Comparison of Gyrokinetic Simulation Against Core Turbulence Fluctuation Measurements via Synthetic Diagnostics

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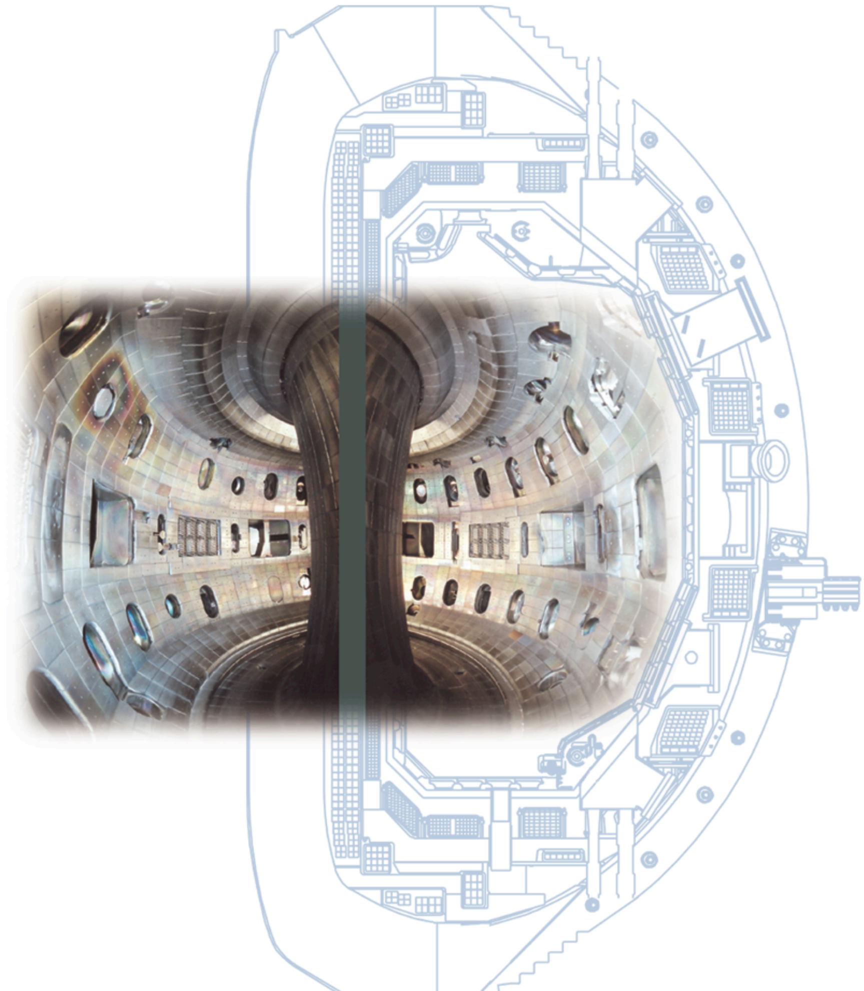

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Motivation

- **Now recognized that Verification and Validation is essential part of predictive modeling**
  - **Verification**: is the model being solved correctly?
  - **Validation**: is the model a good representation of the physics under consideration?

- **In practice, there is now a (minimal) standard set of verification tests for gyrokinetic adiabatic electron ITG flux tube simulations:**
  - 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 /ρ* effects, β-scaling,…), but now appropriate to begin serious validation efforts**

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Motivation (cont.)

- Validation of drift-wave simulations requires comparison against *core* fluctuation measurements, where the underlying gyrokinetic model implmented 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

- Have begun the process of developing a set of IDL tools for post-processing GYRO data to create a synthetic beam emission spectroscopy diagnostic suitable for direct comparison against the system deployed on DIII-D

Outline

1. **Overview of BES system and synthetic diagnostic**
2. **Results from applying synthetic to a simple GYRO simulation**
3. **Study #1:** effects of varying BES light collection volume
4. **Study #2:** effects of finite ExB shear of BES performance
5. **Future work: modeling a slowly-evolving L-mode discharge**

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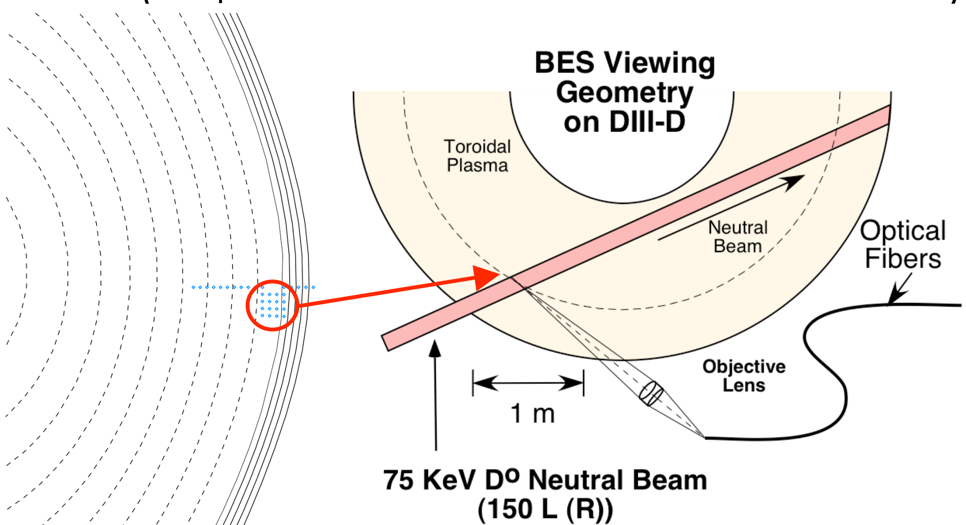
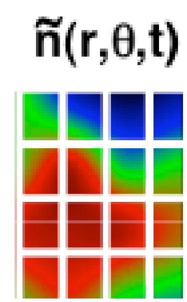
BES System Configured to Provide Zonal Flow Measurements Over Large Fraction of Plasma

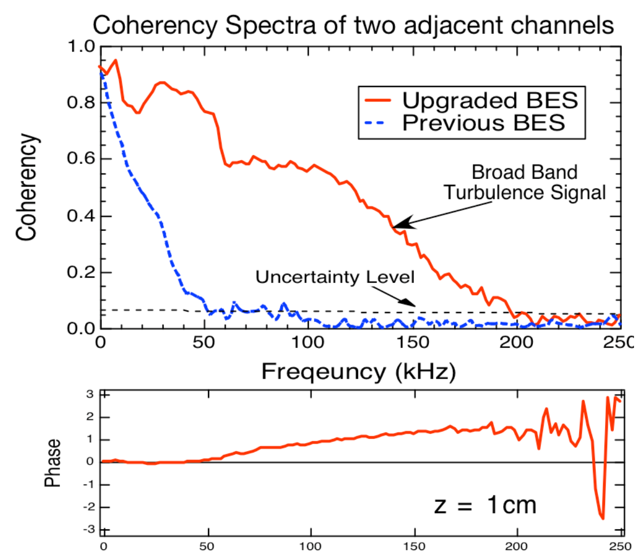
- **Beam Emission Spectroscopy (BES) measures collisionally excited, Doppler-shifted neutral beam fluorescence at multiple spatial locations**

