Investigating electromagnetic effects on core transport in Alcator C-Mod H-mode discharges

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Overview & Summary

- Beginning validation of gyrokinetic simulations for high-β ITER-like H-mode plasmas in Alcator C-Mod
  - β_N=1.3-2.1 H-modes unstable to ITG (r/a~0.5-0.8), sub-dominant microtearing modes (MTM) also predicted
  - Baseline nonlinear simulations are dominated by ITG, but ion/electron heat fluxes *do not* match experiment
  - Varying T_e & T_i gradients to match fluxes changes balance of ITG vs. MTM, challenges nonlinear simulations (requires large numerical resolution)

- Characterizing expected importance of electromagnetic effects
  - Finite β reduces predicted ion heat fluxes from ITG by 50%
  - EM flutter transport contributions are small (1% for heat, 15% for particle flux)

- Using synthetic diagnostic, predict sensitivity of polarimeter diagnostic to δn_e, δB_r using synthetic diagnostic
  - $|\delta B/B_0| \sim 1\% \, |\delta n/n_0|$, negligible influence of δB on Faraday rotation
  - Will likely change if predicted character of turbulence changes (ITG→MTM) with gradient variations

EXPERIMENTAL DETAILS

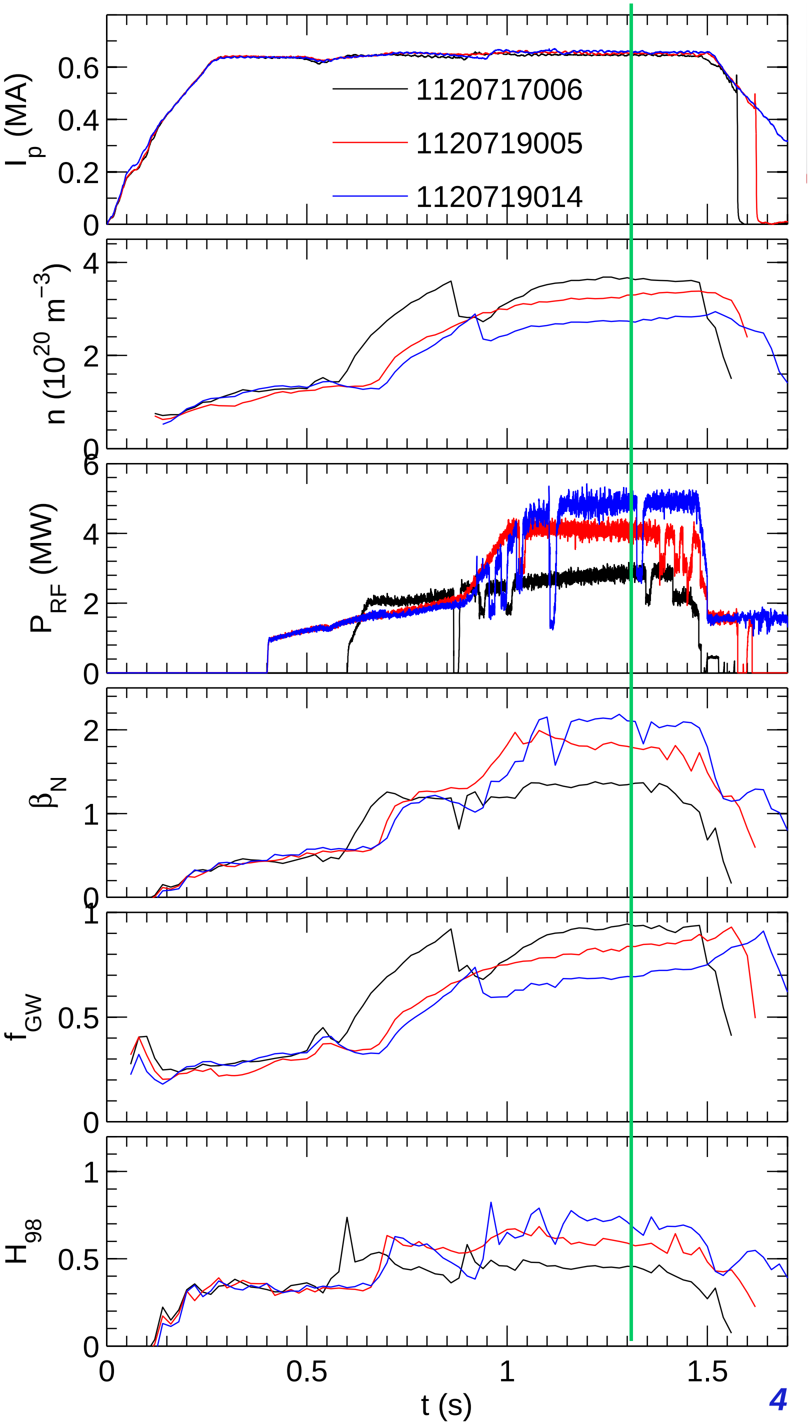
Analysis based on ITER-like H-mode discharges with β_N=1.3-2.1

- ITER-like discharges with 2.5-5 MW ICRH heating (Kessel, NF 2013)

- Using reduced B_T=2.6 T to achieve high β_N and f_{GW} (higher ν_* compared to ITER)

- Dominant electron heating, T_e~T_i, no torque (expect low rotation, *but no measurement*)

- Following transport analysis and gyrokinetic scoping studies around 1.3 s



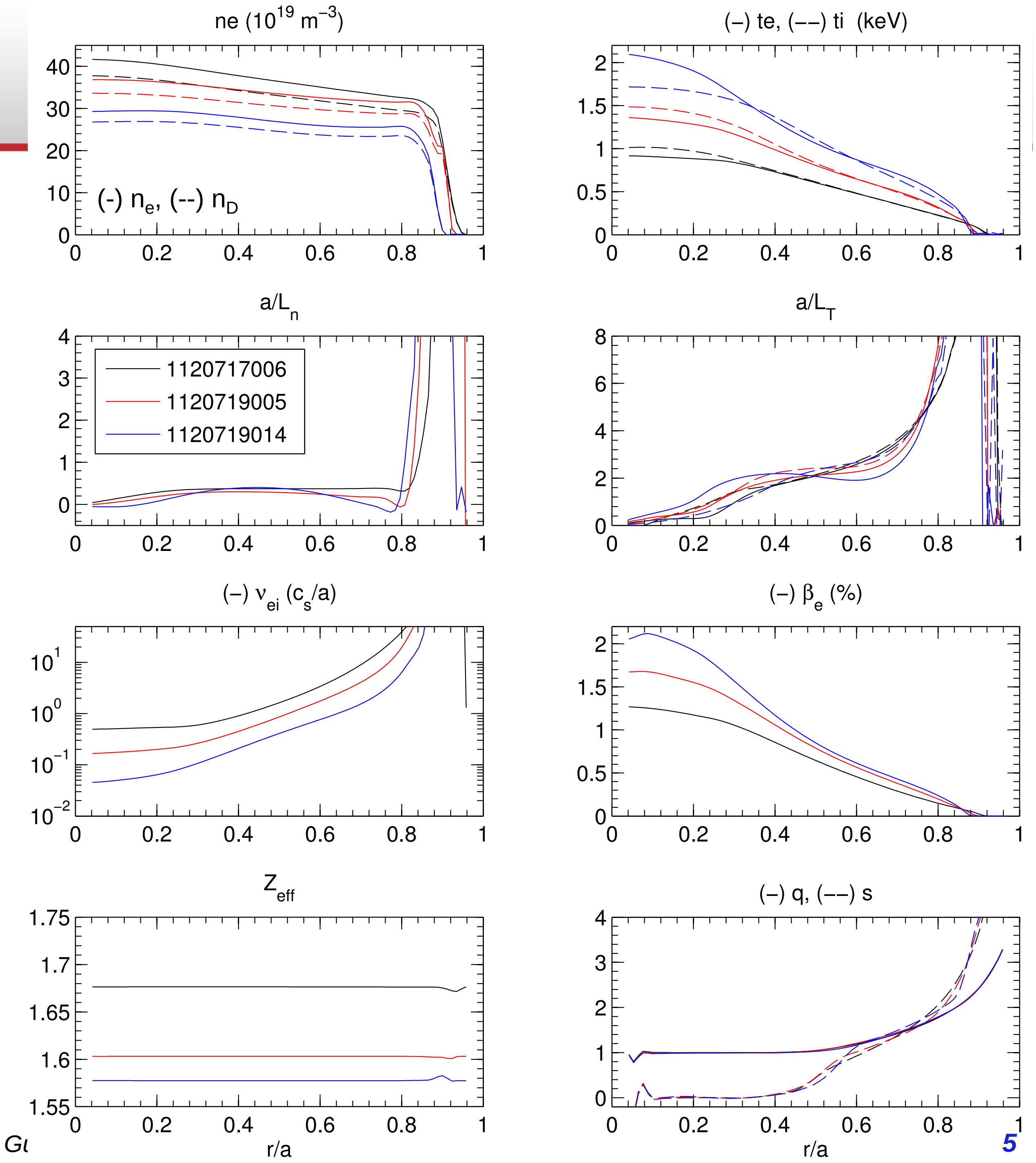
TRANSP runs & profiles

- 1120717006 (1300 ms) TRANSP ID 87637
- 1120719005 (1300 ms) TRANSP ID 87632
- 1120719014 (1300 ms) TRANSP ID 87634

