U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Electron Scale Turbulence and Transport in an NSTX H-mode Plasma Using a Synthetic Diagnostic for High-k Scattering Measurements

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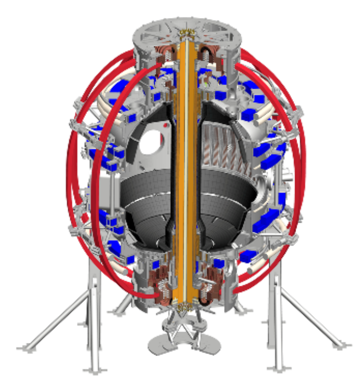
Alcator C-Mod

PPPL



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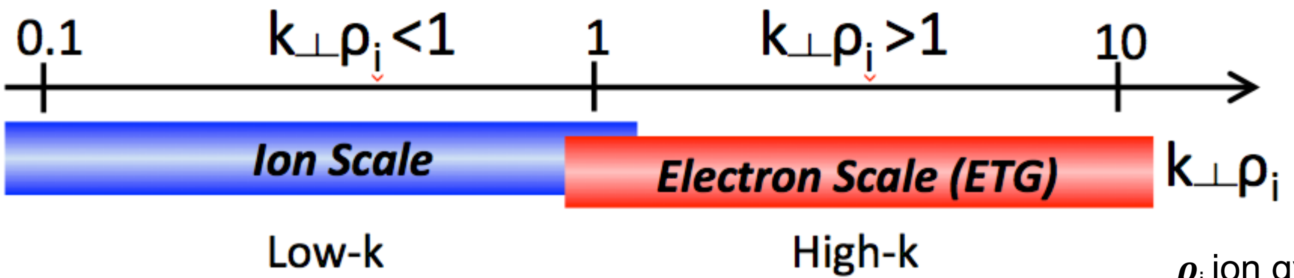
Electron Scale Turbulence and Anomalous Electron Thermal Transport in STs

- 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 and strong plasma shaping*** [*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.



ρ_i ion gyro radius

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

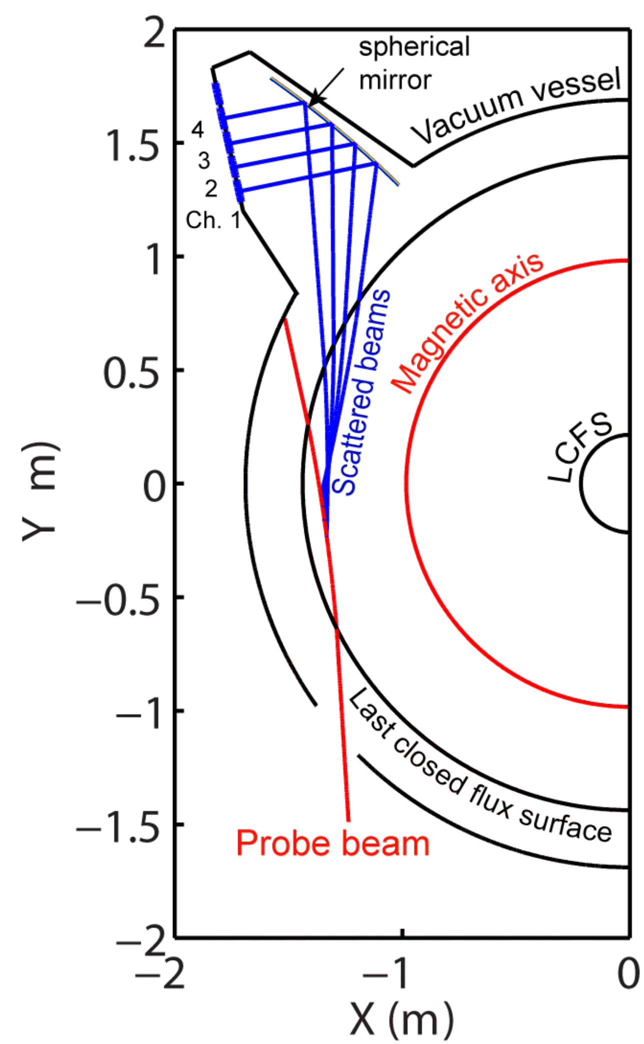
- Scattered power density $P_s \propto \left(\frac{\delta n}{n}\right)^2$

- ***Three wave-coupling*** between incident beam $(\mathbf{k_i}, \boldsymbol{\omega_i})$ and plasma $(\mathbf{k}, \boldsymbol{\omega})$

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

- Details of high-k scattering diagnostic at NSTX

Gaussian microwave probe beam:
15 mW, 280 GHz, $\lambda_i \sim 1.07$ mm, a = 3 cm ($1/e^2$ radius).



View from top of NSTX

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

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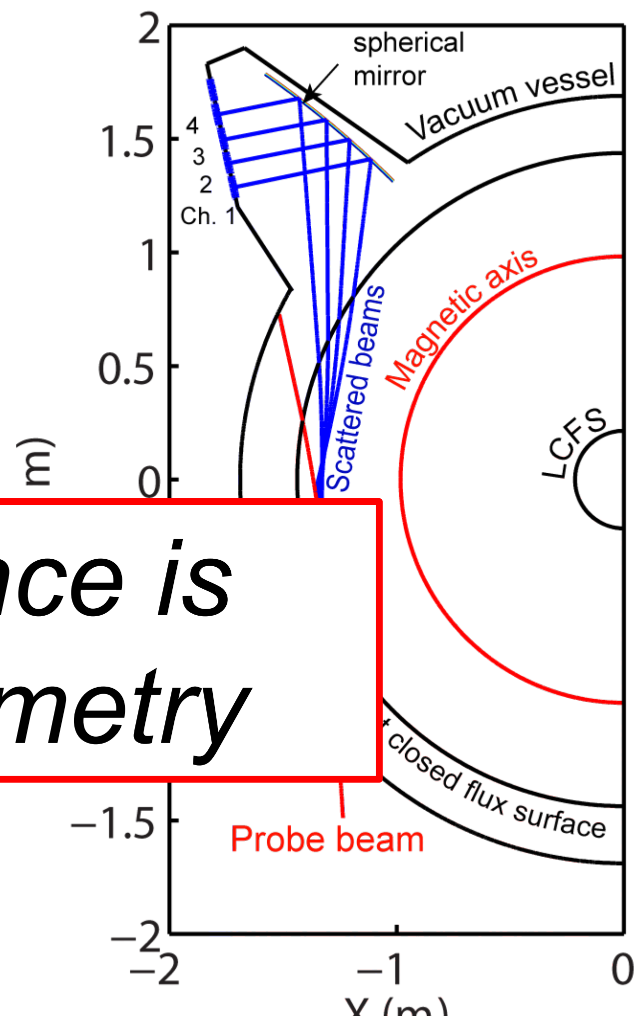
- High-k S

Gaussian m
15 mW, 280
radius).

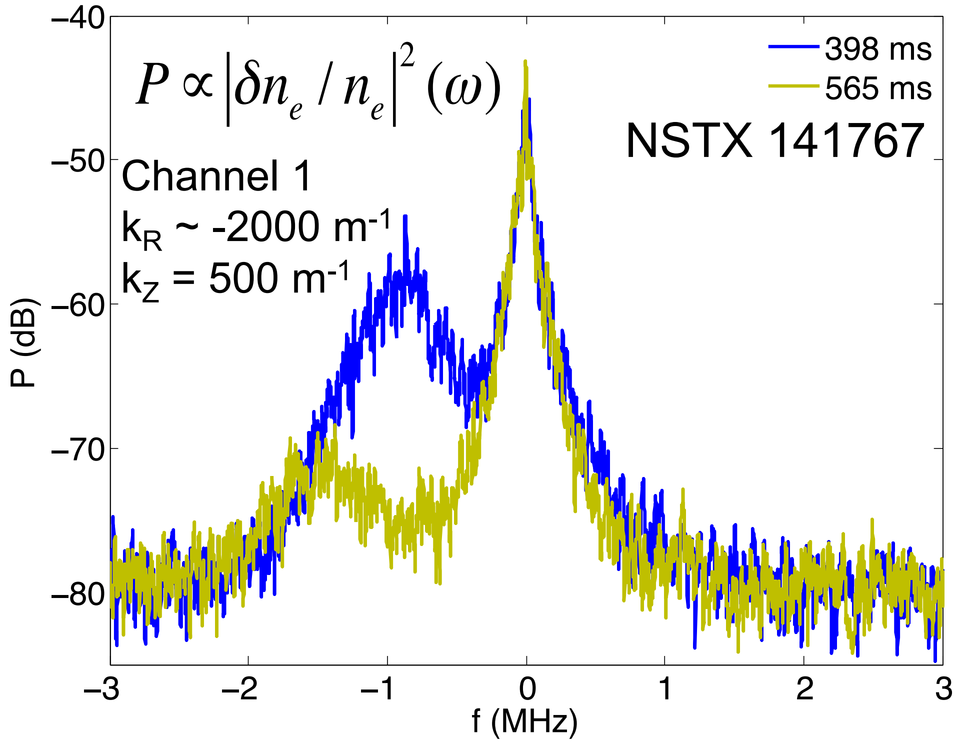
k of the turbulence is selected by geometry



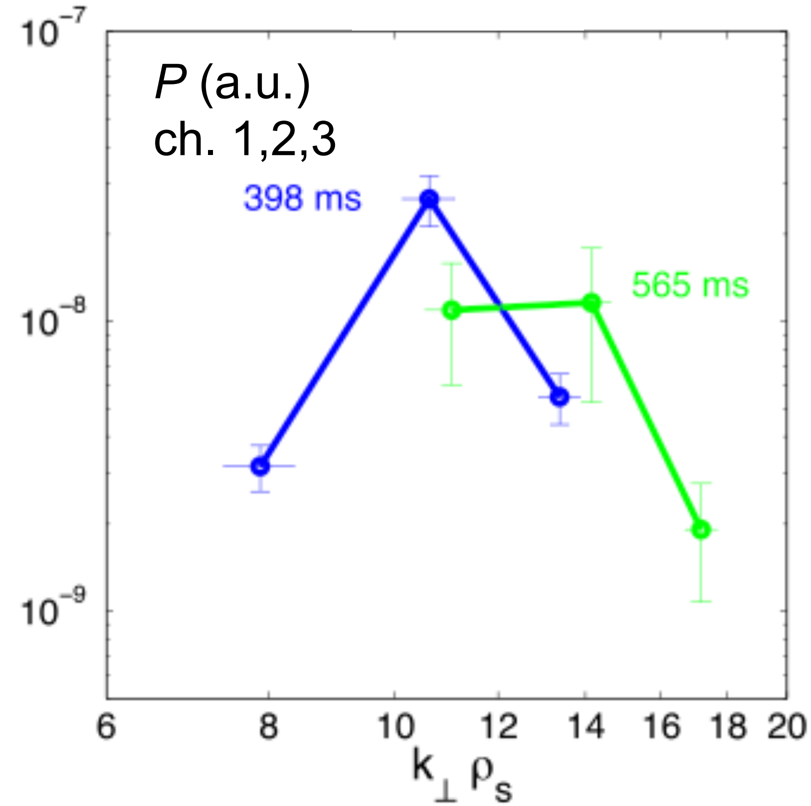
View from top of NSTX

High-k Scattering Diagnostic Provides the Frequency and Wavenumber Spectrum of Electron Scale Turbulence

Frequency Spectrum of density fluctuations



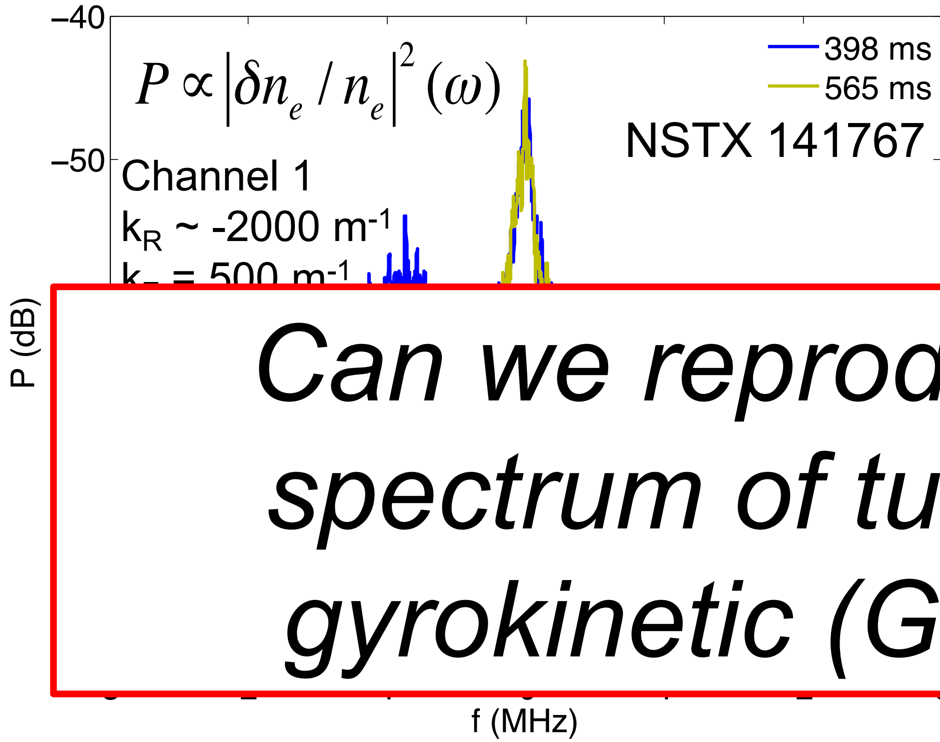
k-spectrum of density fluctuations



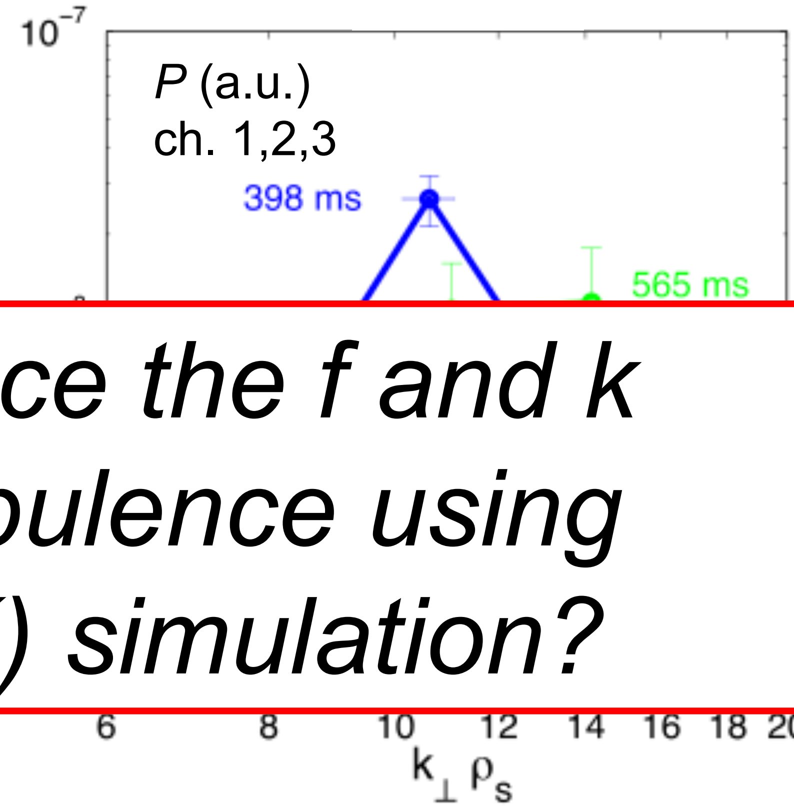
- Frequency analysis of scattered power → **frequency spectrum**.
- Different channels → different k → **wavenumber spectrum** of turbulence

High-k Scattering Diagnostic Provides the Frequency and Wavenumber Spectrum of Electron Scale Turbulence

Frequency Spectrum of density fluctuations



k-spectrum of density fluctuations



Can we reproduce the f and k spectrum of turbulence using gyrokinetic (GK) simulation?

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

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.

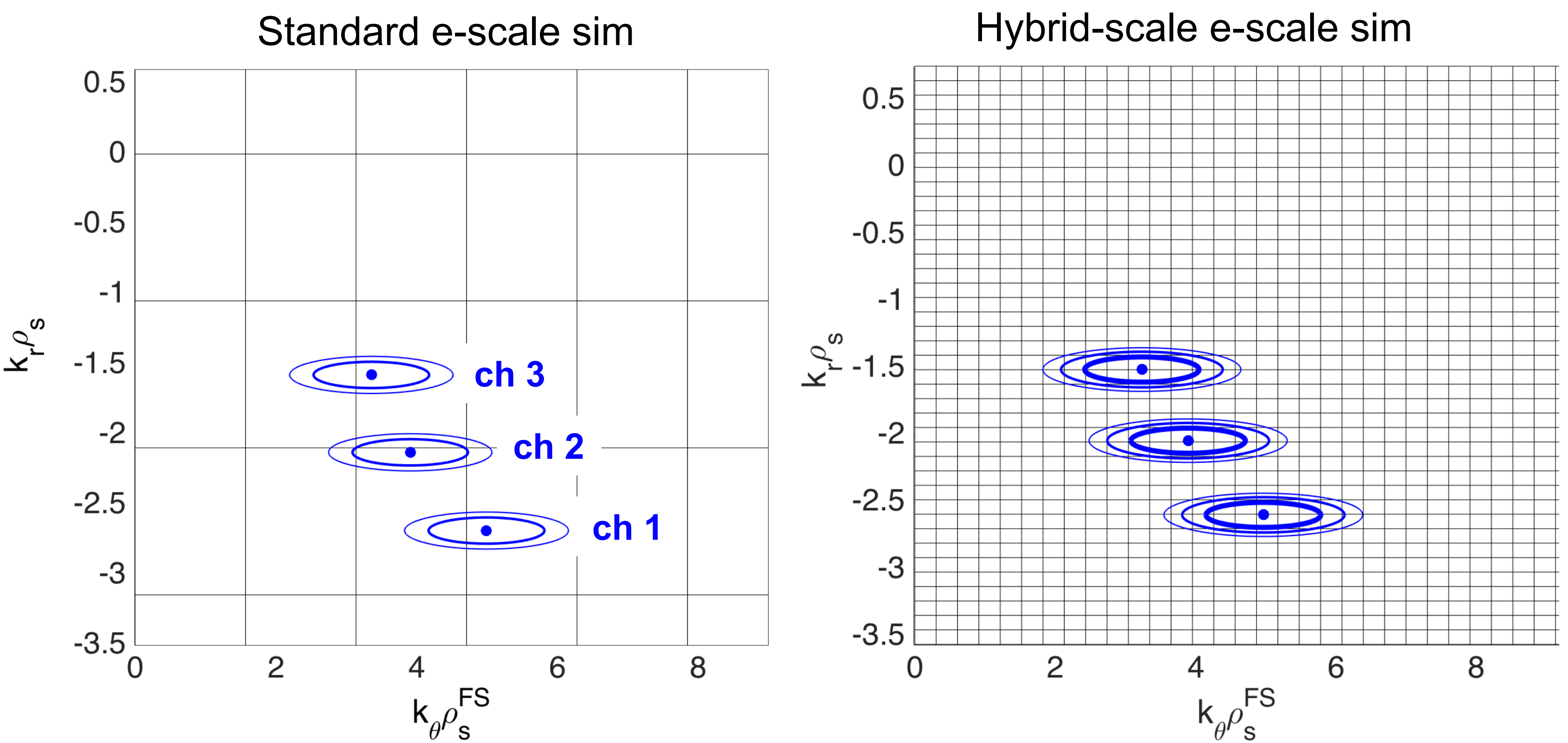
Previous Work on Synthetic High-k Diagnostic on NSTX

- 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.

