U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Investigating High-k Turbulence and Electron Thermal Transport in NSTX with a Synthetic Diagnostic for High-k Scattering

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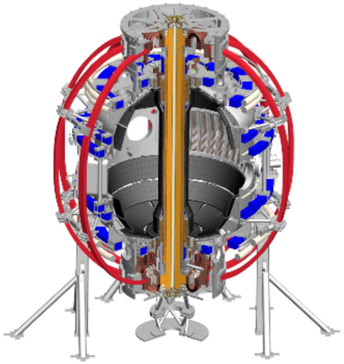
1. MIT 2. PPPL 3. NFRI 4. UC Davis 5. U Wisconsin 6. Nova Photonics, Inc. 7. General Atomics

Physics Meeting
PPPL, April 17, 2018

Alcator C-Mod

PPPL



Work supported by DOE contracts DE-AC02-09CH11466 and DE-AC02-05CH11231

Outline

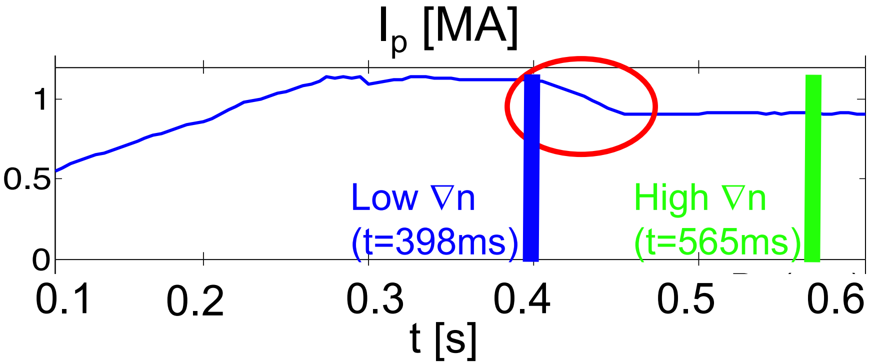
- Past work: NSTX H-mode discharge showing stabilization of ETG by density gradient

- High-k Scattering diagnostic at NSTX

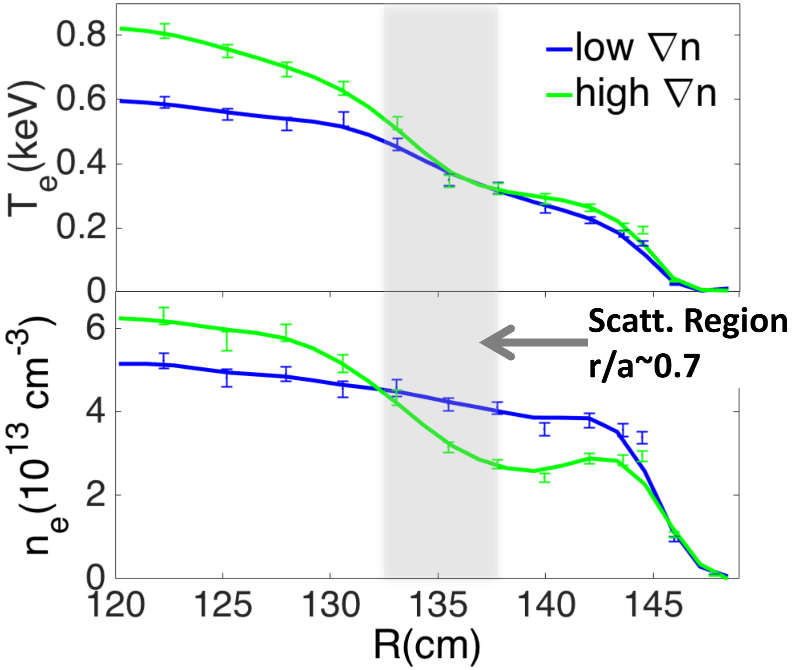
- Synthetic High-k Diagnostic
  - Numerical GYRO Simulations needed
  - Past work on Syn Hk
  - Synthetic comparisons of f-spectrum with experiment
  - High-k Contributions to electron thermal transport

NSTX H-mode Plasma Showed Local Increase in Density Gradient

- NSTX NBI heated H-mode featured a controlled current ramp-down (141767)

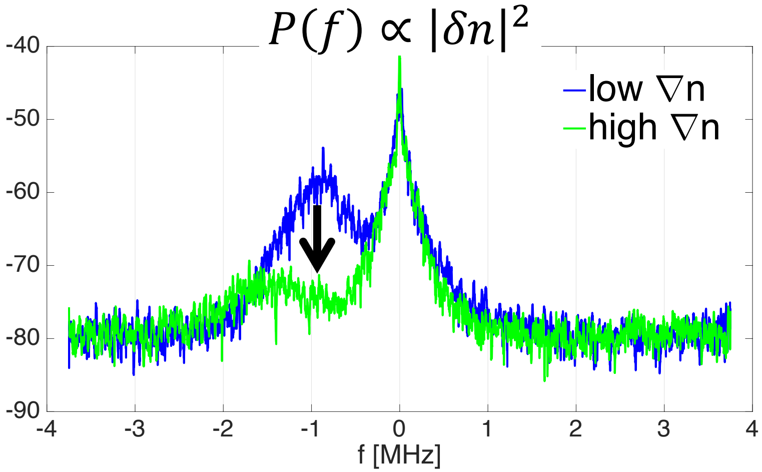


- Produced a local increase in equilibrium background density gradient at the scattering location

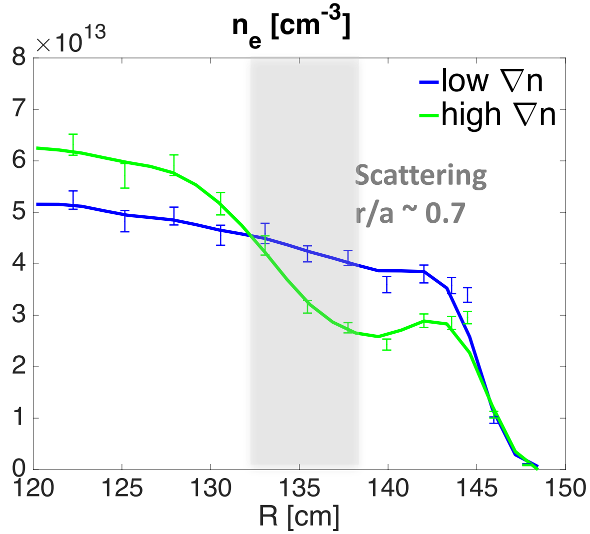


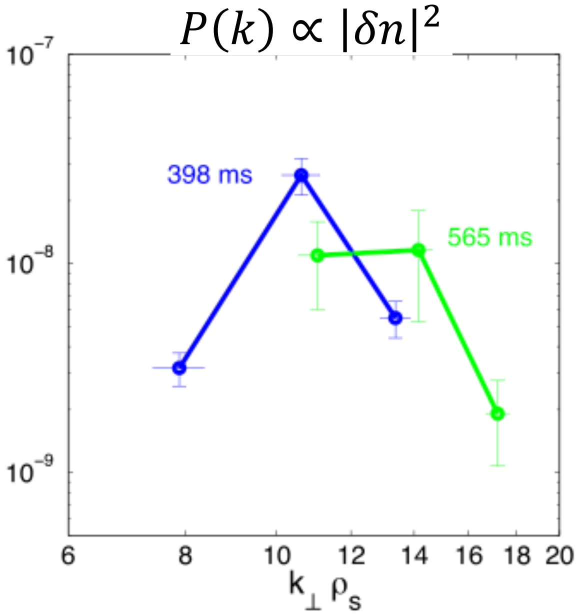
Background Density Gradient Increase was Correlated to Stabilization of e- scale Turbulence

- High-k density fluctuation amplitude $|\delta n|^2$ $(f, k$-spectrum) stabilized by **∇n** increase (measured by a high-k scattering). cf. Ruiz Ruiz PoP 2015.



Local background density profile





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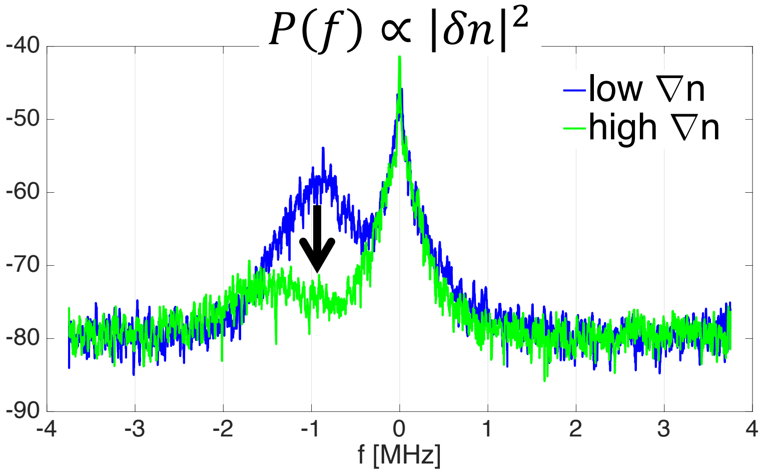

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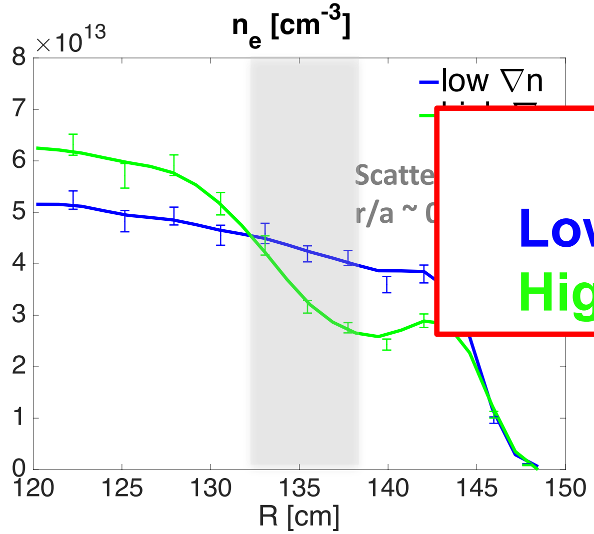
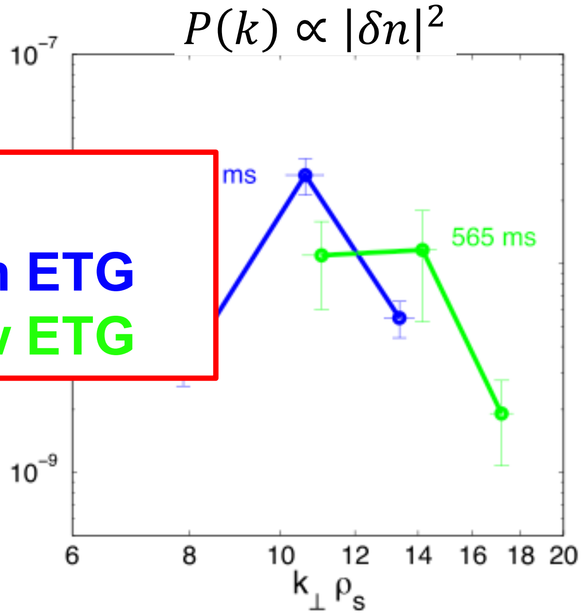


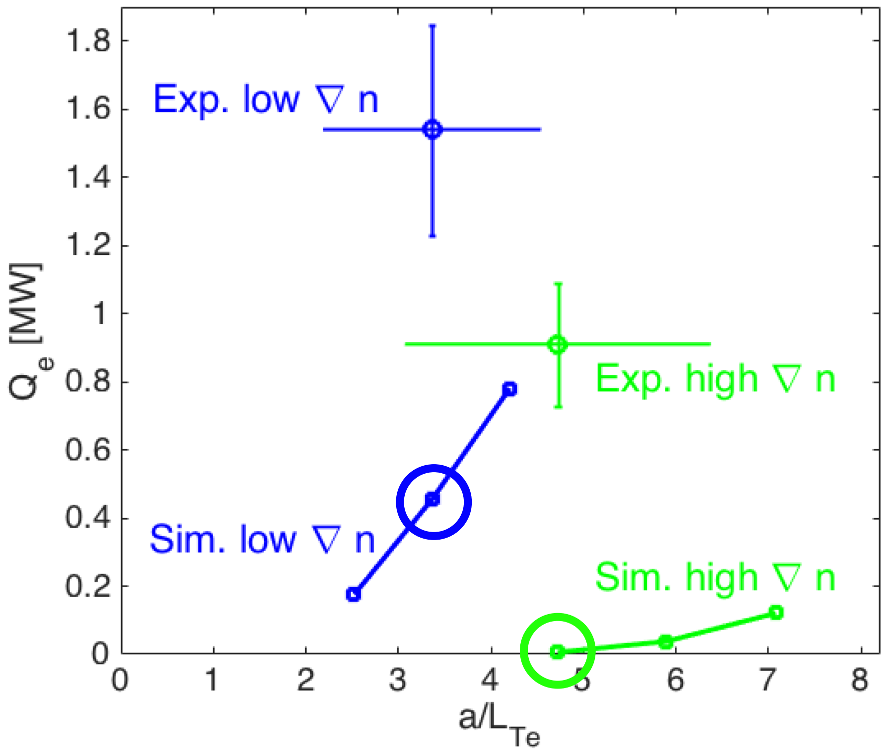


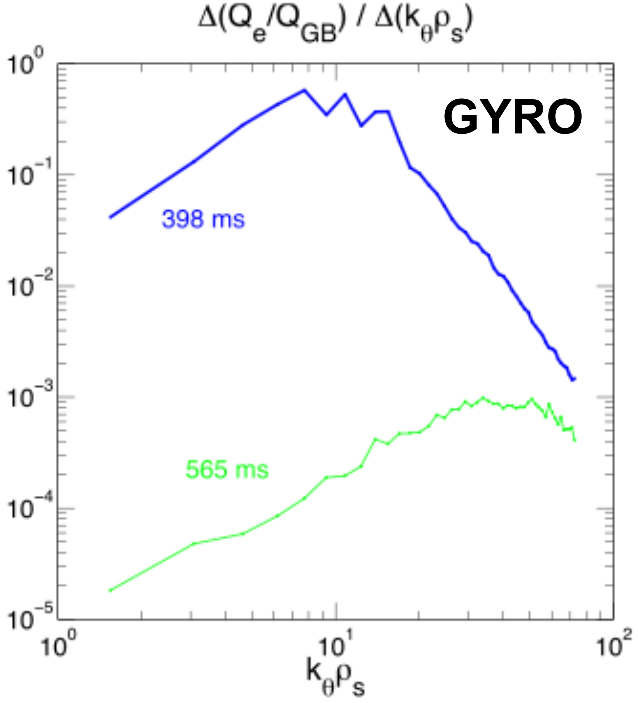
Recall

Low ∇n = High ETG

High ∇n = Low ETG

Nonlinear Electron Scale GYRO Simulations Cannot Explain Experimental Electron Heat Flux





- Q_e underpredicted at low and high ∇n

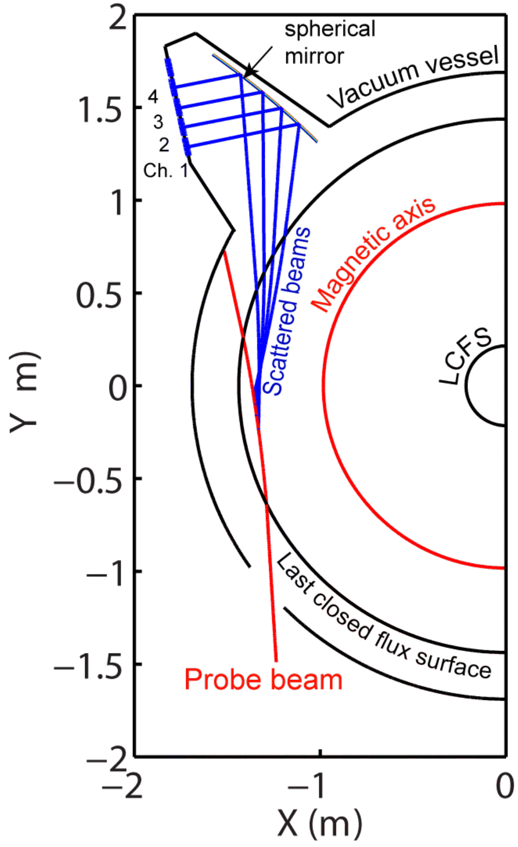
Is simulation not reproducing turbulence accurately, or are there additional sources of transport?

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

- Scattered power density $$P_s \propto \left(\frac{\delta n}{n}\right)^2$$
- Gaussian microwave probe beam
  - f = 280 GHz (>> f_{pe}, f_{ce})
- **Ray tracing to determines $\vec{k}_{plasma}$** $$\begin{cases} \vec{\mathbf{k}}_{\mathbf{s}} = \vec{\mathbf{k}}_{\mathbf{plasma}} + \vec{\mathbf{k}}_{\mathbf{i}} \\ \boldsymbol{\omega}_{\mathbf{s}} = \boldsymbol{\omega}_{\mathbf{plasma}} + \boldsymbol{\omega}_{\mathbf{i}} \end{cases}$$

Scattering system is ***toroidally*** localized in $\boldsymbol{\varphi}_{\mathrm{loc}}$

➔ We model a 2D synthetic diagnostic



View from top of NSTX

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

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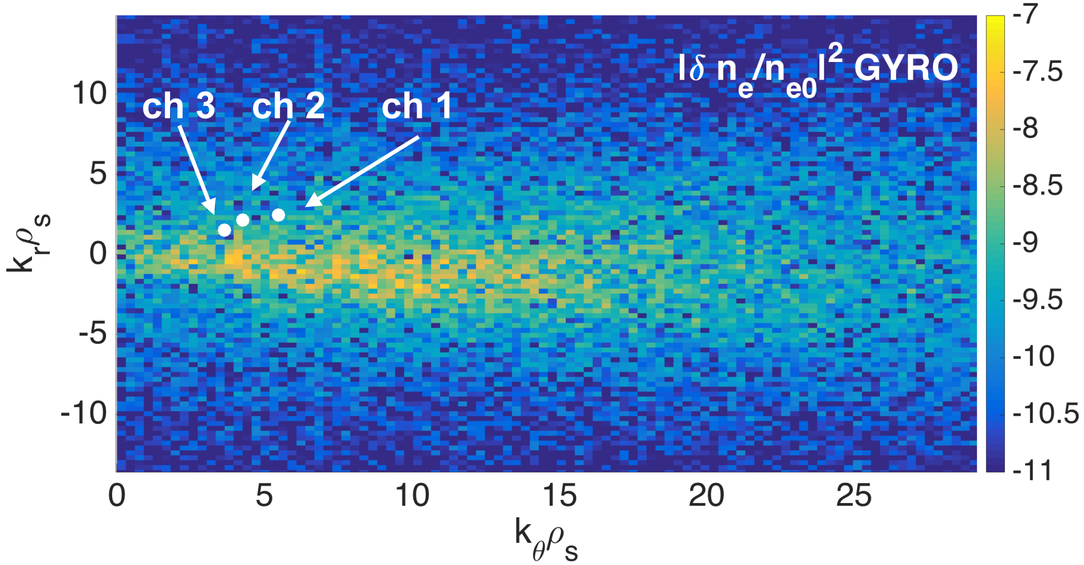
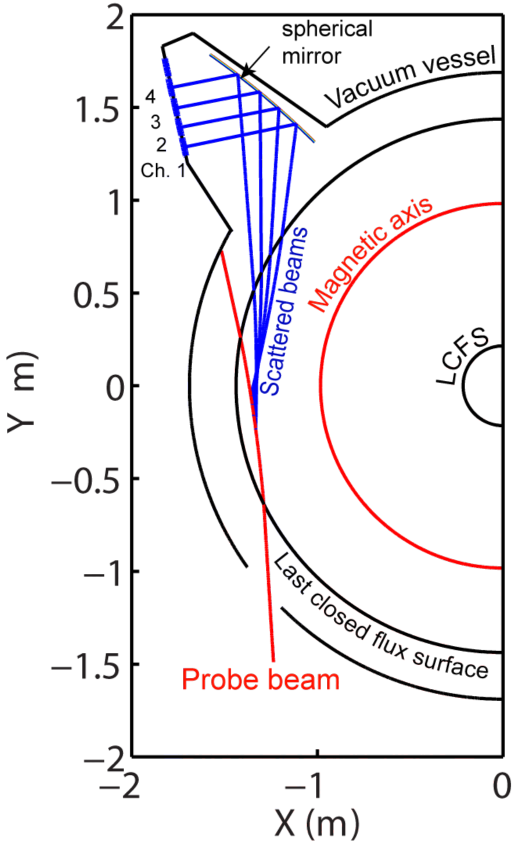
- Map $\vec{k}_{plasma}$ from (k_R, k_φ, k_Z) to GYRO $(k_r, k_\varphi, k_\theta)$





View from top of NSTX

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

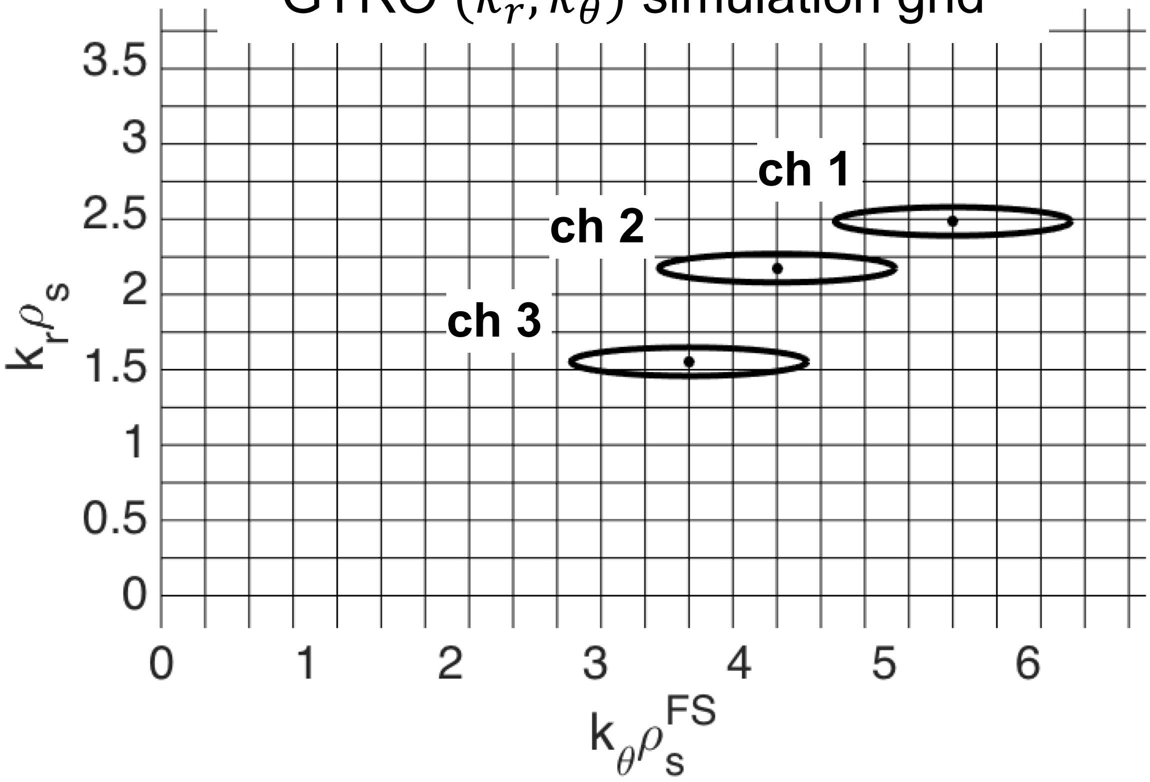
Experimental profiles used as input

Local simulations performed at scattering location (r/a~0.7, R~135 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).