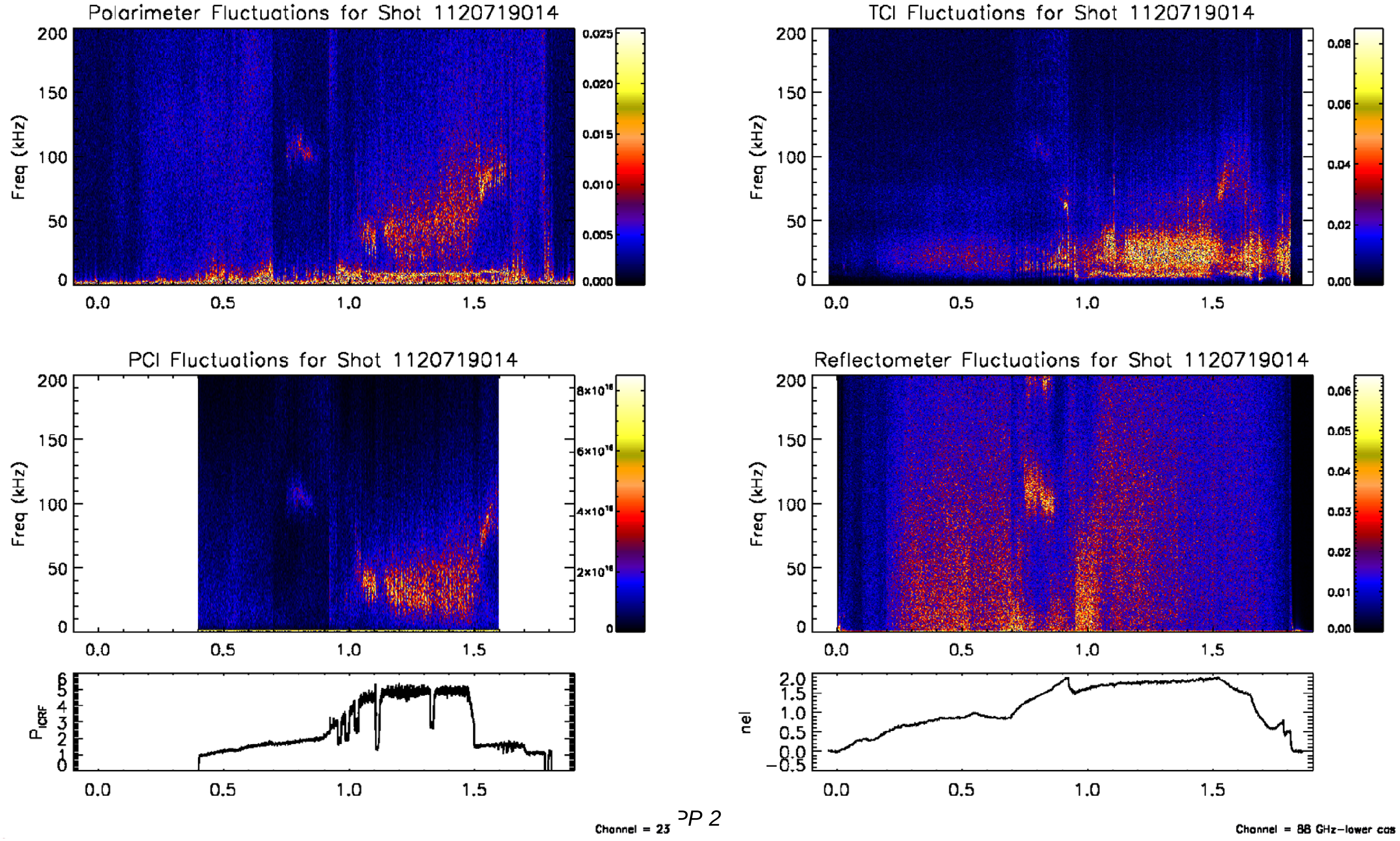
- *Measured T_i profiles unavailable* - scaled $\chi_{i,NC}$ to match neutron rate
  - New experiment planned to get T_i, v_φ, and MSE-constrained q profile

- Flat Z_{eff} assumed

- For GYRO sims, keeping D & B (sometimes Mo)



Fluctuation data available from polarimeter, PCI, TCI and reflectometer for validation with simulations

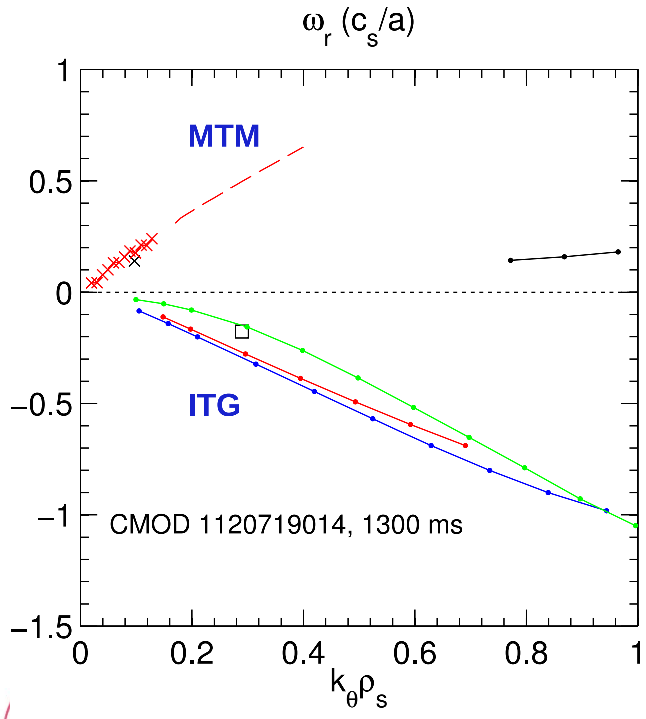


LINEAR GYROKINETICS

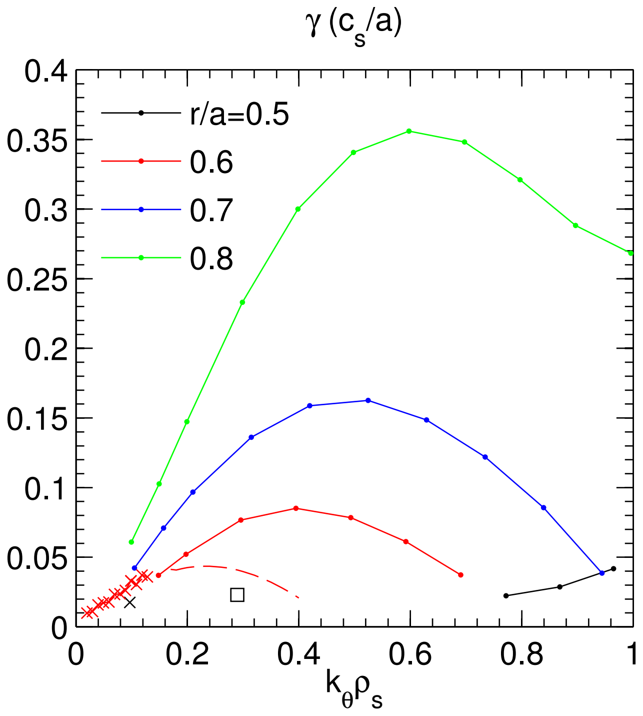
Initial linear GYRO stability simulations show that ITG dominates r/a=0.6-0.8

- Microtearing modes (MTM) exist for $k_\theta \rho_s < 0.4$ at r/a=0.5, 0.6
  - Distinguishable from eigenfunctions/spatial structure (not shown)
  - Tracking MTM when subdominant using eigenvalue solver (dashed line)
- Clearly distinct dispersion in real frequencies
- Similar results for other two shots

Real frequencies



Growth rates



Linear runs using GYRO

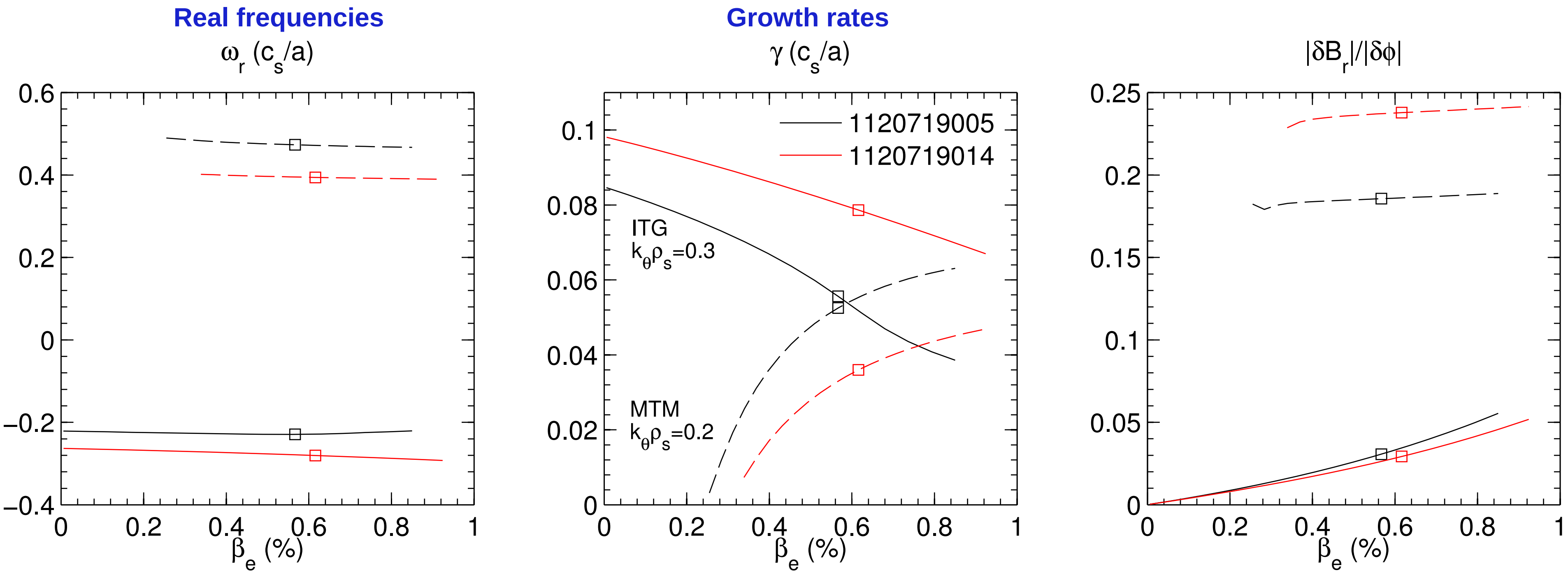
4 kinetic species, D,B,Mo,e (Z_{eff}~1.6)

Electromagnetic ($A_{||}$ only, β_e~0.24-0.85%)

Collisions

Linear ITG weakly stabilized by finite beta (r/a=0.6)

- MTM has threshold at β_e~0.3% ~ 1/2·$\beta_{e,exp}$, predicts much larger EM fluctuations, $|\delta B_{MTM}/B_0|$ ~ 20% of $|\delta n_{MTM}/n_0|$



- Fits for 1120719014 (β_N=2.1) give a/L_{Ti} ~ 1.4·a/L_{Te} (r/a=0.6)
  - a/L_{Ti} ~ a/L_{Te} in the other two shots (no ion measurements)
- Let's investigate sensitivity to gradients

ITG stiff with ion temperature gradient (a/L_{Ti}), MTM stiff with electron temperature gradient (a/L_{Te})