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

- **Measured fluctuation $\delta I/I \propto \delta n/n$ → BES measures localized, long-wavelength ($k_\perp \rho_i < 1$) density fluctuations**
  - Can be radially scanned shot to shot to measure turbulence profiles
  - Recent upgrades allow for BES to measure core fluctuations (Gupta *et al,* Rev. Sci. Inst **75** 3493 2004)







Synthetic BES Development

- **Two key parts of of a synthetic BES tool:**
  - Converting density and temperature fluctuations into D_α light fluctuations
  - Modeling spatial sensitivity of each BES channel

- **Previous work by R. Bravenec found D_α issue can be important at high density**
  - For typical DIII-D densities, δI is roughly proportional to δn

- **Work to date has focused on the spatial sensitivity aspect, using DIII-D specific calculations**

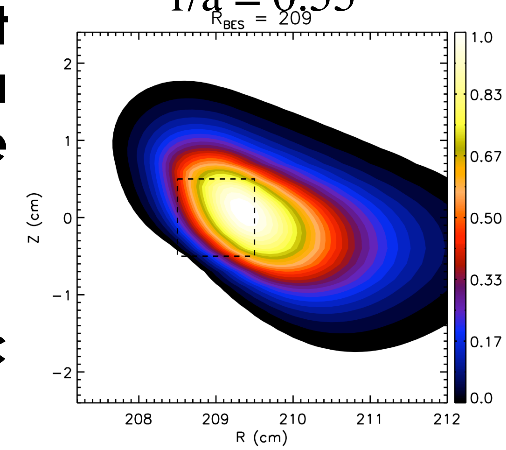
Calculate Point Spread Functions (PSFs) which Describe BES Channel Spatial Averaging

- **Each BES Channel is characterized by a "Point Spread Function" (PSF) which provides a measure of the 2D (R,Z) sample volume of the channel, integrated along the BES sightline**

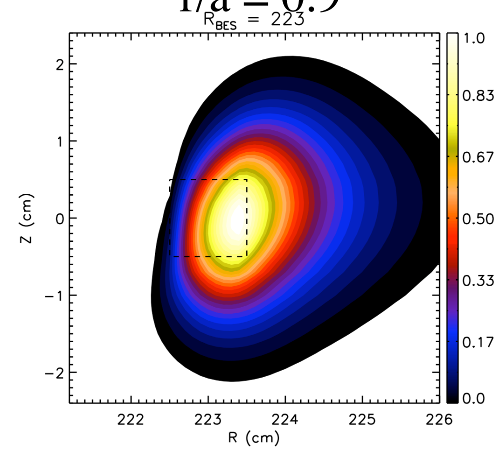
- **Model accounts geometric and atomic effects**
  - Use MSE to account for differences between local field line pitch and viewing angle
  - Finite *n*=3 beam atom lifetime leads to a "smearing" effect

- **Core measurements have non-optimal sightline, leading to reduced radial resolution**
  - Note that PSF peak and "center-of-mass" are not colocated with nominal channel "location"

r/a = 0.55



r/a = 0.9



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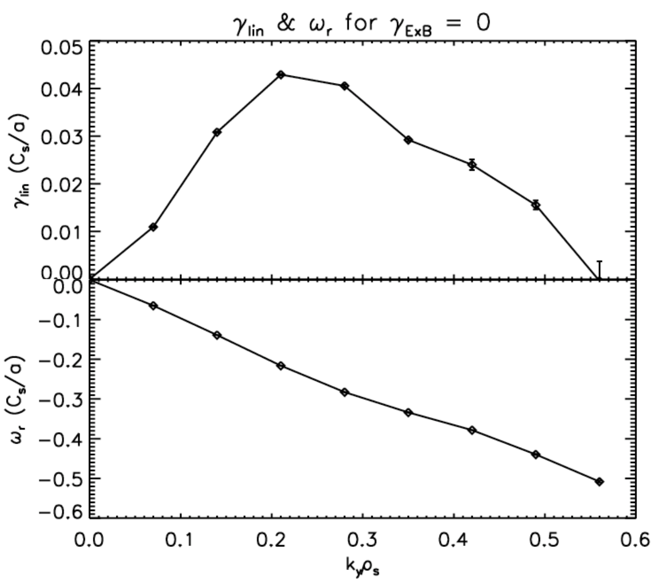
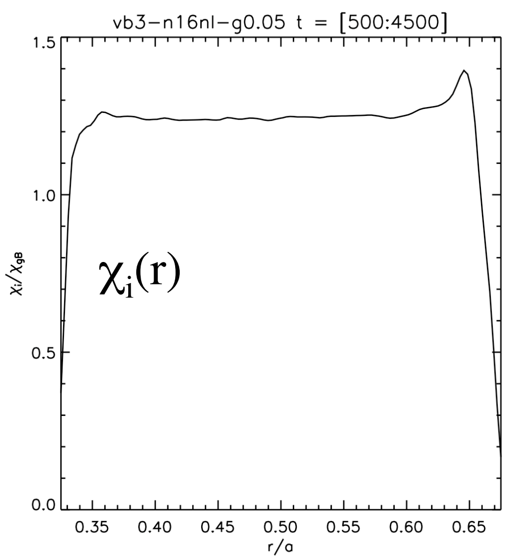
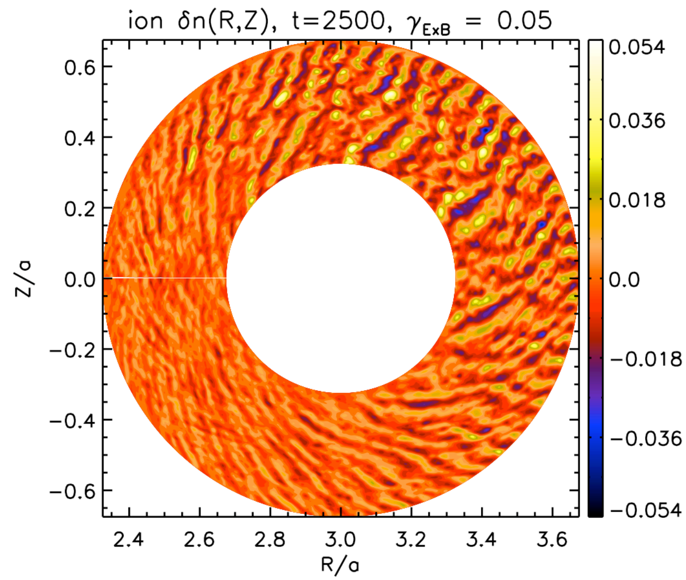
GYRO Simulation Used for Testing

- **Use a long time-run GYRO simulation for initial testing of synthetic BES diagnostic**
  - Electrostatic, adiabatic electrons, no impurities, N_n = 16, t→4500 a/C$_s$
  - Circular s-α geometry, flat profiles, non-periodic radial boundary conditions, **but include finite ExB shear ≈ linear γ_{max}**

$$\tau = 1,\ R_0/r_0 = 3,\ q = 2,\ \hat{s} = 1,\ \rho_* = 0.035,\ a/L_n = 0.6,\ a/L_{Ti} = 2.2,\ \gamma_{ExB} = 0.05\ a/c_s$$