Hybrid-Scale ETG Simulations are Needed to Resolve Experimental Wavenumber

GYRO (k_r, k_θ) simulation grid



Resolution parameters

$L_r \times L_y$ = 20-14 x 21-16 ρ_s
(L/a~0.15-0.07)

$n_r \times n$ = 512-450 x 140-220

Simulation cost ~ 0.5 M CPUh

- ***Hybrid-scale***, NOT multiscale simulation (ions not fully resolved)

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

- Extensive Box size scans show **Hybrid Scale Simulation** is trade off:
  - Computational cost ~ **0.5 M CPU h**
  - Correctly resolving experimental k (does not fully overlap scattering probe beam)

L_r x L_y = 20-14 x 21-16 ρ_s
(L/a~0.15-0.07)
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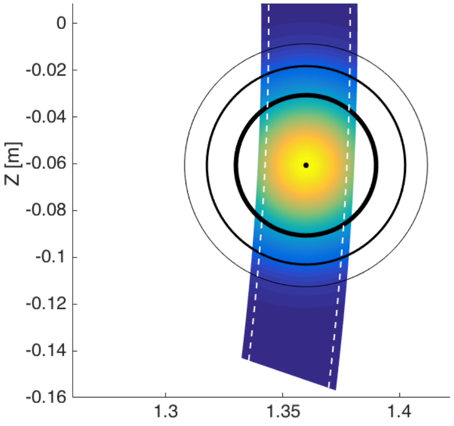
Hybrid Scale



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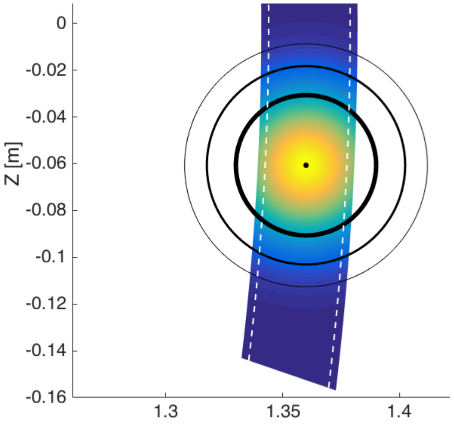
L_r x L_y = 20-14 x 21-16 ρ_s
(L/a~0.15-0.07)
n_r x n = 512-450 x 140-220

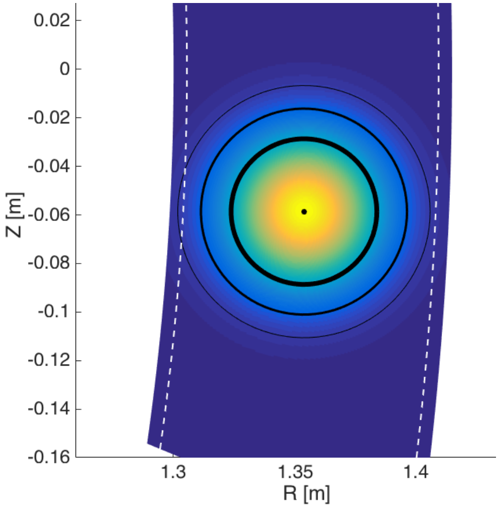
- **Full-Box Hybrid Scale Simulation**:
  - Too computationally intensive **~ 1-2 M CPU h**
  - Numerical convergence issue (ions start being resolved)

L_r x L_y = 50 x 21 ρ_s (L/a~0.2)
n_r x n = 900/1024 x 140/220

Hybrid Scale



Full-Box Hybrid Scale



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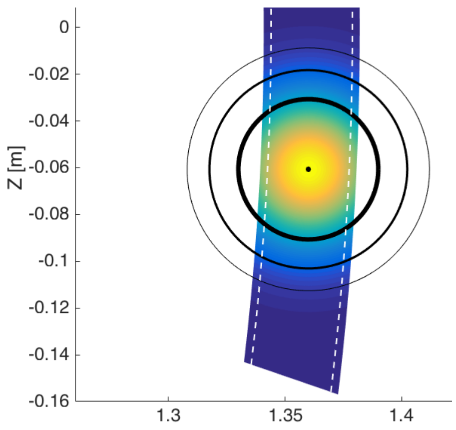
Hybrid Scale



- ~~**Full-Box Hybr**~~ ~~**le Simulation**~~:
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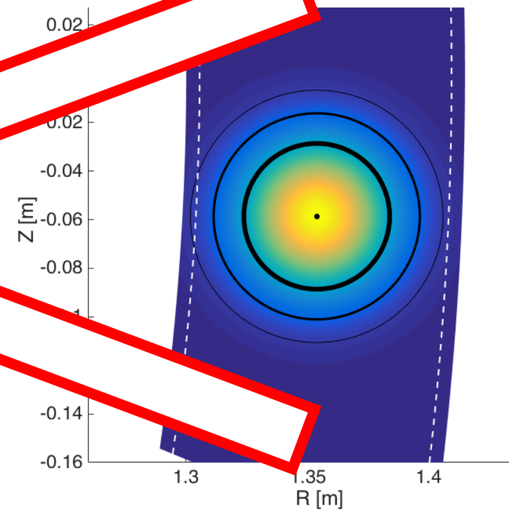
~~L_r x L_y = 50 x 21 ρ_s (L/a~~
~~n_r x n = 900/102~~ ~~/220~~

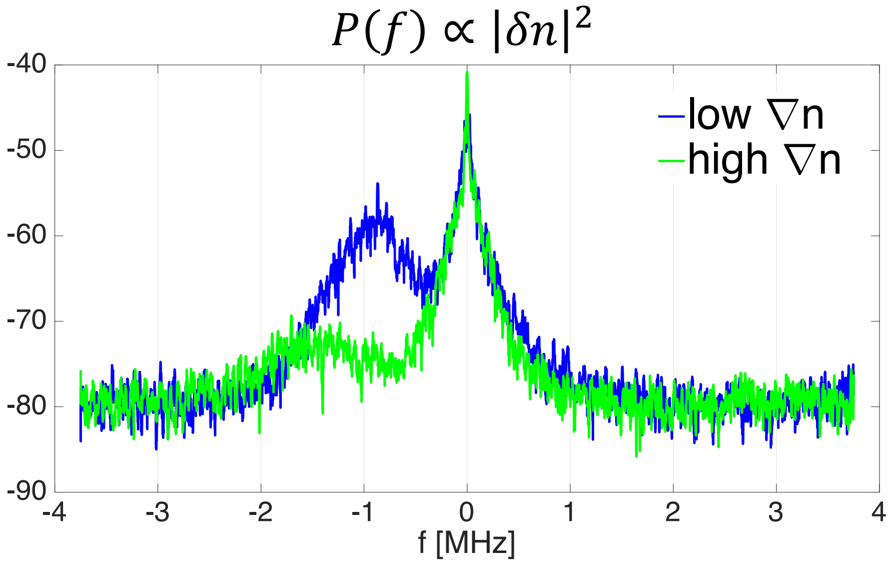
Full-Box H~~y~~brid Scale

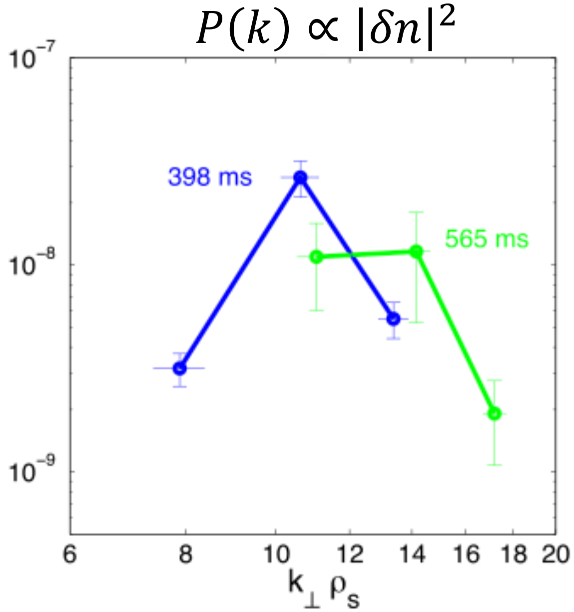


The Need for a Synthetic Diagnostic

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

- Experiment in lab frame, simulation in plasma frame → Doppler shift
- Limited spatial and wavenumber resolution
  → **a synthetic diagnostic**


$P(f) \propto |\delta n|^2$

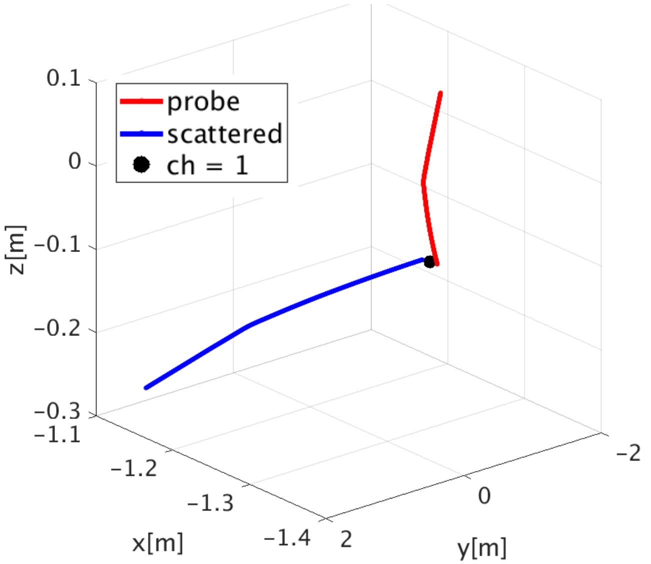

$P(k) \propto |\delta n|^2$

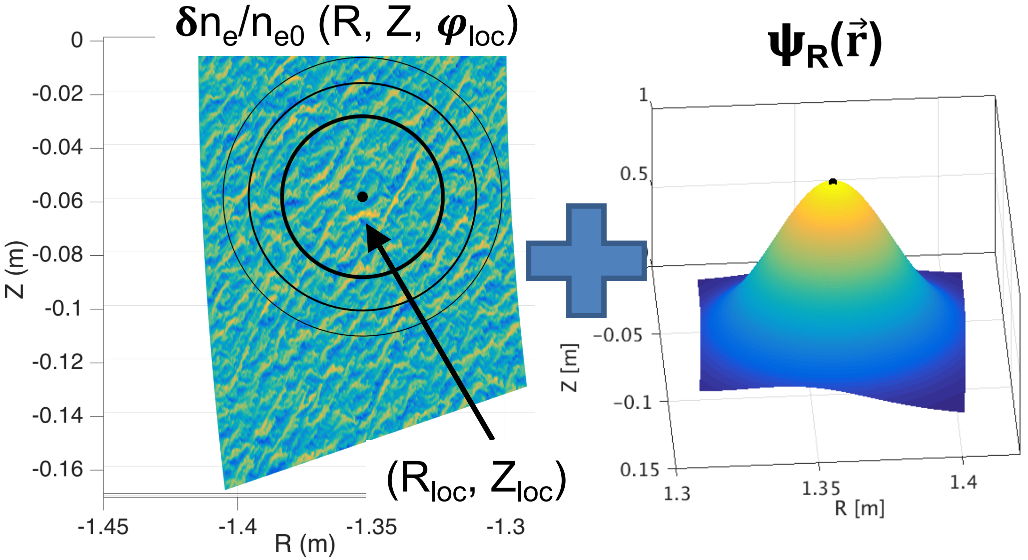
Previous Work on Synthetic High-k Diagnostic on NSTX

- Previous synthetic high-k scattering was implemented with GTS (*cf.* Poli PoP 2010, Poli APS 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.

New Synthetic Diagnostic Implementation Real Space: 2D (R, Z) model

Ray tracing in 3D ➔ Filter turbulence in 2D at φ_{loc}

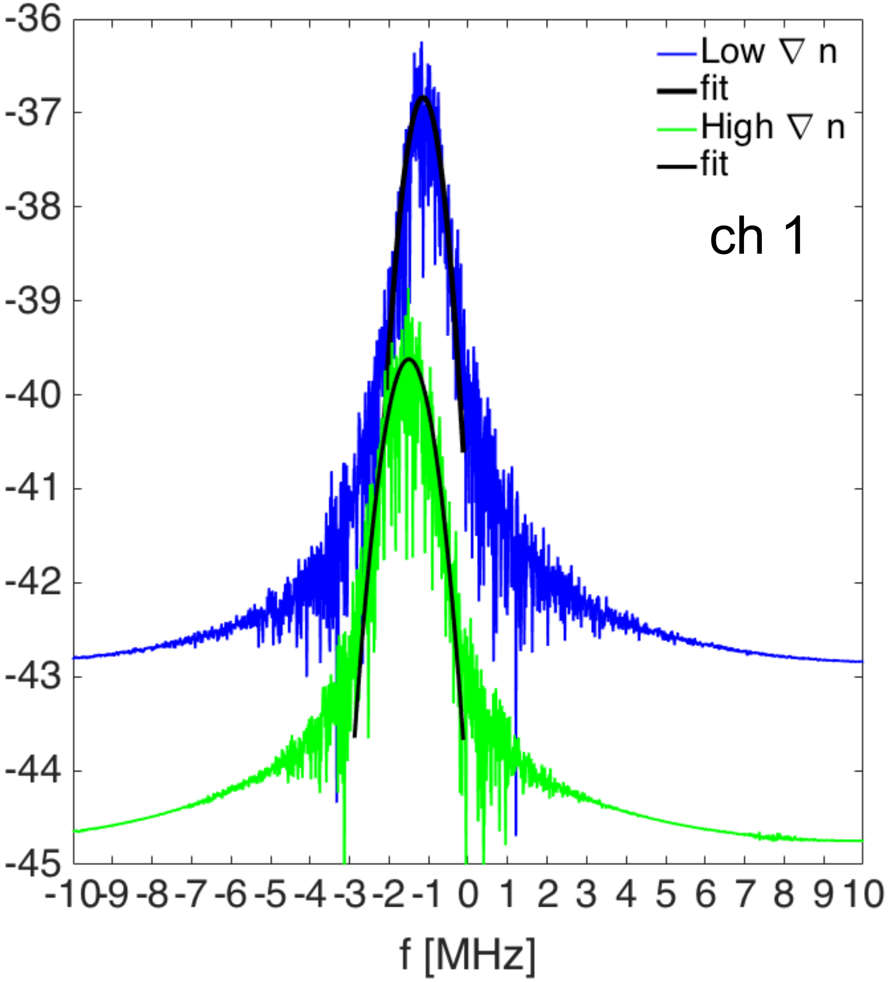




- Gaussian filter in space is applied to raw GYRO density fluct. amplitude
- Obtain a filtered time series of density fluctuations $\delta\hat{n}_e{}^{syn}(t)$ (analyzed the same way as experiment)

Frequency Analysis of Synthetic Time Series $\delta\hat{n}_e{}^{syn}(t)$ Provides Synthetic Diagnostic f-Spectrum $S(f)$

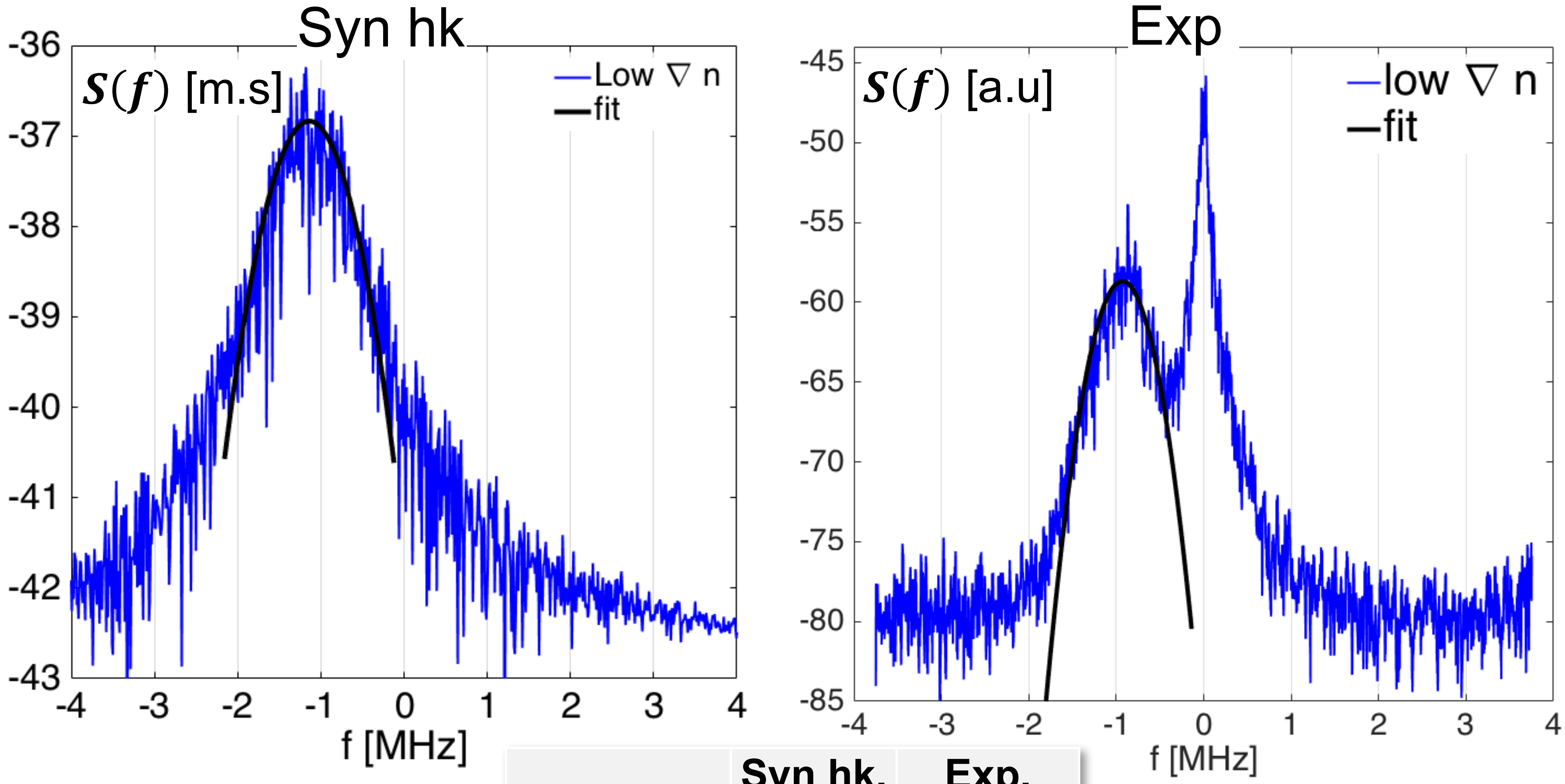
Syn. f-spectrum $S(f) \propto |\delta n|^2$



- Gaussian fit
  → $S_{tot}, < f >, \sigma_f$

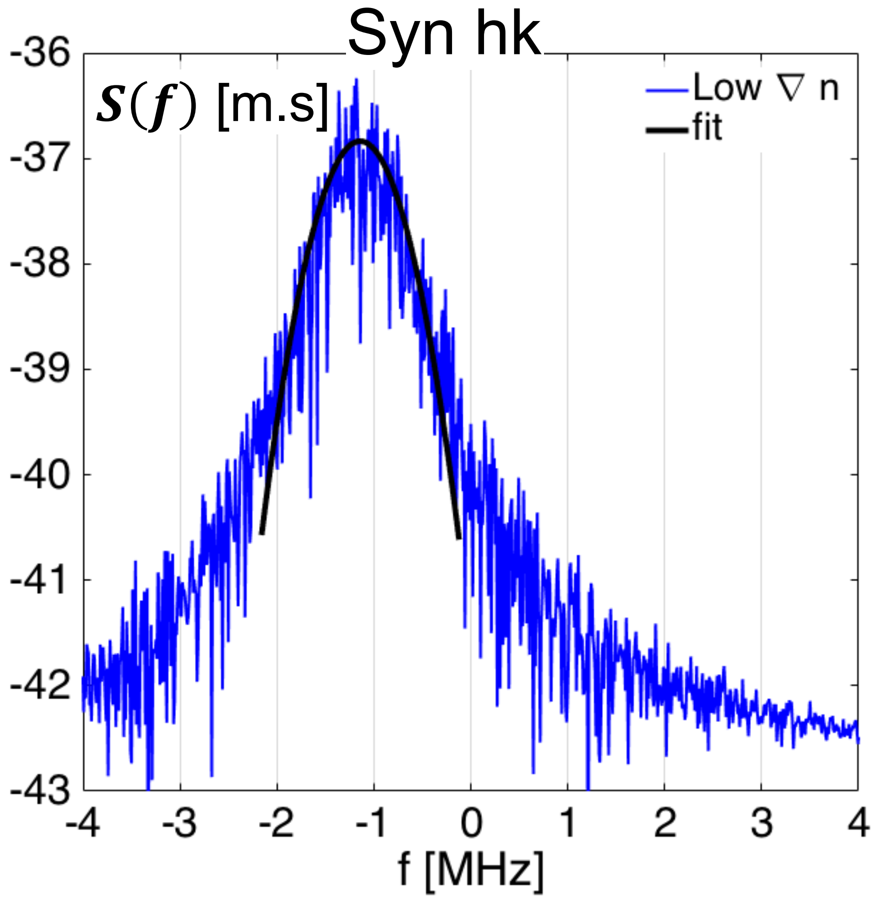
- **Low ∇n → High ∇n**
  - Decrease in S_{tot} → stabilization of ETG
  - Higher frequency f → Doppler shift
    $f_D = \vec{k} \cdot \vec{v} \approx n\omega_0$. Increase in ω_0 (similar $\vec{k}$)
  - Higher spectral width σ_f
    Increase in ω_0 (ω_0 widens spectrum in lab frame)

