Gyrokinetic Anlysis of Turbulent Transport in Alcator C-Mod Ohmic Plasmas*

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in collaboration with

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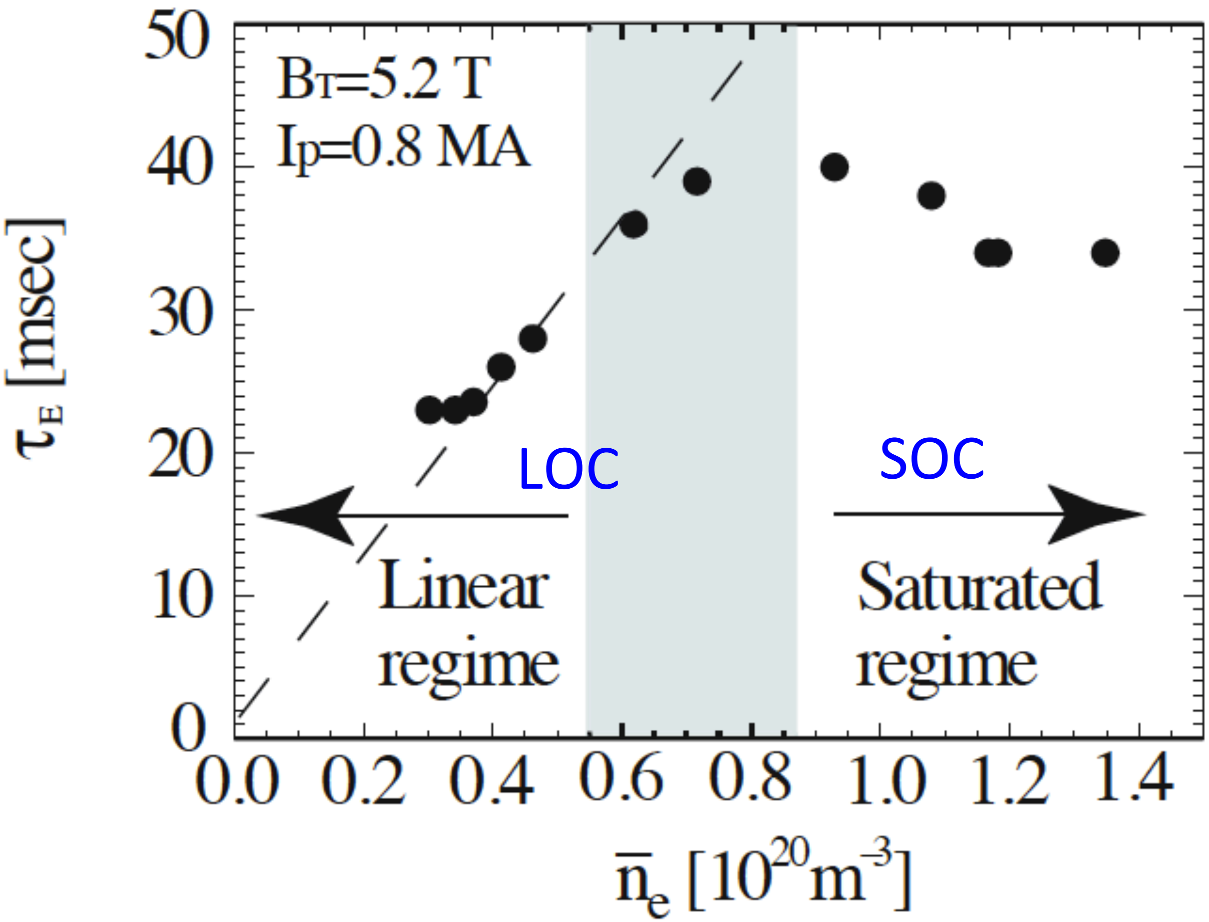
Energy confinement time in ohmically heated plasmas in tokamaks follows a linear scaling with density, followed by a saturated regime; Can gyrokinetic theory (codes) explain this result ?

Alcator C-Mod data



Outline of Talk

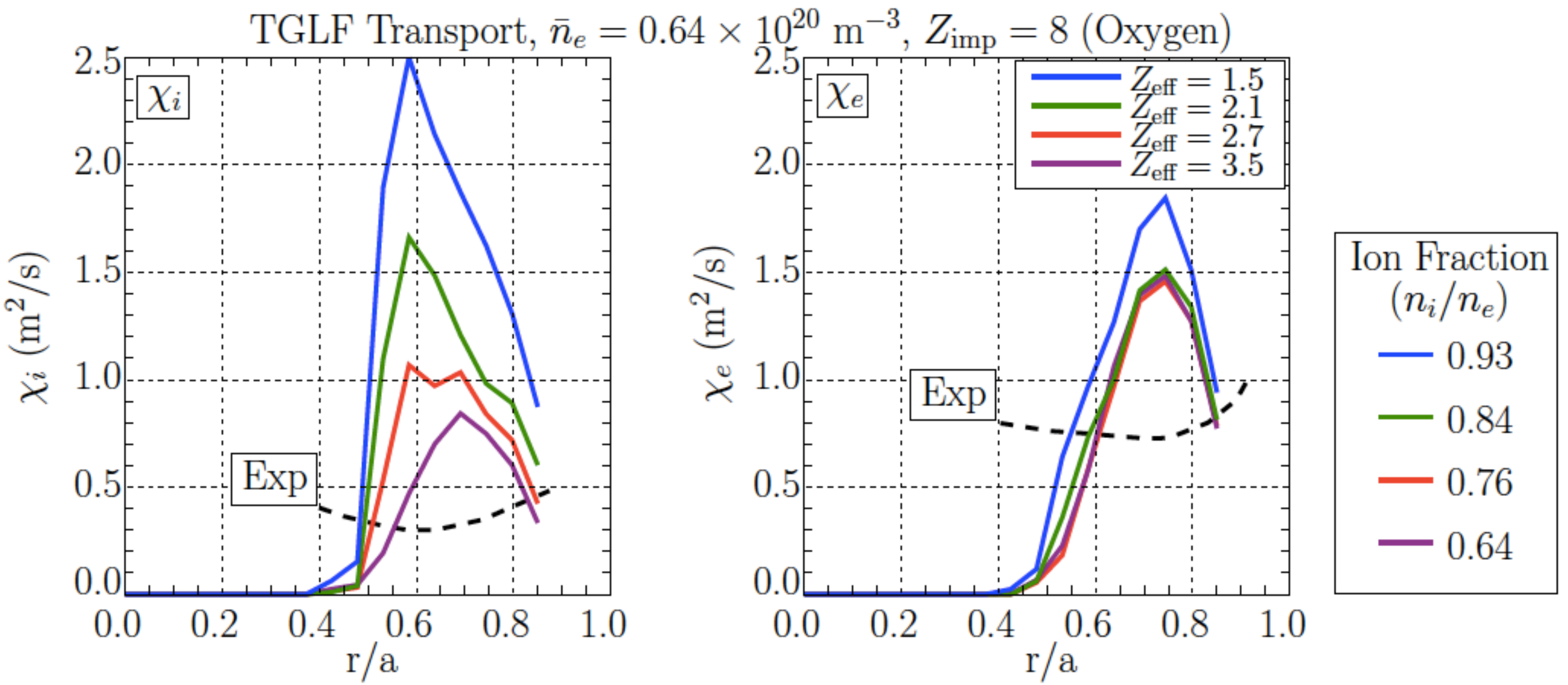
- Pre-2009 transport results in ohmic plasmas (L. Lin)
- Discovery of the importance of medium Z_i impurity ions on ion transport using TGLF
- Observation of plasma rotation and generation of E_r
- GYRO analysis of two ion species plasmas
- Measurement of the turbulent spectrum with PCI
- Impurity analysis with VUV spectroscopy
- Missing transport in the plasma core
- Conclusions

Work on C-Mod up to 2009 APS DPP meeting found disagreement between TRANSP and GYRO

- TRANSP analysis in the linear ohmic regime (LOC, where $\tau \approx n_e$, $T_i < T_e$) indicated that $\chi_i \leq \chi_e$
- However, nonlinear GYRO code simulations for the measured profiles predicted the opposite, namely $\chi_i \geq \chi_e$ (L. Lin et al, Phys Plasmas 2009, **16** 012502)
- GYRO found turbulent transport only in the strong gradient region, $0.6 < r/a < 0.8$, but no turbulence in the core ($r/a < 0.5$)
- Varying the T_i profile and its gradient up to 30 % did not help, ITG modes (and hence ion transport) remained dominant over TEM/ETG and electron transport
- Varying T_e/T_i, collisionality (Z_{eff}) or β_e did not help

