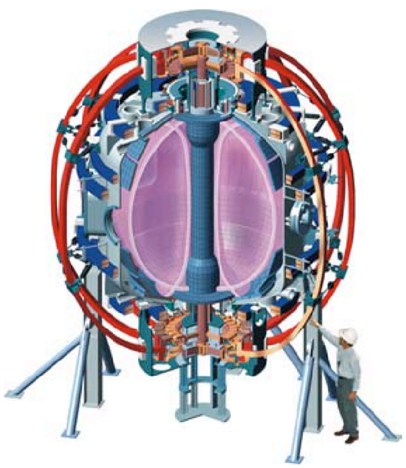
Supported by

Gyrokinetic simulations of turbulence in NSTX

D. R. Mikkelsen, R. E. Bell, S. M. Kaye,
B. P. LeBlanc, PPPL
D. Stutman, Johns Hopkins University,
J. Candy, R.E. Waltz, General Atomics,
S. Kubota, N. A. Crocker, W. A. Peebles, UCLA



APS/DPP Annual Meeting
15 - 19 November, 2004; Savannah

Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
NYU
ORNL
PPPL
PSI
SNL
UC Davis
UC Irvine
UCLA
UCSD
U Maryland
U New Mexico
U Rochester
U Washington
U Wisconsin
Culham Sci Ctr
Hiroshima U
HIST
Kyushu Tokai U
Niigata U
Tsukuba U
U Tokyo
JAERI
Ioffe Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
U Quebec

Overview

ExB shear stabilization of low-k modes is expected in spherical tokamaks.

But application of linear ExB "quench rule" is of questionable validity:
"*We cannot be confident of these modifications and limitations on the quenching condition for general profiles at finite ρ^* without nonlinear simulations. These cannot be done with the fast flux tube codes and require three dimensional (3-D) full radius codes …*"
Waltz, et al., Phys. Plasmas 5 (1998) 1784.

Nonlinear turbulence simulations (GYRO) reported here show:

1) Sheared flows play a very important stabilizing role, but they do not completely stabilize the low-k turbulence. The residual low-k turbulent transport is large.

2) Kinetic electron drive is more important than 'pure' ITG drive.

Introduction

Kotschenreuther and Rewoldt – using model profiles – generally found the linear ExB quench rule is satisfied for low-k modes in STs.
Clarisse Bourdelle – using experimental profiles – found that $\gamma_{ExB} > \gamma_{linear}$ is indeed common for low-k modes in NSTX plasmas.

Bourdelle also found that ETG modes are generally unstable in NSTX.
ETG transport may play an important role in NSTX, but
nonlinear simulations are *very* difficult, and
no high-k diagnostics are available yet.
Deeper study of ETG modes has been deferred.

UCLA group has several reflectometers on NSTX (see Kubota's poster).
They measured $<\tilde{n}/n>$, and $<\Delta r>_{corr}$ in the plasma core.
These will (eventually) be compared to GYRO turbulence simulations.

With *complete* data sets including fluctuation measurements we can test whether predicted power flows *and* turbulence amplitudes *and* radial correlation lengths can *all* be matched.

Experimental Constraints

Turbulence simulations of the core are more tractable than at the edge:
edge scale lengths ~ρ_i , so the basic equations are not valid there.

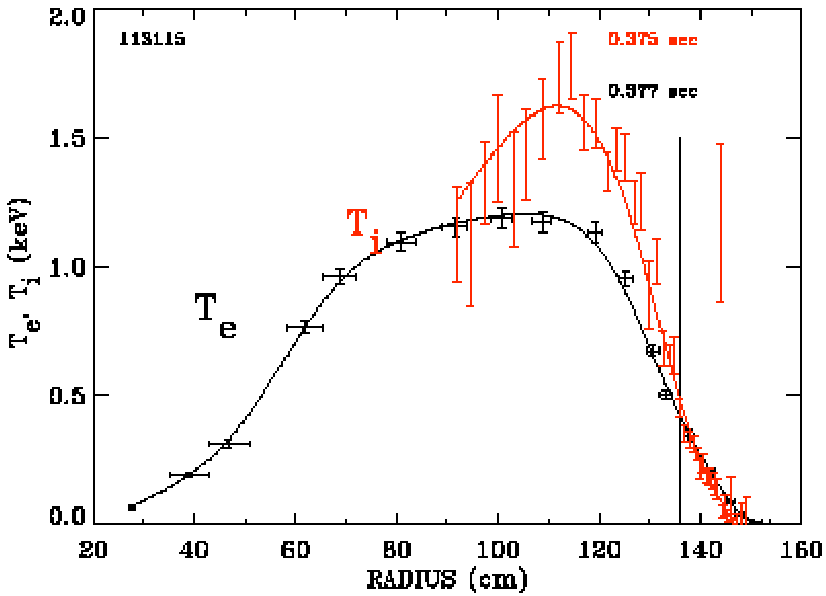
Need fluctuation data combined with transport analysis for definitive test:
Simulations depend on uncertain inputs, so predictions are uncertain.
When predicted power flow matches expt., do fluctuations match, too?