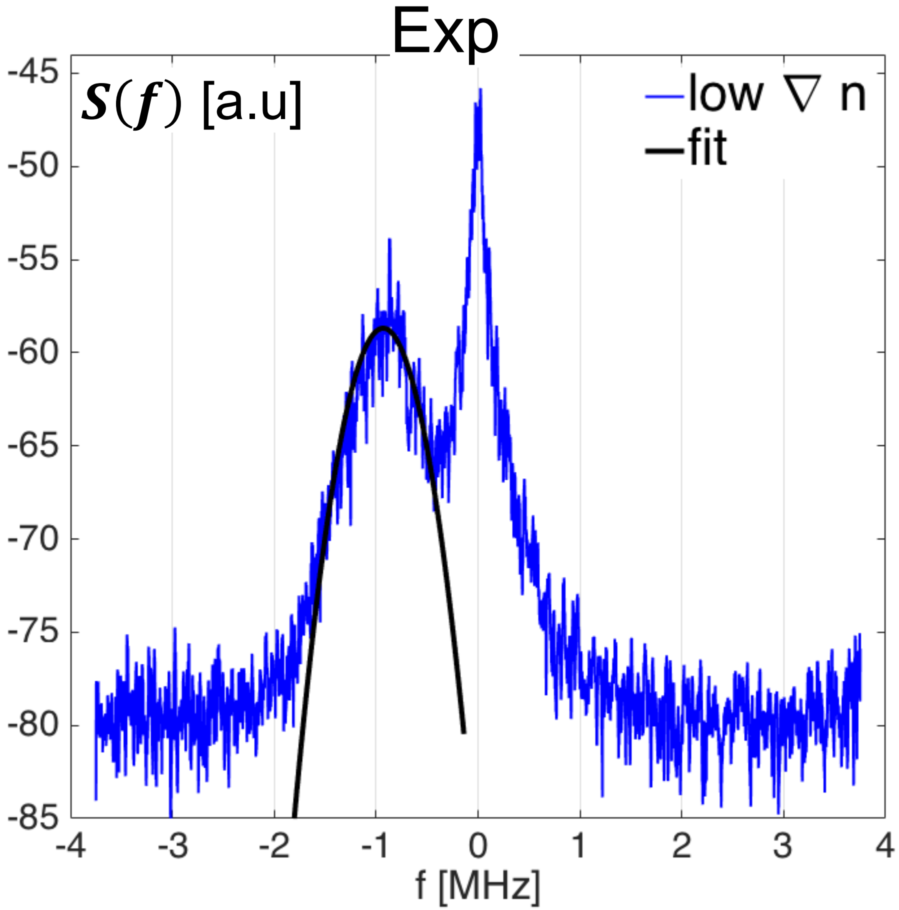
Analyze Synthetic and Exp. Spectrum to Compare $S_{tot}, < f >, \sigma_f$ at Low ∇n



	Syn hk.	Exp.
S_{tot} [m.s]	8.9 10^{-32}	0.849
$< f >$ [kHz]	-1142	-931
σ_f [kHz]	254	250

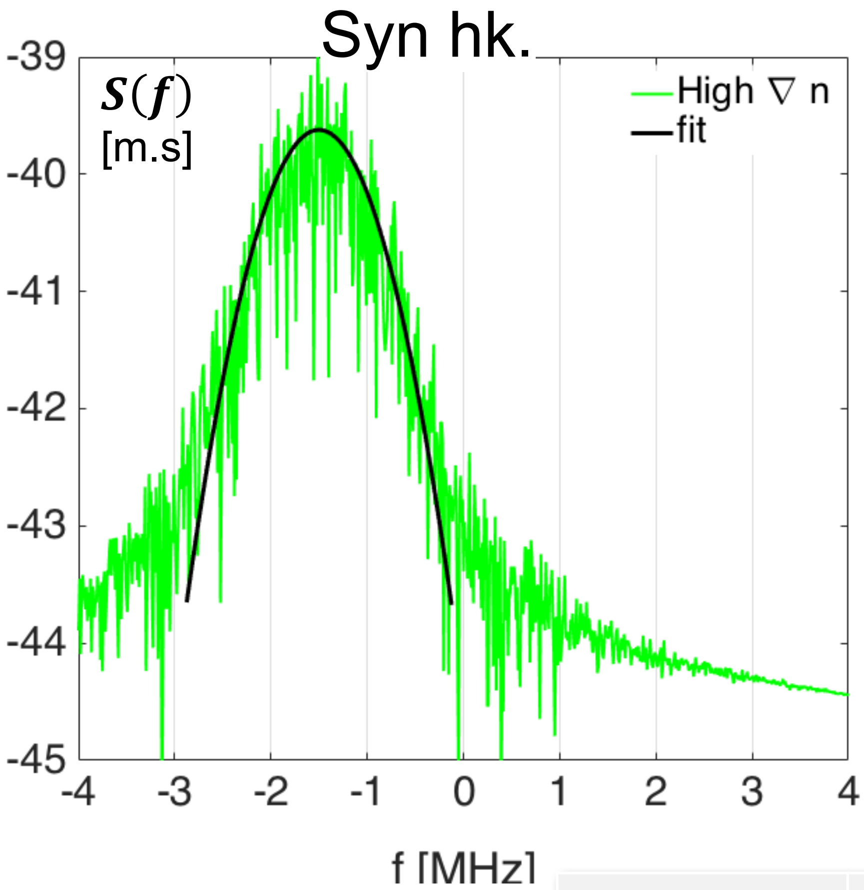
Analyze Synthetic and Exp. Power to Compare $S_{tot}, < \boldsymbol{f} >, \boldsymbol{\sigma_f}$ at Low ∇n

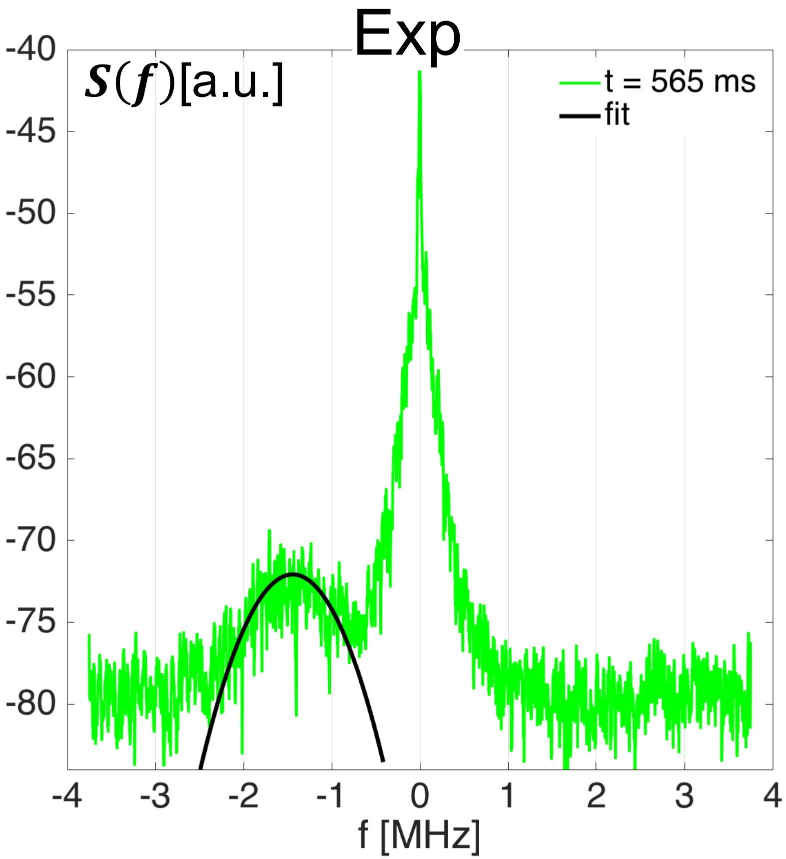




- Quantitative agreement $< \boldsymbol{f} >, \boldsymbol{\sigma_f}$ $(\pm 20\%)$
- **Exp. NOT absolutely calibrated → cannot quantitatively compare S_{tot}**

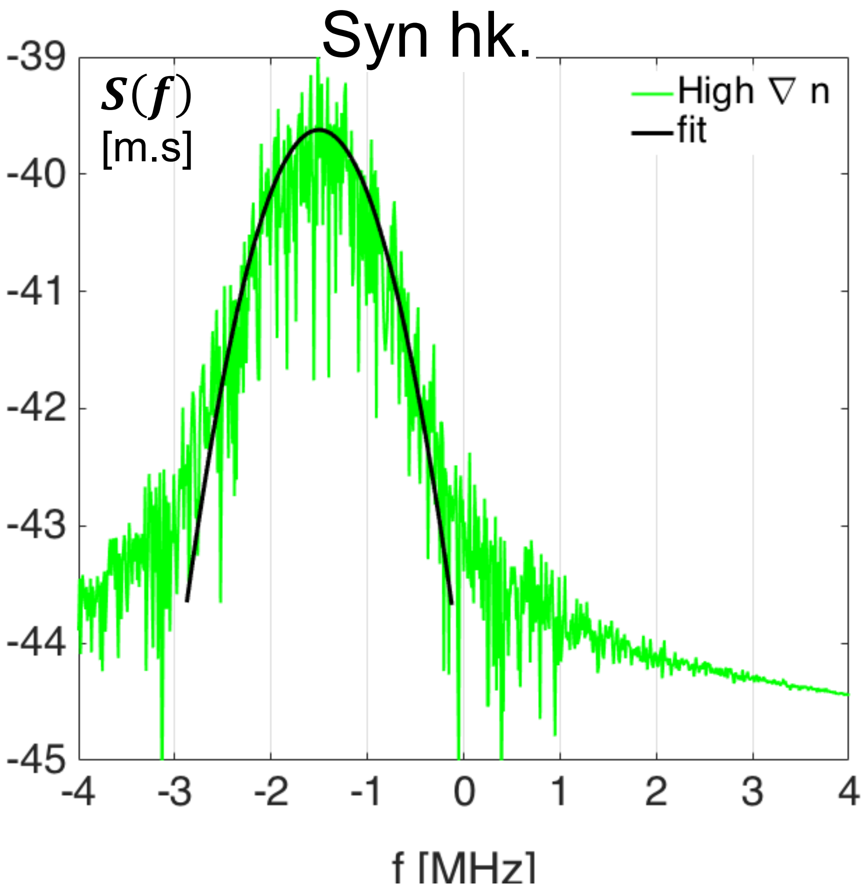
Mean Frequency and Spectral Width Quantitatively Agree with Experiment at High ∇ n (a/Ln=4)

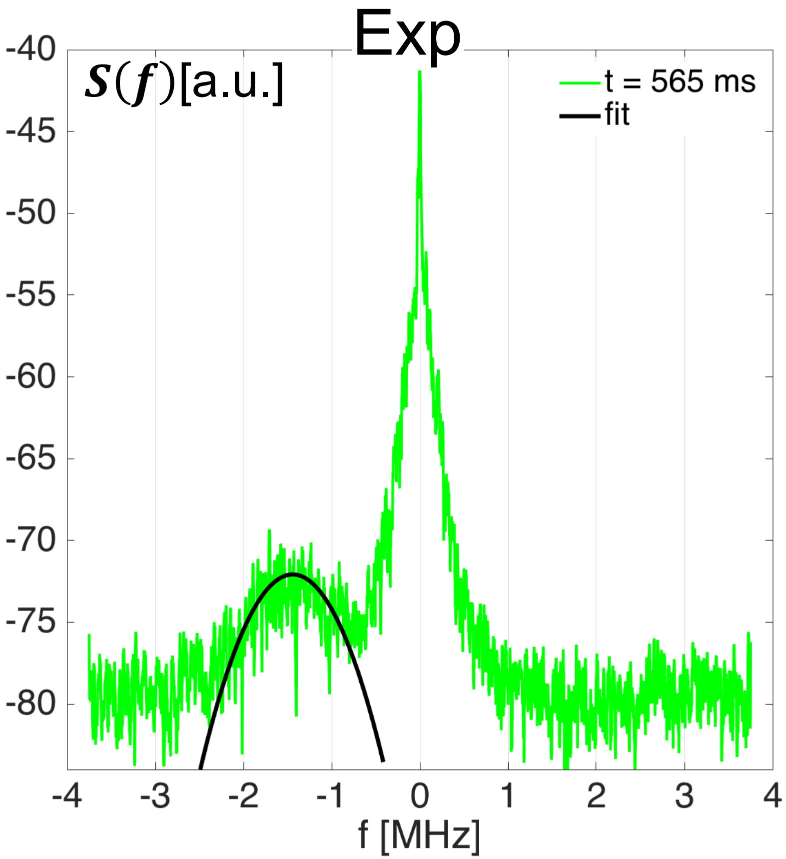




	Syn hk.	**Exp.**
S_{tot} [a.u.]	$1.9\ 10^{-34}$	0.069
$< f >$ [kHz]	-1501	-1442
σ_f [kHz]	345	447

Mean Frequency and Spectral Width Quantitatively Agree with Experiment at High ∇n (a/Ln=4)

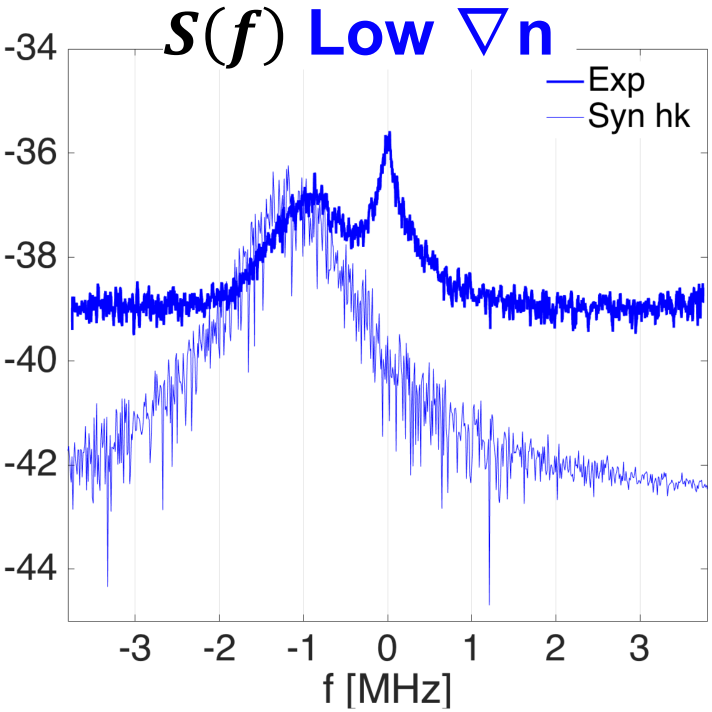


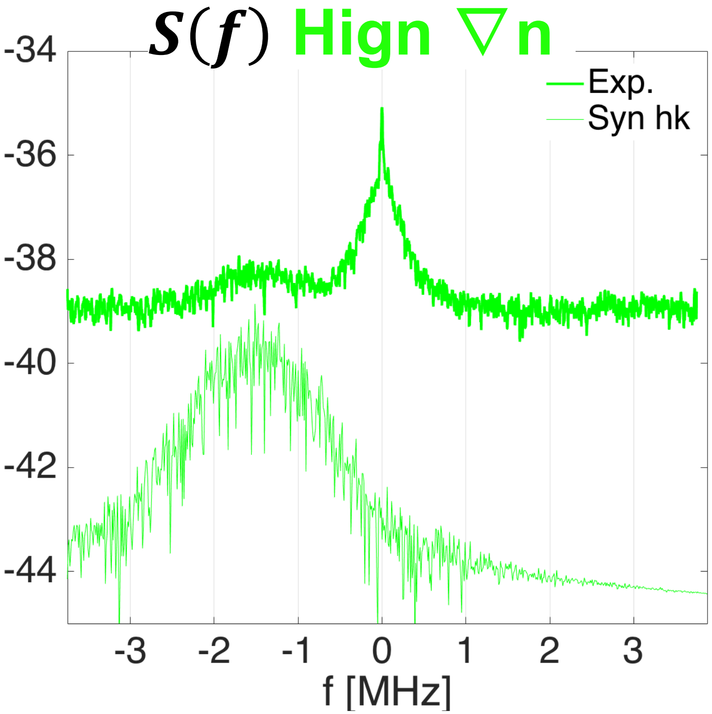


Experiment

- Quantitative agreement $< f >, \sigma_f$ $(\pm 20\%)$
- Rescale $\mathbf{S}_{\mathbf{tot}}^{\mathbf{exp}}$ for quantitative comparisons

Rescale $S(f)^{exp}$ to Quantitatively Compare Power at Low and High ∇n





Rescale $S(f)^{exp}$ at **Low ∇n**

→ Same scaling factor at **High ∇n**

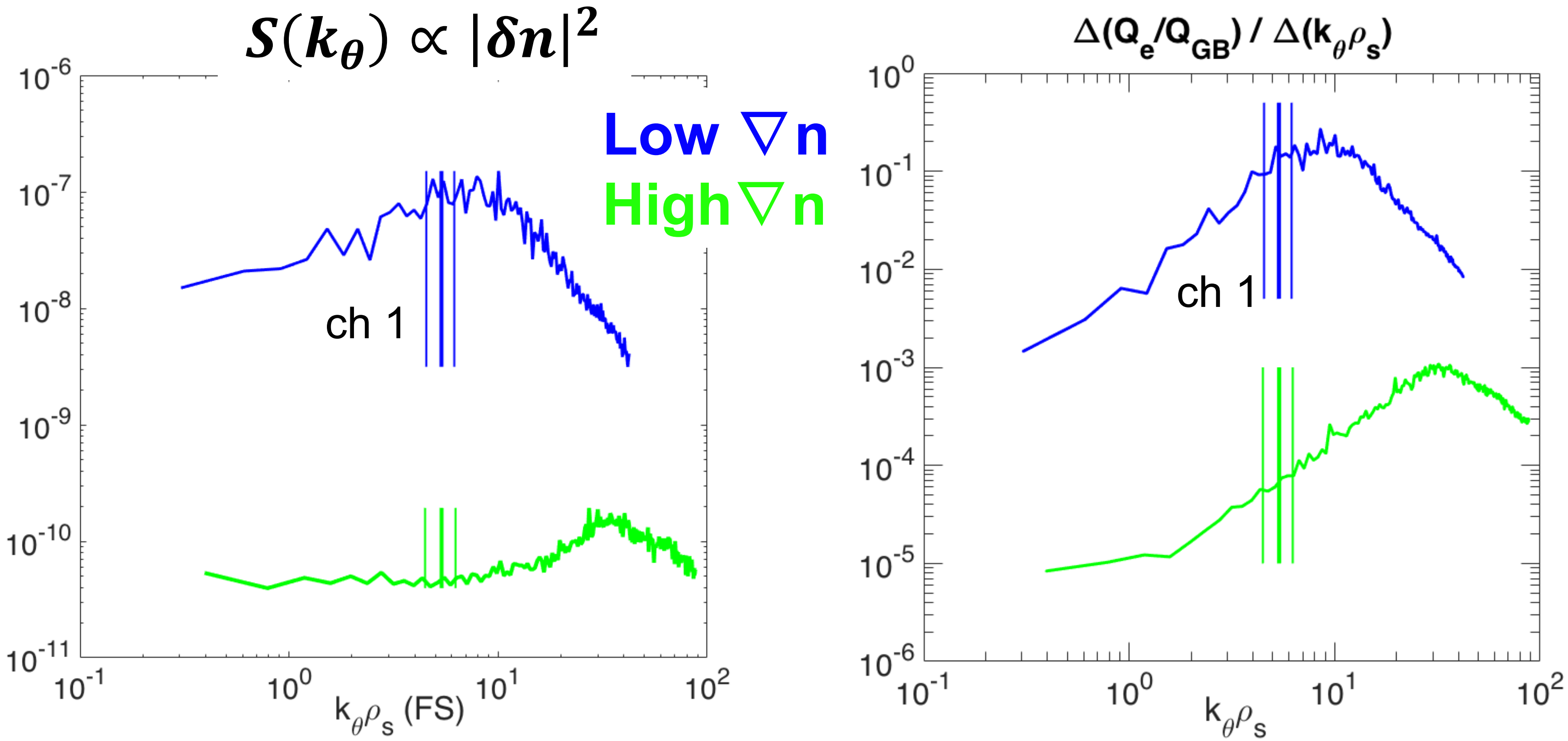
Low ∇n

- Increased noise level in exp.

High∇n

- Underpredicted S_{tot} X 40 !!

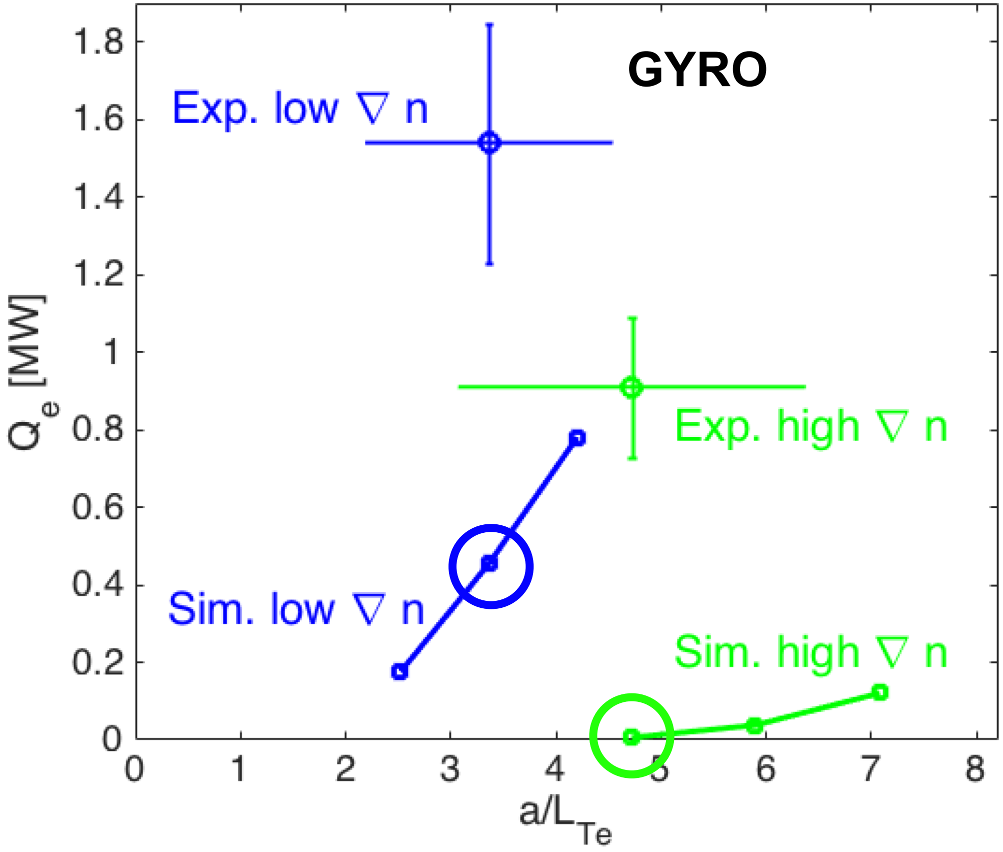
Measurement k is Close to Spectral Peak at Low ∇n, Far From Spectral Peak at High ∇n



Low ∇n → High ∇n

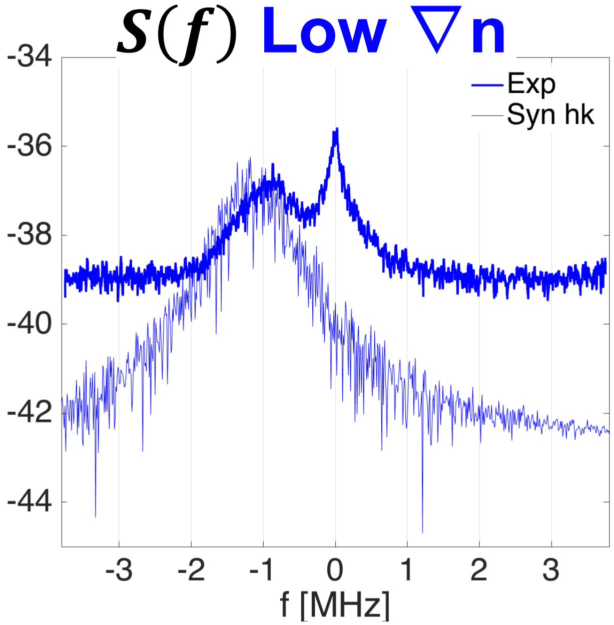
- Decrease in spectral density $S(k_\theta)$ + Q_e→ stabilization of ETG
- Shift spectral peak to higher k_θ

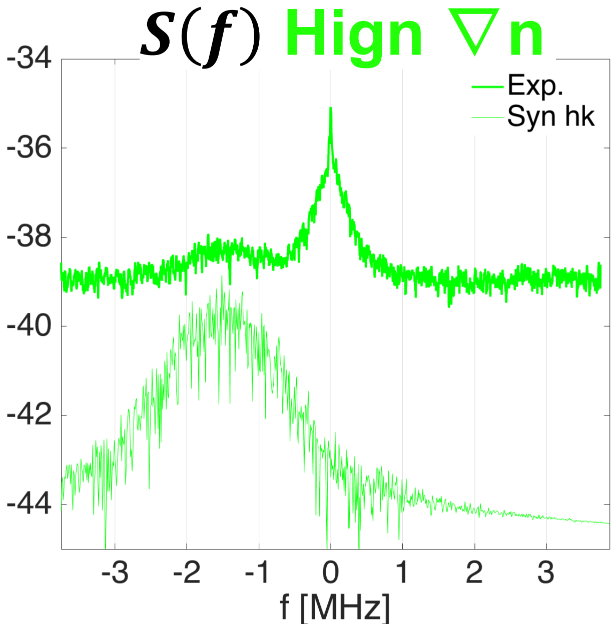
Recall: Nonlinear Electron Scale GYRO Simulations Cannot Explain Experimental Electron Heat Flux



	Low ∇n	**High ∇n**
$\mathbf{Q_e^{sim}/Q_e^{exp}}$	20-30%	~ 0%

Conclusions: Synthetic High-k Matches $< f >, \sigma_f$ at Low ∇n and High ∇n, Underpredicts S_{tot} at High ∇n





- Q_e^{sim} ~ 20-30% Q_e^{exp}
- Sim. ***could*** be capturing correct turbulence
- Should consider additional sources of transport (ion scale, Multi-scale, AEs, …)

- Sim. **NOT** capturing correct turbulence
- Could expect increase in Q_e^{sim} x40
- **Multi-scale** might increase turbulence level

Next Steps

Future Directions

- Quantitatively compare k-spectrum of fluctuations.

