Testing Gyrokinetic Turbulence Simulations

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- Accurate transport predictions are needed for successful future tokamaks
- Nonlinear gyrokinetic simulations can predict turbulent-driven energy, momentum, and species transport and fluctuations
- Comparisons of simulations with measurements help verify (and validate) the simulations
- This talk describes tests of simulations of JET and DIII-D plasmas using the GYRO and TGYRO gyrokinetic codes
- Encouraging agreements are achieved
- Lots of work is needed

Tools

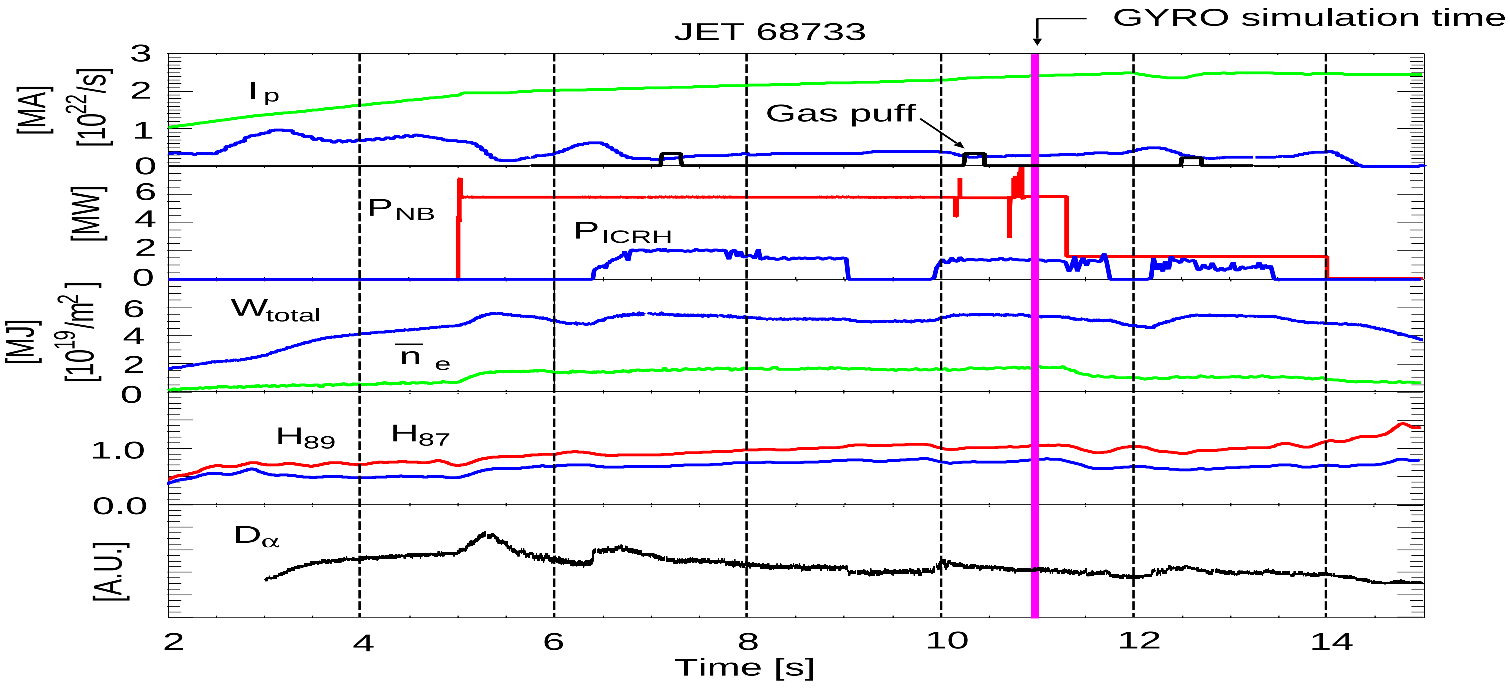
- TRANSP
  - analyzes plasmas for transport and maps plasma profiles
- TRGK $\equiv$ TRANSP-postprocessor $\equiv$ GYRO-preprocessor
  - generates inputs for GYRO/TGYRO
- GYRO
  - time evolution of potential and distribution functions of kinetic species
  - 3 spatial and 2 phase space dimensions
- TGYRO
  - runs GYRO in feedback mode
- SCHRADO2
  - Full-wave 2D microwave scattering from density cut-off region

GYRO simulations

- GYRO solves standard Gyrokinetic Eq's with continuum methods
- Nonlinear runs to saturation of ITG/TEM turbulence ($k_\theta \rho_s$ < 1.0)
- Kinetic electrons and 2 kinetic ion species (bulk and combined impurities)
- Extended radial domain
- Most runs in the electrostatic approximation
- Achieved mixed success simulating radial flows of energy, species, and toroidal angular momentum in DIII-D, JET, and TFTR plasmas
- Examples of simulations of transport and density fluctuations $\tilde{n}_e$
  - JET L-mode with B_{TF}=3.4T, I_p=2MA, P_{NB}=5.9MW, P_{RF} < 2MW
  - DIII-D L-mode with B_{TF}=2.2T, I_p=1MA, P_{NB}=2.6-5.4MW (co-balanced)

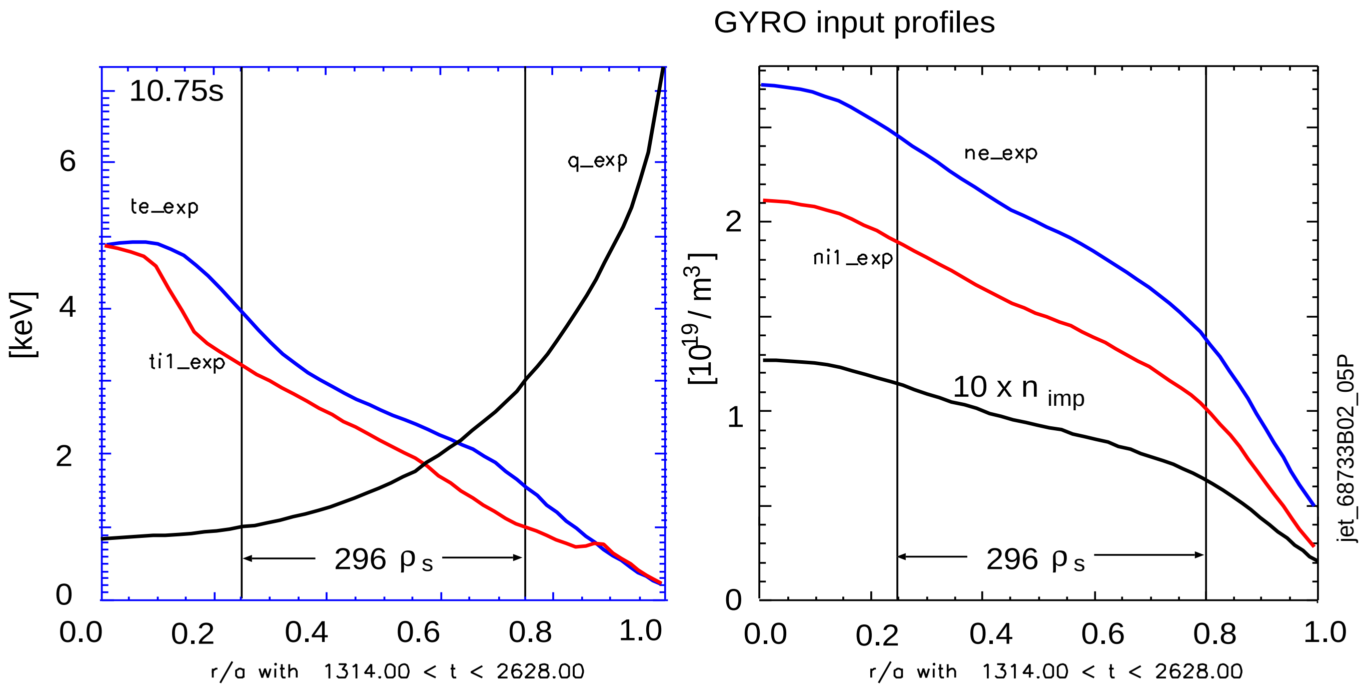
Example of JET shot

- L-mode heated by NBI and fundamental D-ICRH
- $B_{TF} = 3.4T$, $I_p = 2.0MA$, $\kappa = 1.6$, $\delta = 0.2$,
- $P_{nbi} = 5.9MW$, P_{ICRH} < 2 MW, $f_{GW} = 0.3$, $\beta_n = 0.45$