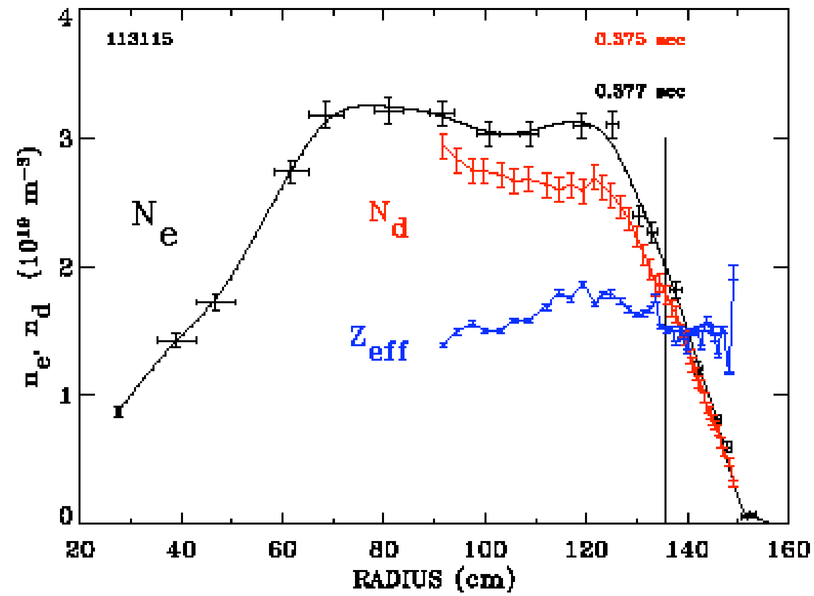
The NSTX reflectometers are based on wave reflection where $\omega = \omega_{pe}$
The density range for NSTX reflectometer operation is $1\text{-}3\times10^{19}$ /m^3 .
In most NSTX plasmas $n_e = 1\text{-}3\times10^{19}$ /m^3 occurs in the pedestal region,

Microwave beam cannot reach the interior of a hollow density profile, so
reflectometry needs a lower density, *peaked* density profile.
H-mode density profiles are often hollow or flat inside the pedestal.

Avoid MHD, it can produce more scattering than the turbulence.
Minimize MHD with low NBI power (fast-ion driven MHD common).
Need some NBI for diagnostics that measure T_i, Z_{eff}, and MSE.