My Goal

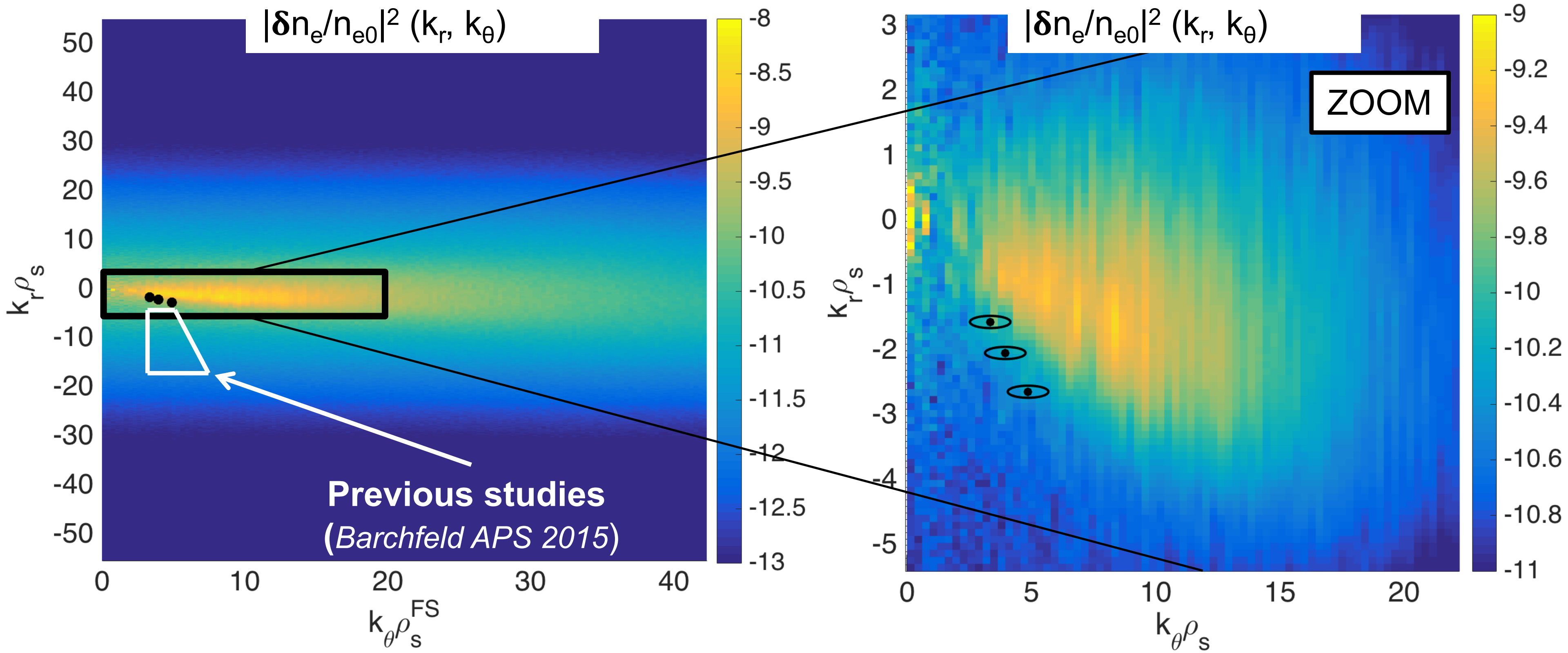
Develop a synthetic diagnostic for quantitative comparisons using the GK code GYRO

GYRO simulation needs to Resolve $(k_R, k_Z)^{exp}$ Hybrid scale simulation



- Experimental k + 1/e filter amplitude mapped to GYRO (k_r, k_θ)-grid.
- Standard e- scale simulation does not accurately resolve experimental k.

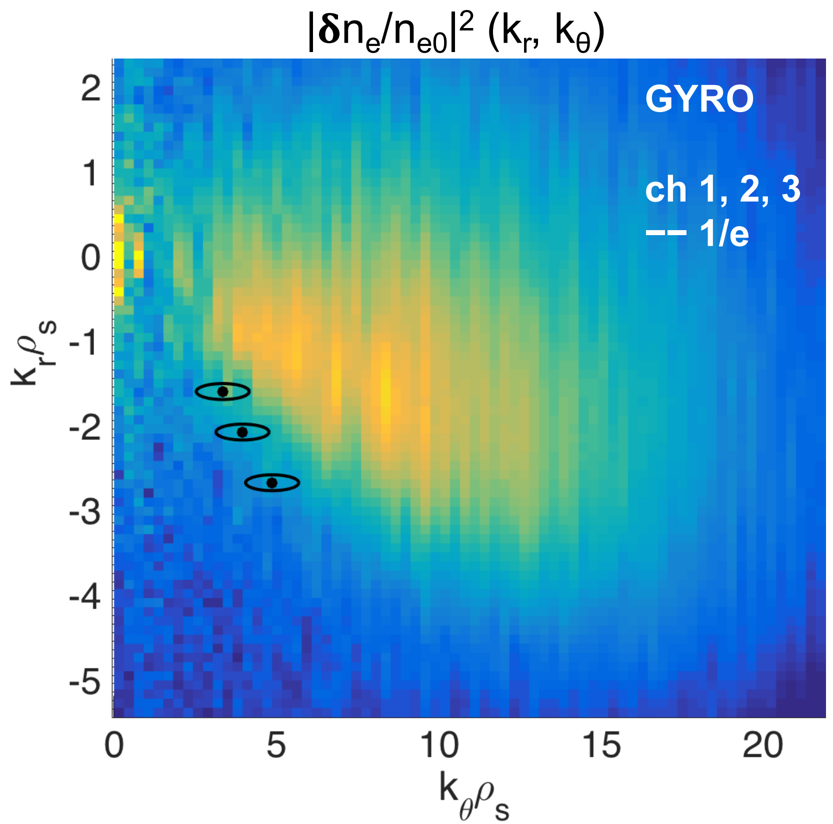
New k-Mapping Shows Experimental k are Closer to the Spectral Peak than Previously Thought



New k-Mapping for GYRO: $(k_R,k_Z)^{cylindrical} \rightarrow (k_r, k_{\boldsymbol{\theta}})^{GYRO}$

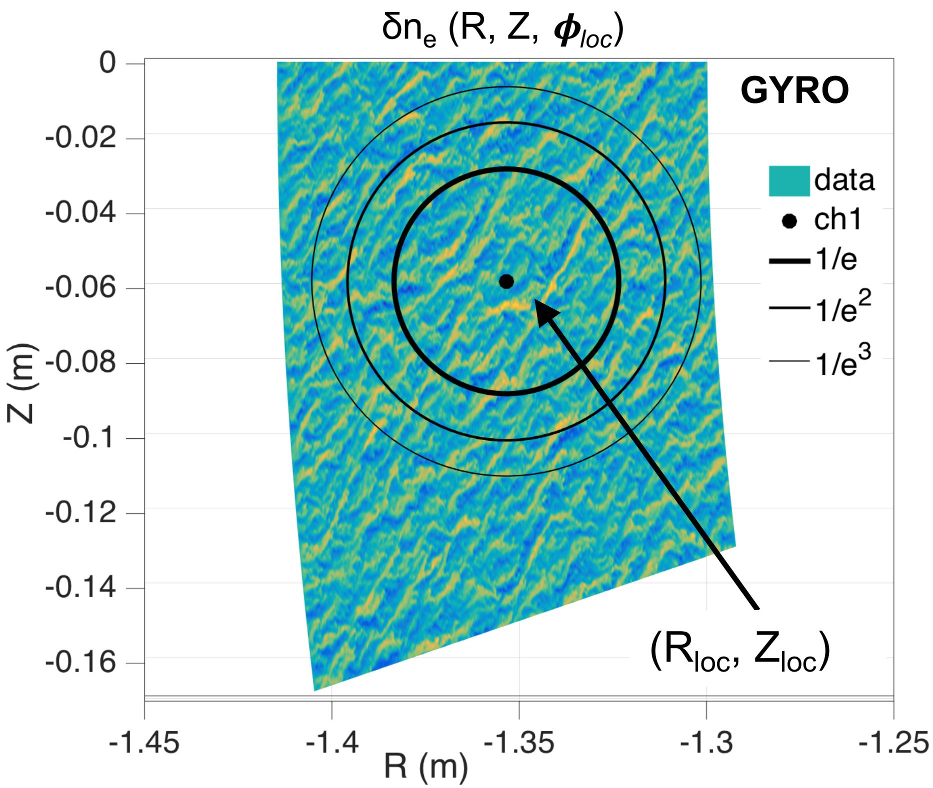
Two Equivalent Ways to Perform a Synthetic Diagnostic for Turbulence Scattering Measurements

Filter fluctuations in k-space



Scattering system is *wavenumber* selective (k_r, k_θ, k_φ)

Filter fluctuations in real space



Scattering system is *spatially* localized (R, Z, φ)

Numerical Resolution Details of GK Simulations Needed for Synthetic Diagnostic of High-k Scattering

Experimental profiles used as input

Local 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~0.13-0.16 c_s/a) + parallel flow shear (γ_p ~ 1-1.2 c_s/a)
- Fixed boundary conditions with Δ^b ~ 2 ρ_s buffer widths (e- scale).

Resolution parameters (hybrid-scale)

- $L_r \times L_y = 50 \times 21\ \rho_s$ (L/a~0.2).
- $n_r \times n$ = 900/1024 x 140/220.
- $k_\theta\rho_s^{FS}$ [min, max] = [0.3, 42/80]
- $k_r\rho_s$ [min, max] = [0.1, 27]
- $[n_{||}, n_\lambda, n_e]$ = [14, 8, 8]

Simulation cost ~ 1 M CPU h

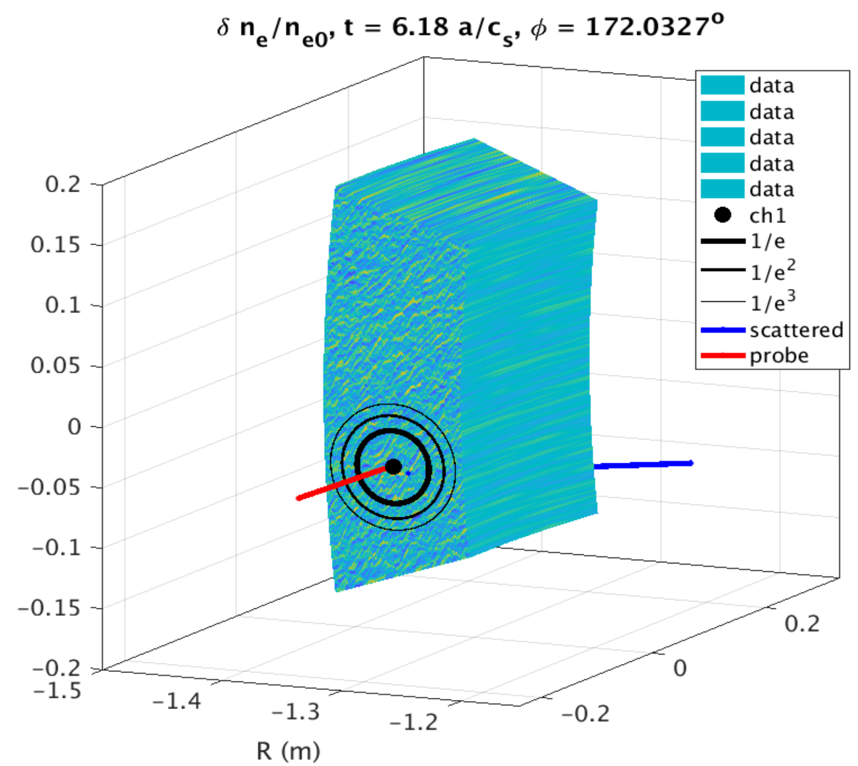
These electron scale runs are ***hybrid-scale***, NOT fully multiscale:

- Ions not correctly resolved $\Delta k_\theta\rho_s$~0.3, $\Delta k_r\rho_s$~0.1.
- Simulation ran only for electron time scales (~20 a/c_s), ions are not fully developed.

Next Steps and Conclusions

Next steps

- Apply synthetic diag. to GYRO output (coming soon!)
- Ion-scale route to synthetic diag.
- 3D synthetic diagnostic

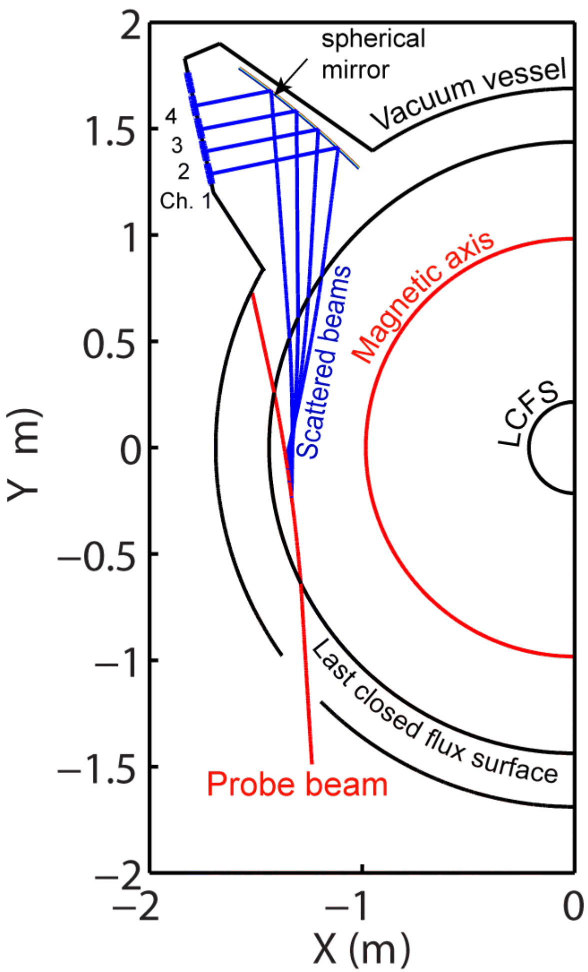


Conclusions

- ***New k-mapping:*** experimental k is closer to spectral peak than previously thought
- Two syn. diagnostic methods (***k-space + real space***) are proposed for quantitative comparison with experimental density fluctuations from high-k scattering
- Computationally intensive ***hybrid-scale*** GK simulations are needed to capture experimental k + full ETG spectrum

Questions
&
Discussion

Details of the High-k Microwave Scattering Diagnostic System at NSTX



View from top of NSTX

(D.R. Smith PhD thesis 2009)

High-k Scattering System

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

High-k scattering is a unique diagnostic in the world that detects small e- scale turbulence.

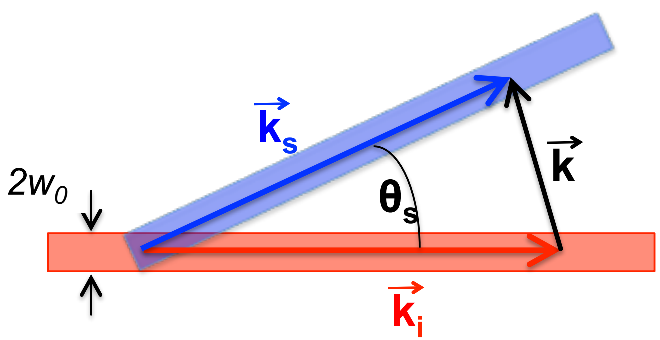
Use a High-k Scattering Diagnostic to Probe Electron Scale Turbulence in NSTX and NSTX-U

- 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**)

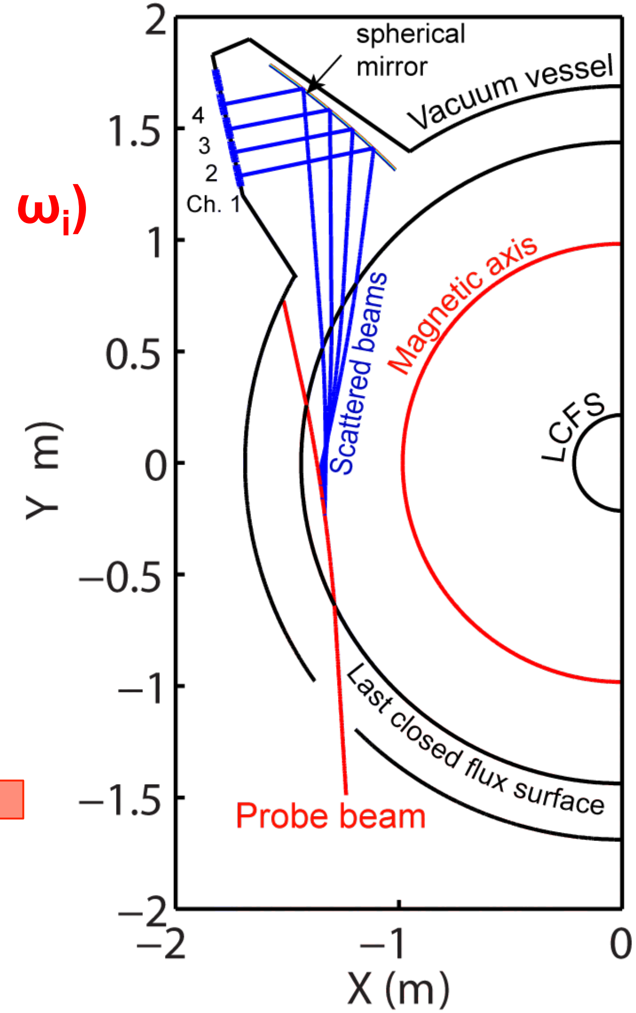
$$\vec{k}_s = \vec{k} + \vec{k}_i \qquad \omega_s = \omega + \omega_i$$

- ω_{i} , ω_s >> **ω** imposes Bragg condition

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

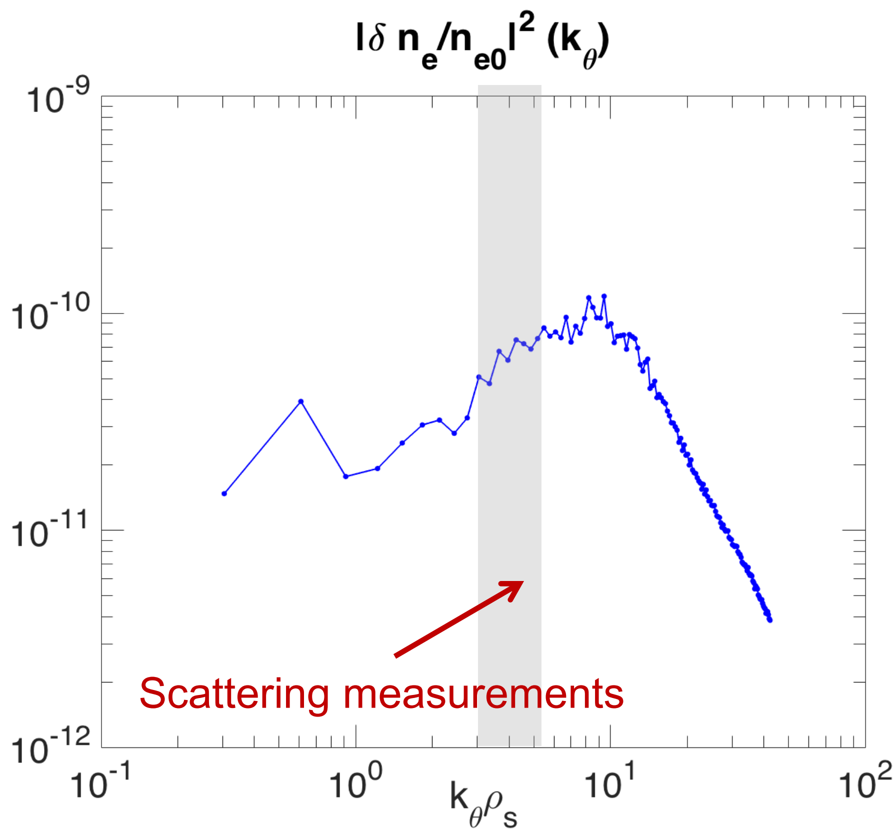


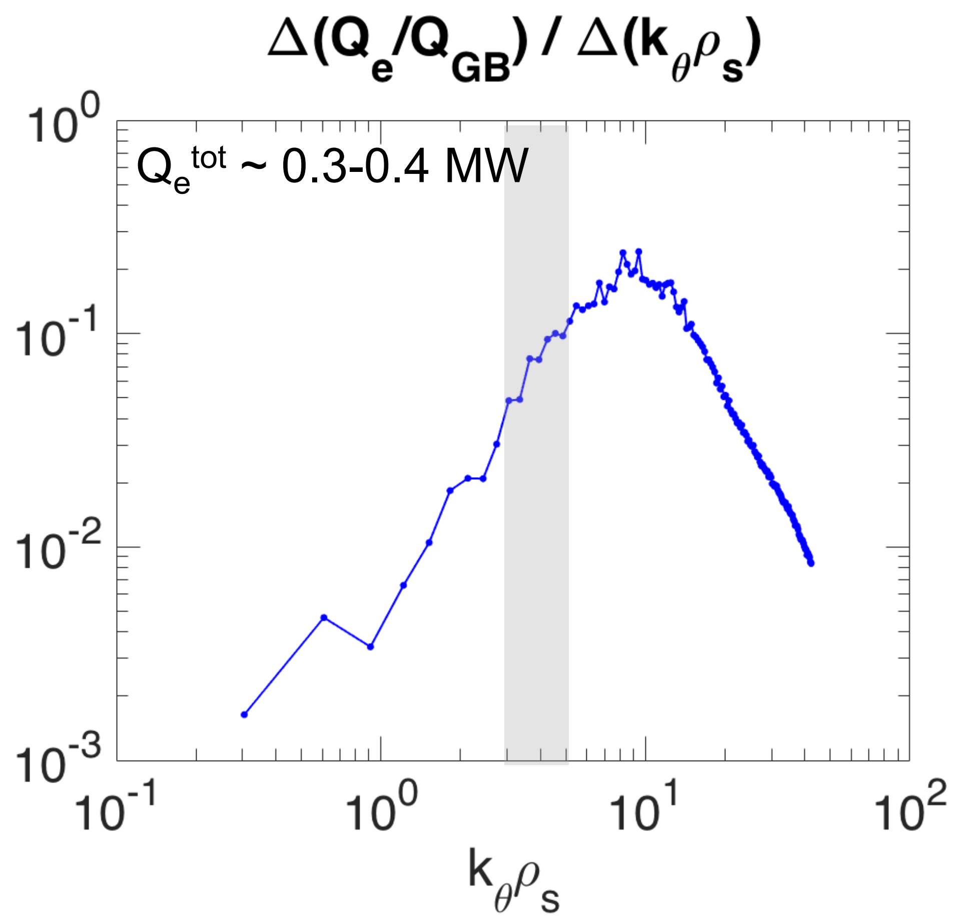
k of the turbulence is selected by geometry.