Example of GYRO inputs

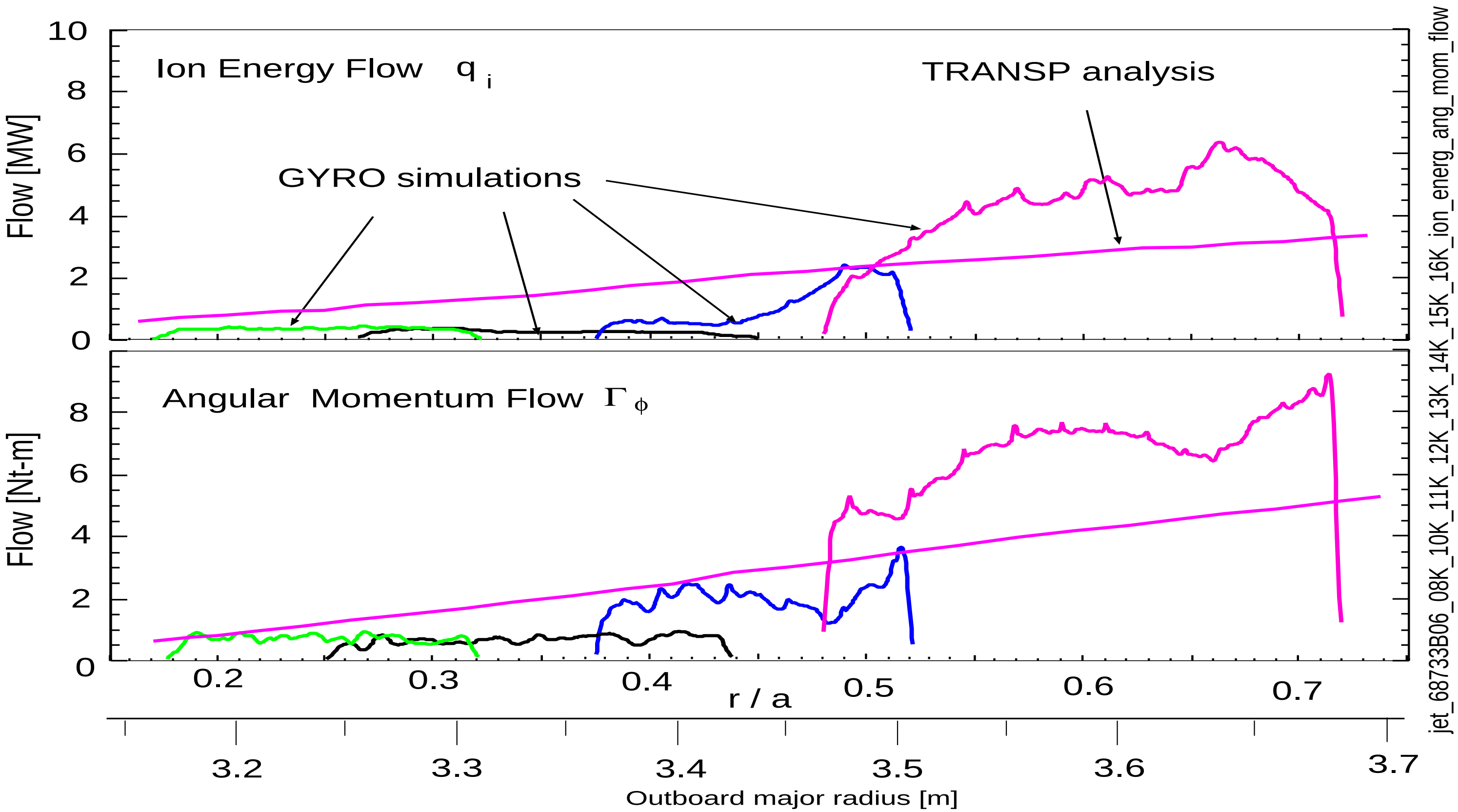
- Measured profiles mapped by TRANSP



- Simulate extended radial domain to allow turbulence room to saturate
- Domain width > > ρ_s (ion sound speed gyro-radius)

Approximate agreement for ion energy and angular momentum flows

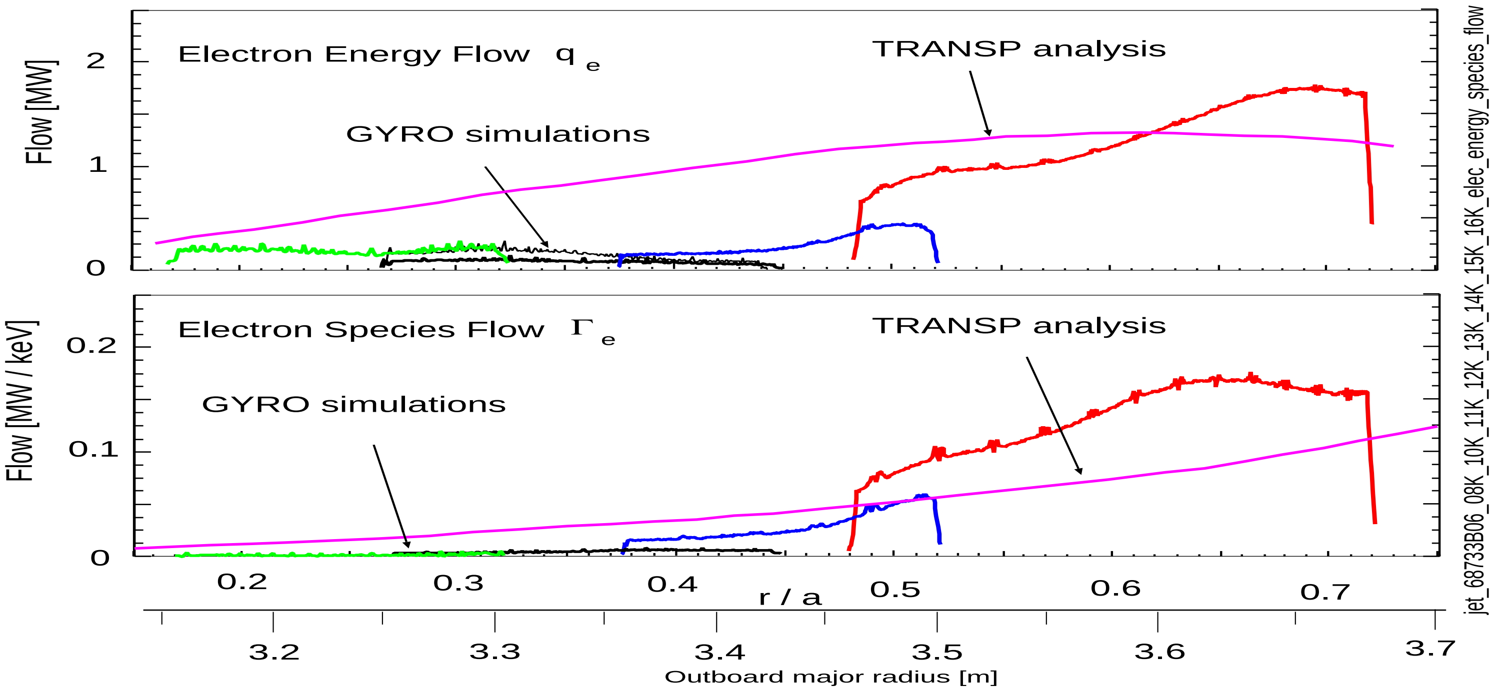
- TRANSPP analysis for ion energy and angular momentum flows
- GYRO runs in 4 overlapping radial regions for more accuracy



