Validation of Nonlinear Transport Codes for Core Tokamak Turbulence: Current Status and Future Directions

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Also acknowledge useful discussions with many other individuals

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What are Verification and Validation? (from Oberkampf’s 2004 TTF presentation)

- **The verification and validation process is how we “assess the accuracy of computational models, … and build confidence and credibility in computational models”**

- **Verification: “The process of determining that a model implementation accurately represents the developer’s conceptual description of the model and the solution to the model”**
  - This entails benchmarking against analytic solutions to the model and multi-code comparisons

- **Validation: “The process of determining the degree to which a model is an accurate representation of the real world, *from the perspective of the intended uses of the model*” (emphasis added)**
  - For our purposes, how well can the simulation reproduce experimental measurements, within experimental and computational uncertainties

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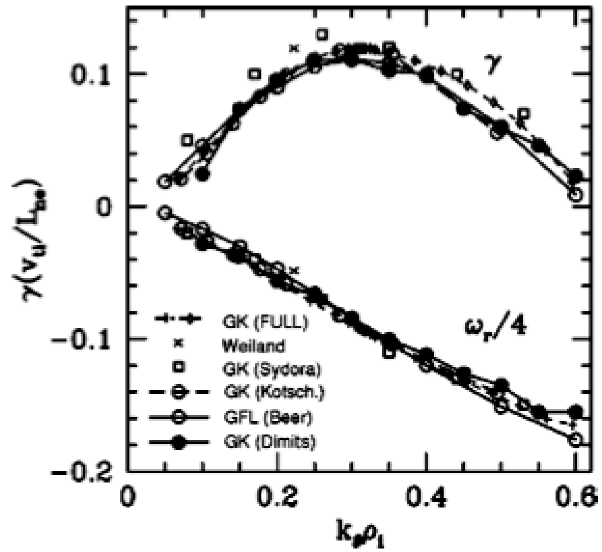
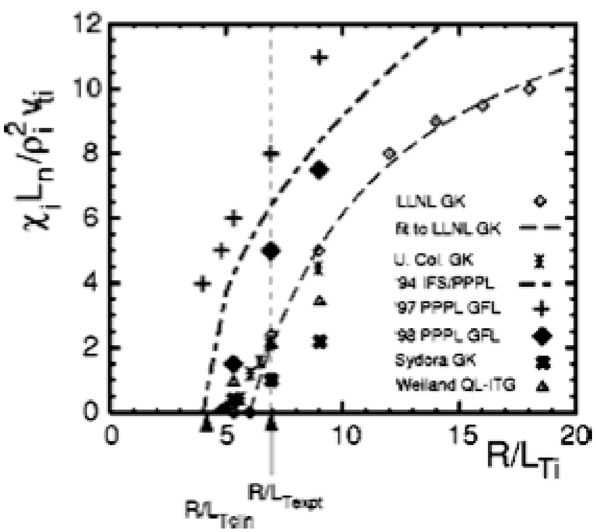
CYCLONE Study as Verification Exercise

- **Transport in tokamaks of dominated by small-scale drift-wave turbulence**
  - Requires numerical simulation for quantitative experimentally relevant predictions
- **In practice, there is now a (minimal) standard set of verification tests for gyrokinetic adiabatic electron ITG flux tube simulations, outlined in CYCLONE study (Dimits *et al*., PoP 2000):**
  - Reproduction of linear growth rate
  - Reproduction of Rosenbluth-Hinton zonal flow damping and residual zonal flow level
  - Reproduction of 'Dimits shift'
  - Reproduction of χ_i for CYCLONE base case parameters
- **Still work to do on verification (kinetic e-, profile /finite ρ* effects, β-scaling,…), but now appropriate to begin serious validation efforts**
  - Should be noted that while the results of a verification exercise for short-wavelength ETG turbulence has recently been published (Nevins *et. al.*, PoP 2007), no such exercise for long-wavelength ITG/TEM turbulence has been performed



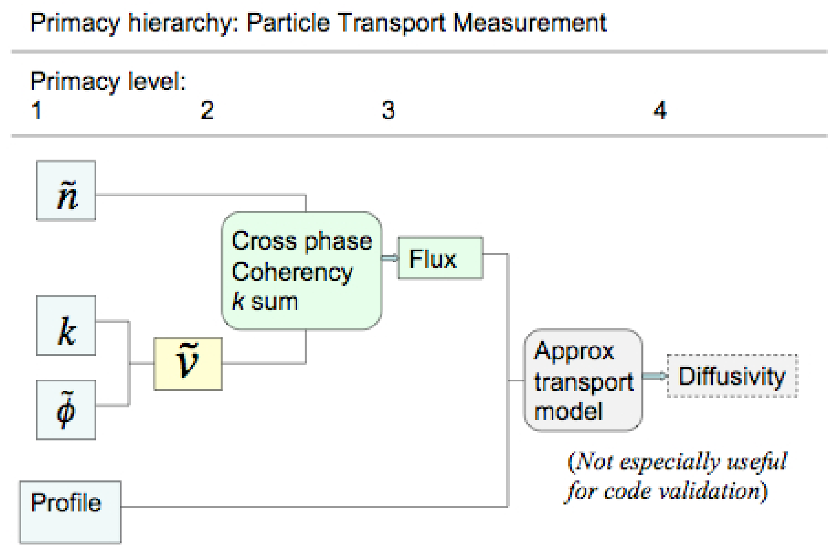


Dimits et al, PoP 2000

Two Key Concepts for Validation: the Primacy Hierarchy and Validation Metrics

From Terry *et al.*, "Validation in Fusion Research: Towards Guidelines and Best Practices", arXiv: 0801.2787v1

- **Primacy Hierarchy:** "Ranking of a measurable quantity in terms of the extent to which other effects integrate to set the value of the quantity. Assesses ability of measurement to discriminate between different non-validated models."



- **Validation Metric:** "A formula for objectively quantifying a comparison between a simulation result and experimental data. The metric may take into account errors and uncertainties in both sets of data as well as other factors such as the primacy of the quantities being compared."

- **Thus, a primacy hierarchy tells us how discriminating a test a specific comparison is, and the validation metric is how we weight various comparisons to quantify the success of a model for a given set of conditions**

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Overview

- Validation of drift-wave simulations requires comparison against *core* fluctuation measurements, where the underlying gyrokinetic model implemented in the simulations (which uses a small ρ^* ordering) is believed to be valid
- Validation also requires using "synthetic" diagnostics which describe the inherent spatio-temporal sensitivities of the experimental diagnostic system under consideration
- In this talk, I'll describe some results from recent work which uses the GYRO code to model a basic DIII-D L-mode plasma, discussing our successes and failures to date, and highlight some areas for future investigation

This Work Builds on Previous Validation Efforts

- **Comparisons of turbulence measurements, simulation, and analytic theory has a long history in community**

- **Some of the more notable recent works in this area:**
  - Ross and Dorland (2002 PoP): first detailed, direct comparisons of fluctuation spectra and heat fluxes using modern gyrofluid and gyrokinetic simulations
  - Bravenec and Nevins (2006 RSI): detailed discussion of implementing synthetic diagnostics
  - Ernst *et al.* (2006 IAEA): combination of gyrokinetic simulation, synthetic diagnostics, and core tokamak fluctuation measurements

- **Major advance in this work is that we quantify agreement between simulation and experiment at multiple locations in the plasma and at multiple levels of the primacy hierarchy**

Full refs: Ross *et al.*, Phys Plasmas **9** 177 (2002), Ross and Dorland, Phys. Plasmas **9** 5031 (2002)
Bravenec and Nevins, Rev. Sci. Inst. **77** 015101 (2006)
Ernst *et al.*, IAEA-CN -149/TH/1-3 (2006) (submitted to PRL)

Some General Notes and Definitions

- **Unless otherwise specified, use**
  - Normalized toroidal flux ρ as measure of radial location
  - Normalized fluctuation levels: $\delta X(\vec{r},t) = \tilde{X}(\vec{r},t) / X_0(\rho)$
- **Define different drfit-wave instabilities as**
  - ITG: drift-waves with linear V_{phase} in ion diamagnetic direction
  - TEM: drift-waves with linear V_{phase} in electron diamagnetic direction, and $k_\theta \rho_s < 1$
  - ETG: drift-waves with linear V_{phase} in electron diamagnetic direction, $k_\theta \rho_s > 1$

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Outline

1. Overview of GYRO code and experimental measurements
2. Implementation of synthetic diagnostics
3. Results from local simulations at $\rho = 0.5$ and $\rho = 0.75$
4. Results from non-local simulations
5. Lessons learned and directions for future work

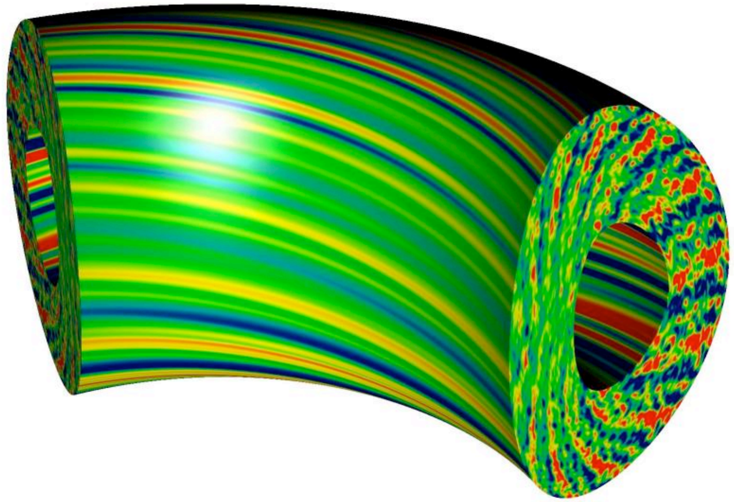
Use GYRO Code to Predict Fluctuation Fields and Associated Fluxes

- **GYRO is an initial value Eulerian (continuium) 5D gyrokinetic code**
  - Calculates evolution of (small) deviations from equilibrium distribution functions using kinetic equations averaged over fast gyromotion in a 5D (x,y,z,ε,μ) phase-space

- **Believed to contain all the necessary ingredients for quantitatively accurate transport predictions**
  - takes measured experimental profiles as inputs
  - realistic geometry (Miller formulation)
  - trapped and passing electrons
  - finite beta (magnetic fluctuations)
  - e-i pitch angle collisions
  - equilibrium sheared ExB and toroidal rotation profiles

A Few More GYRO Details

- **GYRO can be run in a local or nonlocal mode:**
  - **Local:** each equilibrium profile and gradient is taken to have a fixed (and independent) value across the box. This case corresponds to a $\rho^* = \rho_s/a \rightarrow 0$ limit of the GK equations, and is similar to familiar "flux-tube" simulations.
  - **Nonlocal:** spatially varying equilibrium profiles (either measured or predicted by a separate model) are used
- **A nonlinear GYRO simulation uses N_n toroidal modes with separation Δn**
  - Eg: n = 0,10,20,30,40,50,…,150
  - Corresponds to simulating a wedge of $1/\Delta n$ of tokamak (i.e. example above corresponds to simulating 1/10 of torus)
- **These toroidal mode numbers can be related to the local binormal (~ poloidal) wavenumber via $k_\theta \approx k_\alpha = nq(r)/r$**
  - In a local simulation, q/r is fixed giving uniform coverage in k_α
  - In a full-profile simulation, q/r varies with radius and so k_θ resolution varies



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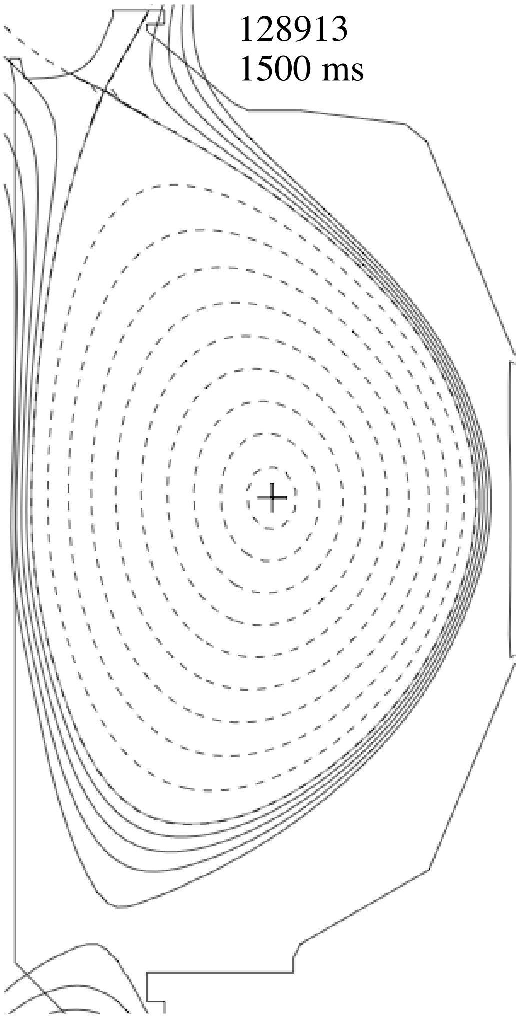
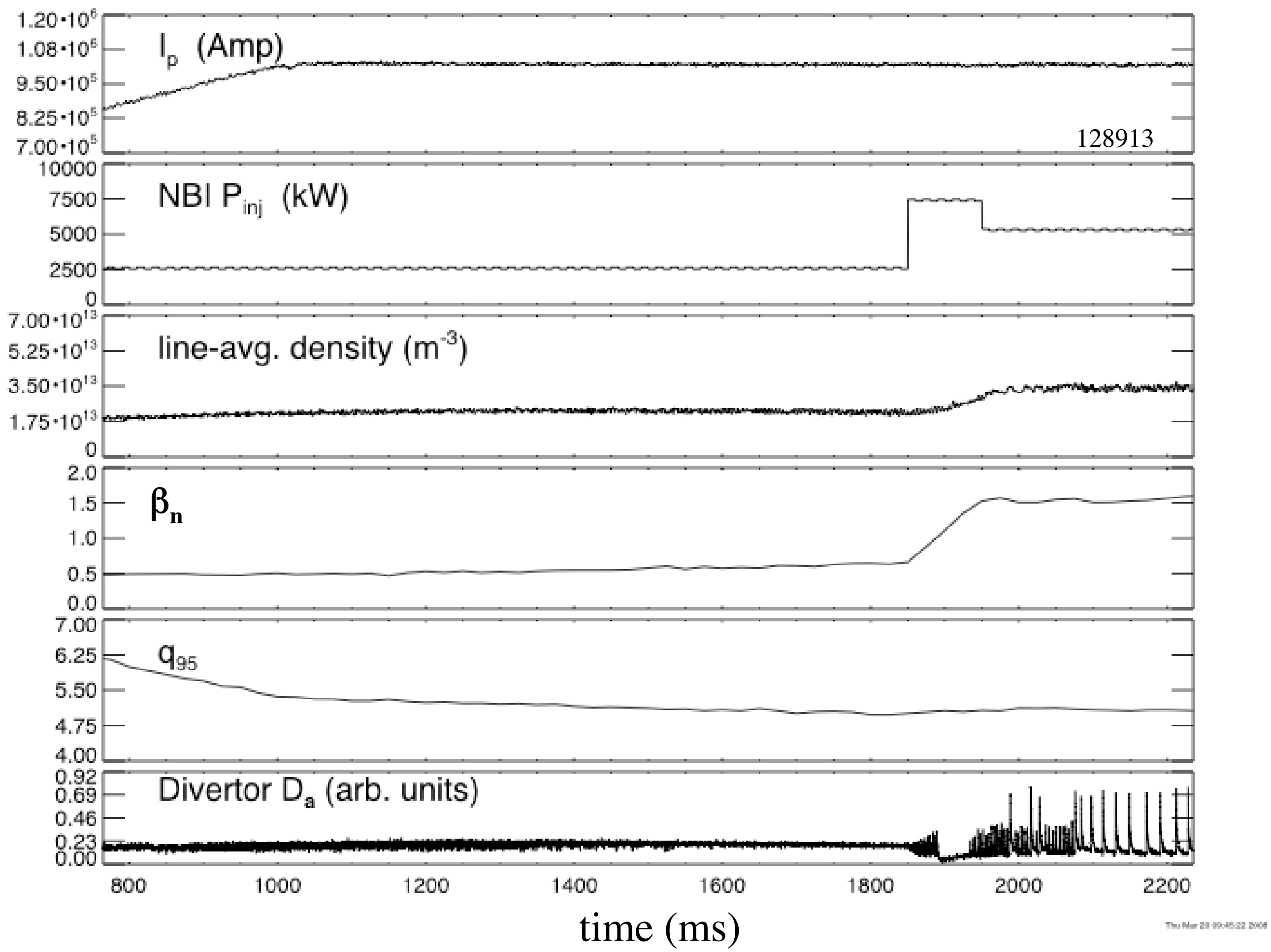
Use 400 ms of Steady L-mode Data for This Exercise





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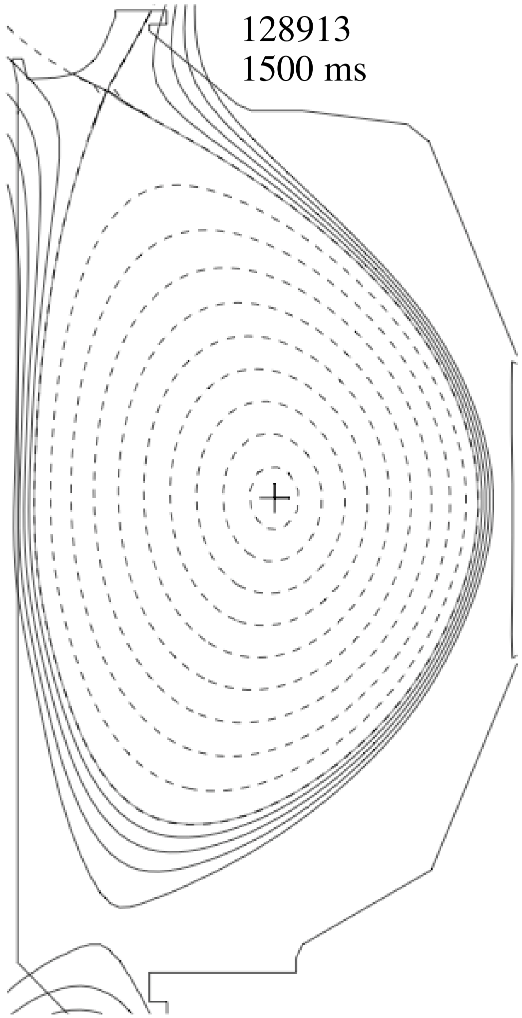
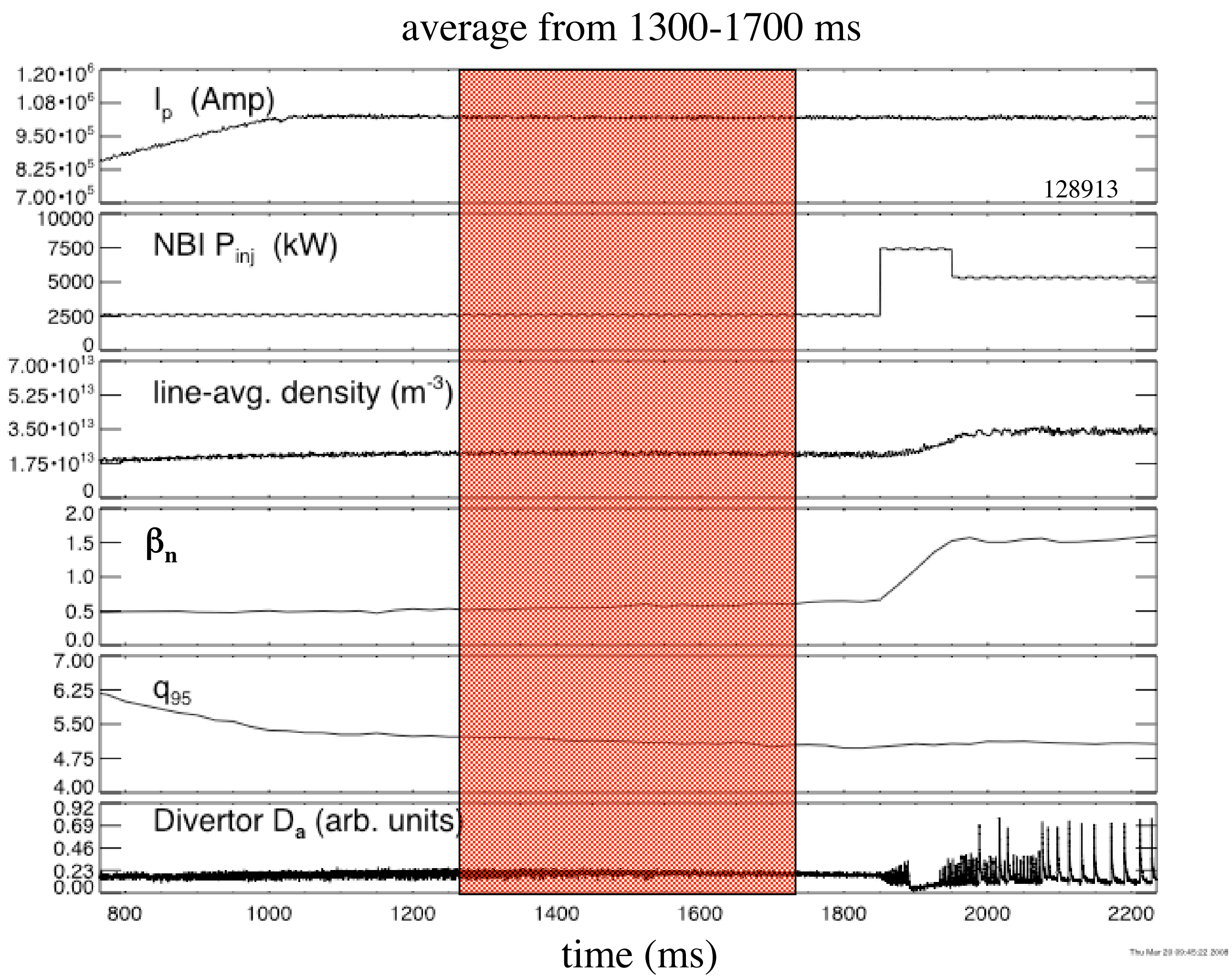
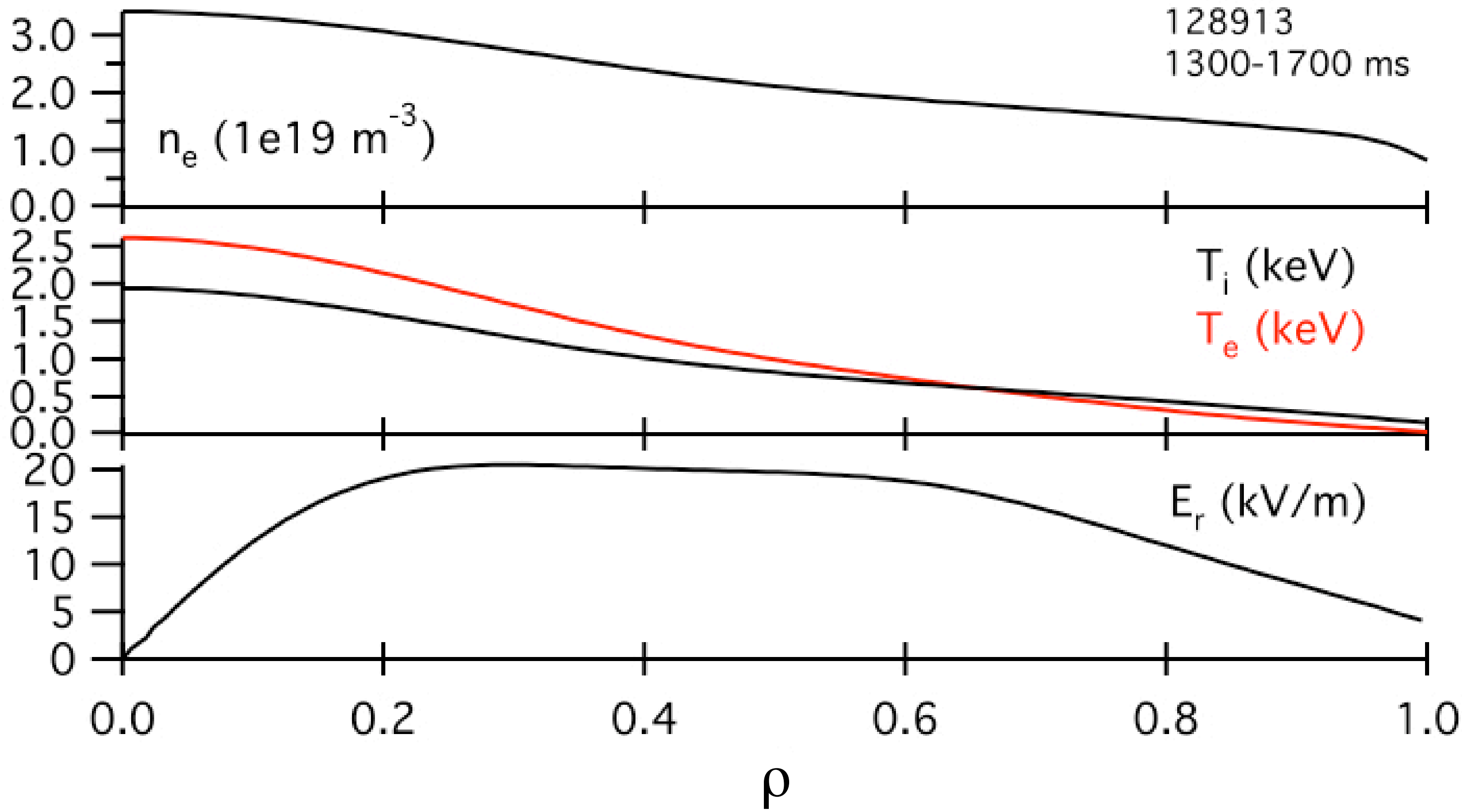