- ITG independent of a/L_{Te}
- MTM independent of a/L_{Ti}

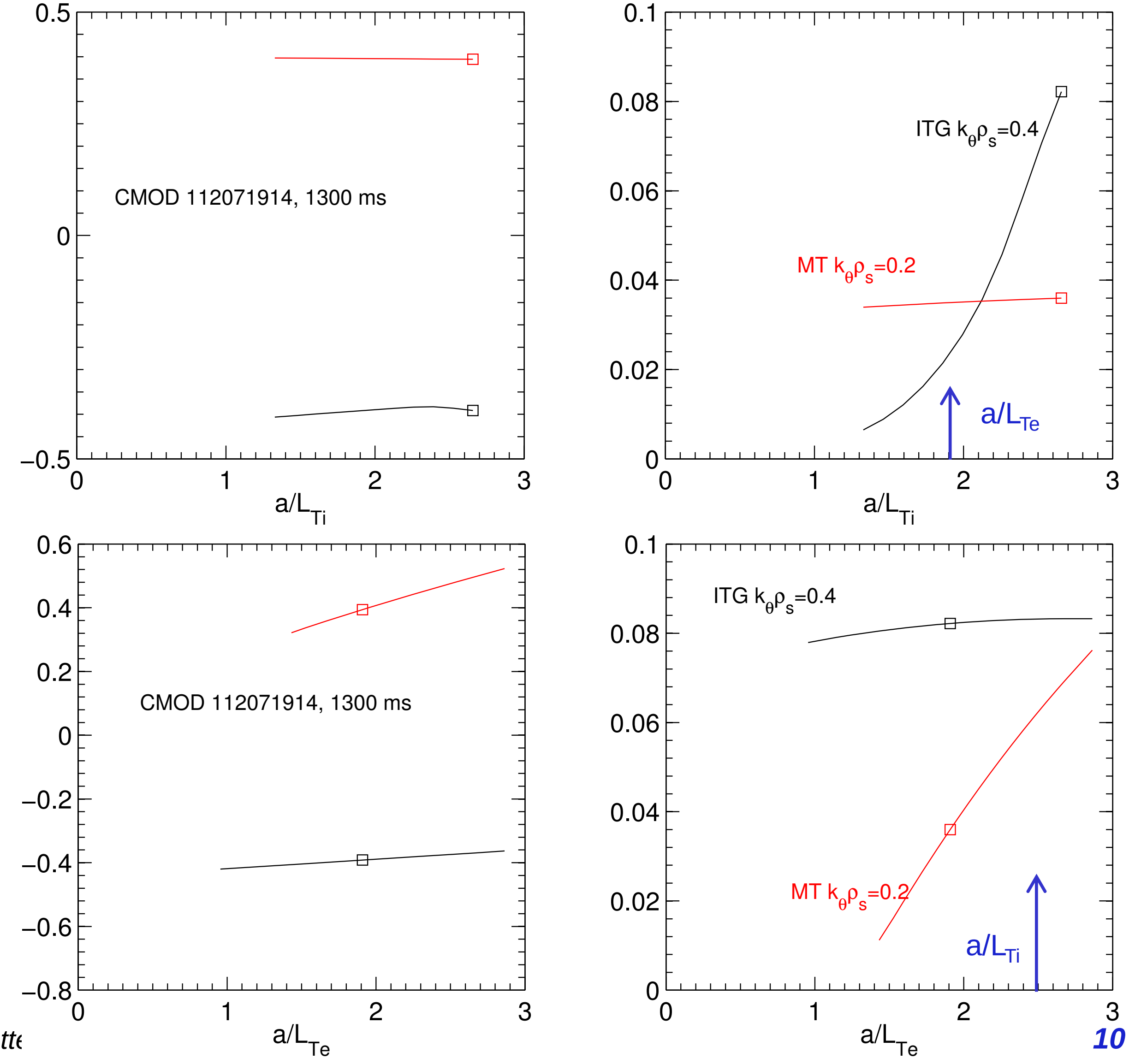
- MTM much stronger when increasing a/L_{Te} to better match a/L_{Ti}~2.7 ⟶

Real frequencies

ω_r (c_s/a)

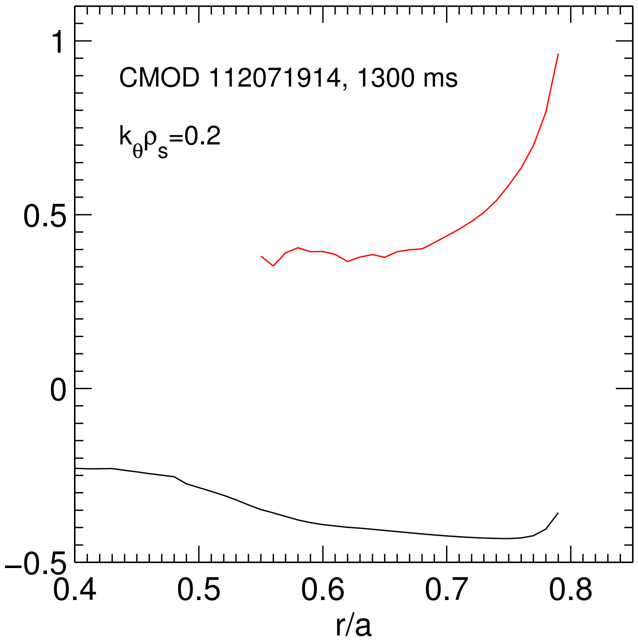
Growth rates

γ (c_s/a)



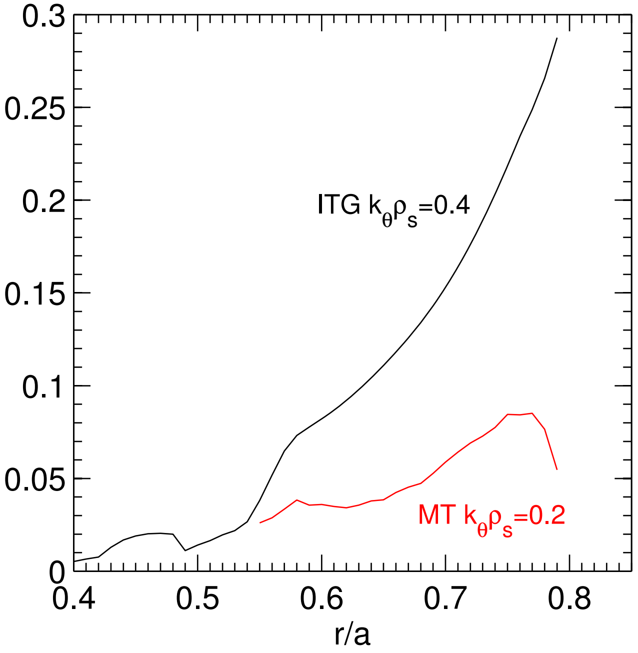
Microtearing present over broad radial region, but always subdominant to ITG

- MTM getting stronger further out in radius, but so is ITG



Real frequencies

ω_r (c_s/a)



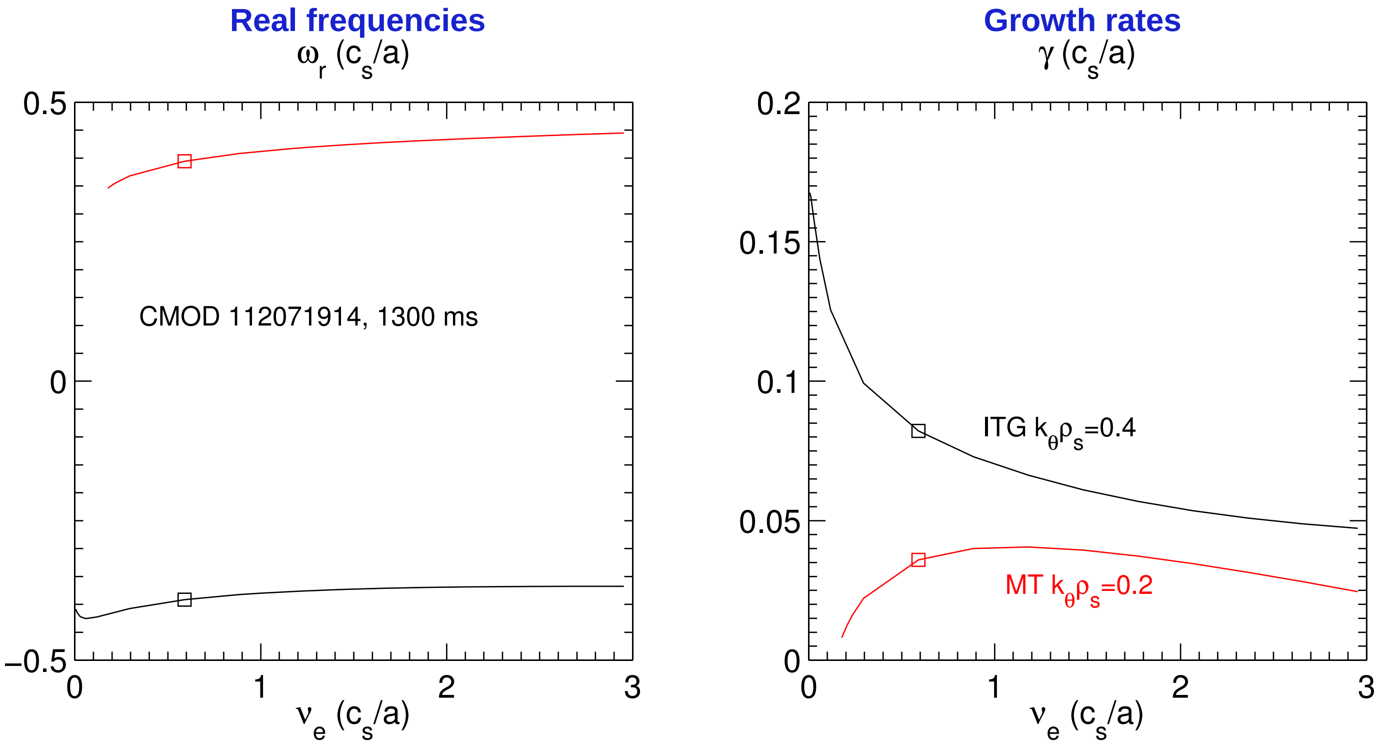
Growth rates

γ (c_s/a)

MTM shows non-monotonic dependence with collisionality, as predicted in core of NSTX & AUG

- Same dependence predicted in core of NSTX [Guttenfelder, 2012] and ASDEX-UG [Doerk, 2012]
- Perhaps expected to be less relevant at lower collisionality

(ITER r/a~0.6, $\nu_e \sim 10^{-2}\ c_s/a$)