- Note discrepancies near core
- Some of the measured transport is neoclassical

Approximate agreement for electron energy and species flows

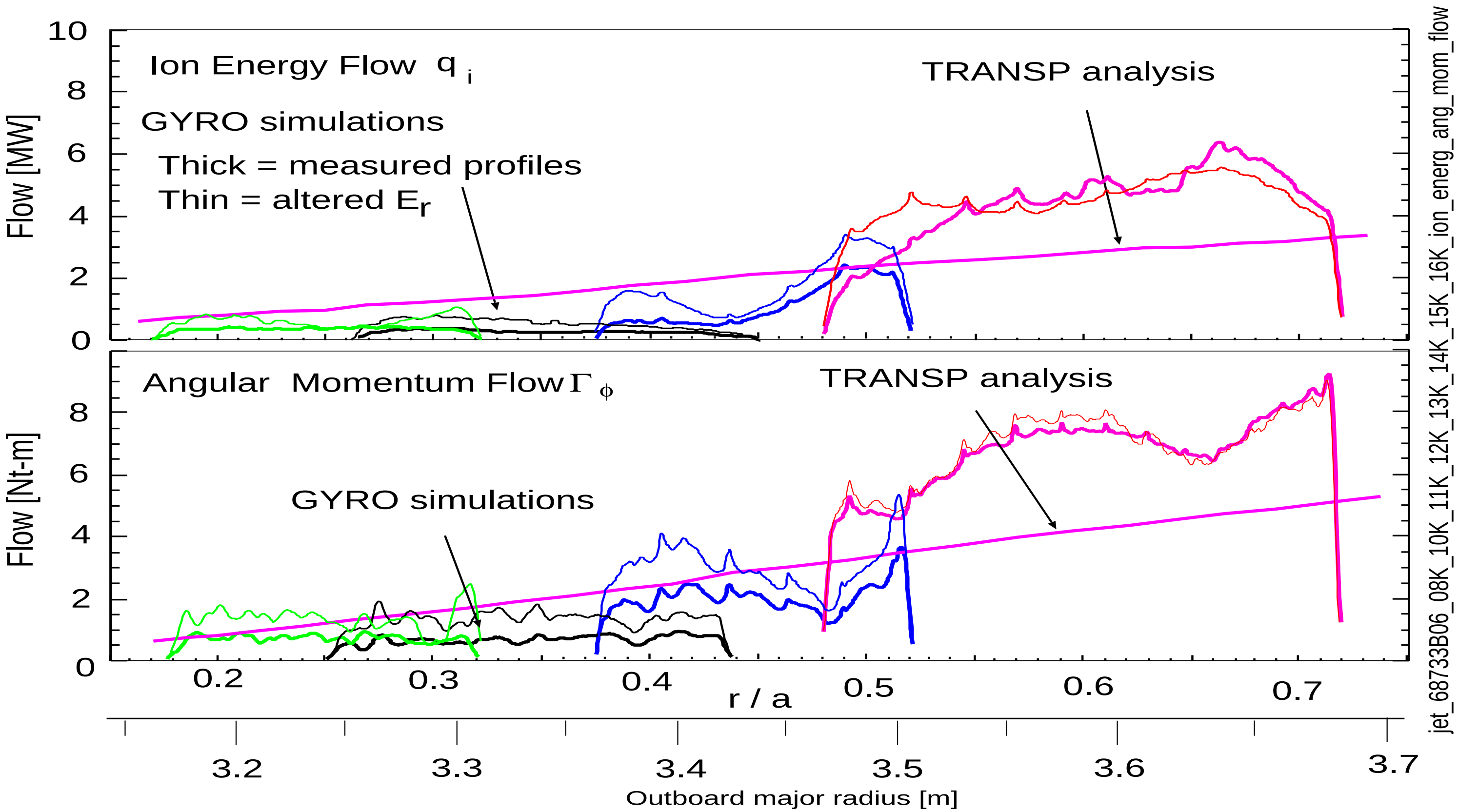
- TRANSP analysis for electron energy and species flows



- Note discrepancies near core
- Hard to quantify uncertainty in flow measurements

Sensitivity of predicted q_i, Γ_ϕ to assumed E_r flow shear

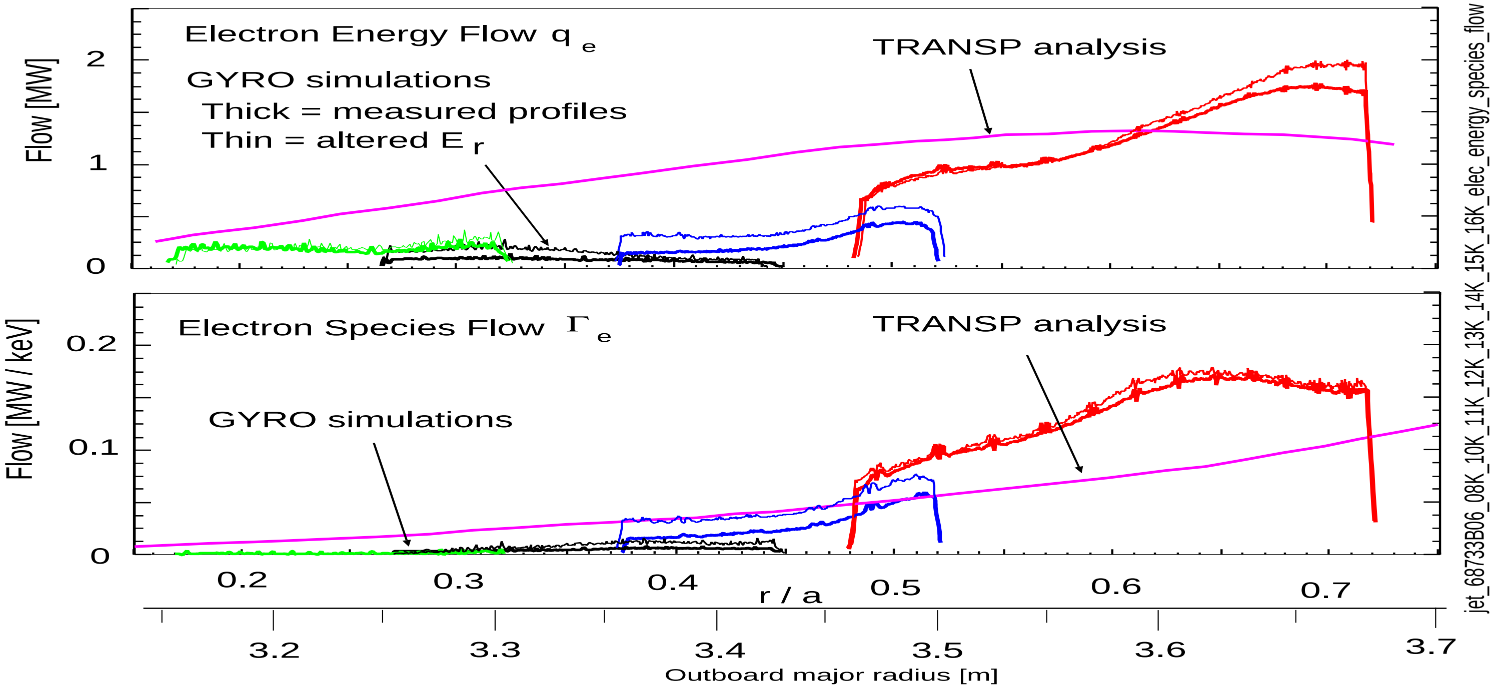
- Hypersensitivity to variations in plasma profiles
- Varied E_r flow shearing and up/down 20 % to study sensitivity