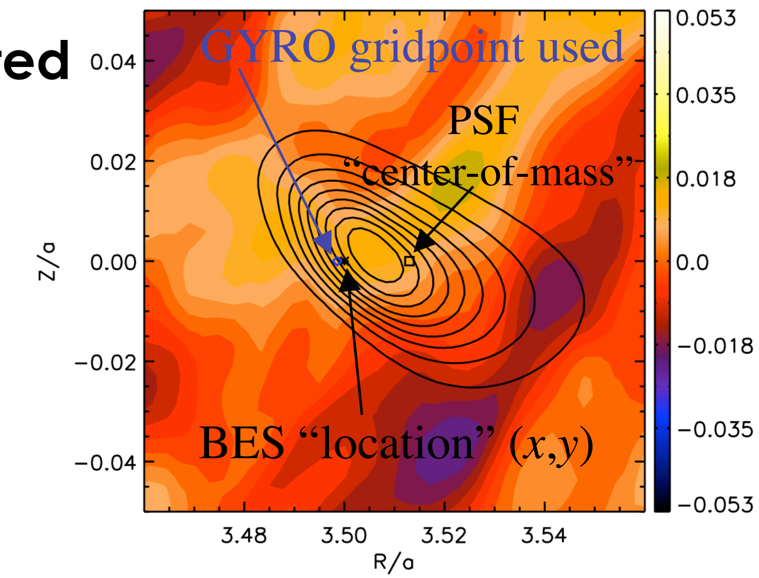


Applying PSF to GYRO Simulation Data

- **IDL post processing tool written to generate synthetic BES array**
- **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), defined via**

$$R(r,\theta) = R_0(r) + r\cos(\theta + x\sin\theta)$$

$$Z(r,\theta) = \kappa(r) r\sin\theta\,, \quad x = \sin^{-1}(\delta)$$



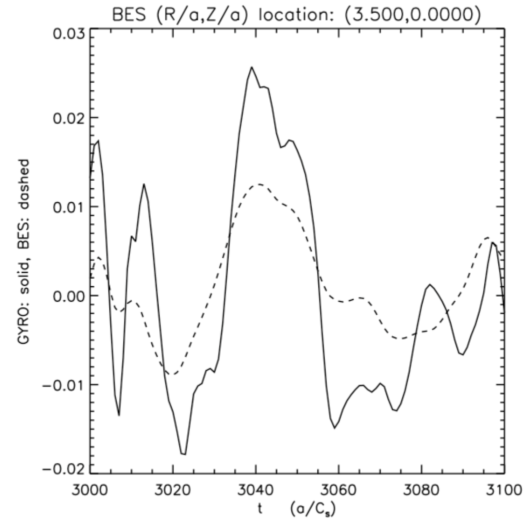
- **At each time point of interest, record**
  - Synthetic signal defined as $n_{synthetic}(x,y,t) = \dfrac{\int d^2x' \psi^{PSF}(x-x', y-y')\tilde{n}_i^{GYRO}(x', y', t)}{\int d^2x' \psi^{PSF}(x-x', y-y')}$
  - GYRO signal at gridpoint closest to nominal BES location

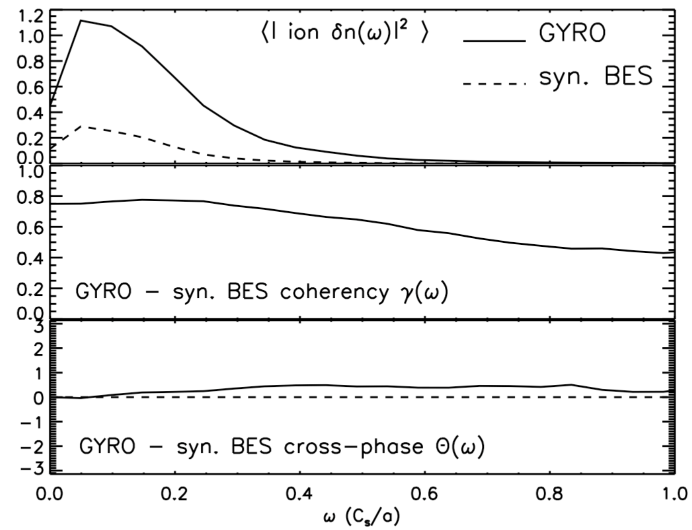
Synthetic signals well-correlated with GYRO signals

- **Synthetic channel exhibits temporal dynamics corresponding GYRO signal**

- **RMS fluctuation levels underestimated by 30%-50%, depending on simulation parameters (50% here)**

- **Confirmed by examining frequency spectra of synthetic and GYRO signals, as well as coherency and cross-phase between them**





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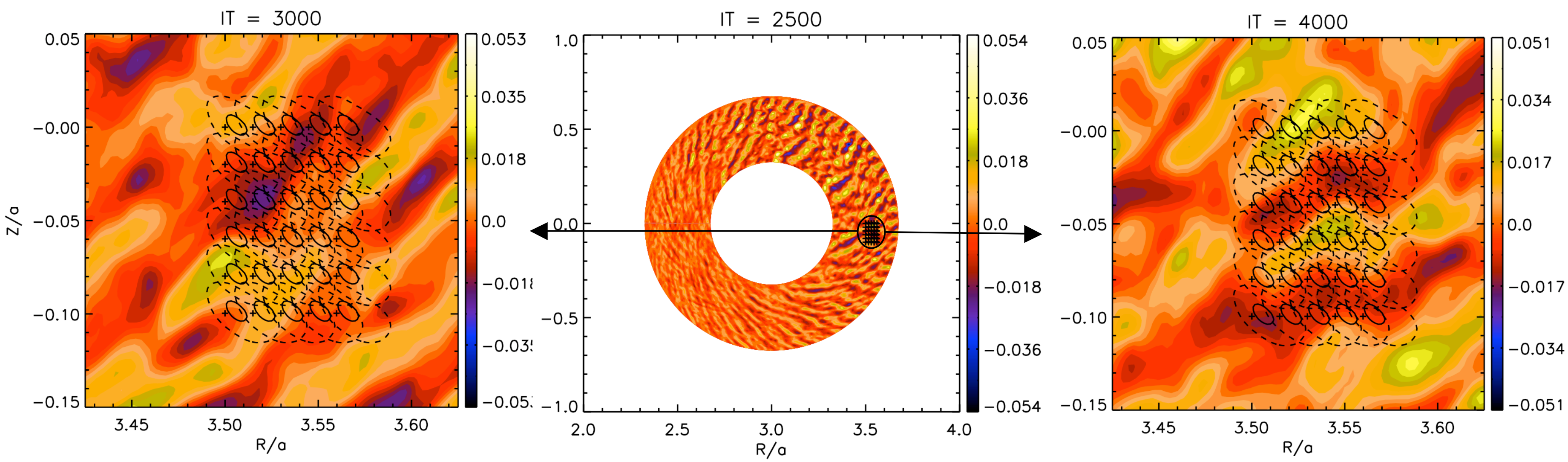
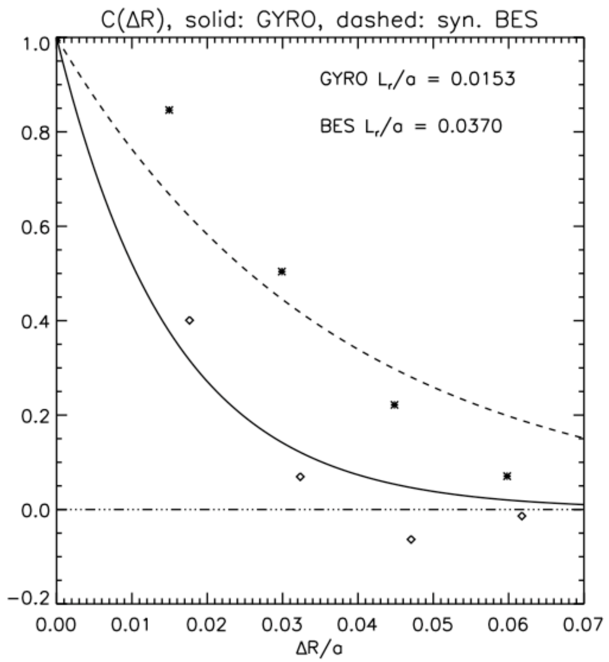
Observe Significant Overlap in Neighboring PSFs