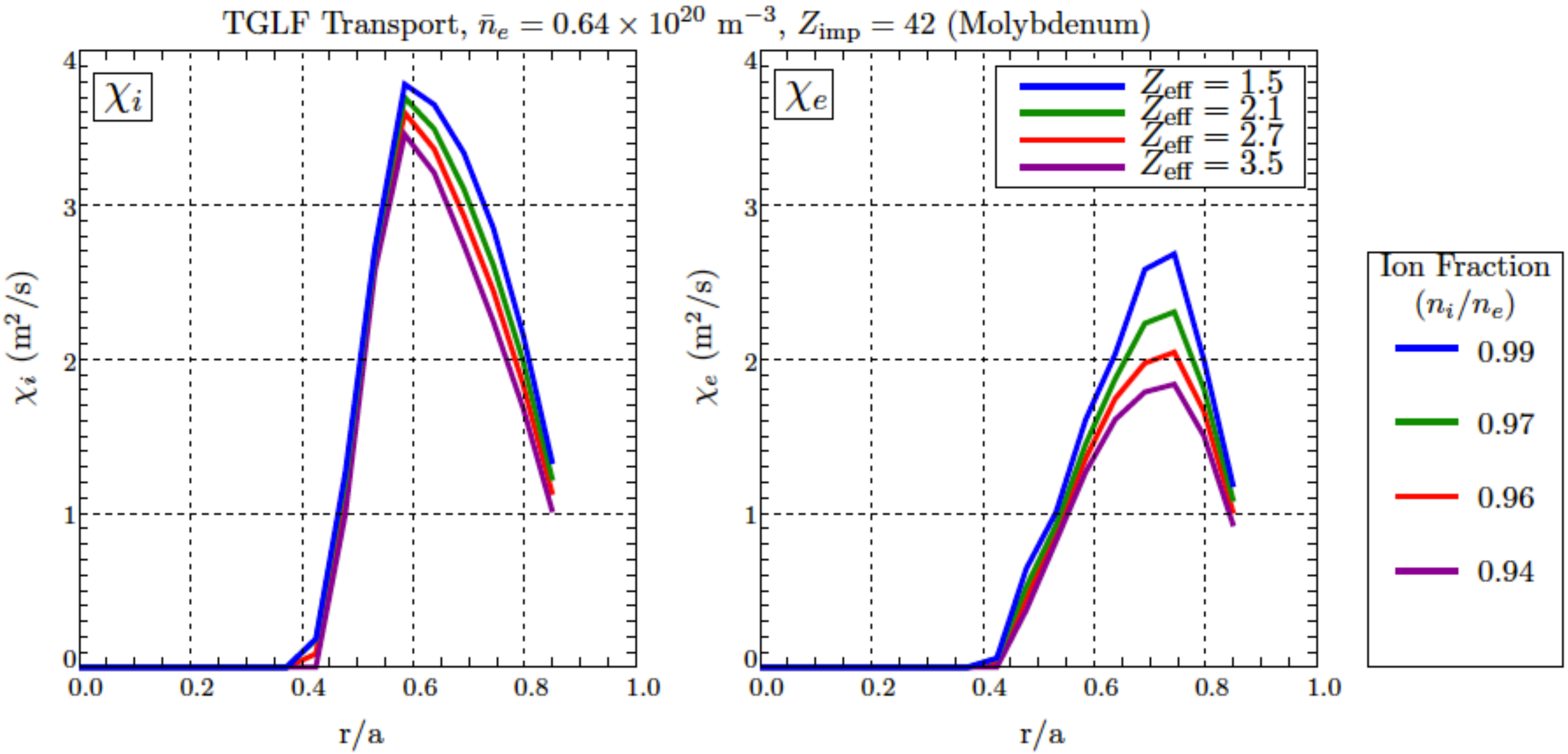
TGLF predicts χ_i to be strongly reduced with increasing Z_{eff} as long as Z_{imp} is not too high (< 10) so the main ion species is diluted; χ_e is only weakly affected

TGLF is the Trapped Gyro Landau Fluid model developed by G.M. Staebler, J. E. Kinsey and R. Waltz, Phys. Plasmas **14**, 055909 (2007)



Reduction in χ_i is due to depletion of the main ion species

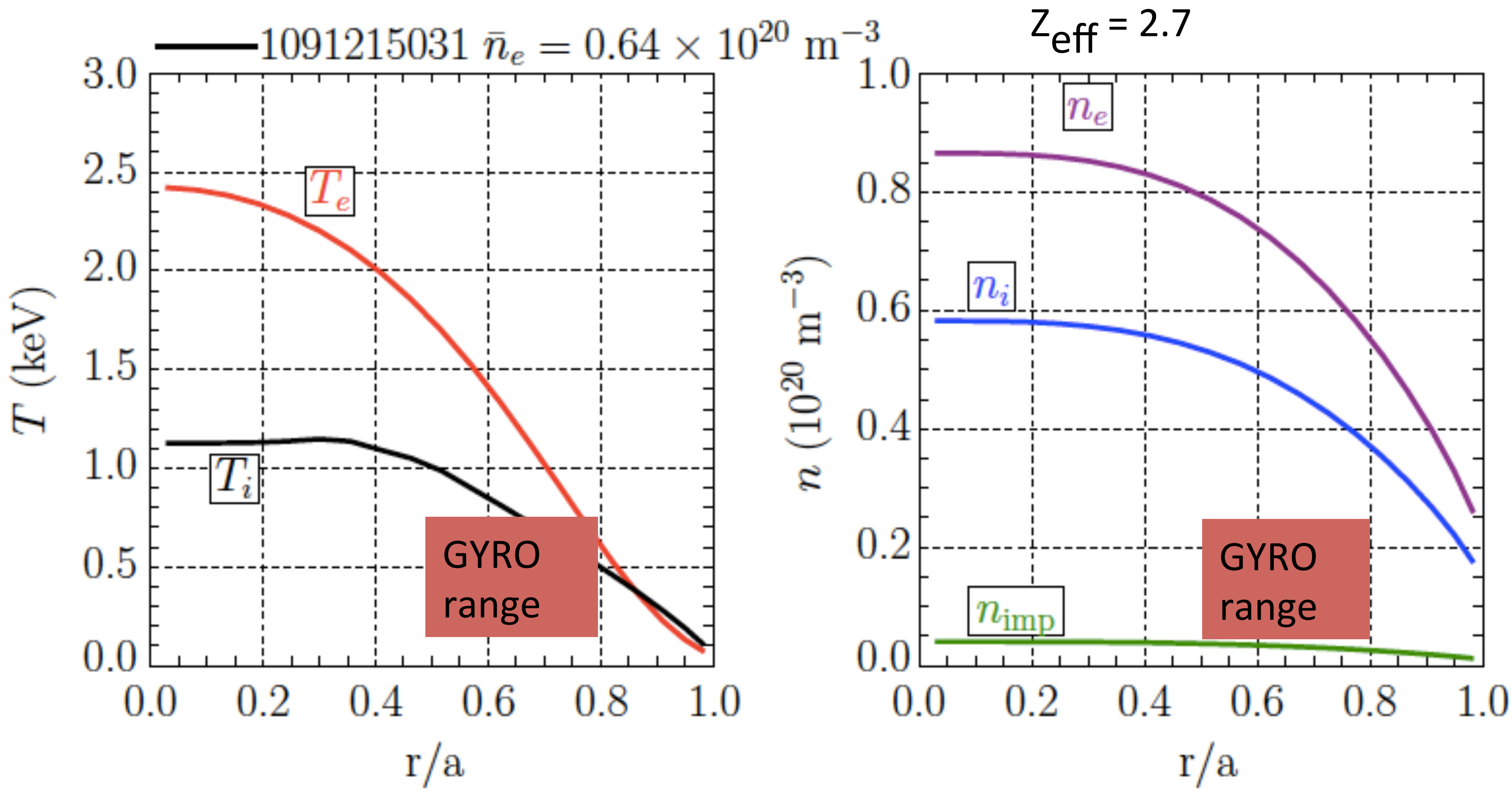
- **Molybdenum, Z=42** does not significantly reduce the TGLF predicted ion transport (χ_i), the high Z impurity does not deplete the main ion density.