Use of Steady Discharge Allows Minimization of *Statistical* Uncertainty



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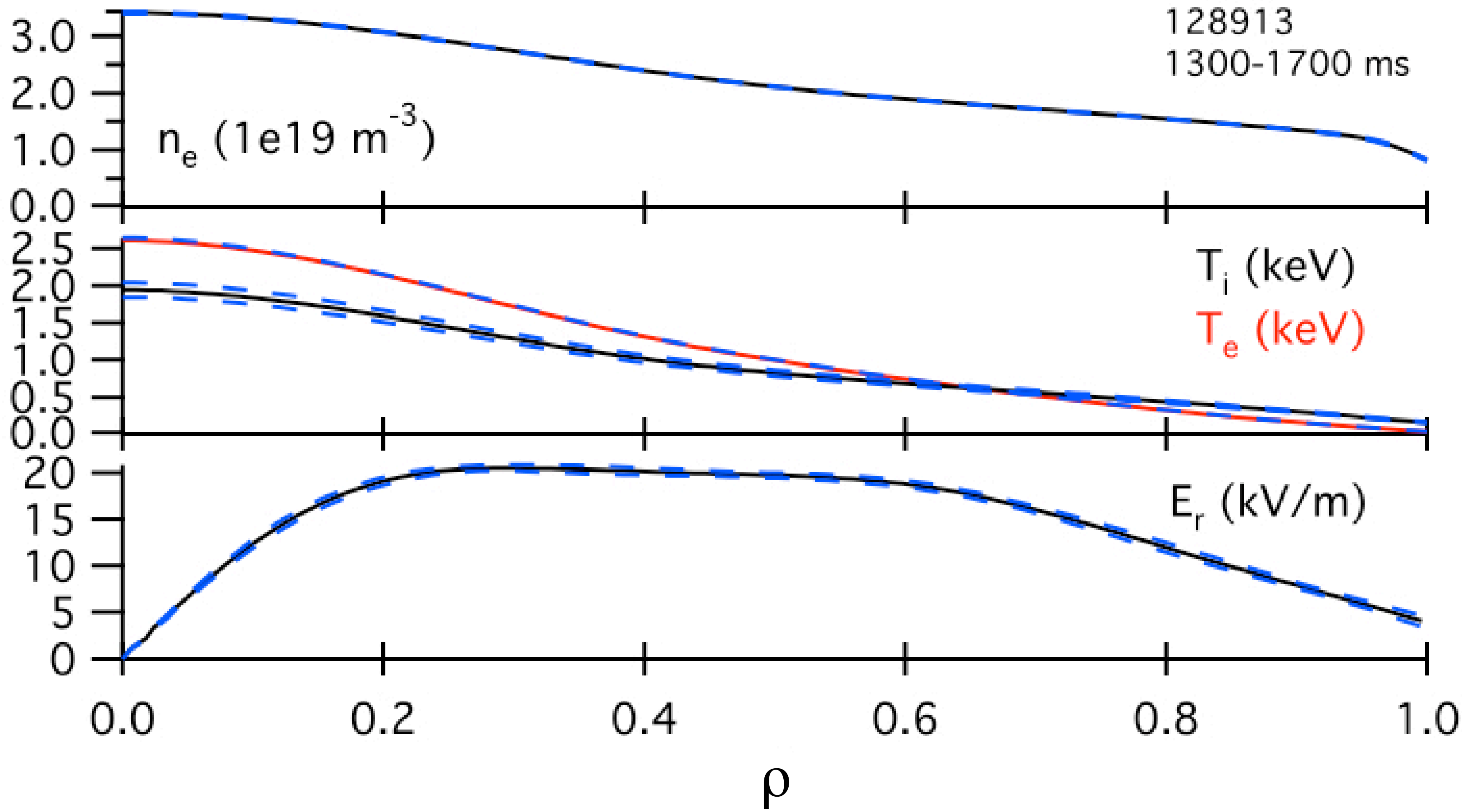
Use of Steady Discharge Allows Minimization of *Statistical* Uncertainty

- - - - - - - - - - - - - - - *Statistical* error ranges

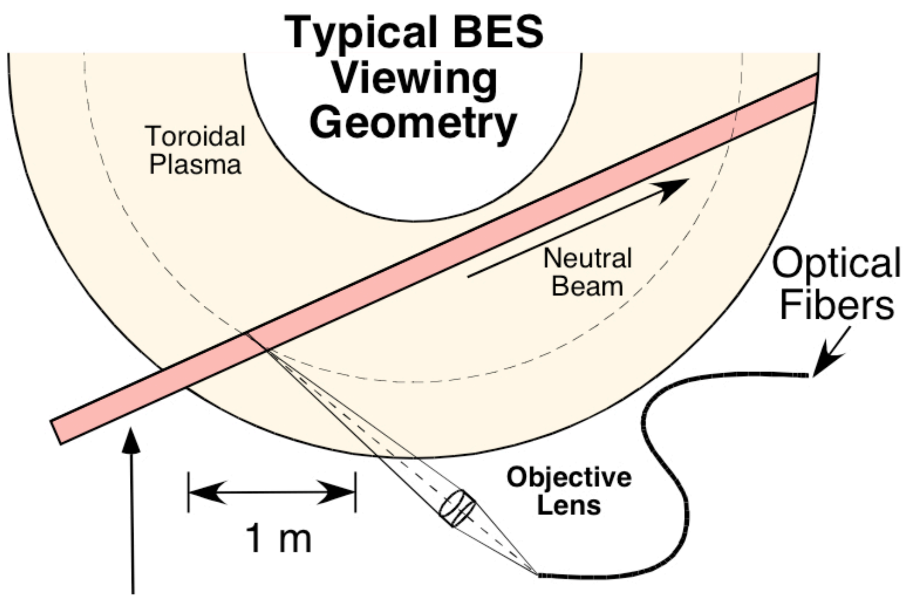


Beam Emission Spectroscopy Measures Spatially Localized, Long-Wavelength ($k_\perp \rho_I < 1$) Density Fluctuations

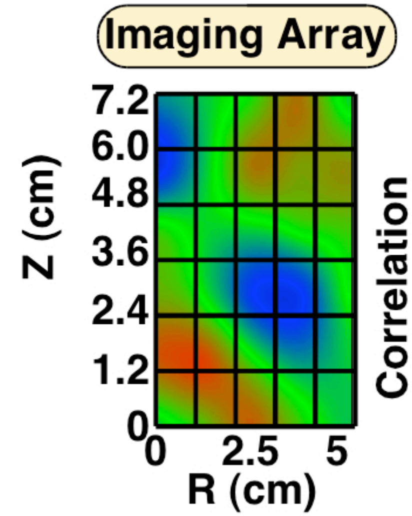
Collisionally-excited, Doppler-shifted neutral beam fluorescence

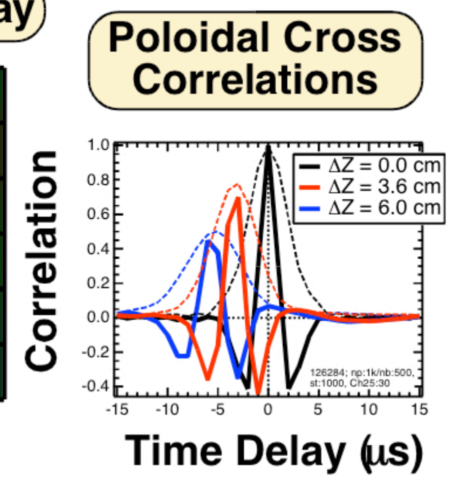
$$D^o + e,i \Rightarrow \left(D^o\right)^* \Rightarrow D^o + \gamma(n = 3 \rightarrow 2, \lambda_o = 656.1 \text{ nm})$$

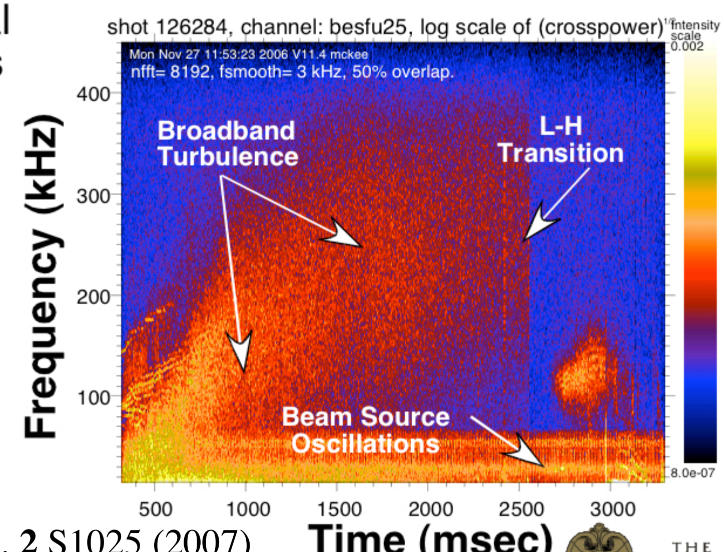
Emission intensity proportional to local density



75 KeV D^o Neutral Beam







G. R. McKee *et al.*, Plasma Fusion Res. **2** S1025 (2007)

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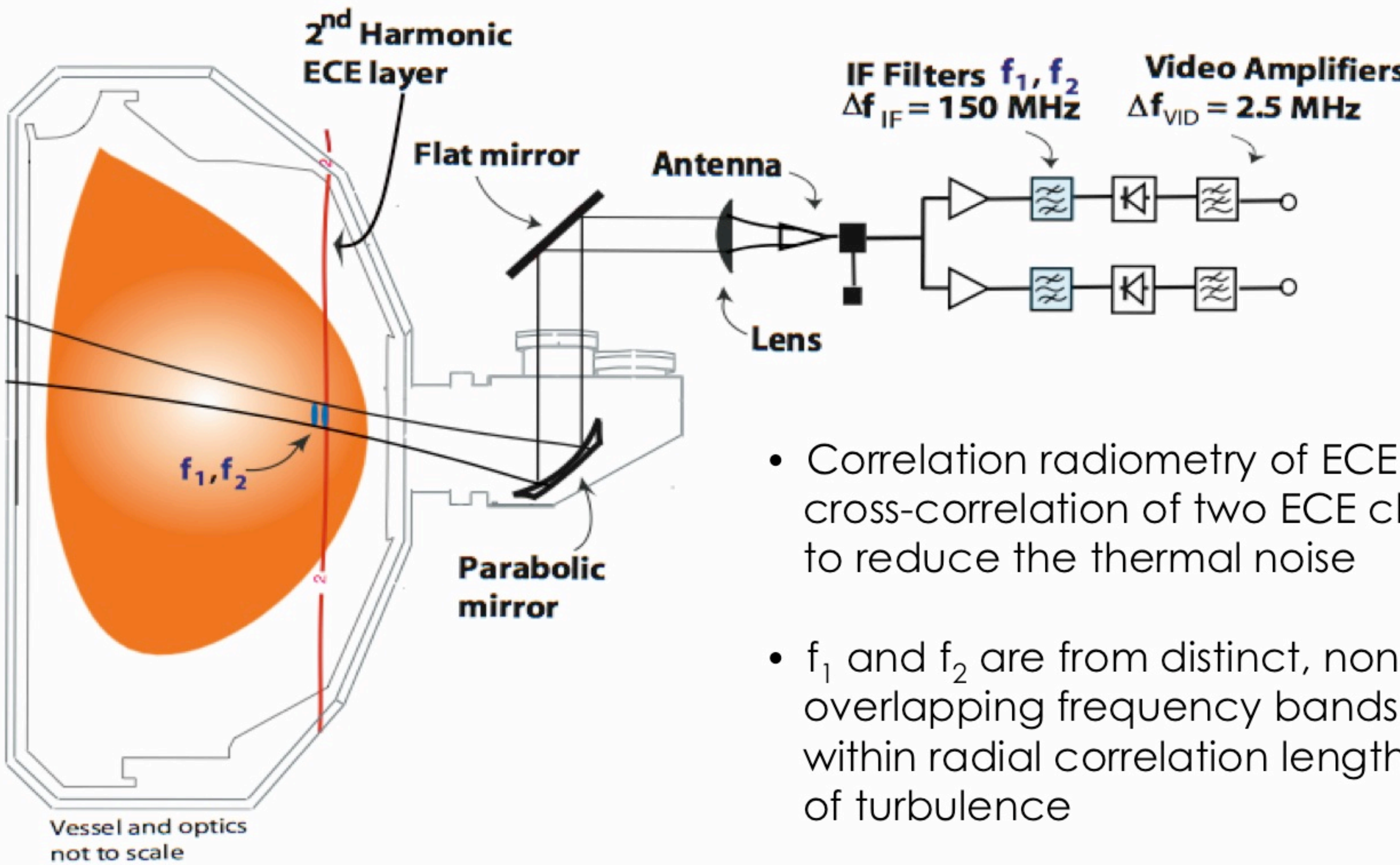
Correlation Electron Cyclotron Emission (CECE) Diagnostic Measures Local, Low-k Electron Temperature Fluctuations



- Correlation radiometry of ECE uses cross-correlation of two ECE channels to reduce the thermal noise
- f_1 and f_2 are from distinct, non-overlapping frequency bands, within radial correlation length of turbulence
- Measure RMS amplitude and power spectrum, $\tilde{T}_e / T_e$

TEXT (Cima 1995)
W7-AS (Sattler 1994)
DIII-D (White 2007)

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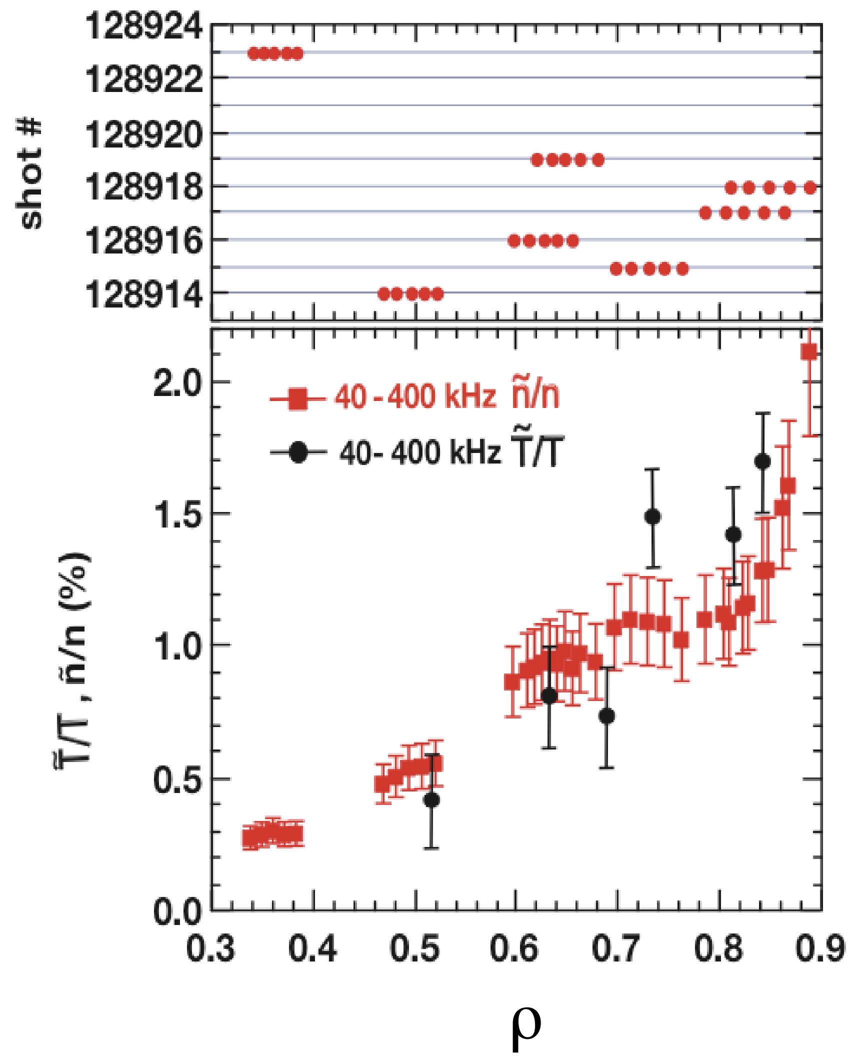
Combining BES and CECE Allows for Detailed Characterization of Microturbulence Across Plasma

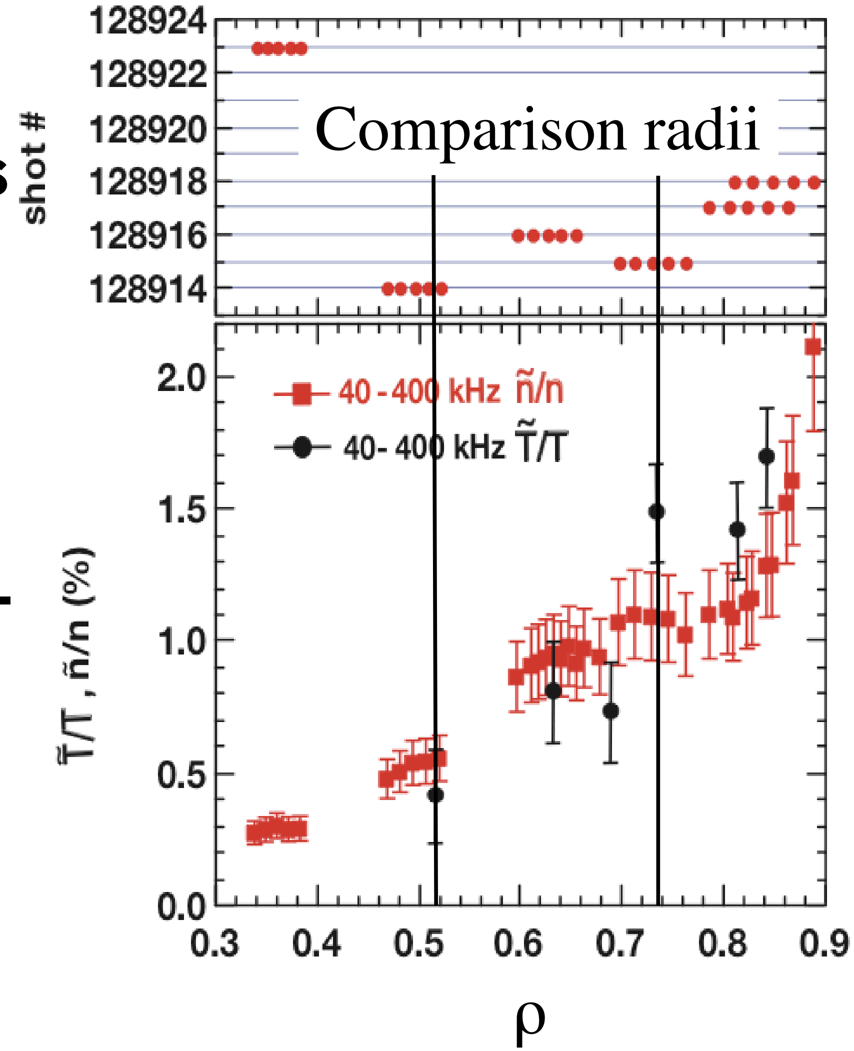
- **By scanning the location of the BES array and CECE diagnostic, one can build up detailed profile of fluctuation measurements**