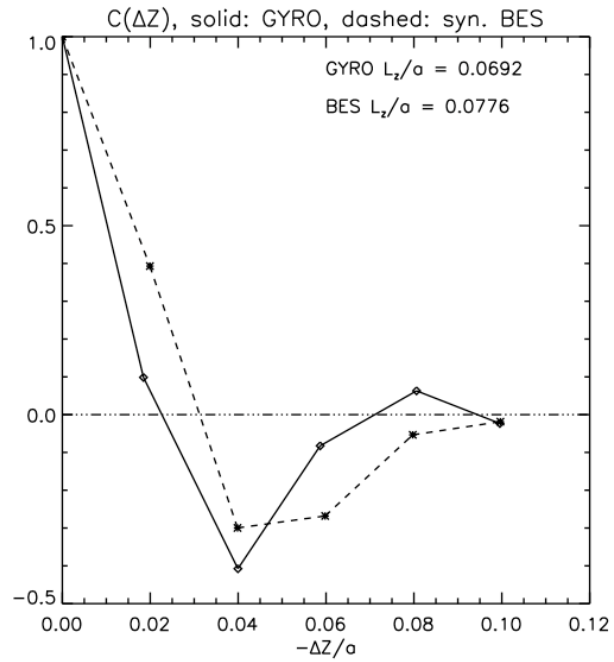
- **1/e = 37% (dashed) and 90% (solid) contours of full BES array at several timepoints shown below**
  - PSF scale leads to significant effective radial overlap in channels, smaller vertical overlap



Comparison of correlation lengths

- **When PSF response is not deconvolved, synthetic diagnostic significantly overestimates radial correlation**
  - Tool for implementing deconvolution still in development
  - Does much better with vertical correlation





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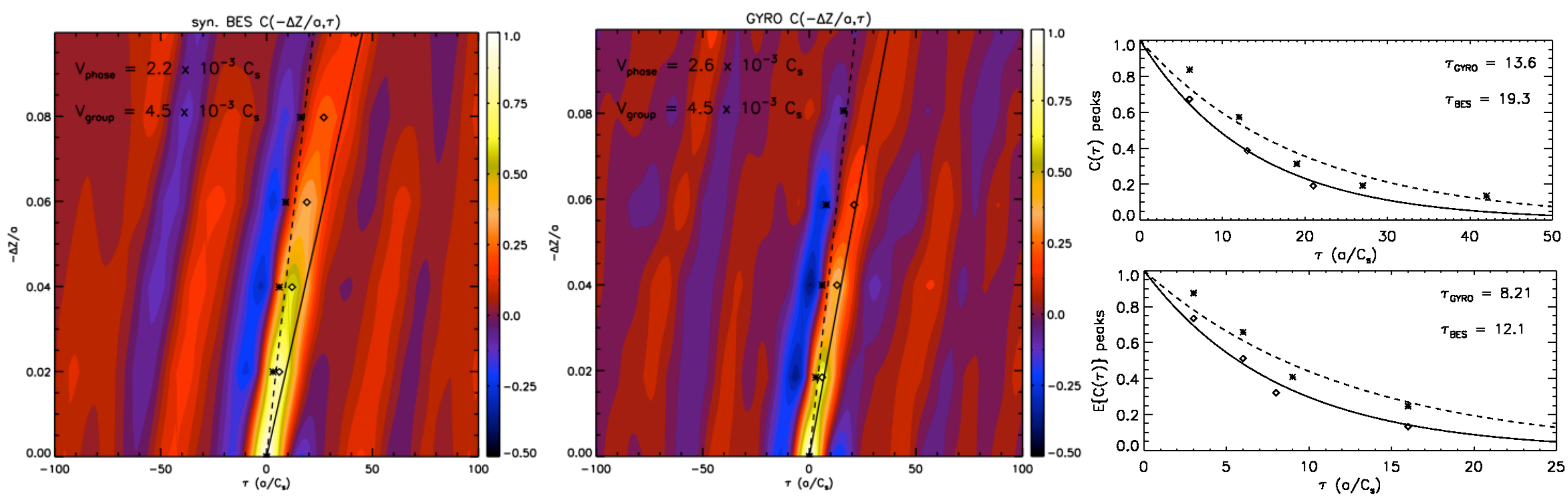
Comparison of decorrelation rates

- **Synthetic diagnostic also appears to significantly overestimate decorrelation rate of fluctuations**
  - Define τ_C by fitting exponential to peaks of $C(\Delta Z, \tau)$ envelope
  - Good agreement in location of peaks of $C(\Delta Z, \tau)$