- The reduction in ion transport is due to a depletion in the main ion density, not simply due to an increase in Z_{eff}

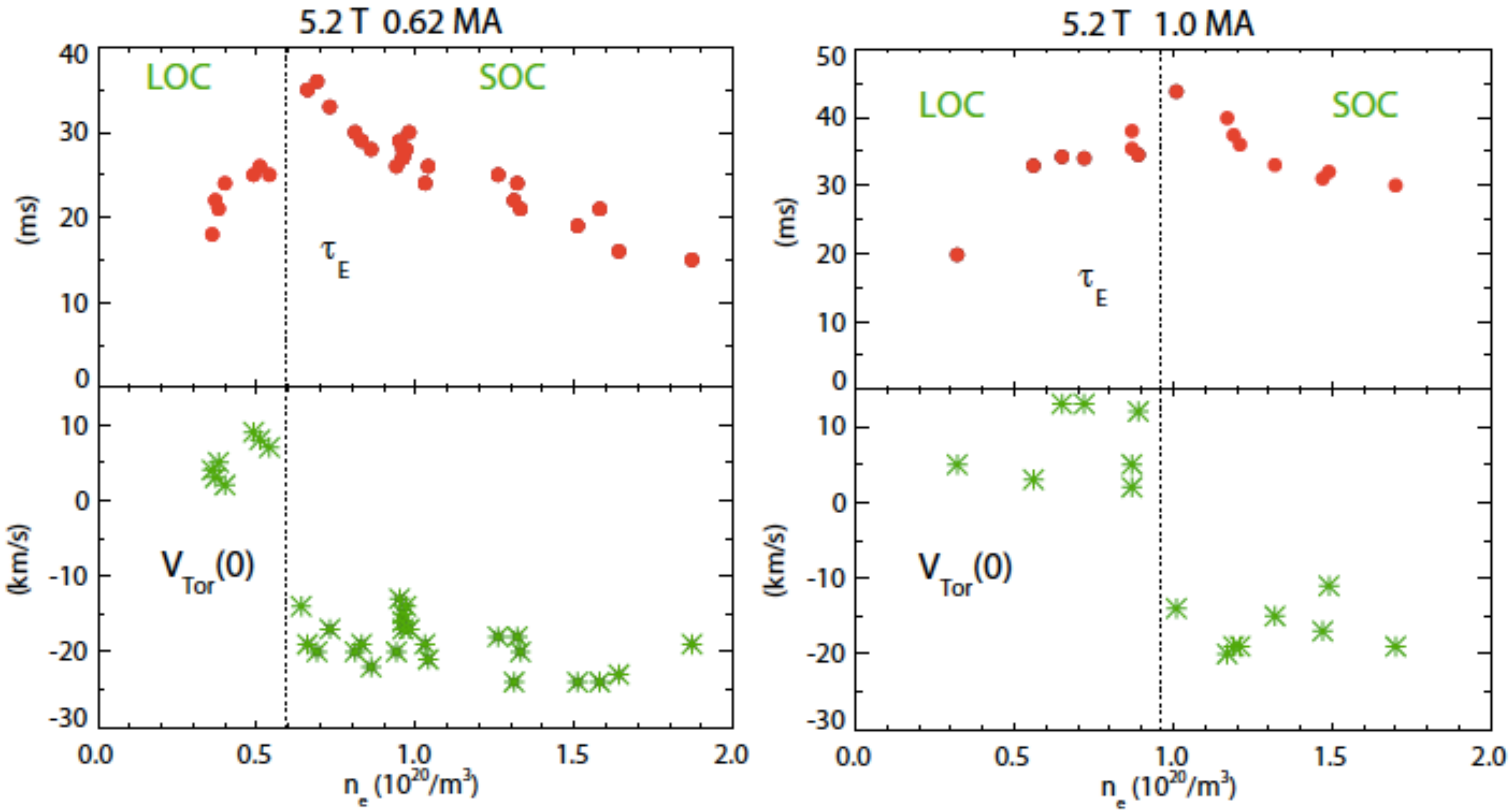
New experiments after 2009 with density and temperature profiles measured by Thomson scattering (T_e) and HIREX (T_i) find higher Z_{eff} but TRANSP and GYRO still do not agree for Z_{imp}= 12;

- Performed extensive scans with TGLF and "agreement" with experiment can be achieved if we use Z_{imp} = 8



LOC/SOC Transition Density and Rotation Reversal Density Correlated Both Increase with Plasma Current

J.E. Rice et al., Nucl. Fusion **51** (2011) 083005.



V_{Tor} gives Er;

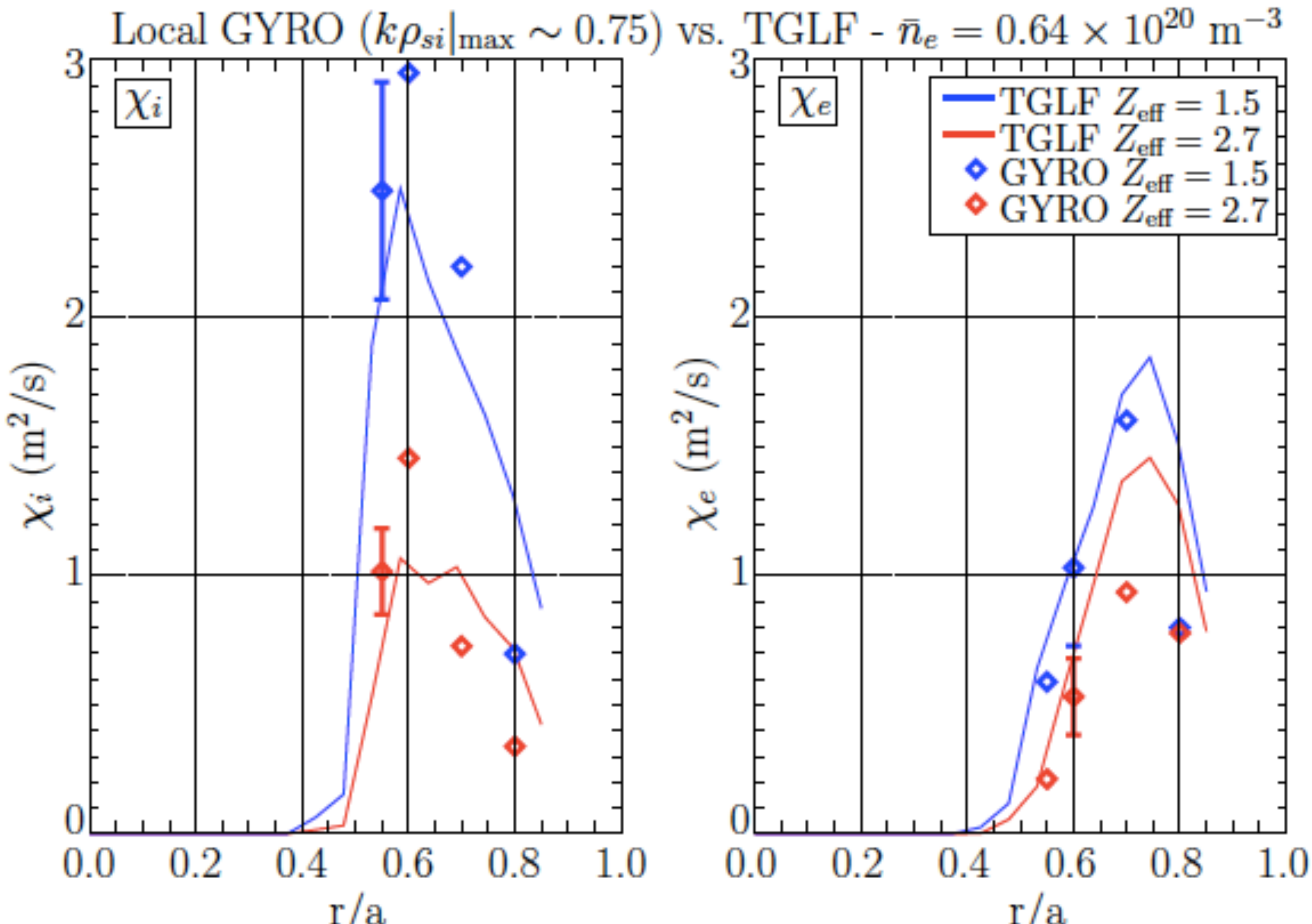
E_r localized to the core of the plasma, at r/a < 0.85