- **RMS fluctuation levels determined via integration of measured power spectra**



Comparisons of Local Simulations Undertaken at ρ = 0.5 and 0.75

- **Primary focus of work to date has been comparisons of local simulations against experiment at ρ = 0.5 and 0.75**
- **Locations represent a trade-off between ease of simulation and signal-to-noise ratio of fluctuation measurements**



Synthetic Diagnostics

Synthetic Diagnostics Essential Component of Quantitative Code-Experiment Comparisons

- In order to do “apples-to-apples” comparisons of simulation and experiment, need to not just model the turbulence, but also how a given diagnostic “sees” the turbulence
- This is done by creating a synthetic diagnostic which attempts to reproduce what the diagnostic would have seen had it observed the simulation fluctuations
- For the BES and CECE systems, this is done by applying point-spread functions (PSFs) to the simulation data to model the spatial sensitivity of each diagnostic

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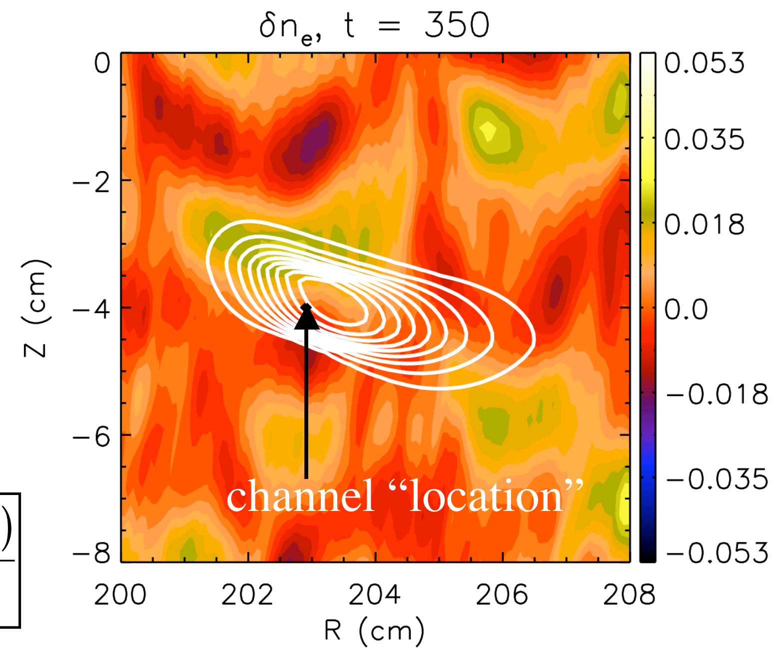
Ex: Applying BES PSF to GYRO Simulation Data

- **IDL post processing tool written to generate synthetic BES array; PSF form taken from calculation by M. Shafer**

- **Tool first interpolates PSF data (generated on a regularly spaced (R,Z) grid) onto a grid compatible with GYRO data (which uses a field-line following (r,θ,α) coordinate system)**



- **At each time point of interest, record**
  - Synthetic signal defined as

$$\boxed{\delta n_{synthetic}(x,y,t)=\frac{\int d^2x'\psi^{PSF}(x-x',y-y')\delta n_e^{GYRO}(x',y',t)}{\int d^2x'\psi^{PSF}(x-x',y-y')}}$$

  - GYRO signal at gridpoint closest to nominal BES location (term this signal the unfiltered GYRO signal in this poster)

- **Because GYRO calculates fluctuations in co-rotating reference frame, must transform data back into the lab reference frame. Linear interpolation is used to increase the effective time resolution (equivalent to sampling rate) of the GYRO data, preventing aliasing due to the introduction of the equilibrium Doppler shift.**

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Synthetic Diagnostic Array Layout

- **Create a 5x6 synthetic BES array centered in middle of simulation**
  - Offset 4 cm below midplane as in experiment
  - 0.9 cm radial spacing, 1.2 cm vertical
  - Use same PSF for all channels

- **Create 5 synthetic CECE measurements across radius**
  - Offset 5.5 cm above midplane, also as in experiment
  - Use 5 equally spaced pairs of asymmetric Gaussians for PSFs. Because simulations are local, all radial locations are "equivalent", can average to improve syn. CECE statistics
  - Radial $1/e^2$ diameter = 1cm, 3.8 cm vertically, based on linewidth and measured antenna pattern

- **Do calculations at 4 equidistant toroidal angles to get more statistics**

- **General note: believe synthetic BES diagnostic to be fairly mature and complete, but synthetic CECE results should be considered to be more preliminary**
  - Main omission in BES is direct calculation of intensity fluctuations, rather than use of "static" linear relationship
  - Still need to consider several physics effects for CECE, such as relativistic electrons and temperature anisotropy

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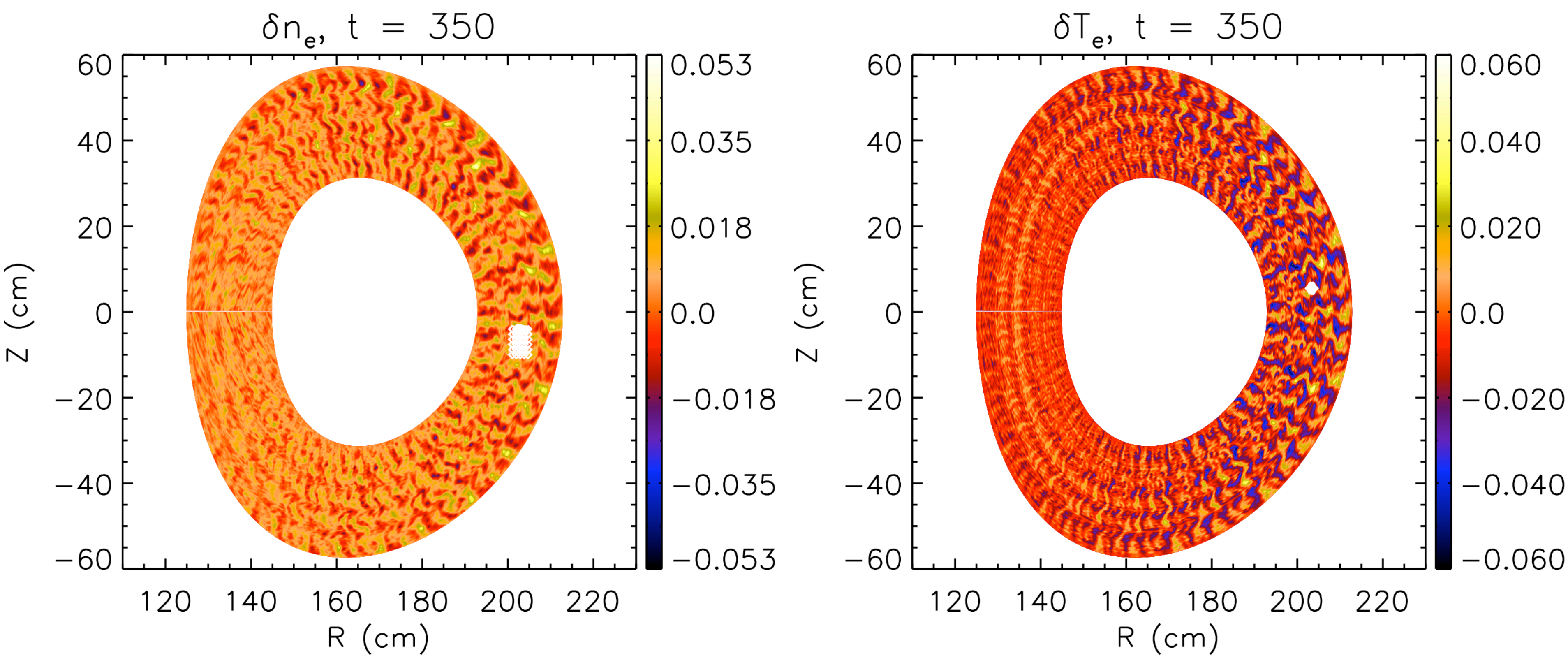
BES and CECE Fluctuation PSF Visualizations in (R,Z) Plane for ρ = 0.5 Simulation



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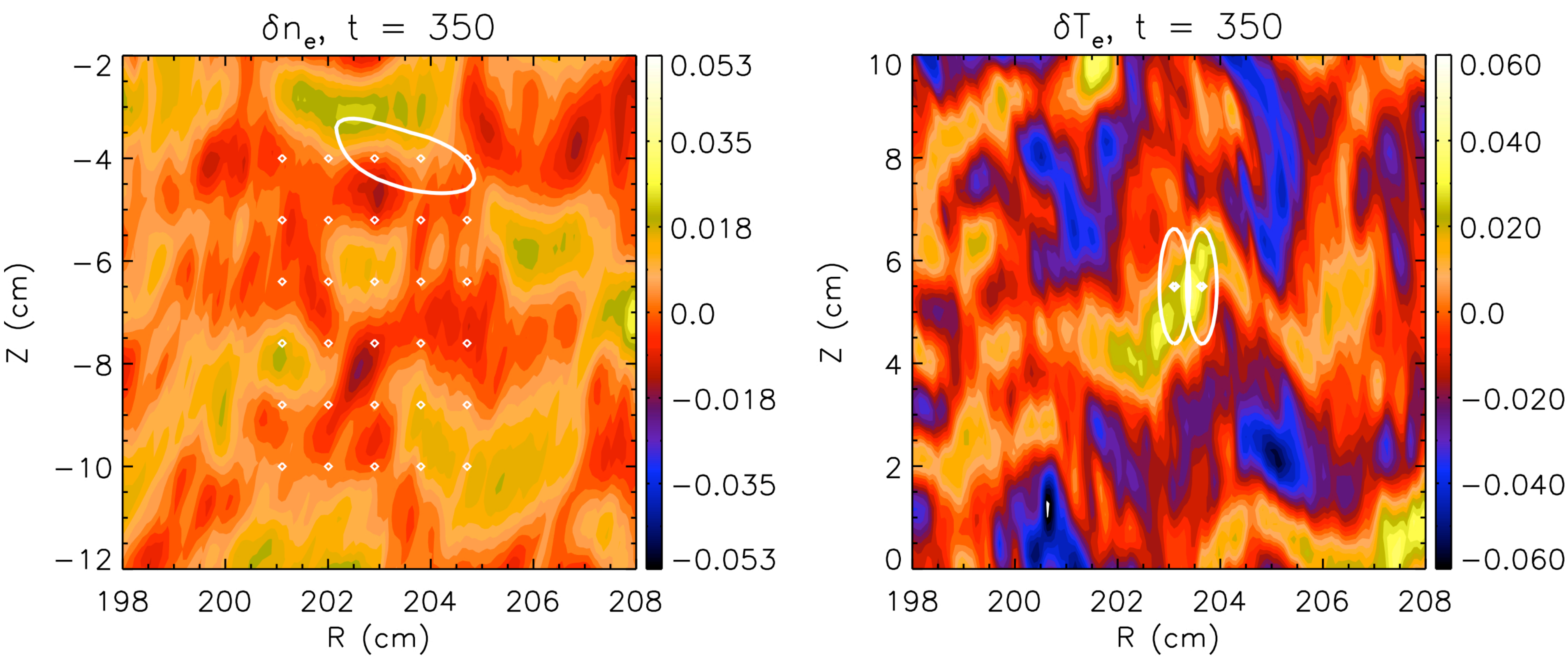
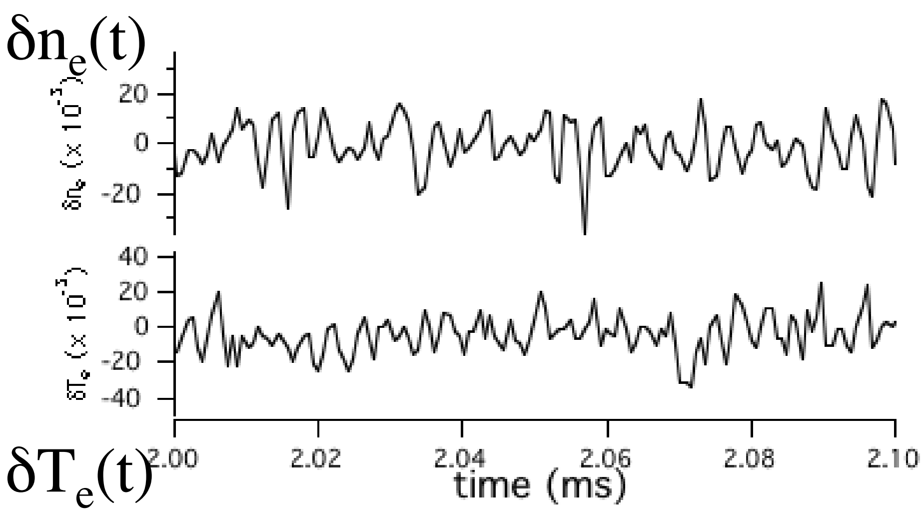
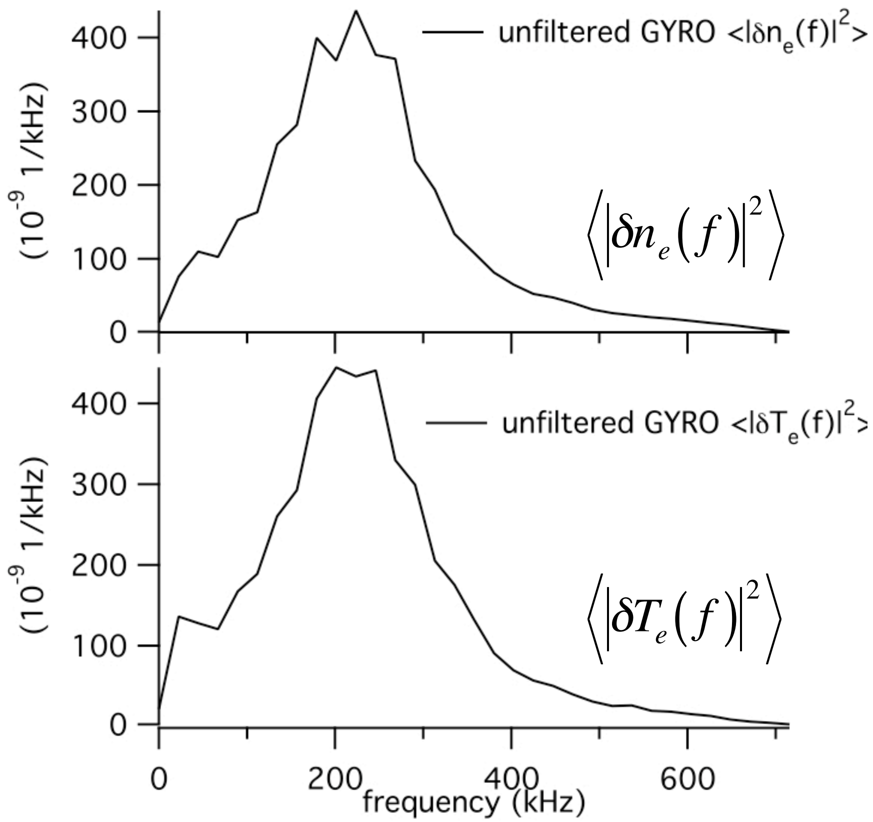


50% contours of BES and CECE PSFs

Synthetic Spectra Reflect Wavelength Sensitivities of Diagnostics

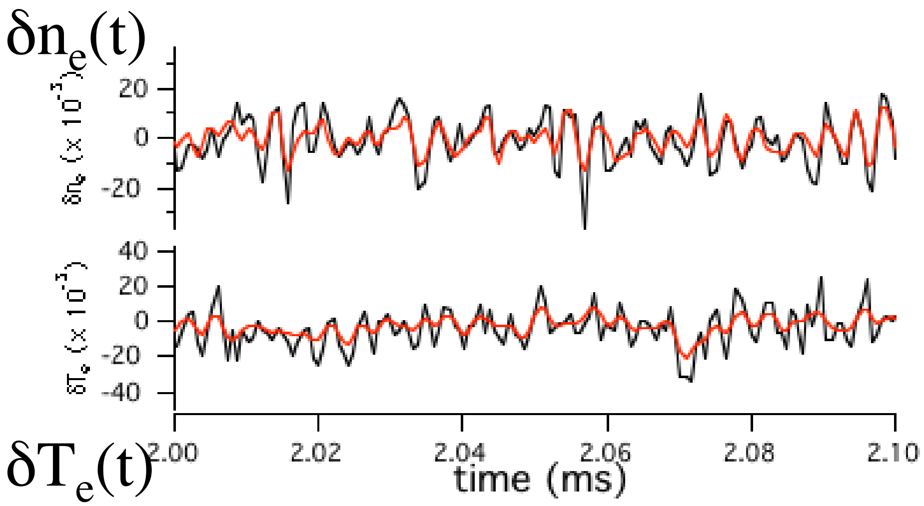
- **Black is unfiltered GYRO**

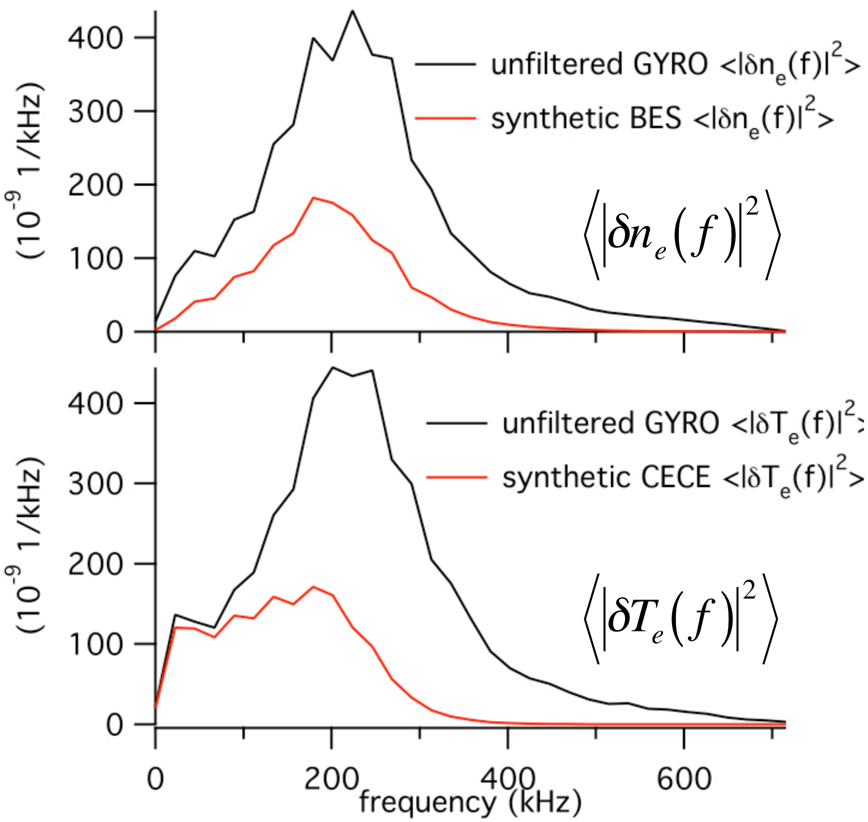




Synthetic Spectra Reflect Wavelength Sensitivities of Diagnostics

- **Black is unfiltered GYRO, red is synthetic BES/CECE**

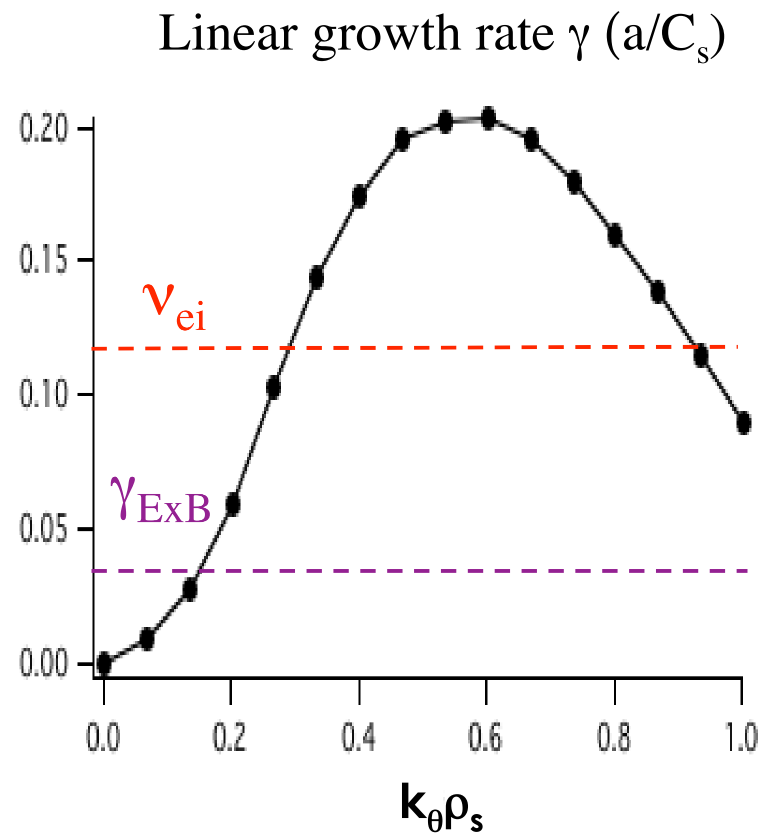




ρ = 0.5 results

ρ = 0.5 Simulation Numerical Details

- **To model this location, started with a series of local simulations using:**
  - 16 toroidal modes with $\Delta n = 8$, covering range of $k_\theta\rho_s = [0,1]$ with resolution $\Delta k_\theta\rho_s = 0.067$
  - DK electrons with physical mass ratio ($\mu = 60$)
  - Magnetic fluctuations and transport included (but very weak effect)
  - Box size $Lx \times Ly = 128 \times 94\ \rho_s$ $\Delta x/\rho_s = 0.43$
  - Save data every $a/C_s = 2.8\ \mu s$



