U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

A Synthetic Diagnostic for Studying Electron Scale Turbulence at NSTX and NSTX-U

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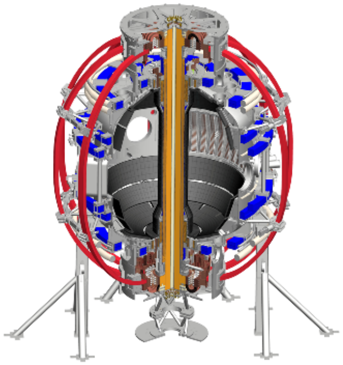
1. MIT 2. PPPL 3. NFRI 4. UC Davis 5. U Wisconsin 6. Nova Photonics, Inc.

NSTX-U Science Meeting

Dec 5, 2016

Alcator C-Mod

PPPL



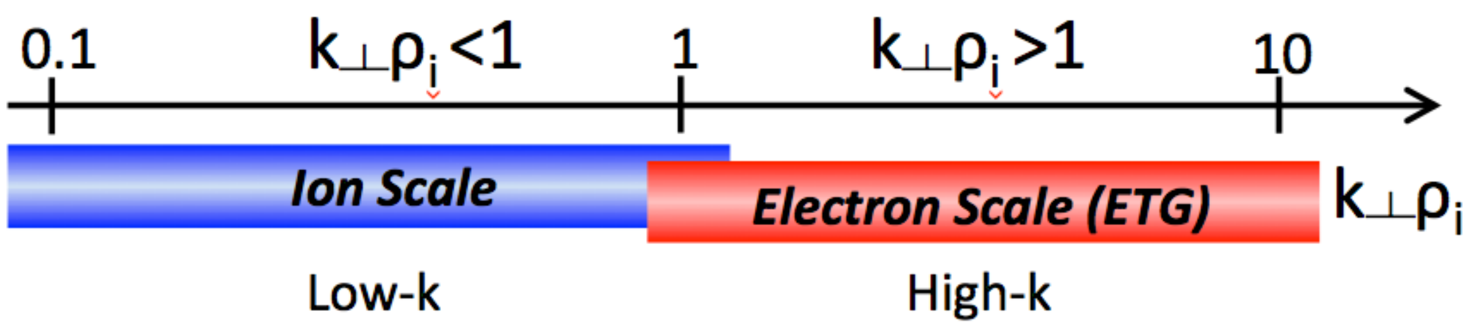
Outline

- **Motivation**
- Old high-k scattering system at NSTX
- The GYRO code
- Previous Work on synthetic high-k
- New Synthetic Diagnostic for the high-k scattering system
  1. Coordinate mapping (this talk)
  2. Filtering (ongoing work)

- Results from Coordinate Mapping
  1. Old high-k system
  2. New high-k system

Understanding Electron Thermal Transport is a Main Thrust in the NSTX and NSTX-U Research Program

- NSTX H-mode plasmas that are driven by neutral beams exhibit ion thermal transport close to neoclassical (collisional) levels, due to ***suppression of ion scale turbulence by ExB shear*** [*cf. Kaye NF 2007*].
- **Electron thermal transport is always anomalous (>> neoclassical).**
- Goal: Study electron thermal transport caused by electron-scale turbulence in NSTX and NSTX-U.



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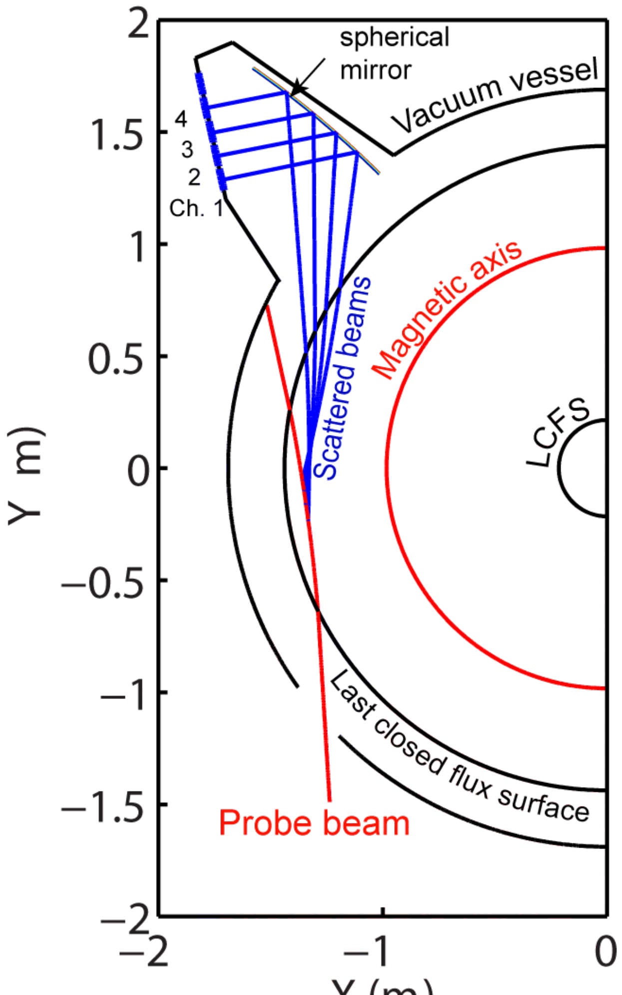
Old High-k Microwave Scattering Diagnostic System at NSTX



View from top of NSTX

(D.R. Smith PhD thesis 2009)

Measurement of density fluctuations

Scattered power density $P_s \propto \left(\frac{\delta n}{n}\right)^2$

Three wave-coupling

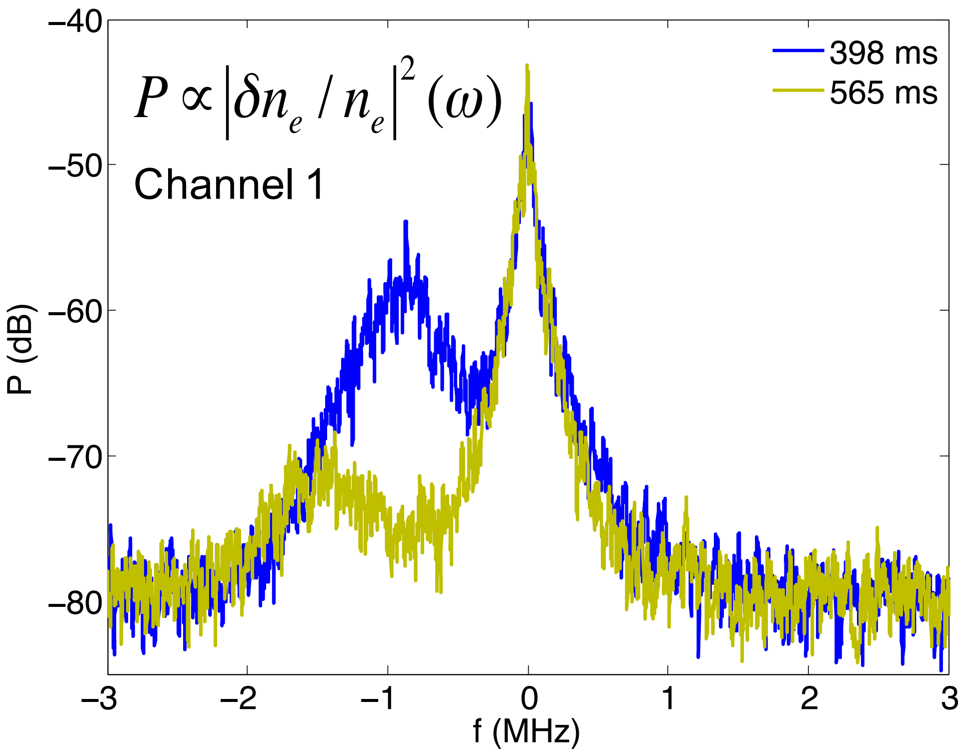
$$\vec{k}_s = \vec{k} + \vec{k}_i \qquad \omega_s = \omega + \omega_i$$

Details of diagnostic

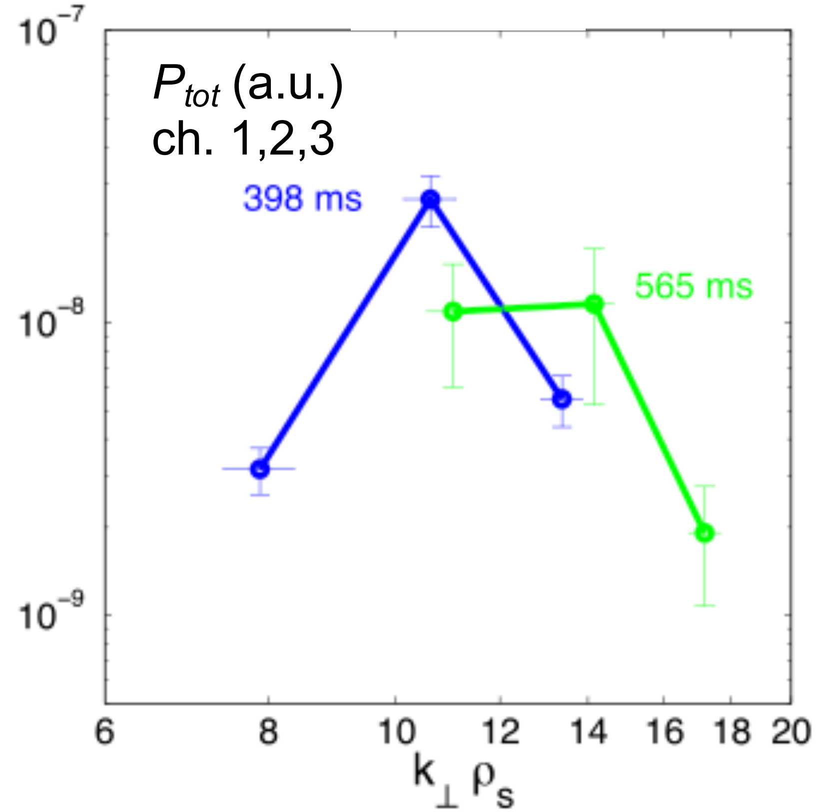
- Gaussian Probe beam: 15 mW, 280 GHz, $\lambda_i \sim 1.07$ mm, a = 3 cm ($1/e^2$ radius).
- Propagation close to midplane => k_r spectrum.
- 5 detection channels => range $k_R \sim 5\text{-}30\ \mathrm{cm}^{-1}$ (high-k).
- Wavenumber resolution $\Delta k = \pm\ 0.7\ \mathrm{cm}^{-1}$.
- Radial coverage: R = 106-144 cm.
- Radial resolution: $\Delta R = \pm\ 2$ cm (unique feature).

High-k Scattering Allows the Study of Frequency and Wavenumber Spectrum of Electron Scale Turbulence

Frequency Spectrum of density fluctuations



k-spectrum of density fluctuations



- Frequency analysis of scattered power → frequency spectrum.
- Different channels → different k → wavenumber spectrum of turbulence

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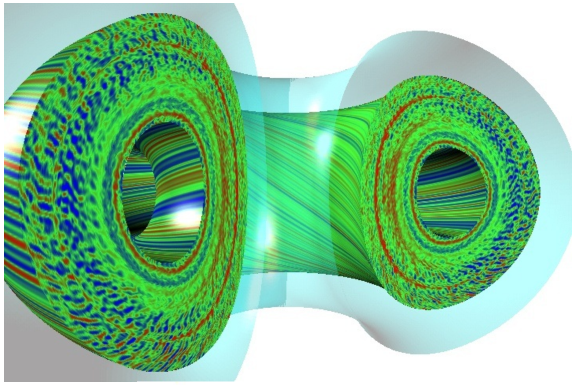
The GYRO code Numerically solves the Gyrokinetic-Maxwell System

- Turbulence and transport in tokamaks is studied with gyrokinetics.

- The gyrokinetic-Maxwwell system cannot be solved analytically except in simple limits
  → needs to be solved numerically (GYRO)



GENERAL ATOMICS

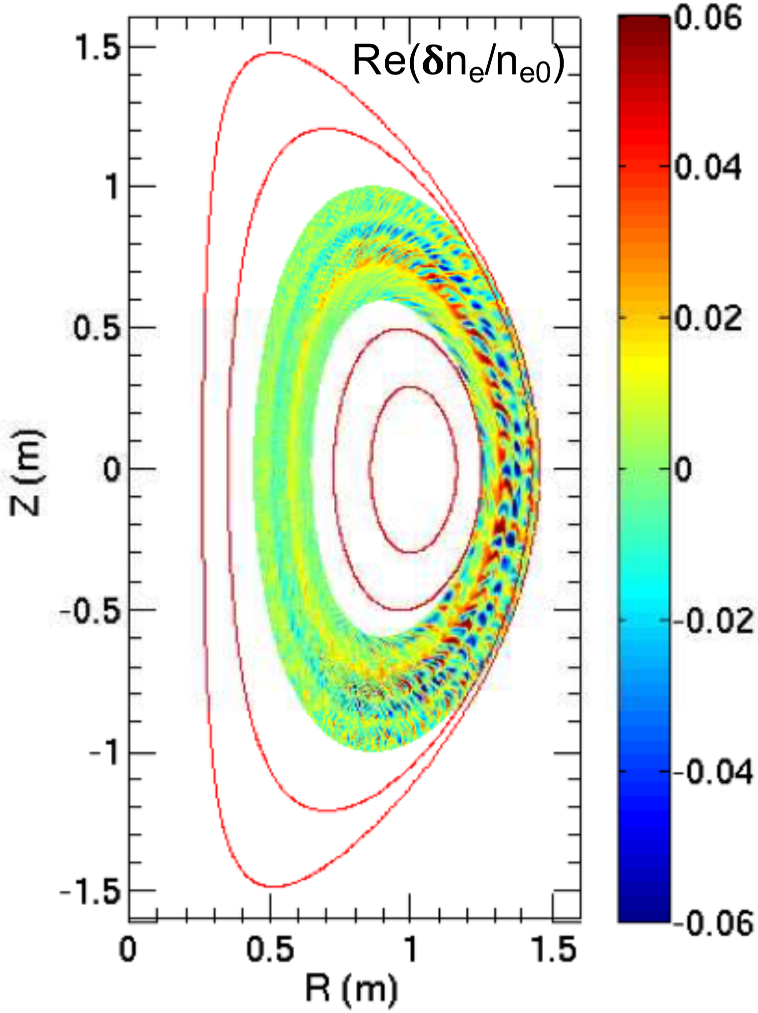
- **Inputs:** experimental plasma parameters
  plasma shape, equilibrium geometry, profiles, …

- **Outputs:** moments and fields
  - Moments of the distribution function $\boldsymbol{h_s}$ — $\delta n_s,\ \delta v_s,\ \delta E_s$
  - Perturbed electromagnetic field components — $\delta\phi,\ \delta A_{||},\ \delta B_{||}$

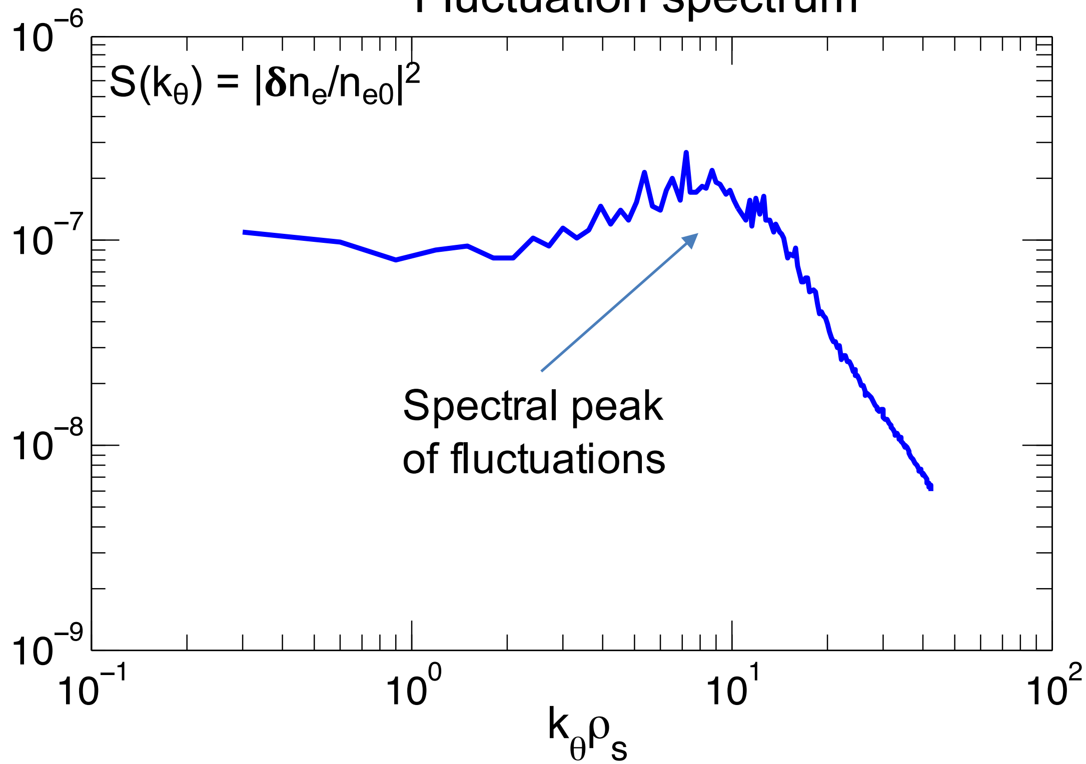
- Turbulent fluxes (particle Γ_s, heat Q_s, …) can be reconstructed from outputs, and compared with experimental values.