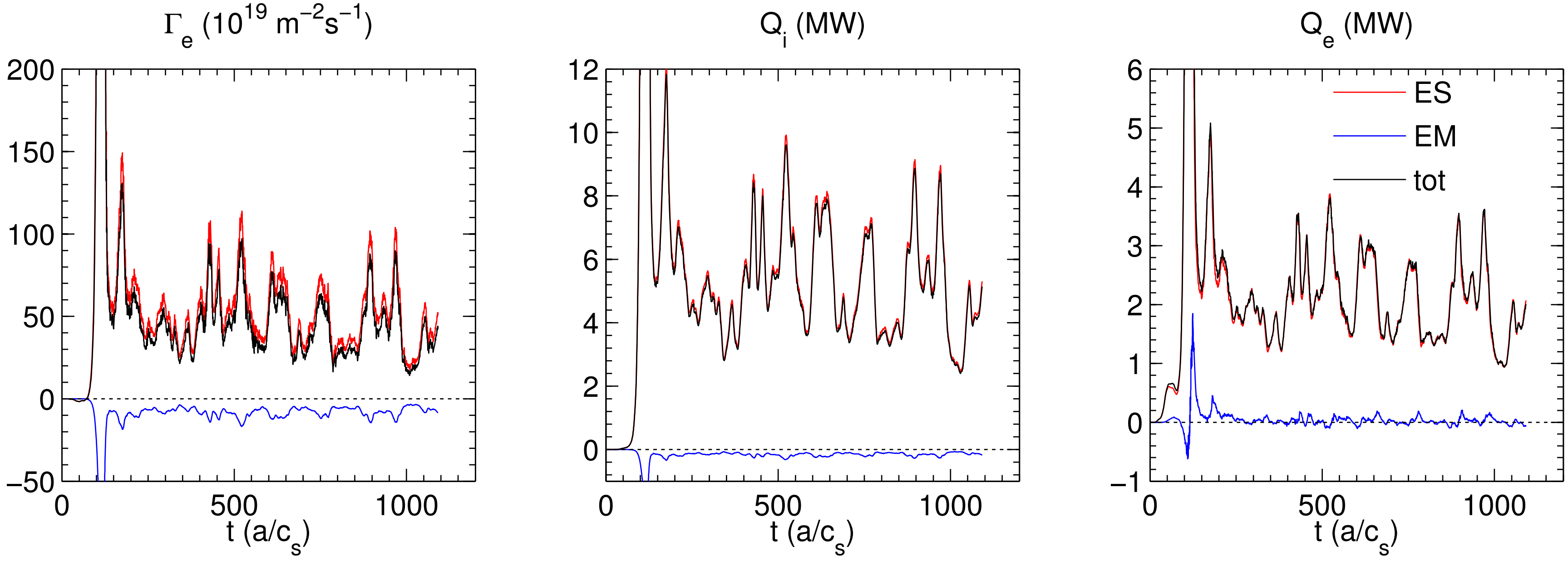

Real frequencies

Growth rates

NONLINEAR GYROKINETICS

Initial nonlinear run for 1120719014, 1300 ms, r/a=0.6

- For base case, fluxes dominated by ES contributions (Q_i=4.8 MW, Q_e=1.9 MW)
- Inconsistent with TRANSP analysis ($Q_{i,exp}$=0.6 MW, $Q_{e,exp}$=4.4 MW)
- Only ~1% EM contribution (~δB_r) to Q_e

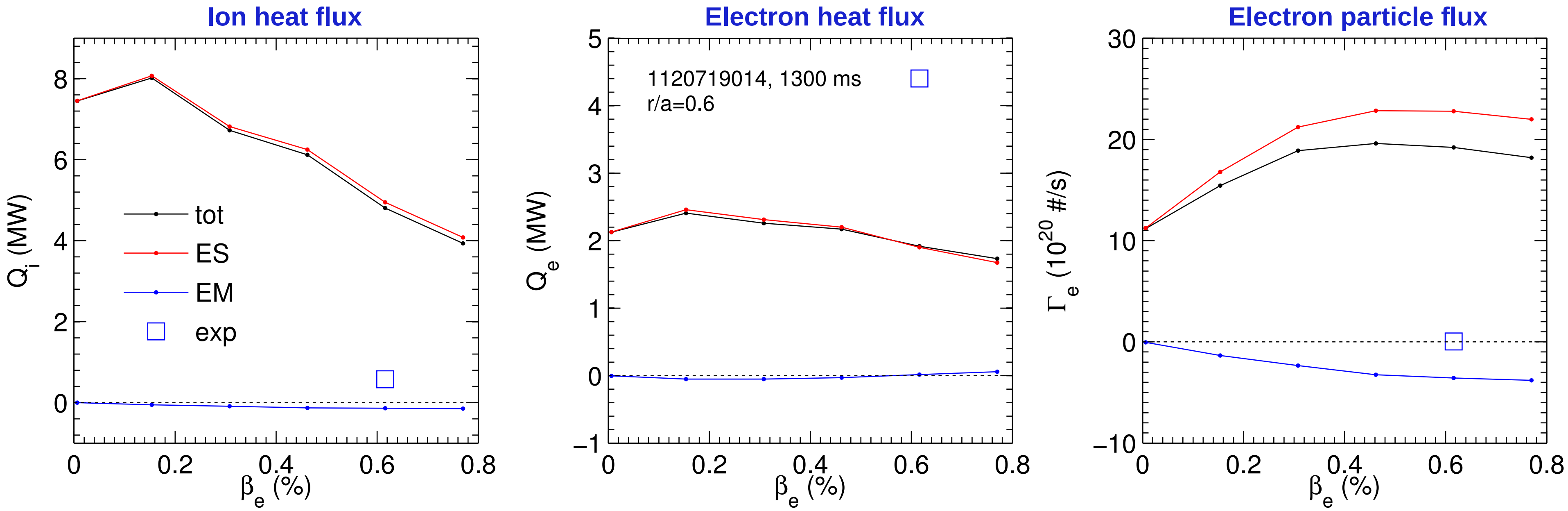


Nonlinear runs using GYRO
3 kinetic species, D,B,e (Z_{eff}~1.6)
Electromagnetic ($A_{||}$, β_e~0.6%)
Collisions

Resolution parameters
$L_x \times L_y = 125 \times 127\ \rho_s$
nx × ny = 256×24 (Δn=5)
$k_\theta \rho_s$ [min, max] = [0.049, 1.14]
$k_r \rho_s$ [min, max] = [0.050, 3.21]
[n||,nλ,ne]=[14,8,8]×2

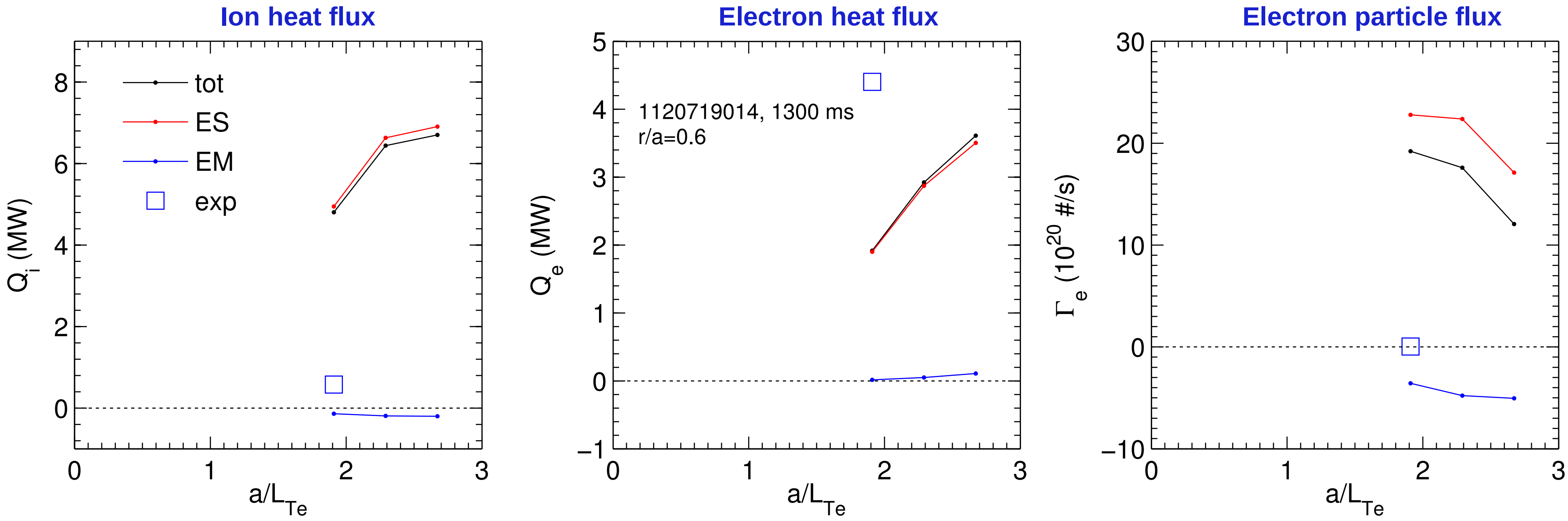
Ion heat flux (Q_i) decreases ~50% with finite β_e

- Q_e shows weaker dependence, Γ_e increases
  - Heat flux dependence similar to previous studies (e.g. Pueschel, PoP 2008)
- Biggest EM flutter contribution is to particle flux (~15% inward)



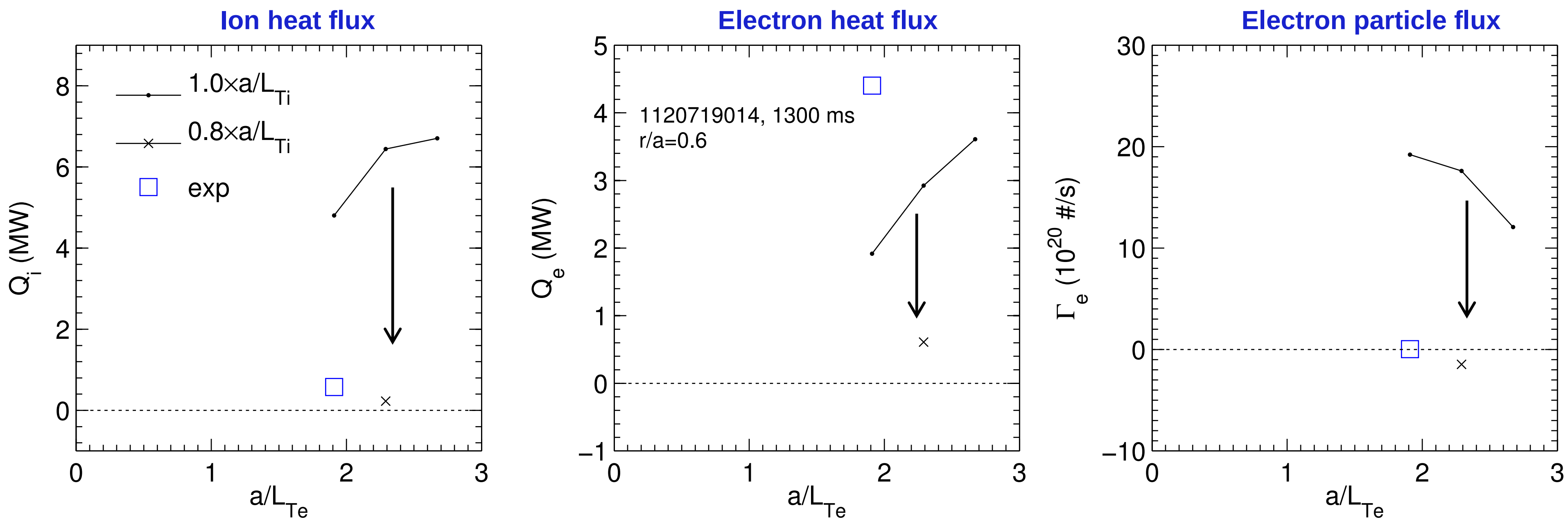
Try to match fluxes by adjusting gradients – 1.2-1.4×a/L_{Te} gives larger Q_e approaching experiment