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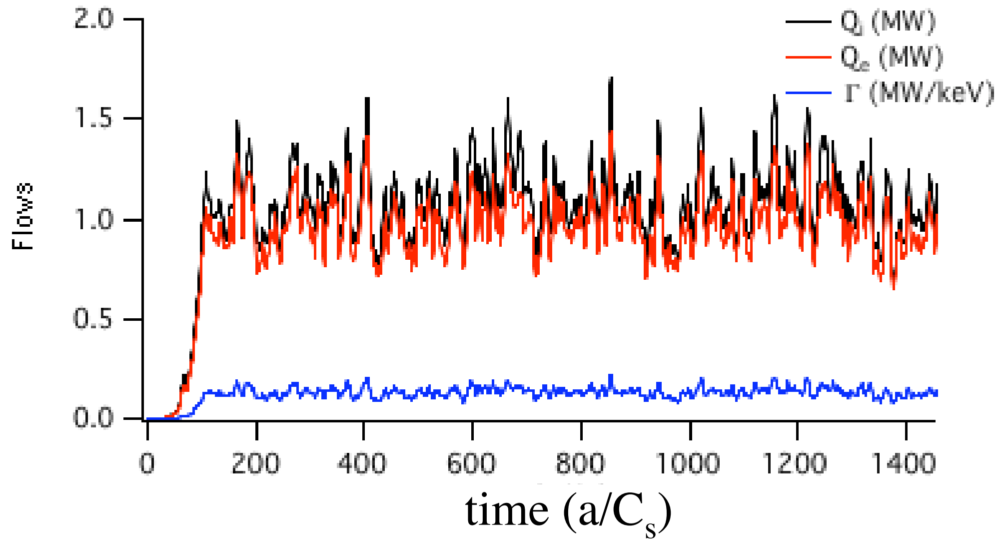
Simulation Exhibits Steady, Well-Converged Spectra at ρ = 0.5

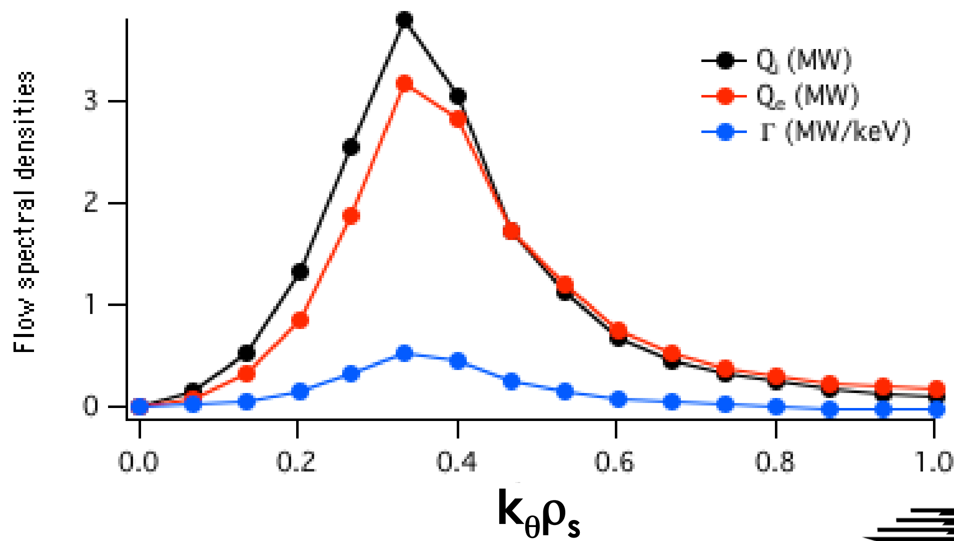
- **Box averaged time history and spectra of Q_i (MW), Q_e(MW), and Γ_e (MW/keV)**

$$Q = \frac{3}{2}\langle \tilde{p}\tilde{V}_r \rangle = -n\chi \frac{dT}{dr}$$

$$\Gamma = \langle \tilde{n}\tilde{V}_r \rangle = -D\frac{dn}{dr}$$

- **Simulation used 3072 cpu-hours on Franklin CRAY XT3 or NERSC**





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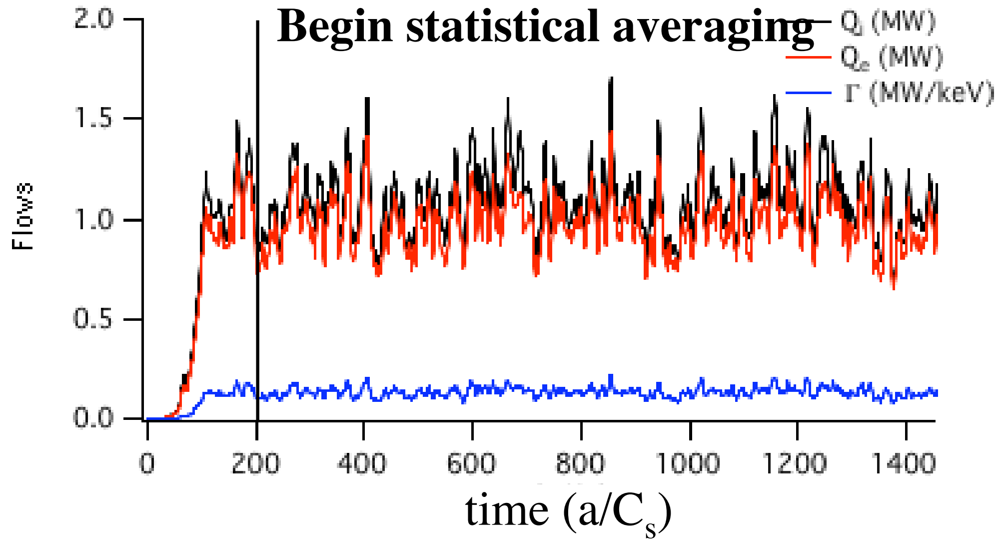

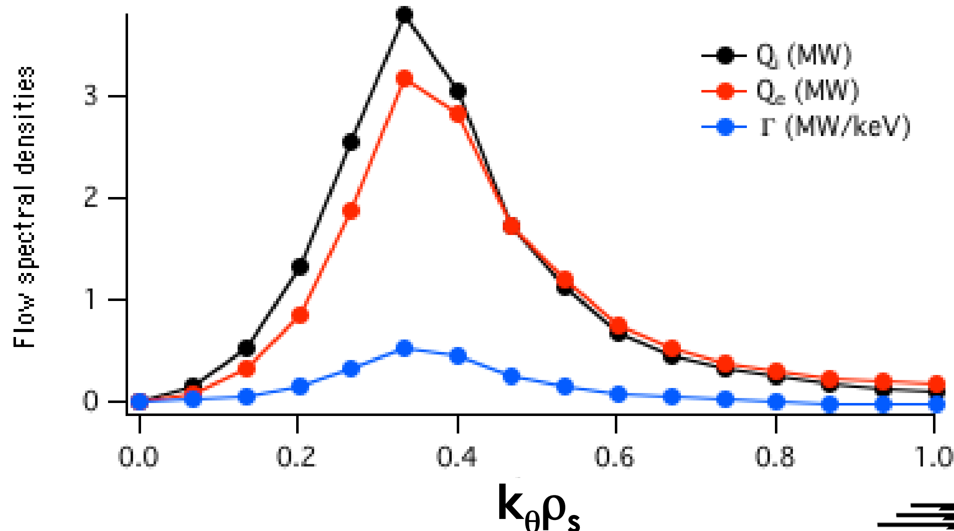

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Need Thousands of CPU-Hours to Simulate Milliseconds of Physical Time

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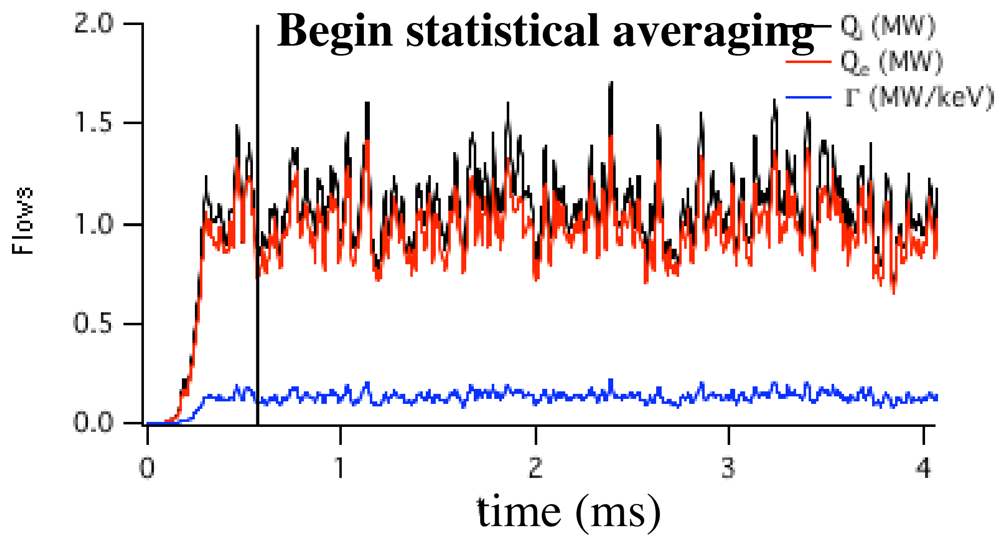

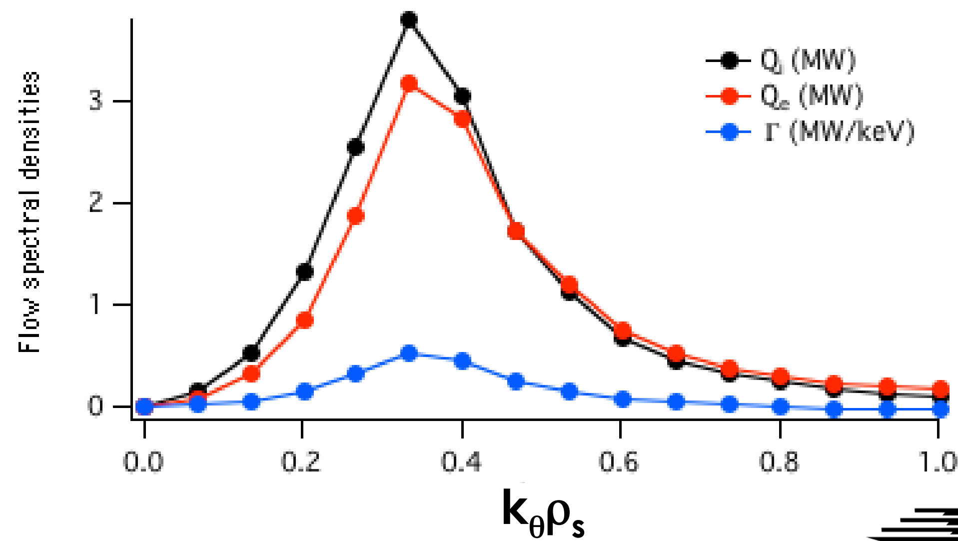

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Simulations Match Experimental Energy Fluxes at $\rho = 0.5$

- Experimental profiles give very good agreement in energy fluxes, gets even better with 5% reduction of ∇T_i
- Predicted particle transport is too high (relative to beam-driven flow), but both experimental and simulation flows much lower than energy fluxes
- Simulation error bars are std. deviations?
  - Q: how do we calculate # of turbulent realizations?

	Q_i (MW)	Q_e (MW)	Γ_{ne} (MW/keV)
Exp.	0.933	0.741	7.07 x 10^{-3}
GYRO	1.09 ± 0.170	0.974 ± 0.138	0.133 ± 0.0242

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GYRO (+20% γ_{ExB})	0.976 ± 0.162	0.861 ± 0.125	0.113 ± 0.0206

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GYRO (+20% γ_{ExB})	0.976 ± 0.162	0.861 ± 0.125	0.113 ± 0.0206
GYRO (-5% ∇T_i, +20% γ_{ExB})	0.793 ± 0.110	0.750 ± 0.0906	0.0927 ± 0.0155

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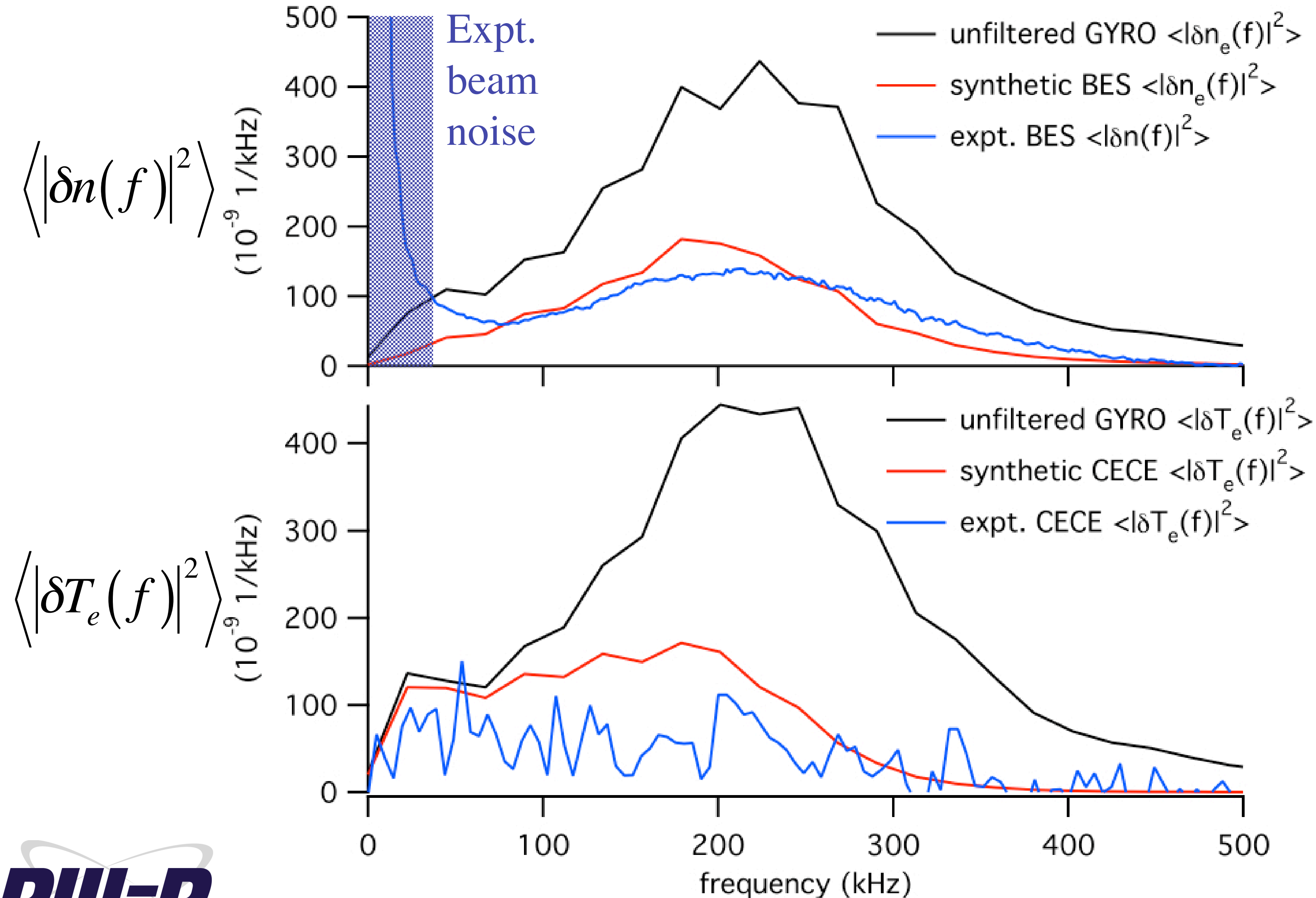
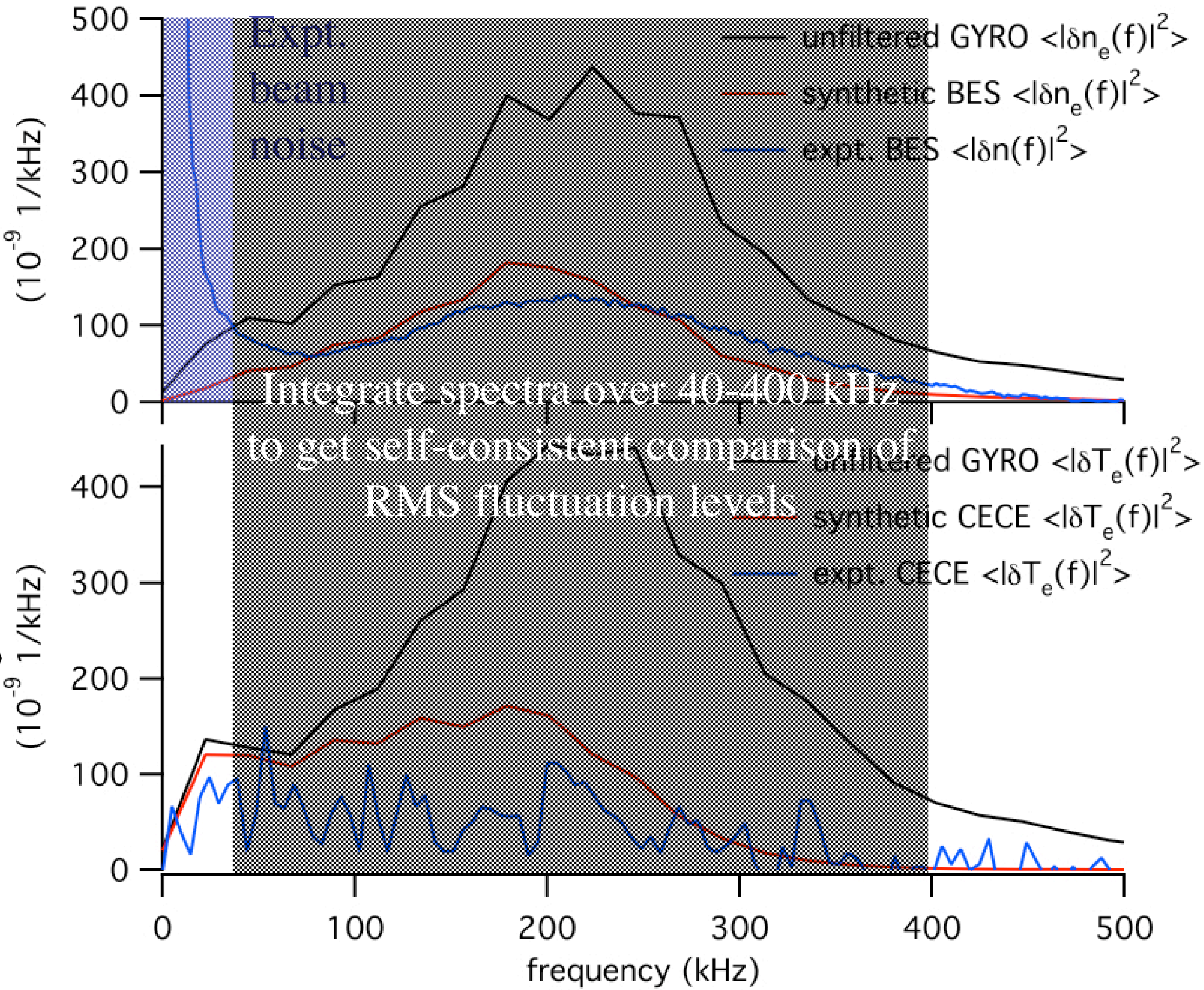
Lab-Frame Spectra Comparisons Show GYRO in Excellent Agreement with BES, but Overpredicting CECE



Lab-Frame Spectra Comparisons Show GYRO in Excellent Agreement with BES, but Overpredicting CECE

$$\left\langle \left| \delta n(f) \right|^2 \right\rangle$$

$$\left\langle \left| \delta T_e(f) \right|^2 \right\rangle$$



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Quantifying RMS Fluctuation Levels at ρ = 0.5

- **Fluctuation levels determined via:** $\delta n_{RMS} = \sqrt{\int_{f_{\min}}^{f_{\max}} df \left\langle \left|\delta n(f)\right|^2 \right\rangle}$

GYRO RMS δn_e (autopower, all *f*)	**1.0%**	**GYRO RMS δT_e (autopower, all *f*)**	**1.4%**

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GYRO RMS δn_e (autopower, all *f*)	1.0%
GYRO RMS δn_e (40 - 400 kHz)	0.90%

GYRO RMS δT_e (autopower, all *f*)	1.4%
GYRO RMS δT_e (40-400 kHz)	0.96%

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GYRO RMS δn_e (autopower, all *f*)	1.0%
GYRO RMS δn_e (40 - 400 kHz)	0.90%
syn. BES RMS δn_e (40 - 400 kHz)	0.55%

GYRO RMS δT_e (autopower, all *f*)	1.4%
GYRO RMS δT_e (40-400 kHz)	0.96%
syn. CECE RMS δT_e (40 - 400 kHz)	0.56%

Quantifying RMS Fluctuation Levels at ρ = 0.5

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GYRO RMS δn_e (autopower, all *f*)	1.0%
GYRO RMS δn_e (40 - 400 kHz)	0.90%
syn. BES RMS δn_e (40 - 400 kHz)	0.55%
expt. BES RMS δn (40-400 kHz)	0.56% ± 0.1%