Examples of GYRO output from an NSTX H-mode plasma

Real space fluctuations

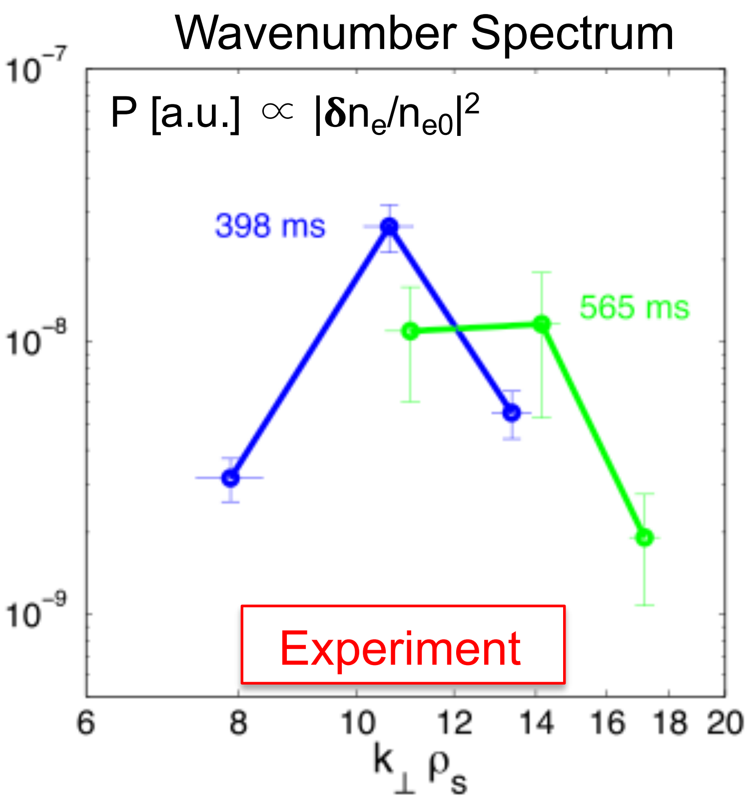


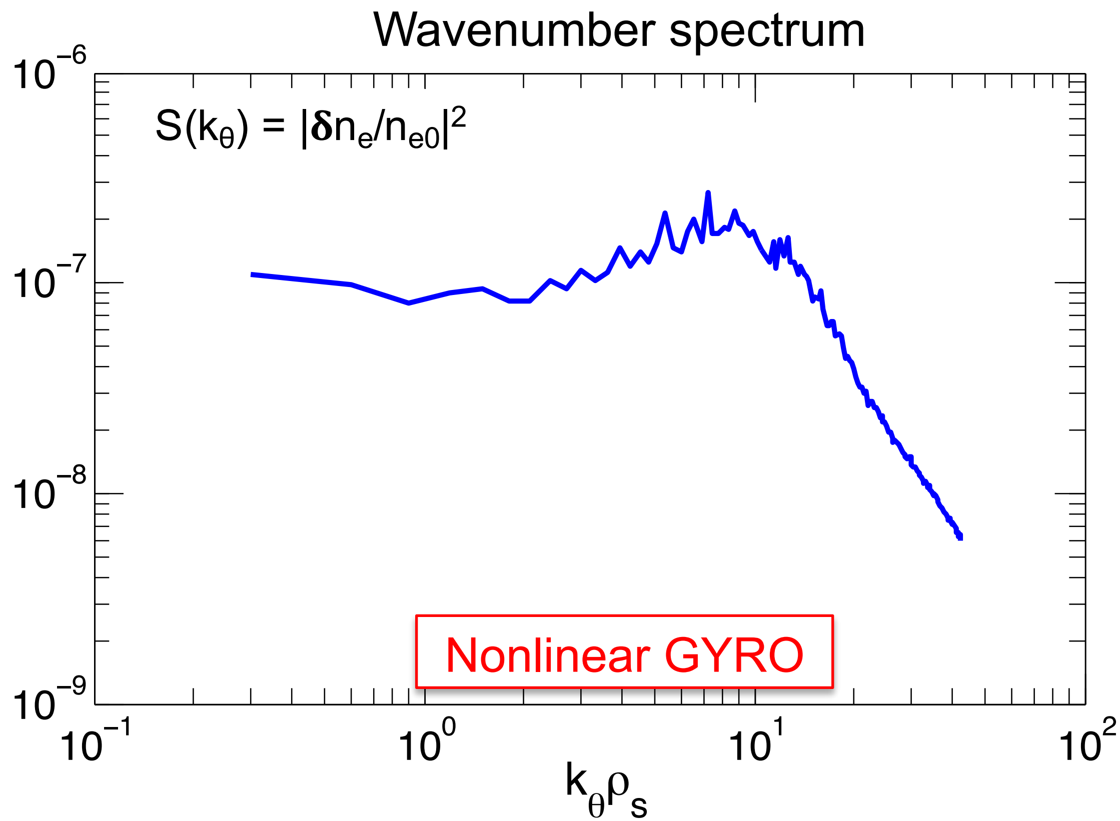
Fluctuation spectrum



$k_\theta = nq/r$ is an internal GYRO definition

A Quantitative Comparison between Experiment and GYRO is not Possible due to Different k-definitions





Experiment

$k_\perp = (k_R, k_Z)$ *(cylindrical coordinates)*

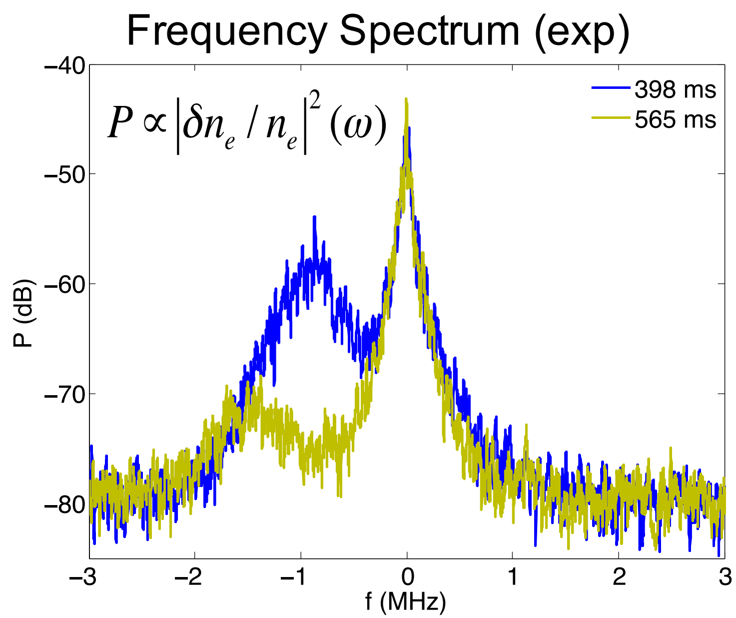
Simulation

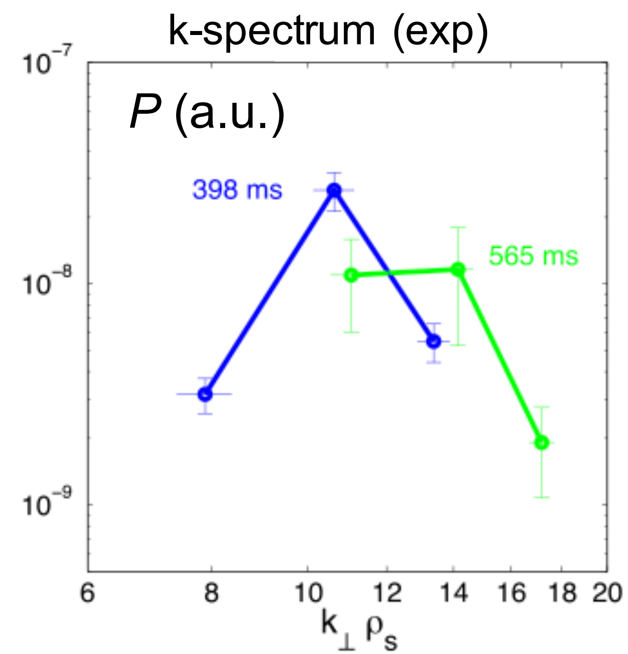
$k = (k_r, k_\theta)$ *(internal GYRO definitions – field aligned coordinate system)*

- $k_\theta = nq/r$

Principles of the Synthetic Diagnostic

- **Goal:** A quantitative comparison between experiment and simulation of electron scale turbulence (e.g. frequency and k-spectrum below).
- Need to map experiment and simulation into a common coordinate system
- I have done: Written a series of Matlab routines that perform the geometric mapping between the experimental frame and simulation frame.





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Previous Work on Synthetic High-k Diagnostic on NSTX

- Previous synthetic high-k scattering was implemented with GTS (*cf.* Poli PoP 2010).
- Synthetic spectra was affected by *'systematic errors'* (simulation run time, low k_θ detected, scattering localization)
- No quantitative agreement was obtained between experimental and simulated frequency spectra.

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Preliminary Steps Prior to the Implementation a Synthetic High-k Scattering Diagnostic using GYRO

Preliminary Steps:

1. High-k scattering diagnostic → experimental density fluctuation spectra $|\delta n_e|^2_{kR,kZ}(\omega)$

2. Ray tracing code:

    - Scattering location + resolution $(R_{loc}, Z_{loc}) + (\Delta R_{loc}, \Delta Z_{loc})$
    - Turbulence wavenumber + resolution $(k_R^{exp}, k_Z^{exp}) + (\Delta k_R^{exp}, \Delta k_Z^{exp})$

3. Run a nonlinear gyrokinetic simulation (used GYRO here) capturing scattering location + resolving the experimentally measured wavenumber.

Summary Steps of the Synthetic High-k Scattering Diagnostic using GYRO

Steps in synthetic diagnostic implementation

1. **Coordinate Mapping (done):**
   Coordinate mapping GYRO (r, θ, φ) ⇔ physical (R, Z, φ)
   Wavenumber mapping $(k_r\rho_s, k_\theta\rho_s)_{GYRO}$ ⇔ (k_R, k_Z)

2. **Filtering:** Apply instrumental selectivity function to simulated density fluctuations from GYRO. Preliminary only (ongoing work)

3. **Quantitative comparison** between experiment and simulation (future work).

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Results of mapping

Experiment
(shot 141767, ch1)

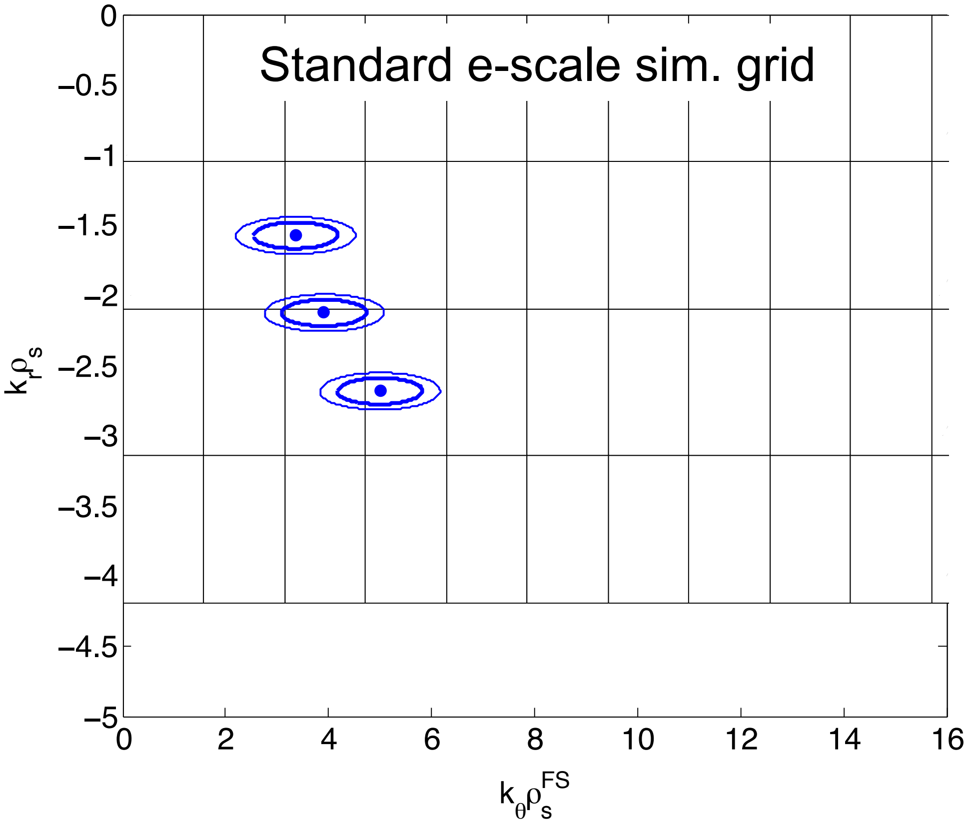
k_R = - 18.57 cm^{-1} ➔ $k_r\rho_s$ = - 2.68
k_Z = 4.93 cm^{-1} ➔ $k_\theta\rho_s$ = 4.99

GYRO

ρ_s^{GYRO} = 0.2 cm

Next step is to run a GYRO simulation that resolves the experimental wavenumbers and the high-k ETG spectrum.

Mapped $(k_R, k_Z)^{exp}$ to GYRO $(k_r\rho_s, k_\theta\rho_s)_{GYRO}$ in Standard electron Scale Simulation



- **Blue dots:** $(k_r\rho_s, k_\theta\rho_s)^{exp}$ of channels 1, 2, 3 of high-k system.
- Ellipses are e^{-1} and e^{-2} amplitude of (k_r, k_θ) gaussian filter (simplified selectivity function)

$$F(k_r, k_\theta) = F_r(k_r)F_\theta(k_r)$$

$$F_r(k_r) = \exp\left(-(k_r - k_r^{\exp})^2 / \Delta k_r^2\right)$$

$$F_\theta(k_\theta) = \exp\left(-(k_\theta - k_\theta^{\exp})^2 / \Delta k_\theta^2\right)$$

Numerical grid of standard e- scale simulation does NOT accurately resolve the experimental wavenumber.

Numerical Resolution Details of the Scale Simulations Presented

<u>Experimental profiles used as input</u>

Local, flux-tube simulations performed at scattering location (r/a~0.7, R~136 cm).

- Only electron scale turbulence included.
- 3 kinetic species, D, C, e (Z_{eff}~1.85-1.95)
- Electromagnetic: $A_{||}+B_{||}$, β_e~ 0.3 %.
- Collisions (ν_{ei} ~ 1 c_s/a).
- ExB shear (γ_E~0.13 c_s/a) + parallel flow shear (γ_p ~ 1 c_s/a)
- Fixed boundary conditions with Δ^b ~ 1.5 ρ_s buffer widths.

<u>Standard e- scale</u> resolution parameters

- L_r x L_y = 6 x 4 ρ_s.
- n_r x n = 192 x 48.
- $k_\theta\rho_s$ [min, max] = [1.5, 74]
- $k_r\rho_s$ [min, max] = [1, 50]
- [$n_{||}$, n_λ, n_e] = [14, 12, 12]

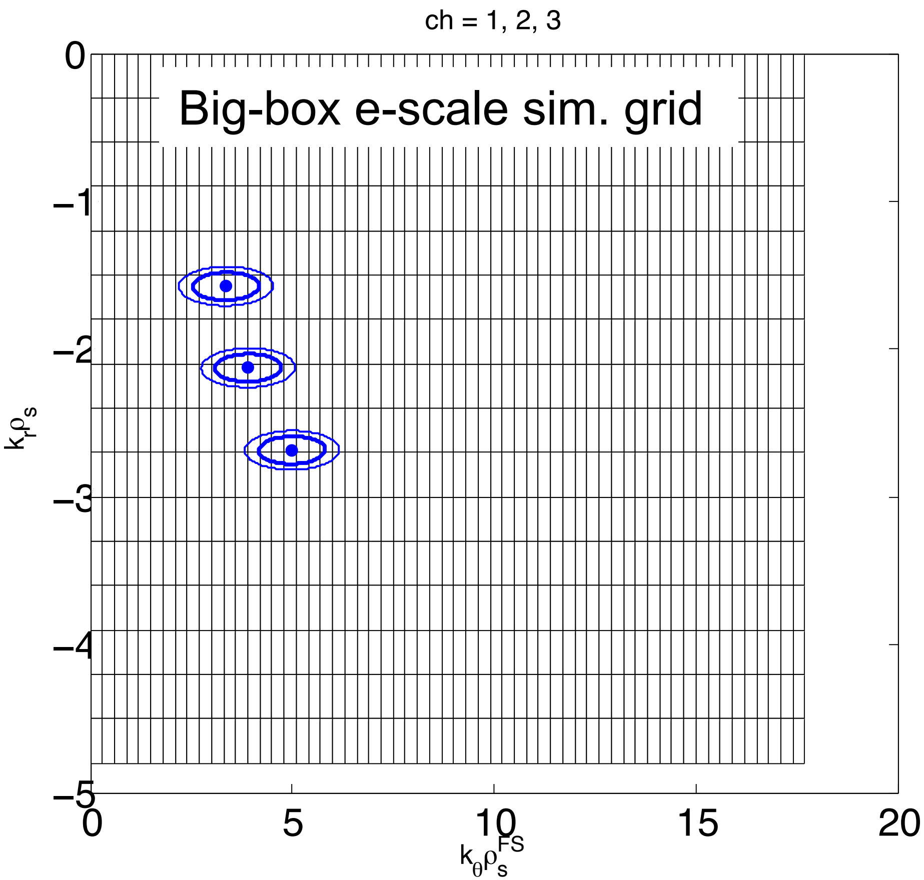
<u>Big-box e- scale</u> resolution parameters

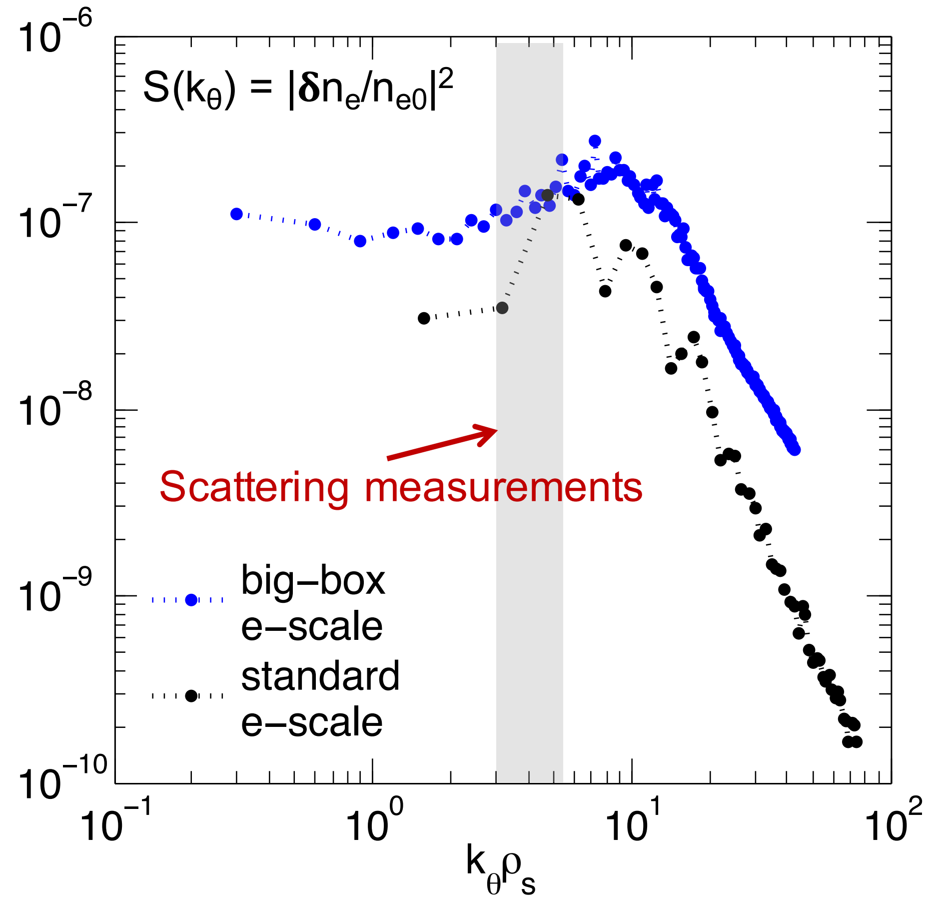
- L_r x L_y = 21 x 21 ρ_s.
- n_r x n = 512 x 142.
- $k_\theta\rho_s$[min, max] = [0.3, 43]
- $k_r\rho_s$ [min, max] = [0.3, 38]
- [$n_{||}$, n_λ, n_e] = [14, 12, 12]

Big-box e- scale runs presented here are NOT multiscale:

- Ions are not resolved correctly $\Delta k_\theta\rho_s$~0.3, L_r x L_y = 21 x 21 ρ_s.
- Simulation ran only for electron time scales (~20a/c_s), ions are not fully developed.