- But also increases Q_i (further from experiment)
- Will probably need a corresponding decrease in a/L_{Ti}



$0.8\times a/L_{Ti}$ (for $1.2\times a/L_{Te}$) reduces Q_i and Γ_e much closer to experiment

- Also brings down Q_e significantly (further from experiment)
- BUT there are serious numerical resolution problems…



Ion heat flux

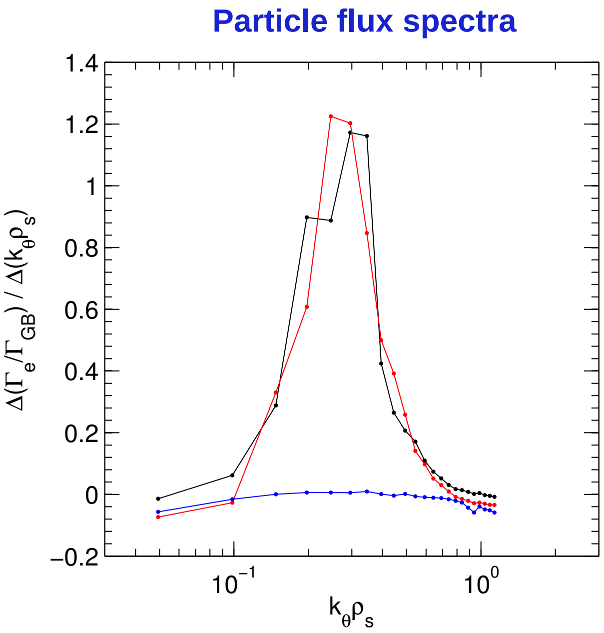
Electron heat flux

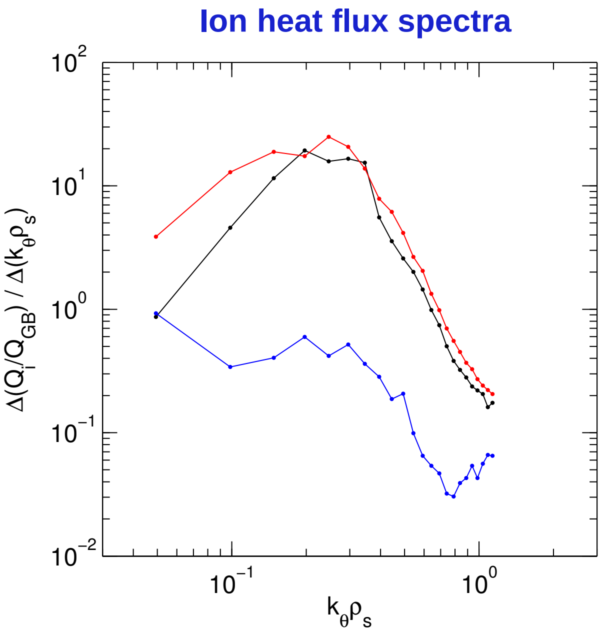
Electron particle flux

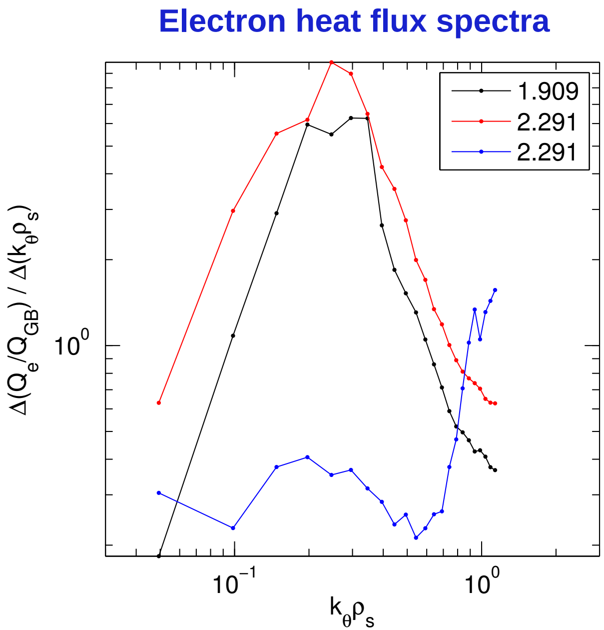
1120719014, 1300 ms
r/a=0.6

Insufficient resolution for reduced a/L_{Ti} simulations

- Pathological peaking at highest $k_\theta\rho_s$ modes in electron heat flux spectra


Particle flux spectra


Ion heat flux spectra

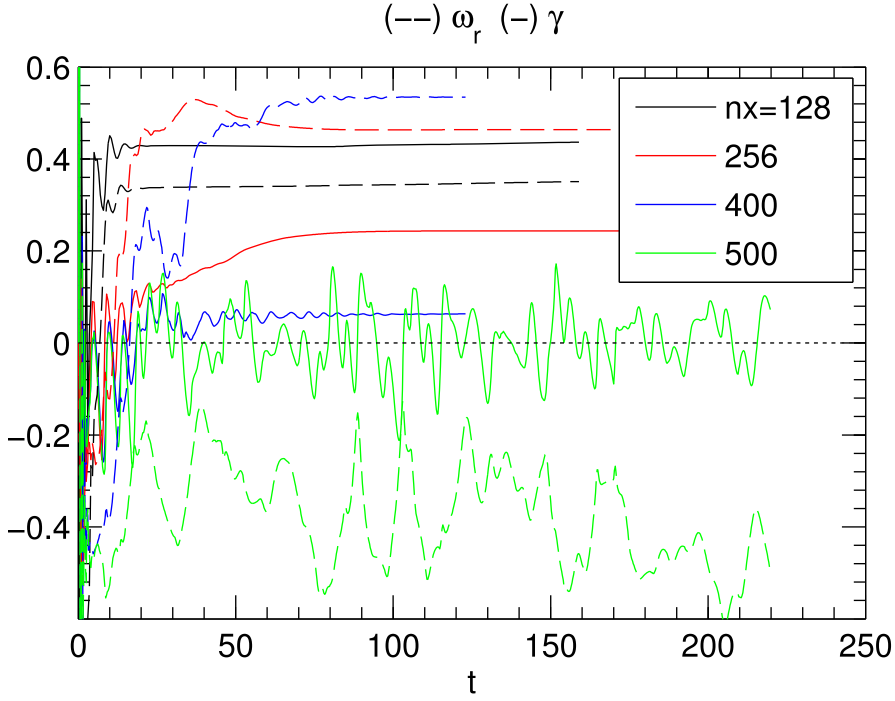

Electron heat flux spectra

Base
1.2×a/L_{Te}
1.2×a/L_{Te}, 0.8×a/L_{Ti}

Alcator C-Mod

Linear tests for n=90 ($k_\theta\rho_s$=0.88) using nonlinear numerical resolution setup show insufficient resolution

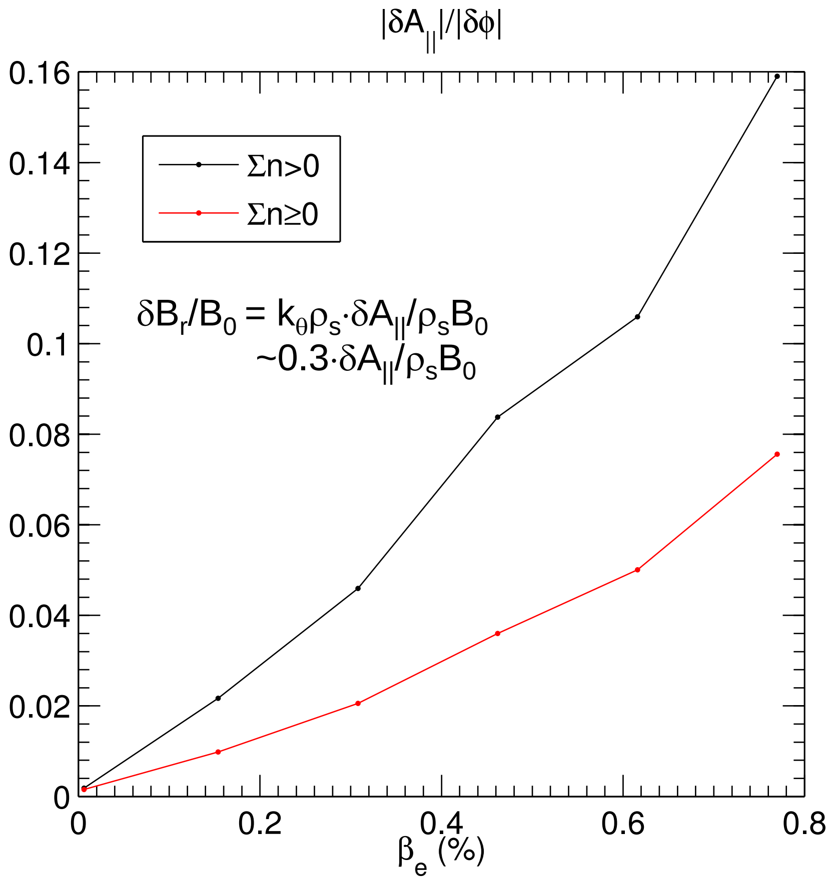
- Artificial growth (n=90, $k_\theta\rho_s$=0.88) with insufficient resolution, need nx~500 to recover flux-tube results (i.e. γ~0, stable mode)