View from top of NSTX

Experimental Wavenumbers Produce non-negligible transport



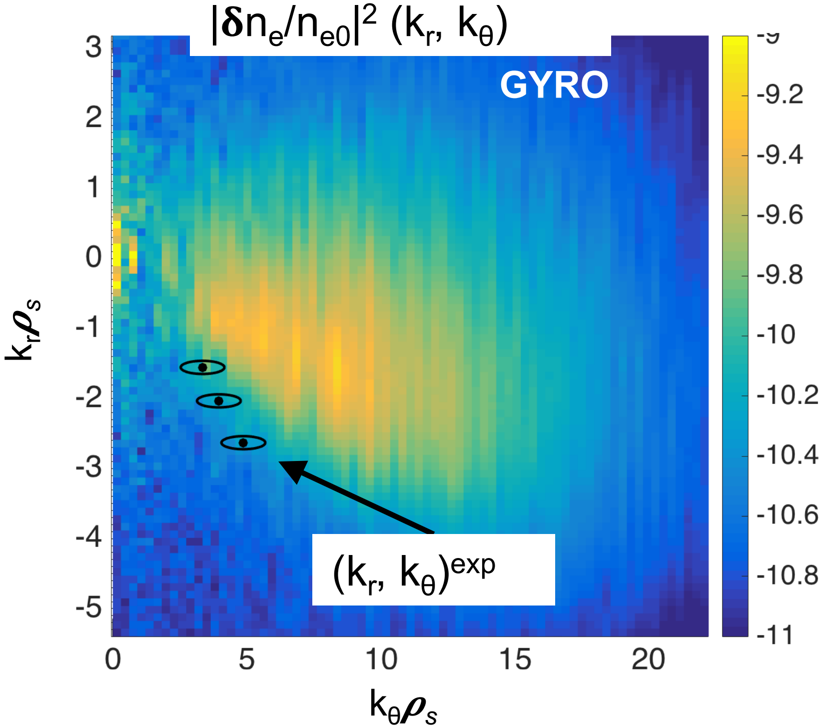


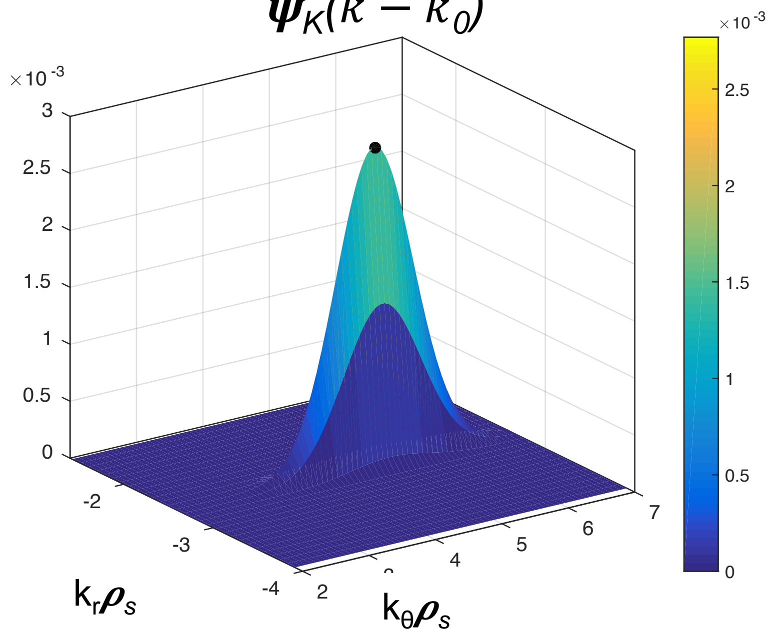
- Scattering measurements close to density and Q_e spectral peak.
- Q_e is consistent with previous standard e- scale simulation results (Q_e~0.4 MW)

Traditional Implementation: filtering in k-space

A scattering system is ***wavenumber*** selective $(k_r, k_\theta, k_\varphi)^{exp}$

Analyze turbulence in k-space **+** *Filter turbulence in k-space*





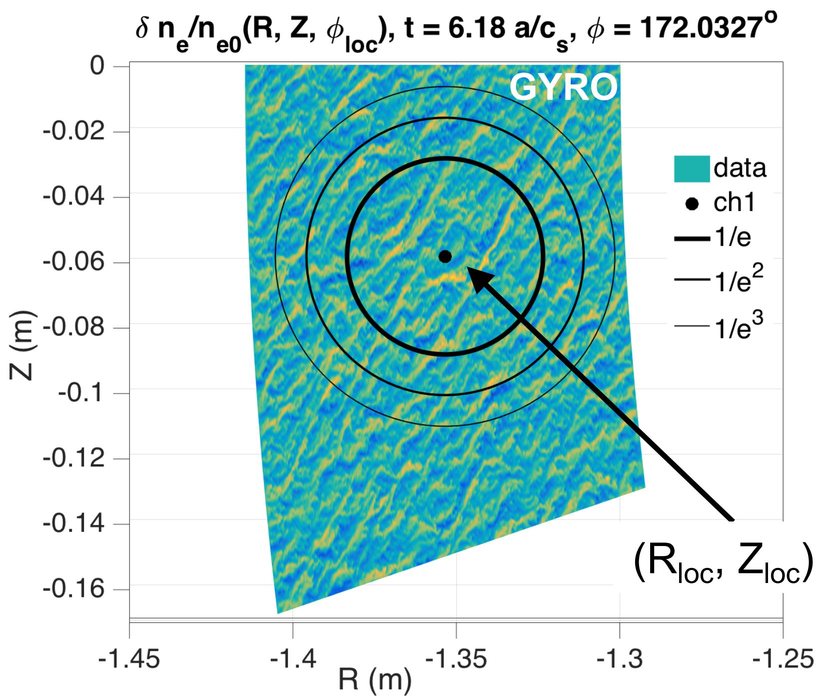
$$\delta\hat{n}_e^{syn}(t) = \frac{1}{(2\pi)^3}\int \tilde{n}_e(\vec{k},t)\boldsymbol{\psi}_K(\vec{k}-\vec{k}_0)\, d^3\vec{\boldsymbol{k}}$$

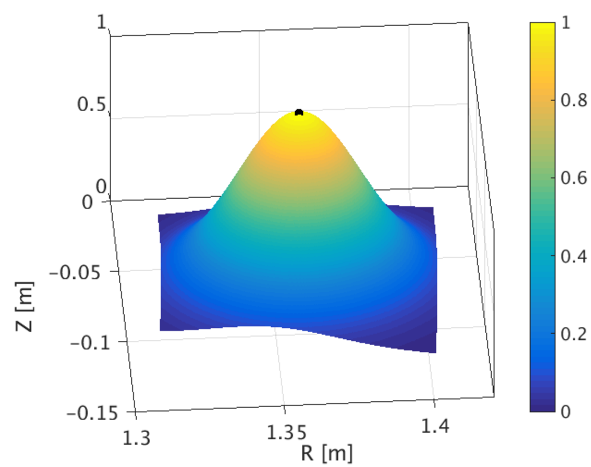
Obtain a time series of turbulent density fluctuations $\boldsymbol{\delta\hat{n}_e^{syn}(t)}$

New Proposed Implementation: filtering in real space

Scattering system is ***spatially*** localized $(R, Z, \boldsymbol{\varphi})_{loc}$

Analyze turbulence in real space **+** *Filter turbulence in real space* $\boldsymbol{\psi}_{R}(\vec{r})$





$$\delta\hat{n}_e^{syn}(t) = \int \tilde{n}_e(\vec{r},t)\boldsymbol{\psi}_{R}(\vec{r})e^{-\imath\vec{k}_0\cdot\vec{r}}d^3\vec{\boldsymbol{r}}$$

Obtain a time series of turbulent density fluctuations $\boldsymbol{\delta\hat{n}_e^{syn}(t)}$

Discussion of r & k filtering methods

***k*-space mapping - Selection of k**

- Traditional way to interpret filtered scattering spectra.
- Delicate to compute, take into account correct wavenumber amplitudes.
- Code-dependent.
- Need to adequately complete k-mapping → painful, but useful!

$(k_R, k_Z, k_\varphi) \rightarrow (k_r, k_\theta, k_\varphi)$

New: Real space filtering

- Common principle to all codes.
- Easier to implement and understand (no k-mapping).
- Need to resolve fine-scale structures (e- scale eddies) → much more computationally intensive (x5) but negligible wrt. turbulence simulations.

Two equivalent ways of interpreting scattering process
Useful to compute both methods to gain confidence in simulated synthetic spectra.

Synthetic Diagnostic is an a posteriori analysis tool

Implementation of the synthetic diagnostic

Goal: A quantitative comparison between experiment and simulation of electron scale turbulence (e.g. frequency and k-spectrum).

Synthetic Diagnostic for the High-k Scattering System

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.

Synthetic Diagnostic applied to Cyclone Base Case (not experiment! yet …)

Cyclone base case physical parameters:

- 2 kinetic species (DK e-)
- ES
- Periodic BC
- Flat profiles
- S-alpha, non-shifted geometry circular geometry
- Doppler shift M = 0.1

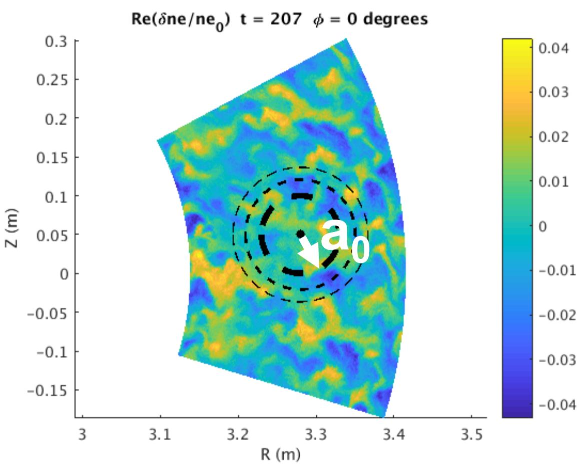
Numerical resolution parameters	
$\Delta k_x \rho_s = 0.049$	$\Delta k_y \rho_s = 0.049$
$k_x \rho_s^{max} = 3.14$	$k_y \rho_s^{max} = 3.093$
$L_x/\rho_s = 128$	$L_y/\rho_s = 128$
dn = 8	Bm = 4.94
$\Delta x/\rho_s = 0.5$	Lx/a = 0.28
$n_x = 256$	$n_n = 64$
Experimental beam width: Δx = 5, 10, 20 cm	
$\Delta k_x \rho_s^{beam}$ =	$\Delta k_y \rho_s^{beam}$ =

Real Space Filters – 2D

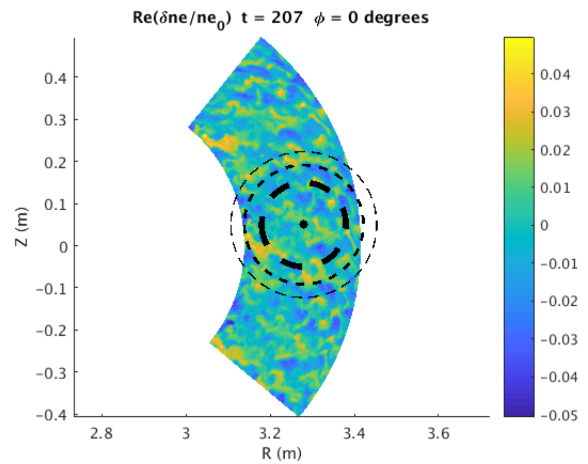
Goal: establish sensitivity of synthetic signal to beam width

To what extent do we need a simulation domain that covers the full microwave beam?