- Improvements in core region

Sensitivity of predicted q_e and Γ_e to assumed E_r flow shear

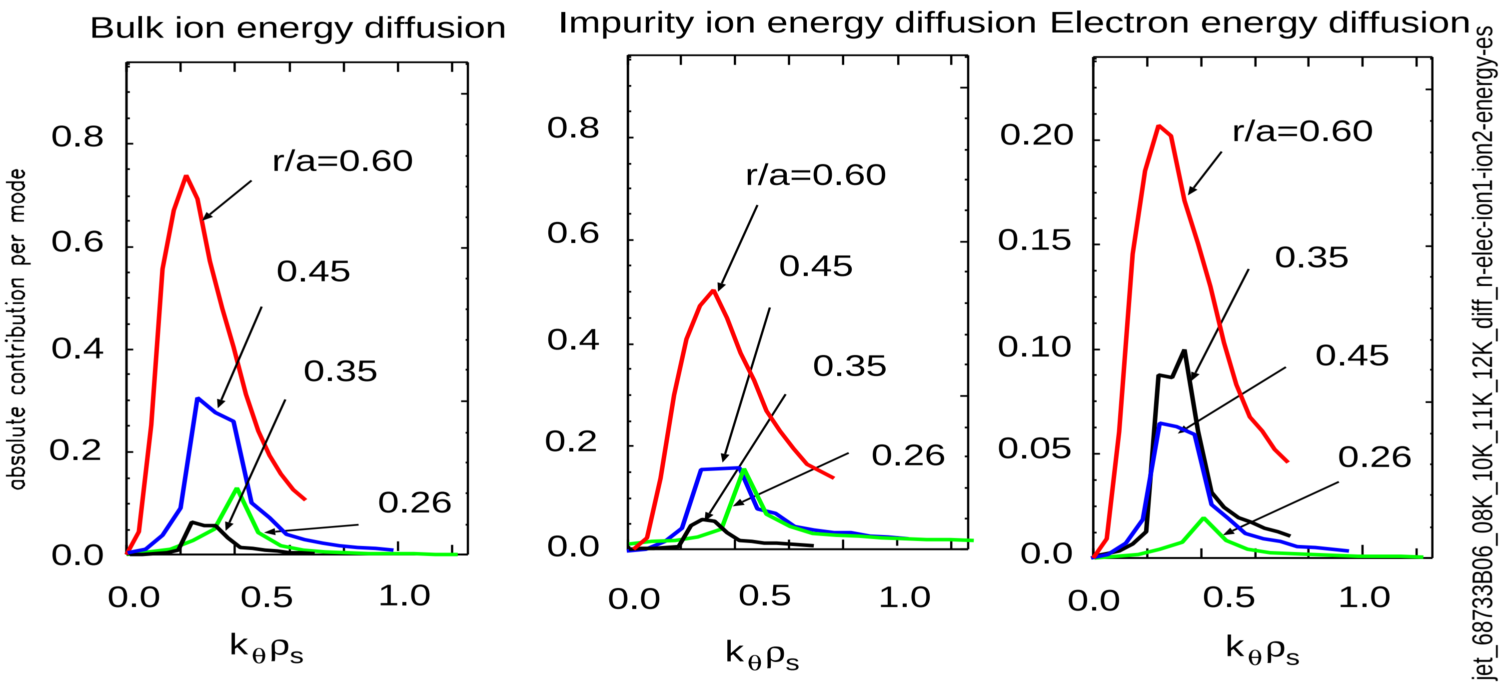
- Variation in E_r flow has less effect in electron channels



- Small improvement in core region

Why are simulated flows low in interior, high outside?

- Compare mode spectra at different radii



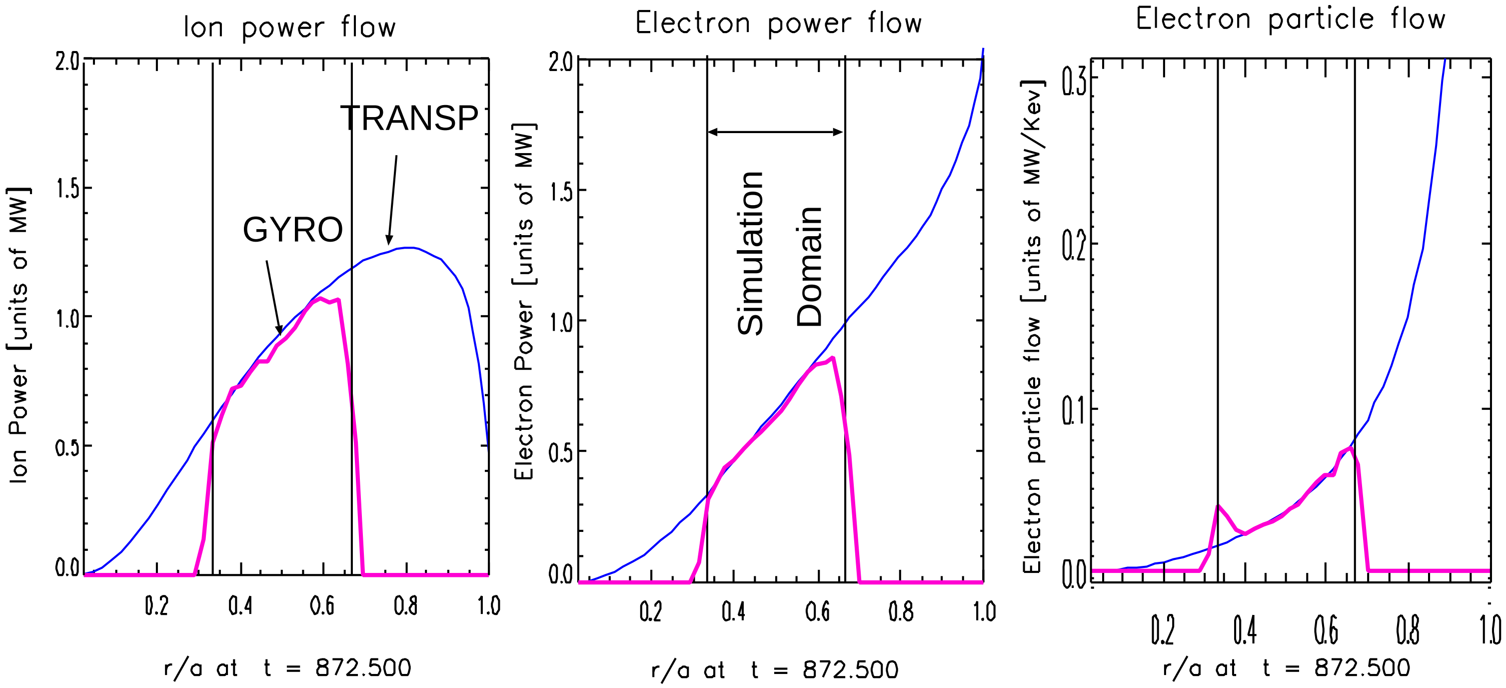
- Simulations very close to marginal near core
- Implies strong sensitivity to drive and suppression terms (plasma gradients and E_r flow shear)