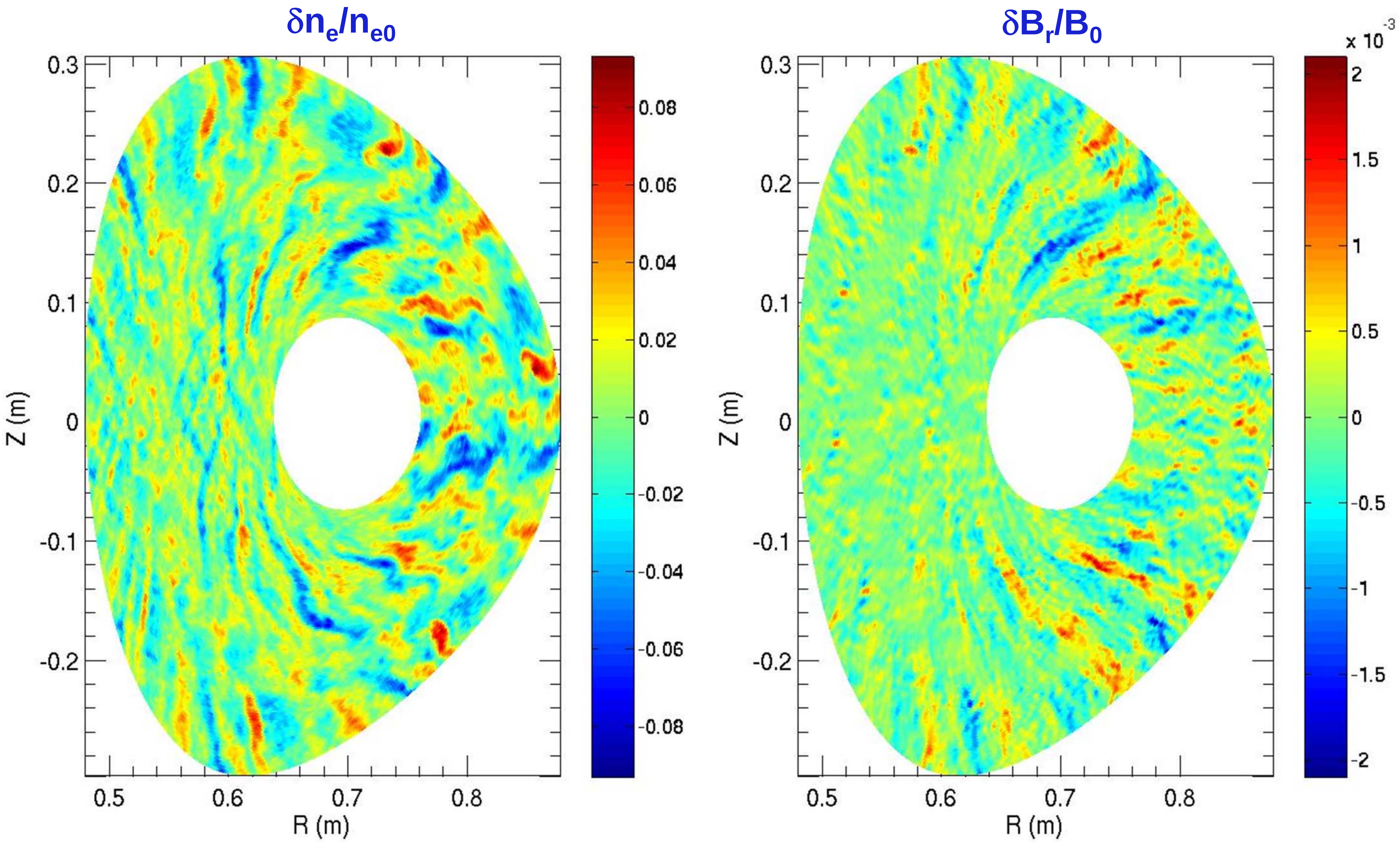
- Seems that it's necessary to resolve rational surfaces associated with highest $k_\theta\rho_s$ modes, $\Delta x/\rho_s \leq 1/(4\cdot s\cdot k_\theta\rho_s)$~0.25 (nx≥500)
  - $\Delta r_{rat}/\rho_s = 1/s\cdot k_\theta\rho_s = 1$ (for $k_\theta\rho_s$=0.88, q=1.17, s=1.13)
  - Working on nonlinear simulations

Relative EM amplitude increases linearly with β_e

- $\delta B_r/B_0$ ~ few % of $e\delta\varphi/T_e \approx \delta n_e/n_{e0}$
- Even if turbulence doesn't change character, expect δB to get bigger → **is polarimeter expected to be sensitive to δB fluctutions?**



2D fluctuation snapshot (in R,Z)
C-Mod 1120719014, 1300 ms



$\delta n_e/n_{e0}$

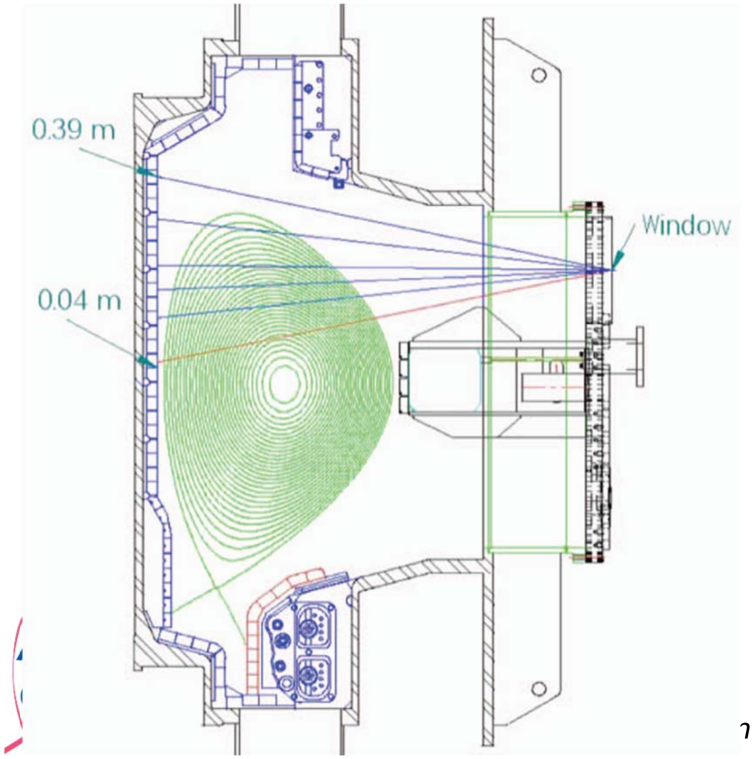
$\delta B_r/B_0$

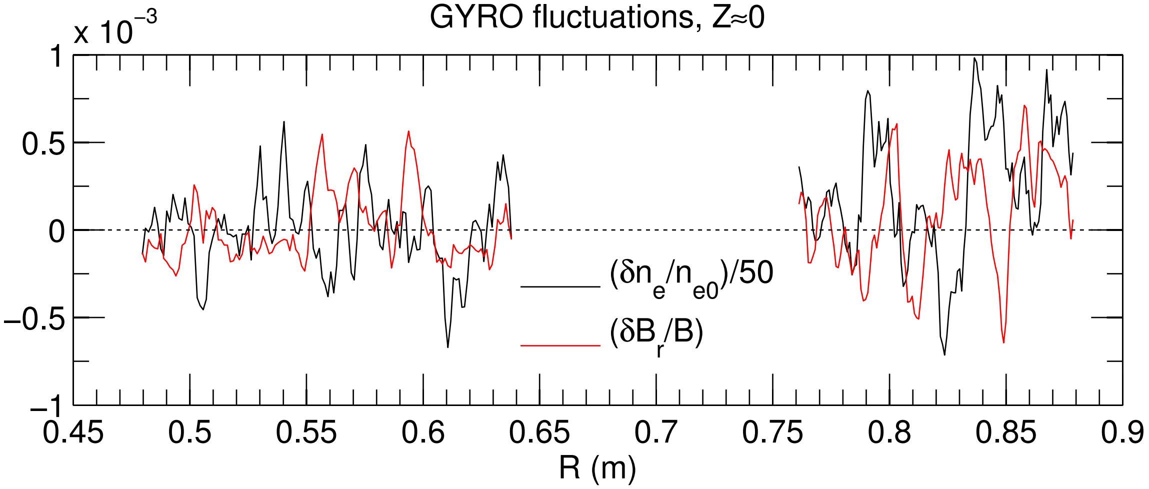
Movie: http://w3.pppl.gov/~wgutten/movies/cmod_nebr_sat.mov

SYNTHETIC FARADAY ROTATION

Utilize synthetic diagnostic to examine sensitivity of polarimeter measurement to δn, δB

- Interested in interferometry, Faraday rotation and Cotton-Mouton effects
  - $\Psi_{int}=c_{int}\lambda \int dL\cdot(n_e)$ $c_{FR}=2.817\times10^{-15}$ m/T, $\lambda=118\mu$m
  - $\Psi_{FR}=c_{FR}\lambda^2 \int dL\cdot(B_{||}n_e)$ $c_{FR}=2.631\times10^{-13}$ 1/T
  - $\Psi_{CM}=c_{CM}\lambda^3 \int dL\cdot(B_\perp{}^2 n_e)$ $c_{CM}=2.456\times10^{-11}$ 1/mT^2
- Equilibrium $n_{e0}(R,Z)$, $B_0(R,Z)$ from Thomson Scattering and EFIT
- On right is plot of GYRO $\delta n_e/n_{e0}$ and $\delta B_r/B$ vs. R (at Z=0)
  - Simulations don't span entire cross-section, at least use what we've got
  - Would be a little more realistic to run a global simulation, still can't include pedestal