Resolving $(k_R,k_Z)^{exp}$ + Complete electron Scale Spectrum Requires a Big-Simulation-Domain e- Scale Simulation



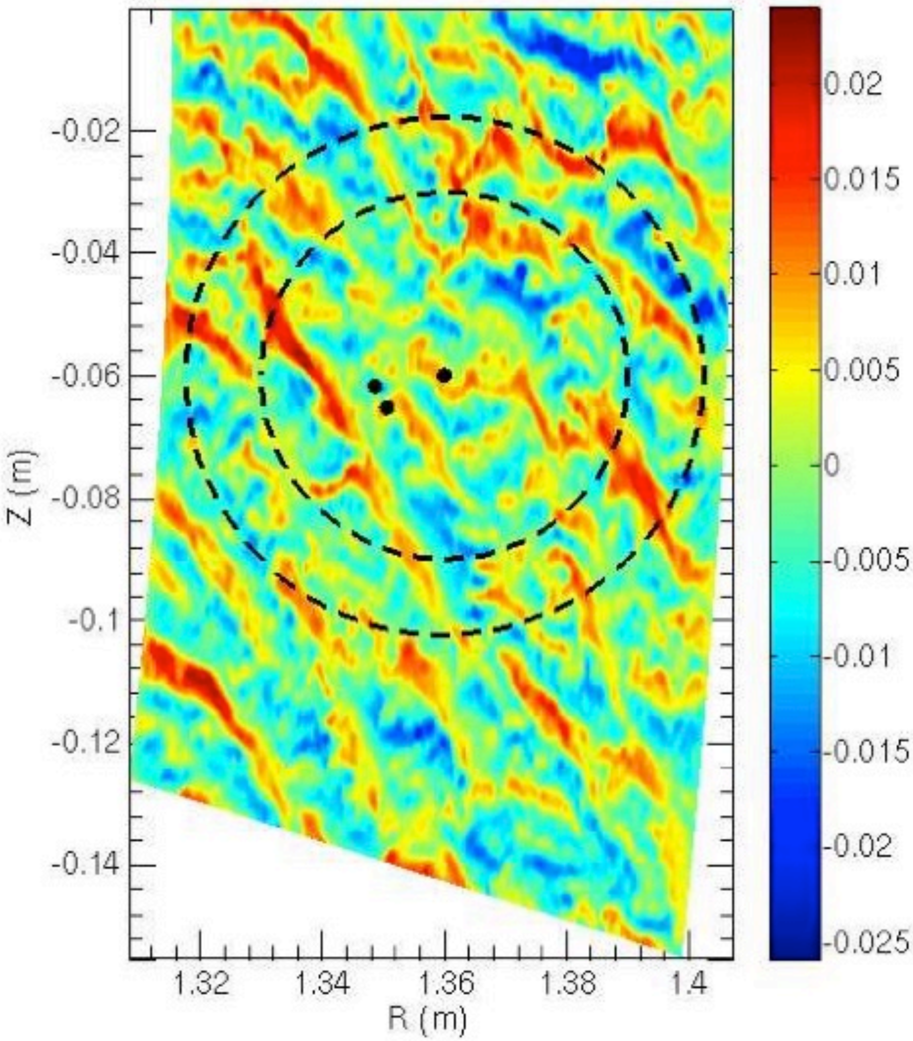


- Big-box simulation spectra show well resolved $(k_R,k_Z)^{exp}$ and electron scale spectrum.

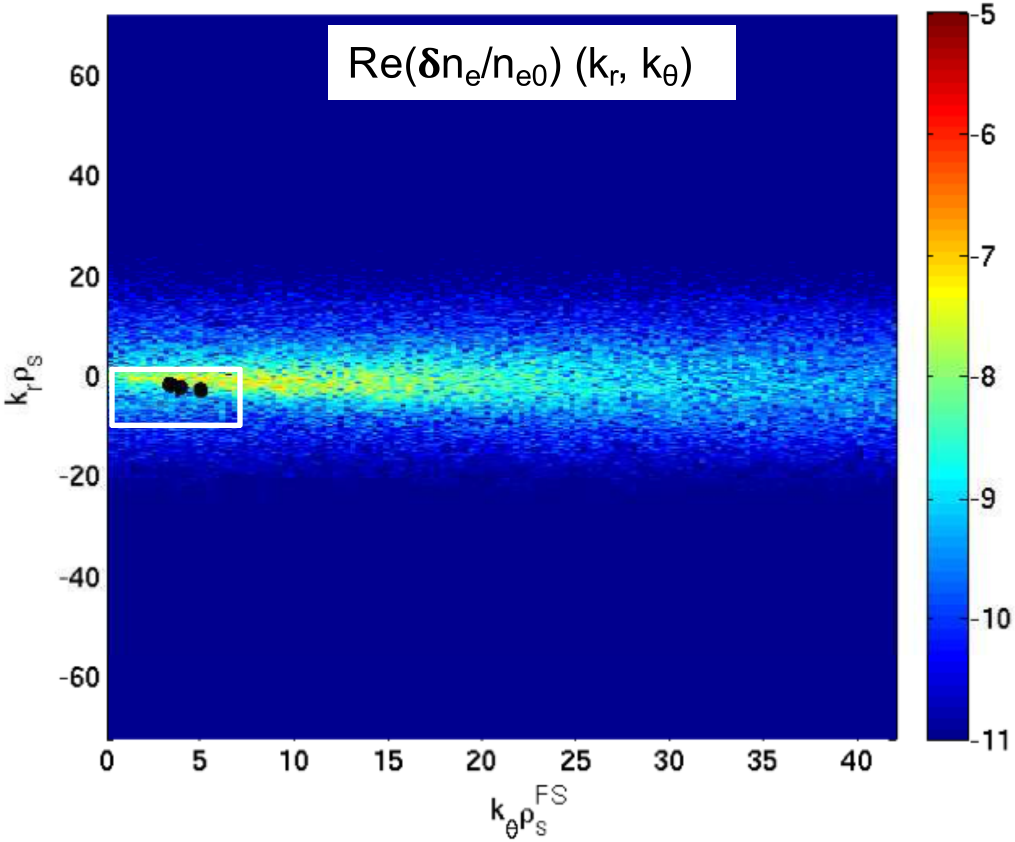
A Big-Simulation-Domain Electron Scale Simulation Was Performed to Apply New Synthetic Diagnostic

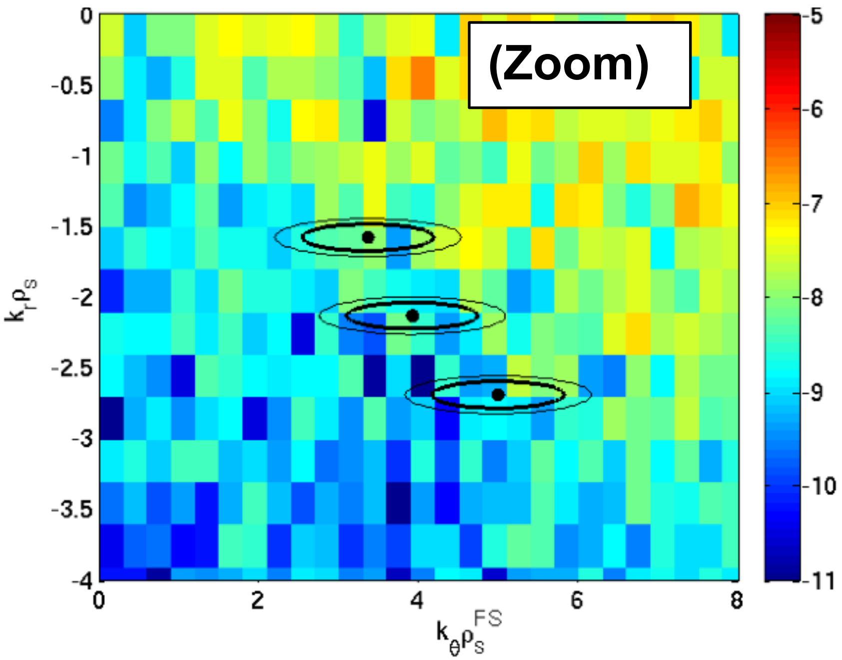
- Outboard mid-plane $\delta n_e(R, Z)$ in a big-simulation domain e- scale GYRO simulation of real NSTX plasma discharge.
- Shot 141767, time t = 398 ms (*cf.* Ruiz Ruiz PoP 2015).
- Dots are scattering location for channels 1, 2, and 3 of high-k diagnostic.
- Dashed circles are e^{-1} and e^{-2} amplitude of microwave beam.
- Scattering location and scattering volume extent are within GYRO simulation domain.

Re(δn_e) (R, Z)



Mapped Experimental Wavenumbers in GYRO Density Spectra





- $(k_r, k_\theta)^{exp}$ are closer to the spectral peak of fluctuations than previously thought → more transport relevant!
- **Black dots:** scattering $(k_r, k_\theta)^{exp}$ for channels 1,2,3

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Operating Space of New High-k Scattering Diagnostic

- A new high-k scattering system is being designed to detect streamers based on previous predictions:
  Old high-k system: high-k_r, intermediate k_θ
  New high-k system: high-k_θ, intermediate k_r → streamers

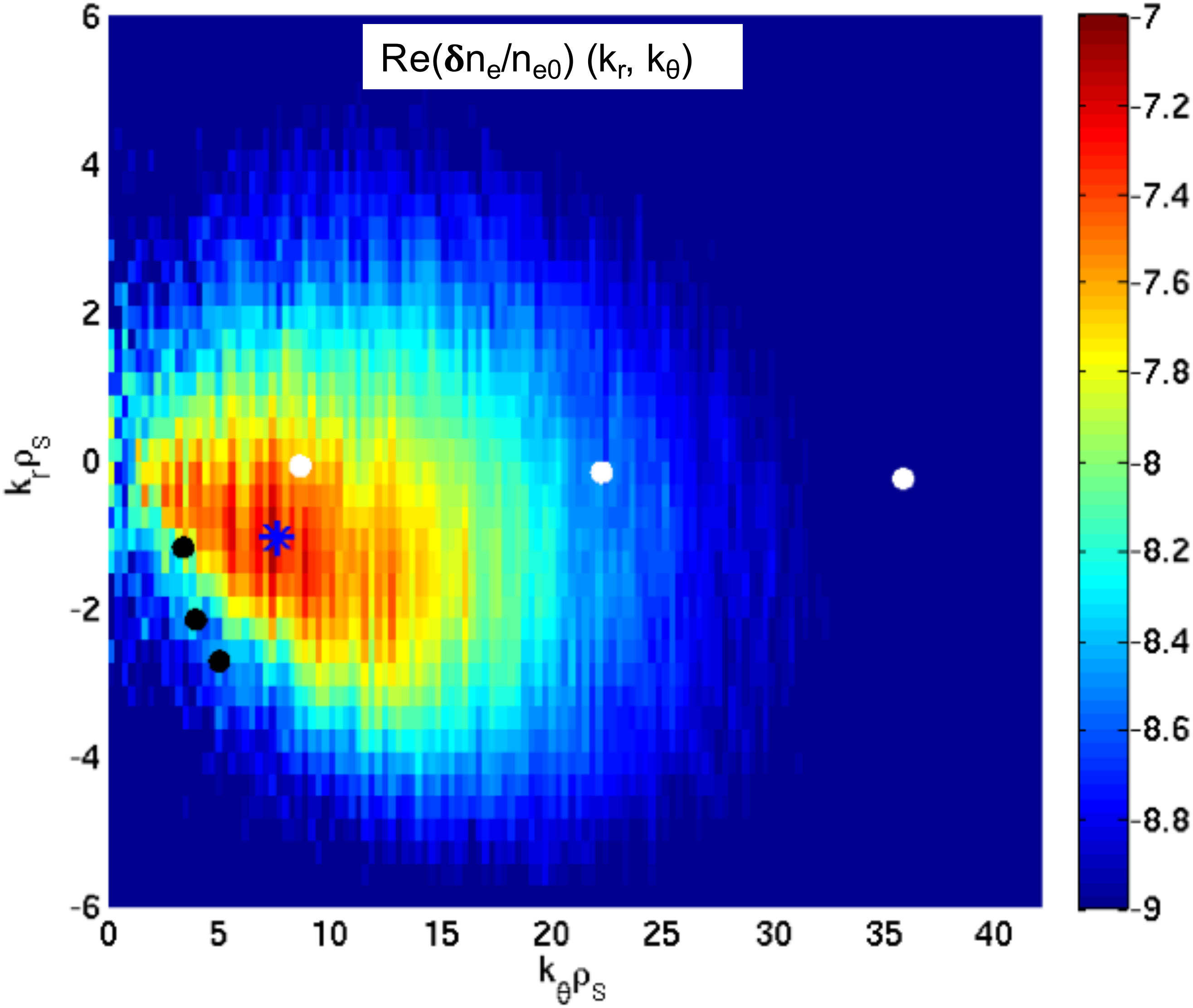
- **My goal**: project the operating space of the new high-k scattering diagnostic using the mapping I implemented.

- **Disclaimer**: k-mapping of new high-k scattering system is based on:

  1. Experimental turbulence wavenumbers from previous studies (*Barchfeld APS 2015, UC-Davis/NSTX-U Review of Fluct. Diagnostics May 2016*).
     k_Z = 7-40 cm^{-1}
     k_R = 0 cm^{-1}
     → High-k_θ scattering diagnostic.

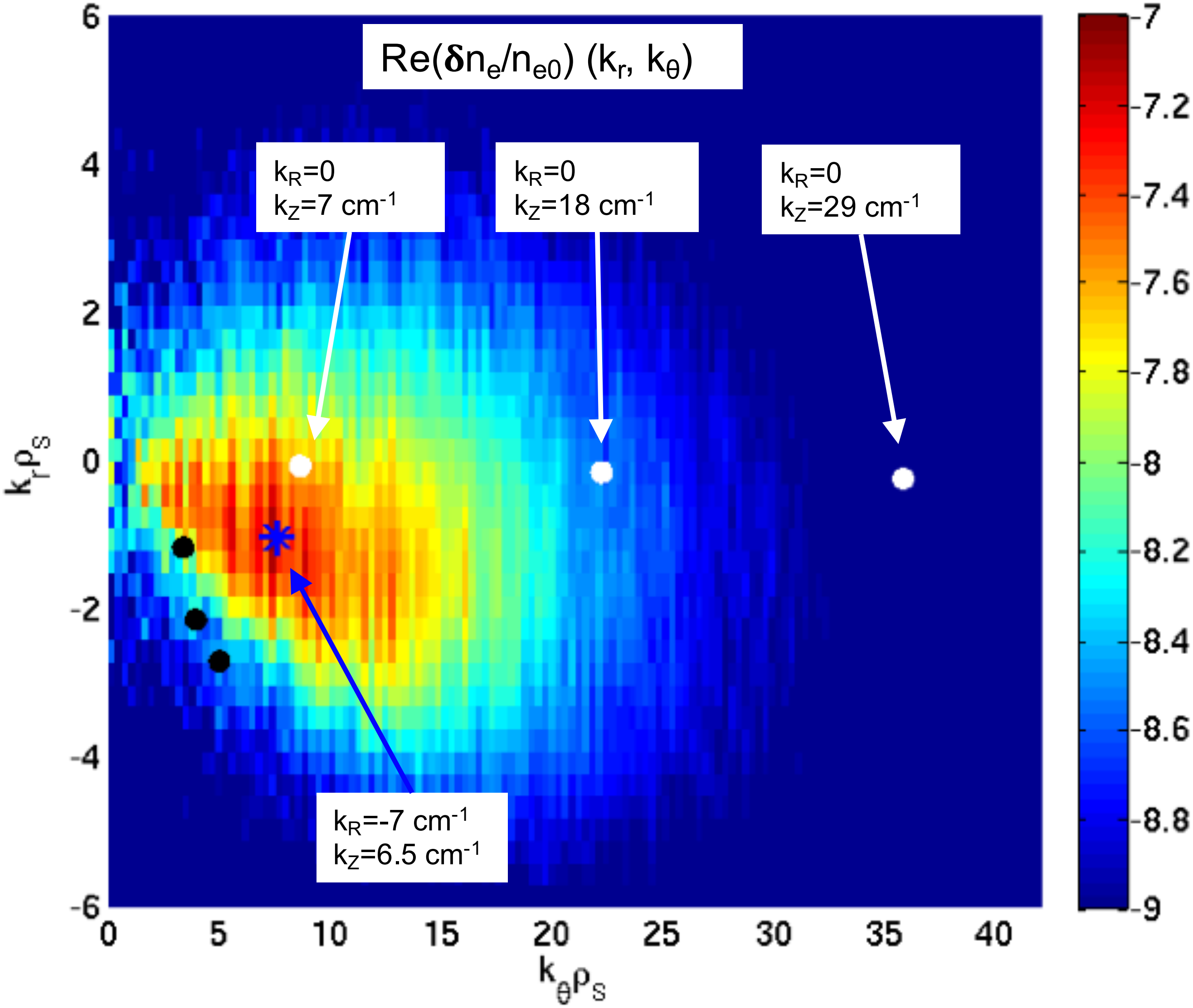
  2. Current plasma conditions (B ~ 0.5 T, T_e ~ 0.4 keV).

Mapped Wavenumbers of New High-k to GYRO 2D Fluctuation Spectrum



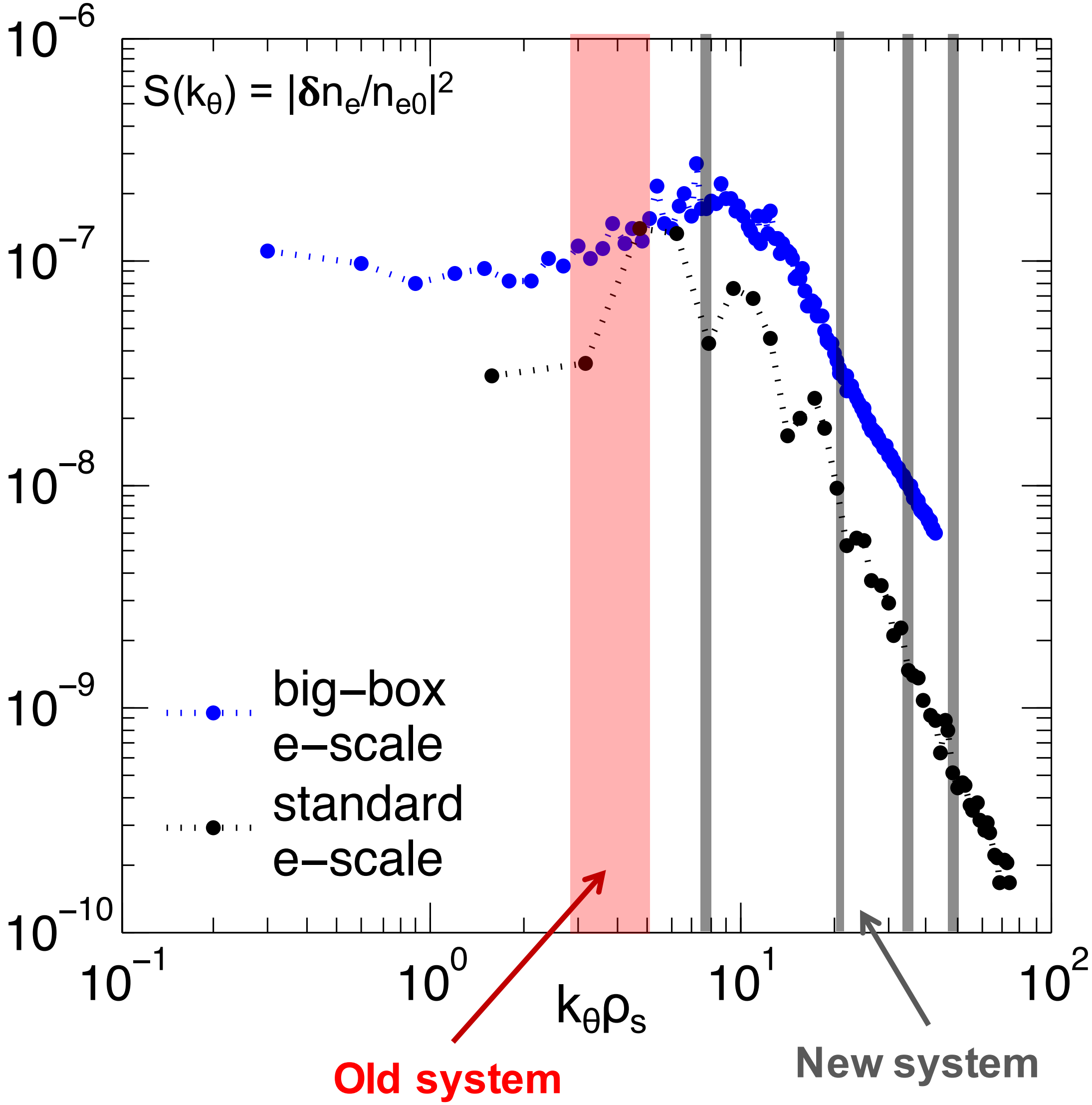
- Black dots: old hk
- White dots: new hk
  Picked k's in predicted measurement range
  k_Z = 7, 18, 29, 40 cm^{-1}
  k_R = 0 cm^{-1}
- Blue star: streamers

Mapped Wavenumbers of New High-k to GYRO 2D Fluctuation Spectrum



- Picked k's in predicted measurement range
  k_Z = 7, 18, 29, 40 cm^{-1}
  k_R = 0 cm^{-1}
- Lowest-k channel closest to streamers
  k_Z=7 cm^{-1}
- Highest-k not captured in simulation
  k_Z = 40 cm^{-1}
- Streamers: finite k_R
  $|k_R| \sim |k_Z|$

Mapped Wavenumbers of New High-k Diagnostic to GYRO k_θ Fluctuation Spectrum



- Spectrum is integrated in k_r.
- Lowest-k channel will be closest to peak of fluctuation spectrum (streamers)
  k_R=0, k_Z=7 cm^{-1}
- Need to resolve very high-k ($k_\theta \rho_s$ ~ 50) to capture highest-k channel.
- **Red band**: measurement range of old system.
- **Gray bands**: measurement range of new system.