Extensive transport studies with TGLF find:

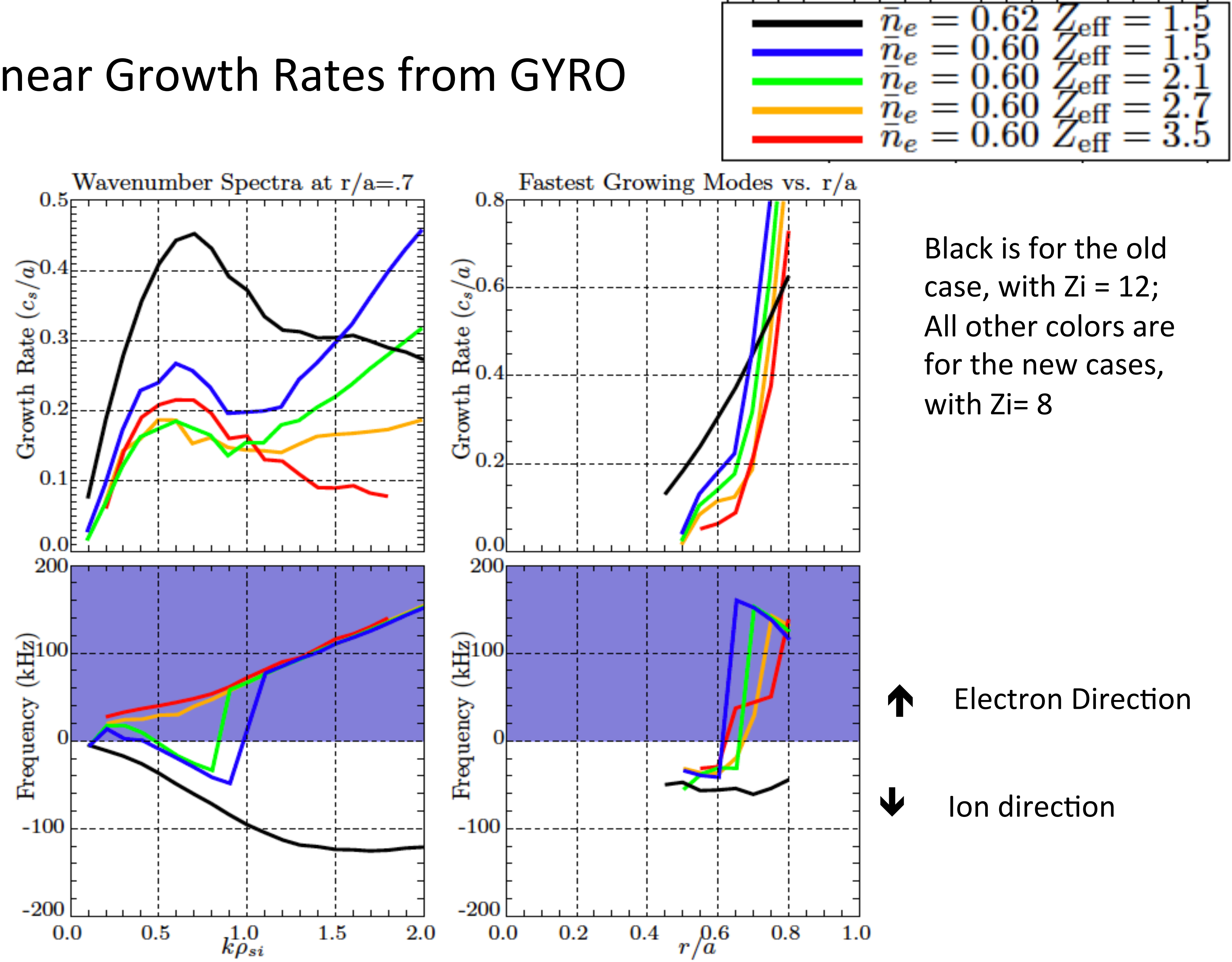
- Using an effective impurity $Z_{imp} \geq 12$ results in negligible deuteron dilution and confirms the results of Lin et al, ie, $\chi_i > \chi_e$
- Collisionality and/or T_e/T_i are not the decisive factors in determining the relative magnitudes of χ_i and χ_e
- E_r (r) (≈14 kV/m) deduced from toroidal rotation measurements has negligible effect on transport in C-Mod (ExB shear small)

- Given that in the past TGLF predicted transport was calibrated against GYRO in the ITG dominated regimes, we examined how GYRO compares with TGLF in the TEM regime
- The two codes are in reasonably good agreement, with some quantitative deviations

GYRO and TGLF are in good agreement, showing the same trend of reducing ion transport as the main ion species (deuterium) is depleted at higher Z_{eff} with moderate Z_i (=8) but both predict negligible transport for r/a < 0.5



Linear Growth Rates from GYRO

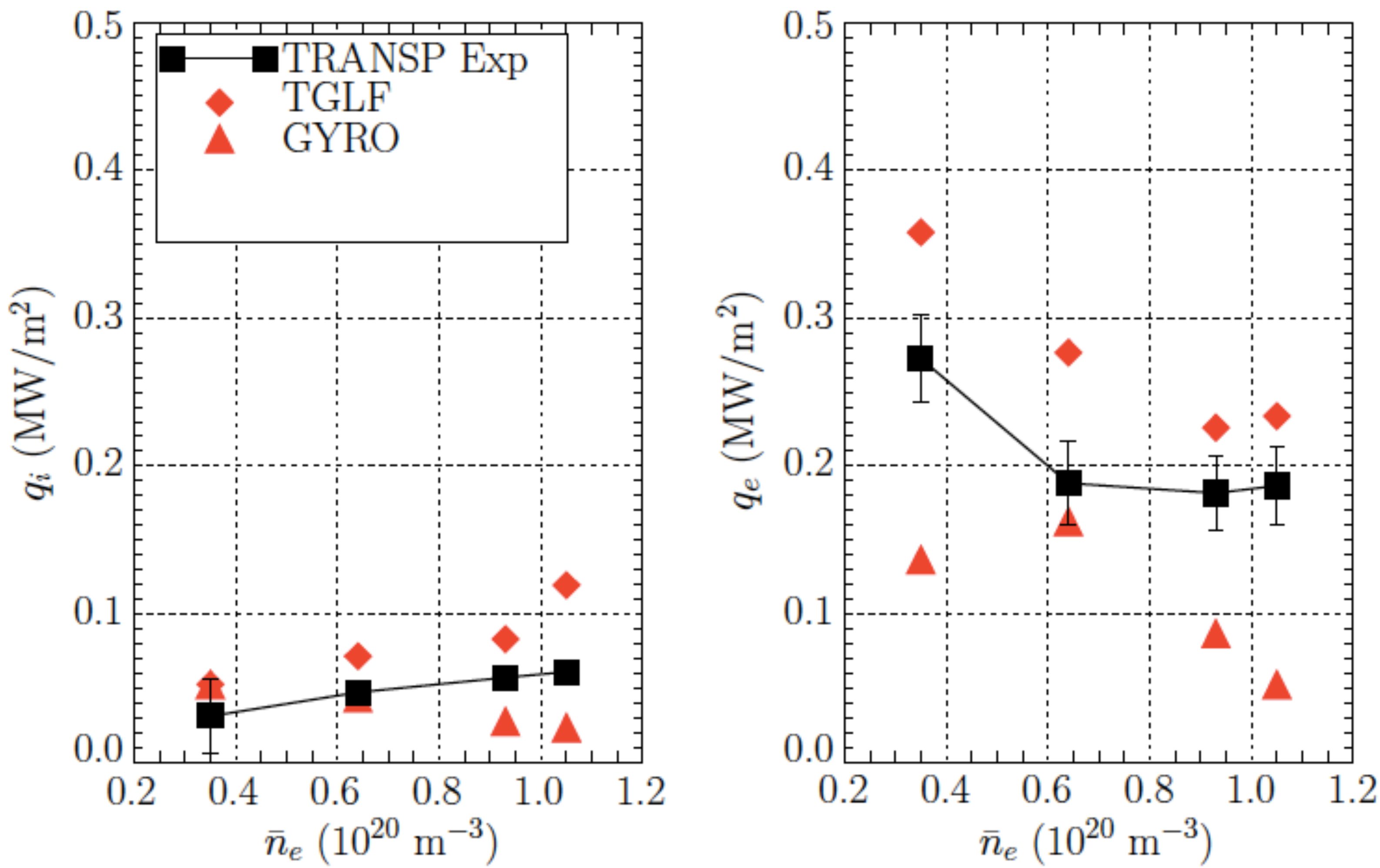


Black is for the old case, with Zi = 12; All other colors are for the new cases, with Zi= 8