GYRO RMS δT_e (autopower, all *f*)	1.4%
GYRO RMS δT_e (40-400 kHz)	0.96%
syn. CECE RMS δT_e (40 - 400 kHz)	0.56%
expt. CECE RMS δT_e (40-400 kHz)	0.4% ± 0.2%

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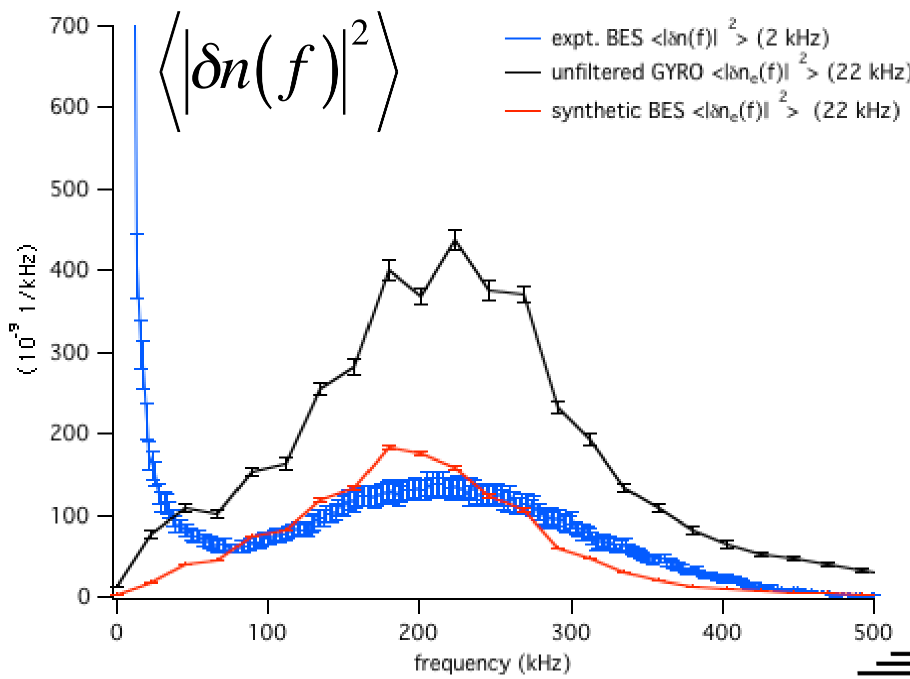
Caveat: Different Frequency Resolutions Used for Synthetic and Experimental Spectra

- **Swindle: used low freq resolution (22 kHz) for syn. diagnostics, vs 2 kHz for expt.**
  - BES spectrum plotted with 10% uncertainty

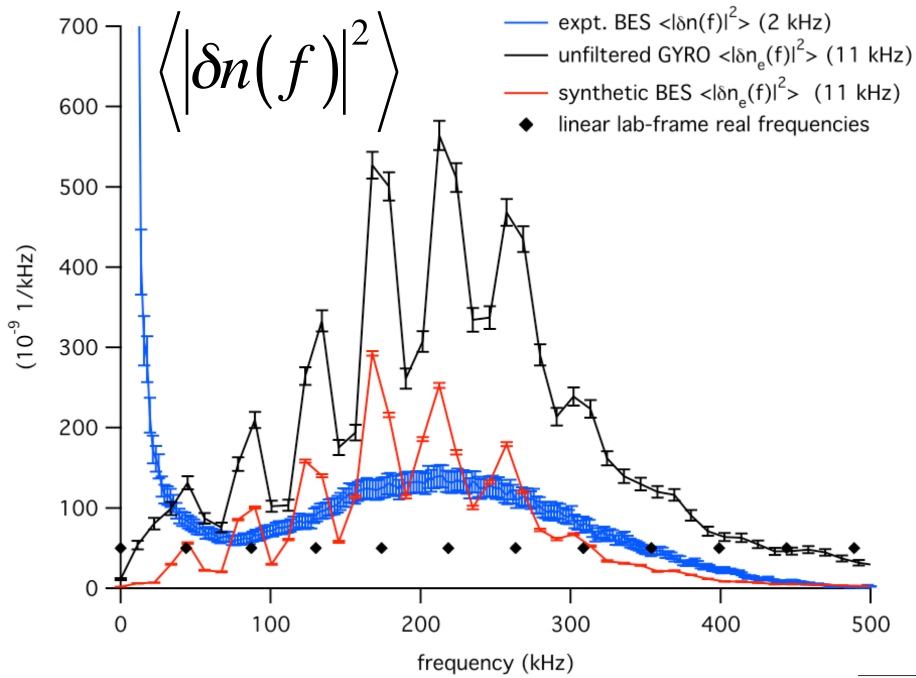
	RMS δn (40 - 400 kHz)	RMS δT_e (40 - 400 kHz)
Expt. (2.5 kHz)	0.56	0.4
Sim (22 kHz)	0.55	0.56



Increased Frequency Resolution Brings Out Finite Δn Structure of Synthetic Signals

- **Swindle: used low freq resolution (22 kHz) for syn. diagnostics, vs 2 kHz for expt**
- **If we calculate synthetic spectra with double freq resolution, observe features well-correlated with discrete *n* values**
  - Features robust with even higher resolution, but SNR decreases quickly

	RMS δn (40 - 400 kHz)	RMS δT_e (40 - 400 kHz)
Expt. (2.5 kHz)	0.56	0.4
Sim (22 kHz)	0.55	0.56
Sim (11 kHz)	0.58	0.57



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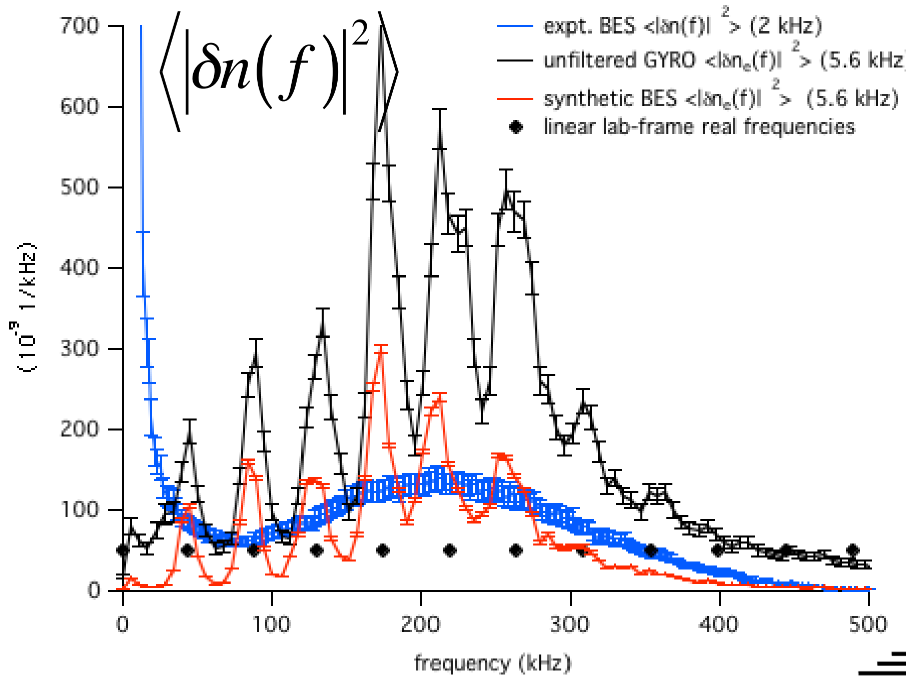
- **If we calculate synthetic spectra with double freq resolution, observe features well-correlated with discrete *n* values**
  - Features robust with even higher resolution, but SNR decreases quickly
- **RMS levels robust, but spectra details not: primacy hierarchy in action?**
  - How do we factor this into a validation metric?

	RMS δn (40 - 400 kHz)	**RMS δT_e (40 - 400 kHz)**
Expt. (2.5 kHz)	0.56	0.4
Sim (22 kHz)	0.55	0.56
Sim (11 kHz)	0.58	0.57
Sim (5.6 kHz)	0.56	0.56



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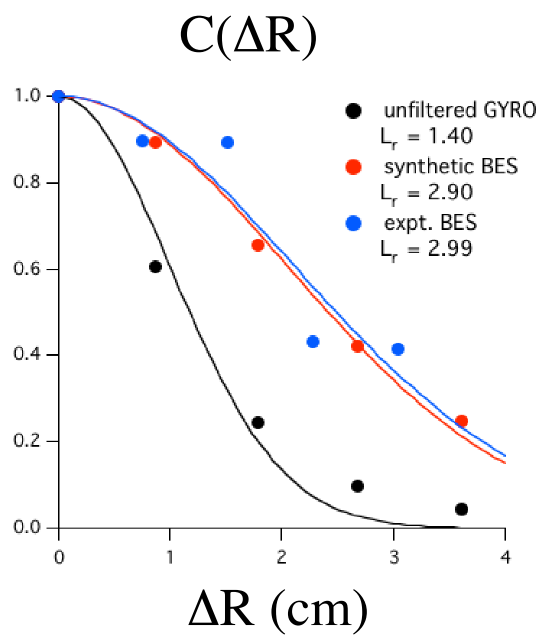
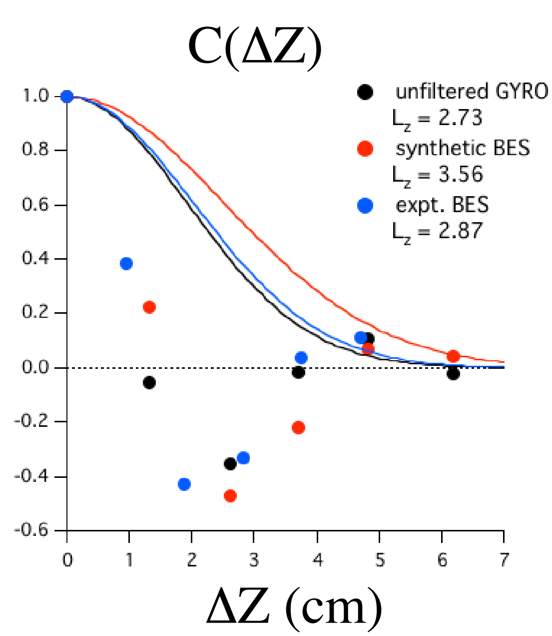
BES PSF Primarily Impacts Radial Correlation Length at ρ = 0.5

- **Find very good agreement between synthetic results and experiment for both radial and poloidal correlation length**
  - Agreement in C(ΔZ) consistent with agreement in lab-frame power spectra
- **Dashed lines are Gaussians fit to experimental BES, synthetic BES and unfiltered GYRO output (fit envelope of C(ΔZ))**

$$C(\Delta x) = \langle n(x,t)\, n(x+\Delta x,t) \rangle_t$$

	L_R (cm)	L_Z (cm)
GYRO (unfiltered)	1.41	2.73
Synthetic BES (all *f*)	2.90	3.56
Expt. BES (40-400 kHz)	2.99	2.87





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Sensitivity Studies Indicate Only "Moderate" Stiffness of Transport at ρ = 0.5

- All simulations used a 20% too large γ_{ExB} value
- As for previous simulations, each column required ~3000 cpu-hours
- All diffusivities normalized to χ_{gB} = 0.866 m^2/s

			a/L_{Ti}		
	Expt.	base	+5%	-5%	-10%
χ_i	4.5	4.74	5.35	4.23	4.05
χ_e	2.1	2.38	2.67	2.17	2.05
D_{ne}	0.05	0.75	0.89	0.64	0.58

$$Q = \frac{3}{2}\left\langle \tilde{p}\tilde{V}_r \right\rangle = -n\chi \frac{dT}{dr} \qquad \Gamma = \left\langle \tilde{n}\tilde{V}_r \right\rangle = -D\frac{dn}{dr}$$

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		a/L_{Ti}				a/L_{Te}		
	Expt.	base	+5%	-5%	-10%	+5%	-5%	-10%
χ_i	4.5	4.74	5.35	4.23	4.05	4.83	5.00	4.87
χ_e	2.1	2.38	2.67	2.17	2.05	2.46	2.53	2.42
D_{ne}	0.05	0.75	0.89	0.64	0.58	0.71	0.87	0.90

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			a/L_{Ti}			a/L_{Te}			a/L_{ne}		
	Expt.	base	+5%	-5%	-10%	+5%	-5%	-10%	+5%	-5%	-10%
χ_i	4.5	4.74	5.35	4.23	4.05	4.83	5.00	4.87	4.72	5.30	5.47
χ_e	2.1	2.38	2.67	2.17	2.05	2.46	2.53	2.42	2.49	2.56	2.52
D_{ne}	0.05	0.75	0.89	0.64	0.58	0.71	0.87	0.90	0.77	0.84	0.87

$$Q = \frac{3}{2}\left\langle \tilde{p}\tilde{V}_r \right\rangle = -n\chi\frac{dT}{dr} \qquad \Gamma = \left\langle \tilde{n}\tilde{V}_r \right\rangle = -D\frac{dn}{dr}$$

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- All diffusivities normalized to $\chi_{gB} = 0.866\ m^2/s$

			a/L_{Ti}			a/L_{Te}			a/L_{ne}			box size		
	Expt.	base	+5%	-5%	-10%	+5%	-5%	-10%	+5%	-5%	-10%	N_n=32 Δ_n = 4	N_n=64 Δ_n = 2	N_n=20 (max ky +25%)
χ_i	4.5	4.74	5.35	4.23	4.05	4.83	5.00	4.87	4.72	5.30	5.47	5.18	5.26	5.74
χ_e	2.1	2.38	2.67	2.17	2.05	2.46	2.53	2.42	2.49	2.56	2.52	2.63	2.72	2.84
D_{ne}	0.05	0.75	0.89	0.64	0.58	0.71	0.87	0.90	0.77	0.84	0.87	0.86	0.88	0.92

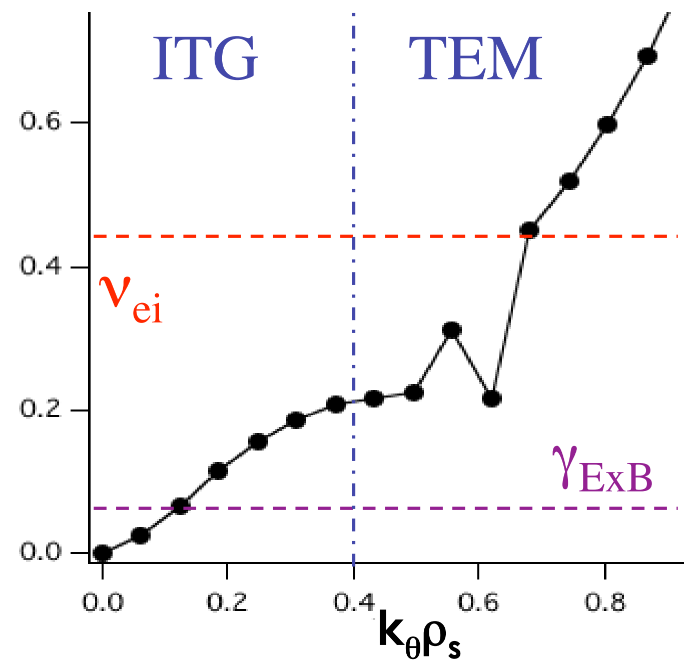
$$Q = \frac{3}{2}\left\langle \tilde{p}\tilde{V}_r \right\rangle = -n\chi\frac{dT}{dr} \qquad \Gamma = \left\langle \tilde{n}\tilde{V}_r \right\rangle = -D\frac{dn}{dr}$$

ρ = 0.75 results

Electron Branch Linearly Dominant at ρ = 0.75

- **Numerical setup similar to r/a = 0.5, except used half the r/a = 0.5 timestep**
  - Makes these simulations twice as expensive to run
  - Use Δn = 12 rather than 8 to acherive same k_θ range and resolution as r/a=0.5

Linear growth rate γ (a/C_s)



Comparison of r/a = 0.5 and 0.75 local parameters

ρ	a/L_{Ti}	a/L_{Te}	a/L_n	q	$\hat{s}$	T_i/T_e	β_e (10^{-4})	Z_{eff}	ρ^* (10^{-3})	ν_{ei}	γ_{ExB}
0.5	1.81	2.64	1.07	1.83	0.625	0.835	9.69	1.32	2.59	0.117	0.0503
0.75	2.55	4.93	1.08	2.77	2.07	1.18	2.55	1.33	1.49	0.438	0.0629

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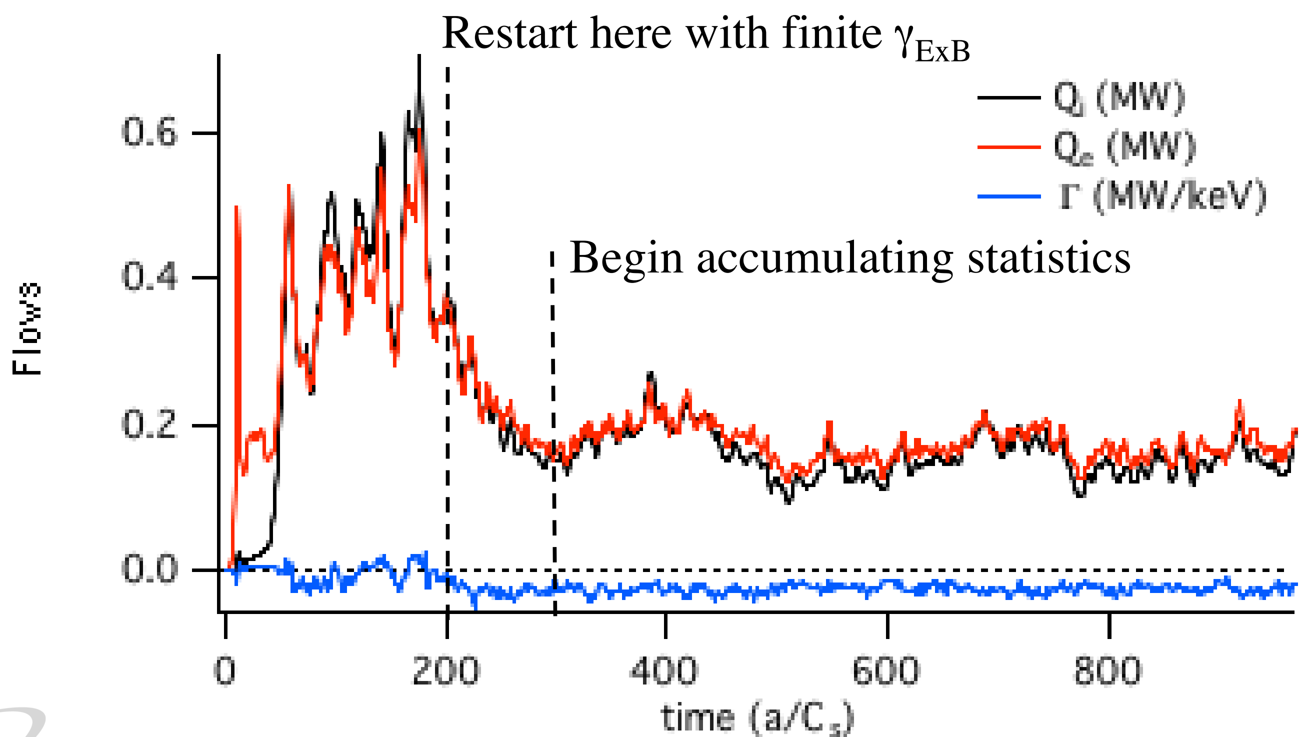
"Two-step" Simulations Needed at $\rho = 0.75$

- **In order to achieve physical results, found it was necessary to begin simulations without equilibrium ExB shear "turned on", and then restart simulations with shearing "turned on" after turbulence has developed**
  - Only use statistics from t > 300 at this location



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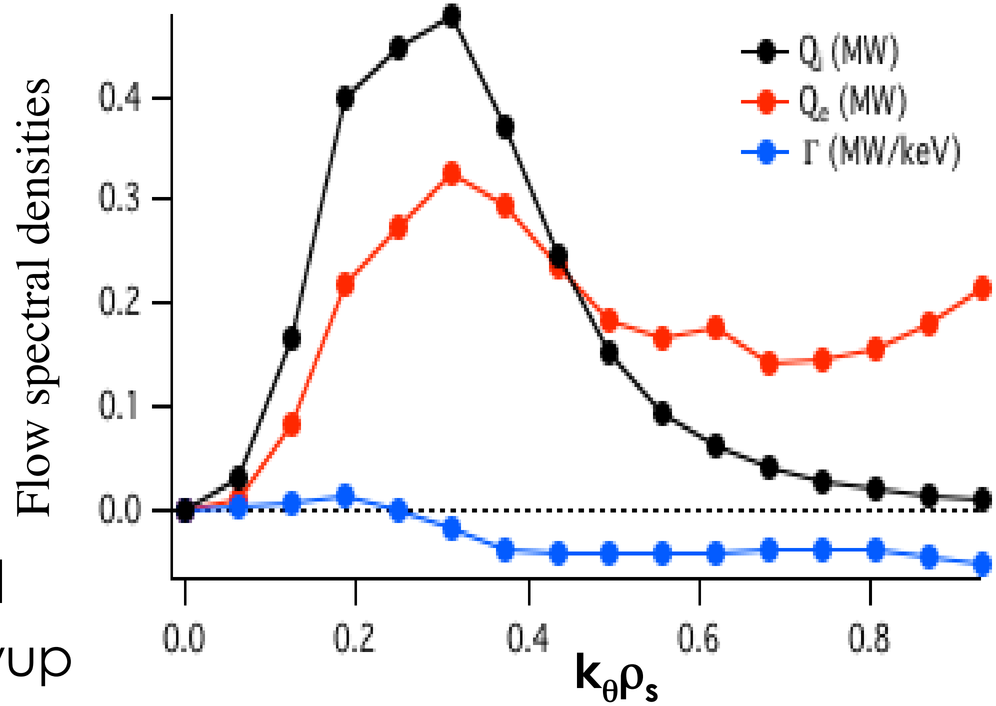
Electron Energy and Particle Flux Under-Resolved in $k_\theta\rho_s$ at ρ = 0.75