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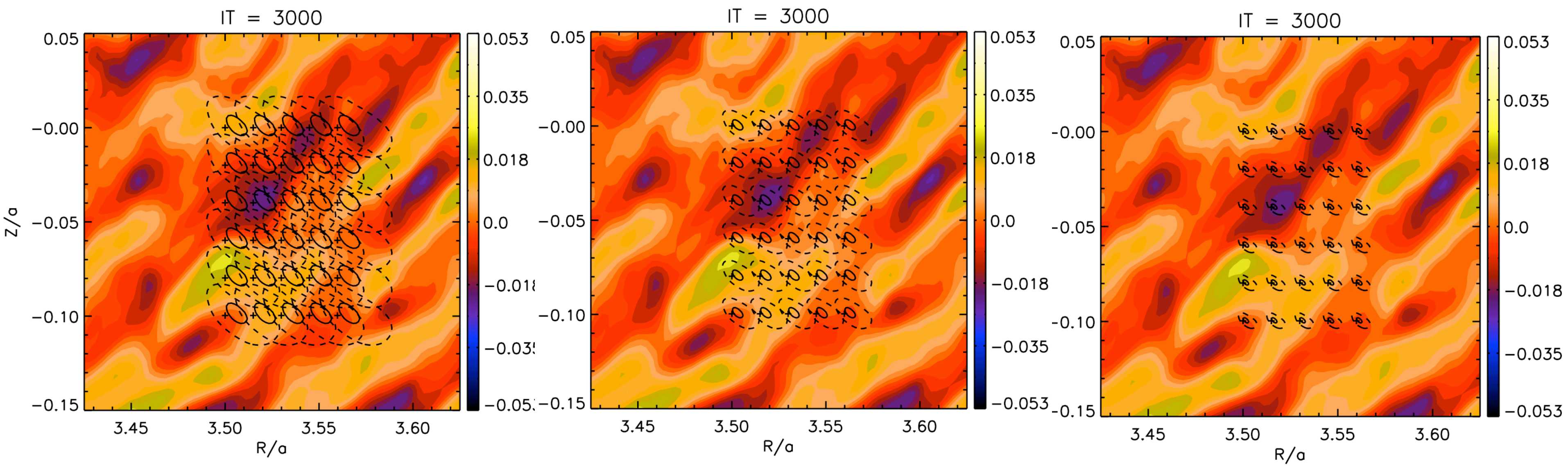
First Study: PSF Size Effects

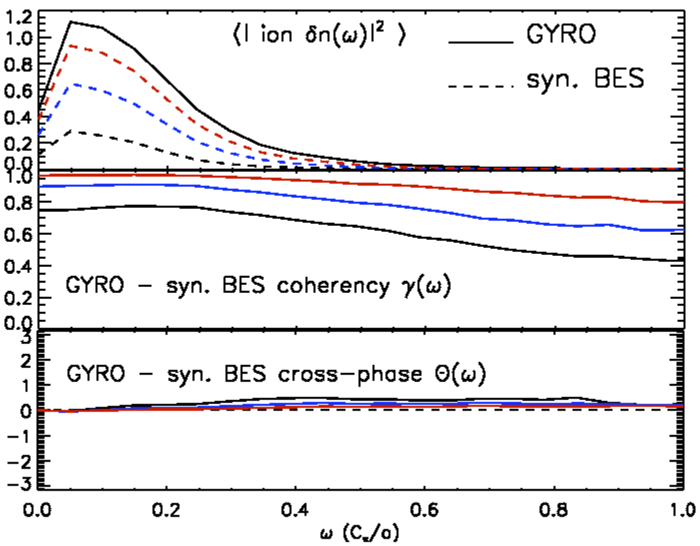
- **First study carried out was a "sanity check" to make sure that as the effective scale of the PSF was reduced, the synthetic signal approached to simulation signal**

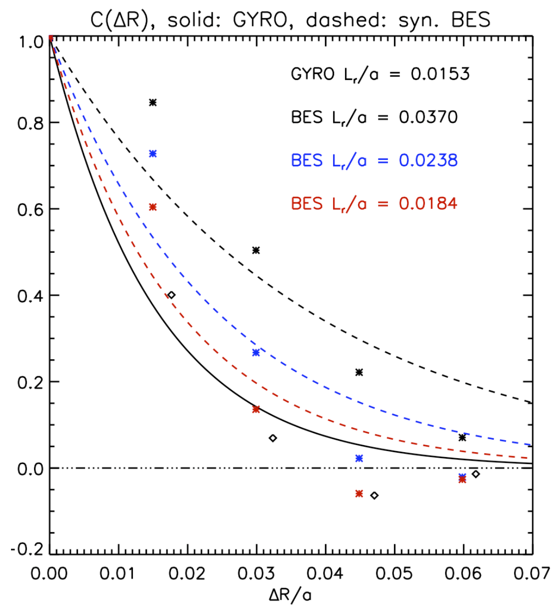
- **Compare effects of using 1/2 and 1/4 size PSF**

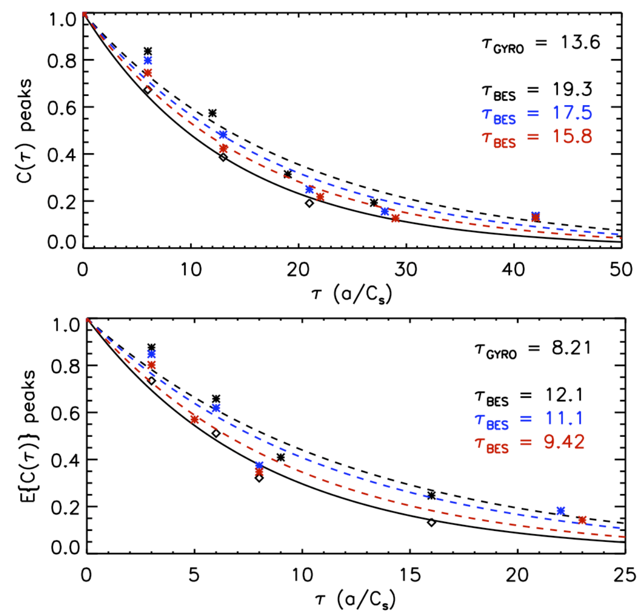


All results converge with PSF size as expected

- **Find improved agreement with 1/2 size, extremely good with 1/4 size array**
  - Note in particular convergence in C(Δr) and τ_C
  - 1/2 size in blue, 1/4 size in red, solid is GYRO, dashed synthetic