↑ Electron Direction

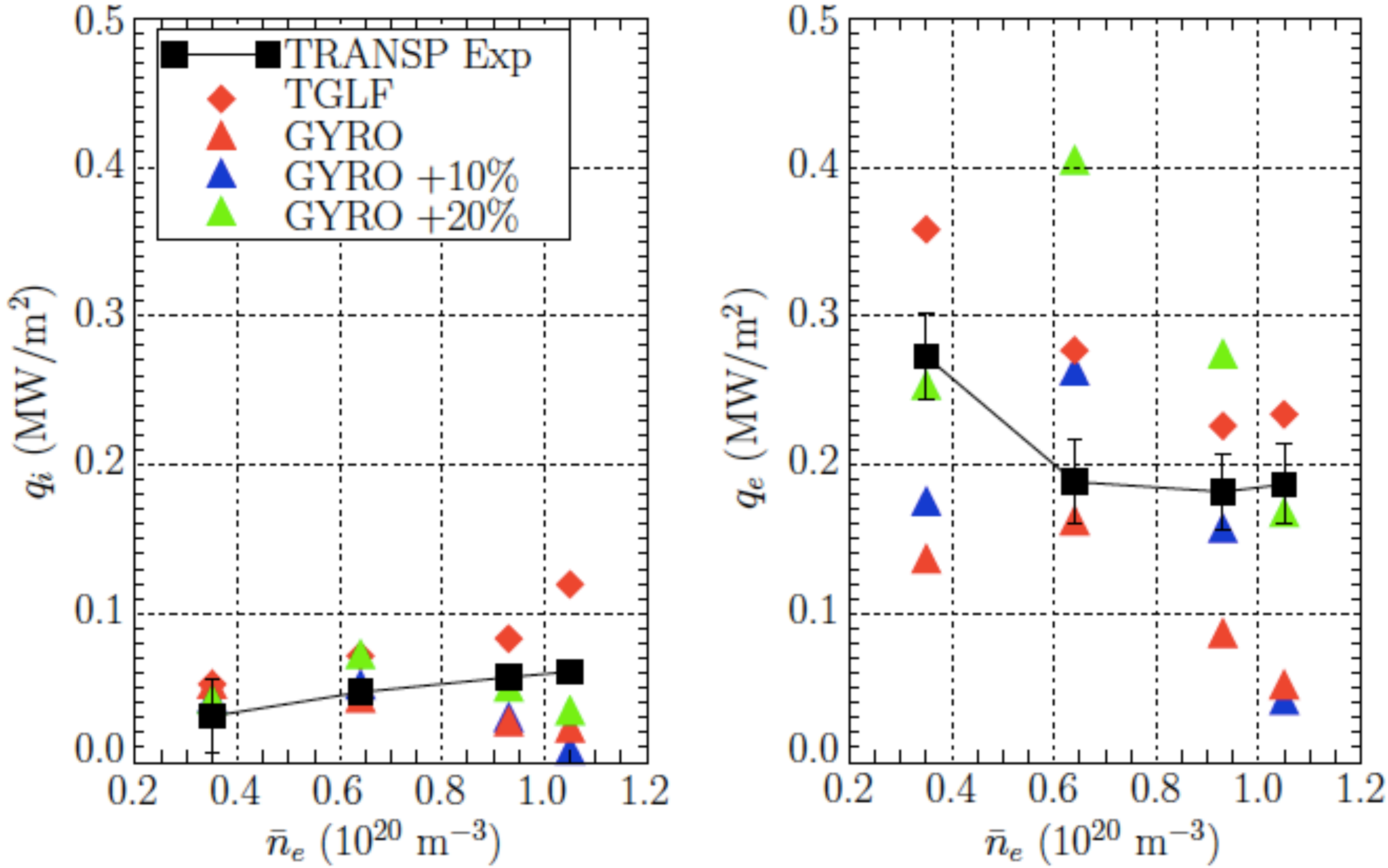
↓ Ion direction

Measured heat fluxes of ions and electrons in "reasonable" agreement with nonlinear GYRO and TGLF predictions