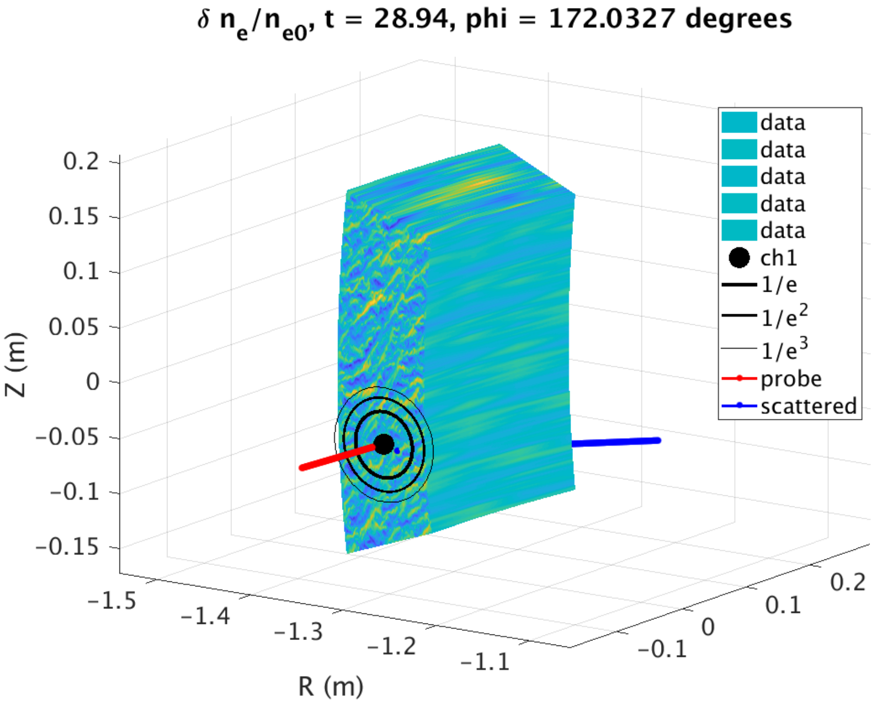
- Ion-scale transport

  GYRO shows $Q_e^{\text{ion scales}} \sim 0$

  → CGYRO

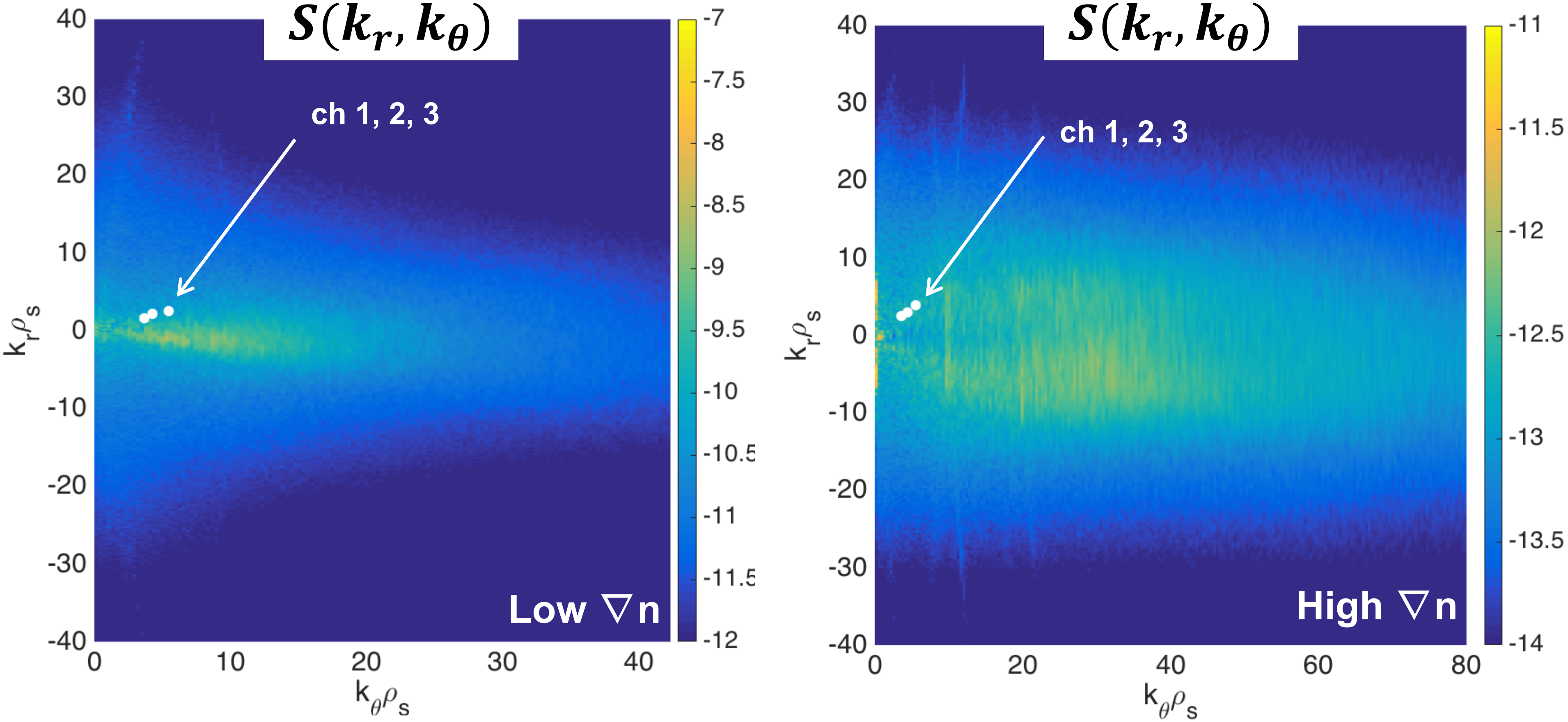
- Implement a 3D synthetic diagnostic to more accurately model scattering volume

- Multi-scale simulation + quantitative comparisons with Synthetic Diagnostic



Questions
&
Discussion

Wavenumber Spectral Range at Low and High ∇n



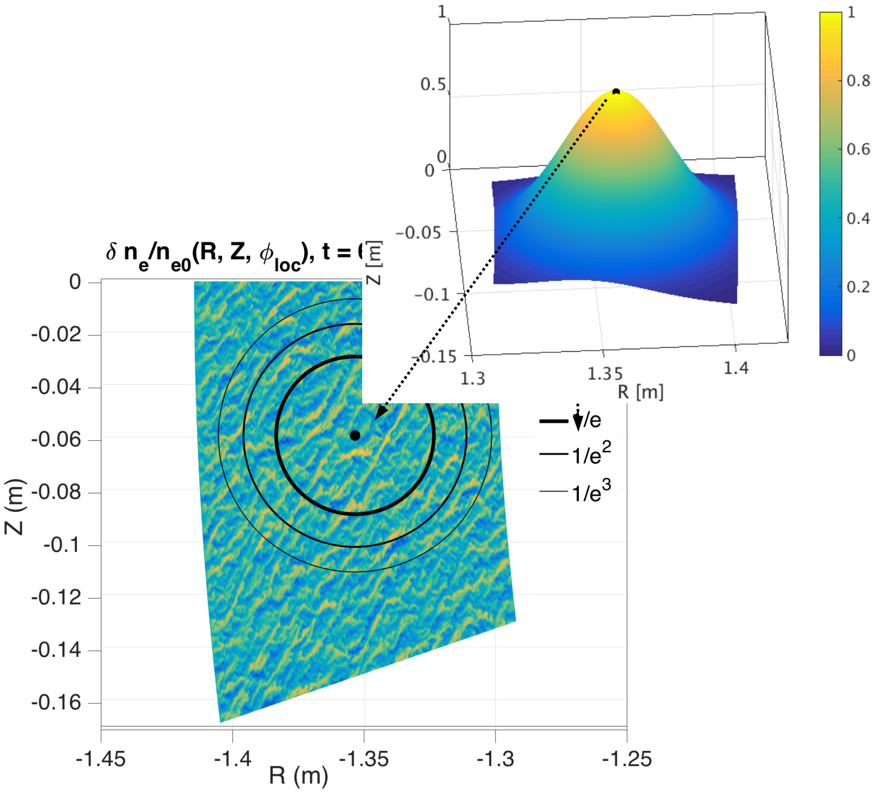
Turbulence from Low ∇n → High ∇n

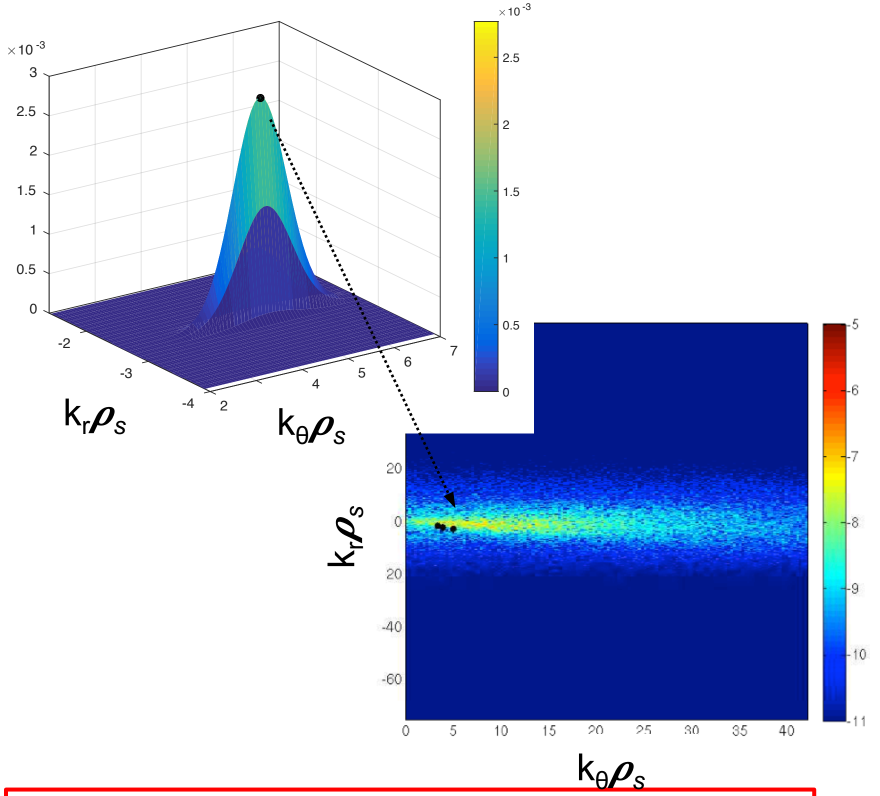
- Decrease in spectral density S → stabilization of ETG
- Shift spectral peak to higher k_θ

1.B. Synthetic Density Fluctuations can be computed in real-space or k-space

Filter in real space: $\boldsymbol{\psi}_R(\vec{r})$

Filter in wavenumber space: $\boldsymbol{\psi}_K(\vec{k}-\vec{k}_0)$



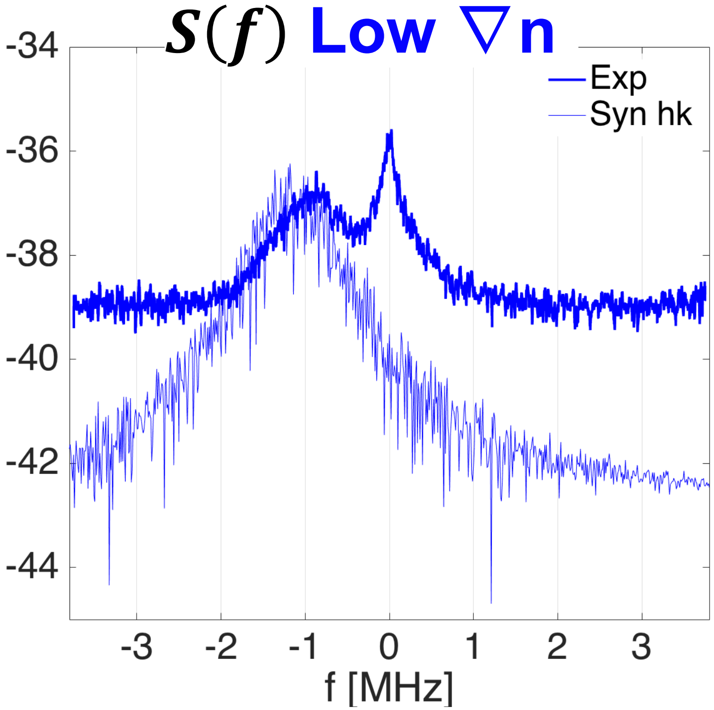


$$\delta\hat{n}_e{}^{syn}(t) = \int \tilde{n}_e(\vec{r},t)\boldsymbol{\psi}_R(\vec{r})e^{-I\vec{k}_0\cdot\vec{r}}\,d^3\vec{\mathbf{r}}$$

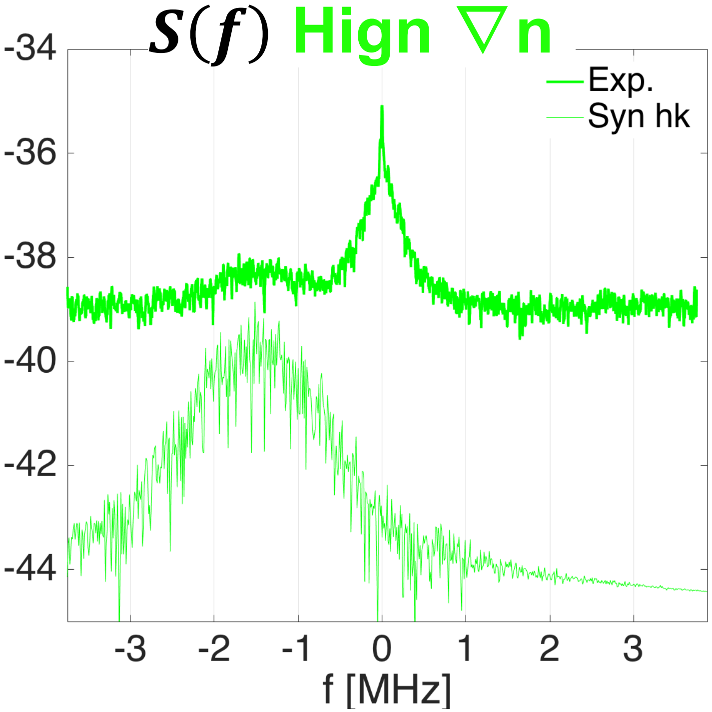
$$\delta\hat{n}_e{}^{syn}(t) = \frac{1}{(2\pi)^3}\int \tilde{n}_e(\vec{k},t)\boldsymbol{\psi}_K(\vec{k}\text{-}\vec{k}_0)\,d^3\vec{\mathbf{k}}$$

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

Rescale Exp. Power to Quantitatively Compare Amplitude at Low and High ∇n



$S(f)$ **Low ∇n**



$S(f)$ **Hign ∇n**

Experiment $S(f)$ rescaled in power at **Low ∇n**, same scaling factor at **High ∇n**

Low ∇n → Quant. agreement $< f >, \sigma_f$

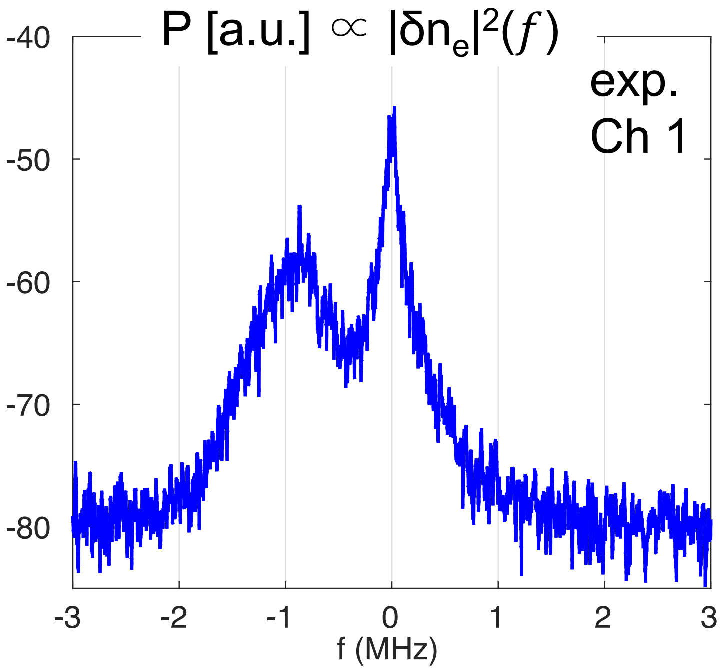
High∇n→ Quant. agreement $< f >, \sigma_f$

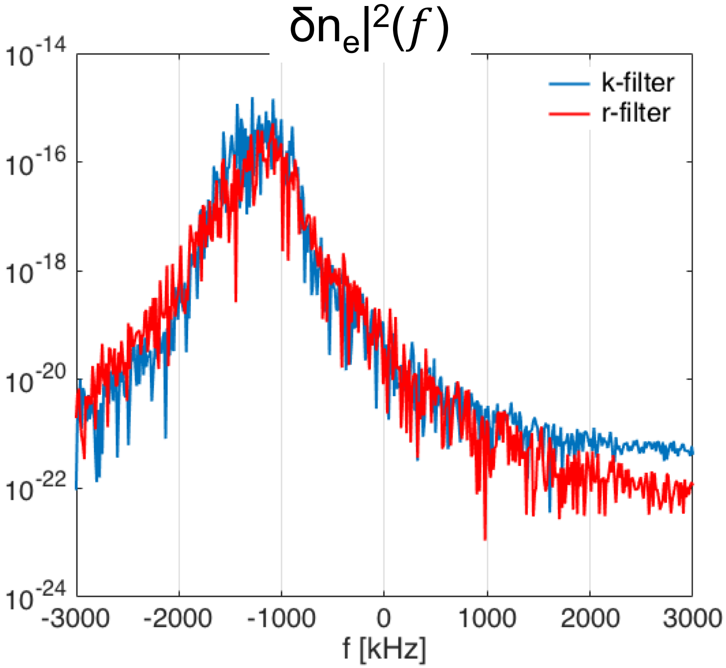
→ Underpredicted P_s x 40

	Syn hk	**Exp.**	**Syn hk**	**Exp.**
P_s [a.u.]	$8.9\ 10^{-32}$	0.849	$1.9\ 10^{-34}$	0.069
$< f >$ [kHz]	-1142	-931	-1501	-1442
σ_f [kHz]	254	250	344	447

1.D. First Preliminary Comparisons with Experiment

Low ∇n (a/Ln=1)

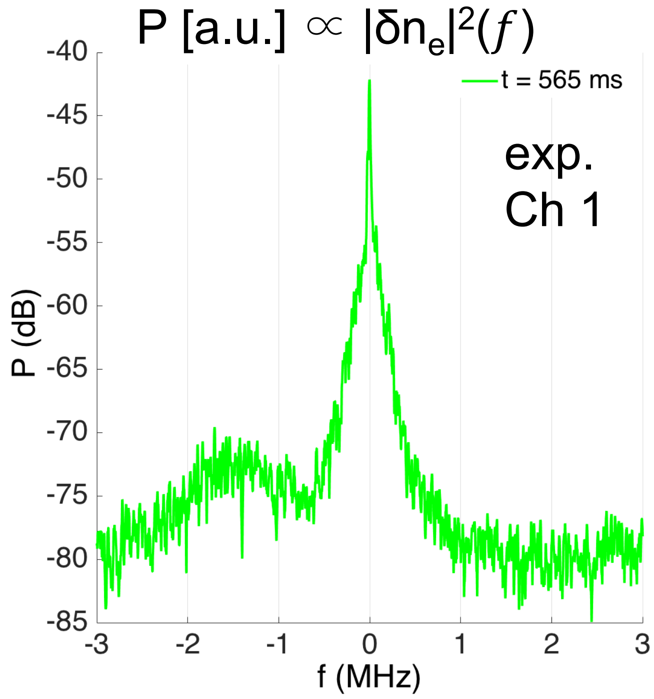


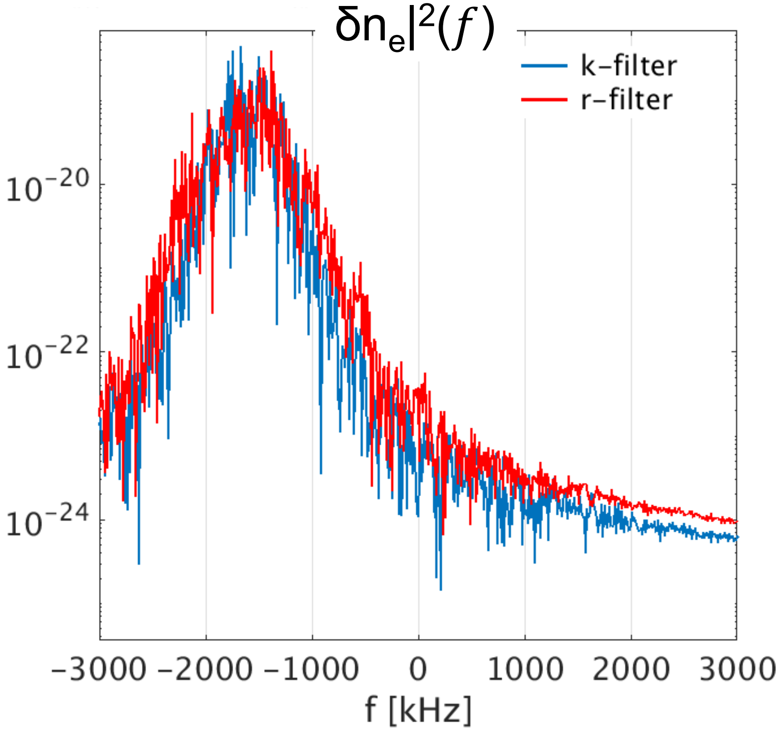


Synthetic parameters	**k-filter**	**r-filter**	**experiment**
P_{abs} [a.u.]	$2.2\ 10^{-10}$	$8.9\ 10^{-11}$	?
f_{mean} [kHz]	-1222	-1182	?
σ_f [kHz]	194	208	?

