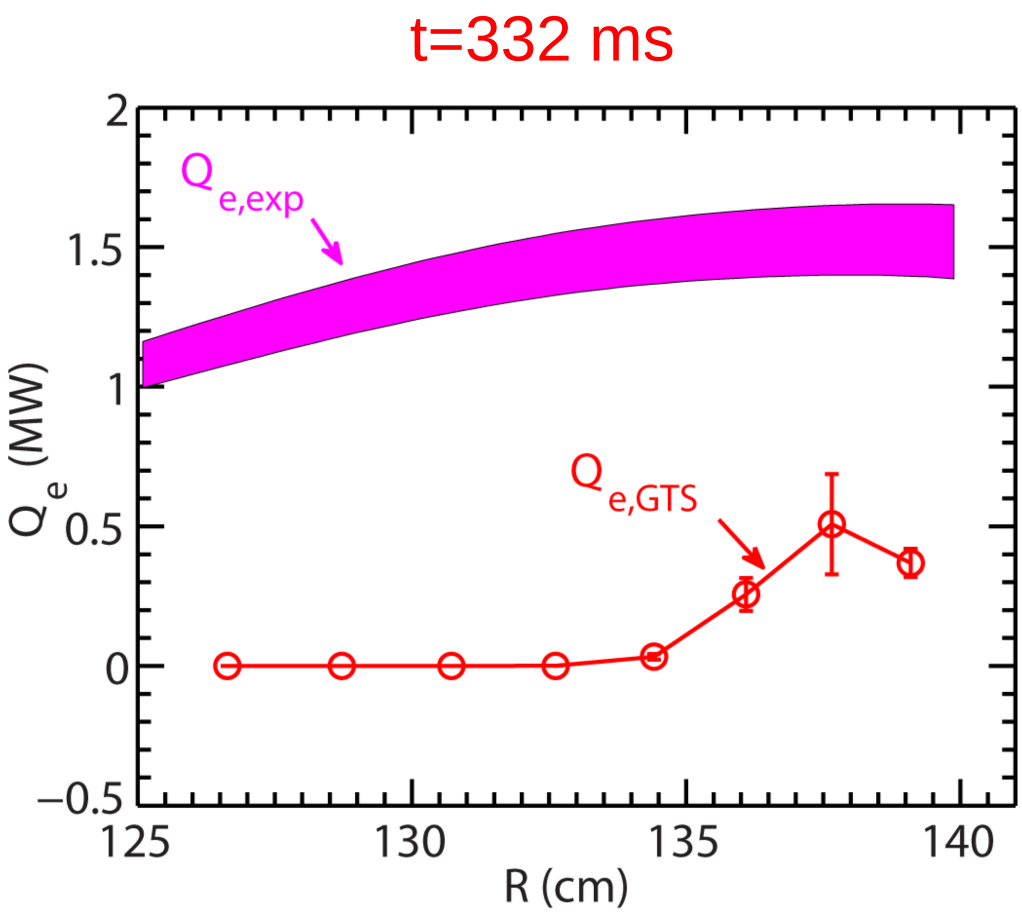
Ion Energy Flux from GTS is in Agreement with Experiment at t=332 ms

t=332 ms



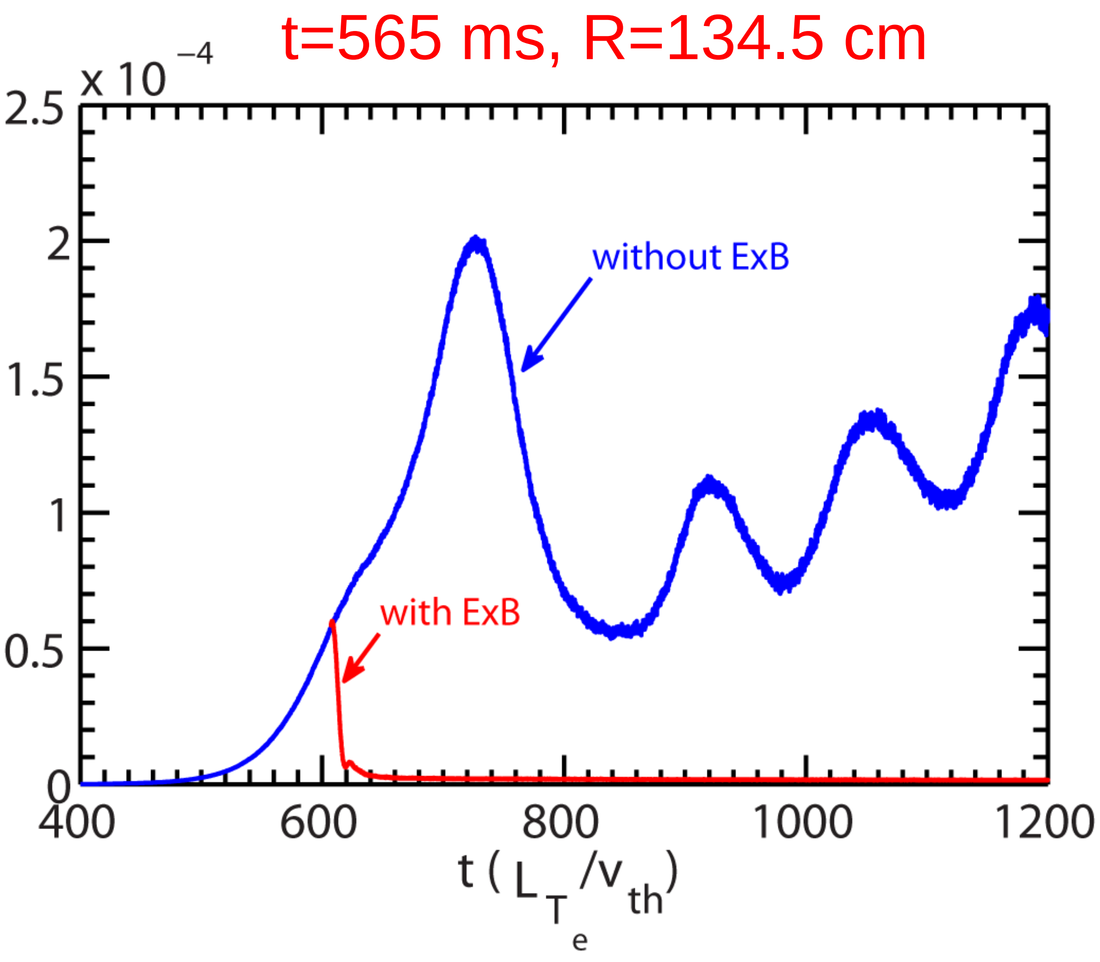
- Ion energy flux from ion-scale turbulence contributes significantly at R>135 cm
- Neoclassical ion thermal transport is important further in the core of the plasma
  - Neoclassical ion thermal transport from NCLASS