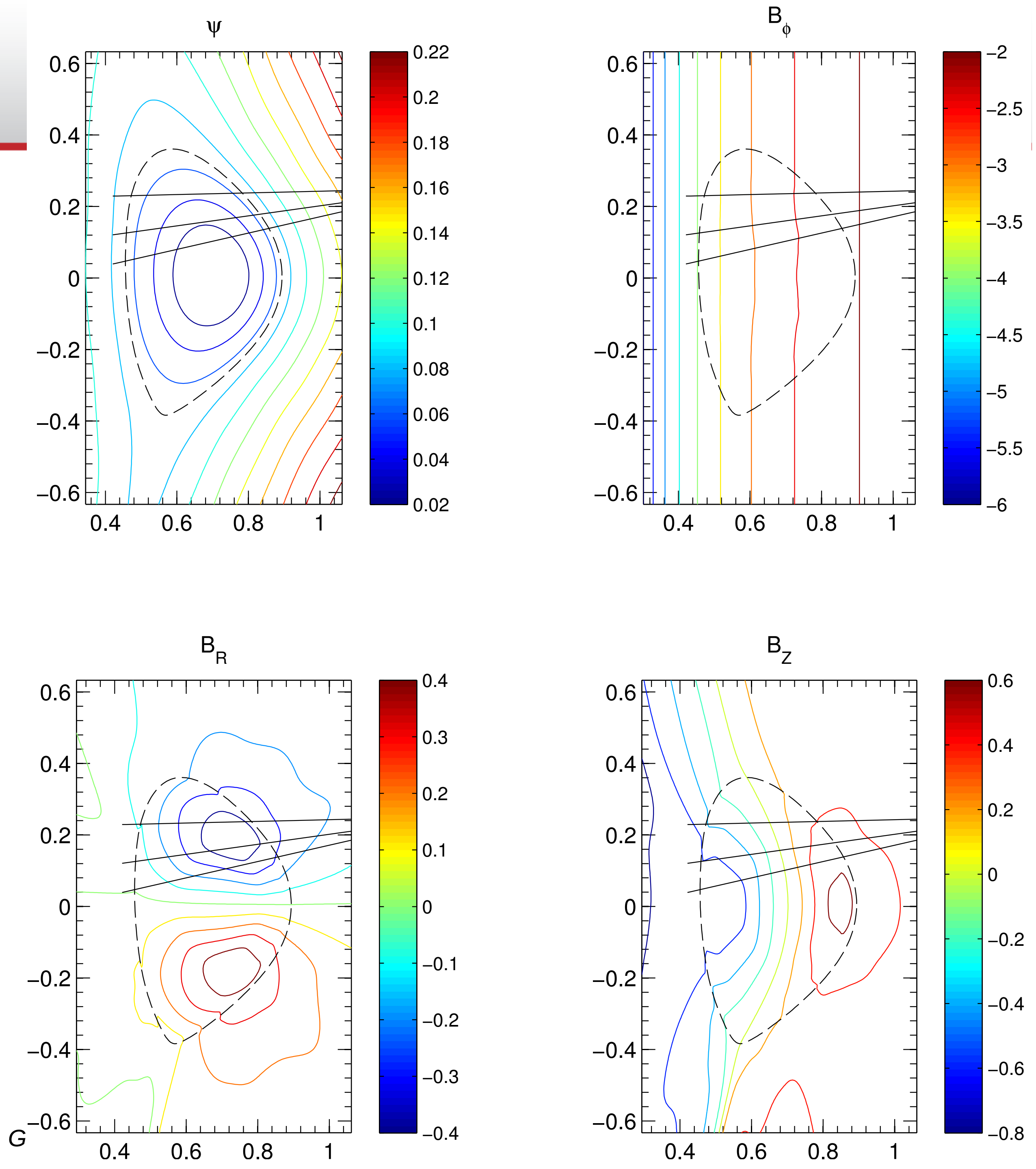




Let’s examine equilibrium first

- Using EFIT (in this case actually .geq from TRANSP plasma state)

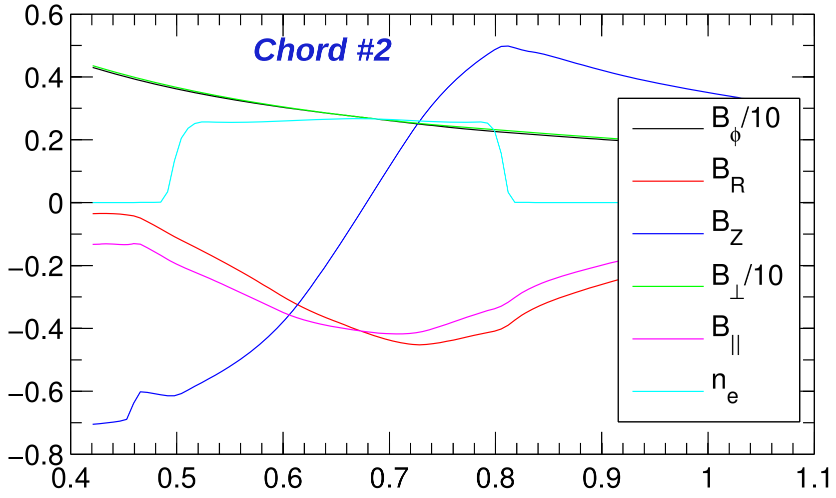
- Shown are three polarimeter chords (1,2,4) where data was acquired



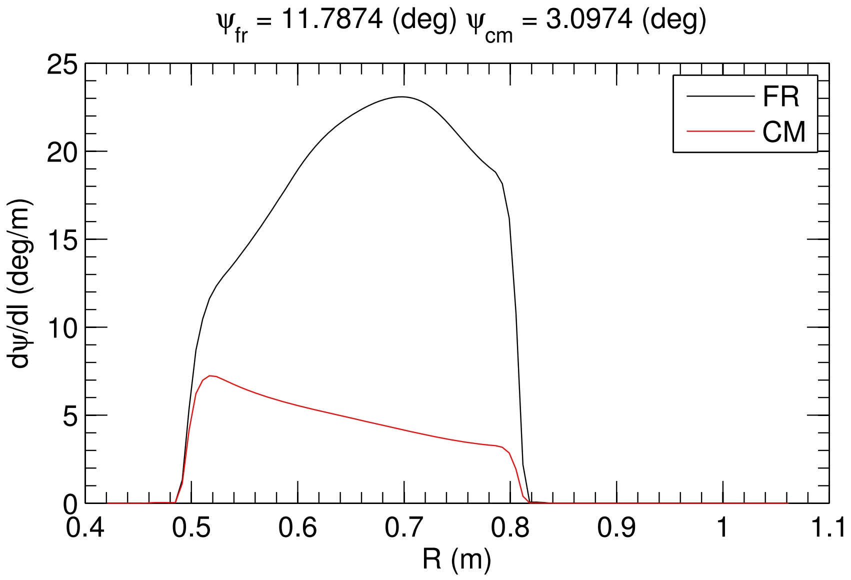
Calculated equilibrium Faraday Rotation bigger than Cotton-Mouton effect, matches experimental measurement

- $\Psi_{FR}=c_{FR}\lambda^2 \int dL\cdot(B_{||}n_e)$ ($c_{FR}=2.631\times10^{-13}$ 1/T), $\lambda=118\mu m$
- $\Psi_{CM}=c_{CM}\lambda^3 \int dL\cdot(B_{\perp}^2 n_e)$ ($c_{CM}=2.456\times10^{-11}$ 1/mT^2)

- Quantities along polarimeter chord #2 shown, e.g. $B_{||}=(B_R\cdot dR+B_Z\cdot dZ)/dL$ →



- Relatively flat density profile, differential FR and CM phase shift follows $B_{||}$ and $B_\perp^2$, respectively

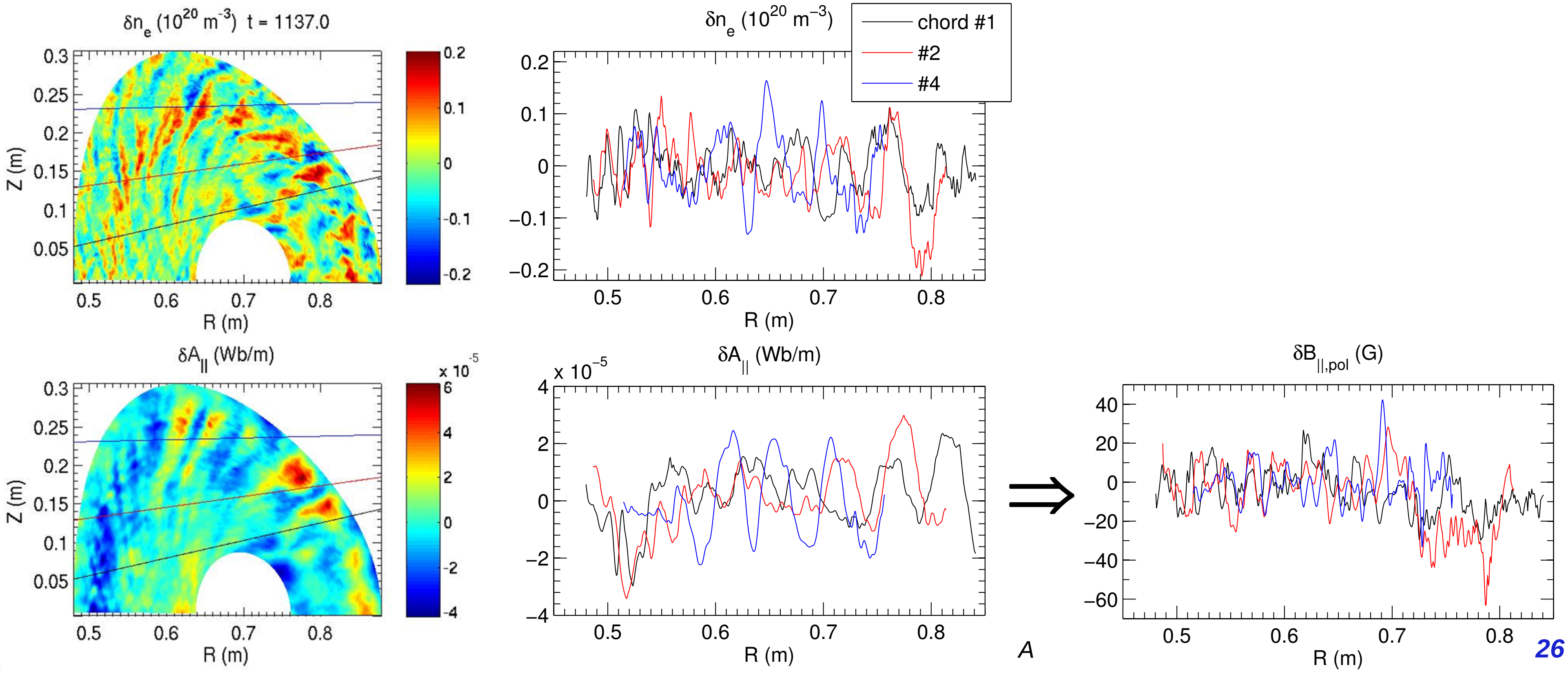


- Integrated phase shift ($2\times\int d\psi$) gives ψ_{FR}=11.8 deg, close to exp. ψ_{FR}=11.3 deg

- **Shown previously to work well by Bergerson, RSI (2010), Xu thesis (2013)**

Incorporating GYRO fluctuations by interpolating in lab space

- For each polarimeter chord (R,Z), determine corresponding GYRO (r/a, θ)
- Interpolate $\delta n_e(r/a,\theta)$ to obtain $\delta n_{e,pol}$
- Interpolate $\delta A_{||}(r/a,\theta)$ onto a 5-point stencil in (R,Z)
- Calculate δB_R, δB_Z from $\delta A_{||}(R\pm\Delta R, Z\pm\Delta Z)$
  - To lowest order in $\rho_s/R \rightarrow \delta B_R = -B_\varphi/B \cdot \delta A_{||}/dZ$, $\delta B_Z = B_\varphi/B \cdot \delta A_{||}/dR$
- Project along chord to obtain $\delta B_{||,pol} \cdot dL = (\delta B_R \cdot dR + \delta B_Z \cdot dZ)$