1.D. First Preliminary Comparisons to Experiment

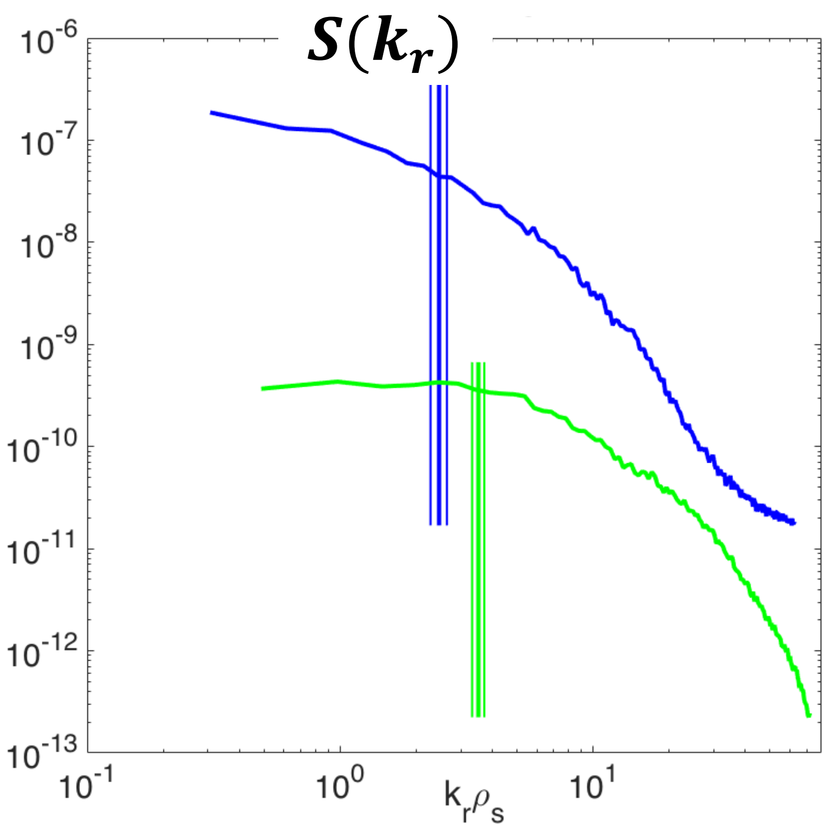
High ∇ n (a/Ln=4)

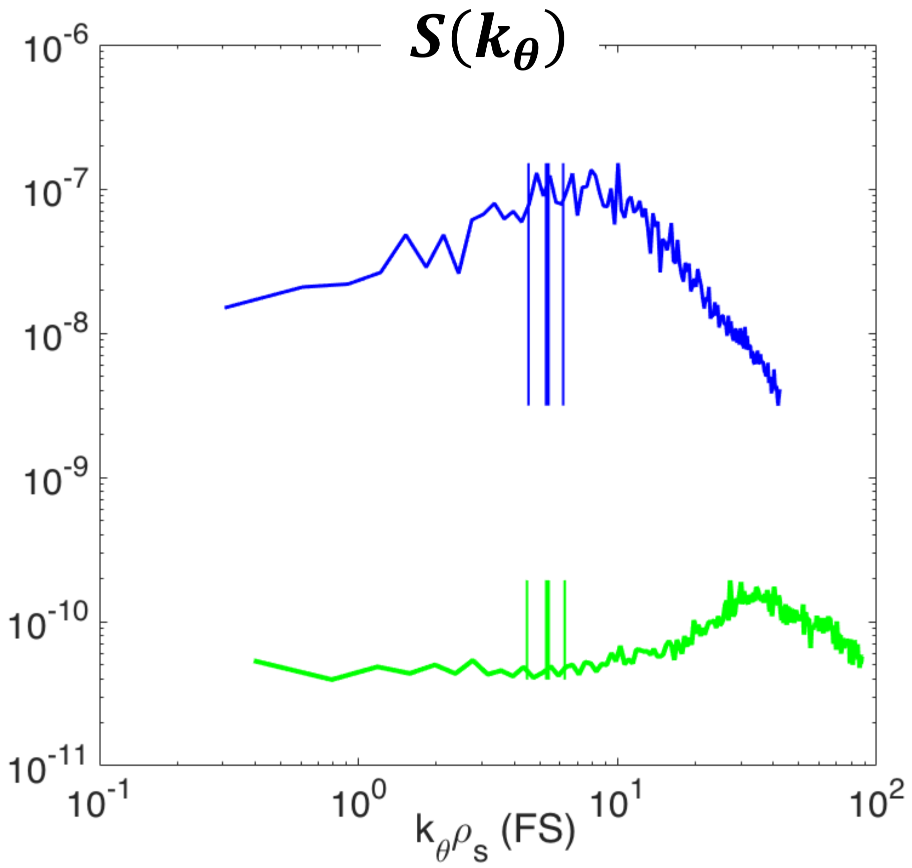




Synthetic parameters	k-filter	r-filter	experiment
P_{abs} [a.u.]	6.4 10^{-14}	5.8 10^{-14}	?
f_{mean} [kHz]	-1609	-1572	?
σ_f [kHz]	218	284	?

Wavenumber Measurement Range at Low and High ∇n





Turbulence from Low ∇n → High ∇n

- Decrease in spectral density S → stabilization of ETG
- Shift spectral peak to higher k_θ

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
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 [ρ_s]	n_r
Ion scale	~ 0.5 ρ_s	~80-100	~ 200
e- scale	~ 2 ρ_e	~ 6-8	~ 200
Multi-scale	~ 3 ρ_e	~ 40-60	~ 1000
High res. e- scale	**2.5 ρ_e**	**20**	**512**

Time analysis

	Hybrid e-	**MS**
(n_r,n)	(142,512)	(500,1000)
t [a/c_s]	30	300
T [M CPUh]	0.5	~ 50

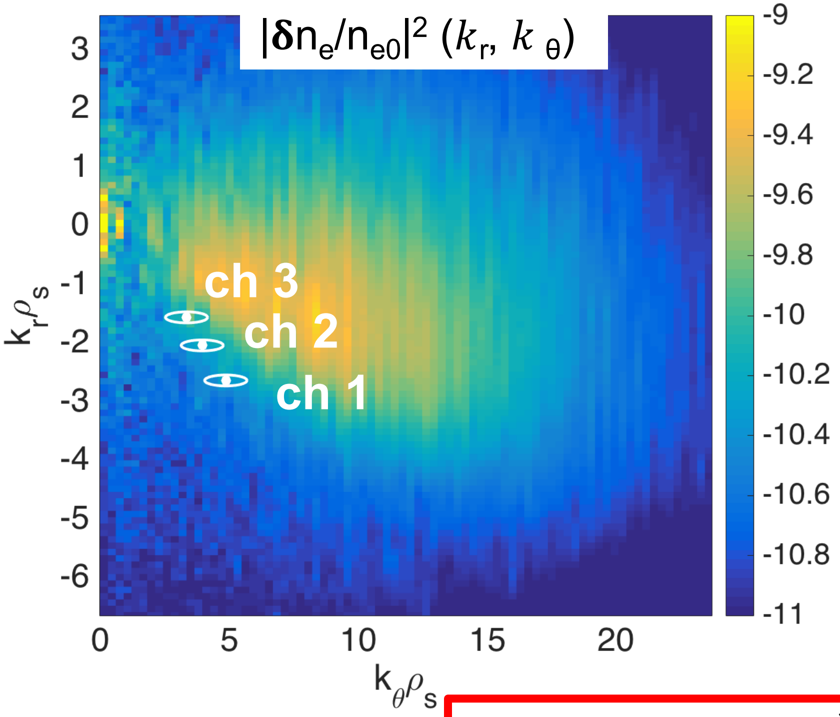
Minimum MS

- More expensive at High ∇n
    - Longer t, EM, n
- MS will not scale linearly with (n_r, n)
    - Expect x1.5, x2 …
- CGYRO could scale better

Synthetic Diagnostic for Coherent Scattering Traditionally Implemented in k-space

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

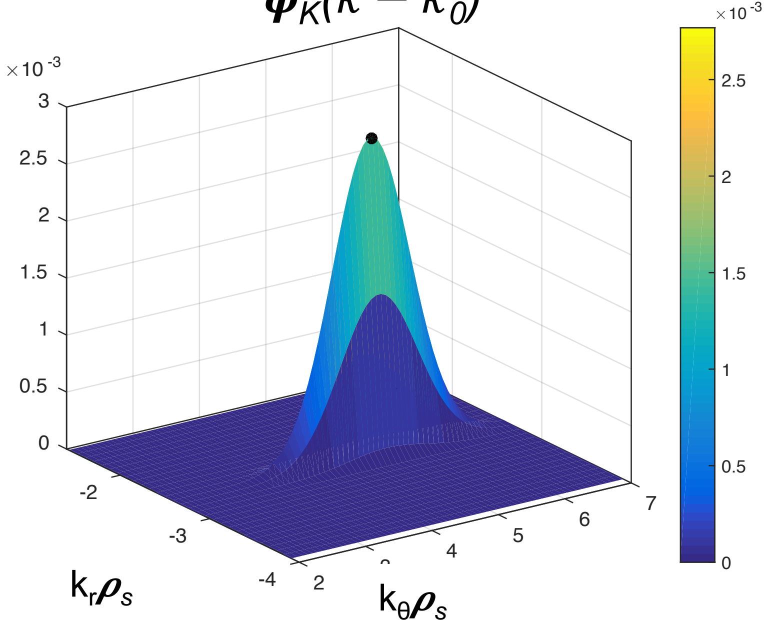
Analyze turbulence in k-space



+

Filter turbulence in k-space

$\psi_K(\vec{k}-\vec{k}_0)$



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

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

Two Equivalent Ways to Perform a Synthetic Diagnostic for High-k Scattering System

k-space filtering vs. real-space filtering

- Mathematically equivalent formulations
- Past work only used k-space filtering (F. Poli PoP 2010)

***k*-space filtering - Selection of k**

- Traditional way to interpret filtered scattering spectra.
- Delicate to compute (wavenumber mapping) $(k_R, k_Z, k_\varphi) \rightarrow (k_r, k_\theta, k_\varphi)$
- Code-dependent.

New: Real space filtering

- Common principle to all codes.
- Easier to implement and understand (no k-mapping).

Computing both methods we gain confidence in simulated synthetic spectra

Synthetic Diagnostic for the High-k Scattering System

Preliminary Steps:

1. High-k scattering diagnostic → experimental density fluctuation spectra $|\delta n_e|^2(\omega)$

2. Location of scattering + detected wavenumber → Ray tracing code:

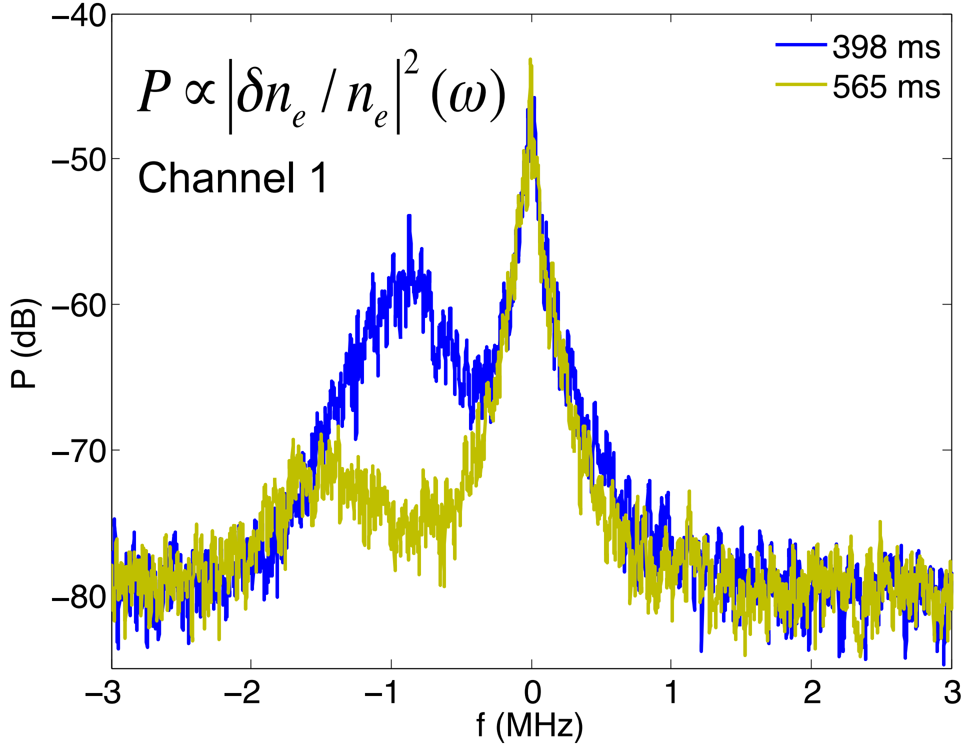
   - Scattering location + resolution $(R_{loc}, Z_{loc}) + (\Delta R_{loc}, \Delta Z_{loc})$
   - Turbulence wavenumber + resolution $(k_R^{exp}, k_Z^{exp}) + (\Delta k_R^{exp}, \Delta k_Z^{exp})$

3. Model of Turbulence → Gyrokinetics

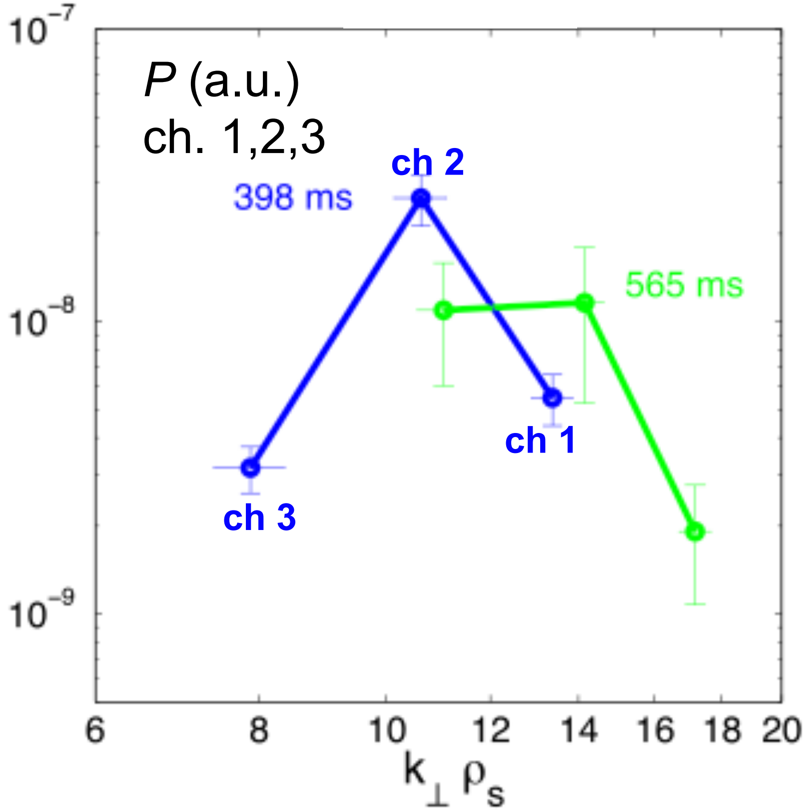
   Run a nonlinear gyrokinetic simulation (used GYRO here) capturing scattering location + resolving the experimentally measured wavenumber.

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

f −spectrum of exp. density fluctuations



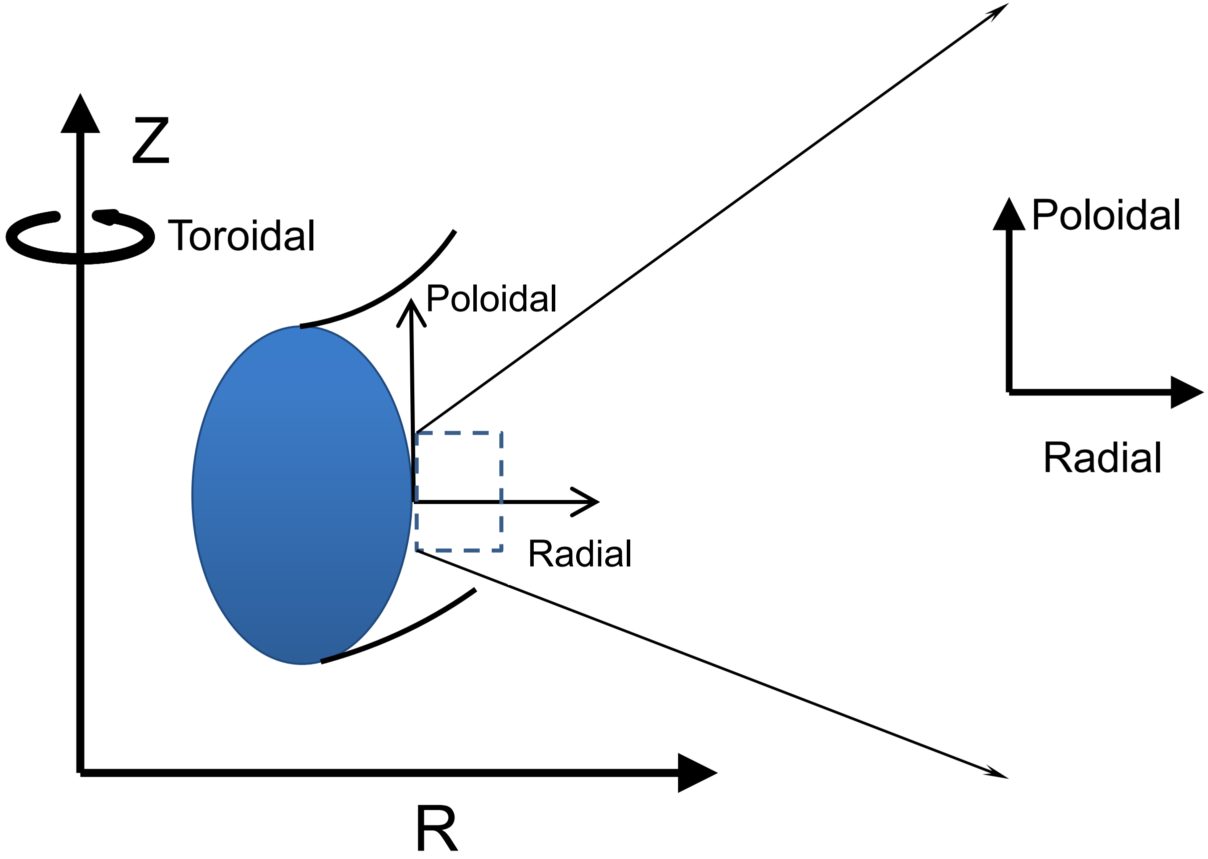
k-spectrum of exp. density fluctuations



- High-k scattering data of NSTX NBI heated H-mode plasma (*cf.* Ruiz Ruiz PoP 2015)
- Frequency analysis of scattered power → **frequency spectrum**.
- Different channels → different k → **wavenumber spectrum** of turbulence

Turbulent Fluctuations are Thought to Dominate Heat Losses in Tokamaks

GYRO nonlinear gyrokinetic simulation



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

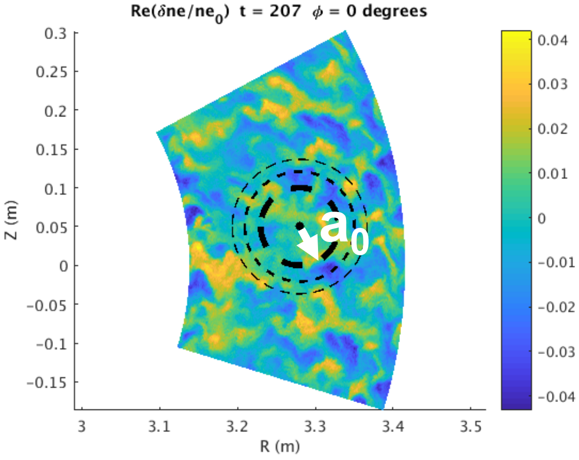
Numerical resolution parameters	
$\Delta k_x \rho_s = 0.049$	$\Delta k_y \rho_s = 0.049$
$k_x \rho_s^{max} = 3.14$	$k_y \rho_s^{max} = 3.093$
$L_x/\rho_s = 128$	$L_y/\rho_s = 128$
dn = 8	Bm = 4.94
$\Delta x/\rho_s = 0.5$	Lx/a = 0.28
$n_x = 256$	$n_n = 64$
Experimental beam width: Δx = 5, 10, 20 cm	
$\Delta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

Real Space Filters – 2D

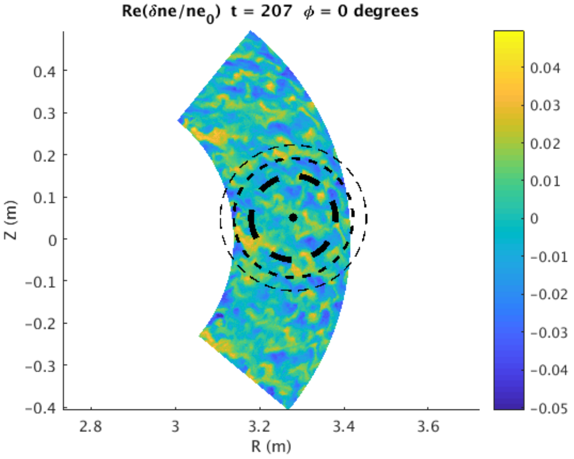
Goal: establish sensitivity of synthetic signal to beam width