Future Work and Conclusions on Synthetic Diagnostic Implementation

Future work

- Implementation of selectivity function and filtering.
- Use syn. diagnostic for quantitative comparisons with experiment.
- Can apply mapping to project operating space of additional scattering diagnostics (e.g. DBS).

Conclusions

- Computationally expensive simulations are needed to simultaneously resolve full ETG spectrum and experimental k in old high-k system (not in the new system).
- Old high-k system is sensitive to k that are closer to the spectral peak of fluctuations than previously thought → more transport relevant!
- New high-k system could detect streamers in lowest-k channel.
- For the first time, we're getting ***close*** to a quantitative comparison experiment-simulation of electron scale turbulence in NSTX and NSTX-U.
  → Important step to **understand electron thermal transport in NSTX-U!**

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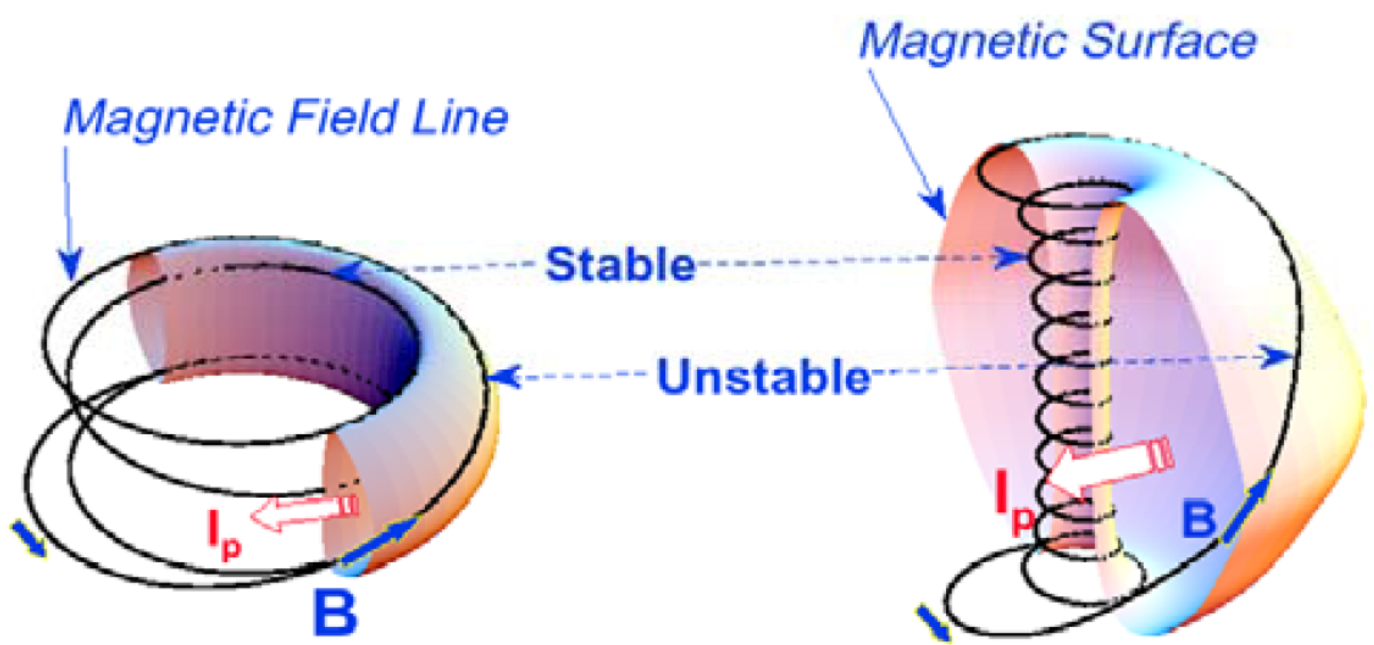
Back-up slides

Spherical Tokamaks such as NSTX Exhibit High Levels of Toroidal Rotation



Standard tokamak

Spherical tokamak (ST)

- Spherical tokamaks are more compact than standard tokamaks: easier to drive toroidal rotation.
- Toroidal rotation gives rise to perpendicular flows (ω_{ExB} shearing rate) → important key parameter in turbulence and transport.

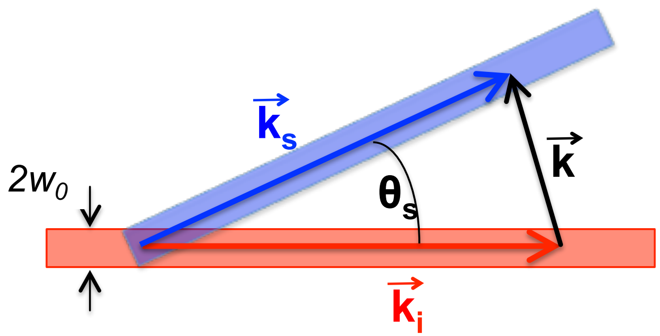
Use a High-k Scattering Diagnostic to Probe Electron Scale Turbulence in NSTX and NSTX-U

- Scattered power density $P_s \propto \left(\frac{\delta n}{n}\right)^2$
- ***Three wave-coupling*** between incident beam **(k_i , ω_i)** and plasma (**k** , **ω**)

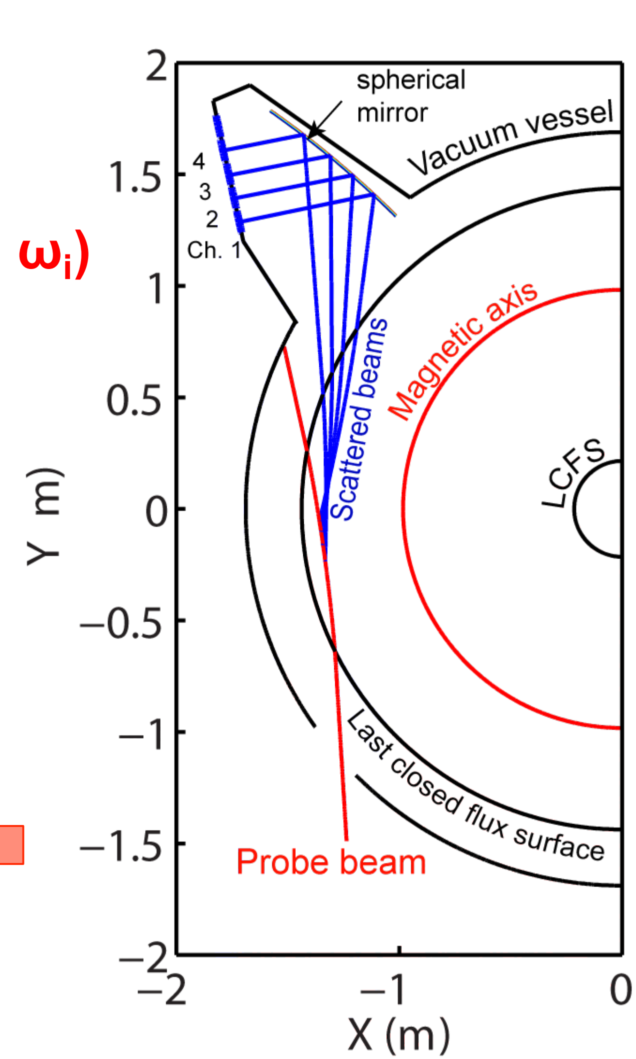
$$\vec{k}_s = \vec{k} + \vec{k}_i \qquad \omega_s = \omega + \omega_i$$

- ω_i , ω_s >> **ω** imposes Bragg condition

$$k = 2k_i \sin(\theta_s/2)$$



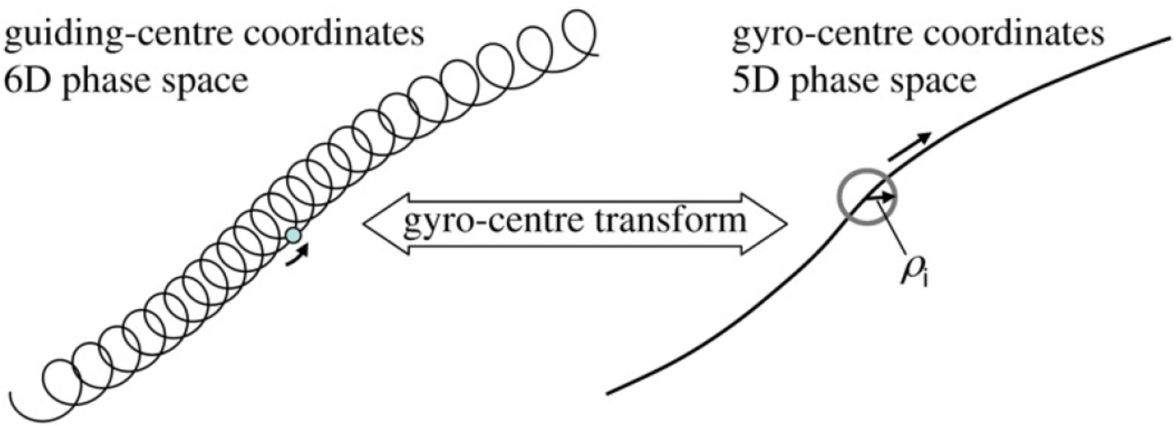
- k of the turbulence is selected by geometry.



View from top of NSTX

Gyrokinetics is the Leading Theory that Describes Turbulence and Transport in Fusion Plasmas

- Start with Fokker-Planck equation + Assume: $k_\perp \rho_i \sim 1$ $\omega/\omega_{ci} << 1$
- Gyroaverage → remove gyrophase coordinate!



- Arrive to the gyrokinetic-Maxwell system: 5D, nonlinear system of coupled equations: unknowns
  - perturbed distribution function of species ***s*** h_s
  - perturbed electromagnetic field components $\delta\phi$, $\delta A_{||}$, $\delta B_{||}$

Real Space Mapping: (R, Z, φ) ➔ (r, θ, φ)

- Start from expression of R(r,θ), Z(r,θ). Ex: Miller-like equilibrium

$$\begin{cases} R(r,\theta) = R_0(r) + r * \cos(\theta + \arcsin(\delta(r))\sin(\theta)) \\ Z(r,\theta) = Z_0(r) + r * \kappa(r) * \sin(\theta + \zeta(r)\sin(2\theta)) \end{cases}$$

κ elongation
δ triangularity
ζ squareness

- Given (R_{loc}, Z_{loc}): Determine (r_{loc}, θ_{loc}) by nonlinear solve of

$$\begin{cases} R(r_{loc}, \theta_{loc}) = R_{loc} \\ Z(r_{loc}, \theta_{loc}) = Z_{loc} \end{cases}$$

- Next: determine k-mapping

Wavenumber Mapping: $(k_R, k_Z) \rightarrow (k_r, k_\theta)$

- Mapping $(k_R, k_Z) \rightarrow (k_r, k_\theta)$ is done using the GYRO definitions of k + transformation of coordinate systems.
  Result is:

$$\begin{cases} k_r - \frac{r}{q}\frac{\partial \nu}{\partial r} k_\theta = \frac{\partial R}{\partial r} k_R + \frac{\partial Z}{\partial r} k_Z \\ -\frac{r}{q}\frac{\partial \nu}{\partial \theta} k_\theta = \frac{\partial R}{\partial \theta} k_R + \frac{\partial Z}{\partial \theta} k_Z \end{cases}$$

- Need to compute $\partial R/\partial r$, $\partial R/\partial\theta$, $\partial Z/\partial r$, $\partial Z/\partial\theta$ @ (r_{loc}, θ_{loc})
- Given $(k_R, k_Z)^{exp}$ (ray-tracing), will obtain $(k_r, k_\theta)^{exp}$ in GYRO coordinates!

Summary of Coordinate Mapping

The mapping in real-space:

obtain (r_{loc}, θ_{loc}) from (R_{loc}, Z_{loc})

$$\begin{cases} R(r_{loc}, \theta_{loc}) = R_{loc} \\ Z(r_{loc}, \theta_{loc}) = Z_{loc} \end{cases}$$

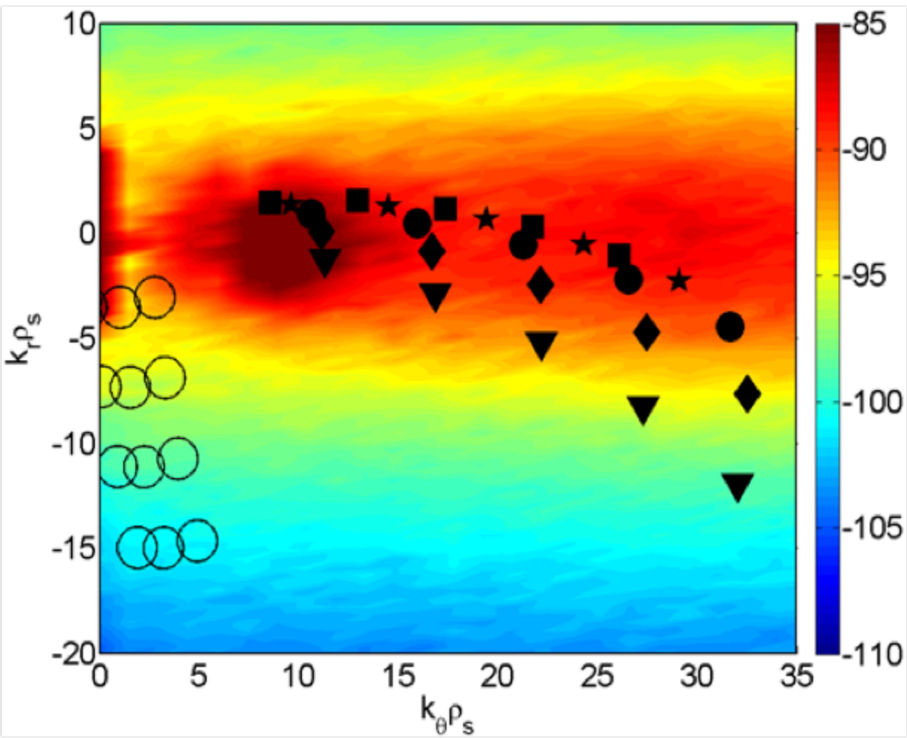
The mapping in k-space:

obtain (k_r, k_θ) from $(k_R, k_Z)^{exp}$

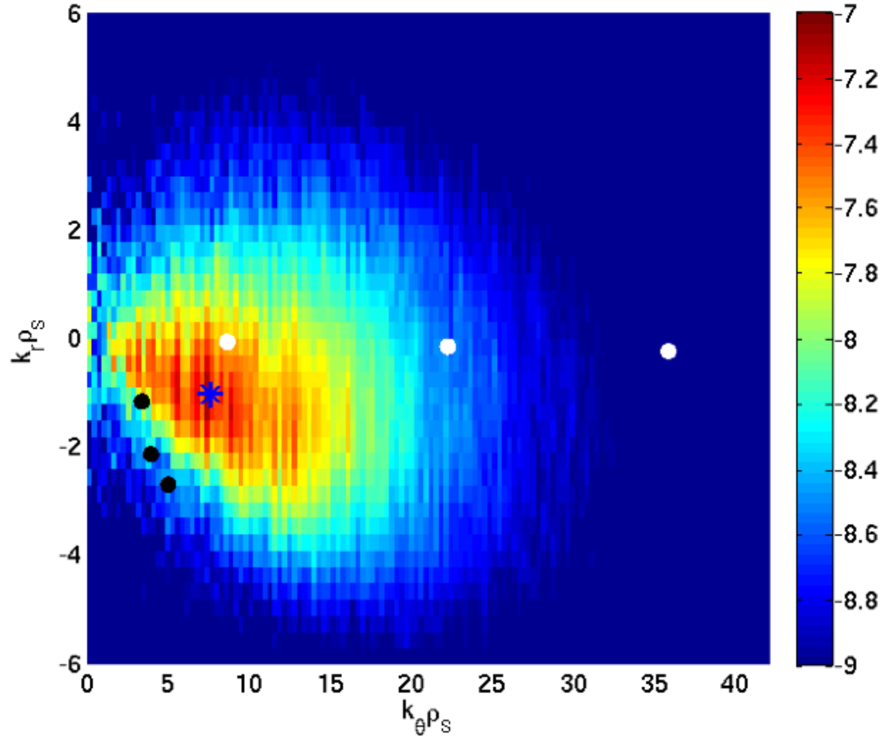
$$\begin{cases} k_r - \frac{r}{q}\frac{\partial \nu}{\partial r} k_\theta = \frac{\partial R}{\partial r} k_R + \frac{\partial Z}{\partial r} k_Z \\ -\frac{r}{q}\frac{\partial \nu}{\partial \theta} k_\theta = \frac{\partial R}{\partial \theta} k_R + \frac{\partial Z}{\partial \theta} k_Z \end{cases}$$

New High-k Scattering System was Designed to Detect Streamers based on Previous Predictions

- Old high-k system: high-k_r, intermediate k_θ
- New high-k system: high-k_θ, intermediate k_r → streamers
- y-axis scales are different, x-axis scales are similar