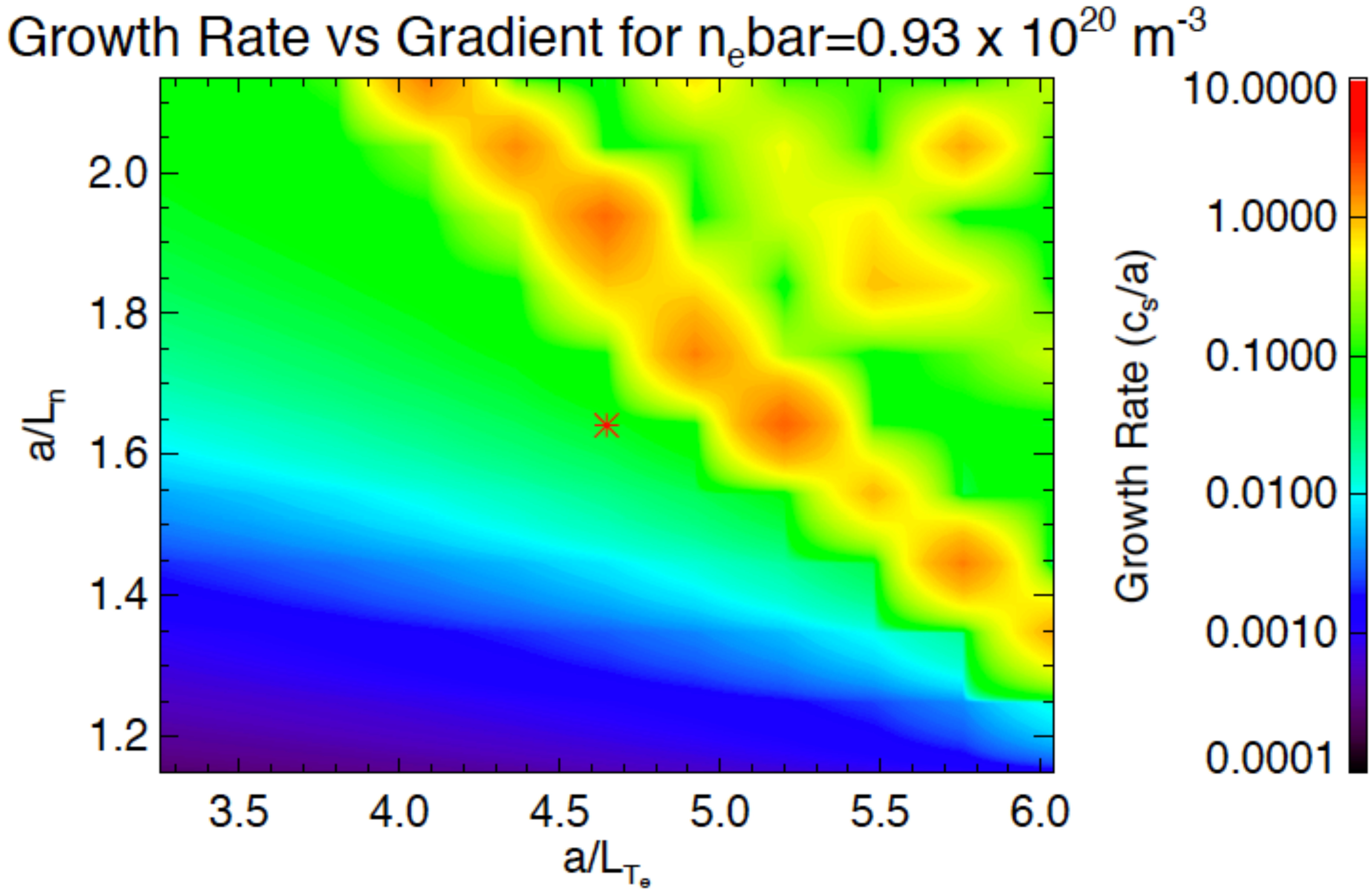


q_i, q_e correspond to r/a = 0.7, Z_i = 8, and Z_{eff} as measured

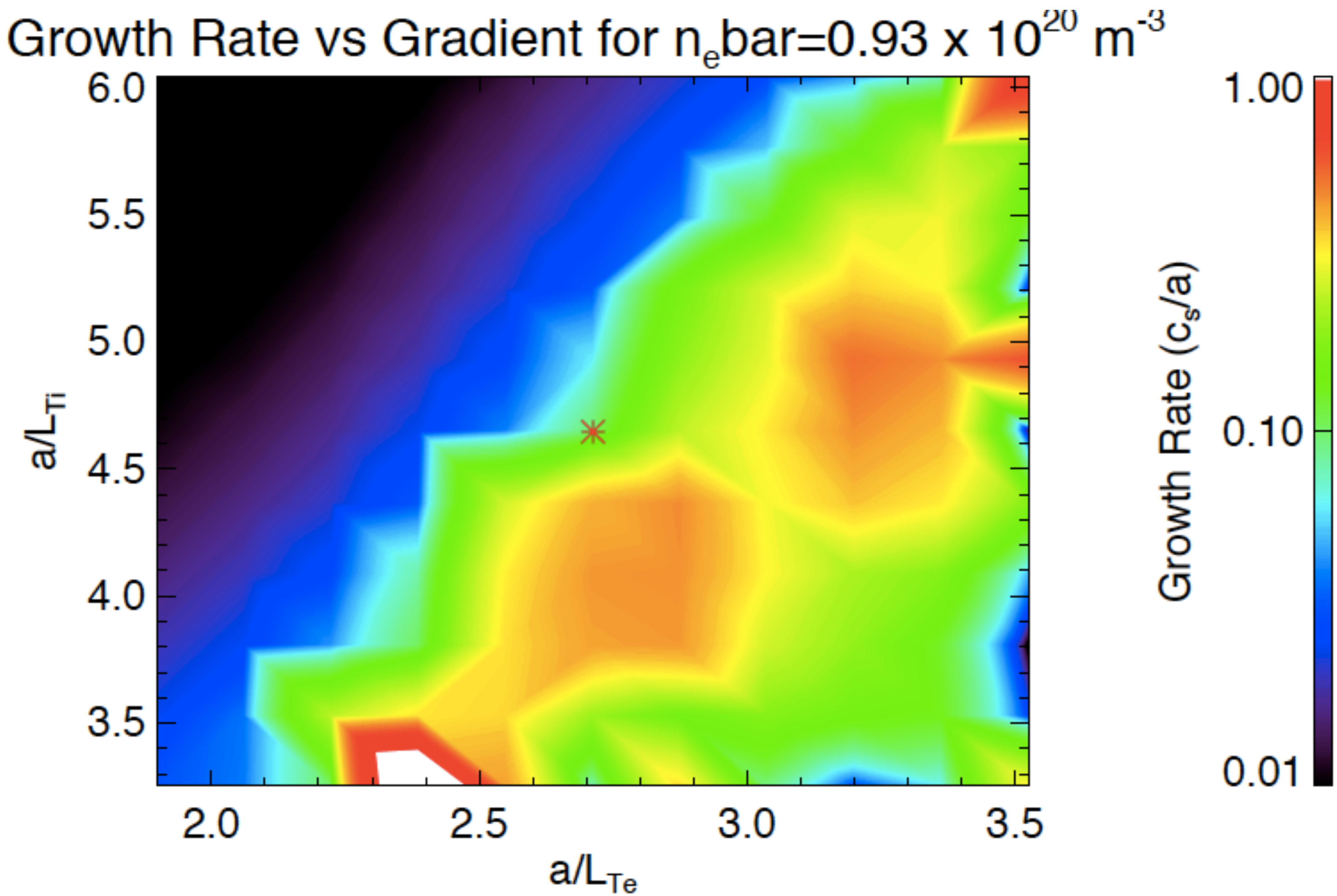
Predicted heat fluxes in good agreement with experiment if the gradients of T_e and n_e are increased in GYRO by 10 - 20% above nominal values, well within experimental error



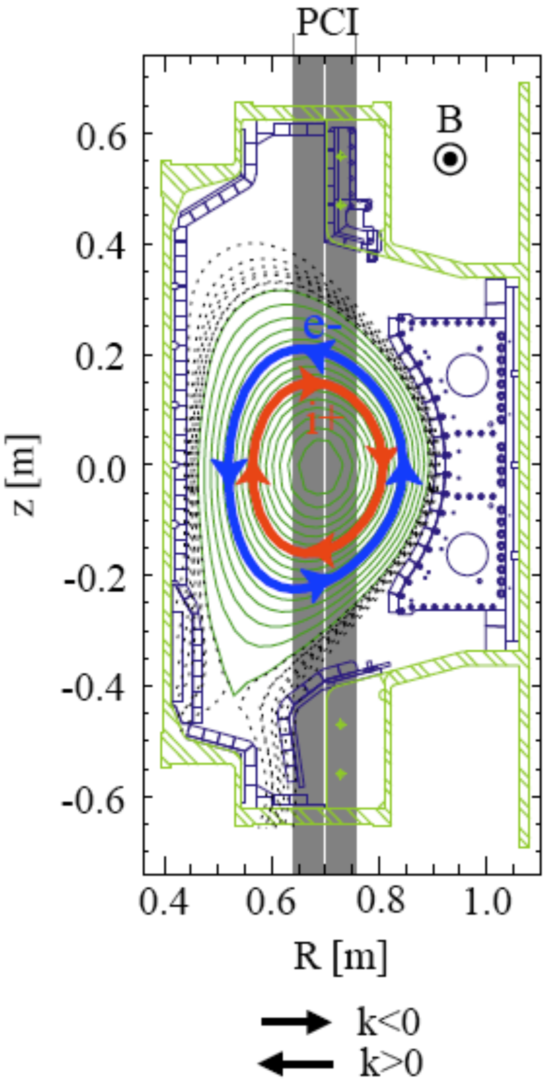
The initial values of a/L_{Te}, a/L_{ne} chosen for the base case are only marginally unstable; if increase the inverse gradients by 15 %, the linear growth rates increase by a factor of 50 and electron transport surges



$a/Ln_e = 1.65$

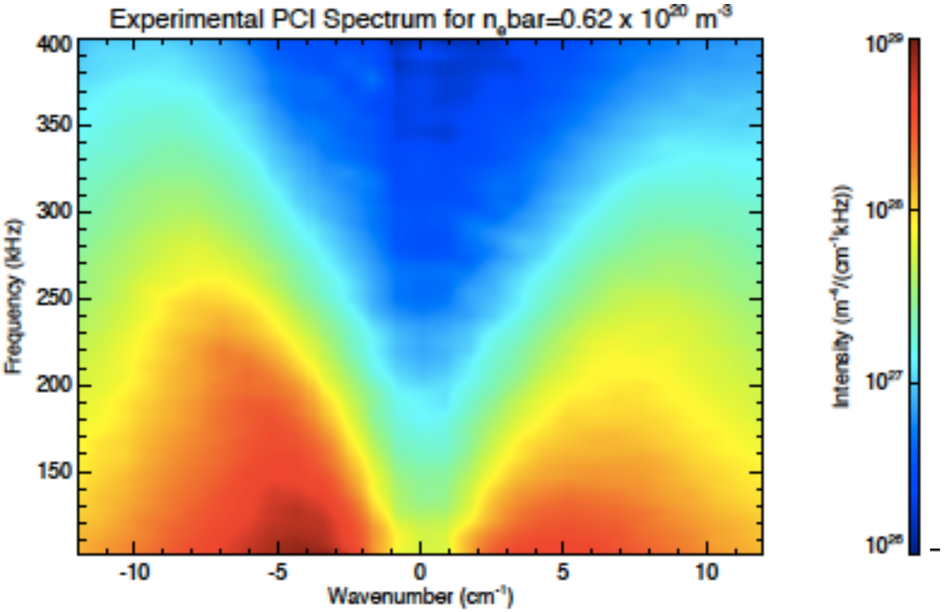

Growth Rate vs Gradient for n_ebar=0.93 x 10^20 m^-3
6.0
5.5
5.0
4.5
4.0
3.5
a/L_Ti
2.0
2.5
3.0
3.5
a/L_Te
1.00
0.10
0.01
Growth Rate (c_s/a)