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

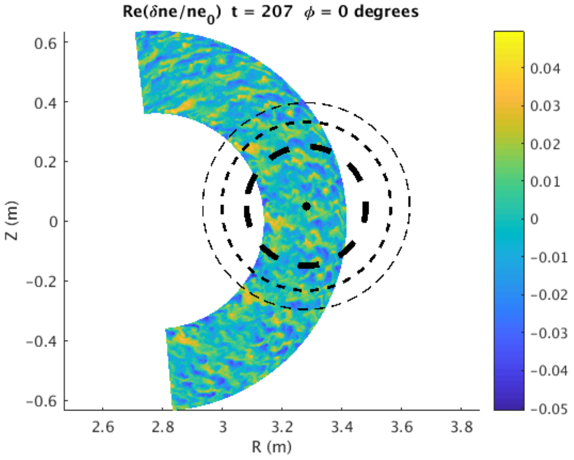
a_0 = 5 cm



a_0 = 10 cm



a_0 = 20 cm



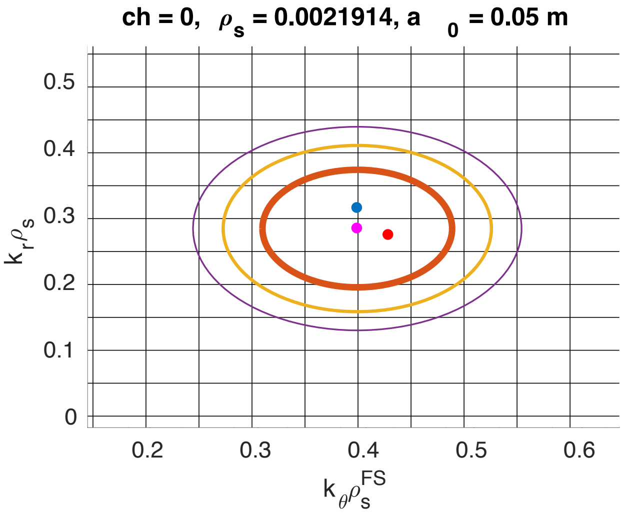
a_0 is the beam width

Wavenumber Space Filters – 2D

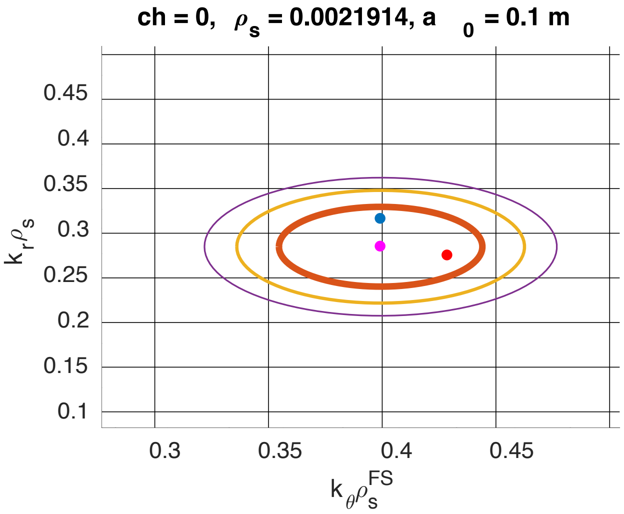
Measurement Wavenumbers

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

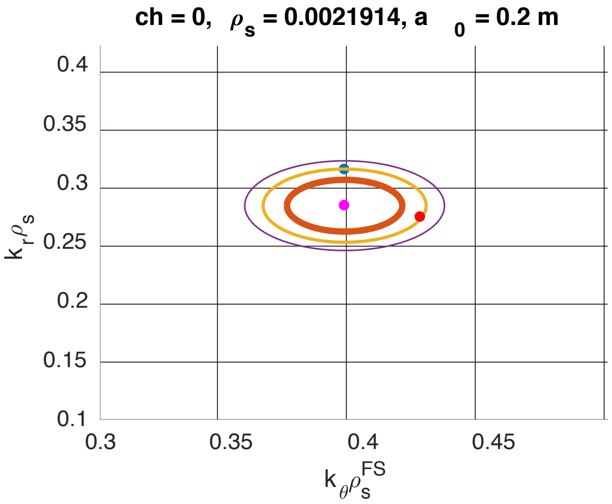
a_0 = 5 cm



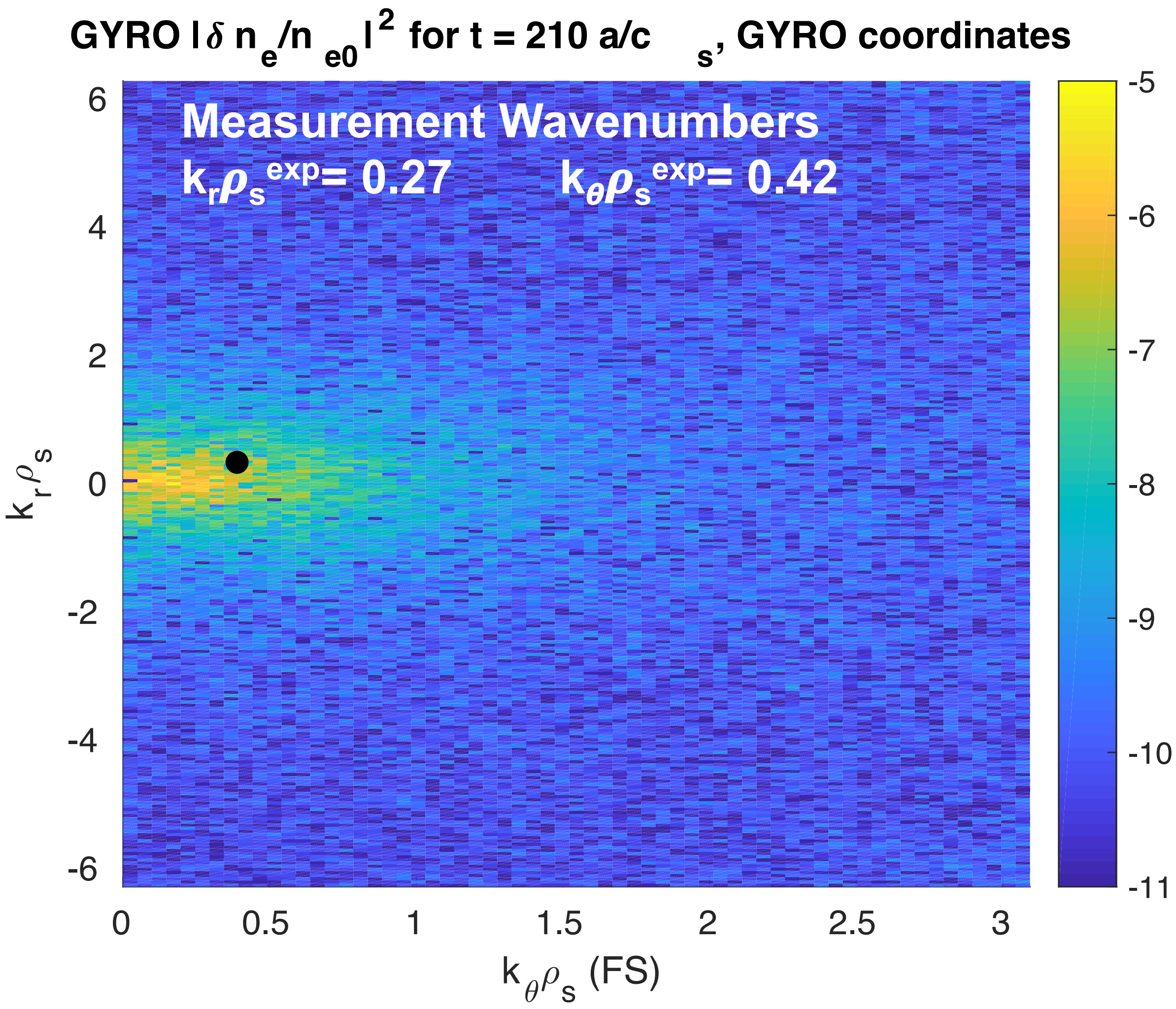
a_0 = 10 cm

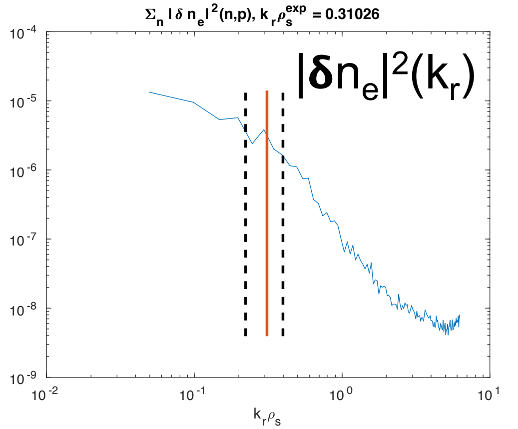


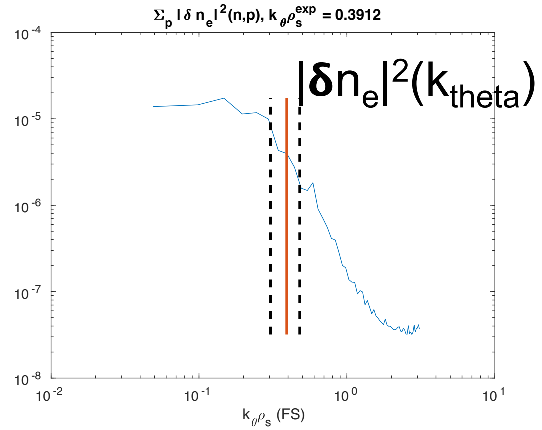
a_0 = 20 cm



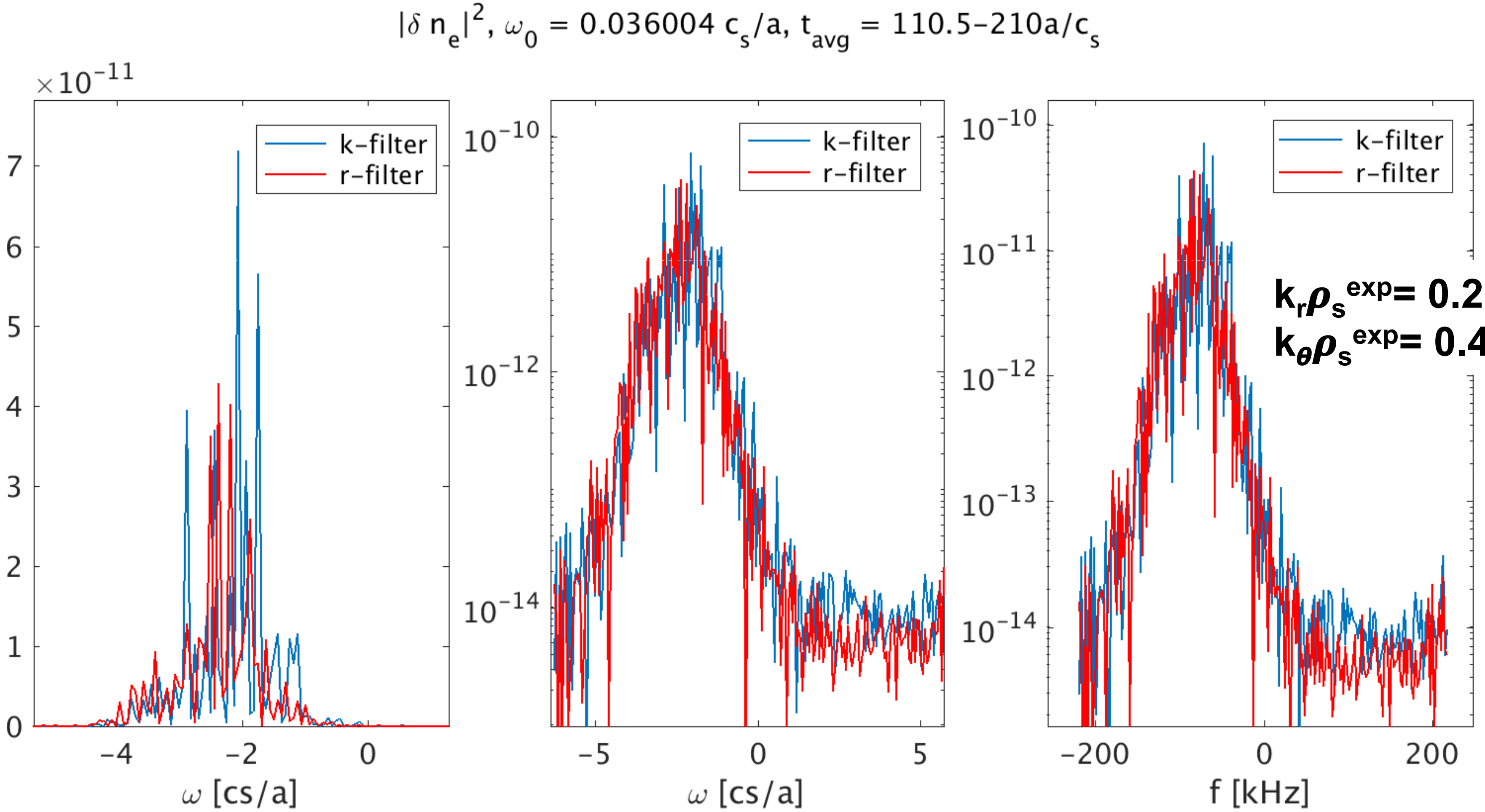
Wavenumber measurement region







Synthetic signal: a_0 = 5 cm

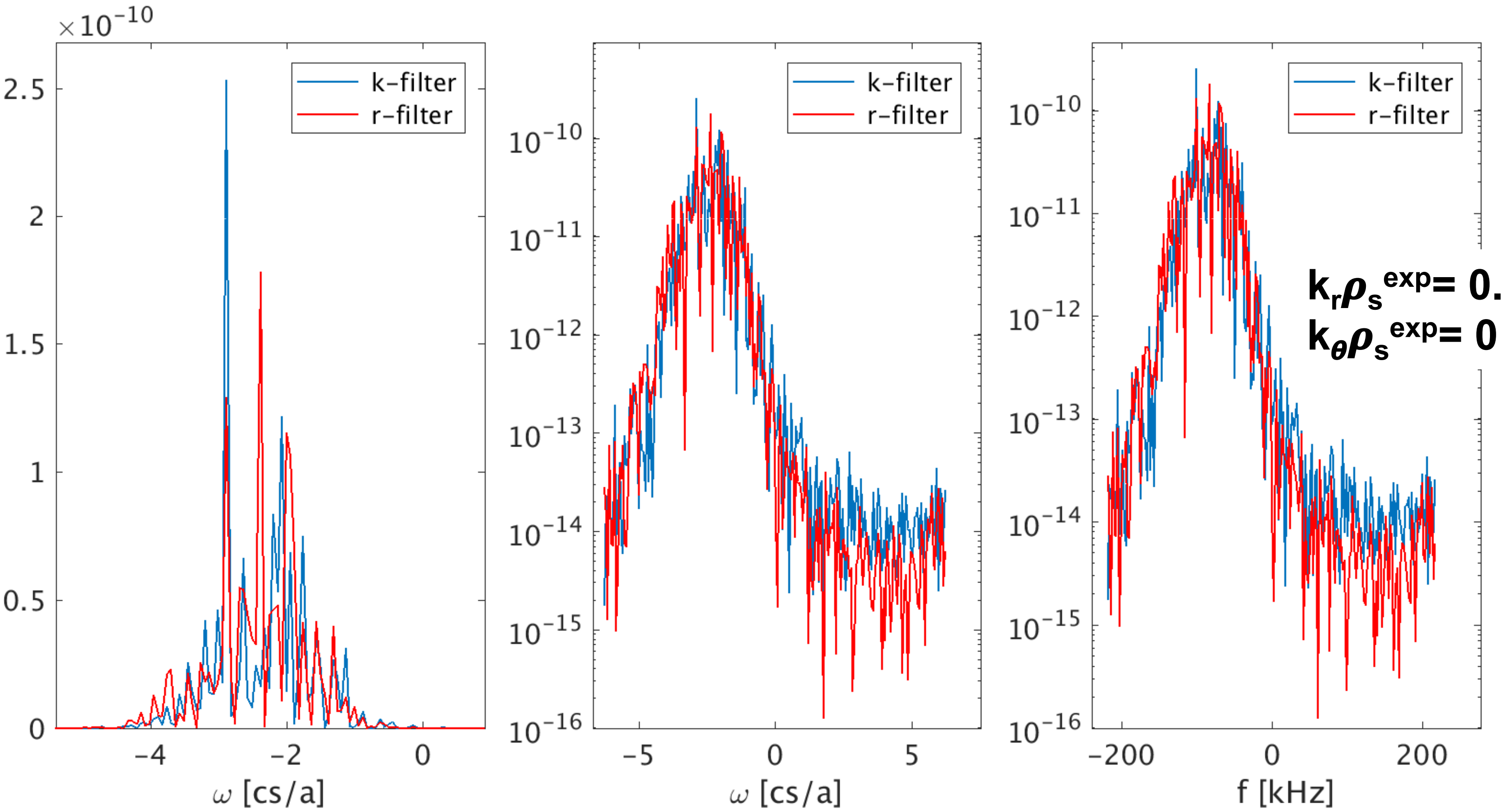


$k_r\rho_s^{exp}$= 0.27
$k_\theta\rho_s^{exp}$= 0.42

GOOD AGREEMENT BETWEEN R & K FILTERS

Synthetic signal: a_0 = 10 cm

$|\delta n_e|^2$, ω_0 = 0.036004 c_s/a, t_{avg} = 110.5-210a/c_s



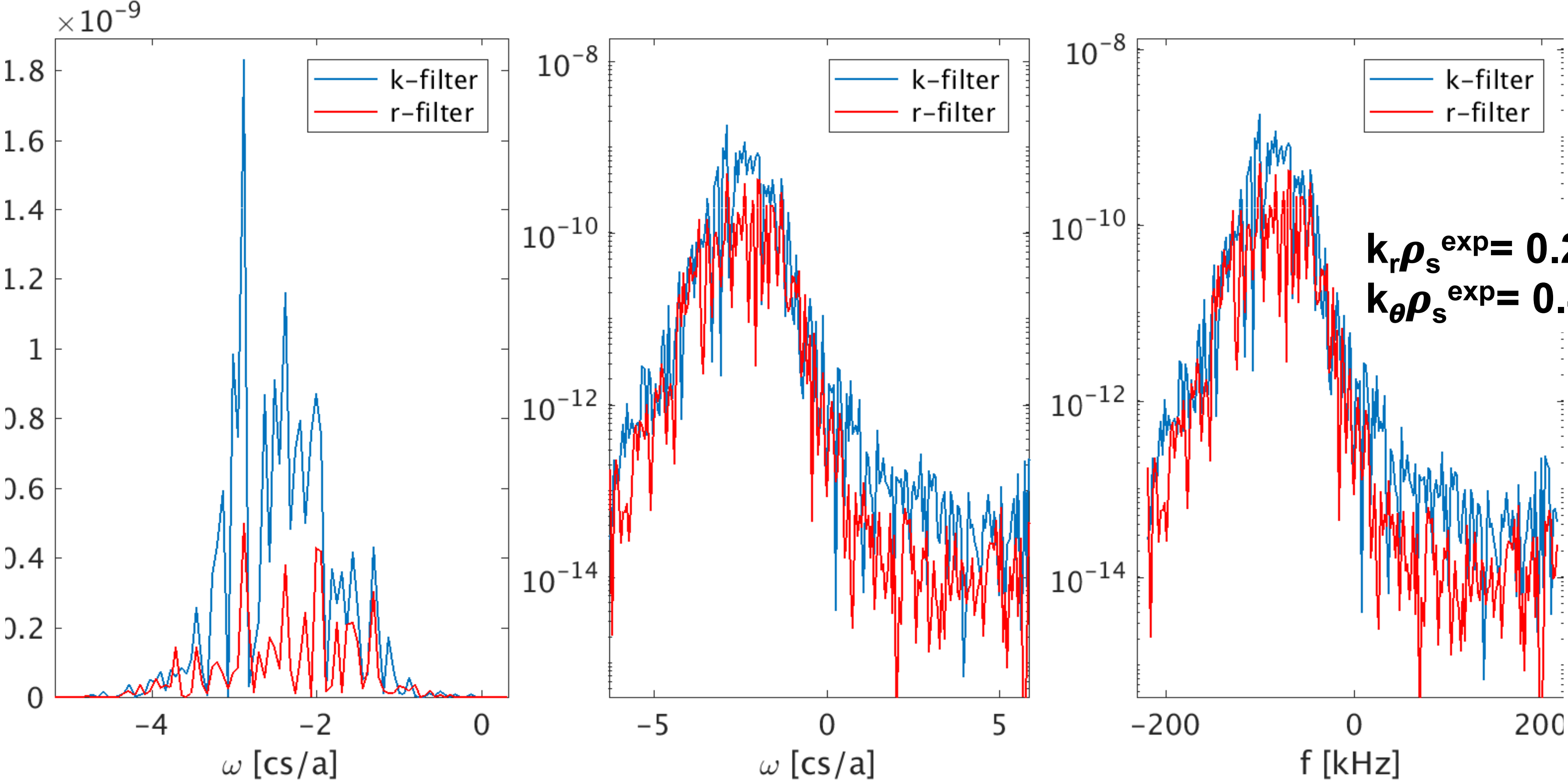
$k_r\rho_s^{exp}$= 0.27

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

GOOD AGREEMENT BETWEEN R & K FILTERS

Synthetic signal: a_0 = 20 cm

$|\delta n_e|^2$, ω_0 = 0.036004 c_s/a, t_{avg} = 110.5-210a/c_s



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

FACTOR x2-3 AMPLITUDE DISCREPANCY

Conclusions from Cyclone Base Case Tests

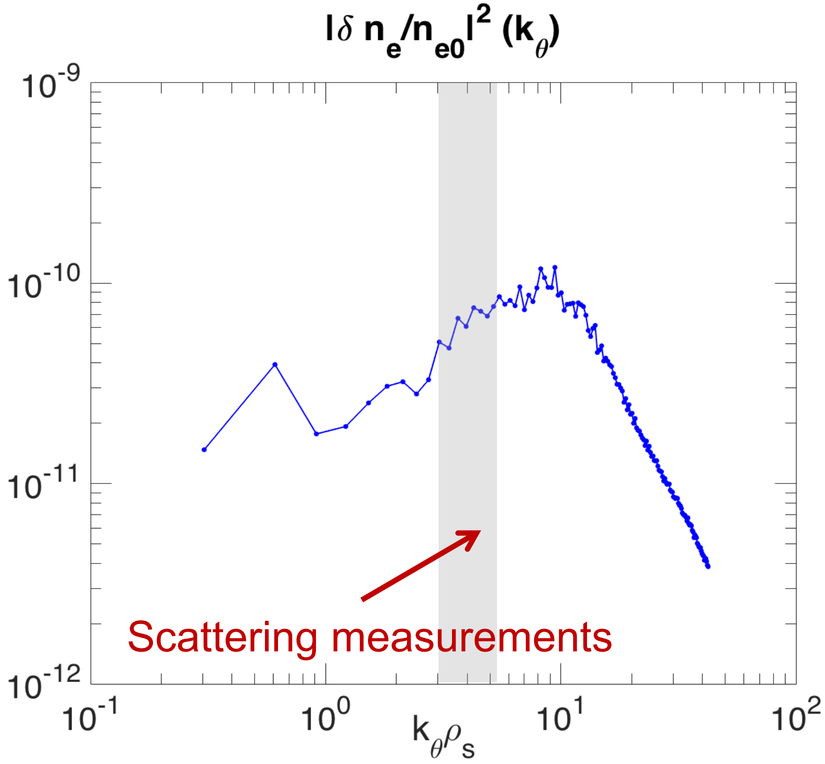
- We have shown good agreement between two alternate ways to approach a scattering synthetic diagnostic
  - filtering in real space (r-filter)
  - filtering in wevenumber space (k-filter)

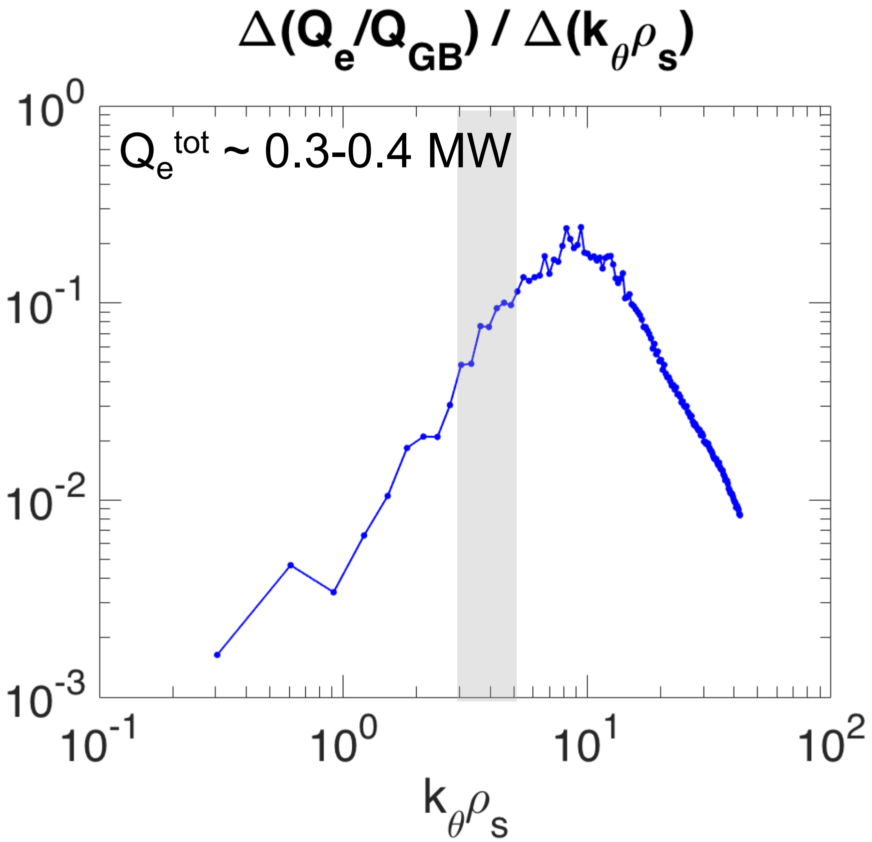
- The beam width was included in the full simulation domain at a_0 = 5 cm, and completely exceeded sim domain at a_0 = 20 cm.