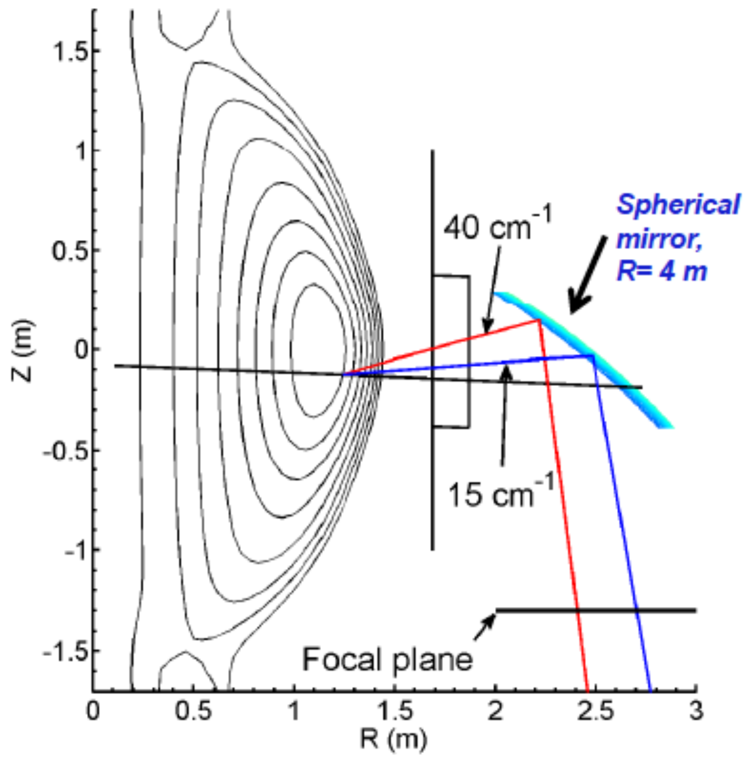
Barchfeld APS 2015



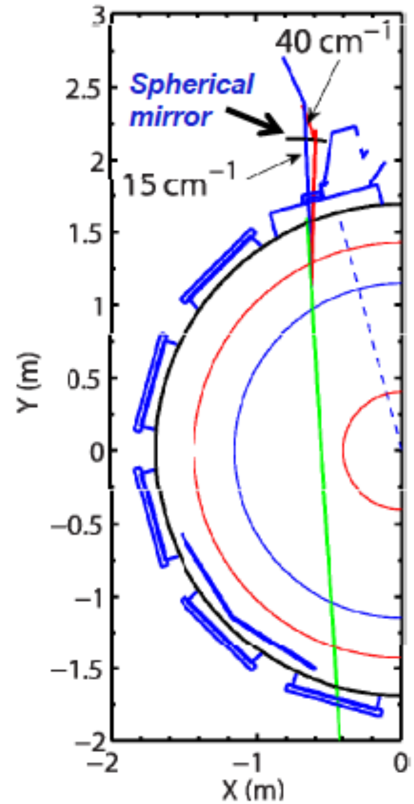
My mapping

New High-k Scattering System was Designed to Detect Peak in Fluctuation Amplitude: streamers

- Old high-k system: high-k_r, intermediate k_θ
- New high-k system: high-k_θ, intermediate k_r → streamers

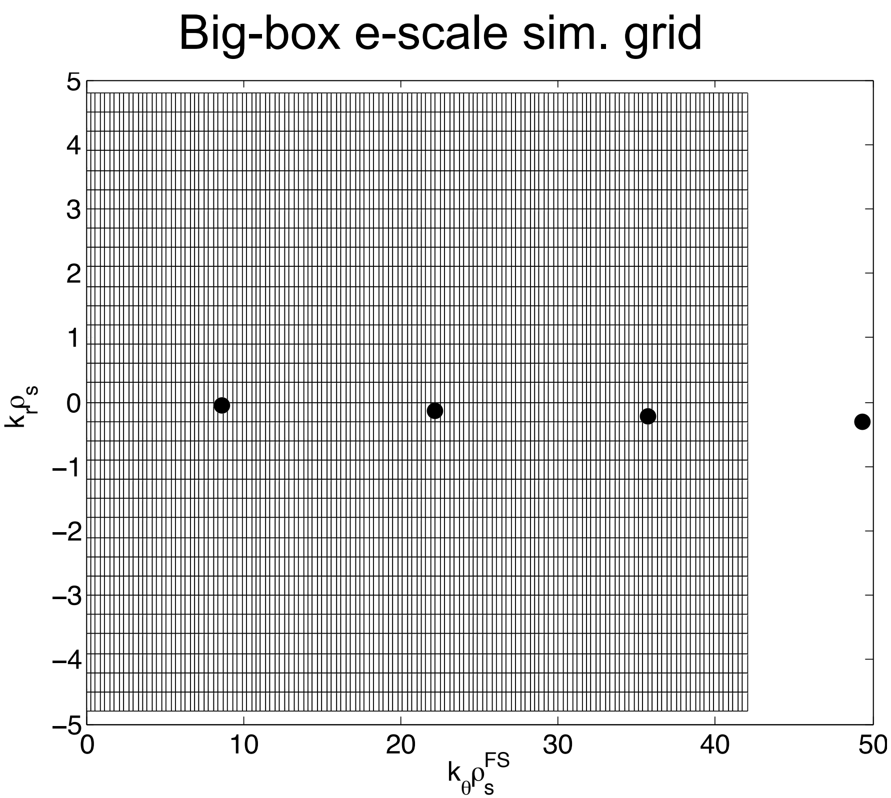


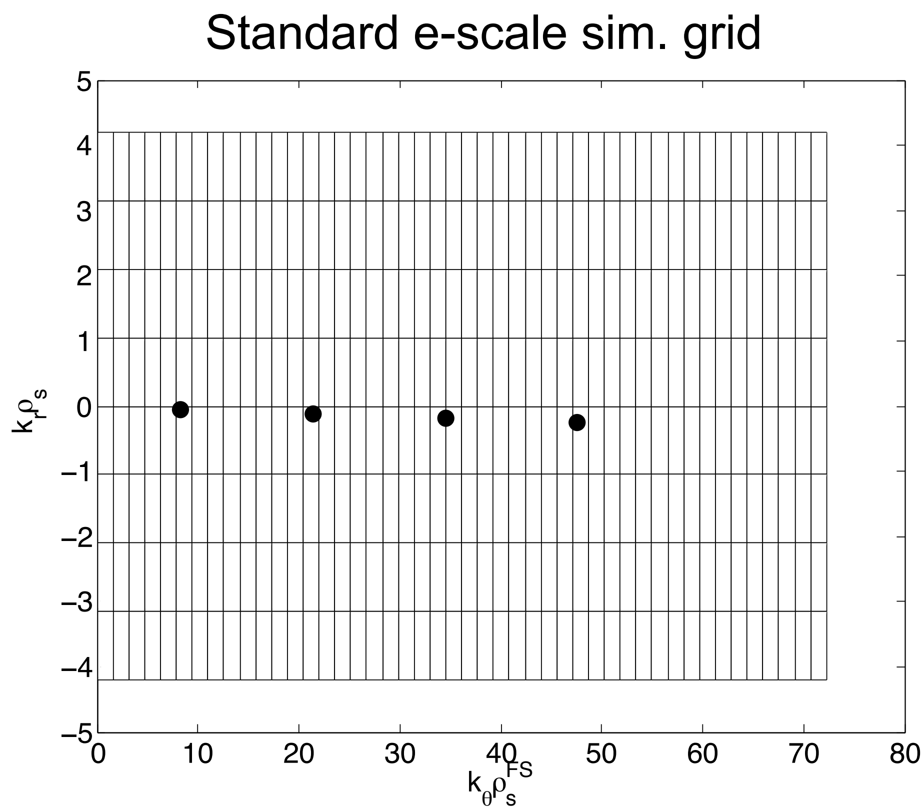
Poloidal cross section



View from top

Standard Electron Scale Simulation Captures Correctly Wavenumbers Detected by New High-k System





- k_θ values are restricted to [-5,5]
- k_r shown are full simulated spectrum.
- A big-box e- scale simulation is not needed to resolve spectrum of new high-k system.

Calculated $(k_r,k_\theta)^{exp}$ in GYRO Geometry

Given from experiment (ray tracing)

k_R = -1857 m^{-1}, k_Z=493 m^{-1} (channel 1 of high-k diagnostic, shot 141767, t = 398 ms)

Get from GYRO (internally calculated)

- $(\rho_s)_{GYRO}$ ~ 0.002 m (B_unit ~ 1.44)
- $|\nabla r|$ ~ 1.43, κ ~ 2

Apply k-mapping : close to the midplane, use simplified approx.

$$\begin{cases} (k_r\rho_s)_{GYRO} = k_R * (\rho_s)_{GYRO} / |\nabla r| \\ (k_\theta\rho_s)^{loc} = k_Z * \kappa * (\rho_s)_{GYRO} \end{cases}$$

Obtain experimental wavenumbers mapped to GYRO

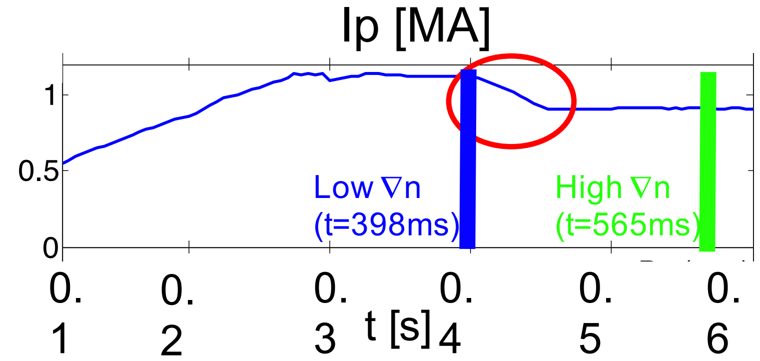
$(k_r\rho_s)_{GYRO} \sim -2.6$

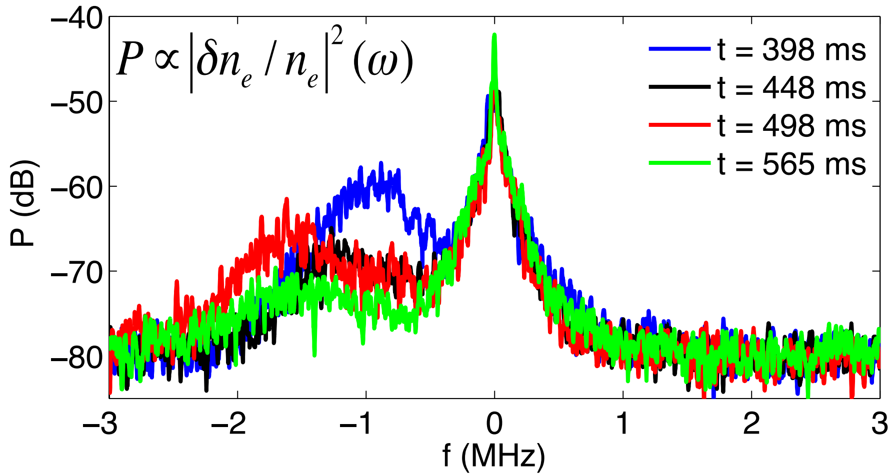
$(k_\theta\rho_s)^{loc} \sim 2.0$ ➔ $(k_\theta\rho_s)_{GYRO} \sim 5$

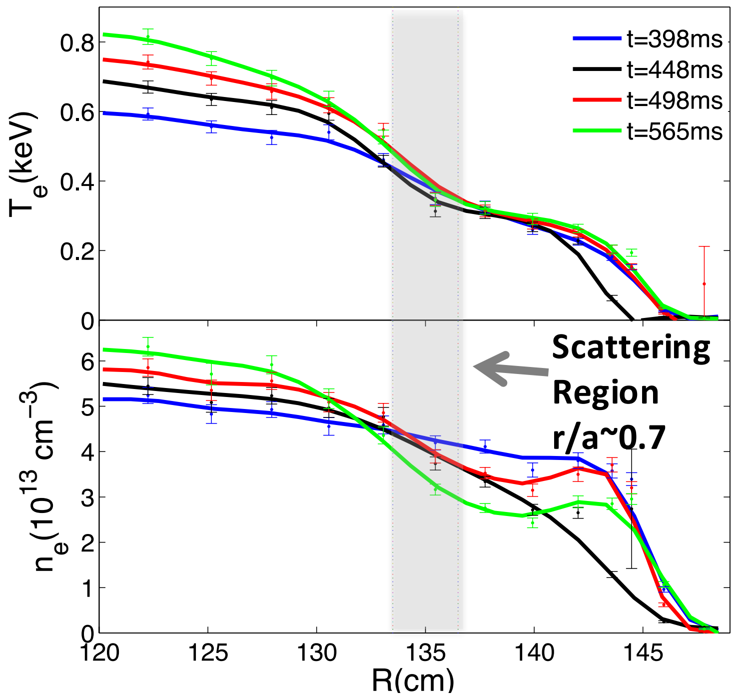
Past Work on NSTX H-mode Plasma Showed Stabilization of e- scale Turbulence by Density Gradient

- NSTX NBI heated H-mode featured a controlled current ramp-down. Shot 141767.

- An increase in the equilibrium density gradient was correlated to a decrease in high-k density fluctuation amplitude (measured by a high-k scattering system). *cf.* Ruiz Ruiz PoP 2015.

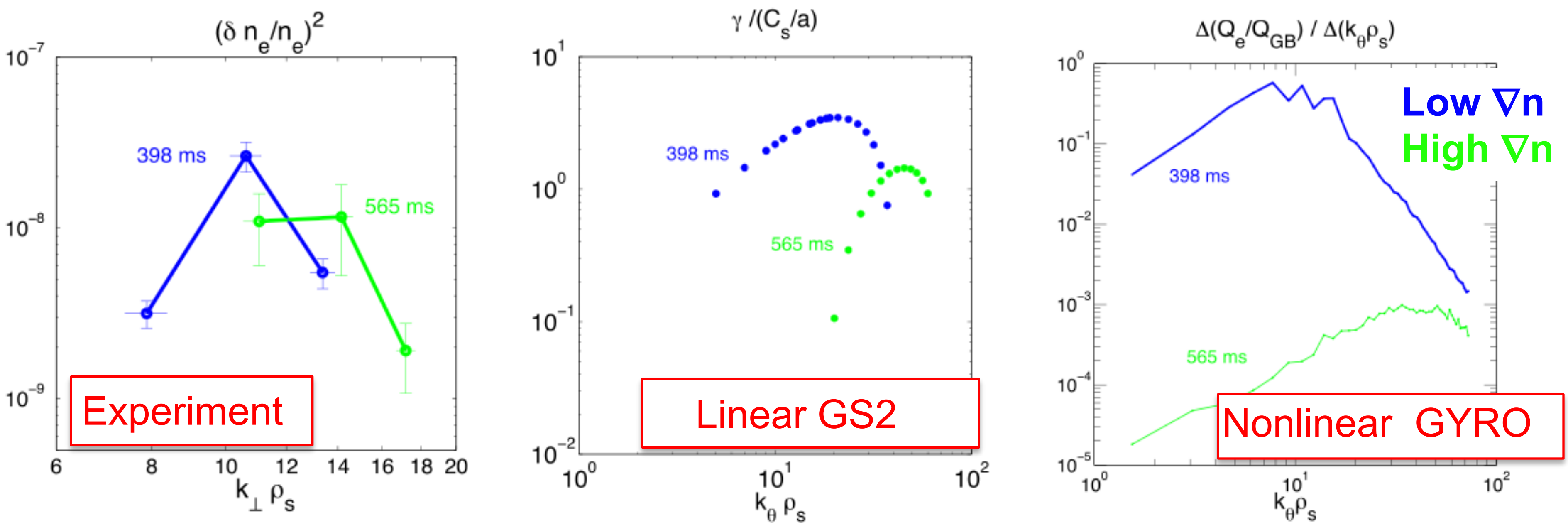






Experiment, Linear and Nonlinear Gyrokinetic Simulation Showed Density Gradient Stabilization of e- scale Turbulence

- Experimental k-spectrum is measured with a high-k scattering diagnostic (*cf.* Smith RSI 2008).
- Peak amplitude in experimental k-spectra, linear growth rate and nonlinear electron heat flux using gyrokinetic simulation is reduced, and shifted to higher wavenumber with increasing density gradient.



Probe Origins of Anomalous Electron Heat Flux Using Two Different Approaches:

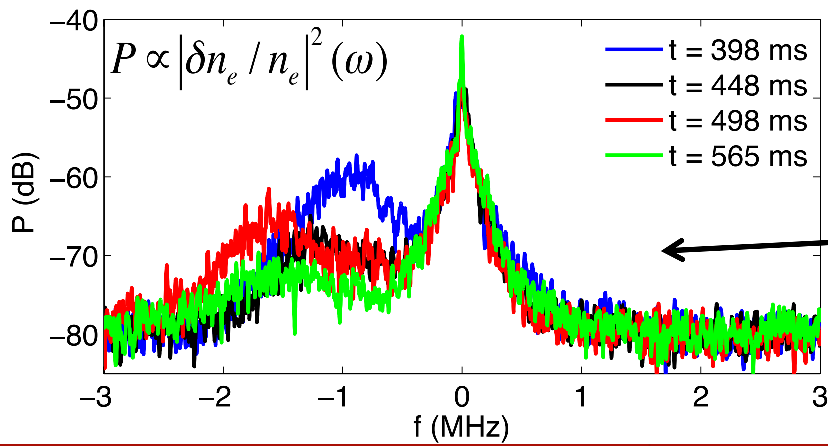
1. Revisit the assumption:

'Ion scale turbulence is suppressed by ExB shear in NSTX NBI heated H-mode plasmas'**.**

Approach: Identify ion scale instability and ion scale turbulence contributions to Q_e using linear and nonlinear gyrokinetic simulation (GYRO).

2. To what level of confidence do we trust transport predictions from previous e-scale simulations?

Approach: **Develop a synthetic high-k scattering diagnostic** for quantitative comparisons between electron scale turbulence measurements and nonlinear GYRO simulations.