- **Significantly stronger TEM/ETG drive at ρ = 0.75 (relative to ρ = 0.5) appears to drive significant short(er) wavelength electron transport**
  - Ion flux remains well resolved

- **Attempts to date to increase maximum $k_\theta\rho_s$ while maintaining box size and resolution have been unsuccessful**
  - Sims exhibit high-k blowup even without ExB shear



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Both Fluxes and Fluctuation Levels Underpredicted at ρ = 0.75 Using Experimental Profiles

- Mismatches in fluxes and fluctuation levels consistent with $\chi \sim (\text{fluc. amp})^2$

	Exp.	GYRO
Q_i (MW)	1.12	0.158 ± 0.0304
Q_e (MW)	1.27	0.174 ± 0.0234
Γ_e (MW/keV)	0.0102	-0.0257 ± 0.00594
RMS δn (40-400 kHz)	1.1%	0.33%
RMS δT_e (40-400 kHz)	1.4%	0.44%

Both Fluxes and Fluctuation Levels Underpredicted at ρ = 0.75 Using Experimental Profiles

- Mismatches in fluxes and fluctuation levels consistent with $\chi \sim (\text{fluc. amp})^2$

	Exp.	GYRO	GYRO (γ_{ExB} -20%)
Q_i (MW)	1.12	0.158 ± 0.0304	0.216 ± 0.0308
Q_e (MW)	1.27	0.174 ± 0.0234	0.227 ± 0.0257
Γ_e (MW/keV)	0.0102	-0.0257 ± 0.00594	-0.0308 ± 0.00663
RMS δn (40-400 kHz)	1.1%	0.33%	0.42%
RMS δT_e (40-400 kHz)	1.4%	0.44%	0.71%

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Both Fluxes and Fluctuation Levels Underpredicted at ρ = 0.75 Using Experimental Profiles

- Mismatches in fluxes and fluctuation levels consistent with $\chi \sim$ (fluc. amp)^2
- Get larger response to change in ∇T_i here than at r/a = 0.5

	Exp.	GYRO	GYRO (γ_{ExB} -20%)	GYRO (∇T_i +10%, γ_{ExB} -20%)
Q_i (MW)	1.12	0.158 ± 0.0304	0.216 ± 0.0308	0.304
Q_e (MW)	1.27	0.174 ± 0.0234	0.227 ± 0.0257	0.295
Γ_e (MW/keV)	0.0102	-0.0257 ± 0.00594	-0.0308 ± 0.00663	-0.0257
RMS δn (40-400 kHz)	1.1%	0.33%	0.42%	TBD
RMS δT_e (40-400 kHz)	1.4%	0.44%	0.71%	TBD

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Parameter Scans Show Results Are Numerically Robust

- **Each row used >= 4096 processor-hours on Jaguar**
- **No ExB shear used in these cases**

	χ_i/χ_{gB}	χ_e/χ_{gB}	D_{ne}/χ_{gB}
expt	**22.5**	**15.5**	**0.25**
base	9.24 ± 0.40	4.79 ± 0.15	-0.46± 0.083
Inc. grad-Ti 10%	11.5	5.5	0.36
Half Δt (short run)	11.3	5.3	0.31
μ=40	9.77	5.43	-.45
EM effects on	10.3	5.36	0.12
Inc. max k_y 25%, Δx 33%, red. Δt 50%	9.69	4.72	0.11
Double max ky, half binormal box size	10.98	5.07	0.47
Inc. ORBIT_GRID	10.8	5.58	-0.76
Inc. ENERGY_GRID	9.84	5.04	-0.28
Inc. radial box size 50%	9.79	5.08	-0.39

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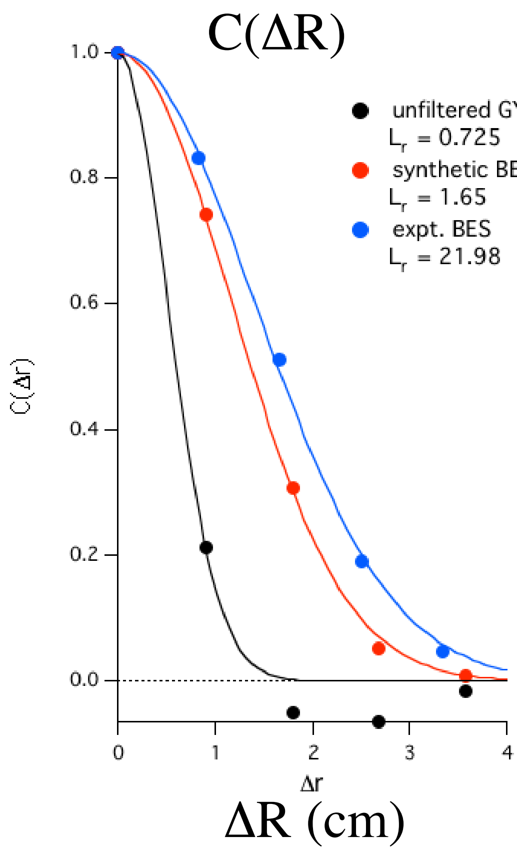
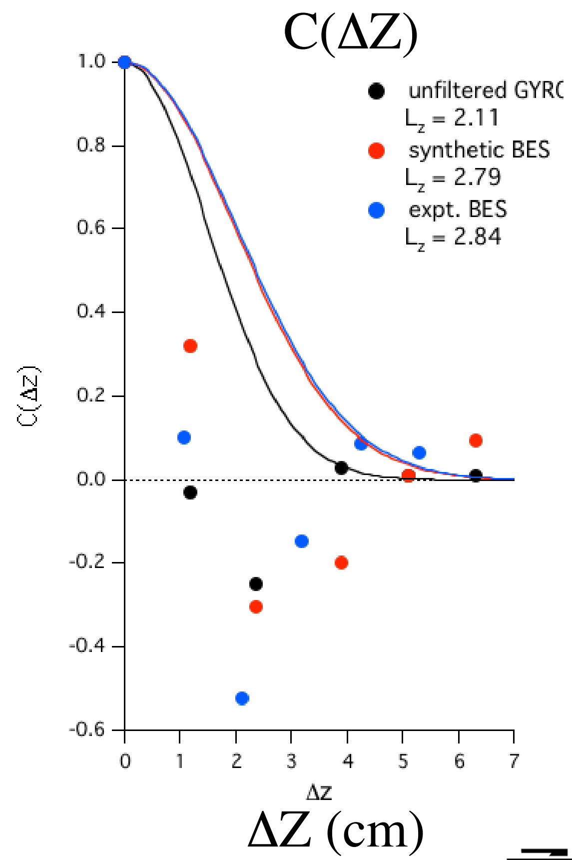
Observe Very Good Agreement in Both Radial and Poloidal Density Correlation Functions at ρ = 0.75

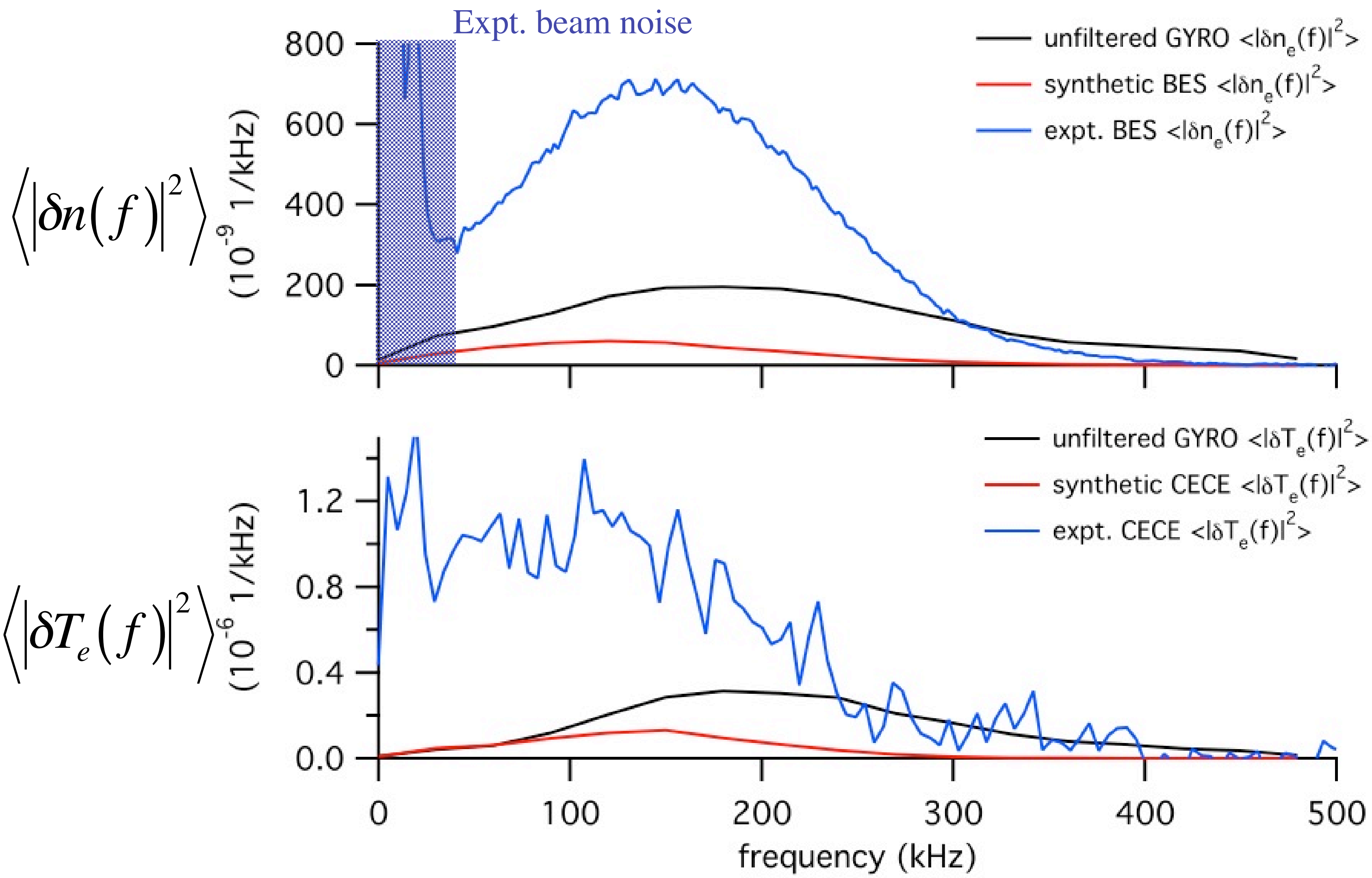
- Improved SNR in BES at this location allows for much "cleaner" experimental correlation functions

	L_R (cm)	L_Z (cm)
GYRO (all *f*)	0.85	2.03
Syn. BES (all *f*)	1.80	2.85
Exp. BES (40-400 kHz)	1.98	2.84





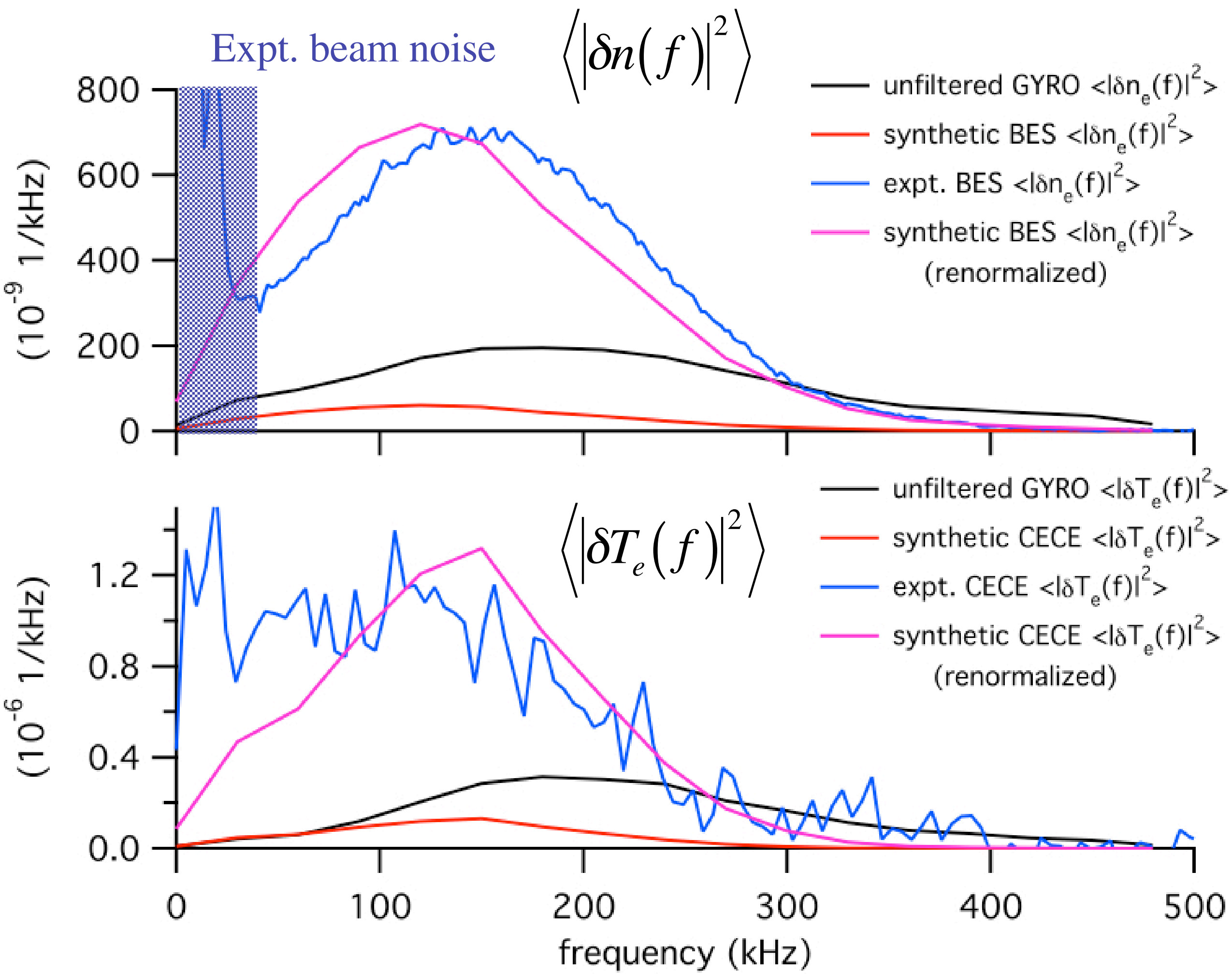
Synthetic Spectra Underpredict Experimental Measurements at all Frequencies



GYRO Lab-Frame Spectra Match Experiment in Shape but not Magnitude at $\rho = 0.75$

- **If synthetic spectra are renormalized to contain same power as experiment, find significant improvement in agreement with measured BES and CECE spectral shapes**

- **Spectral shape more robust than magnitude?**



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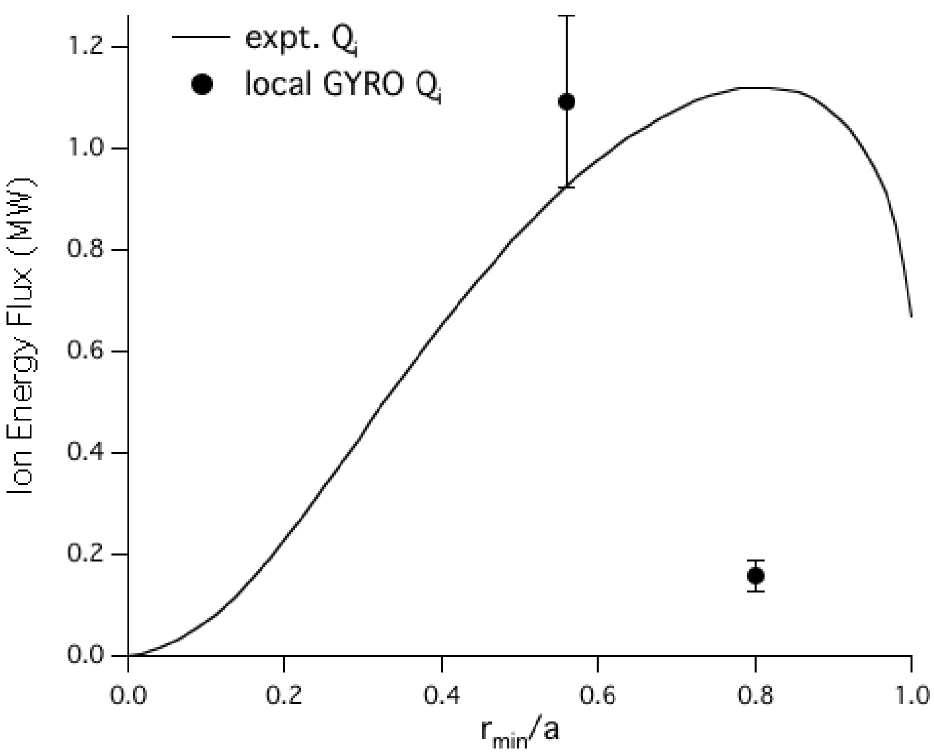
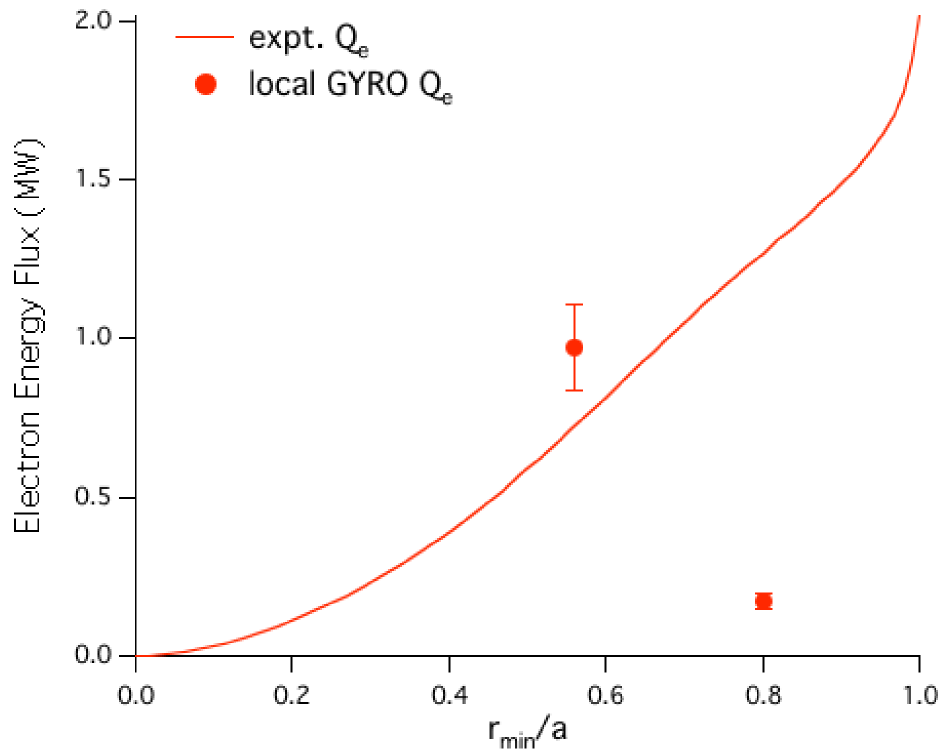
Nonlocal Simulations

Local Fixed-Gradient Sims Match Energy Fluxes and RMS Fluctuation Levels at ρ = 0.5, Underpredict ρ = 0.75

Q_i (MW)



Q_e (MW)



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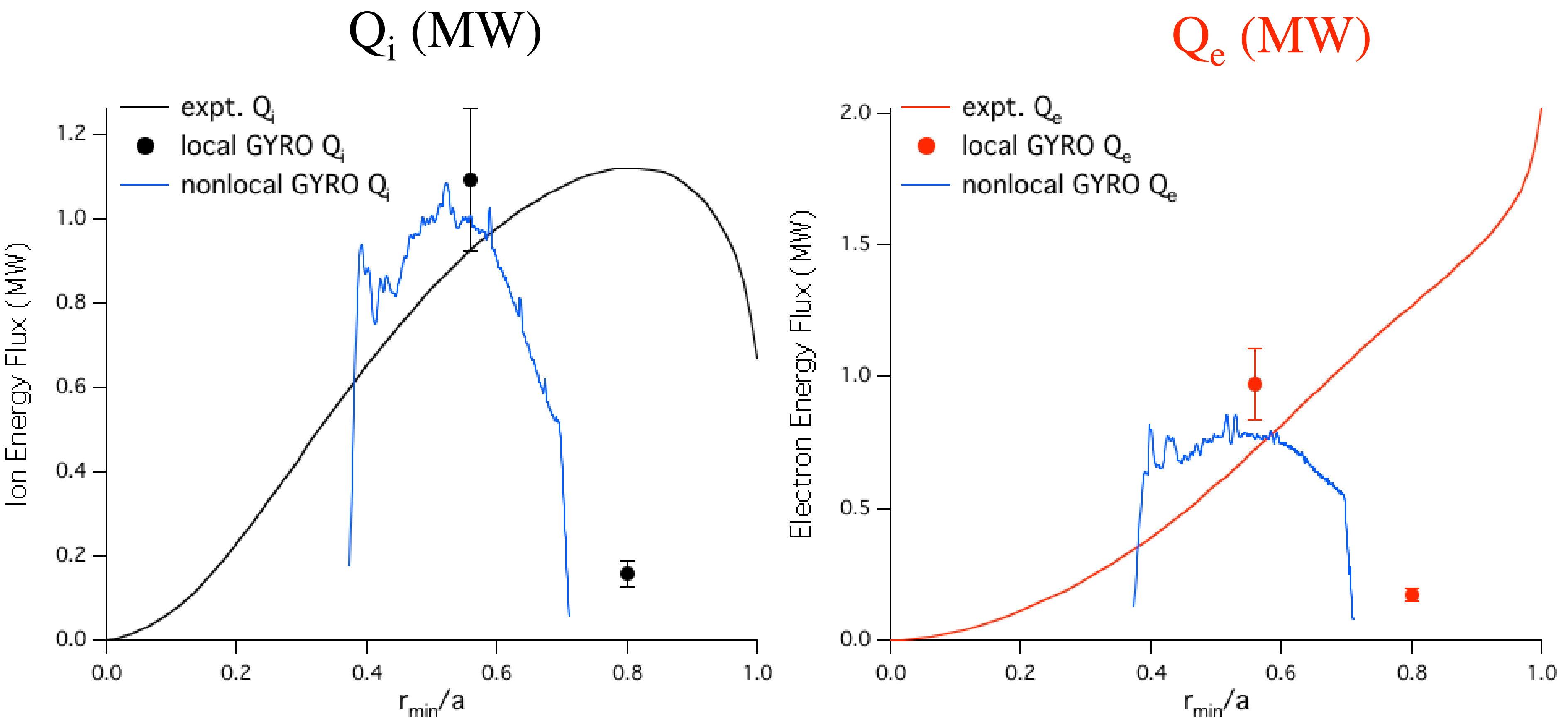
A Nonlocal Simulation Centered at ρ = 0.5 Matches the Local Results at That Location