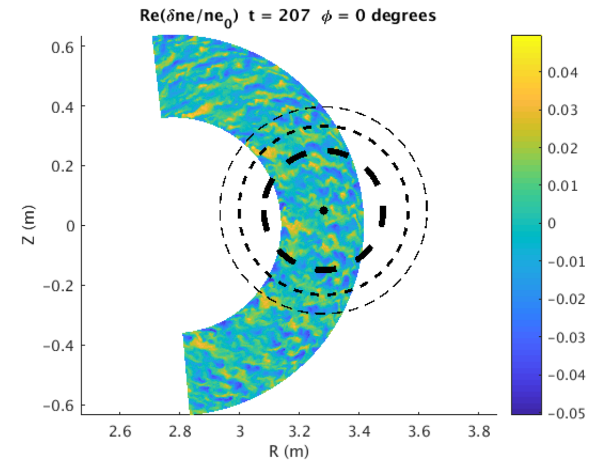
a_0 = 5 cm



a_0 = 10 cm

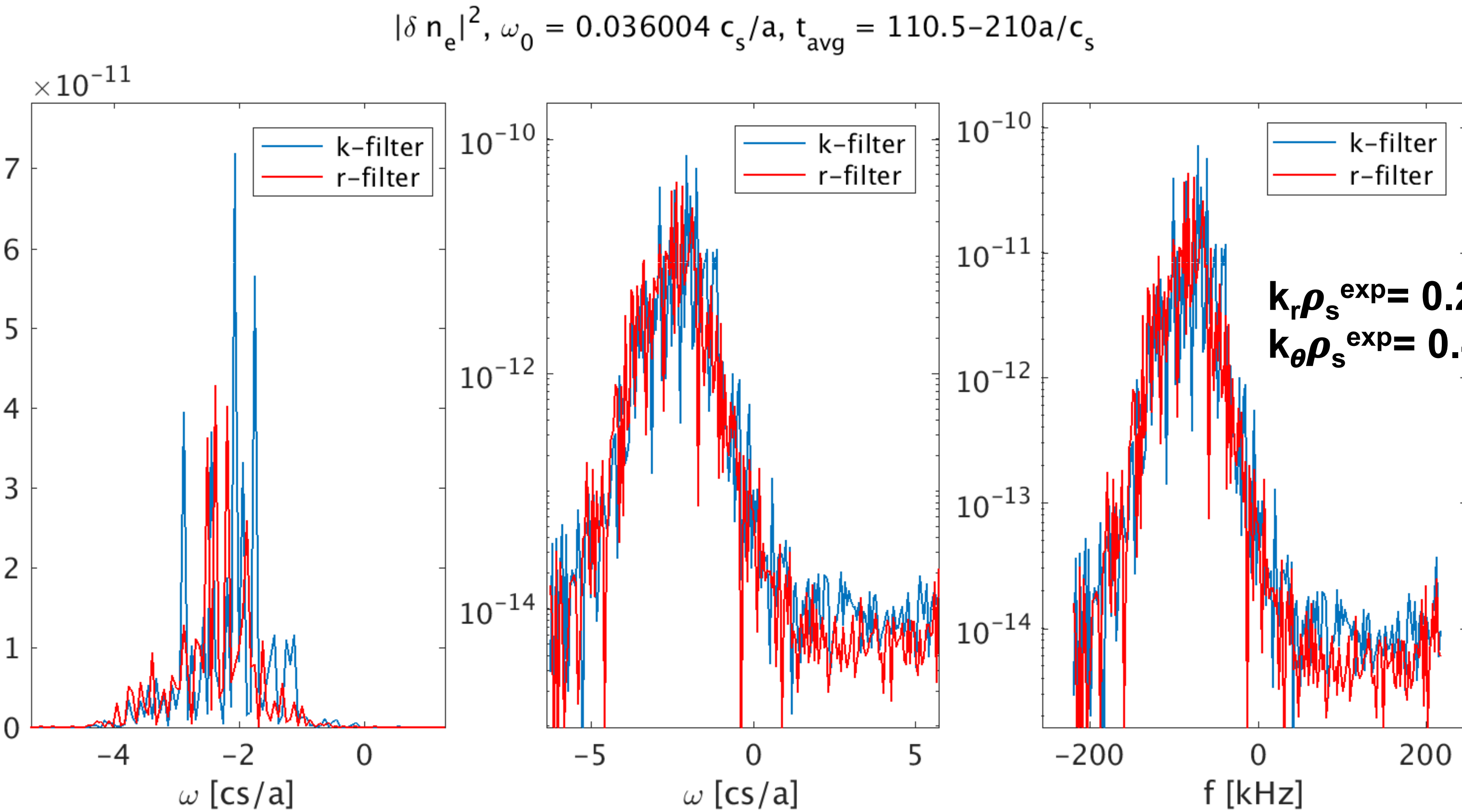


a_0 = 20 cm



a_0 is the beam width

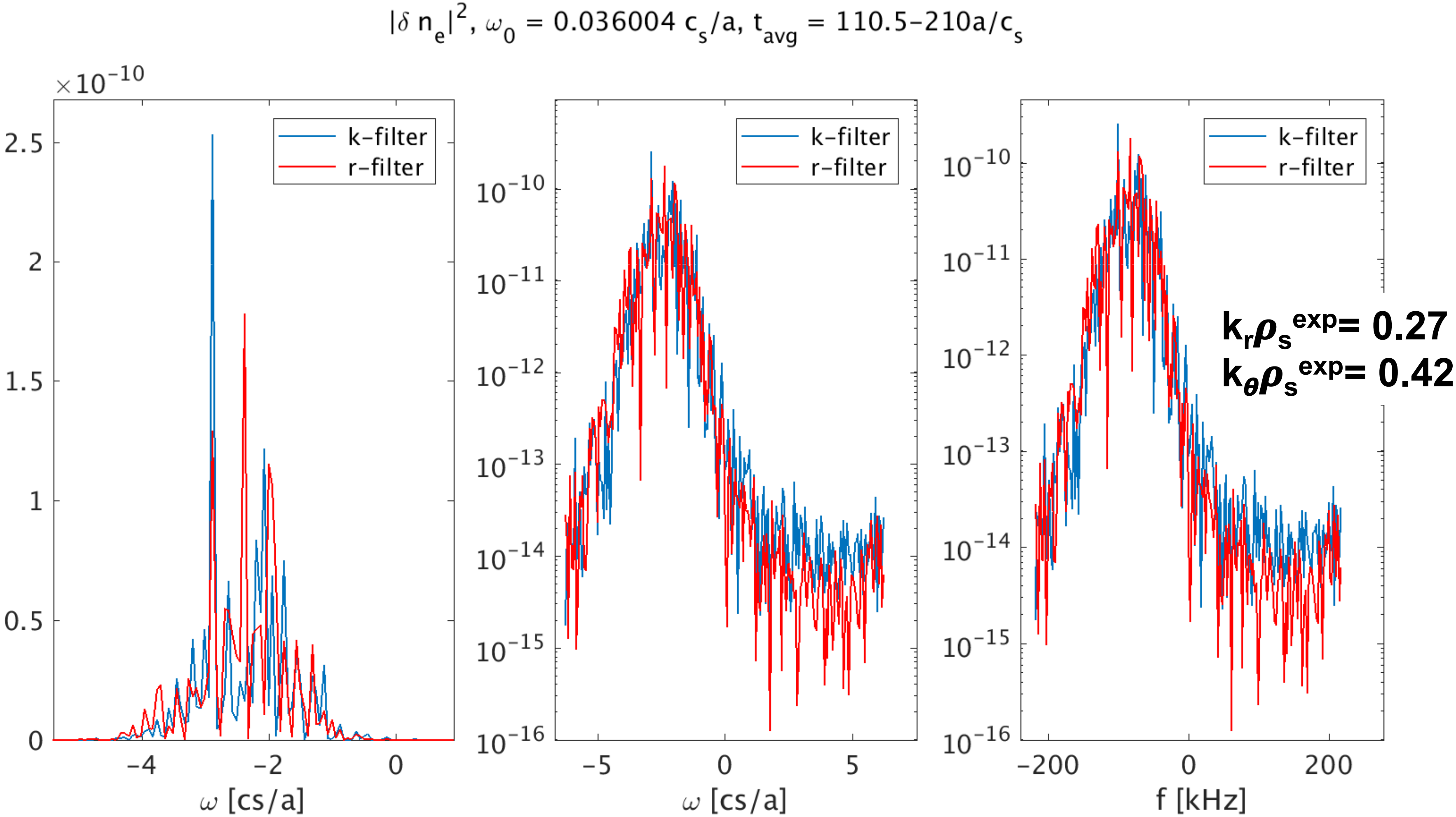
Synthetic signal: a_0 = 5 cm



$k_r\rho_s^{exp}$= 0.27
$k_\theta\rho_s^{exp}$= 0.42

GOOD AGREEMENT BETWEEN R & K FILTERS

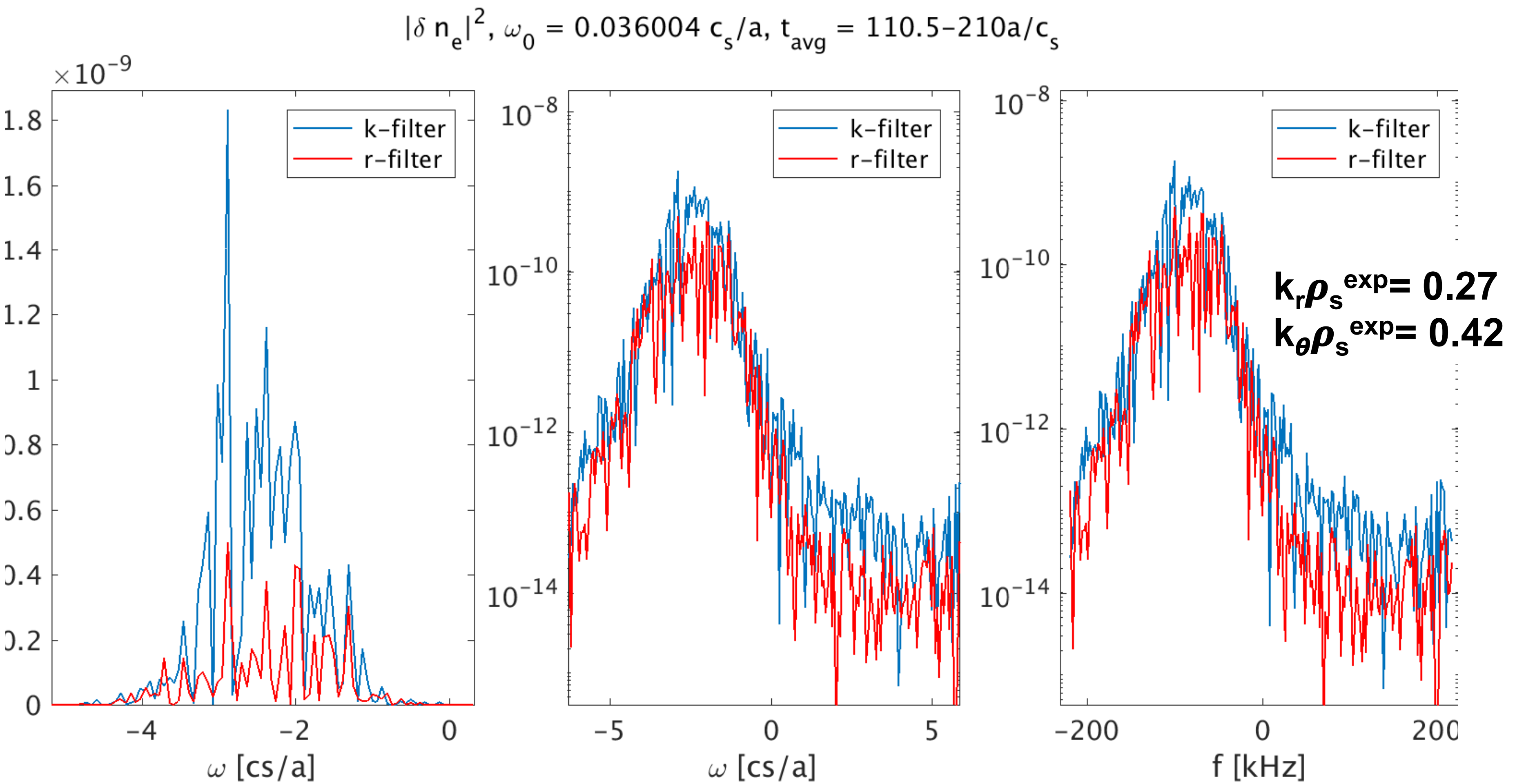
Synthetic signal: a_0 = 10 cm



$k_r\rho_s^{exp}$= 0.27
$k_\theta\rho_s^{exp}$= 0.42

GOOD AGREEMENT BETWEEN R & K FILTERS

Synthetic signal: a_0 = 20 cm



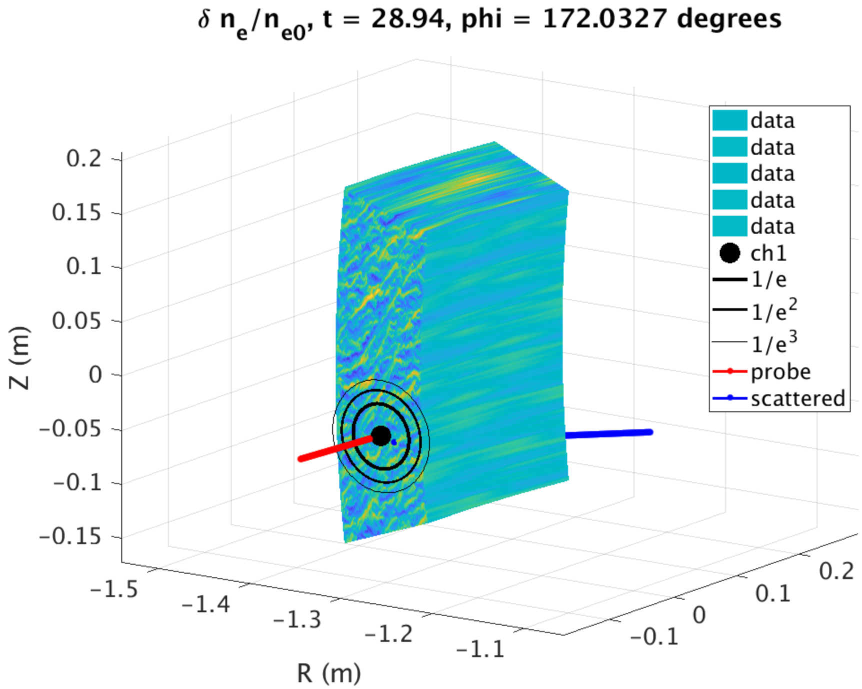
$k_r\rho_s^{exp}$= 0.27
$k_\theta\rho_s^{exp}$= 0.42

FACTOR x2-3 AMPLITUDE DISCREPANCY

Immediate Next Steps

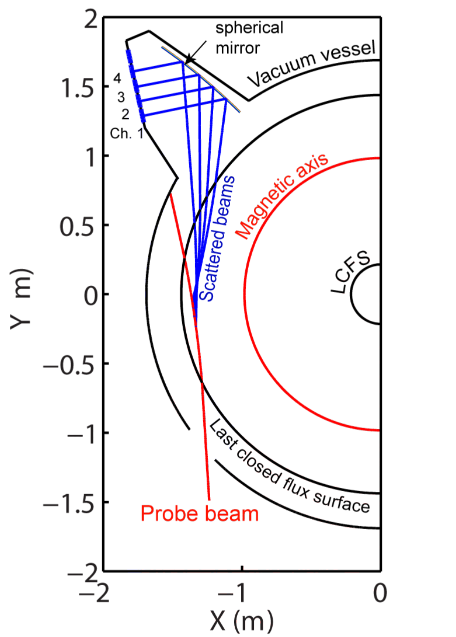
- Apply synthetic diagnostic to realistic NSTX plasma conditions
  - Run expensive GYRO simulations that overlap with scattering beam (~ 2 M CPU h) – **coming in next week**
  - Compare frequency and k-spectrum with experiment

- Implement a 3D synthetic diagnostic for higher fidelity modeling



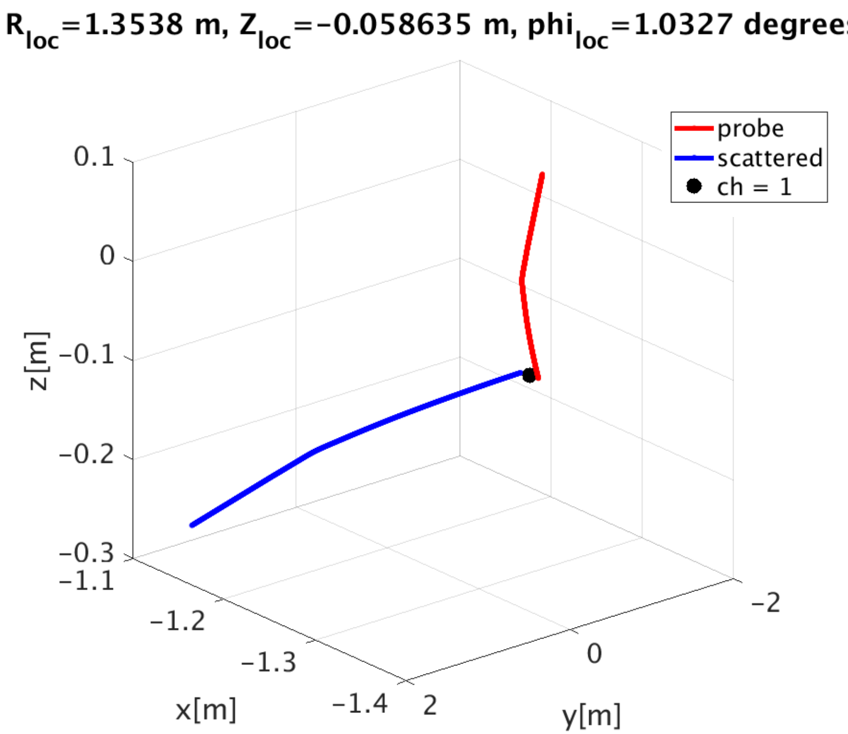
2. Ray Tracing

Solve Ray tracing equations, Appleton-Hartree approximation (propagation of high freq. EM waves in plasma)



View from top of NSTX

(D.R. Smith PhD thesis 2009)

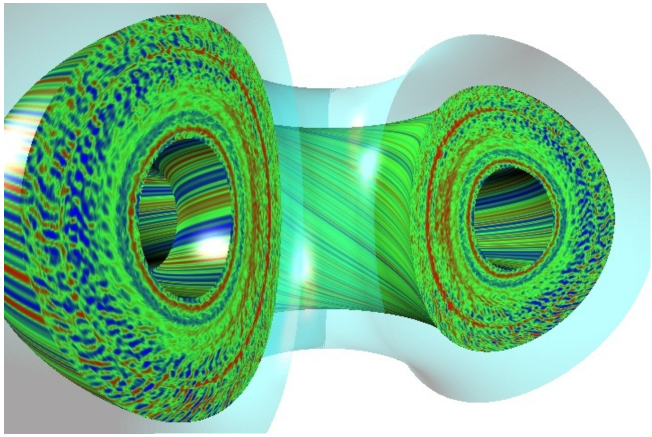


Obtain:

- 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. The GYRO code Numerically solves the Gyrokinetic-Maxwell System

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



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

- **Outputs:** moments and fields
  - Moments of the distribution function $\boldsymbol{h_s}$ — δn_s, δv_s, δE_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.

Numerical Resolution Details of Ion and Electron 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.
- Experimental T_e, n_e, T_i, rotation, etc.
- 3 kinetic species, D, C, e (Z_{eff}~1.85-1.95)
- Electromagnetic: $A_{||}+B_{||}$, $\beta_e \sim 0.3$ %.
- Collisions ($\nu_{ei} \sim 1\ c_s/a$).
- ExB shear (γ_E~0.13-0.16 c_s/a) + parallel flow shear ($\gamma_p \sim$ 1-1.2 c_s/a)
- Fixed boundary conditions with $\Delta^b \sim 2\ \rho_s$ buffer widths (e- scale).

<u>Big-box e- scale</u> resolution parameters (hybrid-scale) ~ 1 M CPU h

- $L_r \times L_y = 50 \times 21\ \rho_s$ (L/a~0.2).
- $n_r \times n = 900/1024 \times 140$.
- $k_\theta \rho_s^{FS}$ [min, max] = [0.3, 42]
- $k_r \rho_s$ [min, max] = [0.3, 28]
- $[n_{||}, n_\lambda, n_e] = [14, 12, 12]$

Large domain electron scale runs are ***hybrid-scale***, NOT multiscale:

- Ions are barely correctly resolved $\Delta k_\theta \rho_s$~0.3, $L_r \times L_y = 50 \times 21\ \rho_s$.
- Simulation ran only for electron time scales (~20a/c_s), ions are not fully developed.

Numerical Resolution Details of the Scale Simulations Presented

Experimental profiles used as input

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.

Standard e- scale resolution parameters

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

Big-box e- scale resolution parameters

- $L_r \times L_y = 50 \times 21\ \rho_s$.
- $n_r \times n$ = 900/1024 x 142.
- $k_\theta\rho_s$[min, max] = [0.3, 42]
- $k_r\rho_s$ [min, max] = [0.3, 28]
- [$n_{||}$, n_λ, n_e] = [10, 8, 8]

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

- Ions are not resolved correctly $\Delta k_\theta\rho_s$~0.3, $L_r \times L_y = 50 \times 21\ \rho_s$.
- Simulation ran only for electron time scales (~20a/c_s), ions are not fully developed.

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

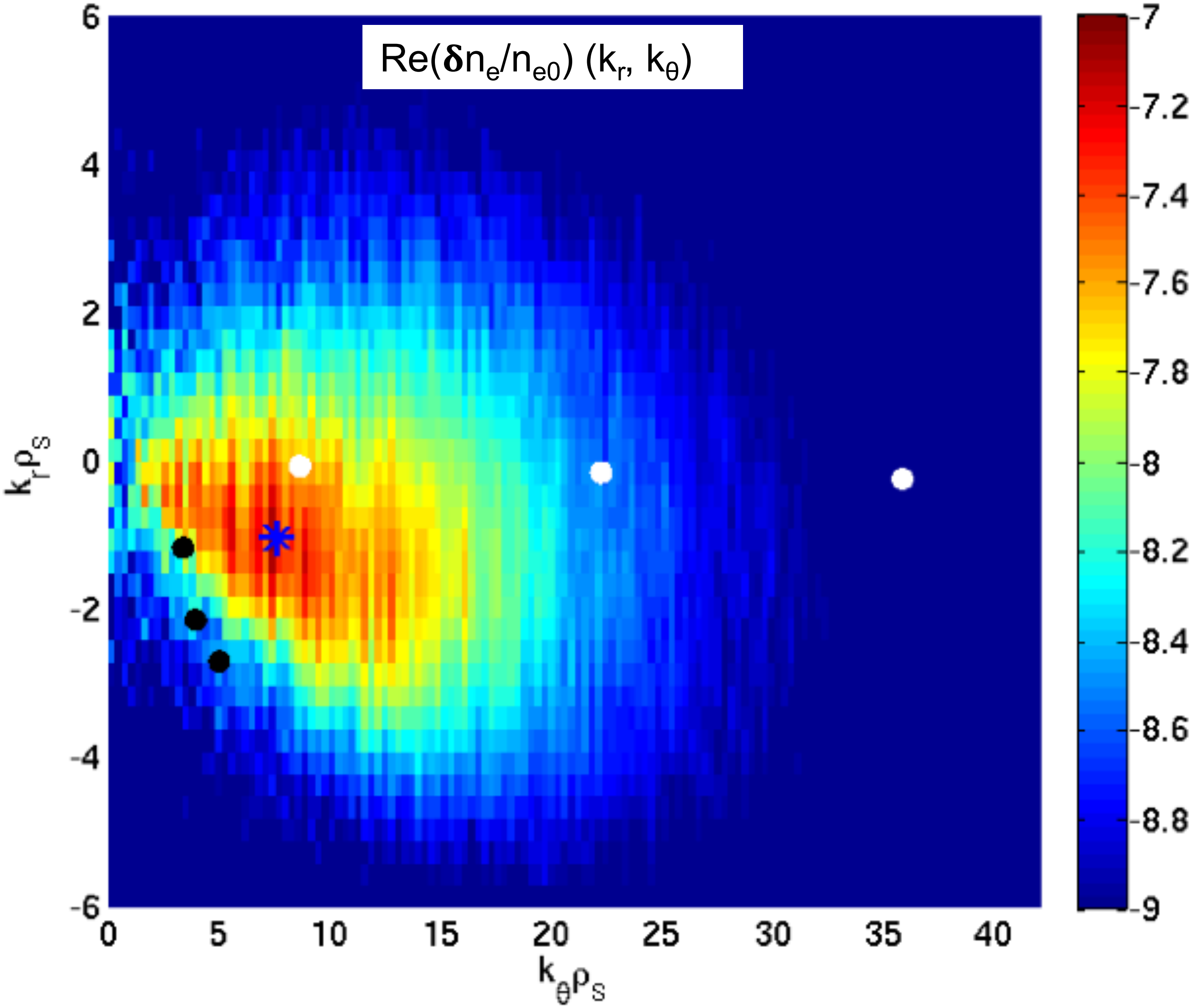
- **My goal**: project the operating space of the new high-k scattering diagnostic using the mapping I implemented.

- **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.

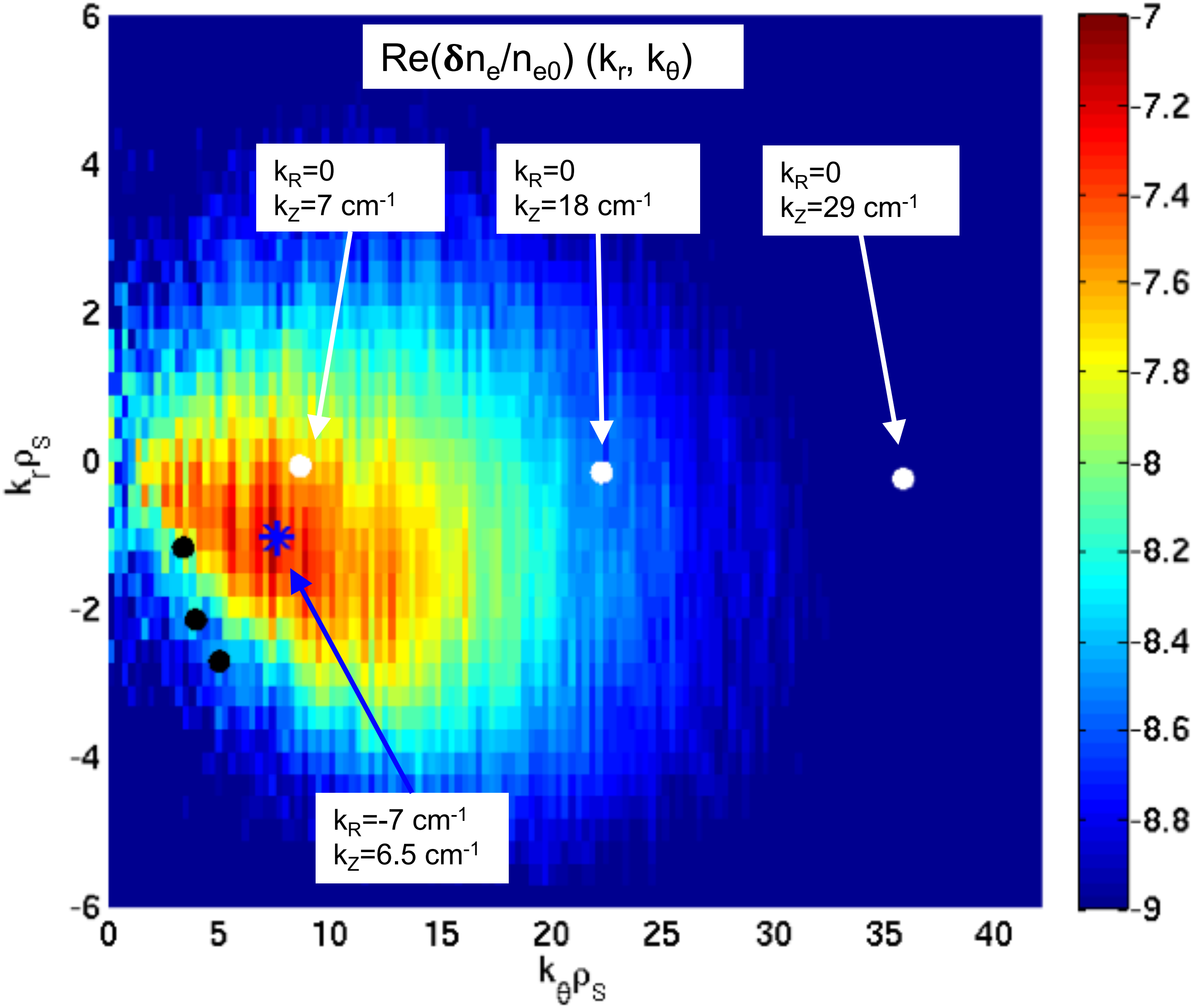
  2. Current plasma conditions (B ~ 0.5 T, T_e ~ 0.4 keV).