- 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)

Experimental Wavenumbers Produce non-negligible transport

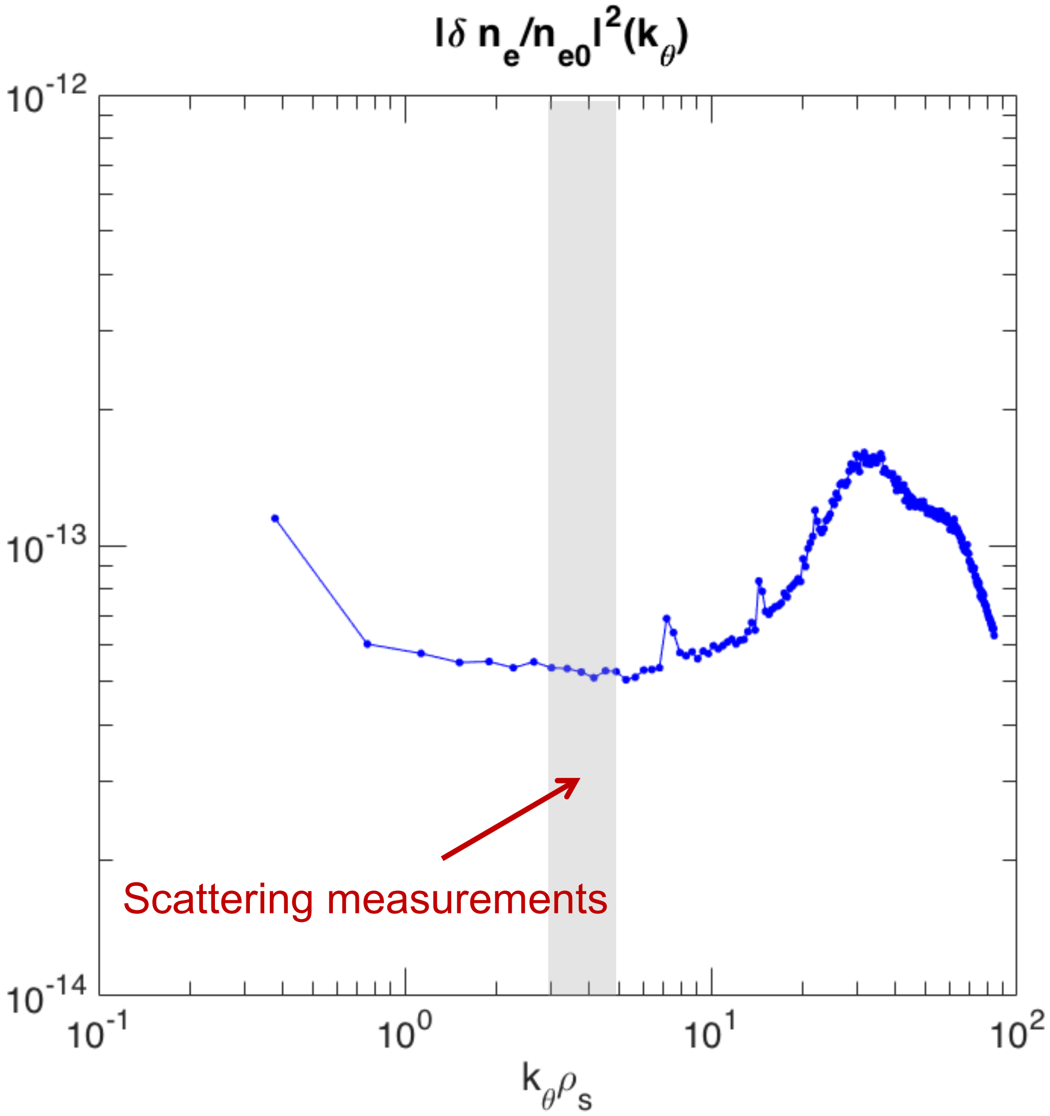




- t = 398 ms
  - Low density gradient case
  - Unstable ETG

- k^{exp} close to density and Q_e spectral peak.
- Q_e consistent with previous standard e-scale sim results(Q_e~0.4 MW)

Experimental Wavenumbers Produce non-negligible transport

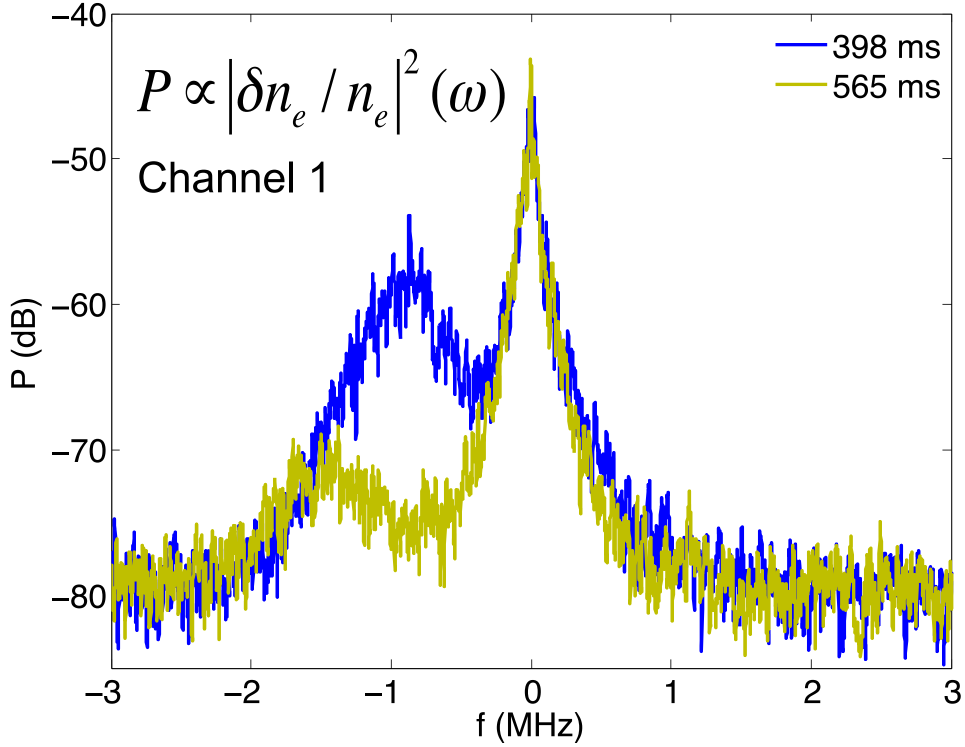


Scattering measurements

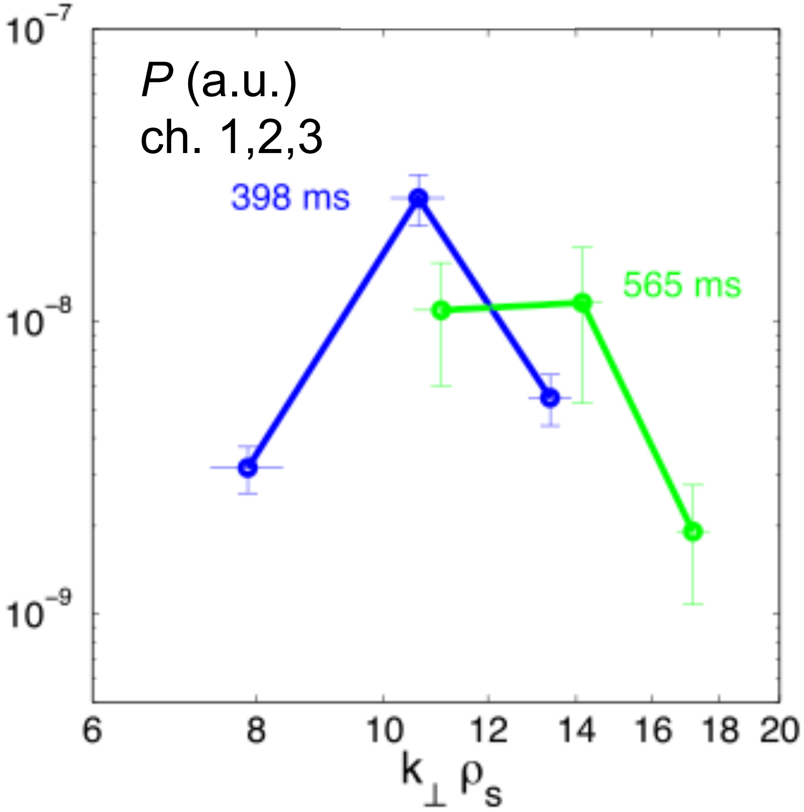
- t = 565 ms.
  - High density gradient case
  - Stabilized ETG
- Low fluctuation levels
- Q_e expected to be very low

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

Frequency Spectrum of density fluctuations



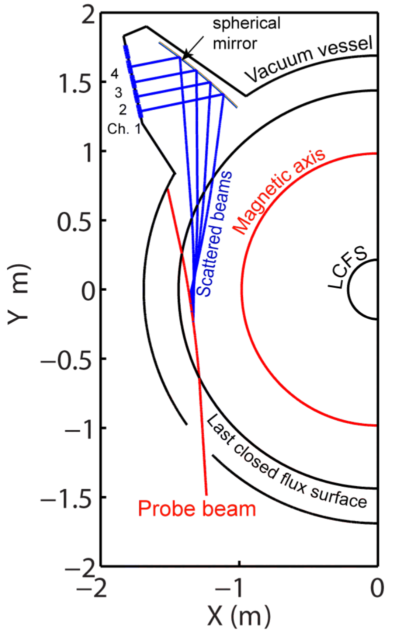
k-spectrum of density fluctuations



- High-k scattering data of NSTX NBI heated H-mode plasma (*cf.* Ruiz Ruiz PoP 2015)
- Frequency analysis of scattered power → **frequency spectrum**.
- Different channels → different k → **wavenumber spectrum** of turbulence

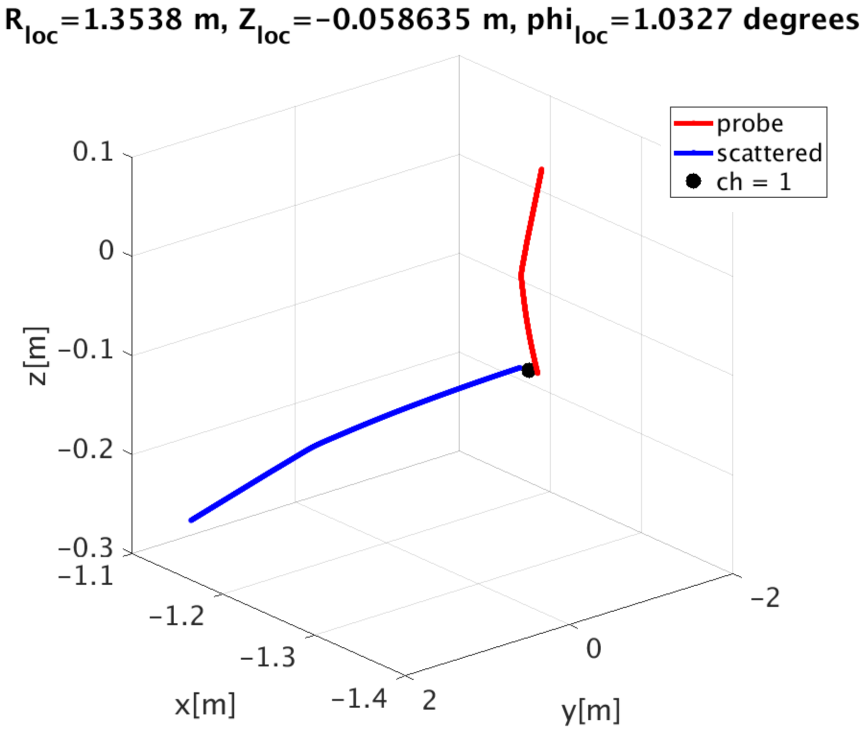
2. Ray Tracing

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



View from top of NSTX

(D.R. Smith PhD thesis 2009)


R_{loc}=1.3538 m, Z_{loc}=−0.058635 m, phi_{loc}=1.0327 degrees

Obtain:

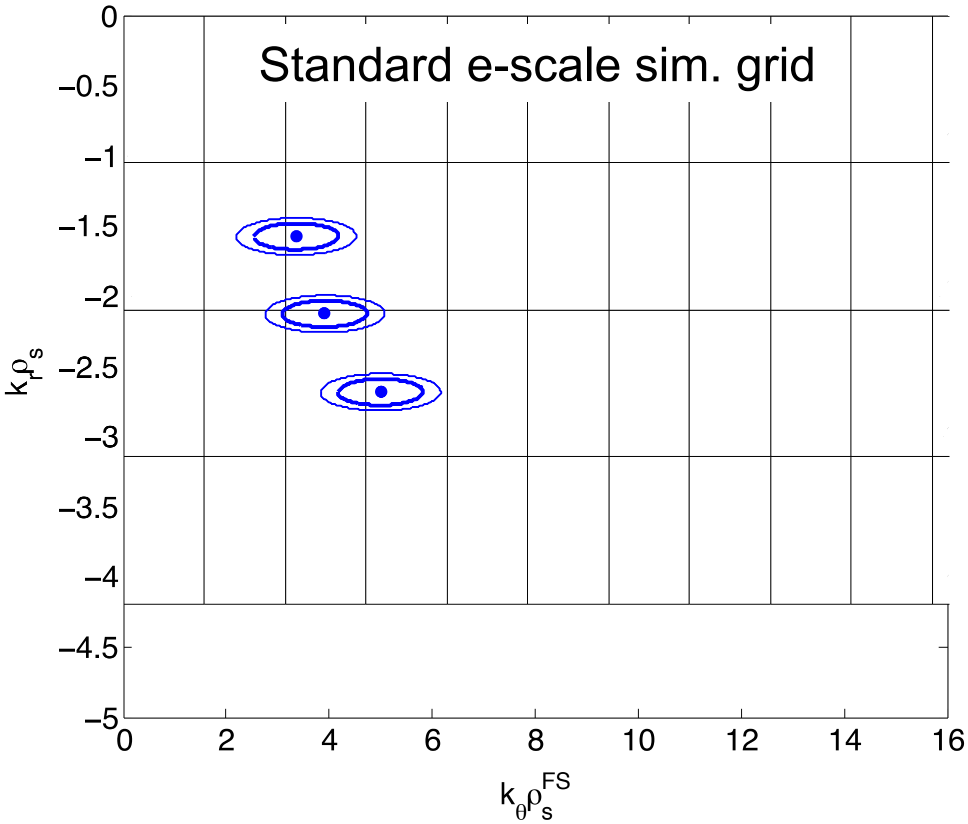
- Scattering location + resolution $(R_{loc}, Z_{loc}) + (\Delta R_{loc}, \Delta Z_{loc})$
- Turbulence wavenumber + resolution $(k_R^{exp}, k_Z^{exp}) + (\Delta k_R^{exp}, \Delta k_Z^{exp})$

Results of wavenumber mapping

Experiment (shot 141767, ch1)	**GYRO**
Cylindrical geometry (R,Z, φ)	Field aligned (r, θ,φ)
Ray Tracing:	New mapping:
$k_R = - 18.57 \text{ cm}^{-1}$	➔ $k_r\rho_s = - 2.68$
$k_Z = 4.93 \text{ cm}^{-1}$	➔ $k_\theta\rho_s = 4.99$
$\rho_s^{exp} = 0.7$ cm	$\rho_s^{GYRO} = 0.2$ 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)

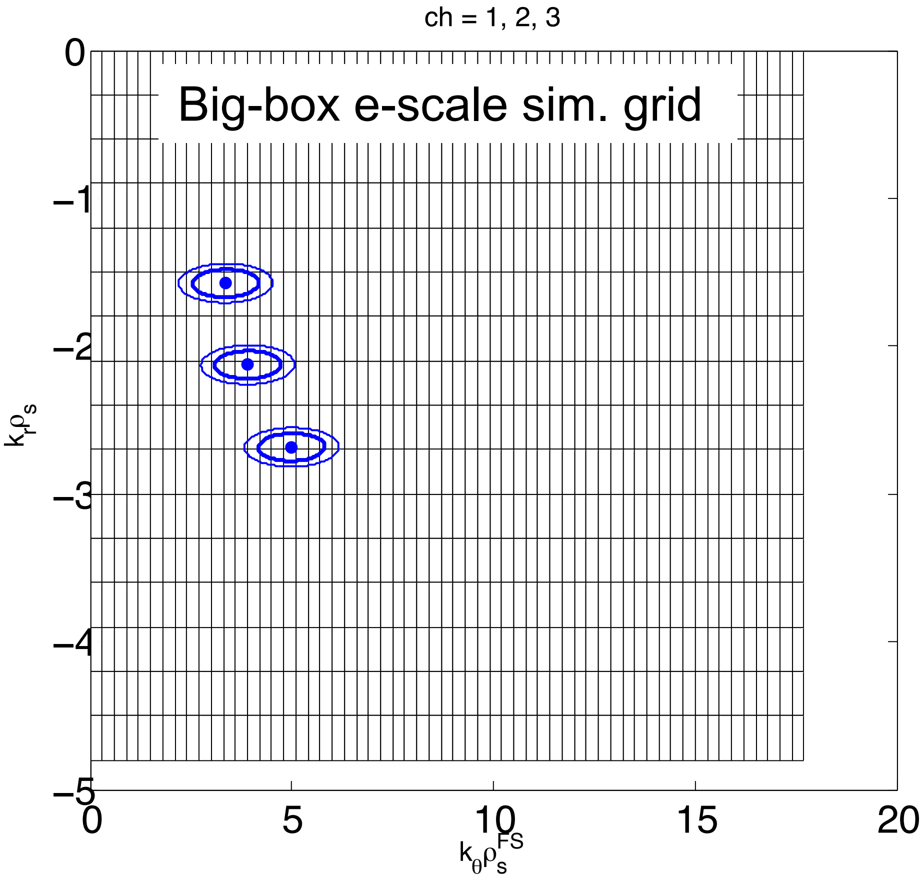
$$F(k_r,k_\theta) = F_r(k_r)F_\theta(k_r)$$

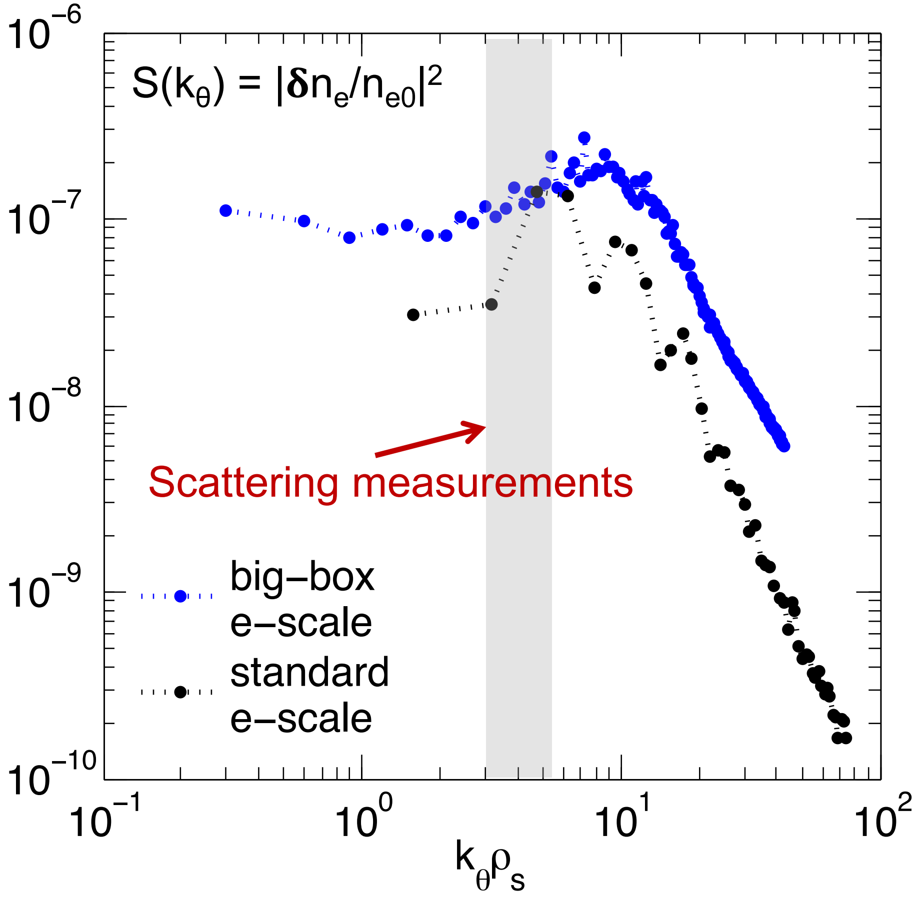
$$F_r(k_r) = \exp\left(-(k_r - k_r^{\exp})^2 / \Delta k_r^2\right)$$

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

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.