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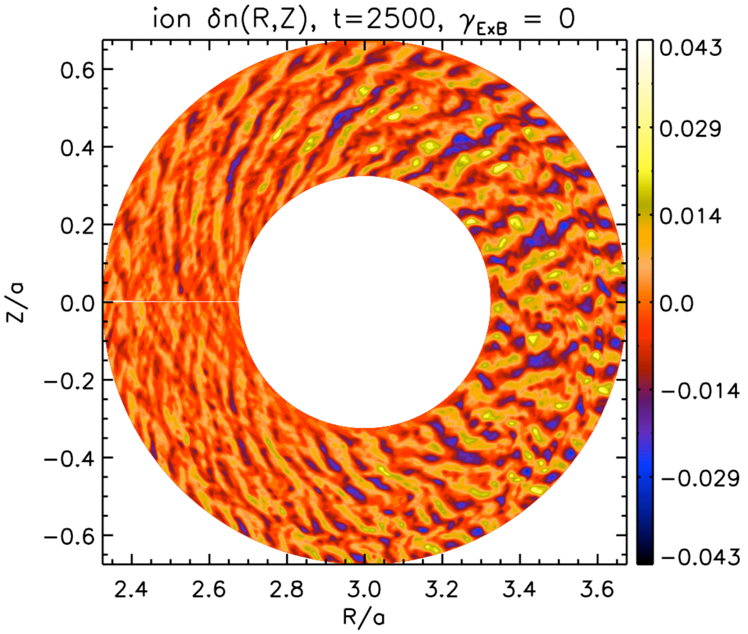
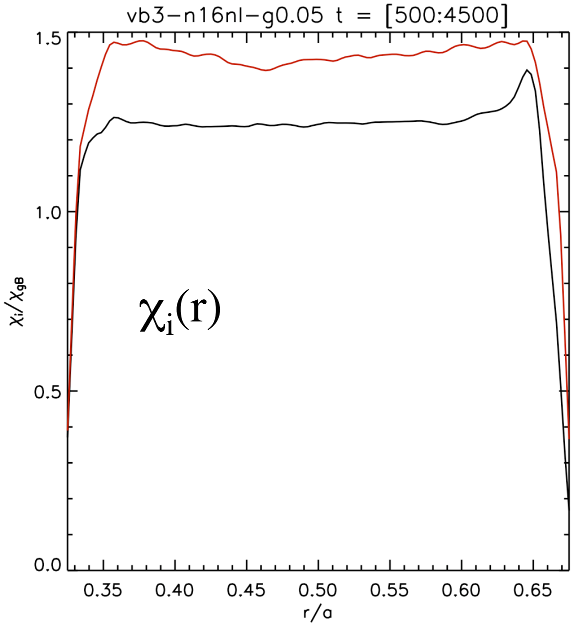
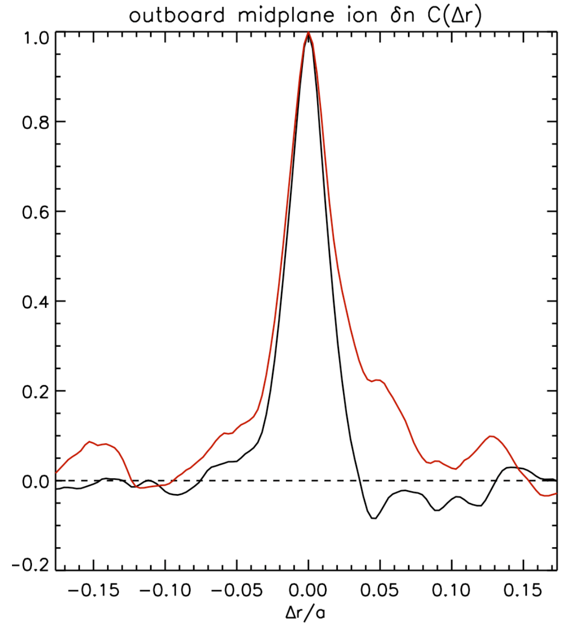
Study #2: Effects of ExB shear

- **Want to assess how ExB shear (which strongly impacts frequency spectra, correlation lengths) affects BES performance**

- **Compare initial results to results from an identical simulation with γ_{ExB} = 0 (γ_{ExB} = 0 in red, γ_{ExB} = 0.05 C_s/a in black)**







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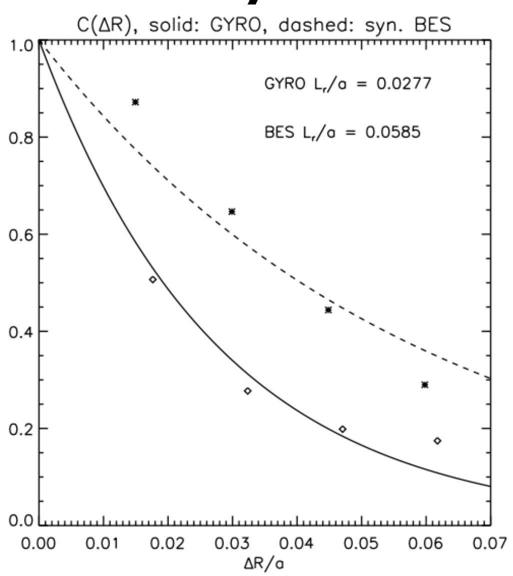
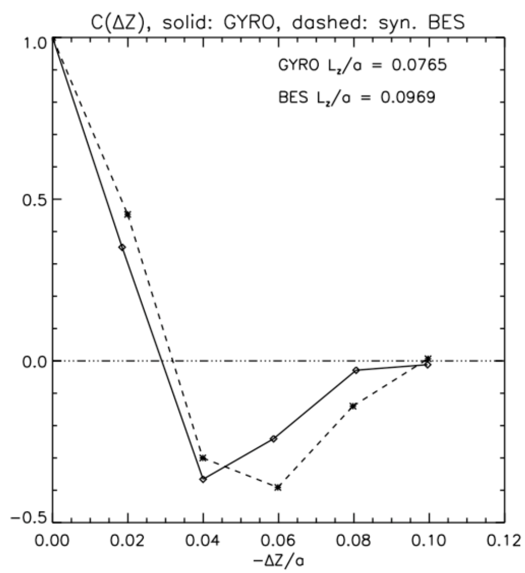
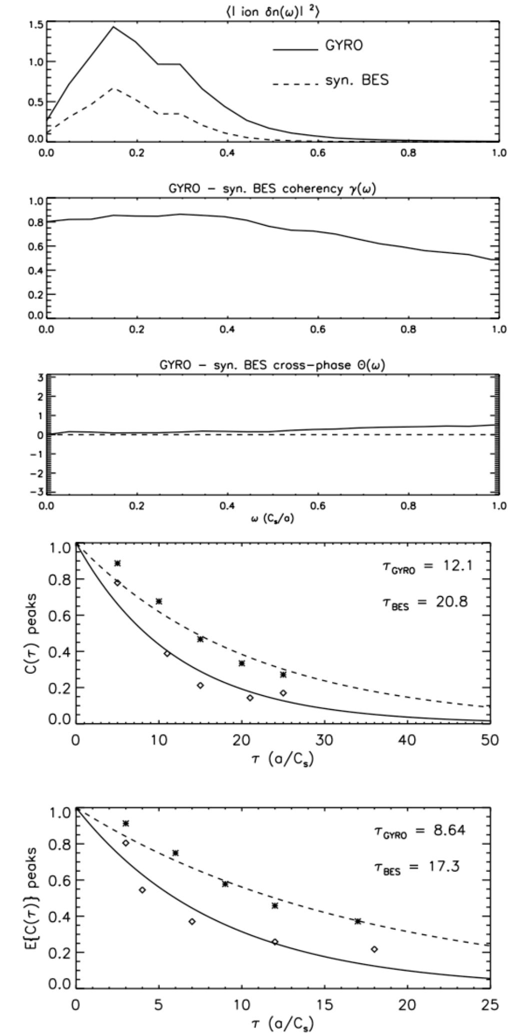
Observe similar performance as sheared case

- **Basic trends from sheared case are repeated: overestimation of radial correlation and τ_c; good agreement on vertical correlation and phase/group velocity**