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



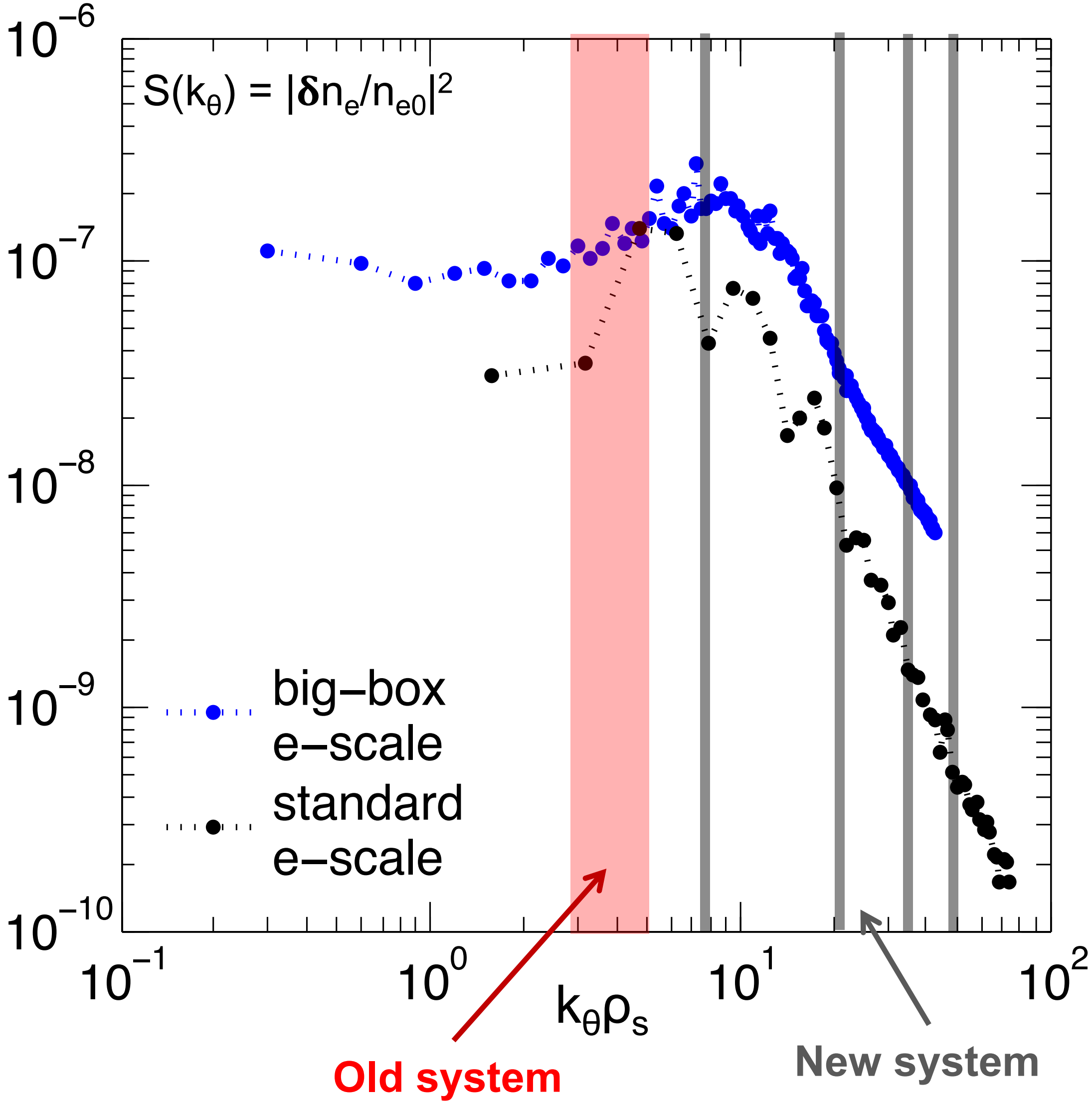
- Black dots: old hk
- White dots: new hk
  Picked k's in predicted measurement range
  k_Z = 7, 18, 29, 40 cm^{-1}
  k_R = 0 cm^{-1}
- Blue star: streamers

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

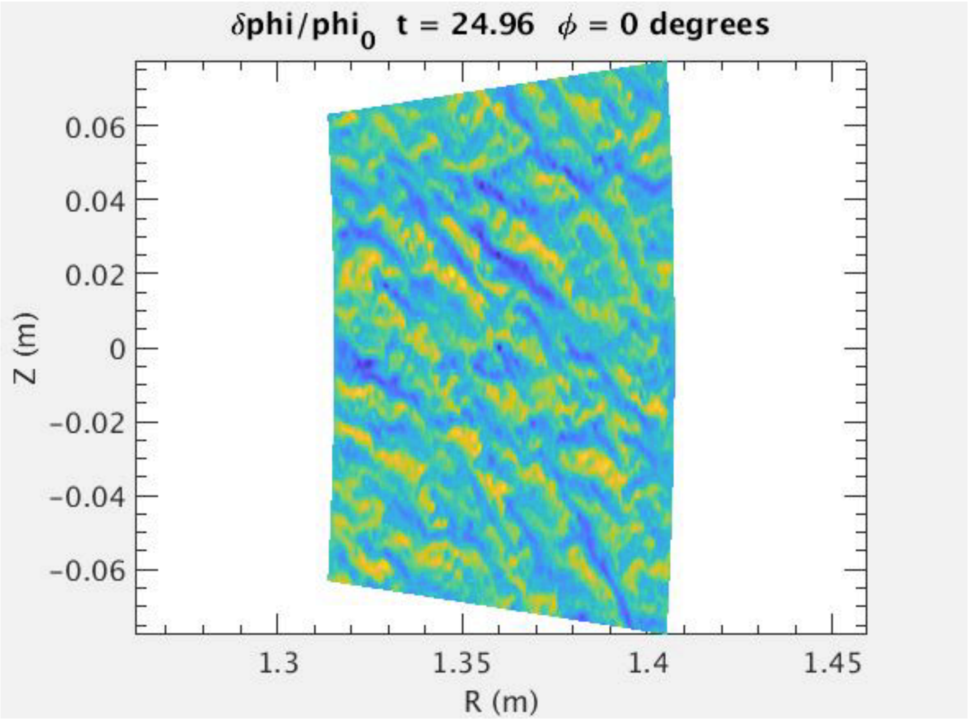


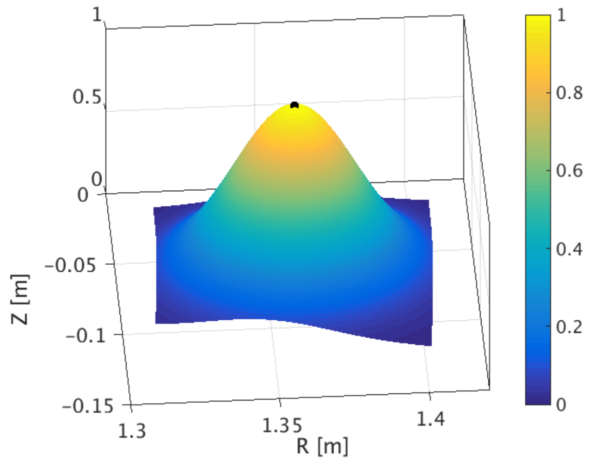
- Spectrum is integrated in k_r.
- Lowest-k channel will be closest to peak of fluctuation spectrum (streamers)
  k_R=0, k_Z=7 cm^{-1}
- Need to resolve very high-k ($k_\theta \rho_s$ ~ 50) to capture highest-k channel.
- **Red band**: measurement range of old system.
- **Gray bands**: measurement range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

New Proposed Implementation: real space filtering

Scattering system is ***spatially*** localized (R, Z, $\boldsymbol{\varphi}$)$_{loc}$

Analyze turbulence in real space **+** *Filter turbulence in real space* $\boldsymbol{\psi}_R(\vec{r})$





$$\delta\hat{n}_e{}^{syn}(t) = \int \tilde{n}_e(\vec{r},t)\boldsymbol{\psi}_R(\vec{r})e^{-i\vec{k}_0\cdot\vec{r}}d^3\vec{\boldsymbol{r}}$$

Obtain a time series of turbulent density fluctuations $\boldsymbol{\delta\hat{n}_e{}^{syn}(t)}$

2. Ray Tracing

Solve Ray tracing equations, Appleton-Hartree approximation (propagation of high freq. EM waves in plasma)

$$||\nabla \boldsymbol{k}|| \ll k^2$$

Cold plasma dispersion tensor **+** Appleton-Hartree dispersion relation (D = det($\boldsymbol{\Lambda}$) = 0)

$$\boldsymbol{\Lambda} = \frac{\omega^2}{c^2}\begin{pmatrix} S - N^2\cos^2\theta & -iD & N^2\sin\theta\cos\theta \\ iD & S - N^2 & 0 \\ N^2\sin\theta\cos\theta & 0 & P - N^2\sin^2\theta \end{pmatrix}$$

$$N^2 = 1 - \frac{X(1-X)}{1 - X - \frac{1}{2}Y^2\sin^2\theta \pm \left[(\frac{1}{2}Y^2\sin^2\theta)^2 + (1-X)^2Y^2\cos^2\theta\right]^{1/2}}$$

Solve the ray-tracing equations, (D = det($\boldsymbol{\Lambda}$) = 0)

$$\frac{d\boldsymbol{r}}{d\tau} = \left.\frac{\partial \mathcal{D}}{\partial \boldsymbol{k}}\right|_{\mathcal{D}=0},$$

$$\frac{d\boldsymbol{k}}{d\tau} = -\left.\frac{\partial \mathcal{D}}{\partial \boldsymbol{r}}\right|_{\mathcal{D}=0}$$

Obtain:

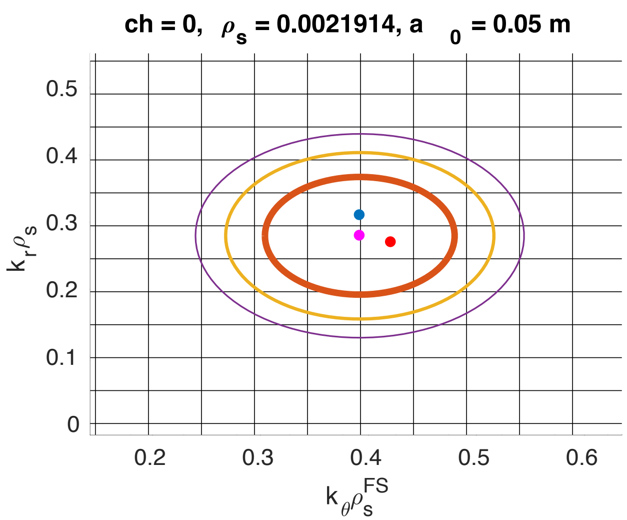
- Scattering location + resolution — $(R_{loc}, Z_{loc}) + (\Delta R_{loc}, \Delta Z_{loc})$
- Turbulence wavenumber + resolution — $(k_R^{exp}, k_Z^{exp}) + (\Delta k_R^{exp}, \Delta k_Z^{exp})$

Cyclone Base Case: Wavenumber Space Filters – 2D

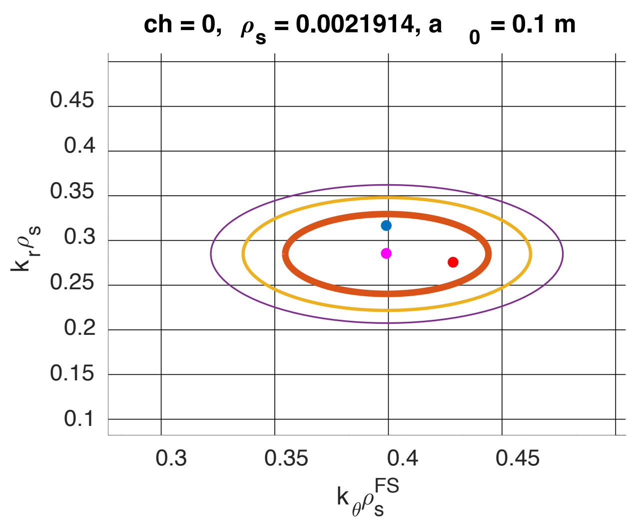
Measurement Wavenumbers

$k_r\rho_s^{exp} = 0.27 \quad k_\theta\rho_s^{exp} = 0.42$

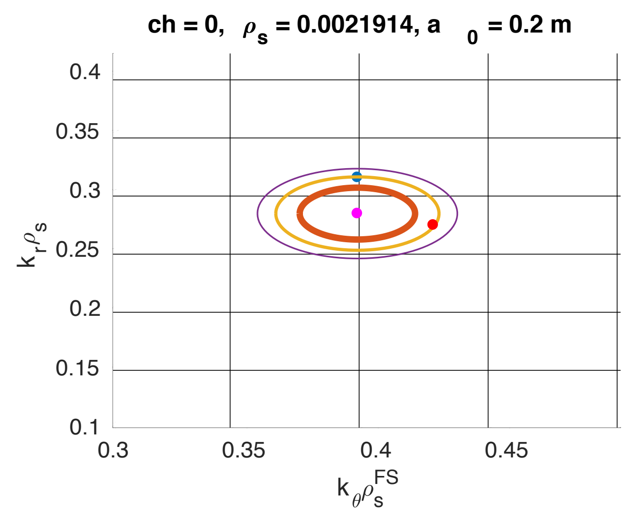
a_0 = 5 cm



a_0 = 10 cm

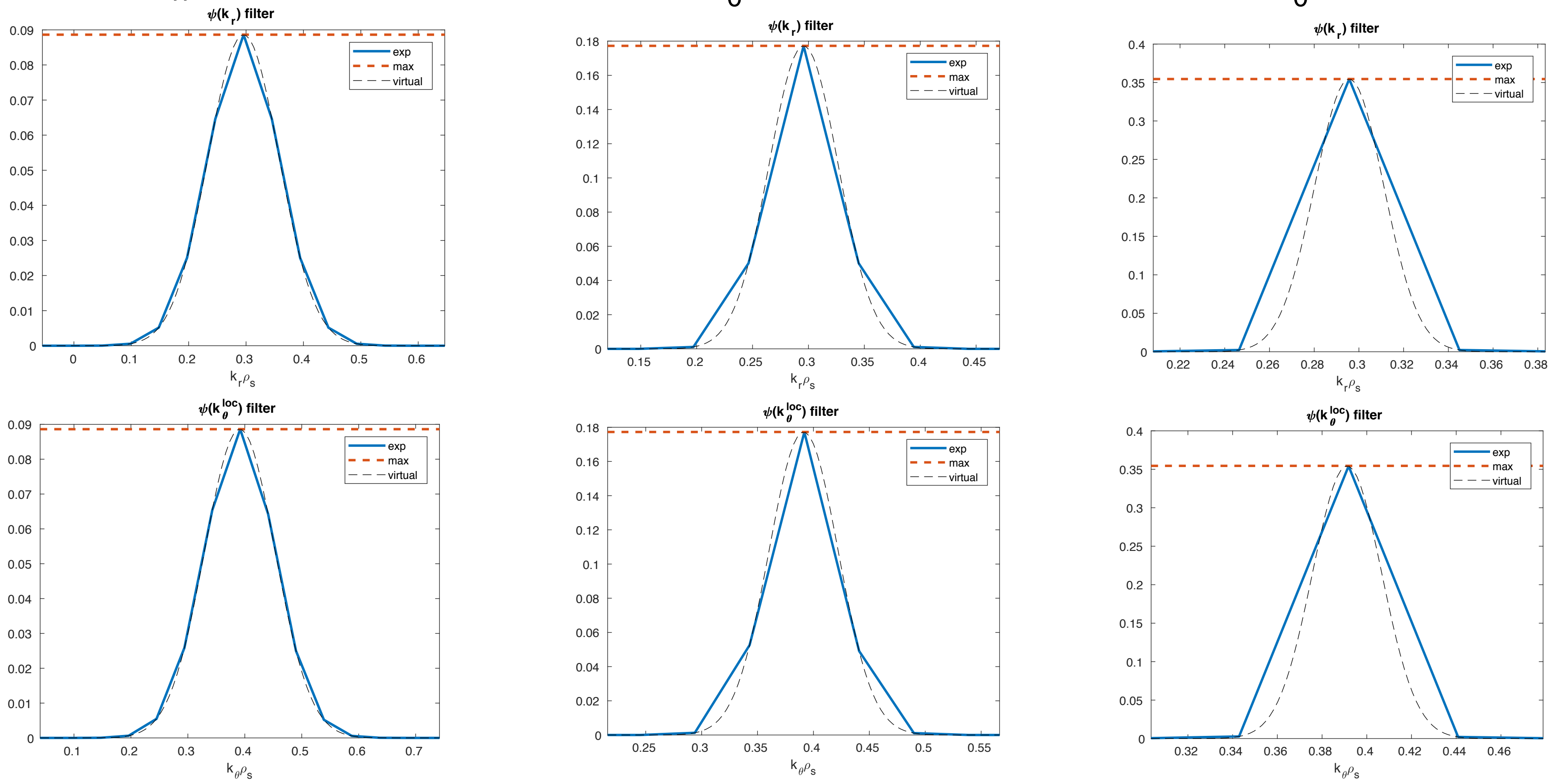


a_0 = 20 cm

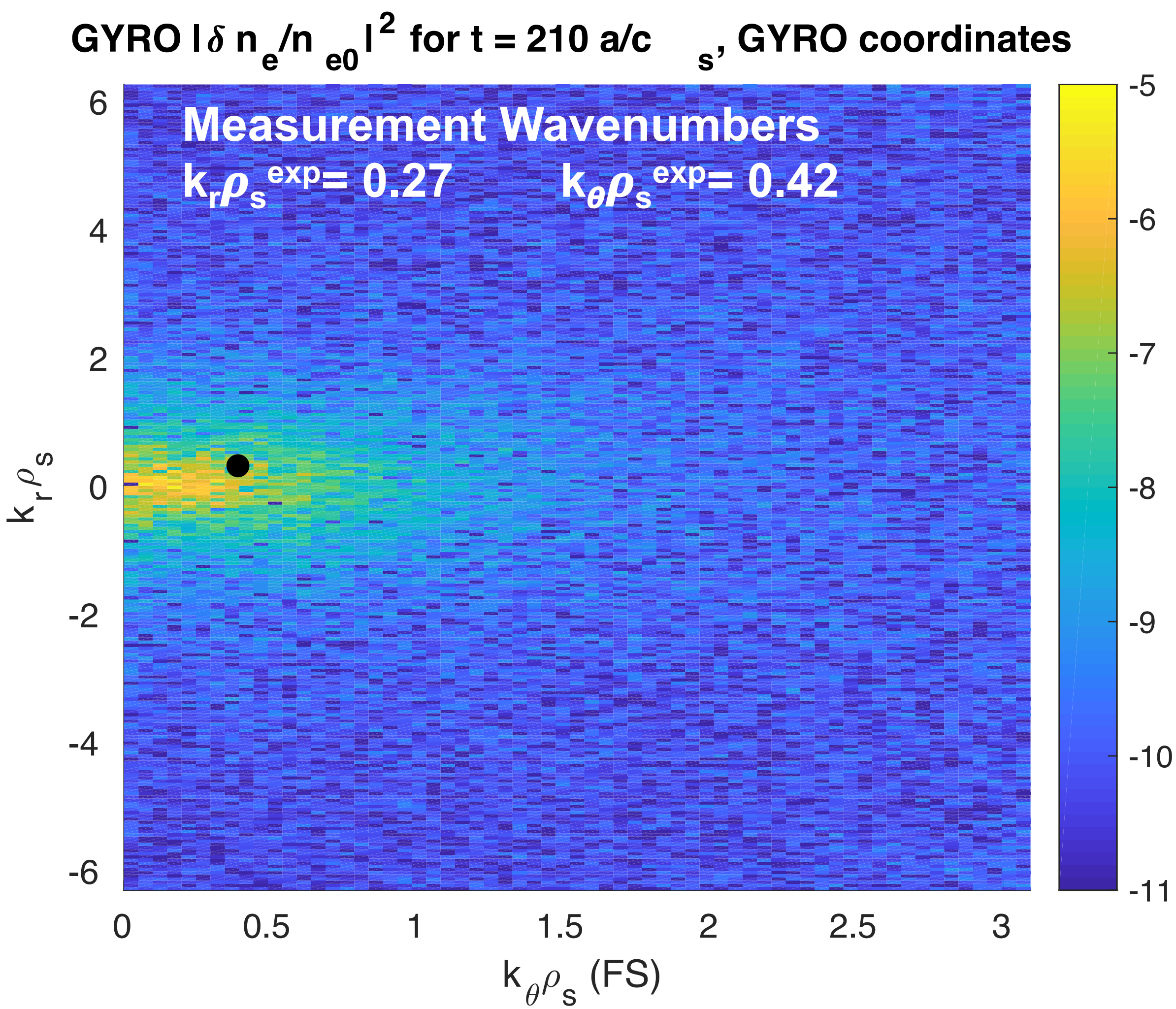


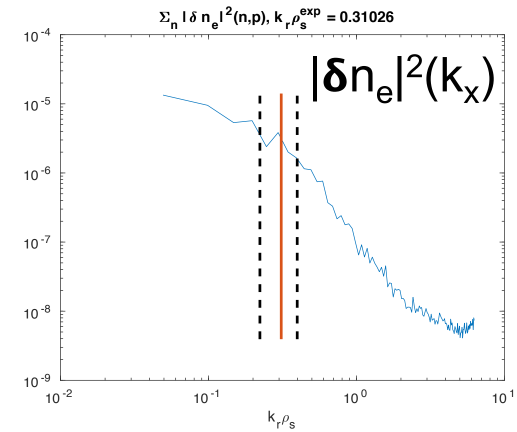
Cyclone Base Case: Wavenumber Space Filters – 1D

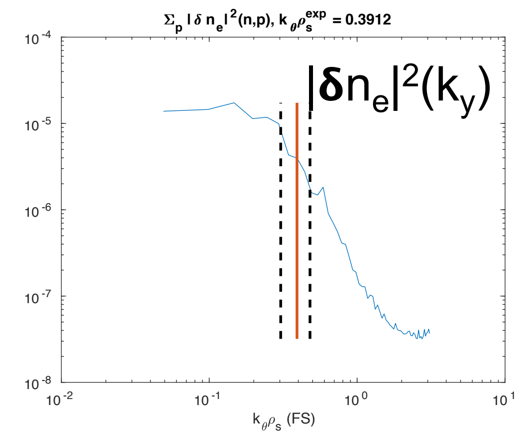
a_0 = 5 cm | a_0 = 10 cm | a_0 = 20 cm



Cyclone Base Case: Wavenumber measurement region







Conclusions from Cyclone Base Case Tests

- We have shown good agreement between two alternate ways to approach a scattering synthetic diagnostic
  - filtering in real space (r-filter)
  - filtering in wevenumber space (k-filter)

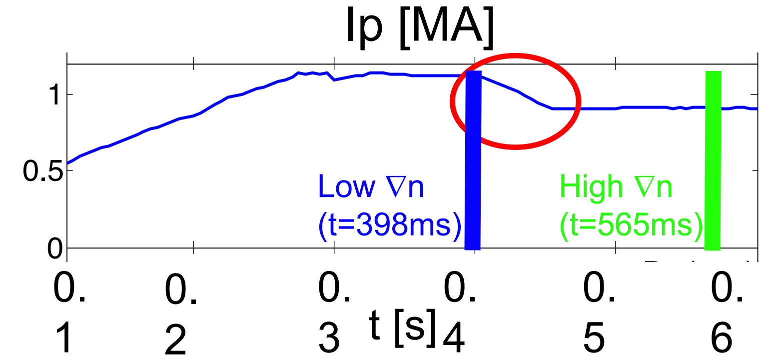
- The beam width was included in the full simulation domain at a_0 = 5 cm, and completely exceeded sim domain at a_0 = 20 cm.