High-k scattering measurements

Prerequisites to Coordinate Mapping

We want to perform:

- *coordinate mapping GYRO (r,θ,φ) ←→ physical (R, Z, φ)*
- *wavenumber mapping $(k_r\rho_s, k_\theta\rho_s)_{GYRO}$ ←→ (k_R, k_Z)*

Prerequisites

- Units: r[m], R[m], Z[m], θ, φ ∈[0,2π]
- **GYRO definition of** k_θ^{loc} and k_θ^{FS}

$$k_\theta^{loc}(r,\theta) = -\frac{n}{r}\frac{\partial \nu}{\partial \theta}, \quad k_\theta^{FS} = \frac{nq}{r}$$

Consistent with GYRO definition of flux-surface averaged k_θ^{FS}=nq/r (*cf.* backup)

- Wavenumber mapping under simplifying assumptions

$$k_R = (k_r\rho_s)_{GYRO}\left|\nabla r\right| / (\rho_s)_{GYRO}$$

$$k_Z = (k_\theta\rho_s)_{GYRO}^{loc} / (\kappa.\rho_s)_{GYRO}$$

- Miller-like parametrization
- ζ=0, dζ/dr=0 (squareness)
- Z_0=0, dZ_0/dr=0 (elevation)
- UD symmetric (up-down symmetry)
  →(θ=0)

Numerical Resolution Comparison with Traditional Ion Scale, Electron Scale and Multiscale Simulation

Poloidal wavenumber resolution ($k_\theta\rho_s$ here means $k_\theta\rho_s^{FS}$)

	$\Delta k_\theta\rho_s$	$k_\theta\rho_s^{max}$	n #tor. modes
Ion scale	~0.05	~1	~20-30
e- scale	~1-1.5	~50	~50
Multi-scale	~0.1	~40	~500
Big-box e- scale	**0.3**	**43**	**142**

Radial resolution Δr– radial box size L_r

	Δr	L_r	n_r radial grid
Ion scale	~ 0.5 ρ_s	~80-100 ρ_s	~ 200
e- scale	~ 2 ρ_e	~ 6-8 ρ_s	~ 200
Multi-scale	~ 2 ρ_e	~ 40-60 ρ_s	~ 1500
Big-box e- scale	**2.5 ρ_e**	**20 ρ_s**	**512**

Input Parameters into Nonlinear Gyrokinetic Simulations Presented

	t=398	t = 565
r/a	0.71	0.68
a [m]	0.6012	0.596
n_e [10^19 m-3]	4.27	3.43
T_e[keV]	0.39	0.401
a/L_{ne}	1.005	4.06
a/L_{Te}	3.36	4.51
β_e^{unit}	0.0027	0.003
a/L_{nD}	1.497	4.08
a/L_{Ti}	2.96	3.09
T_i/T_e	1.13	1.39
n_D/n_e	0.785030	0.80371
n_c/n_e	0.035828	0.032715
a/L_{nC}	-0.87	4.08
a/L_{TC}	2.96	3.09
Z_{eff}	1.95	1.84
nu_{ei} (a/c_s)	1.38	1.03
q	3.79	3.07
s	1.8	2.346
R_0/a	1.52	1.59
SHIFT $=dR_0/dr$	-0.3	-0.355
KAPPA = κ	2.11	1.979
s_k=rdln(κ)/dr	0.15	0.19
DELTA = δ	0.25	168
s_δ=rd(δ)/dr	0.32	0.32
M	0.2965	0.407
γ_E	0.126	0.1646
γ_p	1.036	1.1558
ρ_*	0.003	0.0035
λ_D/a	0.000037	0.0000426
c_s/a (10^5 s-1)	4.4	2.35
Qe (gB)	3.82	0.0436
Qi (gB)	0.018	0.0003

Mapping $(k_r\rho_s, k_\theta\rho_s)_{GYRO} \rightarrow (k_R, k_Z)^{exp}$

We want to perform:

- *coordinate mapping GYRO (r,θ,φ) ←→ physical (R, Z, φ)*
- *wavenumber mapping $(k_r\rho_s, k_\theta\rho_s)_{GYRO}$ ←→ (k_R, k_Z)*

Preamble 1

- Units: r[m], R[m], Z[m] $\theta, \varphi \in [0,2\pi]$
- **GYRO definition of** k_θ^{loc} and k_θ^{FS}

$$ik_\theta^{loc}(r,\theta) = \frac{1}{r}\frac{\partial}{\partial\theta} \Rightarrow k_\theta^{loc}(r,\theta) = -\frac{n}{r}\frac{\partial\nu}{\partial\theta}$$

(To be shown in slide 17)

Consistent with GYRO definition of flux-surface averaged $k_\theta^{FS}=nq/r$ (*cf.* out.gyro.run)

$$k_\theta^{FS} = \frac{1}{2\pi}\int_0^{2\pi} k_\theta^{loc}\, d\theta = \frac{1}{2\pi}\int_0^{2\pi} -\frac{n}{r}\frac{\partial\nu}{\partial\theta} d\theta = \left(-\frac{n}{r}\right)\frac{\nu(r,2\pi)-\nu(r,0)}{2\pi} = \frac{nq(r)}{r}$$

Mapping $(k_r\rho_s, k_\theta\rho_s)_{GYRO} \rightarrow (k_R, k_Z)^{exp}$

Preamble 2 why is $k_\theta^{loc}(r,\theta) = -\frac{n}{r}\frac{\partial \nu}{\partial \theta}$ **??**

GYRO decomposition of fields

$$\delta\phi(r,\theta,\alpha) = \sum_{j=-Nn+1}^{Nn-1} \delta\hat{\phi}_n(r,\theta)\mathrm{e}^{-in\alpha}\, e^{in\bar{\omega}_0 t} = \sum_{j=-Nn+1}^{Nn-1} \delta\phi_n(r,\theta), \quad \alpha = \varphi + \nu(r,\theta)$$

Set φ=0 and ω_0 = 0. Focus on transformation of one toroidal mode n. By definition of k_θ^{loc}

$$ik_\theta^{loc}\delta\phi_n(r,\theta) = \frac{1}{r}\frac{\partial}{\partial\theta}(\delta\phi_n(r,\theta)) = \frac{1}{r}\frac{\partial}{\partial\theta}(\delta\hat{\phi}_n(r,\theta)e^{-in\nu(r,\theta)}) =$$

$$\frac{1}{r}\left(\frac{\partial\delta\hat{\phi}_n}{\partial\theta}e^{-in\nu} + \delta\hat{\phi}_n\left(-in\frac{\partial\nu}{\partial\theta}\right)e^{-in\nu}\right) \Rightarrow \delta\phi_n(r,\theta)\left(\frac{-in}{r}\frac{\partial\nu}{\partial\theta}\right)$$

Conclusion: we assume definition of k_θ^{loc} is **correct.**
There is a one-to-one relation between n and k_θ^{loc} .

$$k_\theta^{loc}(r,\theta) = -\frac{n}{r}\frac{\partial\nu}{\partial\theta}$$

Mapping $(k_r\rho_s, k_\theta\rho_s)_{GYRO} \rightarrow (k_R, k_Z)^{exp}$

Preamble 3 Wavenumber mapping under simplifying assumptions

$$k_R = (k_r\rho_s)_{GYRO}\left|\nabla r\right| / (\rho_s)_{GYRO}$$

$$k_Z = (k_\theta\rho_s)_{GYRO}^{loc} / (\kappa.\rho_s)_{GYRO}$$

- Assumptions
  - $\zeta=0$, $d\zeta/dr=0$ (squareness + radial derivative)
  - $Z_0=0$, $dZ_0/dr=0$ (elevation + radial derivative)
  - UD symmetric (up-down asymmetry of flux surface)

- In the following slides, develop mapping when assumptions are not satisfied, invert

$$(R(r,\theta),Z(r,\theta))=(R_{exp}, Z_{exp}) \rightarrow (r_{exp},\theta_{exp}) .$$

Principle of Geometric Mapping is Independent of Flux Surface Parametrization

Computation of metric coefficients

- Whether you use a Model Grad-Shafranov equilibrium (GS, Miller-type) or a general equilibrium (Fourier), procedure is the same.

- In cases shown here, I use GS equilibrium.
  - In GYRO simulation, I use input parameters THETA_PLOT=8, THETA_MULT=128 (fine poloidal grid).
  - Get r[m] from out.gyro.profiles (use a_{ref} !!)
  - Create a θ array ∈[0,2π], size THETA_PLOT*THETA_MULT+1=1025.
  - Define R(r,θ) and Z(r, θ) (GS or general eq.). Used GS equilibrium here:

$$\begin{cases} R(r,\theta) = R_0(r) + r * \cos(\theta + \arcsin(\delta(r))\sin(\theta)) \quad [m] \\ Z(r,\theta) = Z_0(r) + r * \kappa(r) * \sin(\theta + \zeta(r)\sin(2\theta)) \quad [m] \end{cases}$$

- How am I sure that these derivatives are computed correctly?
  ➔Comparisons with output from out.gyro.geometry_arrays!

Wavenumber Mapping: $(k_R, k_Z) \rightarrow (k_r, k_\theta)$

- Definitions of $k_R, k_Z, k_r, k_\theta^{loc}$ + Jacobian transformation

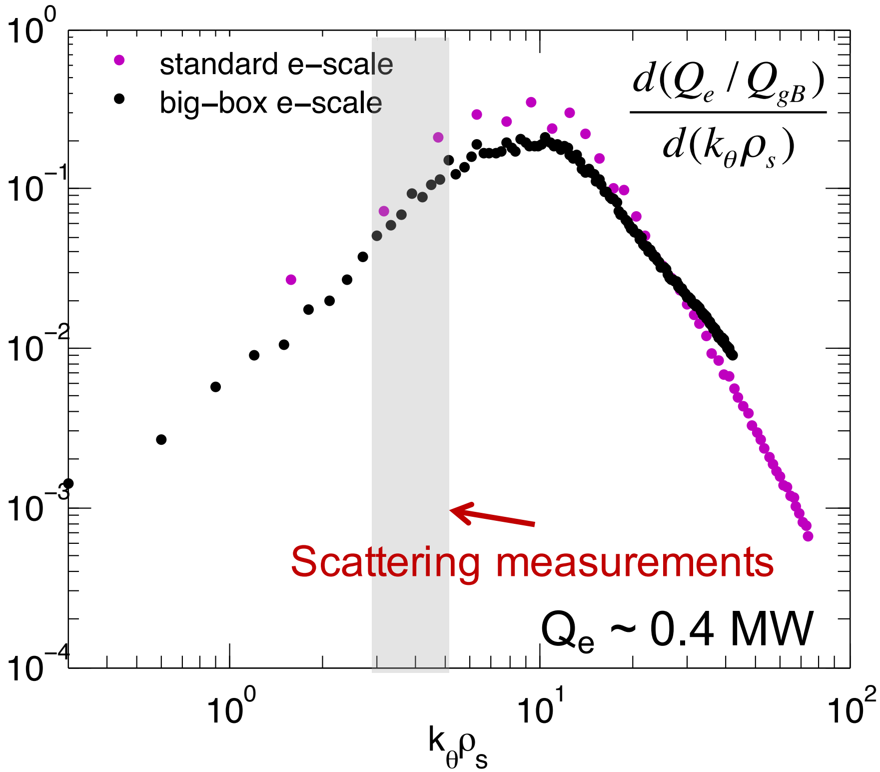
$$\begin{cases} ik_R = \dfrac{\partial}{\partial R}, & ik_Z = \dfrac{\partial}{\partial Z} \\ ik_r = \dfrac{\partial}{\partial r}, & ik_\theta^{loc} = \dfrac{1}{r}\dfrac{\partial}{\partial \theta} \end{cases} \quad + \quad \begin{pmatrix} \dfrac{\partial}{\partial r} \\ \dfrac{\partial}{\partial \theta} \end{pmatrix} = \begin{pmatrix} \dfrac{\partial R}{\partial r} & \dfrac{\partial Z}{\partial r} \\ \dfrac{\partial R}{\partial \theta} & \dfrac{\partial Z}{\partial \theta} \end{pmatrix} \begin{pmatrix} \dfrac{\partial}{\partial R} \\ \dfrac{\partial}{\partial Z} \end{pmatrix}$$

chain rule

$$\Rightarrow \begin{cases} k_r = k_R \dfrac{\partial R}{\partial r} + k_Z \dfrac{\partial Z}{\partial r} \\ k_\theta^{loc} = k_R \dfrac{1}{r}\dfrac{\partial R}{\partial \theta} + k_Z \dfrac{1}{r}\dfrac{\partial Z}{\partial \theta} \end{cases}$$

- **Need to compute $\partial R/\partial r$, $\partial R/\partial \theta$, $\partial Z/\partial r$, $\partial Z/\partial \theta$ @ (r_{loc}, θ_{loc})**
- Given k_R^{exp}, k_Z^{exp}, will obtain $(k_r, k_\theta)_{exp}$ in GYRO coordinates!

Resolving $(k_R,k_Z)^{exp}$ + Complete ETG Spectrum Requires a Big-Simulation-Domain e- Scale Simulation



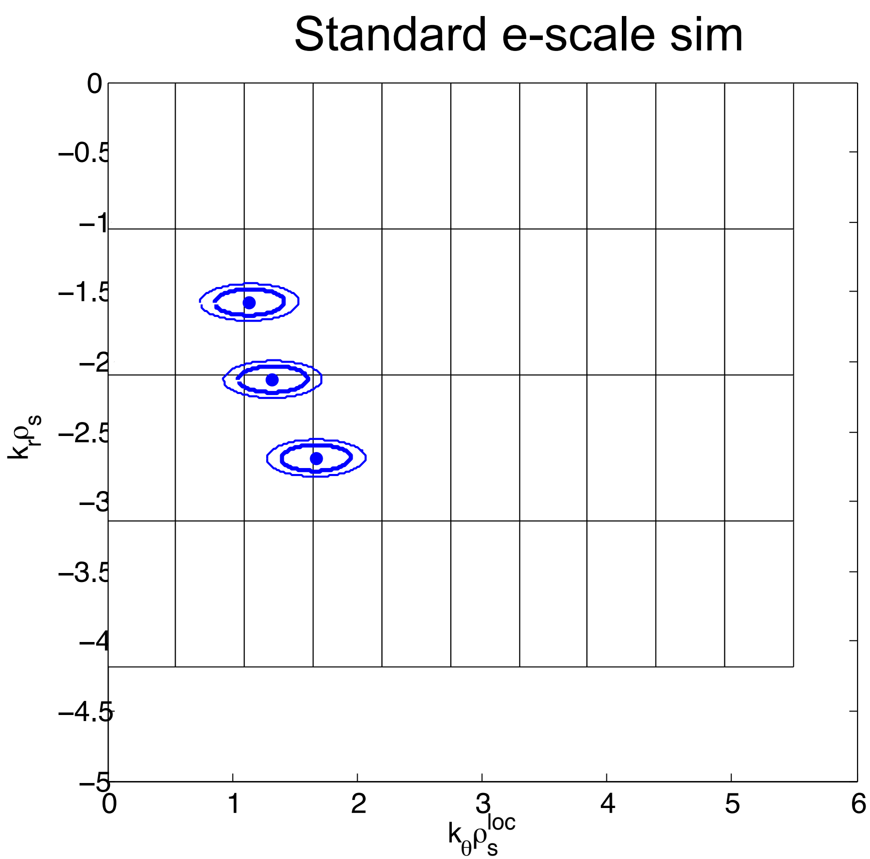
Resolution parameters

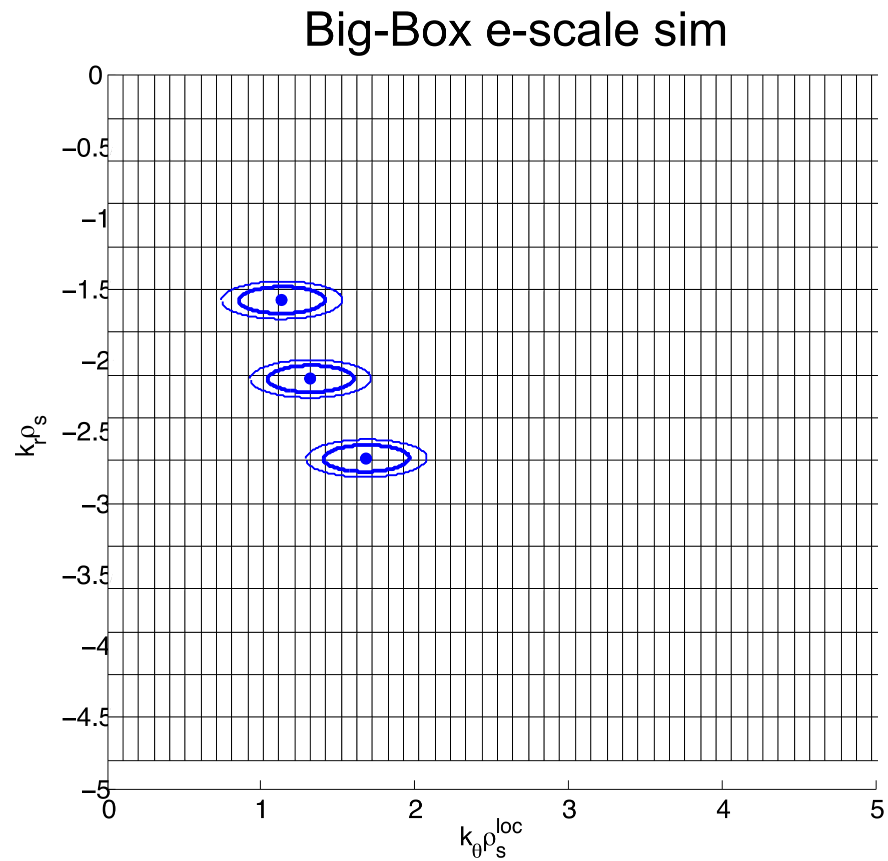
	Standard e-scale	Big-box e-scale
L_r [ρ_s]	6	21
L_y [ρ_s]	6	21
Δr [ρ_e]	~ 2	2.5
n_r (radial grid)	~ 200	512
$\Delta k_\theta \rho_s$	1-1.5	0.3
$k_\theta \rho_s^{max}$	40-50	43
n (tor. modes)	~50	142

$k_\theta \rho_s$ here means $k_\theta \rho_s^{FS}$

- Standard e- scale simulation does not accurately resolve experimental k.
- Big-box simulation spectra show well resolved $(k_R,k_Z)^{exp}$ and ETG spectrum.
- Experimental wavenumbers produce non-negligible δn_e and Q_e consistent with previous e- scale simulation results (Q_e ~ 0.4 MW).

Resolving $(k_R,k_Z)^{exp}$ + Complete ETG Spectrum Requires a Big-Simulation-Domain e- Scale Simulation





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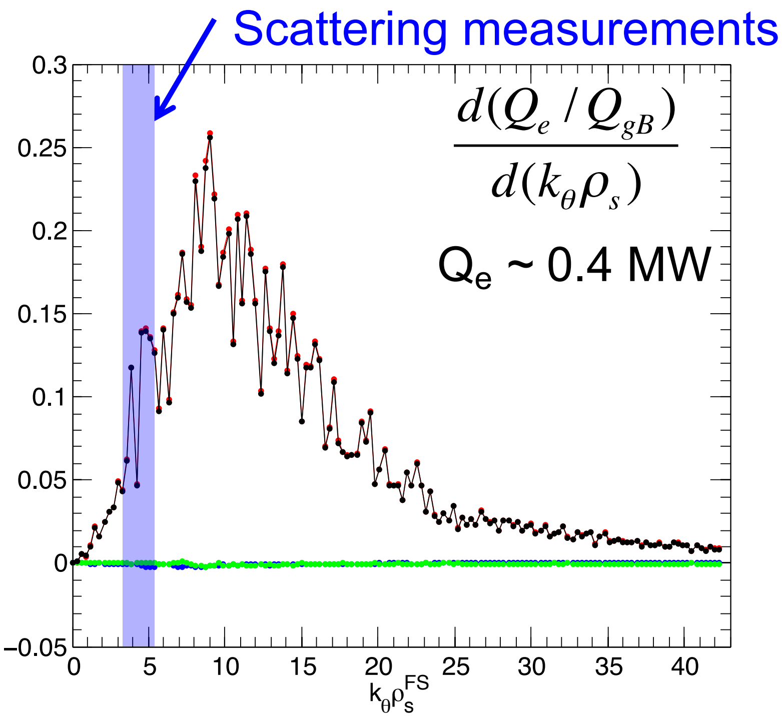
Resolving $(k_R,k_Z)^{exp}$ + Complete ETG Spectrum Requires a Big-Simulation-Domain e- Scale Simulation

<u>**Resolution constrains:**</u>

- Resolve $(k_R,k_Z)^{exp}$ → $\Delta k_\theta \rho_s^{FS} \sim 0.3$.
- Resolve full ETG spectrum → $(k_\theta \rho_s^{FS})^{max} \sim 43$.
- Radial overlap with scattering beam width → $L_r \sim 8$ cm ($L_r \sim 21\ \rho_s$)
- Resolve e- scale turbulence eddies → $\Delta r \sim 2\rho_e$.