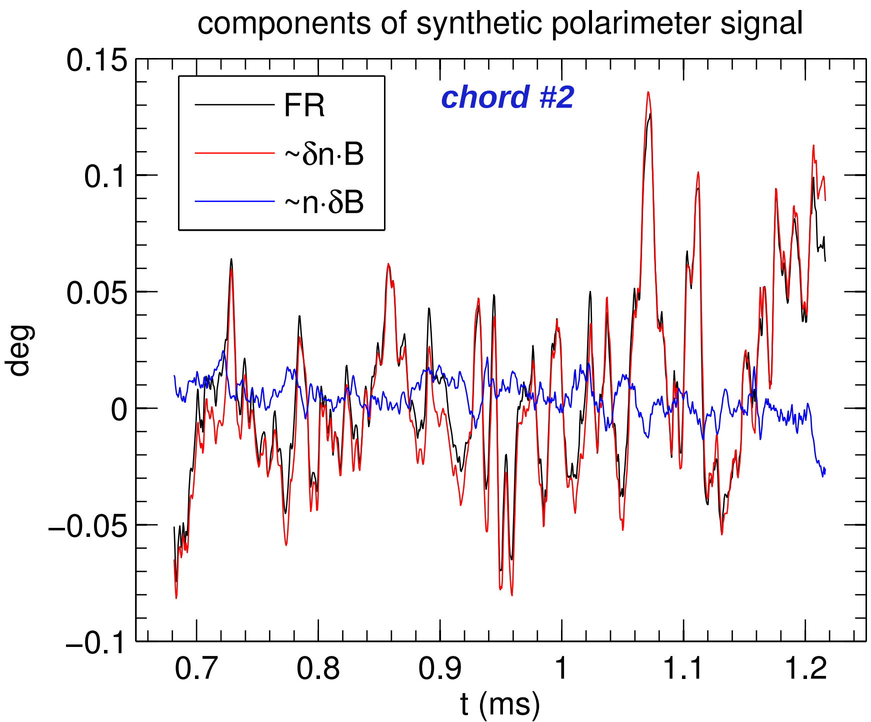


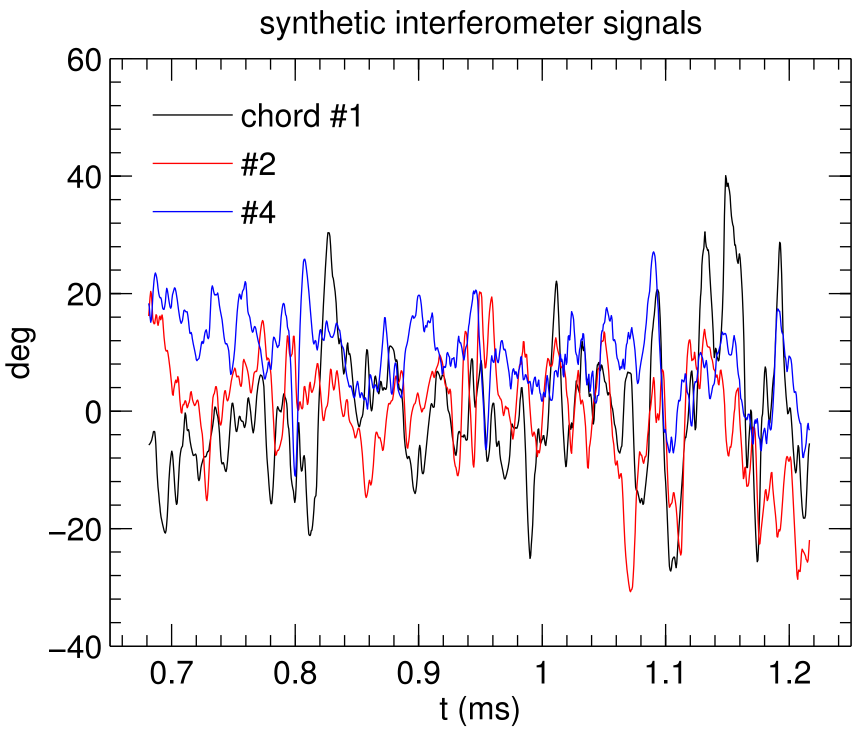
Predicted Faraday rotation dominated by $\delta n_e \cdot B_{||0}$, Interferometric signal ~300× bigger than Faraday rotation

- **$(\delta n_e \cdot B_{||0}) \sim 6 \times (n_{e0} \cdot \delta B_{||})$**
- $\delta n_e \sim 0.1 \cdot 10^{20}\ \mathrm{m}^{-3}$ $\delta B_{||} \sim 2 \cdot 10^{-3}$ T
- $n_{e0} \sim 2.5 \cdot 10^{20}\ \mathrm{m}^{-3}$ $B_{||0} \sim 3 \cdot 10^{-1}$ T

- $\delta\Psi_{int} = c_{int}\lambda \times \int dL \cdot (\delta n_e)$
- $\delta\Psi_{FR} \approx c_{FR}\lambda^2 B_{||0} \times \int dL \cdot (\delta n_e)$
- **$c_{int}\lambda \sim 300 \times c_{FR}\lambda^2 B_{||0}$**

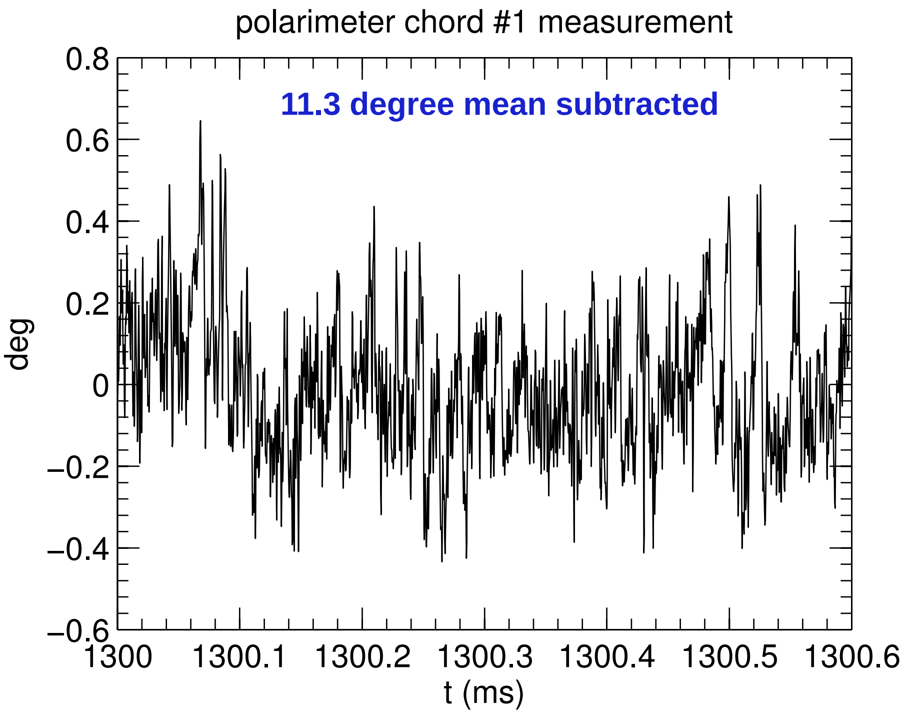
⇒ Will estimate sensitivity of Faraday rotation to interferometric contamination due to non-collinearity of two FIR paths

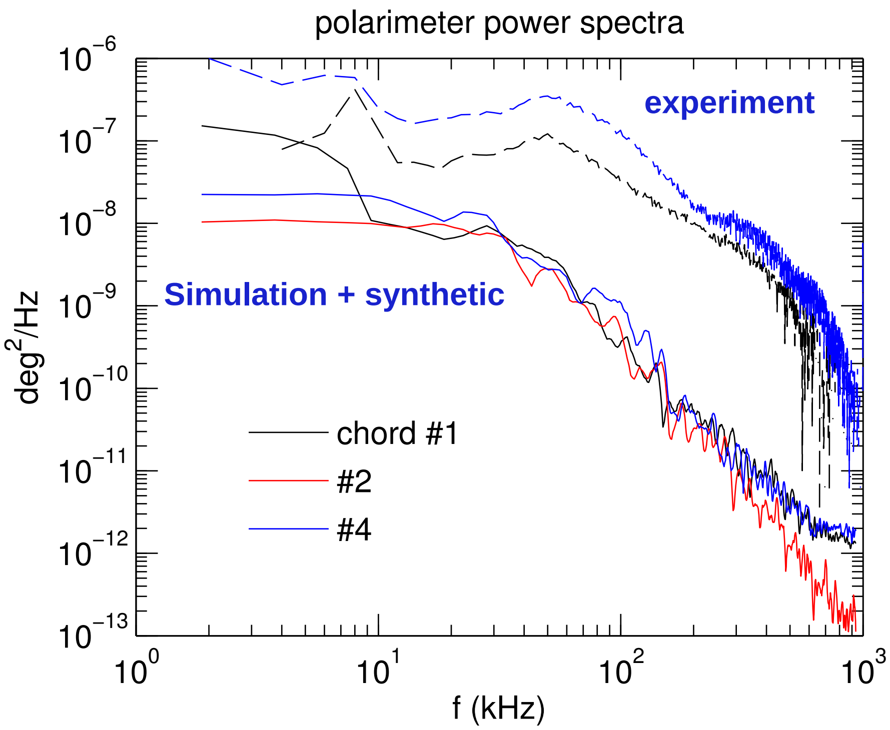

components of synthetic polarimeter signal


synthetic interferometer signals

Simulated synthetic polarimeter phase predicts Faraday rotation fluctuations ~5x smaller than experiment

- Experimental values averaged over 200 ms polarimeter signal (1250-1450 ms)
- RMS amplitude ~5x bigger than synthetic
  - rms $\delta\psi_{exp}$ = [0.14, ------ ,0.26] degrees
  - rms $\delta\psi_{syn}$ = [0.029, 0.037, 0.051] degrees
- Possible sources of error: (i) haven't matched heat fluxes (possible change in turbulence character) (ii) local, not global, simulations, (iii) not simulating edge and/or near-axis, (iv) contamination from interferometric effects, (v) …





Future work

- Complete flux-matching simulations with sufficient resolution
  - Will MTM become a more significant contributor?
- Clarify discrepancy between measured and synthetic polarimeter signal
  - If not resolved with local flux-matched simulations consider running global simulations
- Apply synthetic diagnostics for comparison with other available turbulence data (PCI, TCI and reflectometer)
- Possibly run new experiment in 2015 to obtain ion measurements (planned for 2014)