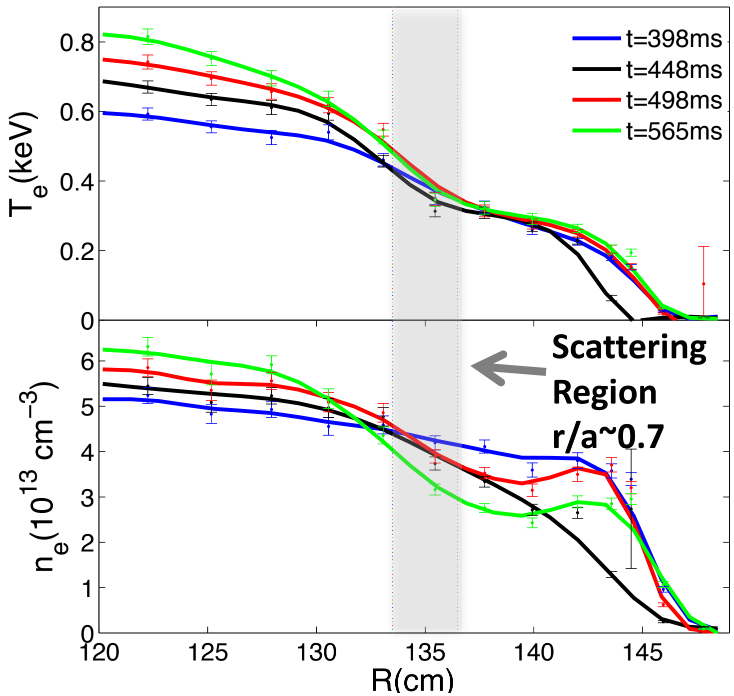
- Agreement between r & k filters was best at a_0 = 5 & 10 cm.

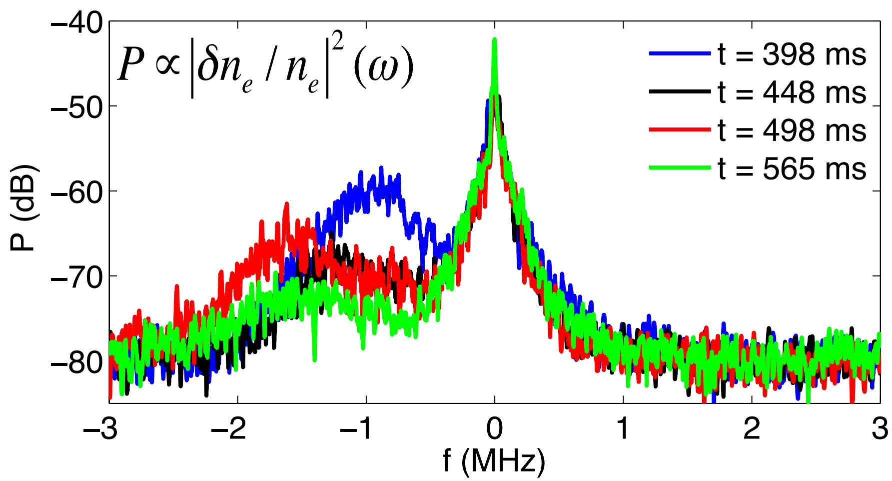
- At a_0 = 20 cm, the r-filter was a factor 2-3 smaller amplitude than the k-filter method (possibly due to beam exceeding sim domain at a_0 = 20 cm)

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

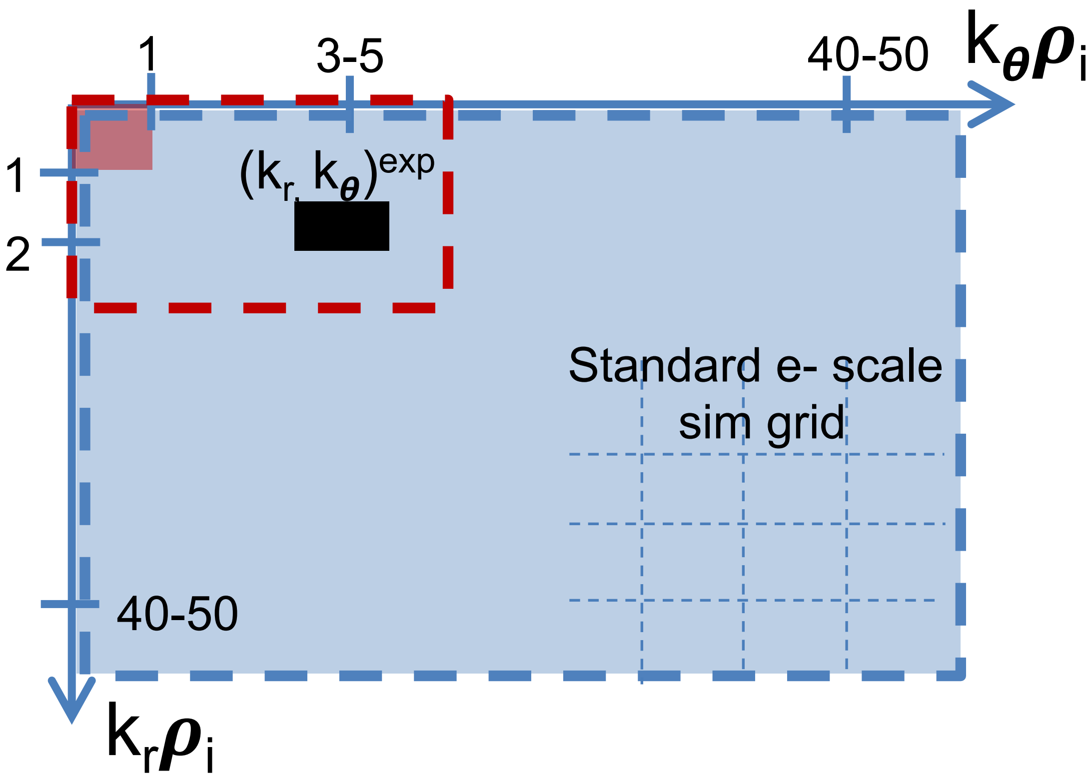
- NSTX NBI heated H-mode featured a controlled current ramp-down. Shot 141767.
- An increase in the equilibrium density gradient was correlated to a decrease in high-k density fluctuation amplitude (measured by a high-k scattering system). *cf.* Ruiz Ruiz PoP 2015.





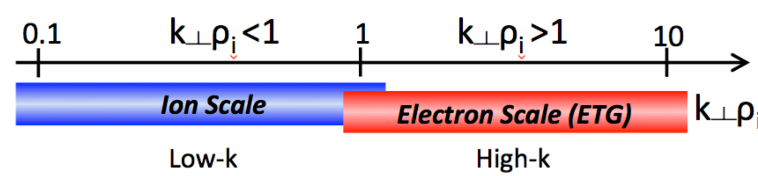


Ion–scale route to a synthetic diagnostic comparison



Simulation resolution in k-space

- Standard ion scale simulation $k \in [0.03, 1]$
- Standard e- scale simulation $k \in [1, 40]$
- High-k scattering: $(k_r, k_\theta)^{exp}$
- Big-box e- scale simulation $k \in [0.3, 40]$
- High-k ion scale simulation $k \in [0.03, 6]$



ρ_i ion gyro radius

- e- scale sim. covers k^{exp}, but grid is too coarse
  → need big box e- scale sim, finer k-grid (expensive!)
- Ion scale sim. has good grid space, but does not cover k^{exp}
  → need to extend sim from k = 1 to k^{exp} (expensive!)

Results of wavenumber mapping

Experiment
(shot 141767, ch1)

Cylindrical geometry (R,Z, φ)

Ray Tracing:
k_R = - 18.57 cm^{-1}
k_Z = 4.93 cm^{-1}

ρ_s^{exp} = 0.7 cm

GYRO

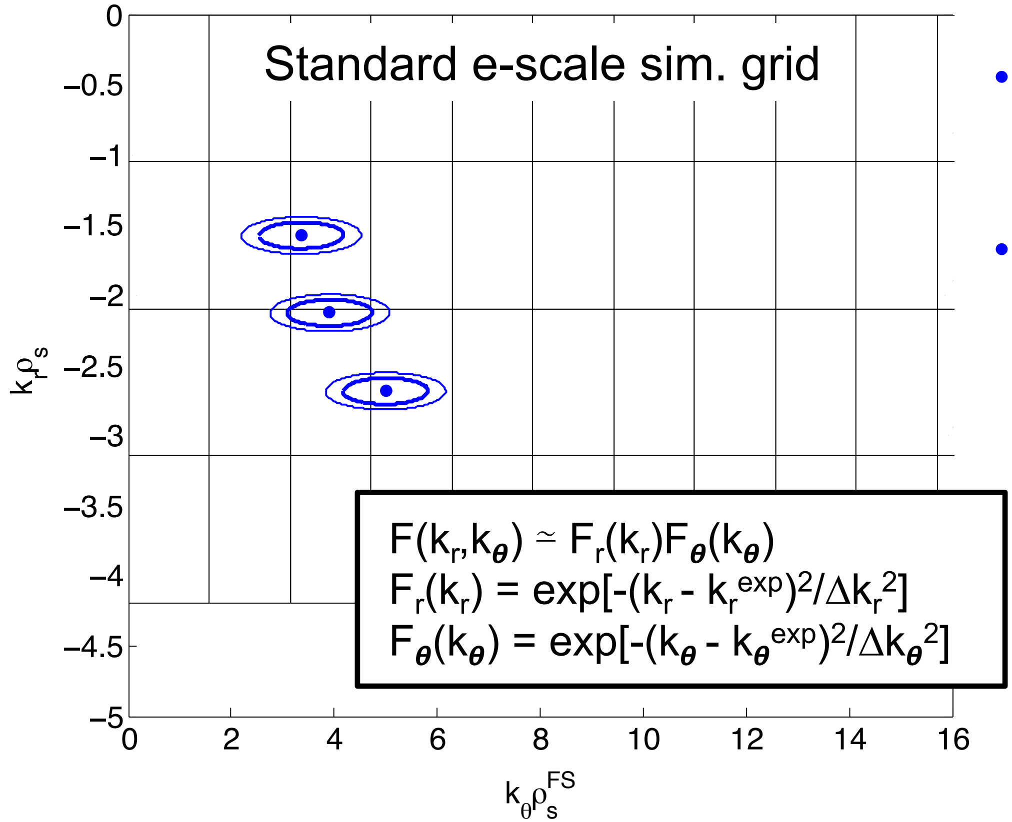
Field aligned (r, θ,φ)

New mapping:
➔ $k_r\rho_s$ = - 2.68
➔ $k_\theta\rho_s$ = 4.99

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.
- Old high-k system is sensitive to k that are closer to the spectral peak of fluctuations than previously thought → more transport relevant!

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)

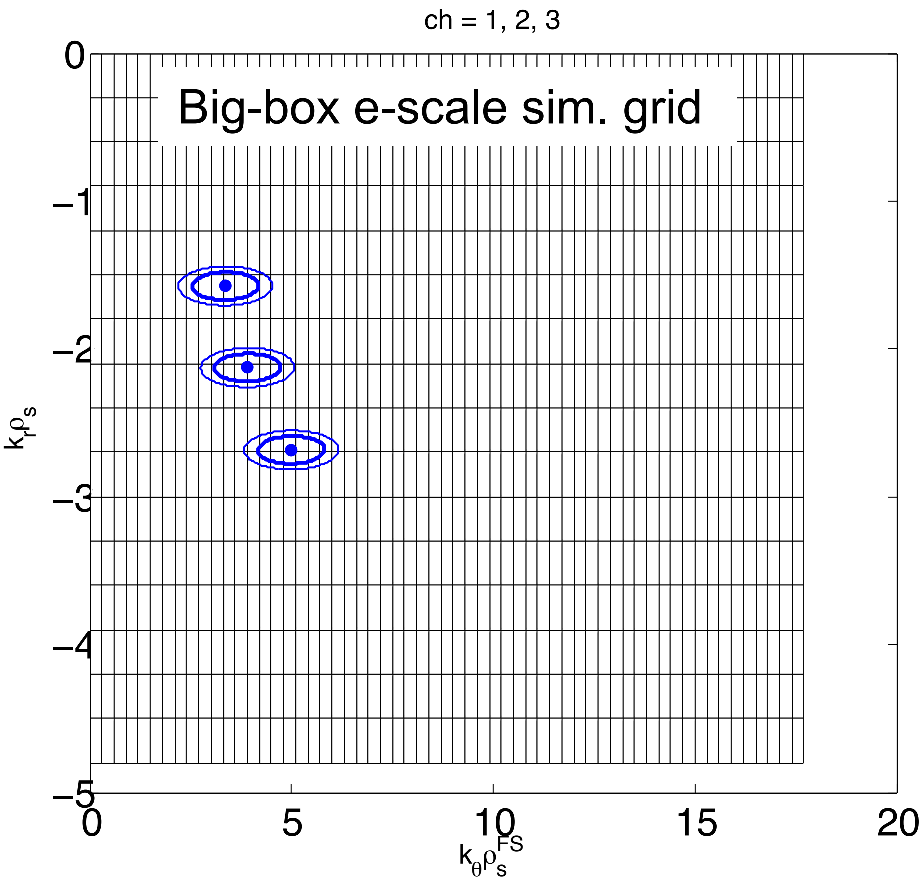
$$F(k_r,k_\theta) = F_r(k_r)F_\theta(k_r)$$

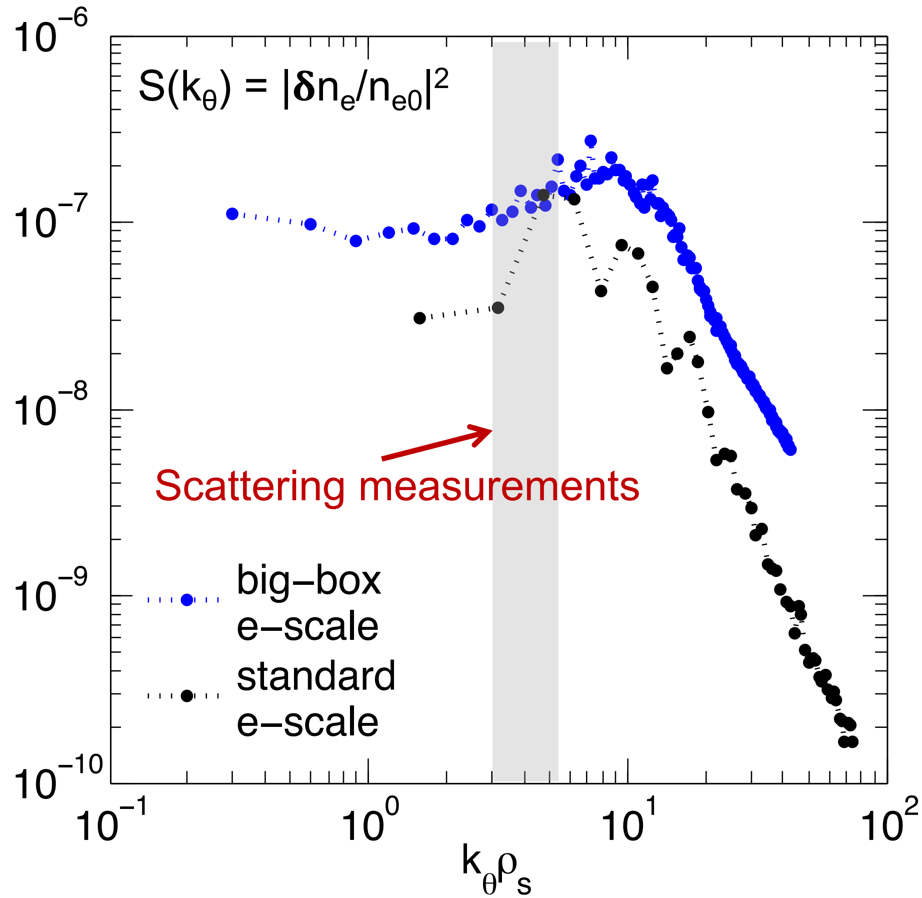
$$F_r(k_r) = \exp\left(-(k_r - k_r^{\exp})^2 / \Delta k_r^2\right)$$

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

Numerical grid of standard e- scale simulation does NOT accurately resolve the experimental wavenumber, wavenumber grid is too sparse (*cf.* Guttenfelder PoP 2011).

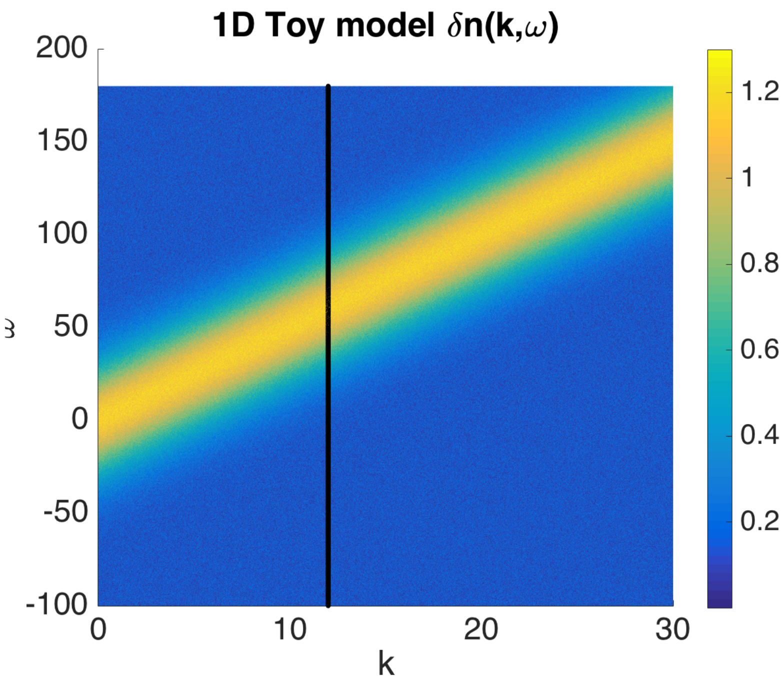
Resolving $(k_R,k_Z)^{exp}$ + Complete electron Scale Spectrum Requires a Big-Simulation-Domain e- Scale Simulation



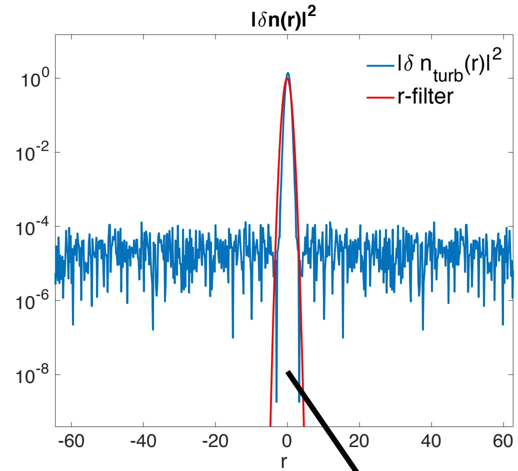


- Big-box simulation spectra show well resolved $(k_R,k_Z)^{exp}$ and electron scale spectrum.