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

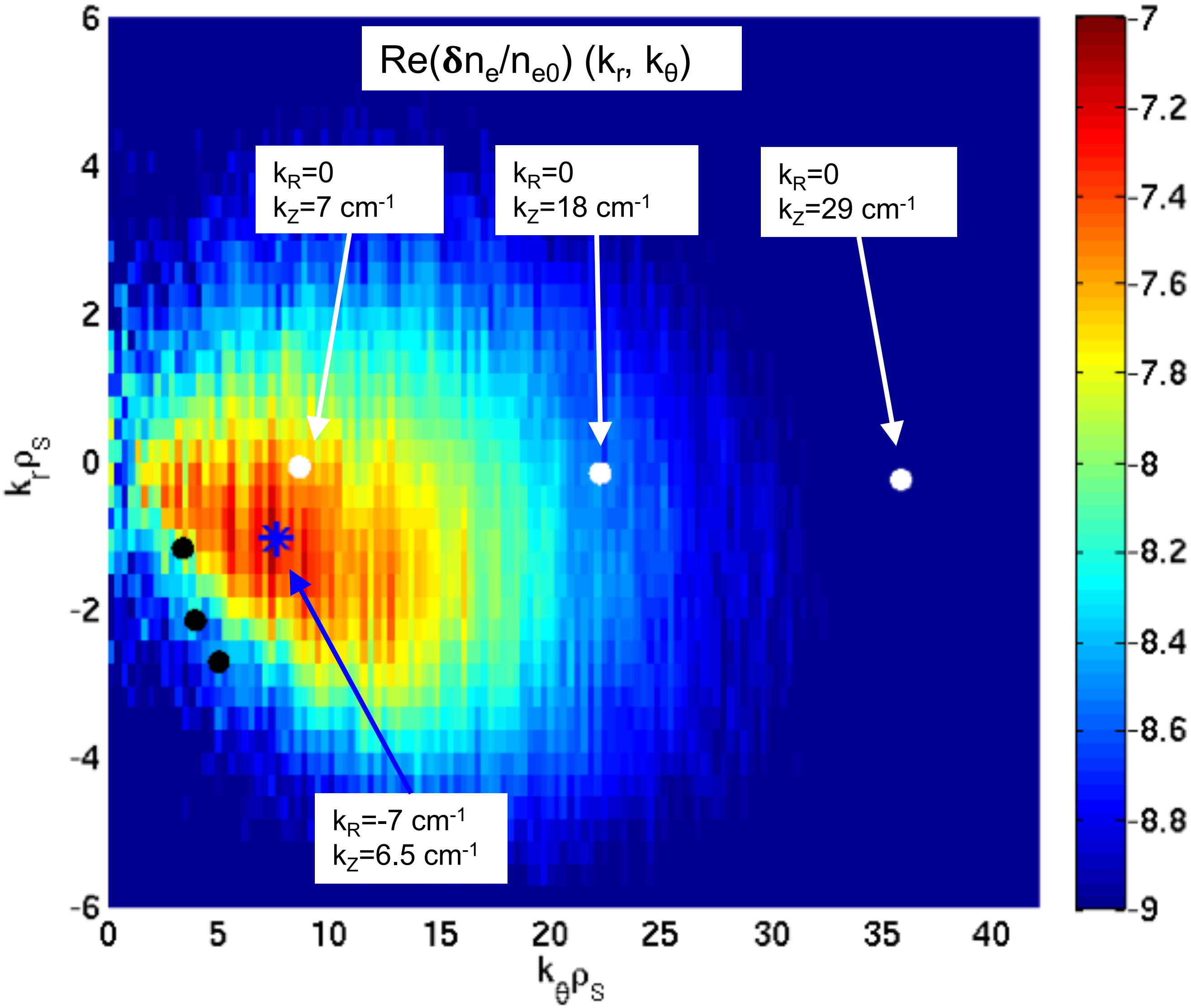
- **My goal**: project the operating space of the new high-k scattering diagnostic using the mapping I implemented.

- **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*).
     $k_Z = 7\text{-}40\ \mathrm{cm}^{-1}$
     $k_R = 0\ \mathrm{cm}^{-1}$
     → 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

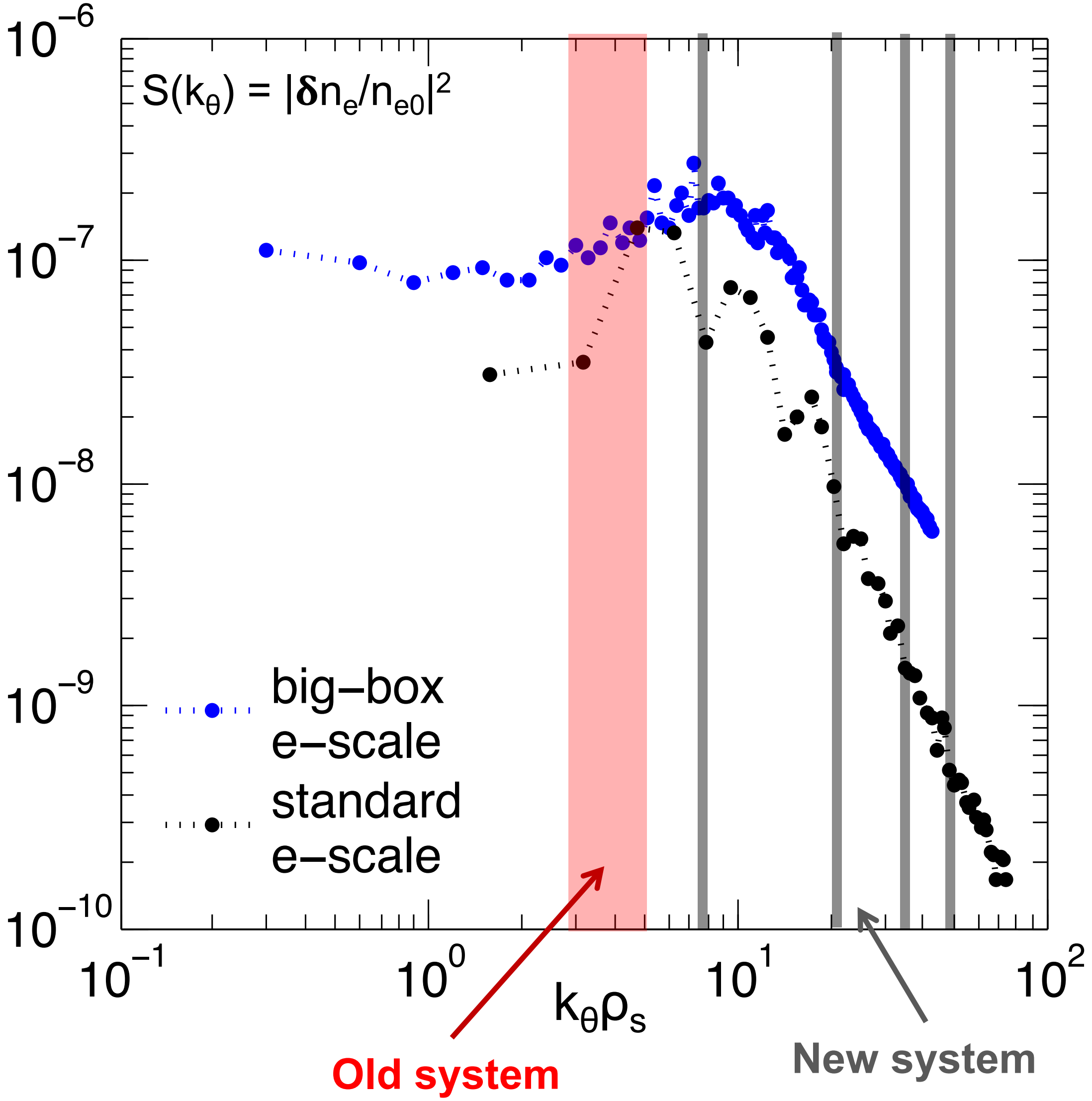
- Picked k's in predicted measurement range
  k_Z = 7, 18, 29, 40 cm^{-1}
  k_R = 0 cm^{-1}

- 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

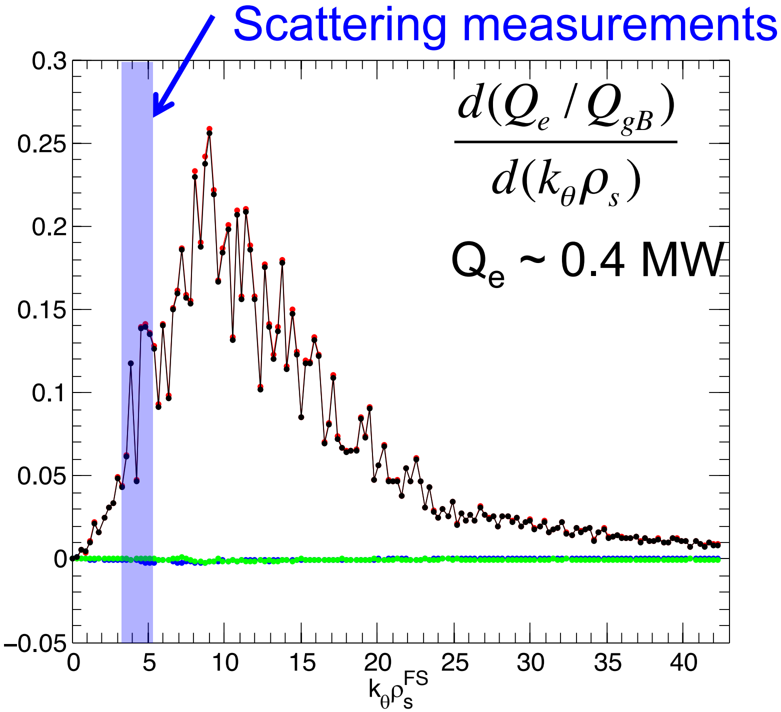


- Spectrum is integrated in k_r.
- Lowest-k channel will be closest to peak of fluctuation spectrum (streamers)
  k_R=0, k_Z=7 cm^{-1}
- Need to resolve very high-k ($k_\theta\rho_s$ ~ 50) to capture highest-k channel.
- **Red band**: measurement range of old system.
- **Gray bands**: measurement range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

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 Details of Ion and Electron 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.
- Experimental T_e, n_e, T_i, rotation, etc.
- 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 ~ 8/1.5 ρ_s buffer widths (ion/e- scale).

Ion scale resolution parameters

- $L_r \times L_y = 74 \times 56\ \rho_s$ (L/a~0.4).
- $n_r \times n = 192 \times 14$.
- $k_\theta\rho_s^{FS}$ [min, max] = [0.1, 1.4]
- $k_r\rho_s$ [min, max] =[0.85, 4]
- $[n_{||}, n_\lambda, n_e] = [14, 12, 12]$

Big-box e- scale resolution parameters

- $L_r \times L_y = 21 \times 21\ \rho_s$ (L/a~0.16).
- $n_r \times n = 512 \times 142$.
- $k_\theta\rho_s^{FS}$ [min, max] = [0.3, 43]
- $k_r\rho_s$ [min, max] = [0.3, 38]
- $[n_{||}, n_\lambda, n_e] = [14, 12, 12]$

High-resolution electron scale runs presented here are NOT multiscale:

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

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

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

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

Summary of Coordinate Mapping

The mapping in real-space:

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

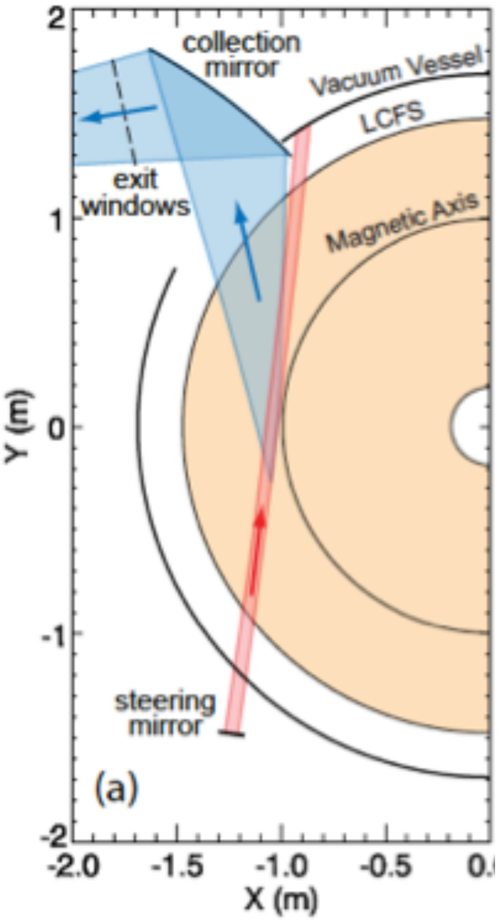
$$\begin{cases} R(r_{loc}, \theta_{loc}) = R_{loc} \\ Z(r_{loc}, \theta_{loc}) = Z_{loc} \end{cases}$$

The mapping in k-space:

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

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

Operation of Old High-k Microwave Scattering Diagnostic System at NSTX



View from top of NSTX (D.R. Smith PhD thesis 2009)

Old High-k Scattering System

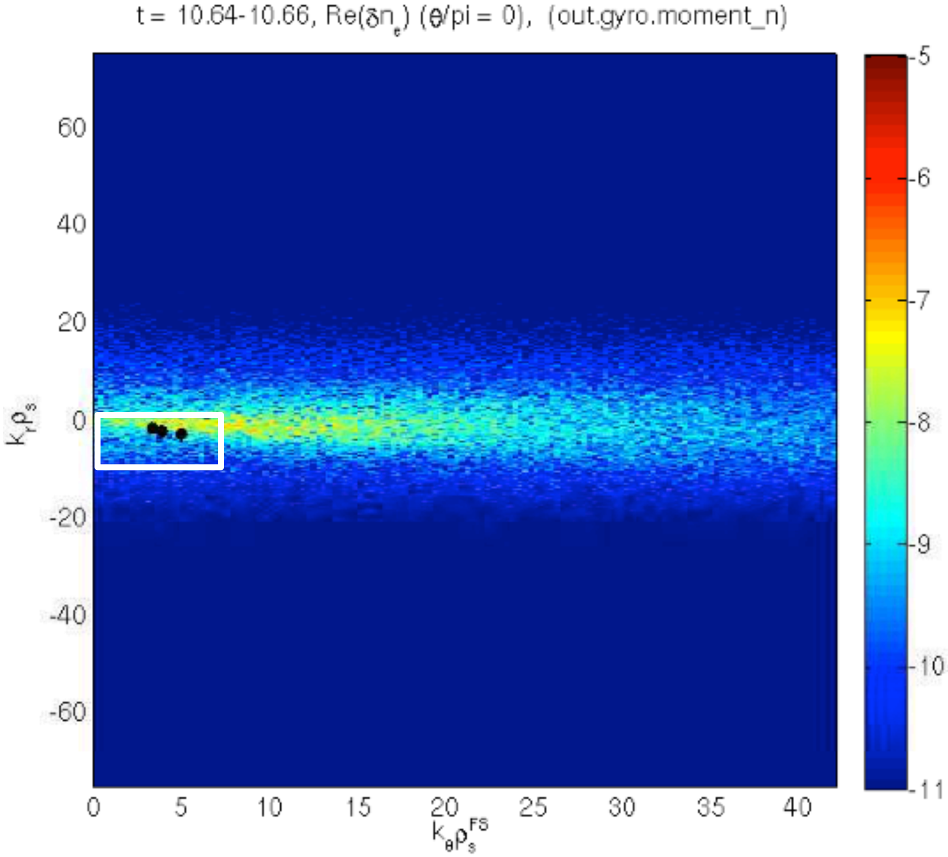
- Gaussian Probe beam: 15 mW, 280 GHz,
  λ_i ~ 1.07 mm, a = 3cm (1/e^2 radius).
- Propagation close to midplane => k_r spectrum.
- 5 detection channels => range k_r ~ 5-30 cm-1 (high-k).
- Wavenumber resolution $\Delta k = \pm$ 0.7 cm-1.
- Radial coverage: R = 106-144 cm.
- Radial resolution: $\Delta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

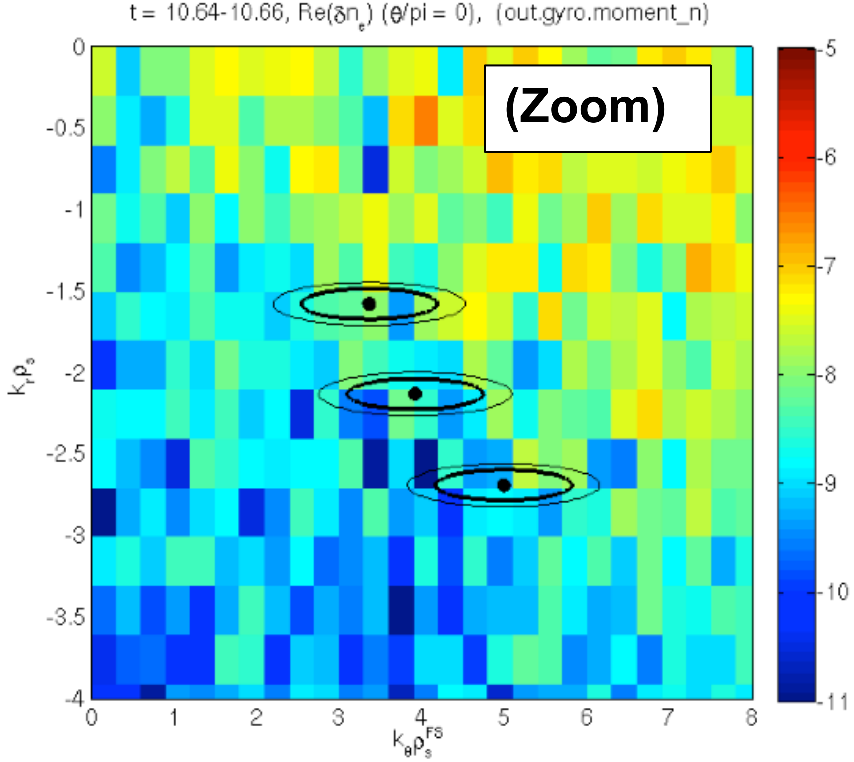
Previous Work on Synthetic high-k

cf. Poli PoP 2010

- Previous synthetic high-k scattering was implemented with GTS (*cf.* Wang PoP 2006).
- Synthetic spectra affected by systematic errors (simulation run time, low k_θ detected)

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
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	0.168
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 $(k_r\rho_s, k_\theta\rho_s)_{GYRO}$ ➔ $(k_R, k_Z)^{exp}$

Preamble 3 Wavenumber mapping under simplifying assumptions

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

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

- 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

  $(R(r,\theta),Z(r,\theta))=(R_{exp}, Z_{exp})$ ➔(r_{exp},θ_{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

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  - – Edit the text box (meeting, title, author, date) at the bottom of the page
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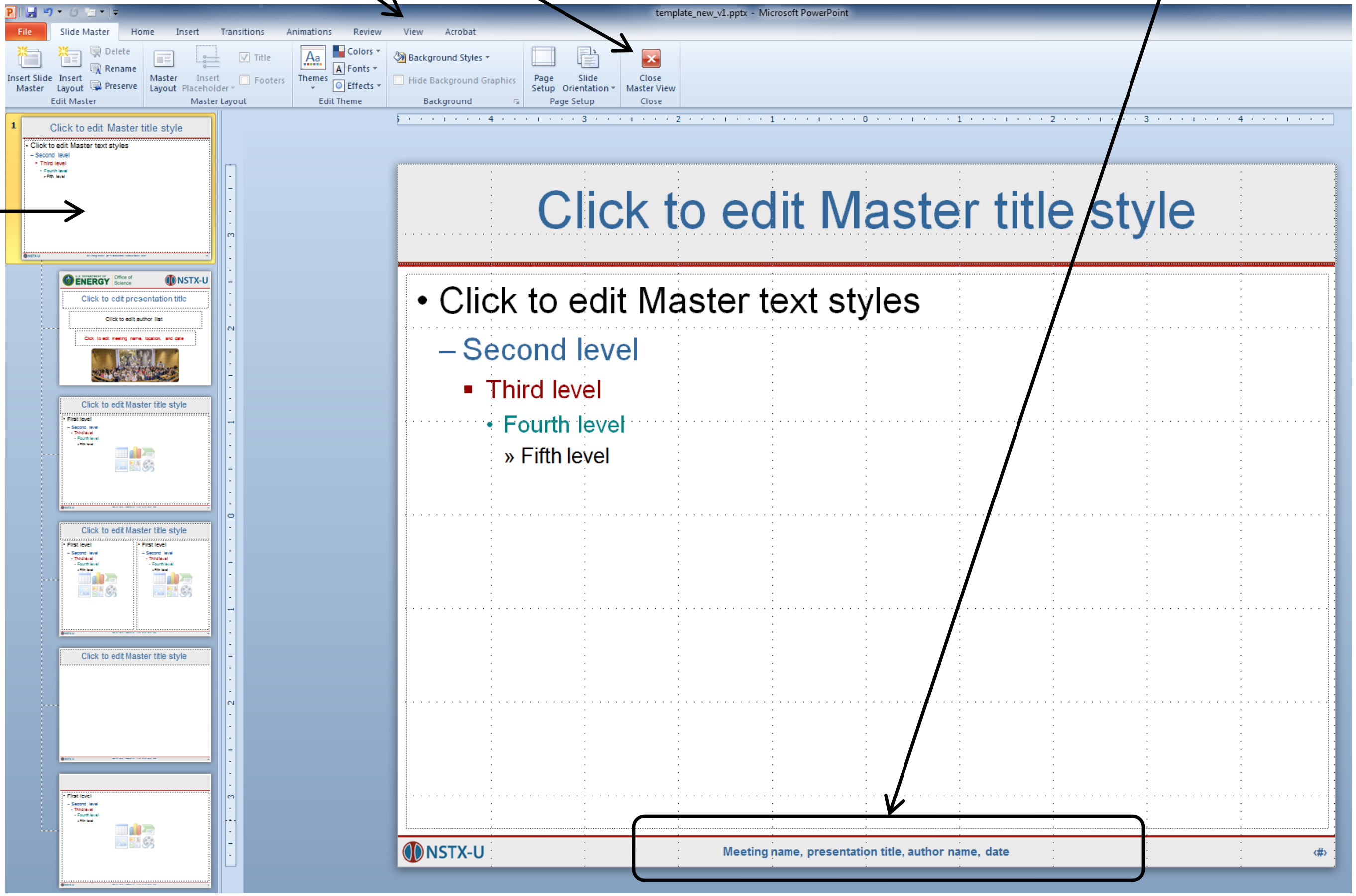

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