Resolution parameters

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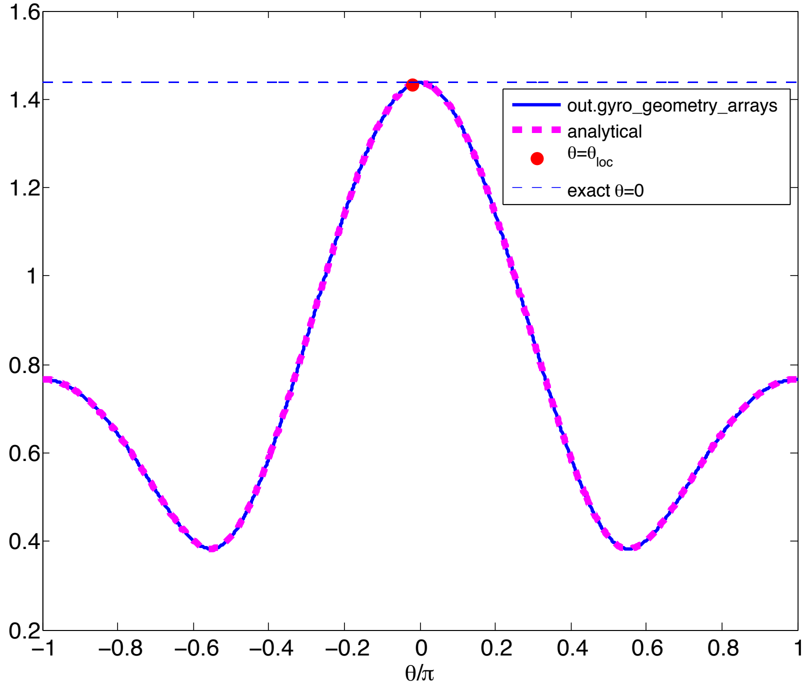
$k_\theta \rho_s^{max}$	40-50	43
n (tor. modes)	~50	142

$k_\theta \rho_s$ here means $k_\theta \rho_s^{FS}$

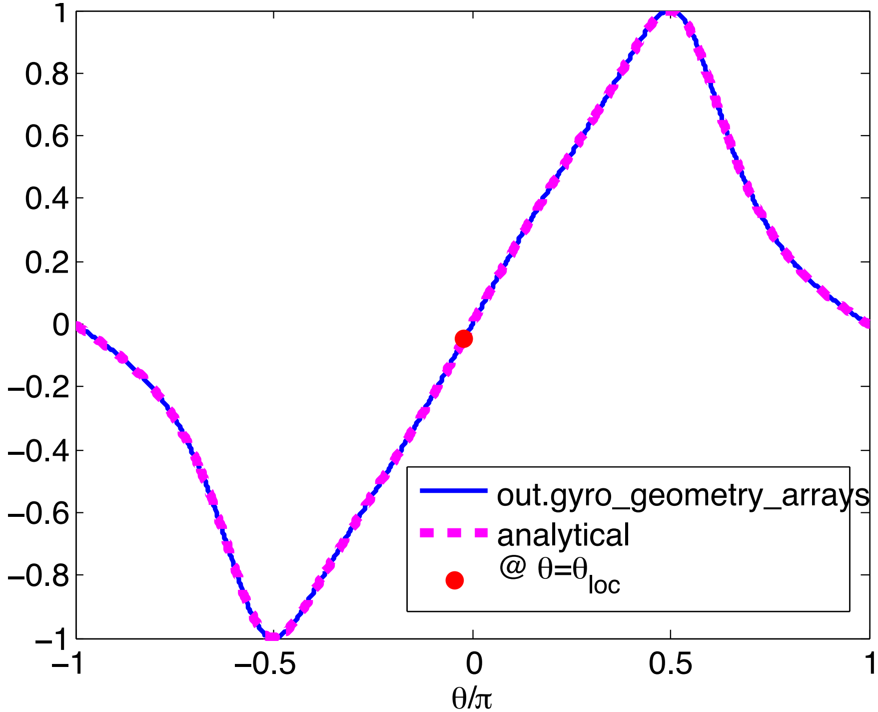
- Spectra show well resolved $(k_R,k_Z)^{exp}$ and ETG spectrum.
- Experimental wavenumbers produce non-negligible δn_e and Q_e consistent with previous e- scale simulation results ($Q_e \sim 0.4$ MW).

Computed GYRO Geometric Coefficients agree with GYRO output

$$|\nabla r|(r,\theta)=\frac{\left(\left(\frac{\partial R}{\partial \theta}\right)^2+\left(\frac{\partial Z}{\partial \theta}\right)^2\right)^{1/2}}{\frac{\partial R}{\partial r}\frac{\partial Z}{\partial \theta}-\frac{\partial R}{\partial \theta}\frac{\partial Z}{\partial r}}$$

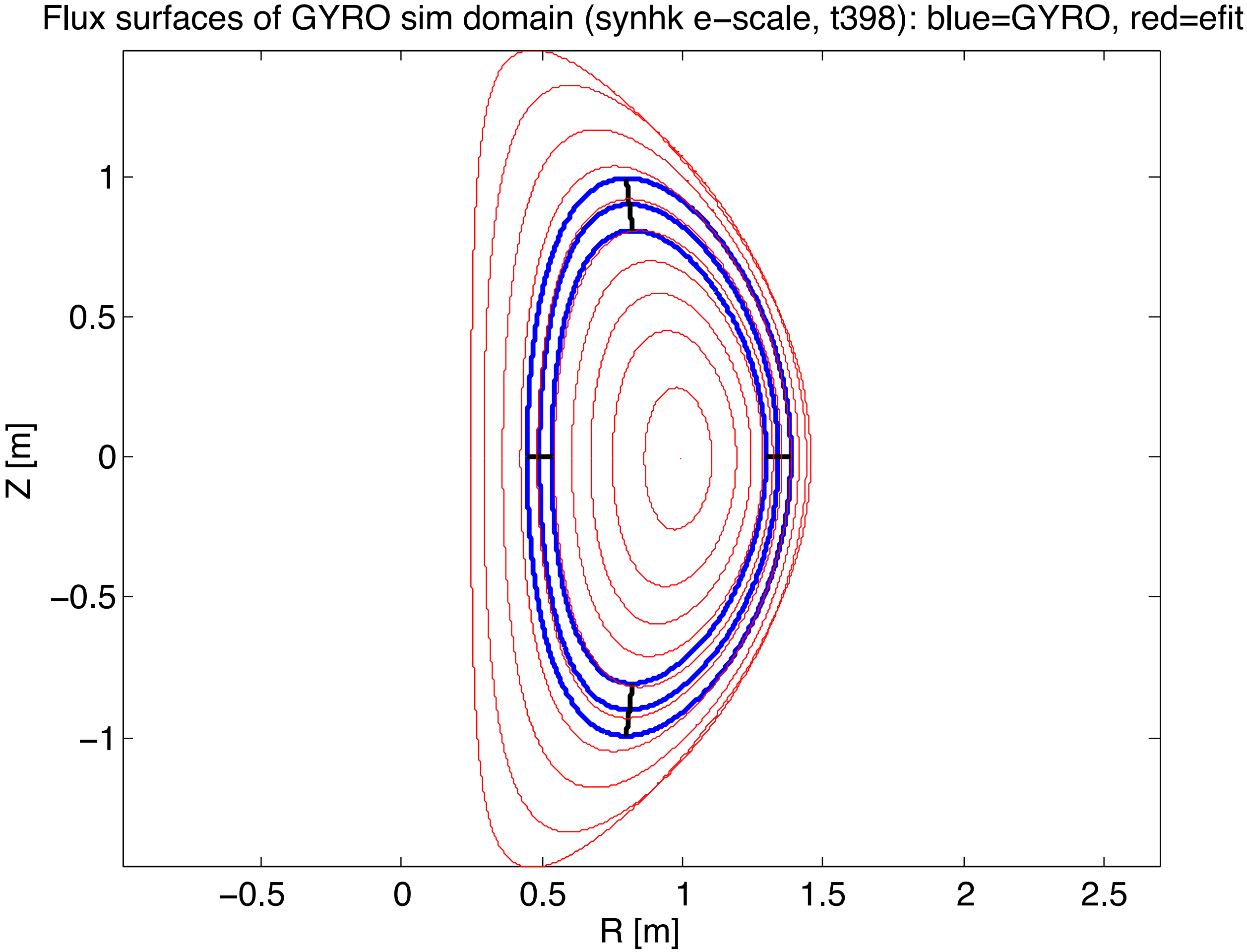


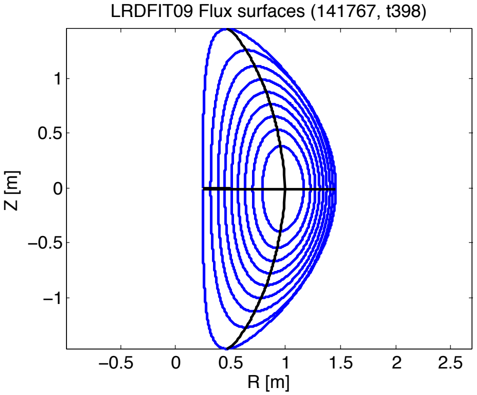
$$\sin u(r,\theta)=\frac{-\frac{\partial R}{\partial \theta}}{\left(\left(\frac{\partial R}{\partial \theta}\right)^2+\left(\frac{\partial Z}{\partial \theta}\right)^2\right)^{1/2}}$$



Conclusion: Agreement between output from out.gyro.geometry_arrays and computed coefficients gives us confidence the mapping is being performed correctly.

Poloidal Cross Section of High-Resolution Electron Scale Simulation

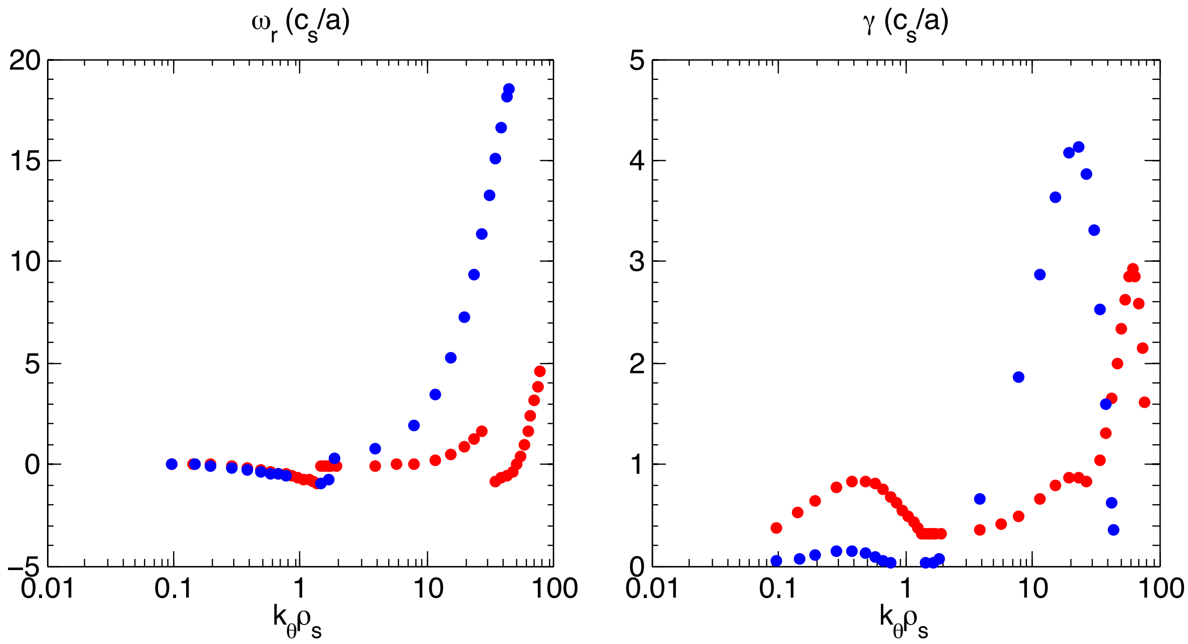




Local simulation
r/a ~ 0.7

Linear Growth Rates for Low-k and High-k Turbulence

- Note ion propagating high-k mode + electron propagating, non-balloning mode at krho~12.
- Microtearing turbulence?



k_θ resolution in synhk GYRO sim.

<u>Huge e- scale run for syn hk</u> (tested it in debug! → 1h30m for 1 a/cs)

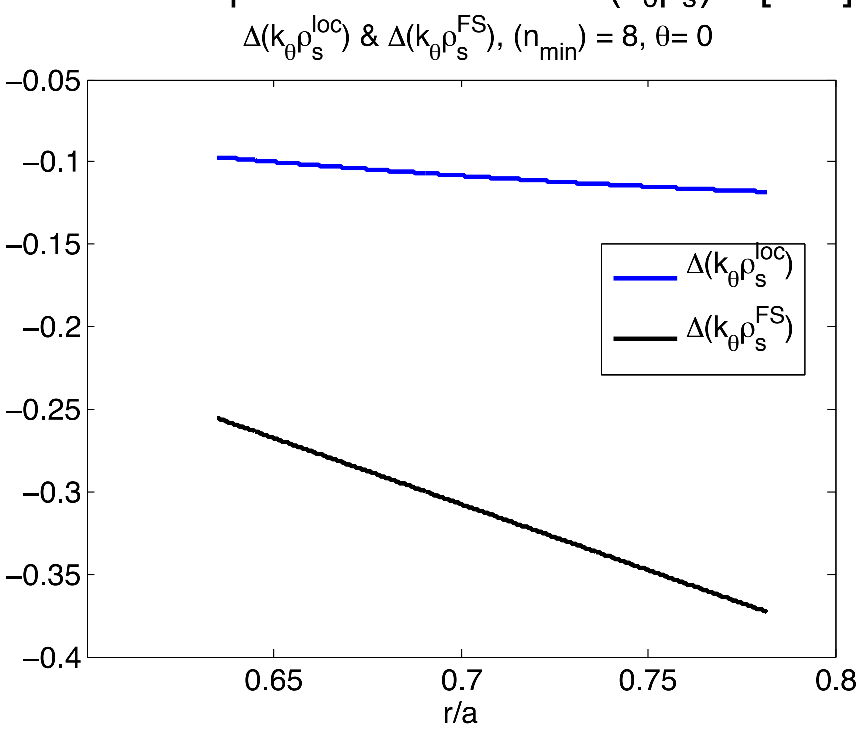
16,488 cores, ~ 24h, 4 open MP threads(4x4,032cores), Edison (x1.2) →**500,000 h (400,000h)**

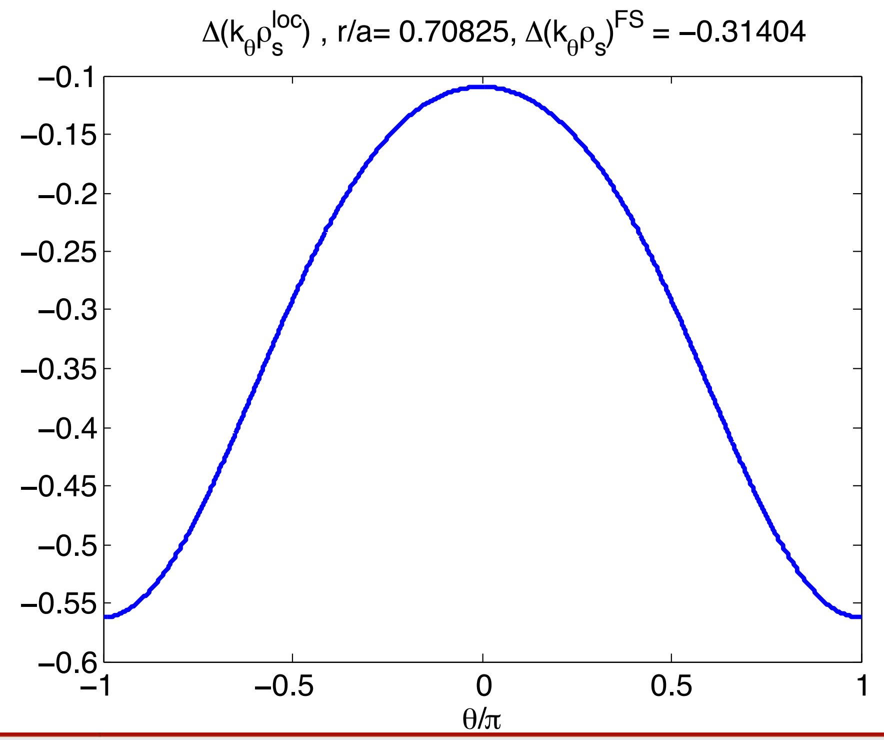
Run for 20 a/cs

Distribution points 495,452,160

$$k_\theta^{loc} = -\frac{n}{r}\frac{\partial \nu}{\partial \theta}(\bar{r}, \theta = 0)$$

Radial and poloidal variation of $(k_\theta \rho_s)^{loc}$ [θ=0]





Appendix: Compute (Δk_R, Δk_Z) ➔($\Delta k_r\rho_s$, $\Delta k_\theta\rho_s$)^{GYRO}

Assume $\Delta k_R = \Delta k_Z = \Delta k = 66.7 m^{-1}$

$$\begin{cases} k_r = k_R \dfrac{\partial R}{\partial r} + k_Z \dfrac{\partial Z}{\partial r} \\ r k_\theta = k_R \dfrac{\partial R}{\partial \theta} + k_Z \dfrac{\partial Z}{\partial \theta} \end{cases} \Rightarrow \begin{cases} (\Delta k_r)^2 = (\Delta k_R)^2 \left(\dfrac{\partial R}{\partial r}\right)^2 + (\Delta k_Z)^2 \left(\dfrac{\partial Z}{\partial r}\right)^2 \\ (\Delta k_\theta)^2 = (\Delta k_R)^2 \left(\dfrac{1}{r}\dfrac{\partial R}{\partial \theta}\right)^2 + (\Delta k_Z)^2 \left(\dfrac{1}{r}\dfrac{\partial Z}{\partial \theta}\right)^2 \end{cases}$$

This assumes beam radius a = 3cm, such that $\Delta k = 2/a = 66.7 m^{-1}$
As a first approximation, assume simplest selectivity function: gaussian is k_r and k_θ

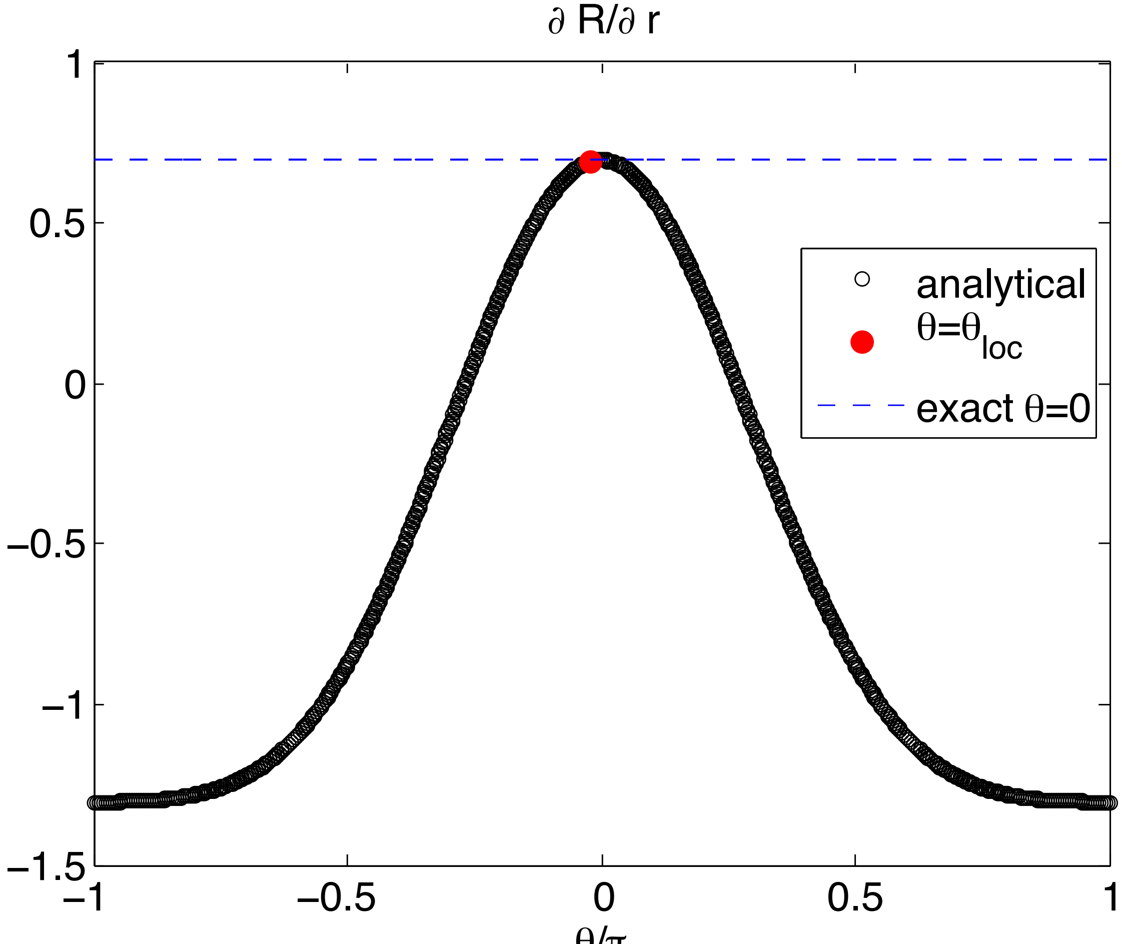
$$F(k_r, k_\theta) = F_r(k_r) F_\theta(k_r)$$

$$F_r(k_r) = \exp\left(-(k_r - k_r^{\exp})^2 / \Delta k_r^2\right)$$

$$F_\theta(k_\theta) = \exp\left(-(k_\theta - k_\theta^{\exp})^2 / \Delta k_\theta^2\right)$$