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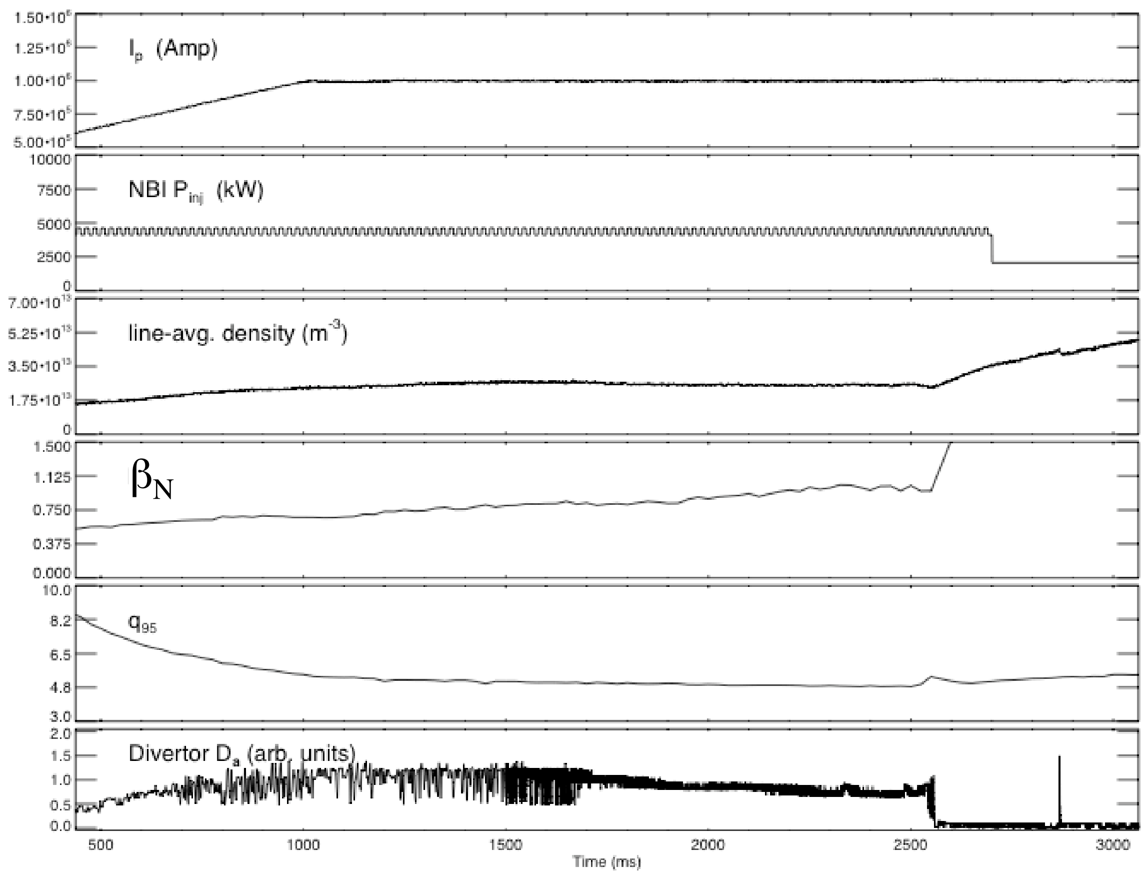
Next step: direct comparison against against experiment

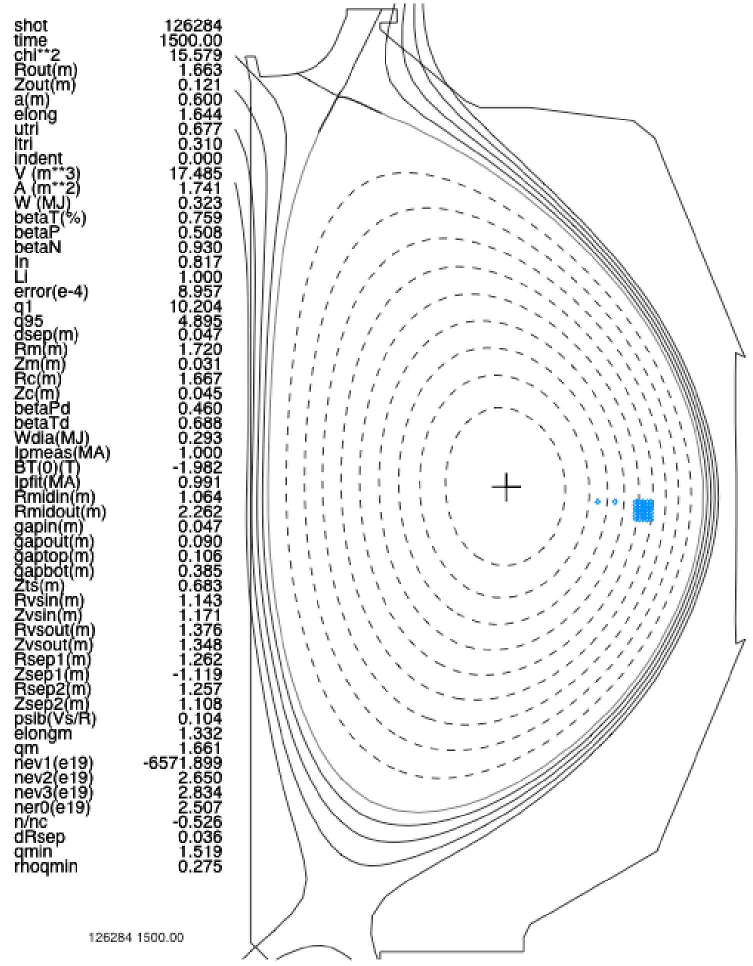
- **Now that synthetic BES post-processing tools are (just about) done, can begin process of direct comparison to experimental data**

- **Initial study will use a series of identical discharges which have long, slowly evolving L-mode phases**
  - Multiple repeat discharges allowed BES array to be scanned radially, allowing characterization of fluctuations over large fraction of plasma volume
  - See George McKee's (TTF) talk and poster for more info on these discharges

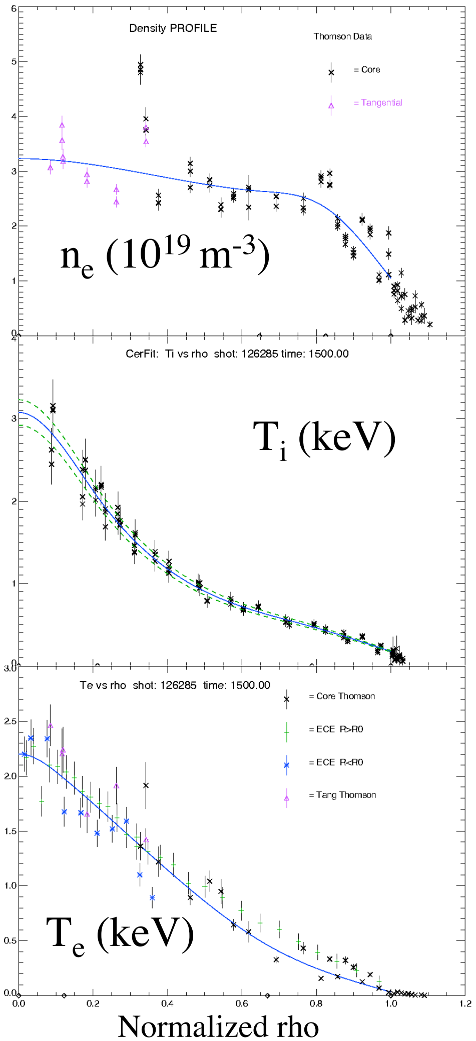
- **Profile analysis done; ready to do transport analysis and then start in on "full-physics" simulations**
  - Goal: have results ready for APS.