TGYRO simulations

- Very recent development by Ron Waltz and Jeff Candy (GA)
- TGYRO $\equiv$ controller that calls and runs GYRO
- Starts with nonlinear GYRO, then shifts to feedback mode to match measured q_i, q_e, and Γ_e profiles
- Adjusts $\nabla(T_i)$, $\nabla(T_e)$, and $\nabla(n_e)$ pivoting at norm radius

TGYRO feedback to match transport

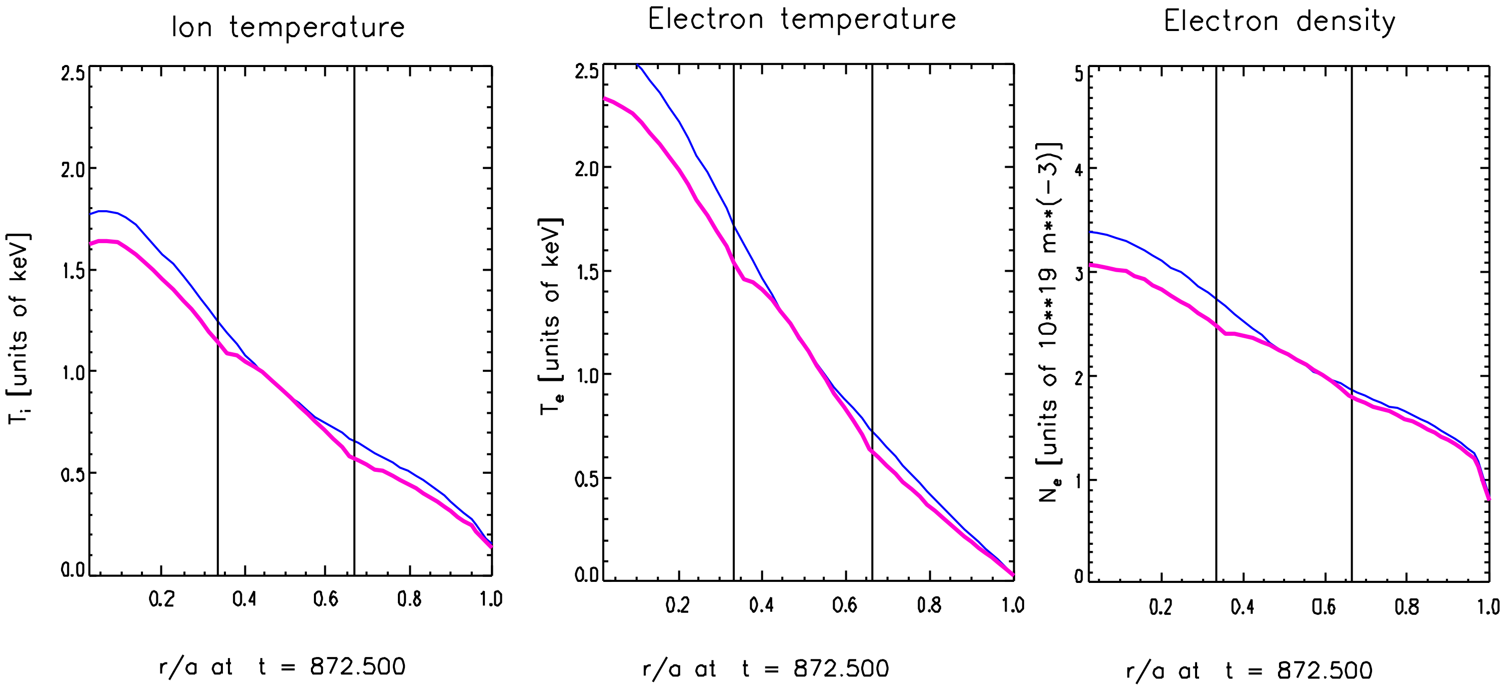
- Very preliminary results for DIII-D L-mode
- Match q_i, q_e, and Γ_e profiles from TRANSP



- Need to check convergence: box size, grids, etc

TGYRO feedback: altered plasma profiles

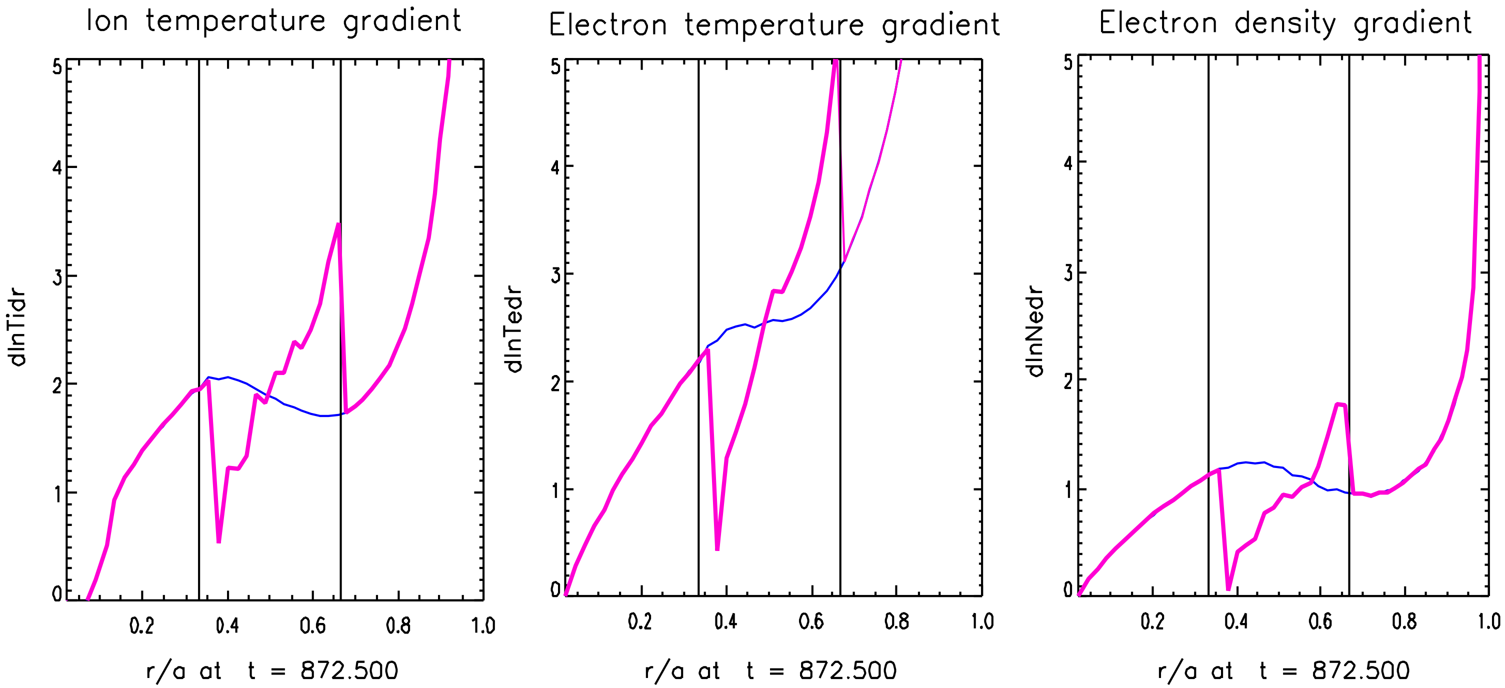
- Results for T_i, T_e, and n_e to match measured q_i, q_e, and Γ_e



- Good agreement achieved by pivoting T_i, T_e, and n_e profiles
- Are TGYRO fitted T_i, T_e, and n_e consistent with measurements?