Step 2: Compute derivatives: $\frac{\partial R}{\partial r}(r_{loc}, \theta)$

(r_{loc}, θ_{loc}) is location of scattering



Analytical value at θ=0 is (GS eq

$$\frac{\partial R}{\partial r}(r,\theta=0) = 1 + \frac{\partial R_0}{\partial r}(r,\theta=0)$$

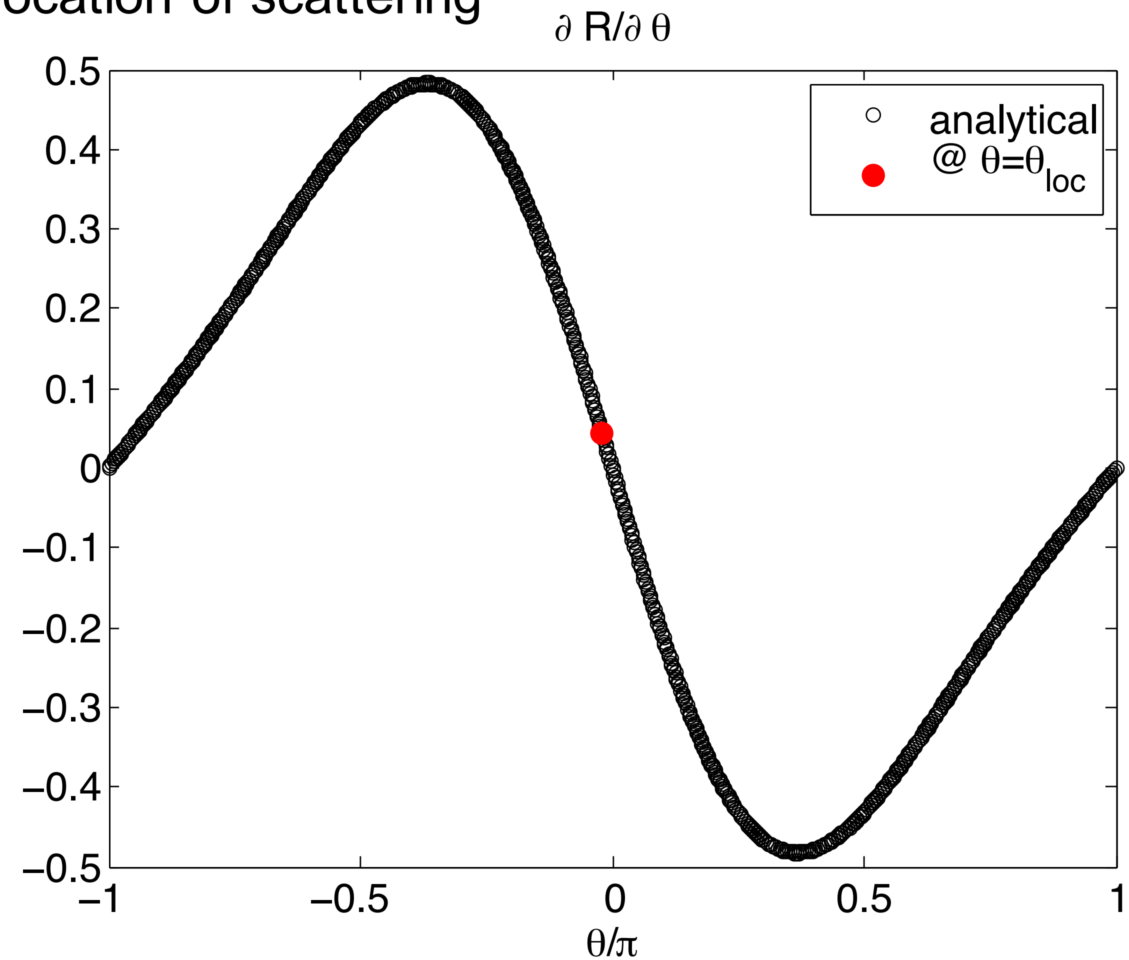
$$= 1 + SHIFT$$

60

Inverse Mapping $(k_R, k_Z) \rightarrow (k_r\rho_s, k_\theta\rho_s)^{GYRO}$

Step 2: Compute derivatives: $\frac{\partial R}{\partial \theta}(r_{loc}, \theta)$

(r_{loc}, θ_{loc}) is location of scattering



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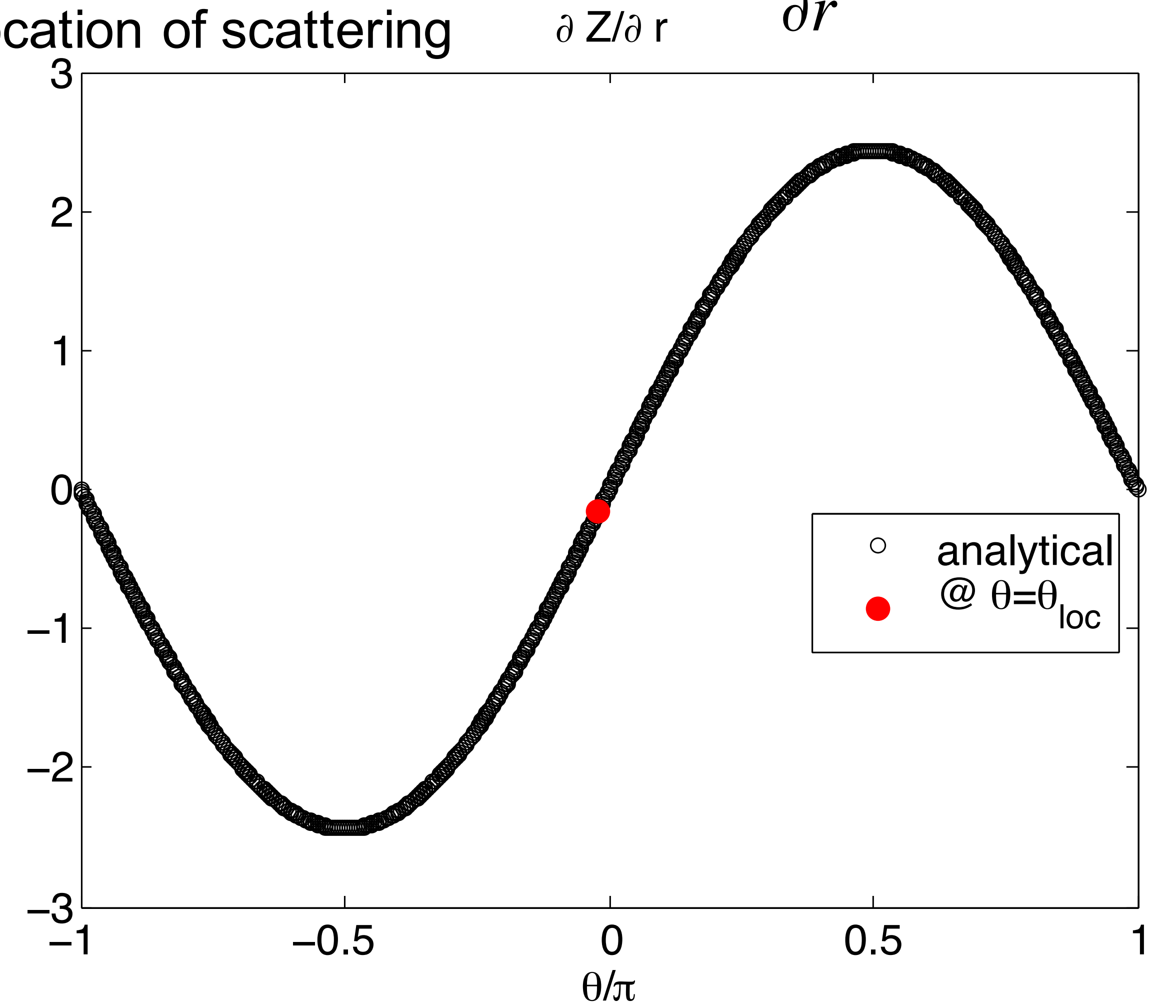
Inverse Mapping $(k_R, k_Z) \rightarrow (k_r\rho_s, k_\theta\rho_s)^{GYRO}$

Step 2: Compute derivatives: $\frac{\partial Z}{\partial r}(r_{loc},\theta)$

(r_{loc}, θ_{loc}) is location of scattering



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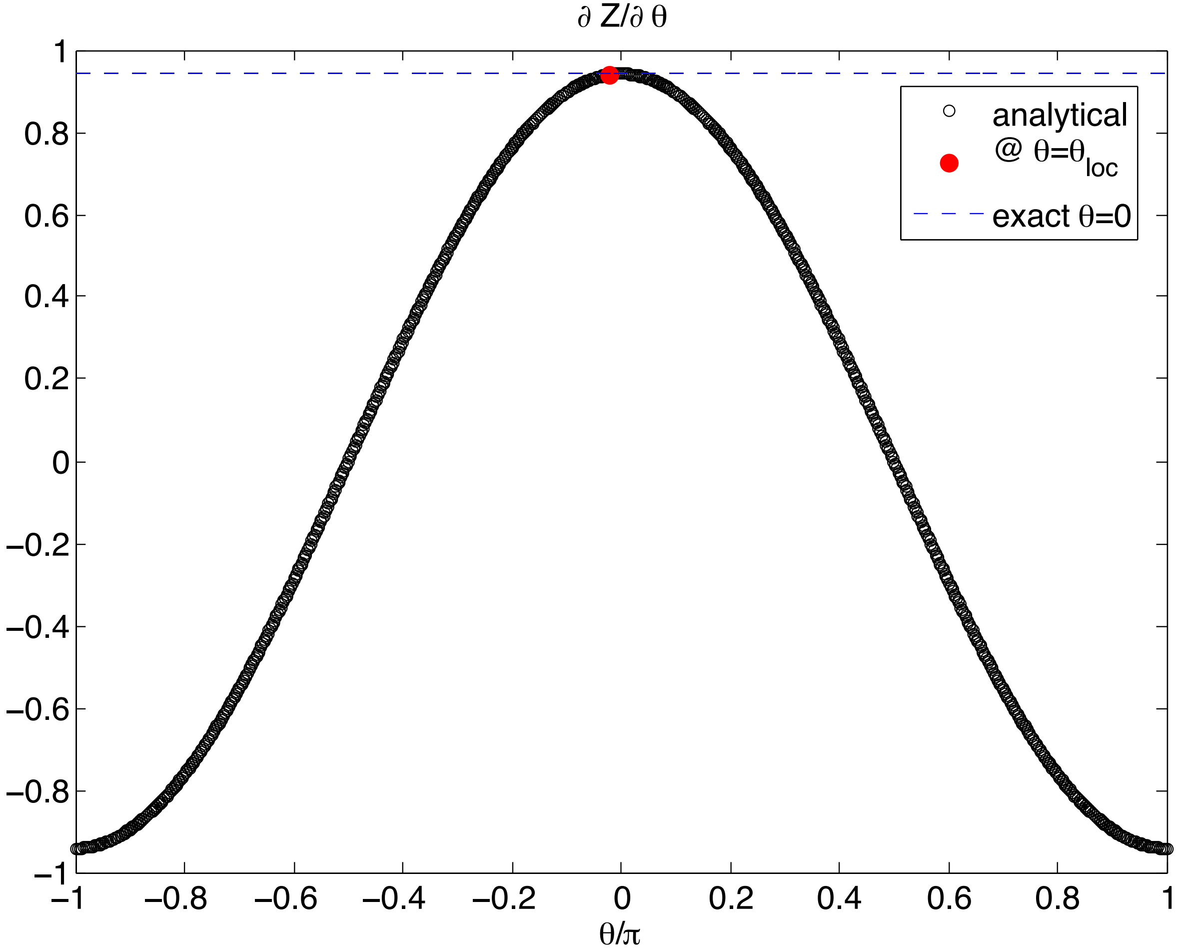
Step 2: Compute derivatives: $\frac{\partial Z}{\partial \theta}(r_{loc}, \theta)$

(r_{loc}, θ_{loc}) is location of scattering



Analytical value at θ=0 is (GS eq

$$\frac{\partial Z}{\partial \theta}(r, \theta = 0) = r\kappa$$

$$= r_{loc} * KAPPA$$

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Appendix: Compute Inverse Derivatives

Start from the coordinate transformation

$$\begin{pmatrix} \delta R \\ \delta Z \end{pmatrix} = \begin{pmatrix} \frac{\partial R}{\partial r} & \frac{\partial R}{\partial \theta} \\ \frac{\partial Z}{\partial r} & \frac{\partial Z}{\partial \theta} \end{pmatrix} \begin{pmatrix} \delta r \\ \delta \theta \end{pmatrix} = J \begin{pmatrix} \delta r \\ \delta \theta \end{pmatrix} \quad \Leftrightarrow \quad \begin{pmatrix} \delta r \\ \delta \theta \end{pmatrix} = J^{-1} \begin{pmatrix} \delta R \\ \delta Z \end{pmatrix}$$

Additionally, we can write the inverse transformation

$$\begin{pmatrix} \delta r \\ \delta \theta \end{pmatrix} = \begin{pmatrix} \frac{\partial r}{\partial R} & \frac{\partial r}{\partial Z} \\ \frac{\partial \theta}{\partial R} & \frac{\partial \theta}{\partial Z} \end{pmatrix} \begin{pmatrix} \delta R \\ \delta Z \end{pmatrix}$$

Compute inverse matrix J^{-1}

$$J^{-1} = \frac{1}{\det J} \begin{pmatrix} \frac{\partial Z}{\partial \theta} & -\frac{\partial R}{\partial \theta} \\ -\frac{\partial Z}{\partial r} & \frac{\partial R}{\partial r} \end{pmatrix}, \quad \det J = \frac{\partial R}{\partial r}\frac{\partial Z}{\partial \theta} - \frac{\partial R}{\partial \theta}\frac{\partial Z}{\partial r}$$

* Recall dRdθ =0
* Recall dZ/dr =0

Appendix: Compute Inverse Derivatives

We find

$$\begin{cases} \dfrac{\partial r}{\partial R} = \dfrac{1}{\det J}\dfrac{\partial Z}{\partial \theta} \\ \dfrac{\partial r}{\partial Z} = -\dfrac{1}{\det J}\dfrac{\partial R}{\partial \theta} \\ \dfrac{\partial \theta}{\partial R} = -\dfrac{1}{\det J}\dfrac{\partial Z}{\partial r} \\ \dfrac{\partial \theta}{\partial Z} = \dfrac{1}{\det J}\dfrac{\partial R}{\partial r} \end{cases}$$

$$\det J = \frac{\partial R}{\partial r}\frac{\partial Z}{\partial \theta} - \frac{\partial R}{\partial \theta}\frac{\partial Z}{\partial r}$$

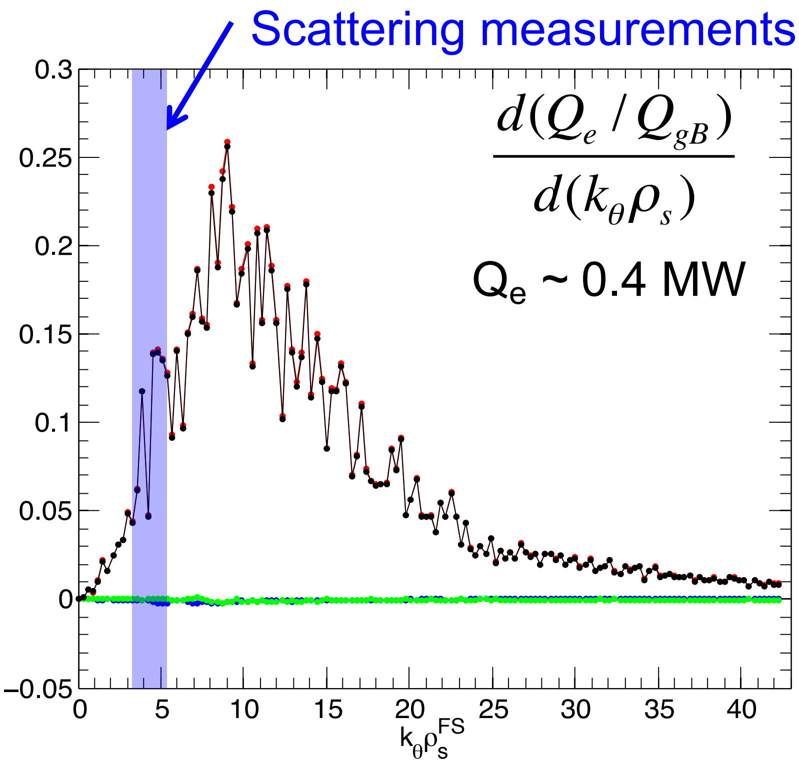
Steps:

Compute forward derivatives

Compute inverse derivatives

Complete (k_R,k_Z) mapping

Resolving $(k_R,k_Z)^{exp}$ + Complete ETG Spectrum Requires a Big-Simulation-Domain e- Scale Simulation



Resolution parameters

	Standard e-scale	Big-box e-scale
L_r [ρ_s]	6	21
L_y [ρ_s]	6	21
Δr [ρ_e]	~ 2	2.5
n_r (radial grid)	~ 200	512
$\Delta k_\theta \rho_s$	1-1.5	0.3
$k_\theta \rho_s^{max}$	40-50	43
n (tor. modes)	~50	142

$k_\theta \rho_s$ here means $k_\theta \rho_s^{FS}$

- Spectra show well resolved $(k_R,k_Z)^{exp}$ and ETG spectrum.
- Experimental wavenumbers produce non-negligible δn_e and Q_e consistent with previous e- scale simulation results (Q_e ~ 0.4 MW).

Conclusions and Future Work on Synthetic Diagnostic

- Implement instrumental selectivity function and wavenumber filtering.

- **Goal**: a direct, quantitative comparison between experiment-GYRO simulation of e- scale turbulence.
  - Compare fluctuation spectrum high-k diagnostic/synthetic high-k.
  - Study energy transfer between different k's (different channels).

- Project operating space of new high-k diagnostic.
  - Are streamers predicted to be detected with the new high-k system?

- Study turbulence characteristics in high-resolution e- scale run → towards multiscale simulation in NSTX-U.
  - High-resolution electron scale runs presented here are NOT multiscale
    - Ions are not resolved correctly $\Delta k_\theta \rho_s$~0.3, L_r x L_y = 21 x 21 ρ_s.
    - Simulation ran only for electron time scales (~20a/c_s), ions are not fully developped.
  - In future, can apply synthetic high-k to multiscale simulation in NSTX-U.

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Title here

- Column 1

- Column 2

Intro

- First level
  - Second level
    - Third level
      - You really shouldn't use this level – the font is probably too small

Here are the official NSTX-U icons / logos

NSTX Upgrade

NSTX Upgrade

NSTX-U

NSTX-U

National Spherical Torus
eXperiment Upgrade

National Spherical Torus eXperiment Upgrade

Instructions for editing bottom text banner

- Go to View, Slide Master, then select top-most slide
  - Edit the text box (meeting, title, author, date) at the bottom of the page
    - Then close Master View