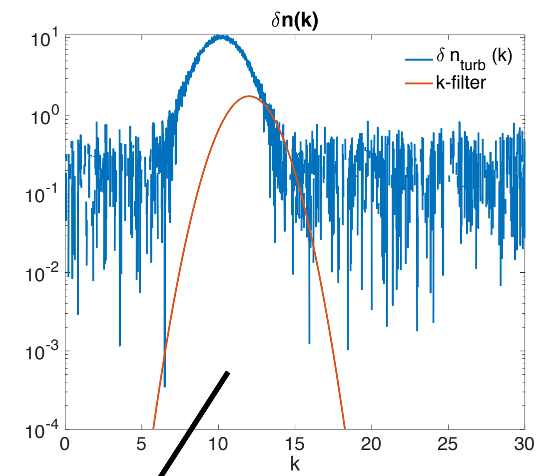
1D synthetic turbulence: proof of principle of equivalence between k & r filtering

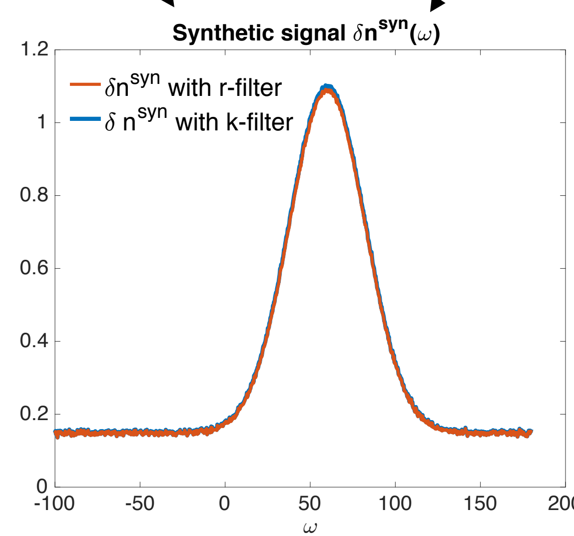


Filter in real space



Filter in k-space



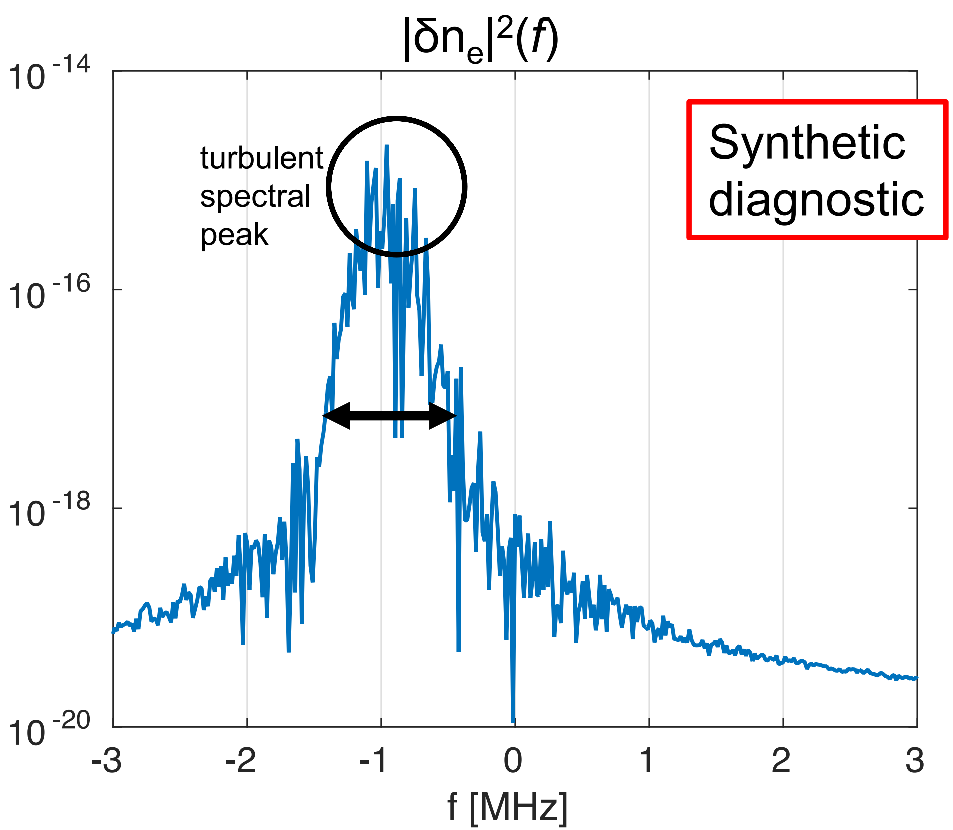


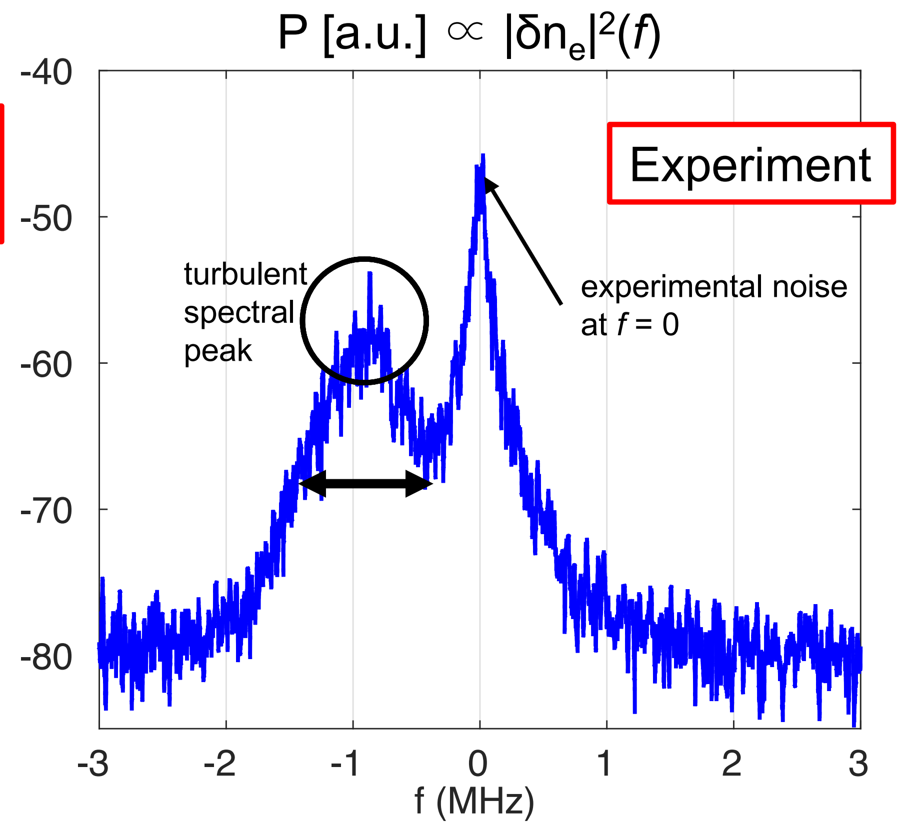
- 1D synthetic turbulence toy model shows proof of principle of equivalence between r & k filtering techniques.

$$\delta\hat{n}_e{}^{syn}(t) = \int \tilde{n}_e(r,t)\boldsymbol{\psi}_{\mathrm{R}}(\mathrm{r})e^{-ik_0 r}\,dr$$

$$\delta\hat{n}_e{}^{syn}(t) = \frac{1}{2\pi}\int \tilde{n}_e(k,t)\boldsymbol{\psi}_{\mathrm{K}}(k\text{-}k_0)\,dk$$

Towards a Quantitative Comparison of Plasma Turbulent Frequency Spectrum





- Recovered spectral peak, spectral width.
- **NOTE**: a quantitative comparison is not yet available: correct experimental units determining the amplitude are not included in Synthetic diagnostic.

Discussion of r & k filtering methods

***k*-space mapping - Selection of k**

- Traditional way to interpret filtered scattering spectra.
- Delicate to compute, take into account correct wavenumber amplitudes.
- Code-dependent.
- Need to adequately complete k-mapping → painful, but useful.

Real space filtering

- Common principle to all codes.
- Easier to implement and understand (no k-mapping).
- Need to resolve fine-scale structures (e- scale eddies) → much more computationally intensive (x5).

Two equivalent ways of interpreting scattering process
Useful to compute both methods to gain confidence in simulated synthetic spectra.

Operating Space of New High-k Scattering Diagnostic

- A new high-k scattering system is being designed for NSTX-U 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

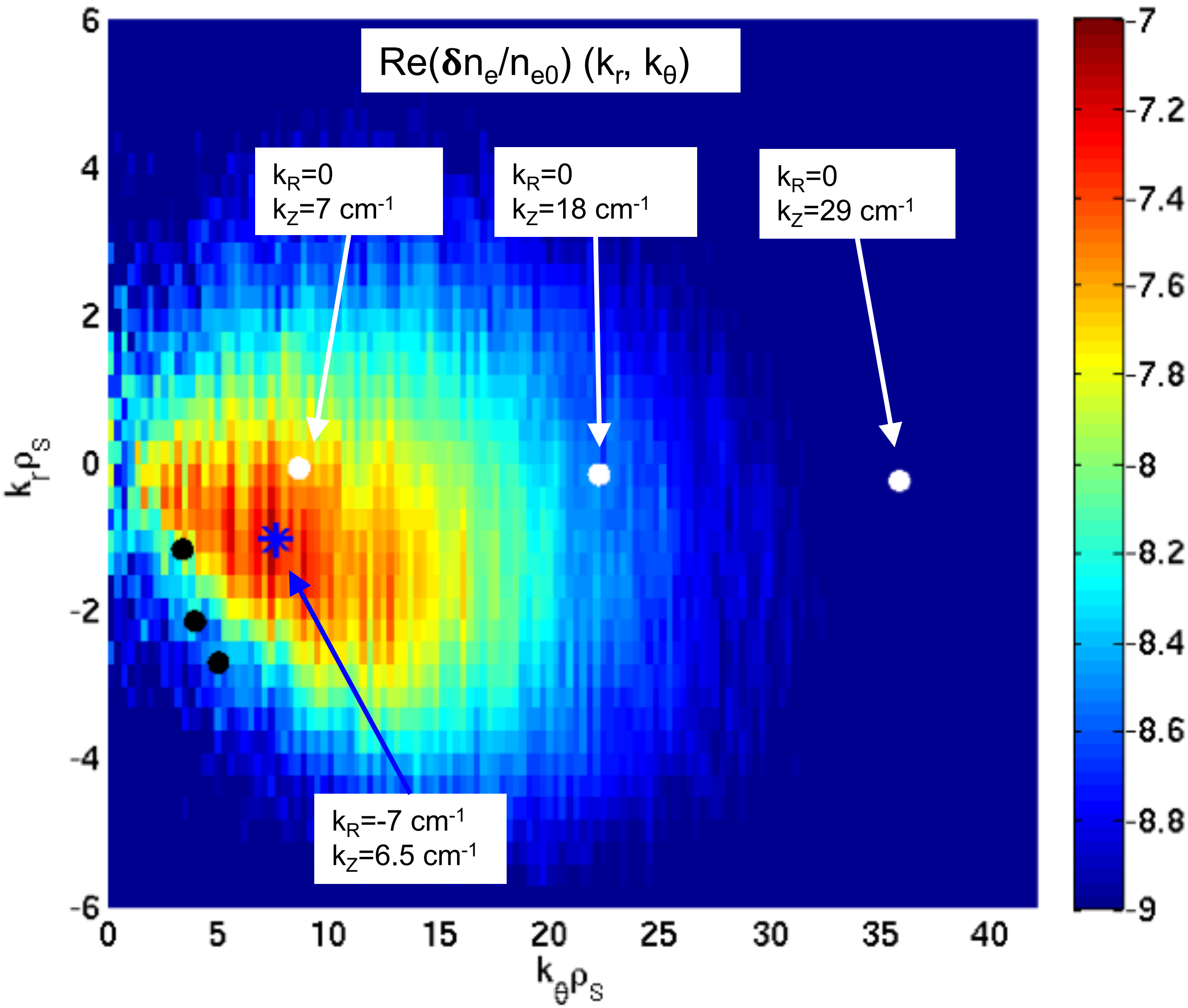
- **My goal**: project the operating space of the new high-k scattering diagnostic using the mapping I implemented.

- **Assumptions**: 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
- Blue star: streamers

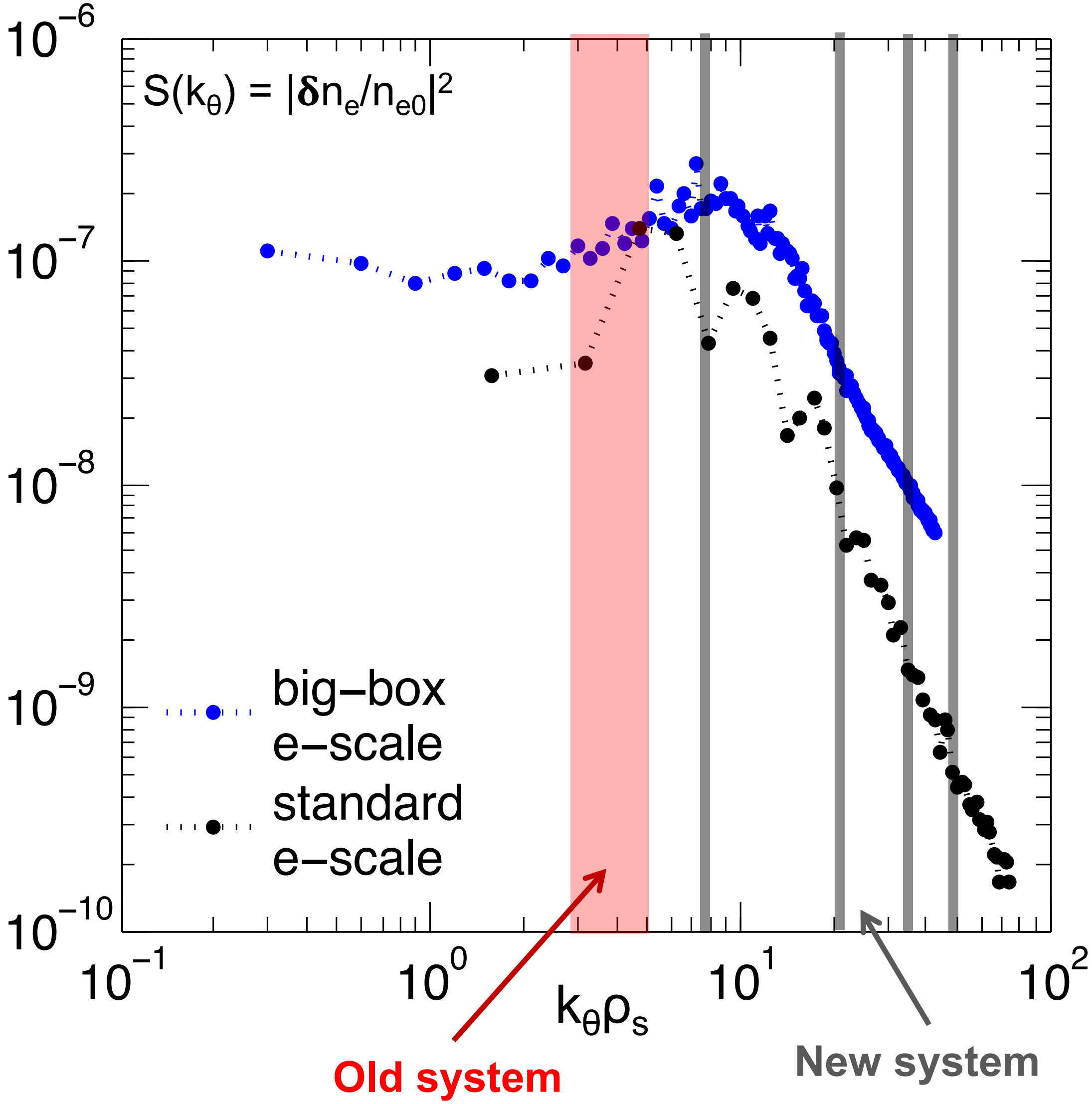
- Picked k's in predicted measurement range
  k_Z = 7, 18, 29, 40 cm^{-1}
  k_R = 0 cm^{-1}

- Lowest-k channel closest to streamers
  k_Z=7 cm^{-1}

- Highest-k not captured in simulation
  k_Z = 40 cm^{-1}

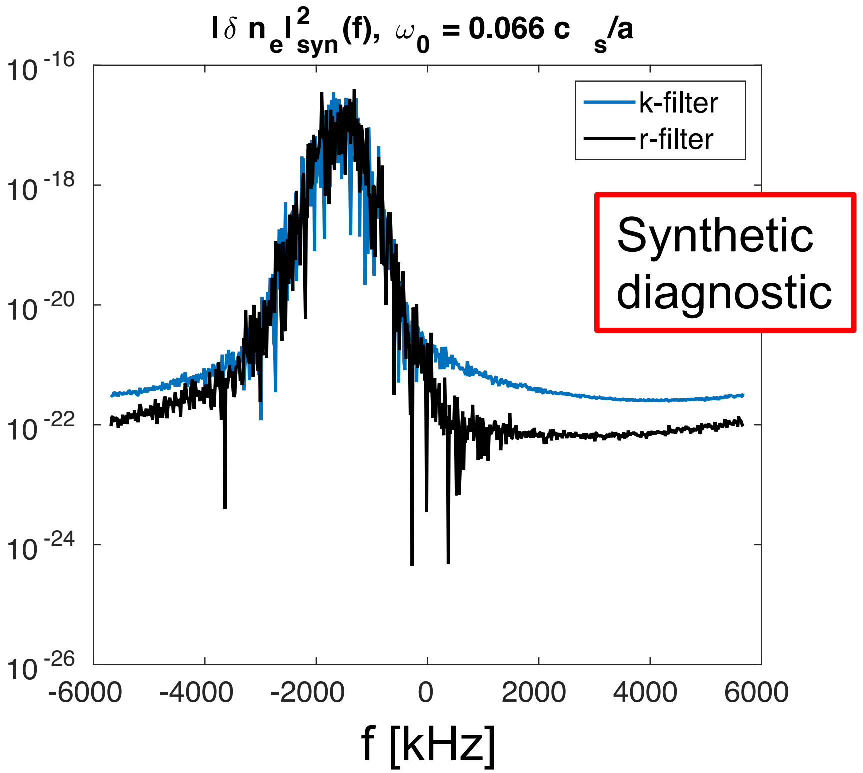
- Streamers: finite k_R
  $|k_R| \sim |k_Z|$

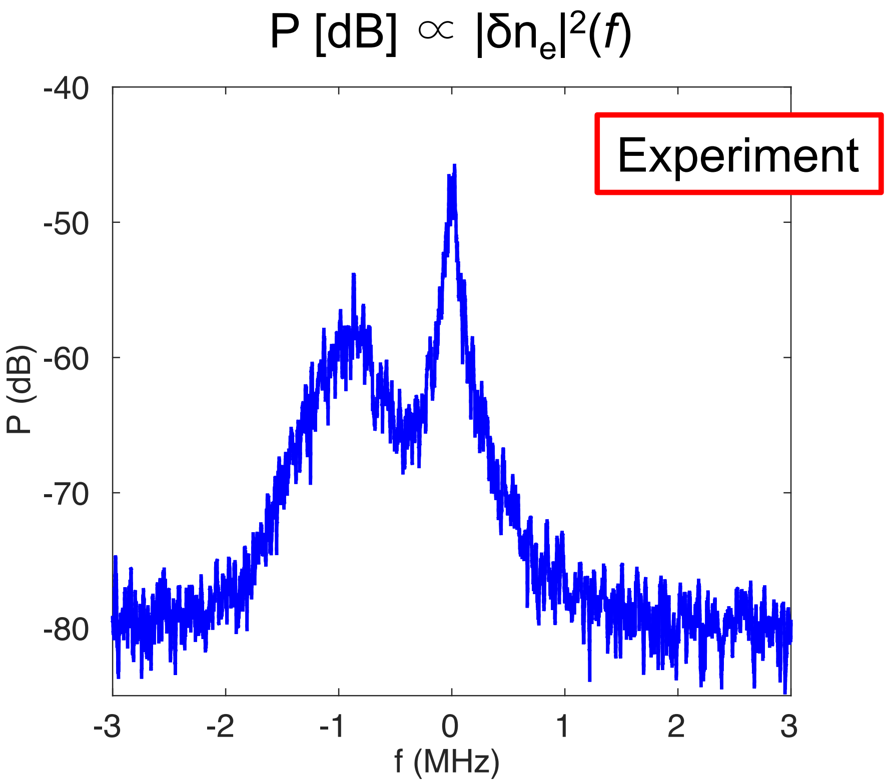
Mapped Wavenumbers of New High-k Diagnostic to GYRO k_θ Fluctuation Spectrum



- 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.

Towards a Quantitative Comparison of Plasma Turbulent Frequency Spectrum



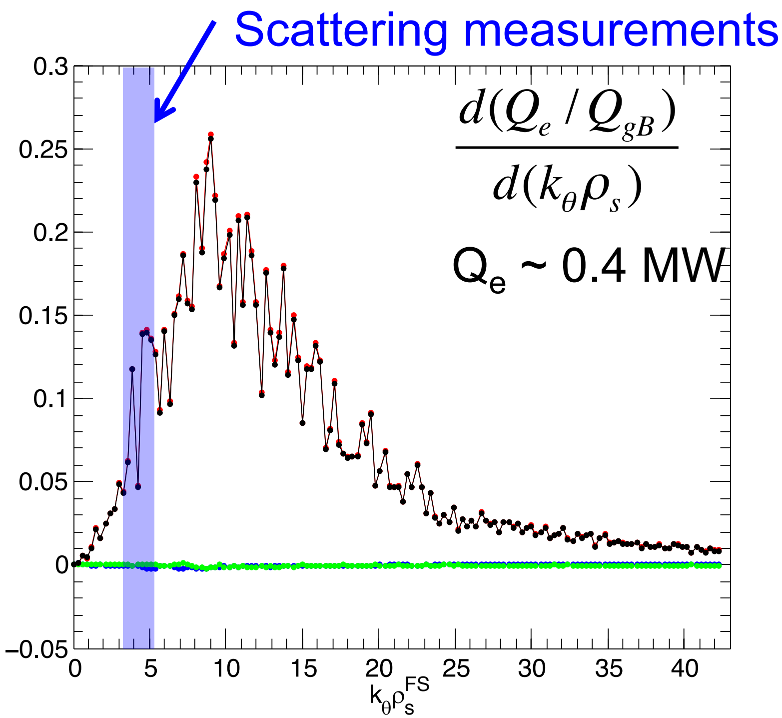


- Similar spectral shape: spectral peak, spectral width.
- **NOTE**: a quantitative comparison is not yet available: correct experimental units are not included in Synthetic diagnostic.

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

Resolution constrains:

- 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

	Standard e-scale	Big-box e-scale
$L_r\ [\rho_s]$	6	21
$L_y\ [\rho_s]$	6	21
$\Delta r\ [\rho_e]$	~ 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 (*cf.* slide 22).
- Experimental wavenumbers produce non-negligible δn_e and Q_e consistent with previous e- scale simulation results ($Q_e \sim 0.4$ MW).