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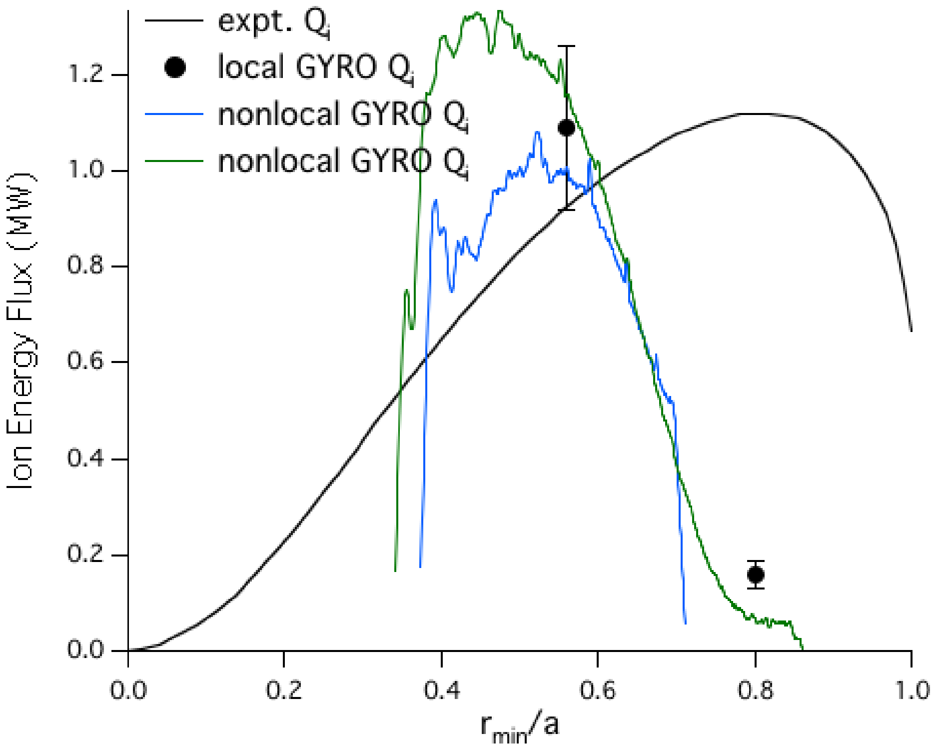
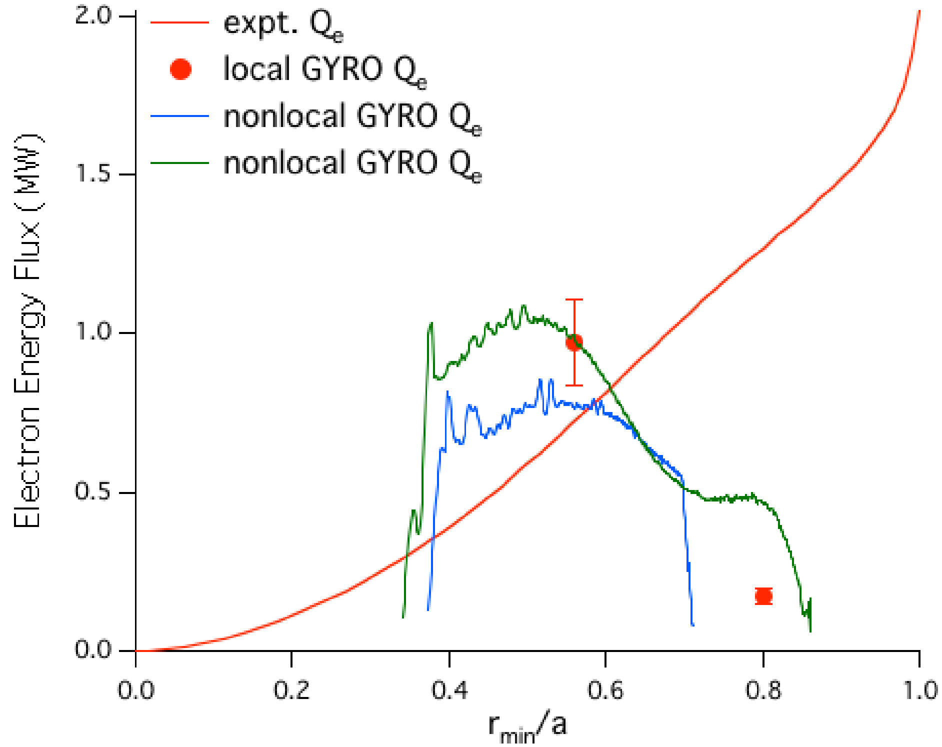
A Nonlocal Simulation Centered at ρ = 0.6 Smoothly Connects the Local Results

Q_i (MW)



Q_e (MW)



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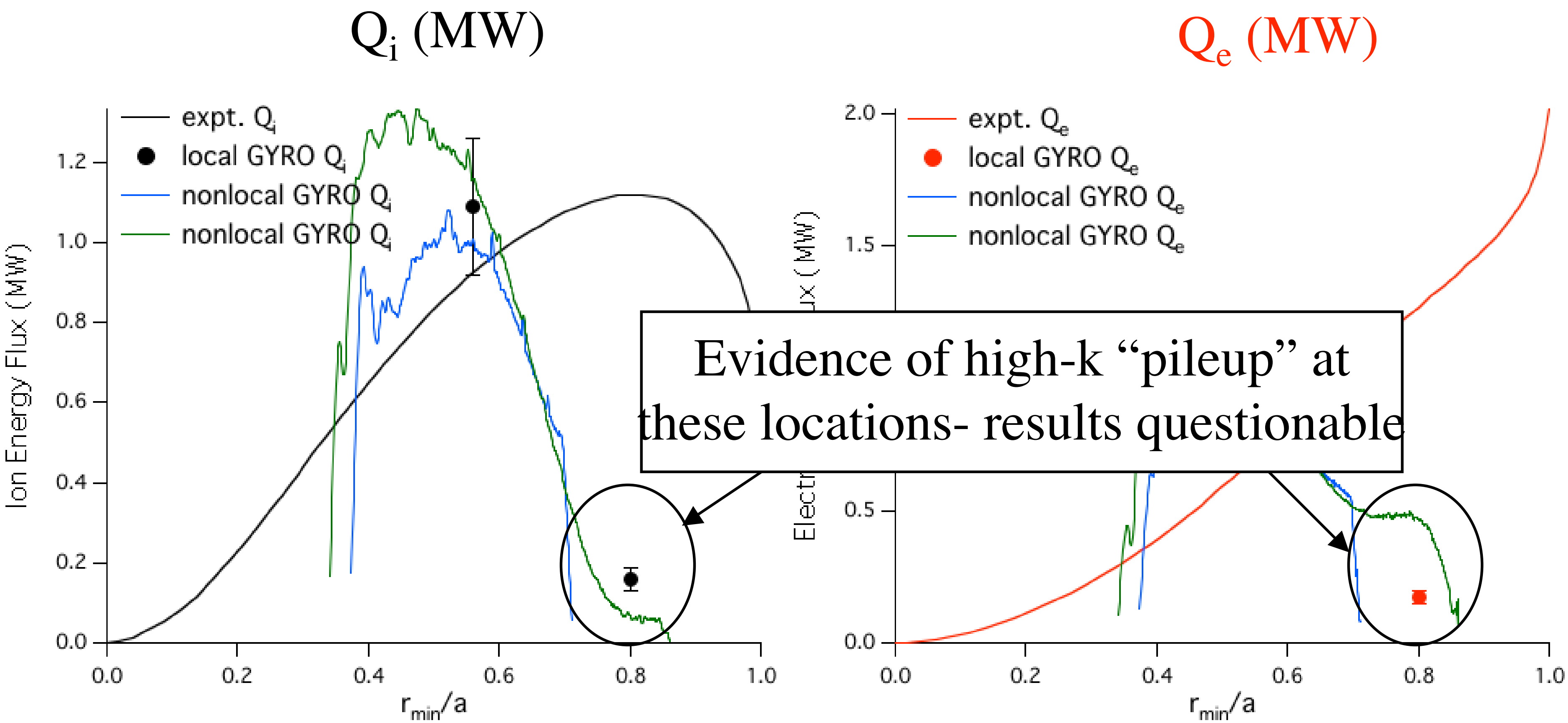
A Nonlocal Simulation Centered at ρ = 0.6 Smoothly Connects the Local Results



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Fixed-Flux Simulations

Need for Flux-Matching Simulations

- **Well-known that stiff transport is one of the defining characteristics of drift-wave turbulence**

- **Systematic uncertainties in fitting equilibrium profiles create large uncertainties in equilibrium gradients**
  - Fitted profiles rely on diagnostic calibrations, analyst selection of spline knot number and location
  - Translates to even larger uncertainties in fluxes predicted by simulation
  - Propagating these uncertainties through nonlinear simulations unlikely to be feasible in near-term

- **One way of addressing this issue is to predict the set of profiles needed match the energy and particle fluxes calculated via power balance, and compare against fitted profiles (or directly against the data)**
  - Because fluxes are volume integrals of sources, have in general less uncertainty than profiles

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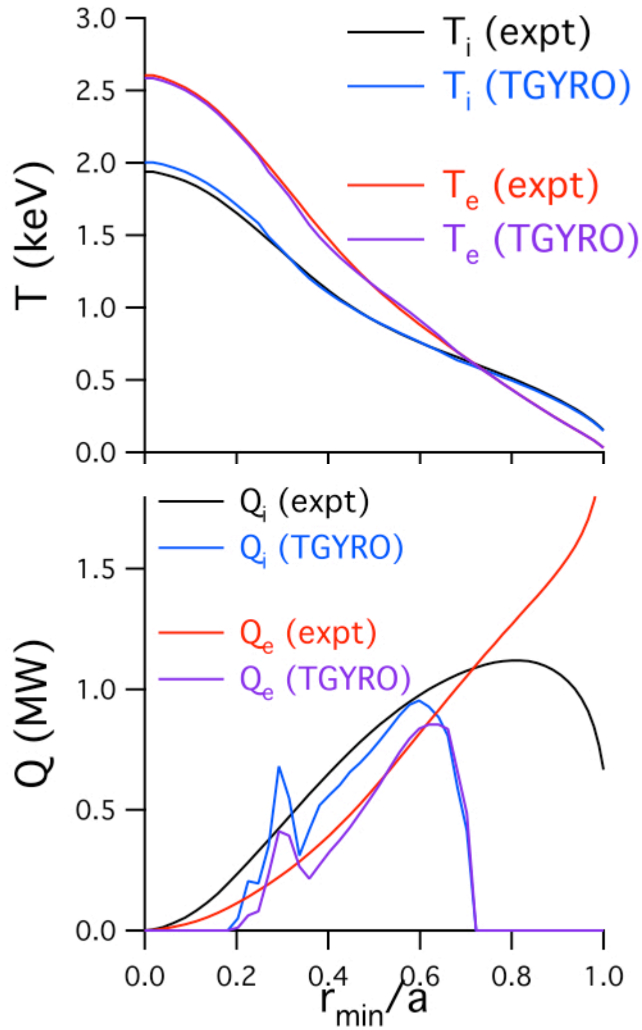
Initial Flux-Matching Algorithm Has Been Implemented for Use with GYRO

- **New TGYRO code under development to predict flux matching profiles**
- **Basic algorithm: every a/C_s, adjust local scale lengths by amount proportional to difference between GYRO simulation and power balance fluxes at each radial location**
- **e.x.: $\Delta(a/L_{Ti}) \propto (Q_i^{TGYRO} - Q_i^{PB})$**
  - Every ~50 a/C_s, update dimensionless equilibrium parameters
  - Currently only evolves density and temperatures- E_r/rotation profiles fixed
  - Still a "postdictive" rather than truly predictive formulation, but major step forward



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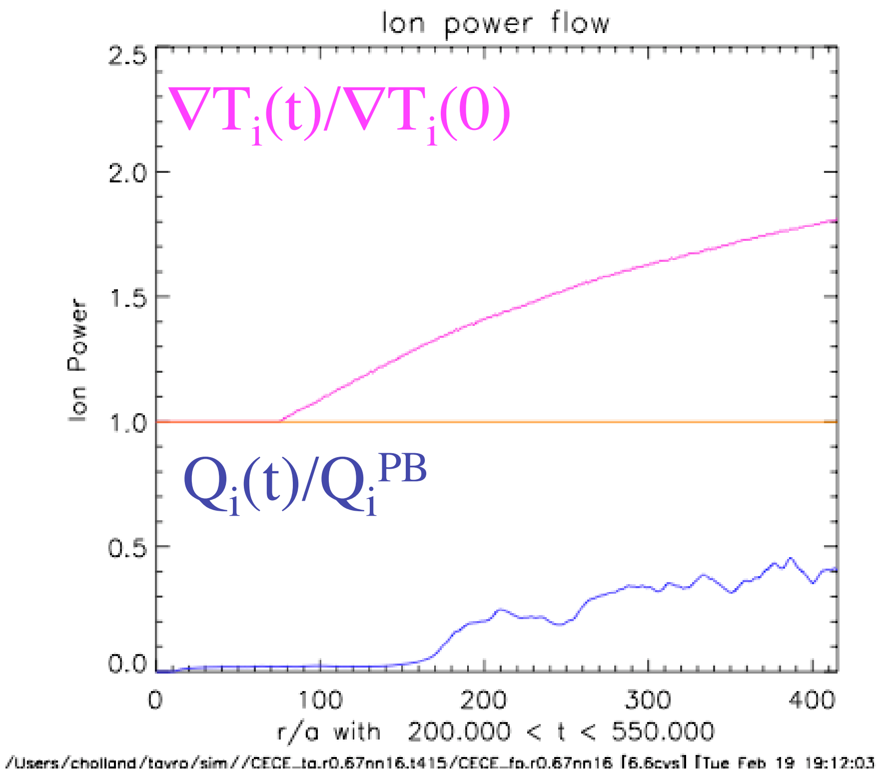
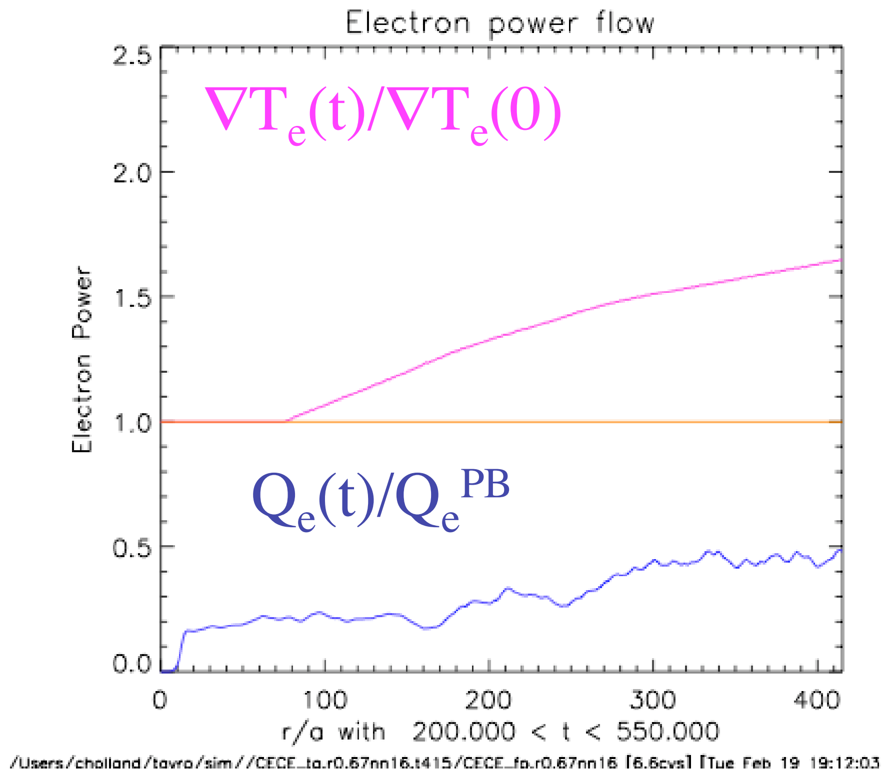
Preliminary Results Suggest More Significant Profile Changes Needed to Match Energy Flows at Larger Radii

Evolution at $\rho = 0.72$ ($r_{min}/a = 0.78$)





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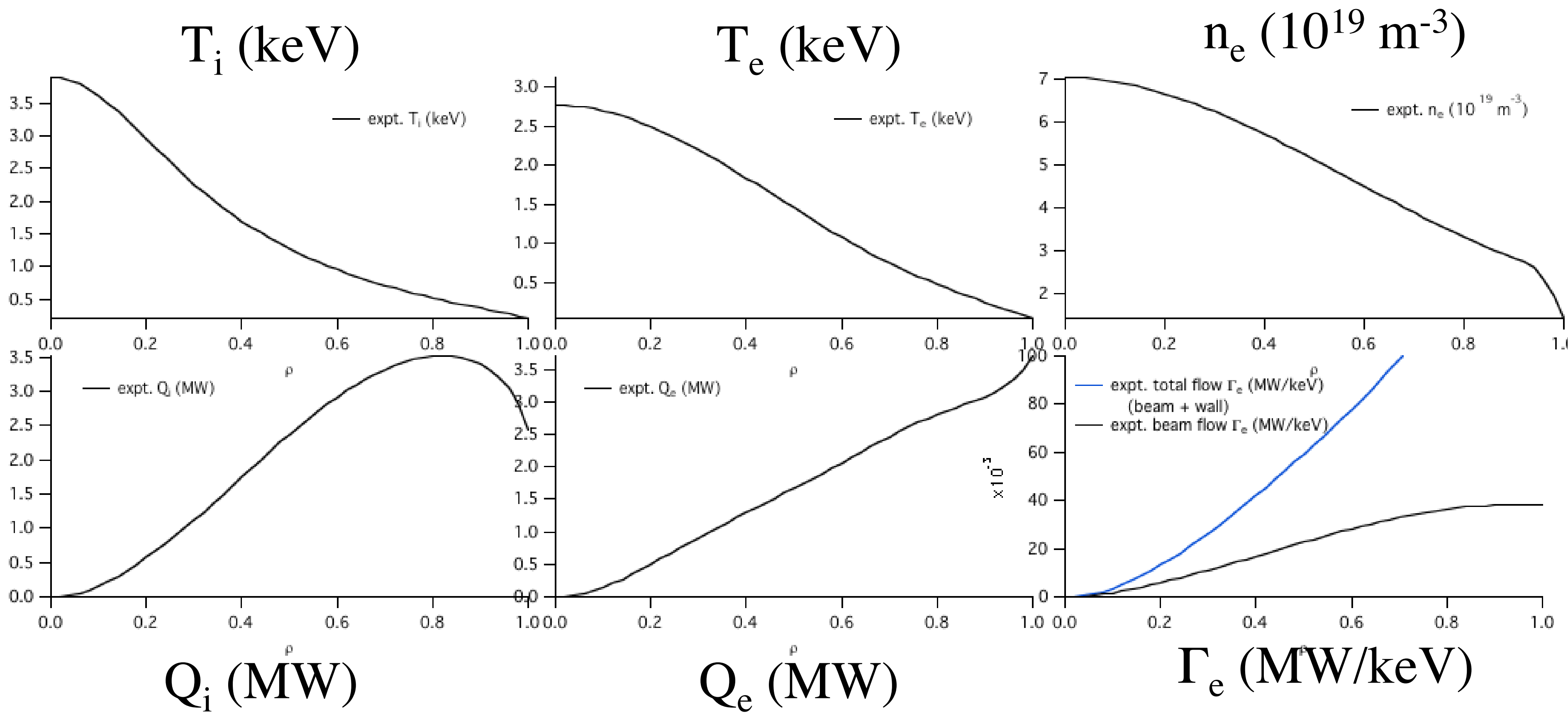
Interesting Counterpoint: TGYRO is Able to Match Energy And Particle Flows for Different DIII-D L-Mode Discharge

Black Γ_e is beam-driven flow, blue is total (beam + wall)