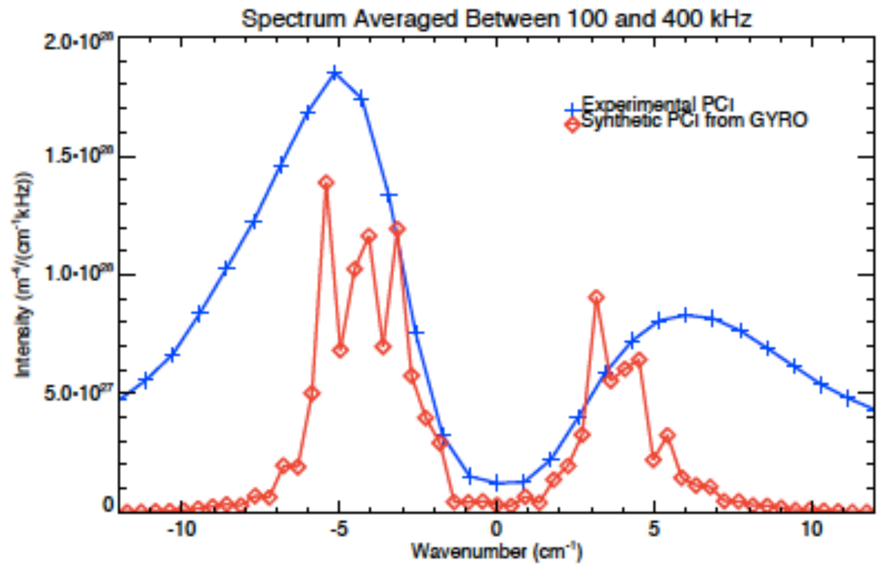
Phase Contrast Imaging (PCI) in Alcator C-Mod



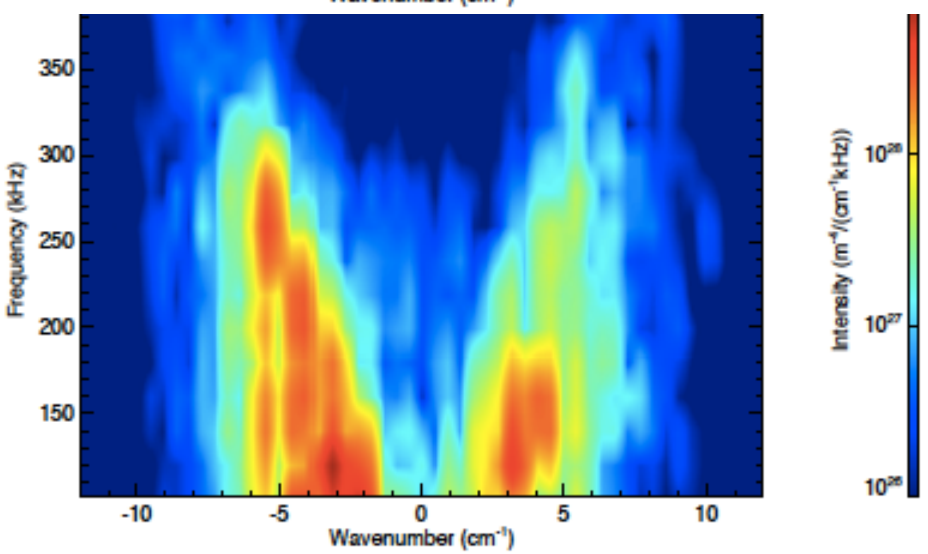
- CW, CO_2 laser
- $k_R = 1.5\text{-}16\ \mathrm{cm}^{-1}$
- $f = 5\text{-}5000$ kHz
- 32 channel HgCdTe photoconductive detector array
- Heterodyne frequency: 40-80 MHz

Experimentally measured power spectrum with Phase Contrast Imaging (PCI) in good agreement with global nonlinear GYRO as interpreted with a synthetic PCI technique



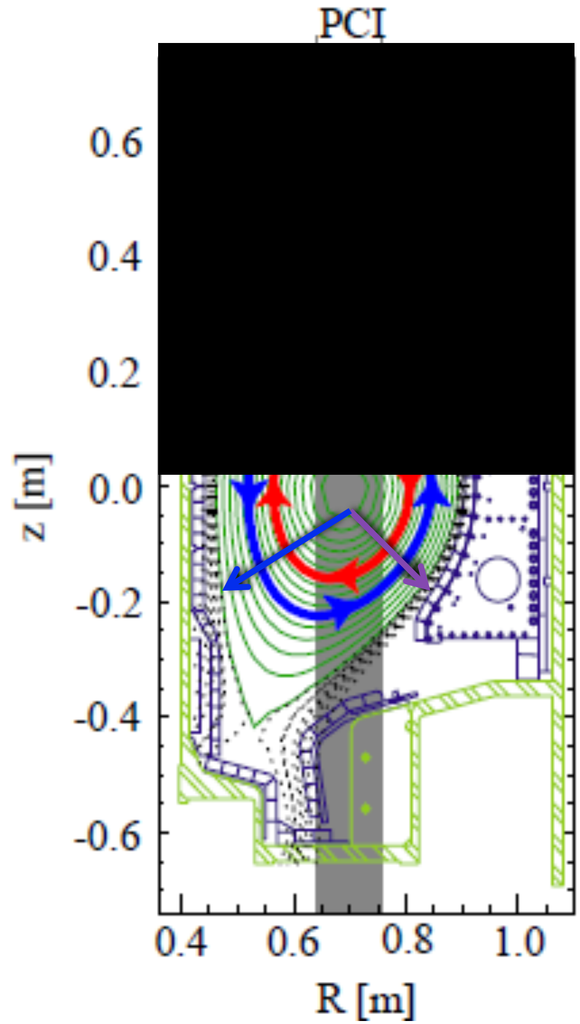


Power spectrum versus $k_\perp$ averaged over 100-300 kHz;



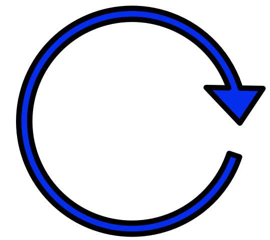
"Global "GYRO" spectrum Doppler shifted with E_r = 14 kV/m, as measured