Electron Thermal Transport is Significantly Under-predicted by GTS at t=332 ms



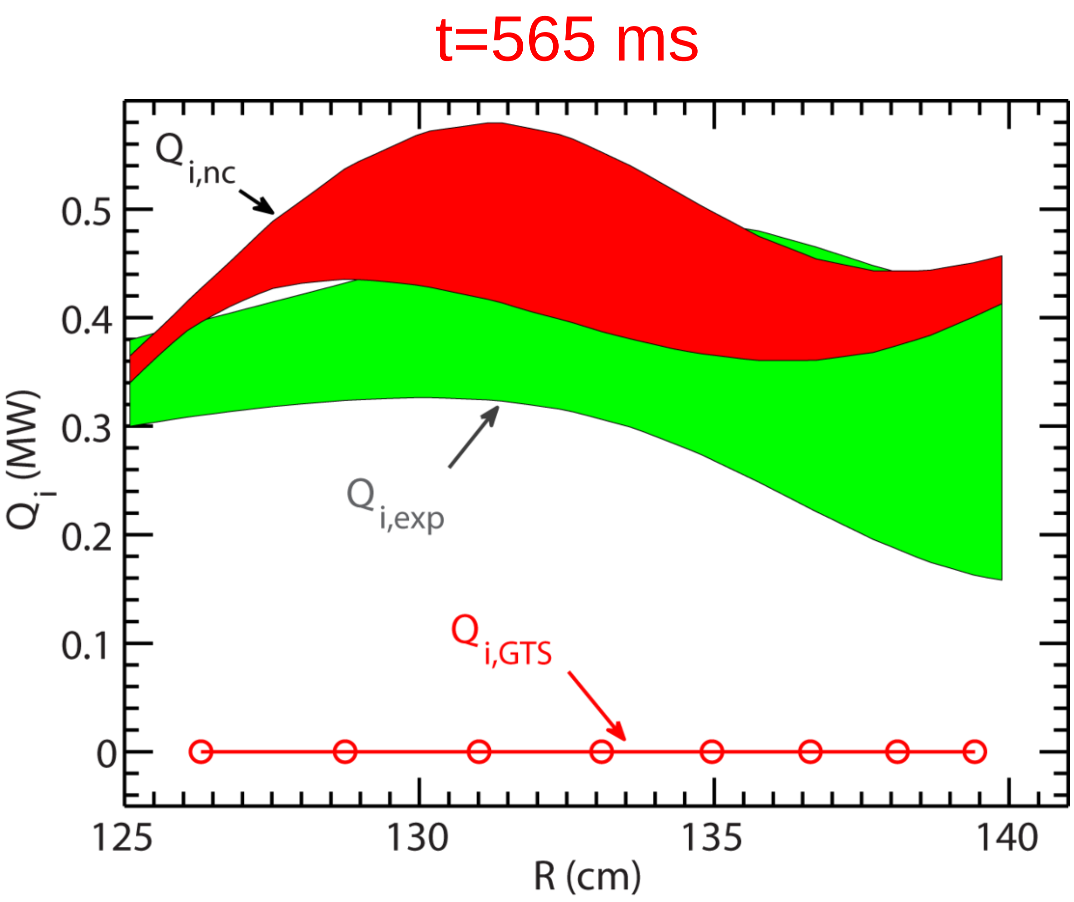
- Electron energy flux from GTS is only significant at R>135 cm
  - Much smaller than experimental electron thermal transport
- Contribution from ETG and electromagnetic effects may be important

Complete Suppression of Ion-scale Turbulence is Observed in GTS Simulation at t=565 ms



- Turbulence is suppressed after ExB shear is turned at t~600
- No Turbulence growth if ExB shear is turned on at the beginning of the simulation

Ion Energy Flux from GTS is Still in Agreement with Experiment at t=565 ms



- Neoclassical ion thermal transport is comparable to experimental ion thermal transport level
  - Neoclassical ion thermal transport from NCLASS
- ETG is significantly suppressed by density gradient (See poster GP12-61)
  - Electromagnetic effects may be important

Conclusion

- We have started to make serious efforts to validate global gyrokinetic simulations with NSTX experiments
- Global gyrokinetic simulations with GTS have helped identify the possible importance of nonlocal flux-driven mechanics in electron thermal transport in NSTX RF-heated L-mode plasmas
- Global ion-scale gyrokinetic simulations with GTS for a NSTX NBI-heated H-mode plasma showed nice agreement with experiment in ion thermal transport but not in electron thermal transport