Shot 101391



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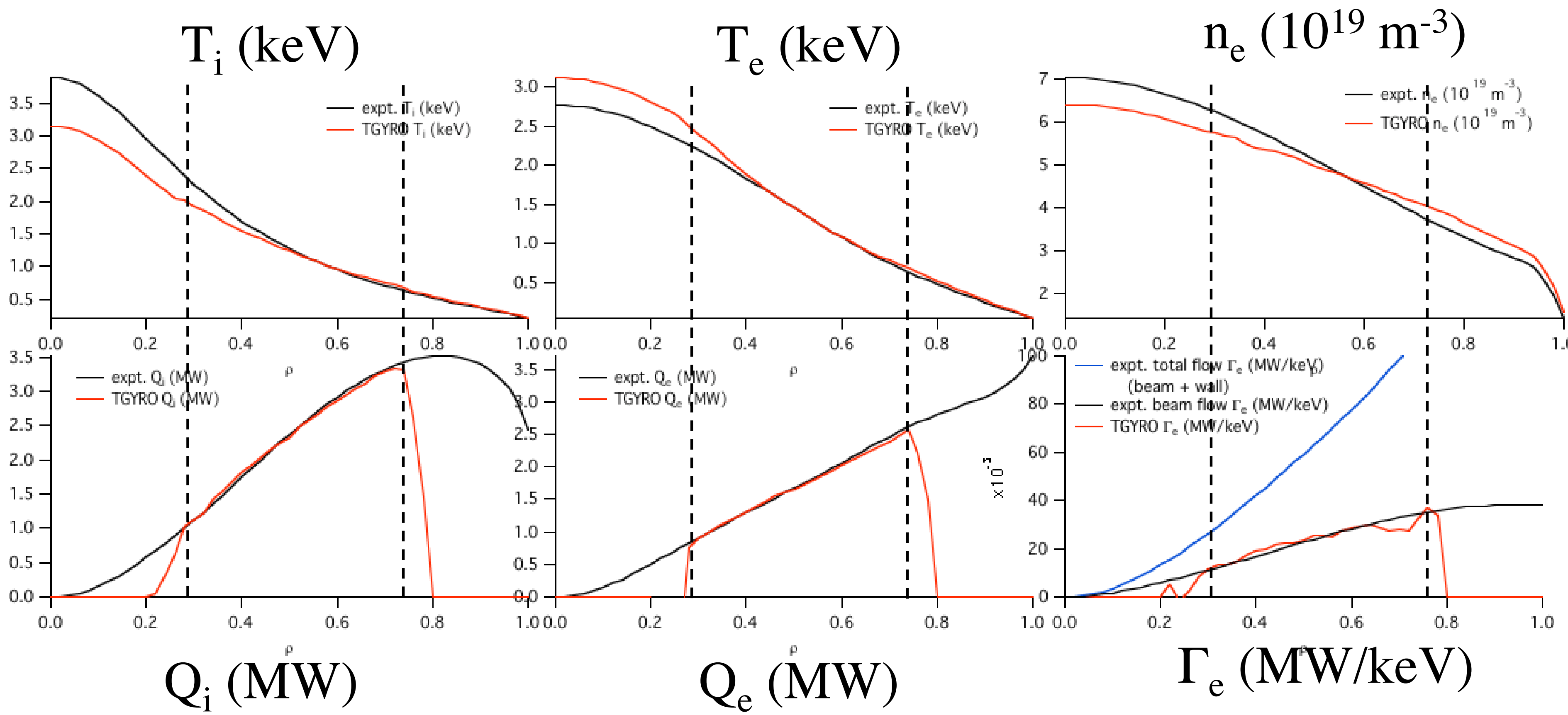
Interesting Counterpoint: TGYRO is Able to Match Energy And Particle Flows for Different DIII-D L-Mode Discharge

Experiment in black, TGYRO prediction in red

Shot 101391



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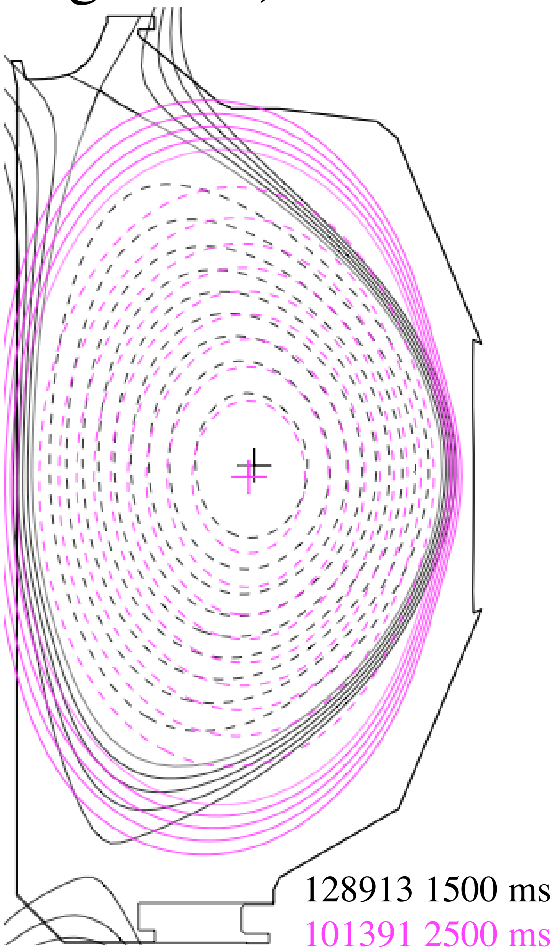
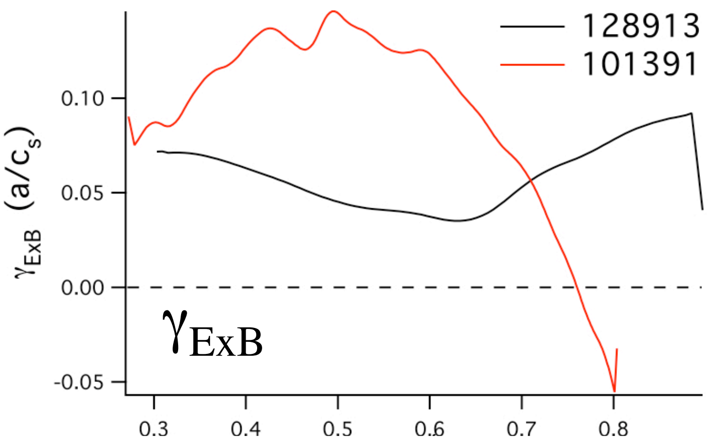
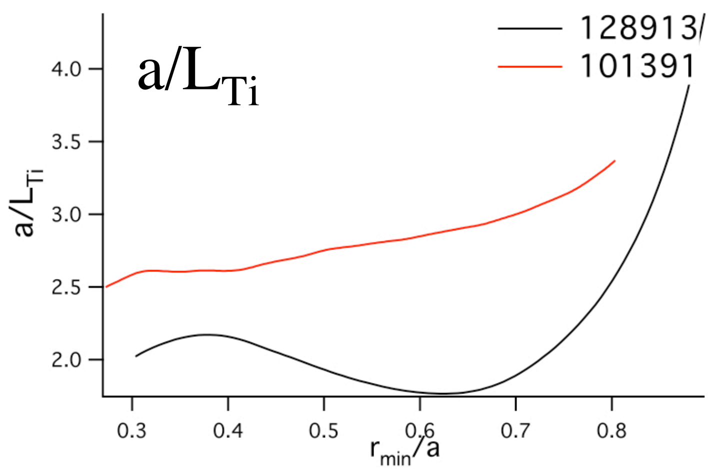
Comparison of EFITs and Profiles for 128913 and 101391

Note that magnitude of shear for 101391 becomes small (going through zero) at r/a = 0.7 while increasing for 128913







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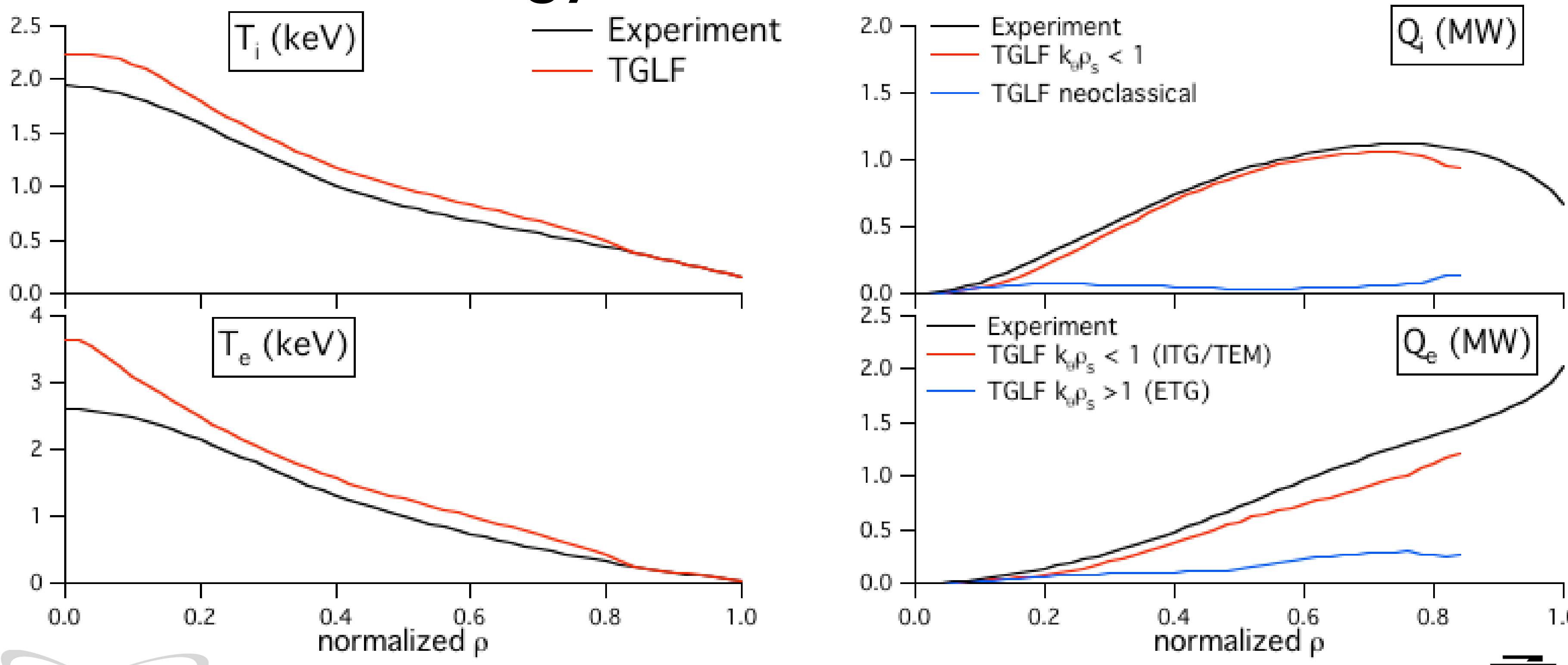
Preliminary Result: Using TGLF to Generate Initial Prediction of Flux-Matching Profiles

- **Used new TGLF code (discussed by J. Kinsey this afternoon) to predict a set of profiles necessary to match energy fluxes**



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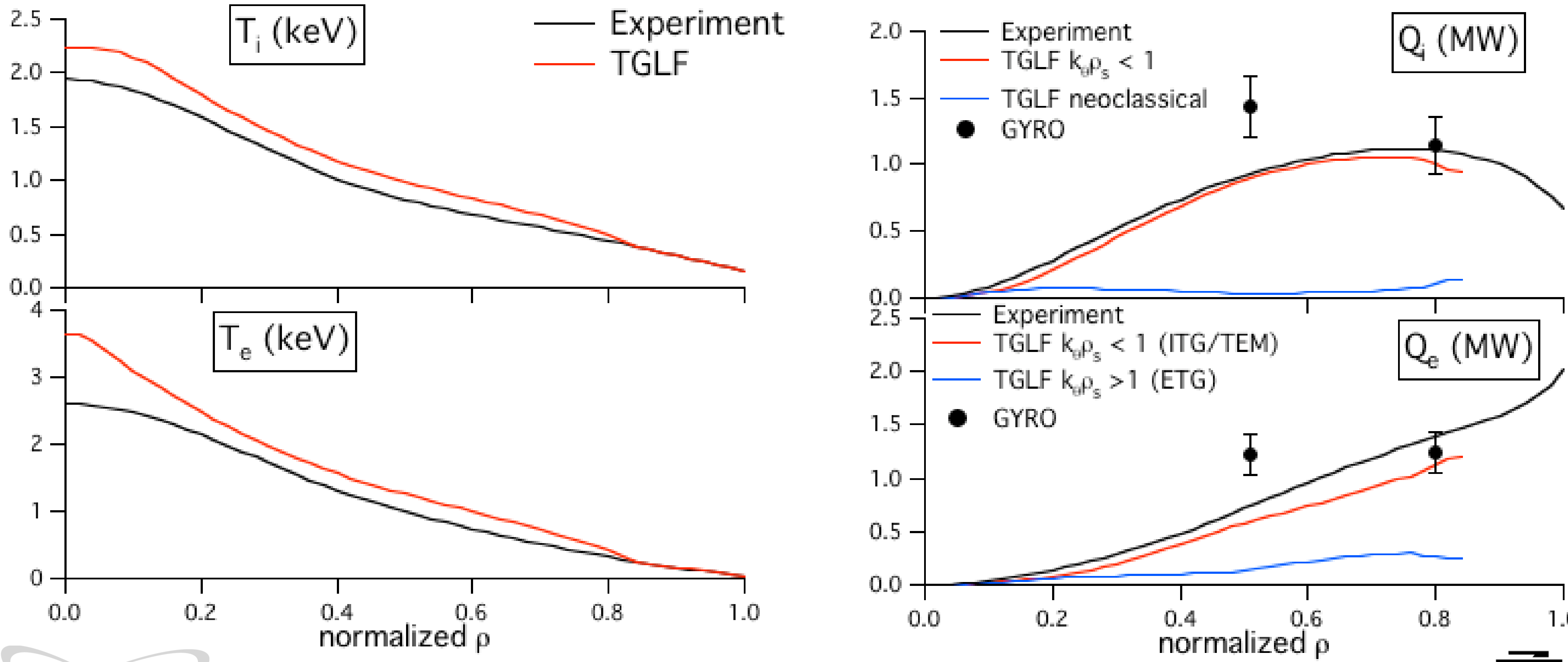
Preliminary Result: GYRO Simulation Using TGLF Profiles Exhibits Much Better Agreement at ρ = 0.75

- **Local GYRO simulations using the TGLF profiles show moderate disagreement in heat fluxes at ρ = 0.5, but significant improvements at ρ = 0.75**



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Future Directions

Issue 1: Systematic Uncertainties and Errors in Equilibrium Profiles

- **Steady-state plasmas can have negligible statistical profile uncertainties, relative to the systematic uncertainties and errors**
  - Uncertainty/error in magnetic equilibrium at least as important as density/temperature/rotation profiles
  - Input datafiles for nonlinear simulation codes often manufactured by other codes- easy to introduce errors (as discussed last year by R. Bravenec)

- **Propagation of these uncertainties through nonlinear fixed gradient simulations not likely to be readily feasible in near-term**
  - Would require ensemble of profile fits used to calculate ensemble of simulations to be compared against ensemble of power balance analysis
  - Are there any comprehensive assessments of what systematic uncertainties there are in the power balance flux calculations for use with fixed-flux simulations?

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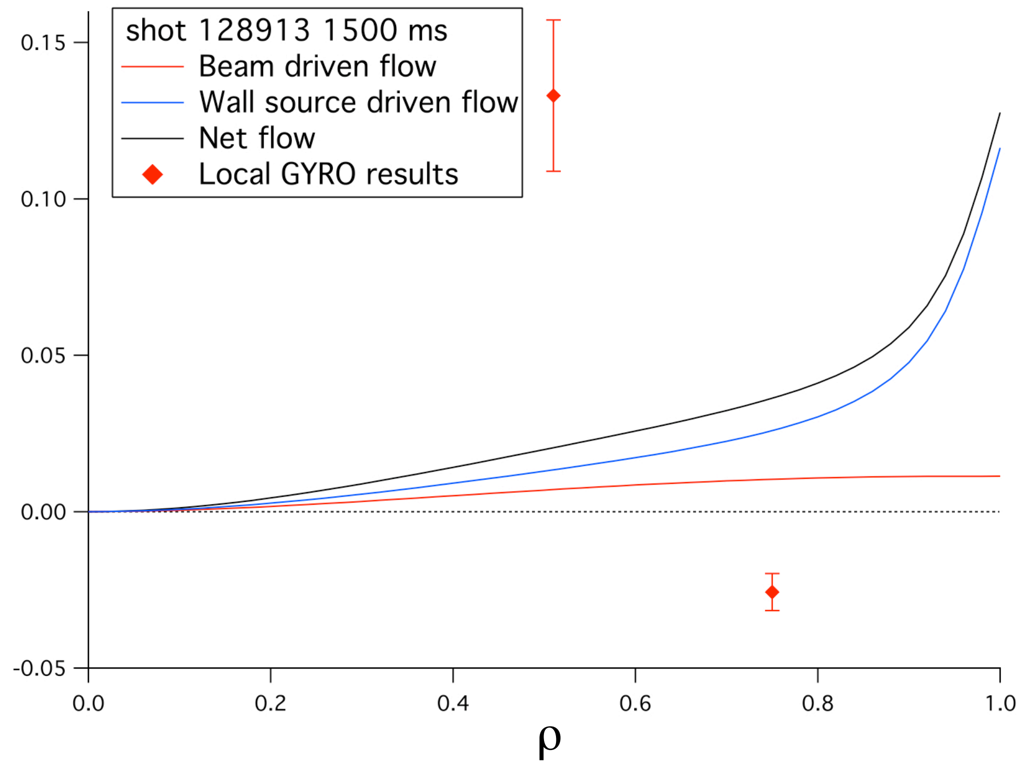
Issue 2: Impact of Wall Neutral Source

- **There is significant uncertainty in net particle flow due to the relatively unknown magnitude of the "wall" particle source**
  - Particularly likely to be true in low-power L-modes with little NBI heating/fueling
  - Introduces uncertainty into energy flows via charge exchange and radiation source terms



- **Implications-**
  - Limits our ability to validate particle transport in either fixed-gradient or fixed-flux simulation
  - May also impact on intrinsic rotation studies (where rotation pinch may be correlated particle pinch)

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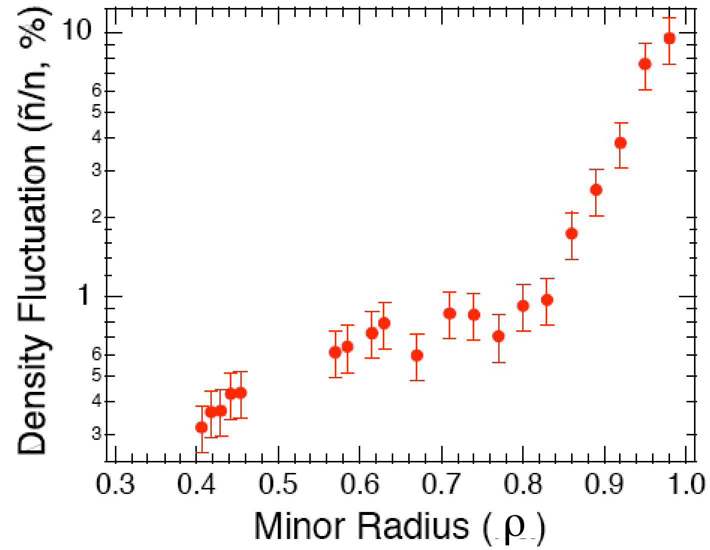
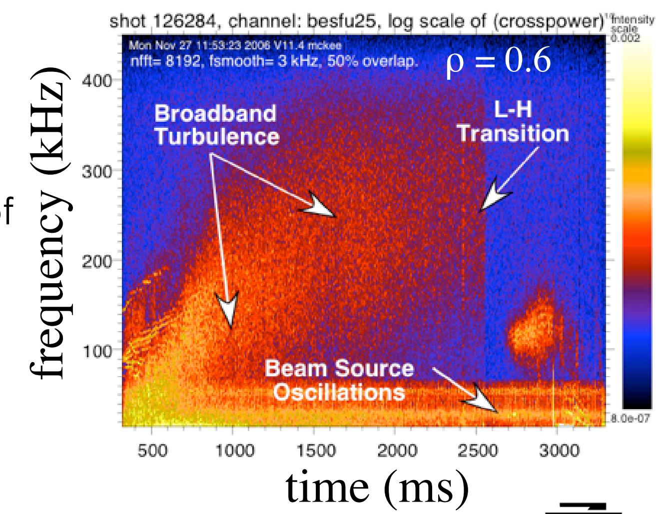
Issue 3: Core-Edge Coupling

- **Implicit in the work presented here is that core transport is essentially local in nature**
  - Supported by the non-local simulation results briefly described
  - The robustness of this approximation has received limited attention. In particular, to what extent does is hold for H-modes and more highly sheared plasmas?
- **Of particular concern is that current simulations (GYRO or otherwise) do not have any way representing turbulence propagating inward from edge region**
  - Question intrinsically requires use of edge simulations which include separatrix and scrape-off layer to address numerically
  - Represents a real experimental opportunity because of relatively broader set of edge fluctuation diagnostics
  - Ex: how far in do “holes” associated with blobs propagate?
  - Issue will be particularly relevant for validation of anomalous rotation theories





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Issue 4: A Few Thoughts on Metric Development

- **(A) goal of validation is to develop a metric which quantifies how well a given code reproduces the experimental physics under consideration**

- **A few thoughts:**
  - I would argue that until we have a better quantitative feel for what the relevant test quantities are for electromagnetic, shaped core turbulence with kinetic electrons, that should focus on simple rather than complex metrics
  - It would be a worthwhile exercise to quantify the relative sensitivities of different turbulence statistics to identify which are the best tests of the model.
    - Particularly relevant for the realistic edge turbulence case when both ITG and TEM/ETG are present
    - Until this is done, hard to know how to "weight" different quantities (e.g. RMS fluctuation level vs. spectral shape)
  - How do we incorporate systematic uncertainties into a metric?
  - How do we calculate the number of "turbulent realizations" in order to assign statistical uncertainties to simulation quantities?

Some Proposed Validation Experiments and Diagnostics (In No Particular Order)

- **Non-local edge transport- how far in do burst holes propagate?**
- **Test whether simulations exhibit same stiffness as experiment?**
- **Comparisons of measured and simulated zonal flow characteristics**
- **Better validation tests of ITG turbulence need potential and T_i fluctuations**
  - requires multi-channel HIBP combined with BES T_i fluctuations
- **Validation of particle and momentum transport would be greatly facilitated by improved neutral measurements**
- **Development of an accurate, robust velocimetry algorithm for use with BES or GPI**
- **Cross-diagnostic tests:**
  - Ex: leverage multiple density fluctuation diagnostics to get simultaneous, independent measurements