TGYRO feedback: altered plasma gradients

- Results for T_i, T_e, and n_e gradients to match q_i, q_e, and Γ_e



- Gradients about right at pivit point (r/a=0.5)
- Large excursions from measurements away from pivit point

TGYRO improvements

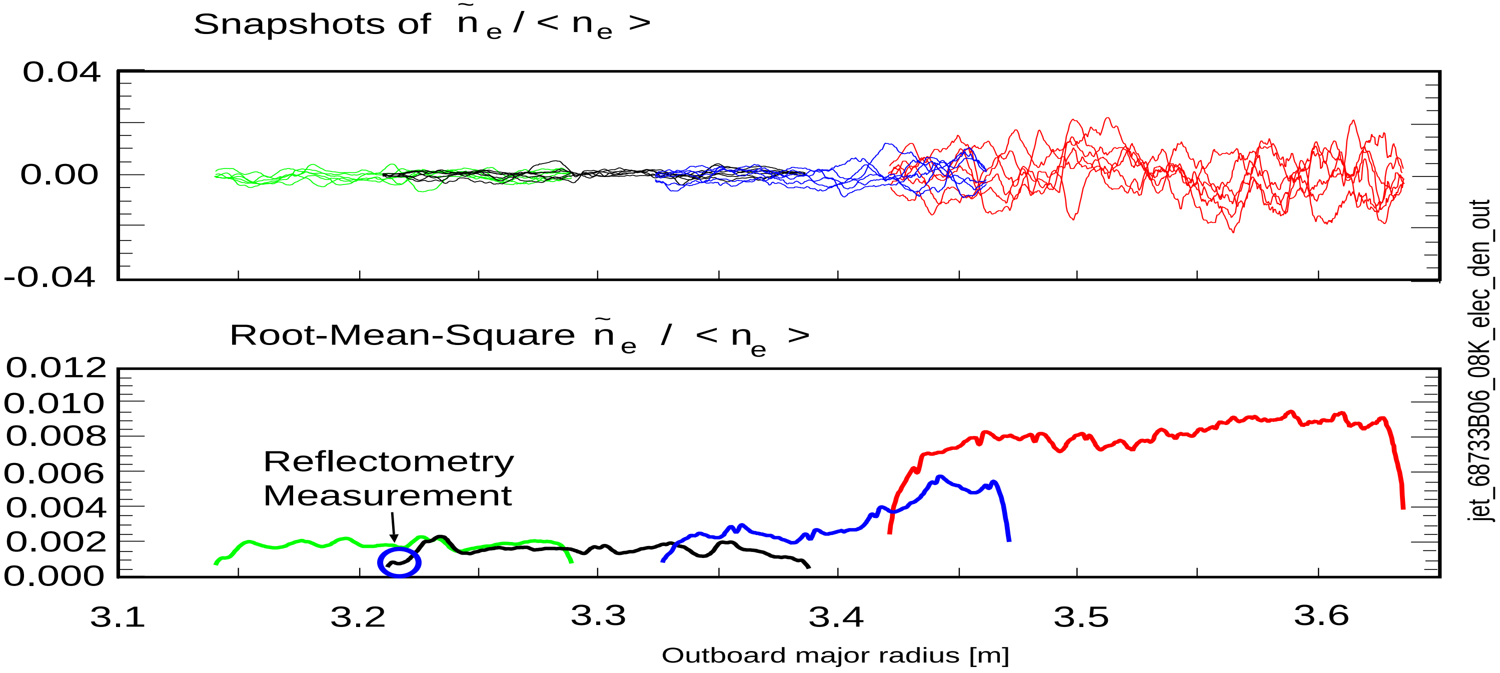
- Jeff Candy improving feedback over large domain
  - Split radial domain into regions for different methods: neoclassical, TGLF, or nonlinear GYRO
  - Plasma profiles input as boundary at edge of simulation domain
- Desired future improvements
  - feedback to match more measured profiles: Γ_ϕ
  - feedback adjustment of more profiles: v_{tor}, E_r, impurity profiles

Fluctuation measurements help validate GYRO

- Integrate electron distribution to get $\tilde{n}_e$ in 3D and time
  - Use postprocessor to get $\tilde{n}_e(r, \theta, \phi = 0, t)$
  - Compute Root-Mean-Square along outer mid-plane ($\theta = 0$)
- Tunable microwave reflectometers operating in X-mode ($E \perp B_{TF}$)
  - TFTR: 132-140 GHz
  - JET: 92-96 and 100-106 GHz
- Measurements to compare with simulations:
  - Density fluctuation $\tilde{n}_e(r)$ RMS levels
  - Radial correlations of $\tilde{n}_e(r)\tilde{n}_e(r')$ and correlation length λ_r
  - Power spectra: Fourier Transform of $\tilde{n}_e(t)\ \tilde{n}_e(t')$