Direction of ExB rotation may be determined by masking



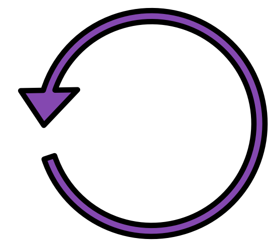
$E_r \times B_t$ || Ion Drift

In LOC $E_r > 0$



$E_r \times B_t$ || Electron Drift

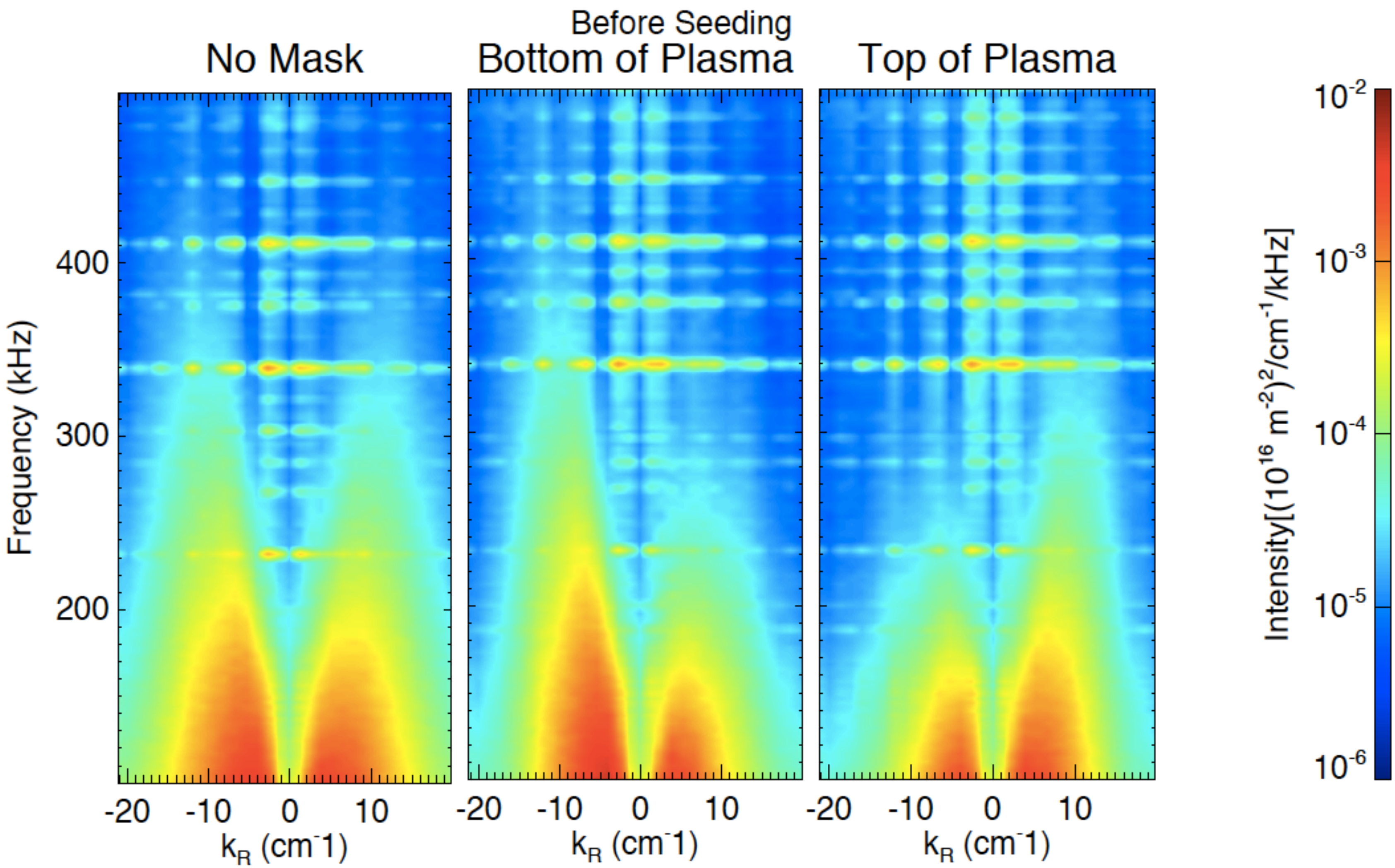
In SOC $E_r < 0$



→ $k_R > 0$ (Electron Diamagnetic Direction)

← $k_R < 0$ (Ion Diamagnetic Direction)

PCI signal after masking bottom(top) of plasma shows propagation in the E_rxB direction



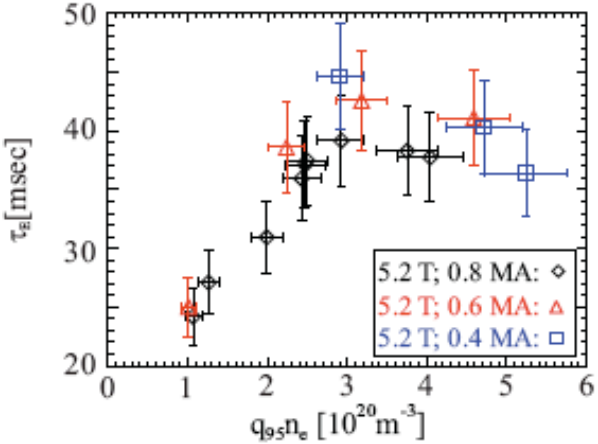
Impurity Measurements

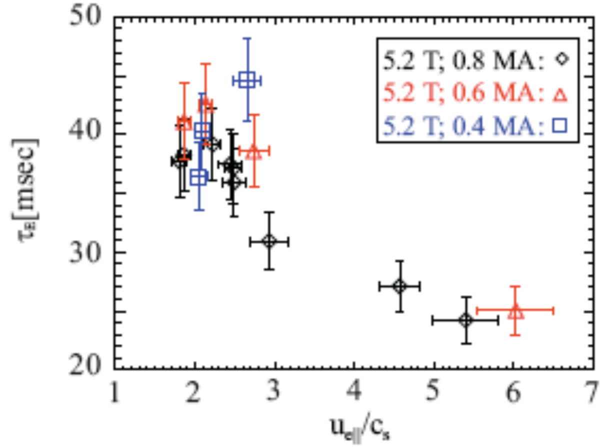
- The impurities are identified via soft X-ray (SXR) and vacuum ultraviolet (VUV) line emission (1-6 nm, and 10-30 nm, respectively)
- The calibration constants for the different impurity lines were found from the equation for Z_{eff} :

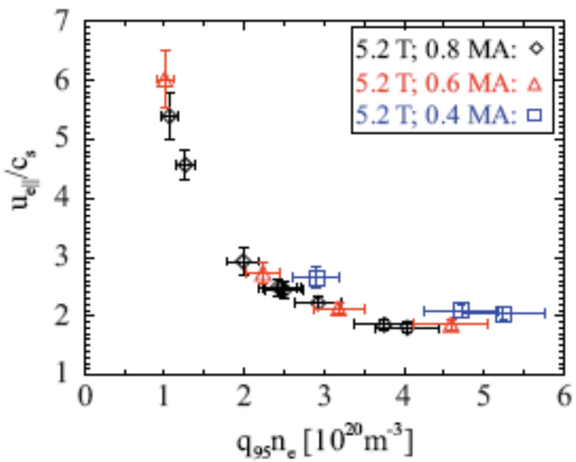
$$Z_{eff} = 1 + \sum_{species} \frac{Z_i \times (Z_i - 1)}{n_e} \times (\text{Brightness}) \times (\text{Calibration Constant})$$

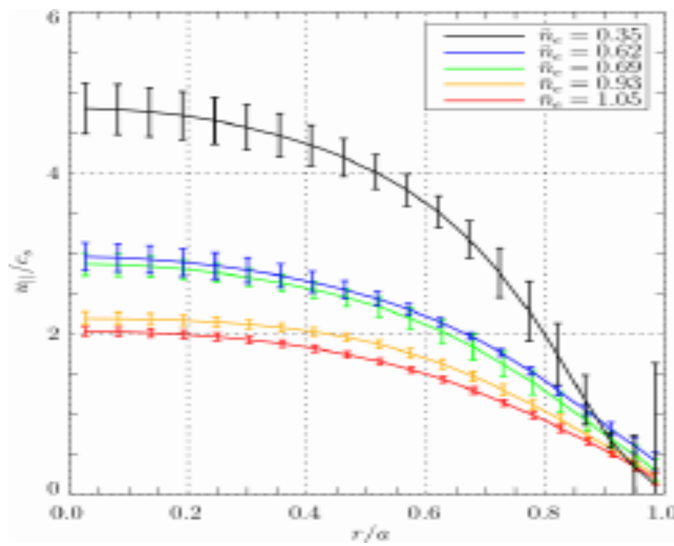
- Z_{eff} was inferred from neoclassical resistivity when one impurity dominated
- An effective Zi = 9.1-9.7 was found at different densities
- Experiments were also performed by injecting impurity gases (N_2) and Zi = 8.1-8.7 was obtained with increased dilution

Core confinement issues: as the density increases the ohmic electron drift speed decreases to c_s in the saturated confinement regime









- ***Do current driven drift waves play a role in the plasma core ?***
- ***Or perhaps current gradient driven modes ? Or mild sawteeth ?***

Summary

- After extensive analysis with TGLF/GYRO we find that in the LOC regime, using an "effective" impurity ion species $Z_i \approx 8$, electron modes (TEM), rather than ITG modes dominate as a result of significant (up to 35 %) dilution of the main ion species (deuterons)
- In agreement with experiment, electron thermal diffusivities and heat fluxes dominate over those of ions in the radial range r/a= 0.5 - 0.8
- The fluctuation spectrum intensity measured with Phase Contrast Imaging is in reasonable agreement with synthetic PCI predictions from global GYRO; E_r shear is not important for stability calculations
- In the inner plasma core ($r/a < 0.5$) transport predicted by TGLF/GYRO is too small relative to experimental values; potential candidates for enhanced transport may be current driven drift waves ($U_{\|}/C_S$ = 2-5) or mild sawtooth activity, and hence we still do not fully understand the variation of energy confinement with n_e or qn_e