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
High res. 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
High res. e- scale	**2.5 ρ_e**	**20 ρ_s**	**512**

	Previous studies	**New k-mapping**
$\mathbf{k_r\rho_s^{exp}}$	**-4/-15**	**-1.5/-3**
$\mathbf{k_\theta\rho_s^{exp}}$	3-6	3-5

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)

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)

Get from GYRO (internally calculated)

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

Apply mapping (simplified approx.)

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

cf. slide 15

Obtain experimental wavenumbers mapped to GYRO

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

$(k_\theta\rho_s)_{GYRO}$~ 2.0

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:

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

- 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})

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

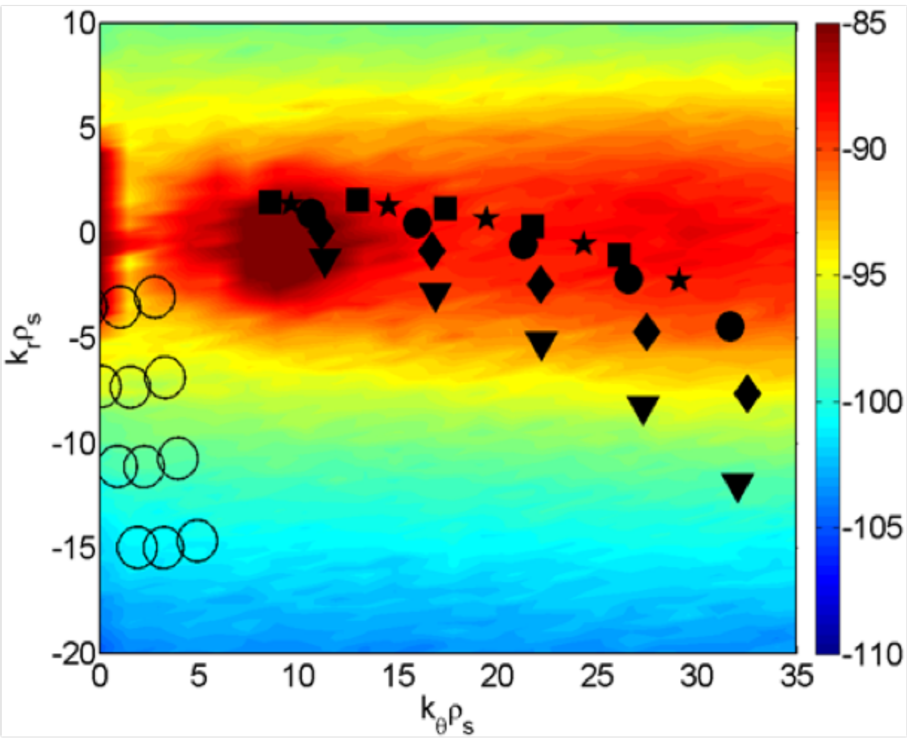
The mapping in k-space:

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

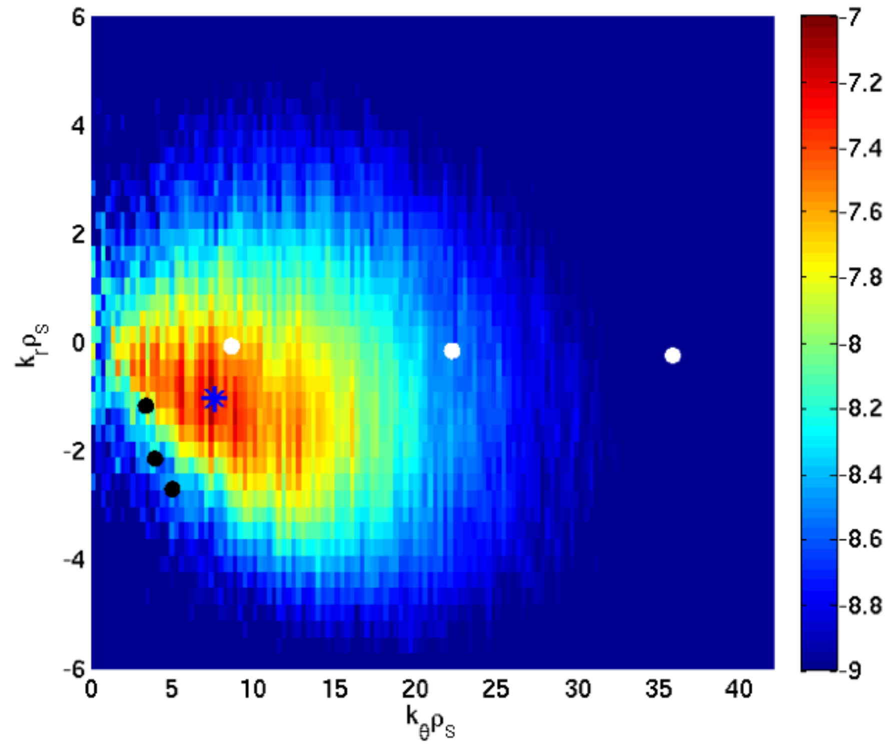
$$\begin{cases} k_r - \frac{r}{q}\frac{\partial \nu}{\partial r} k_\theta = \frac{\partial R}{\partial r} k_R + \frac{\partial Z}{\partial r} k_Z \\ -\frac{r}{q}\frac{\partial \nu}{\partial \theta} k_\theta = \frac{\partial R}{\partial \theta} k_R + \frac{\partial Z}{\partial \theta} k_Z \end{cases}$$

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



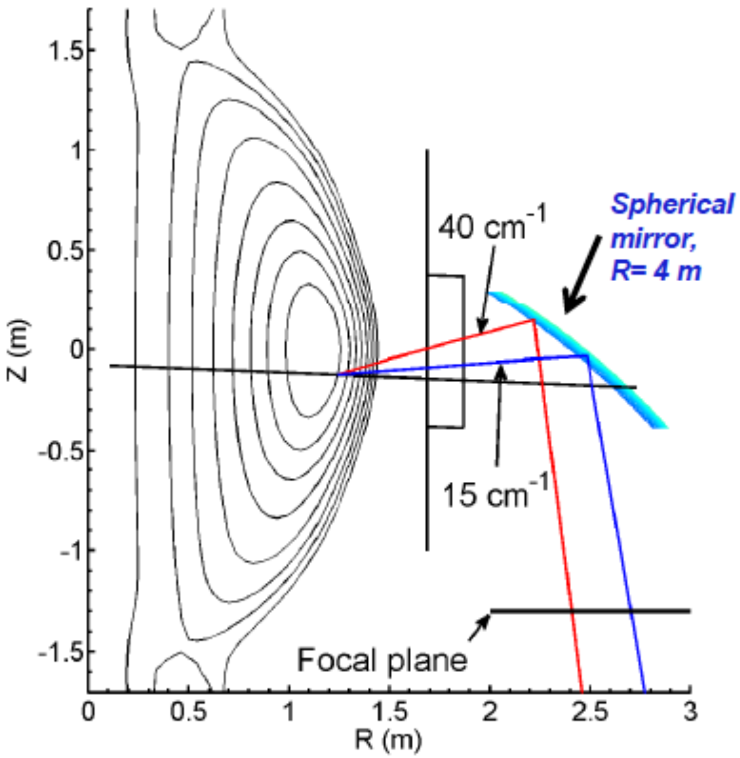
Barchfeld APS 2015



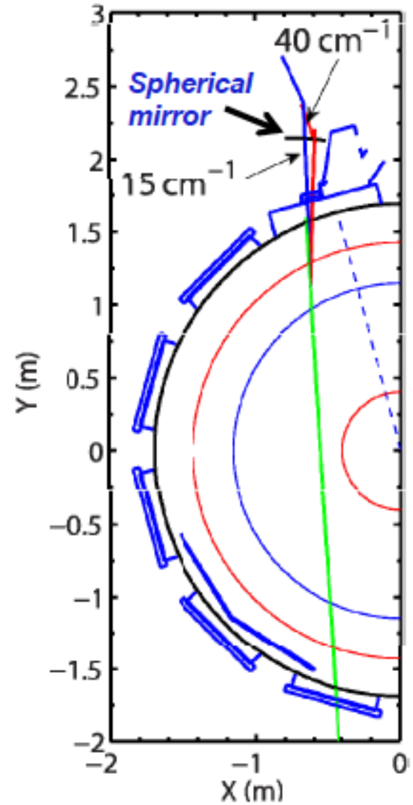
My mapping

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

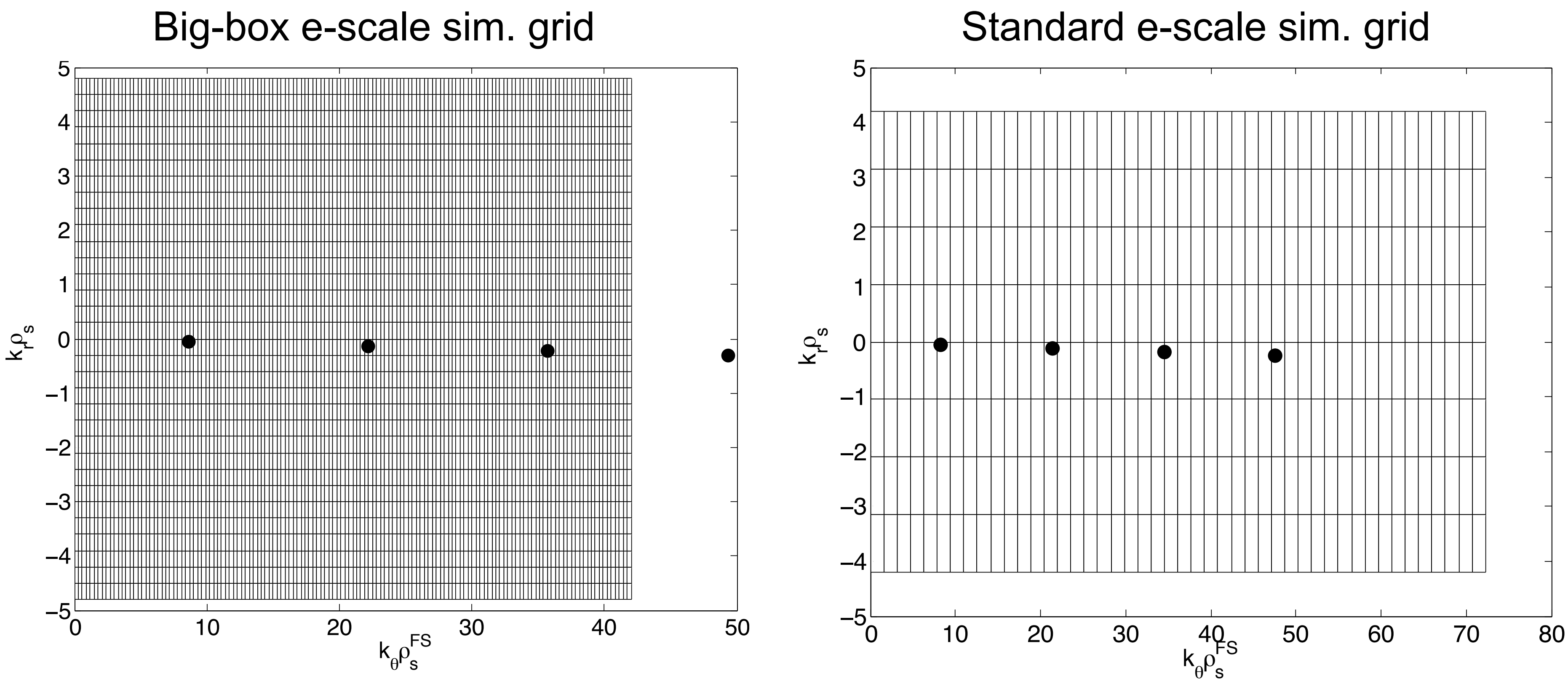


Poloidal cross section



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.

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

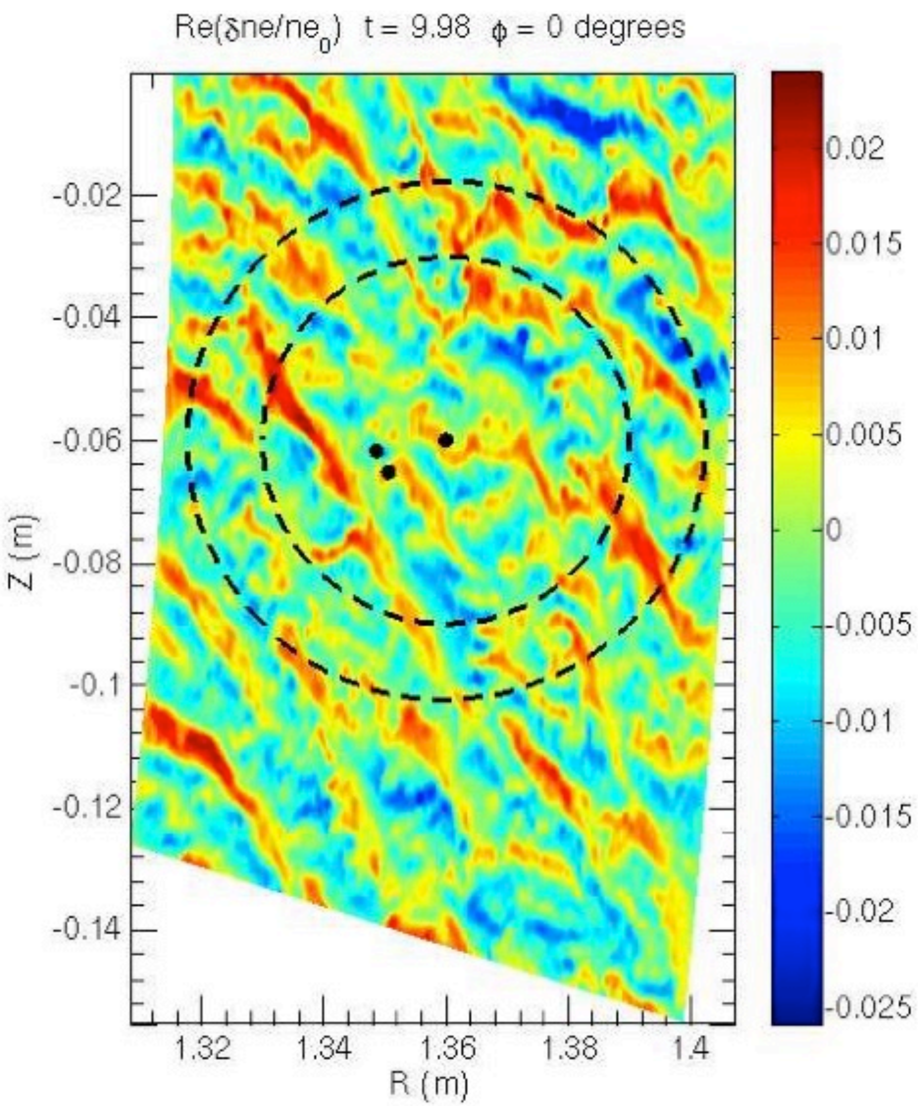
- Outboard mid-plane $\delta n_e(R, Z)$ in high resolution e- scale GYRO simulation of real NSTX plasma discharge.

- Shot 141767, time t = 398 ms (*cf.* Ruiz Ruiz PoP 2015).

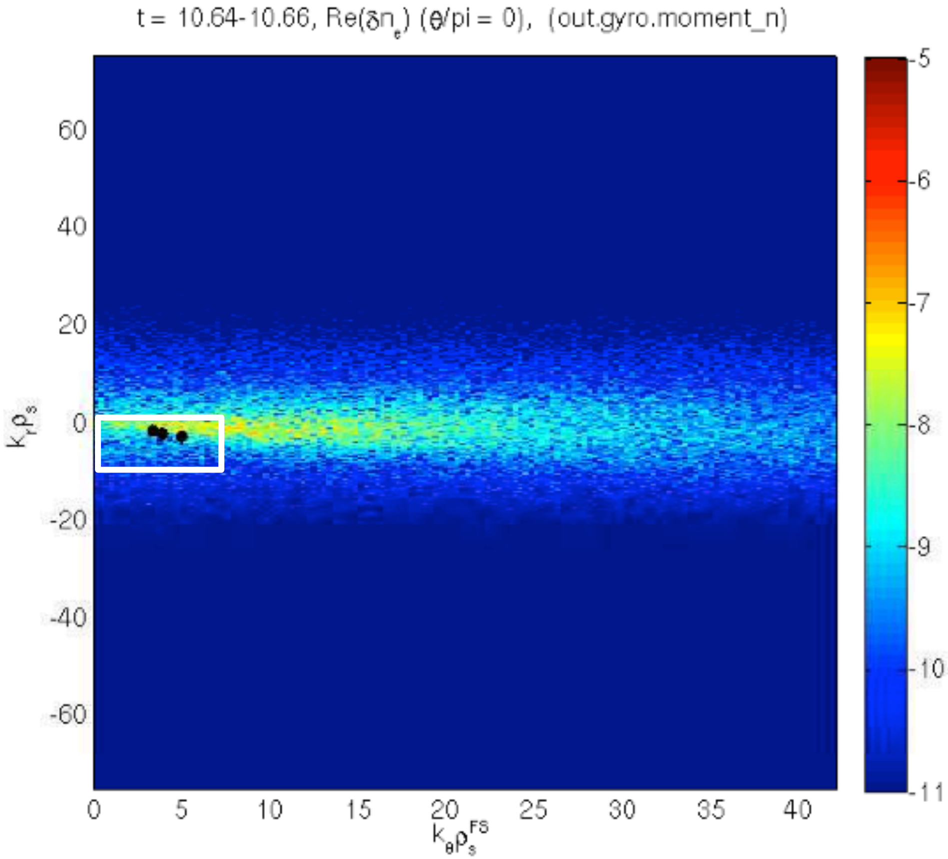
- Scattering location and scattering volume extent are within GYRO simulation domain.

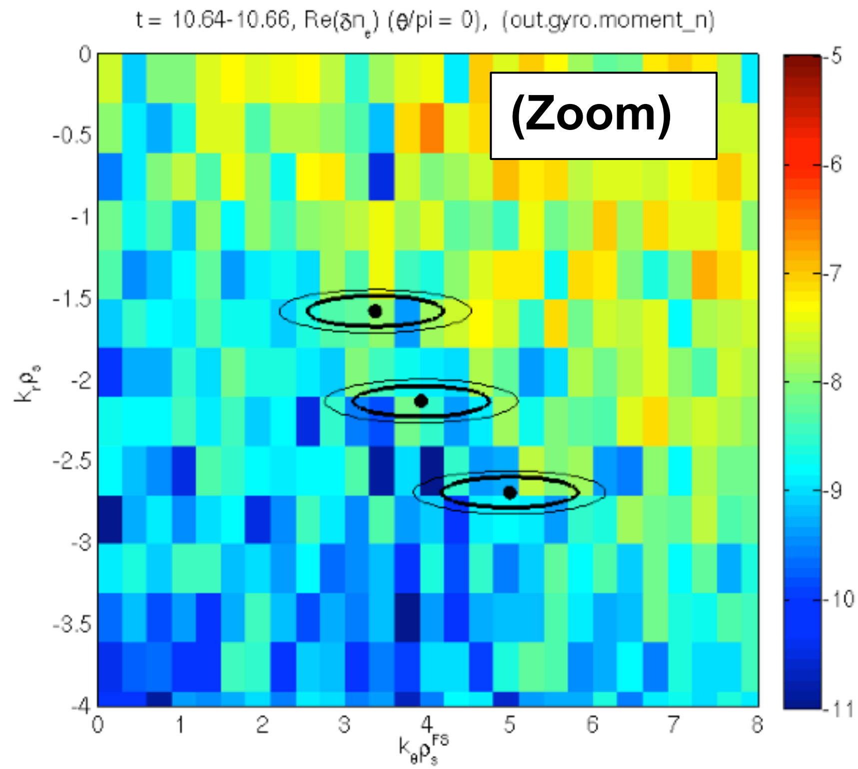
- Dots are scattering location for channels 1, 2, and 3 of high-k diagnostic.

- Dashed circles are 3cm and √2*3 cm microwave beam radii (for channel 1).



Mapped Experimental Wavenumbers in GYRO Density Spectra





$$k_\theta^{FS} = \frac{1}{2\pi}\int_0^{2\pi} k_\theta^{loc}\, d\theta = \frac{nq}{r}$$

- **Note**: Plotting $k_\theta\rho_s^{FS}$, not $k_\theta\rho_s^{loc}$!!
- **Black dots:** scattering $(k_r, k_\theta)^{exp}$ for channels 1,2,3 (note in these figures, spectrum is output at θ=0, and black dots correspond to θ~-0.06 rad).
- **Ellipses:** e^{-1} and e^{-2} amplitude of (k_r, k_θ) gaussian filter (simplified selectivity function).

Input Parameters into Nonlinear Gyrokinetic Simulations Presented

	t=398	t = 565
r/a	0.71	0.68
a [m]	0.6012	0.596
B_{unit} [T]	1.44	1.27
n_e [10^19 m-3]	4.27	3.43
T_e[keV]	0.39	0.401
RHOSTAR	0.00328	0.003823
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

	t=398	t = 565
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
$s_k=r d\ln(\kappa)/dr$	0.15	0.19
DELTA = δ	0.25	168
$s_\delta=rd(\delta)/dr$	0.32	0.32
M	0.2965	0.407
γ_E	0.126	0.1646
γ_p	1.036	1.1558
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)

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

<u>Preamble 2</u> 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

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

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

- 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

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

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