Simulated $\tilde{n}_e$ consistent with reflectometry

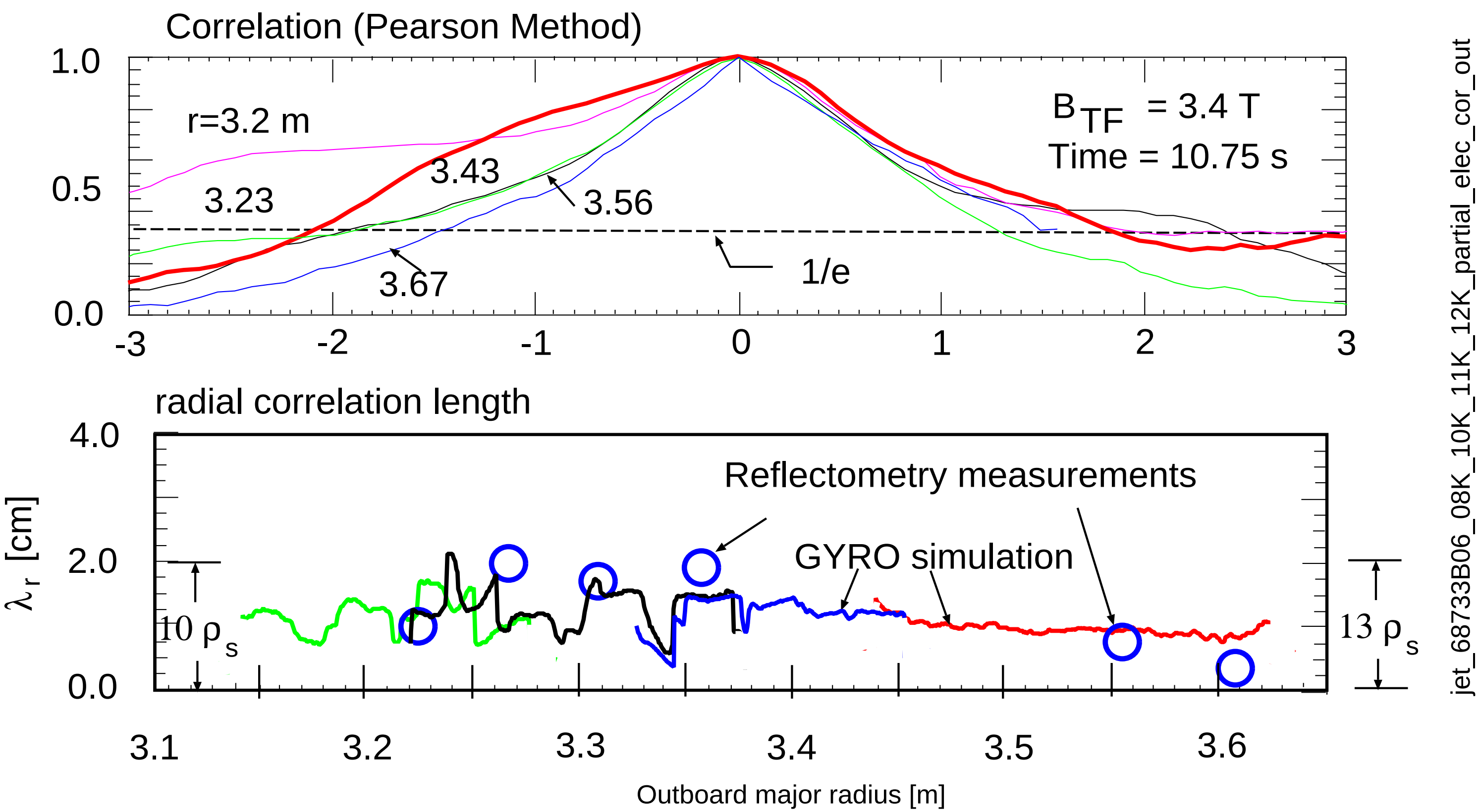
- Compute Root-Mean-Square along line-of-sight



- Both simulation and measurement are less than about 0.2%
- No measurements for regions of large $\tilde{n}$

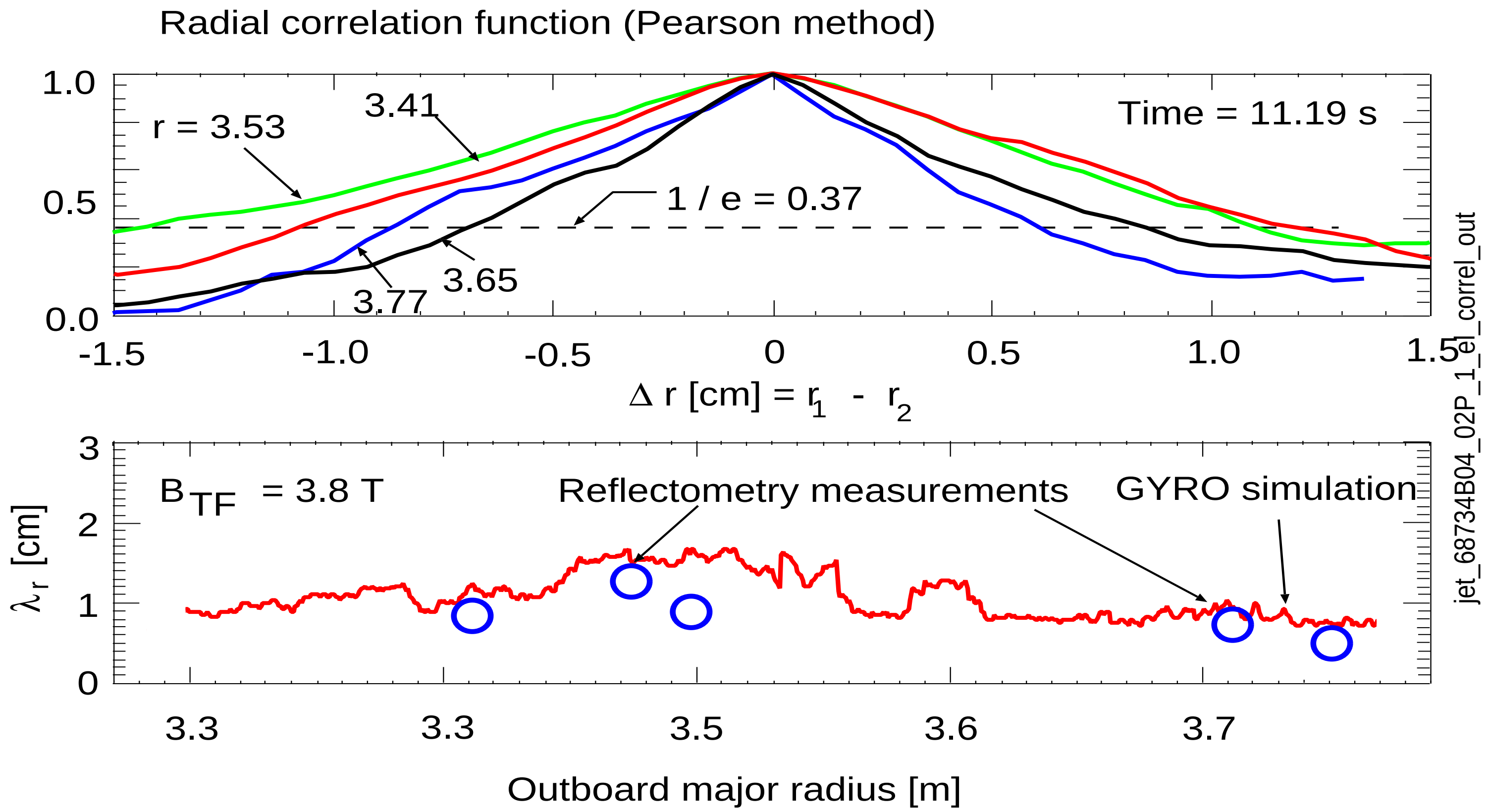
Radial correlations also consistent with reflectometry

- Correlation of $\tilde{n}_e(r_1, t)$ and $\tilde{n}_e(r_2, t)$
- λ_r defined by Δr where correlation decreases below 1/e
- Magnetic axes at 2.97m and outboard separatrix at 3.85m



Similar levels of agreement in another JET L-mode

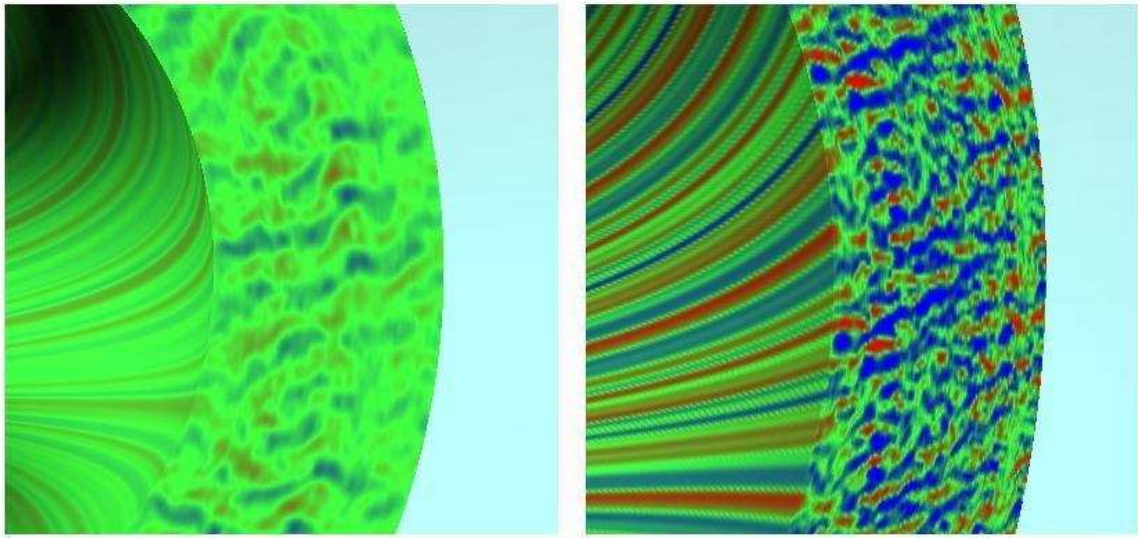
- Similar to previous shot, but B_{TF}: 3.4 $\longrightarrow$ 3.8 T