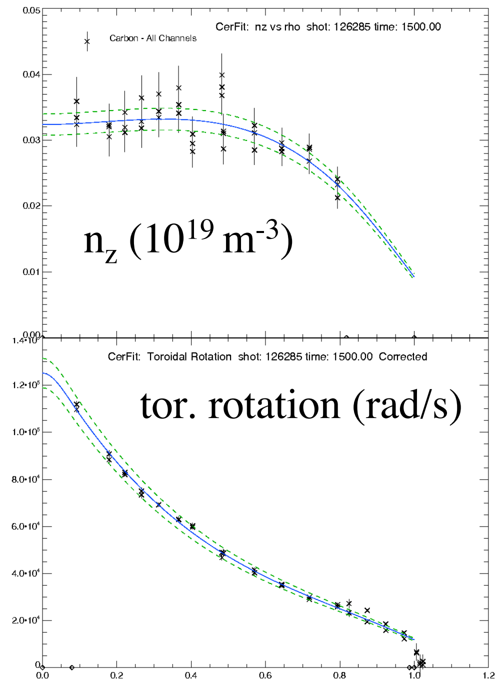
Use steady L-mode phase for initial study

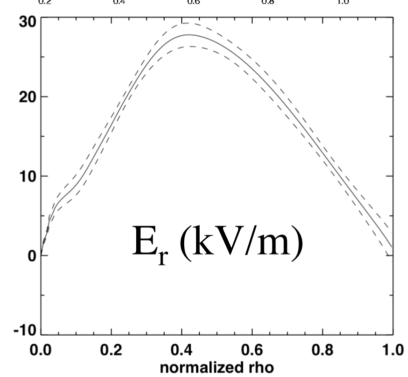




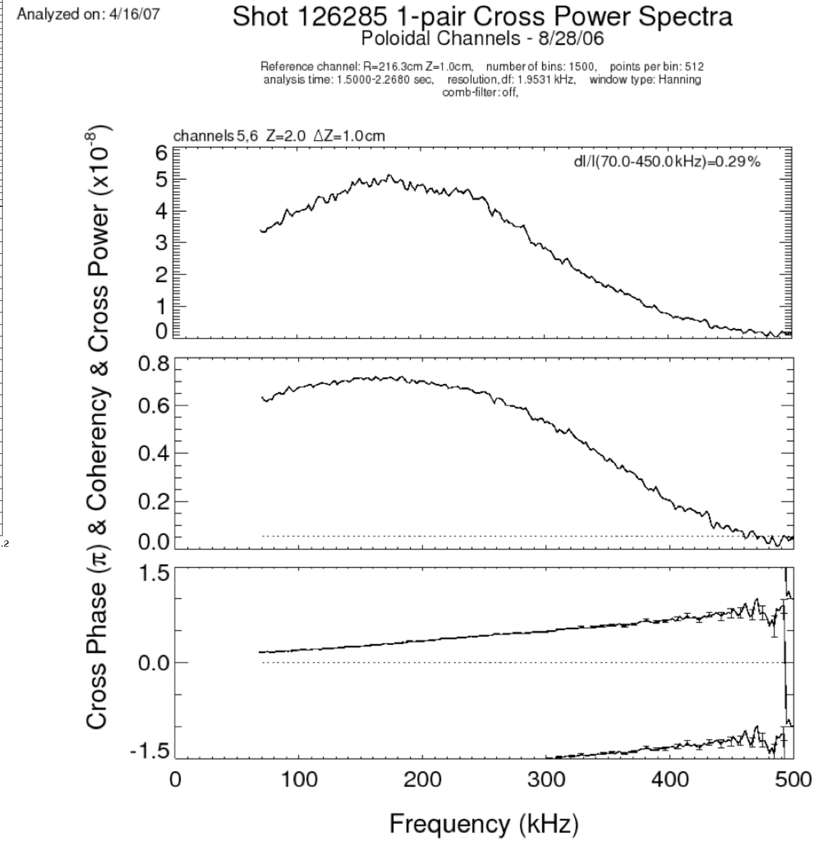
Full set of equilibrium profile and fluctuation data ready for comparison







BES 2-channel cross-spectra

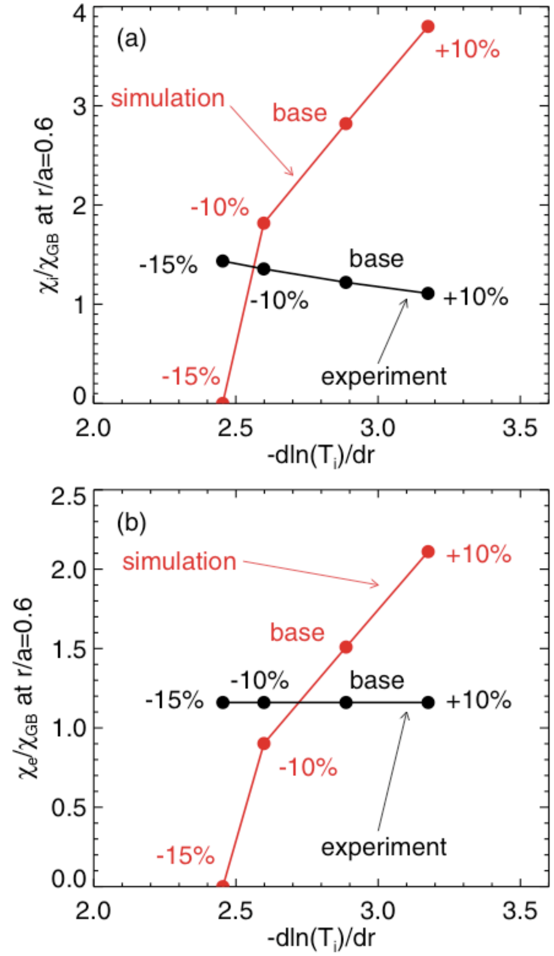


Long-term goal: using fluctuations to constrain simulation-experiment flux comparisons

- **Accurate calculation of flux profiles is a primary goal of predictive modeling**

- **Profile stiffness makes this difficult: can vary profile gradients +/- 10% (within error bars), and change flux by a factor of 2**

- **Fluctuations give us another data point to "fit": if we vary gradients to best match fluctuation characteristics (e.g. amplitudes, correlation lengths, etc.), how well do we reproduce experimental fluxes?**



Candy and Waltz 2003 PRL

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Conclusions and Future work

- **IDL tools for post-processing GYRO simulation results to generate a "synthetic" BES array are now mostly completed**
  - Still need to integrate GYRO->D_α light filter
  - Significant radial overlap of channels strongly impacts radial correlation length estimates; deconvolution tool underway
  - Would like to understand why synthetic decorrelation rates so large, despite good agreement in vertical correlation length & V_{phase}, V_{group}
  - Verified that synthetic diagnostic accurately reproduces simulation dynamics when PSF size is sufficiently reduced
  - ExB shear has no strong impact on BES performance(?)

- **Ready to move on to direct simulation-experiment comparisons. Next step is to begin "full-physics" simulations**

- **Long-term goal: examine how constraint of matching fluctuation characteristics affects predictions of stiff transport**