- Note smaller λ_r at higher B_{TF}

Animation

- Plan to place two 2D animations of $\tilde{n}_e$ at R=3.22 and 3.55m here

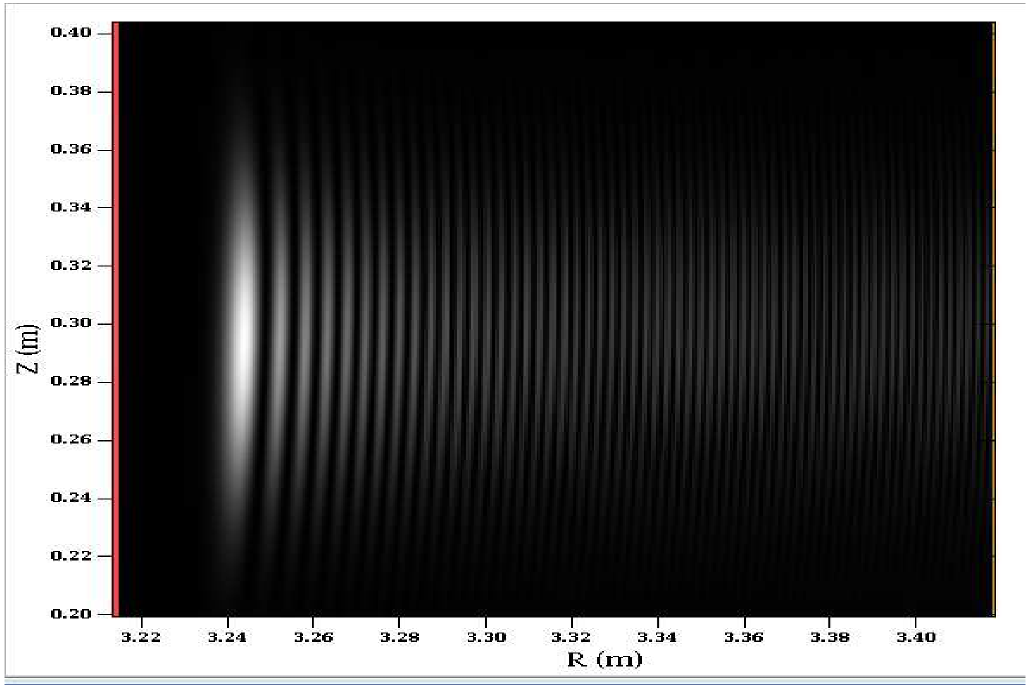


GYRO Simulation of $\tilde{n}_e$ in Jet 68733

R = 3.22 m	R = 3.53 m
r / a = 0.26	r / a = 0.60
$n_e = 2.58 \times 10^{19} / m^3$	$n_e = 1.80 \times 10^{19} / m^3$
RMS($\tilde{n}_e / n_e$) = 0.002	RMS($\tilde{n}_e / n_e$) = 0.009
λ_r = 1.0 cm	λ_r = 0.9 cm

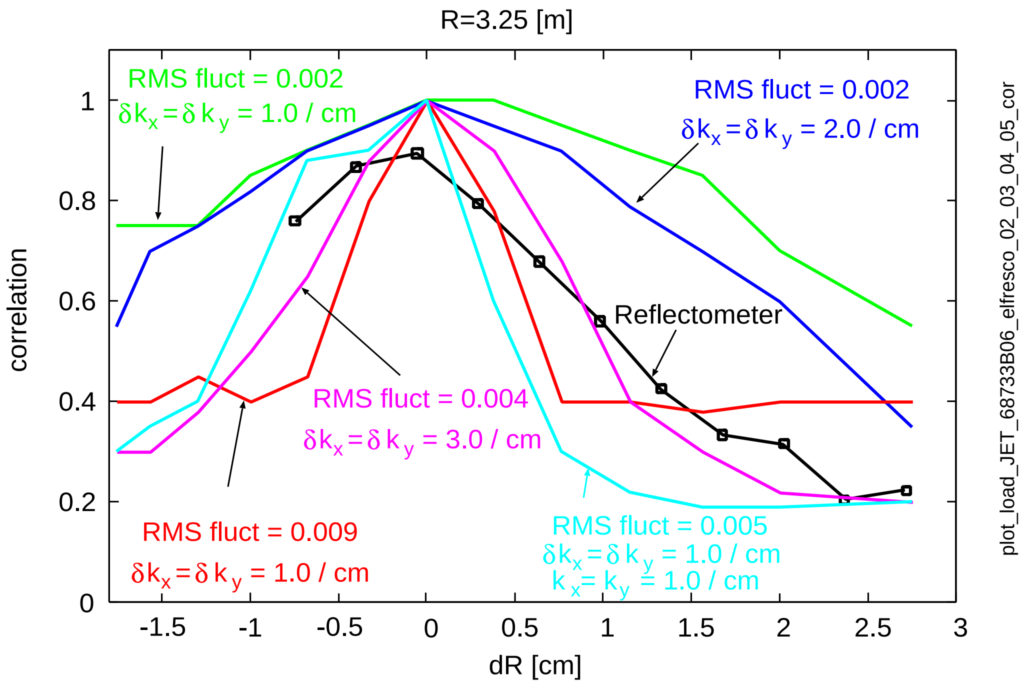
How to improve the measurements

- Use SCHRADO2 to calculate full wave scattering
- Horizontal launch of microwaves
- Interference with reflections from density cut off region



Improved comparisons with fluctuation measurements

- Simulate measurements assuming 2D scattering from Gaussian fluctuations
  - assume k_x, δk_x k_y, δk_y



- Want to input GYRO simulations of $\tilde{n}_e(r)$ into SCHRADO3

Summary

- Nonlinear GYRO simulations of transport and $\tilde{n}_e$ over extended radial domains
- Found approximate agreement between simulations and measurements of transport and $\tilde{n}_e$
- Not yet strong validation of model:

  1. Uncertainties of measured profiles
  2. Hypersensitivity of simulations to profiles

- Preliminary TGYRO runs to feedback on measured q_i, q_e, and Γ_e

Interesting topics needing work

- Angular momentum simulations
  - GYRO now simulates radial flow of parallel and perp angular momenta
- Reflectometry measurements
  - 3D reflections from GYRO-simulated fluctuations momenta
- Electromagnetic effects
  - ES easier, but EM effects expected, especially in core and in enhanced confinement
- Test ITER predictions
  - Predictions use models such as GLF23 need to be benchmarked