Simple Profile Shapes



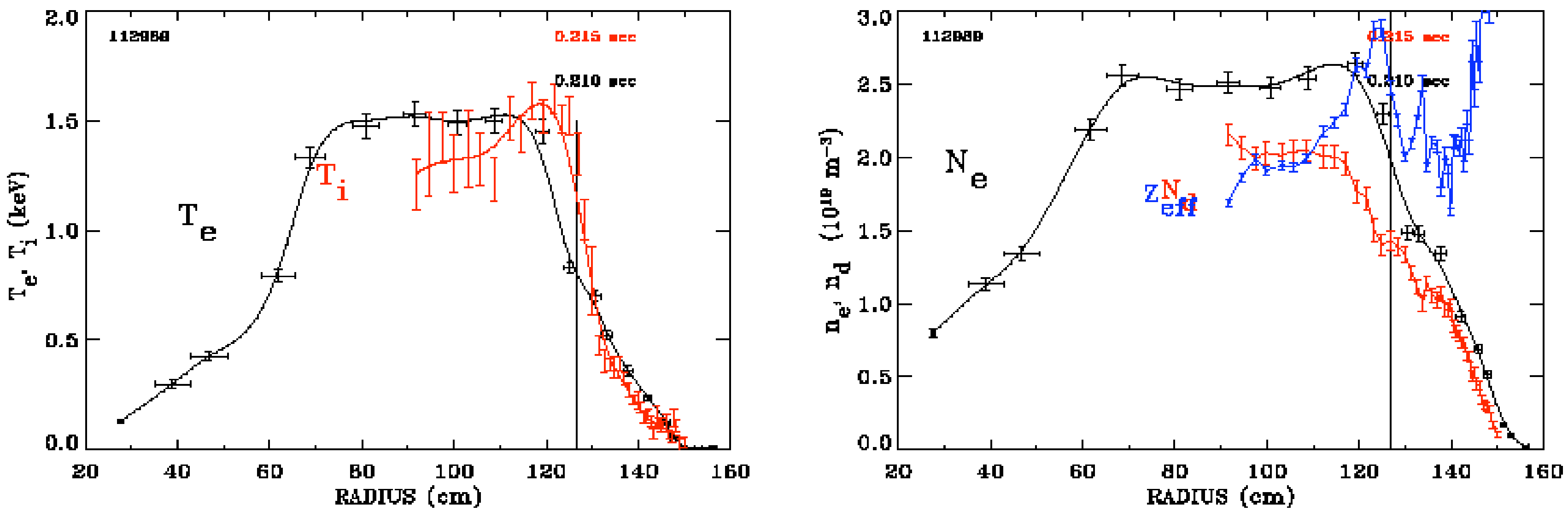


$T_i \sim T_e$ at the reflectometer radius.

Cleaner than average correlation signal.

Moderate v_{tor} rotational shear.

Very steep T_e and T_i



Possible ITBs are seen transiently (50 msec).

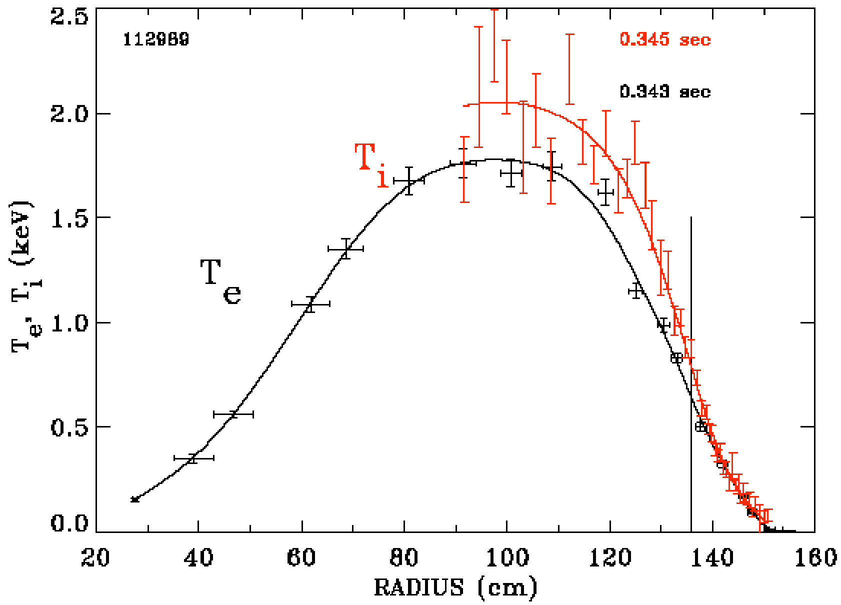
May be associated with reversed shear.

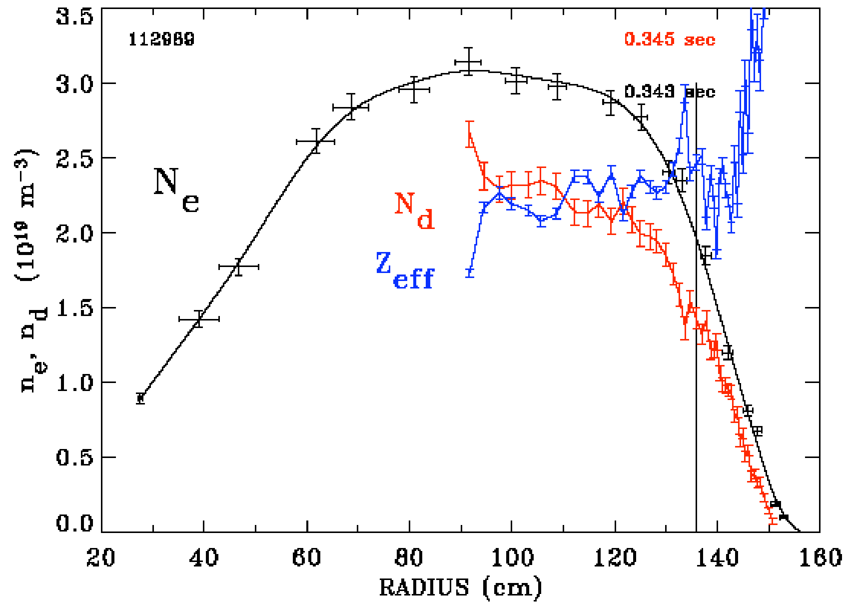
Strong temperature gradient drive for instabilities.

Has much stronger shearing of v_{tor}, too.

See Dan Stutman presentation NI1.001 on Thursday morning.

Simple Shape, but Hotter



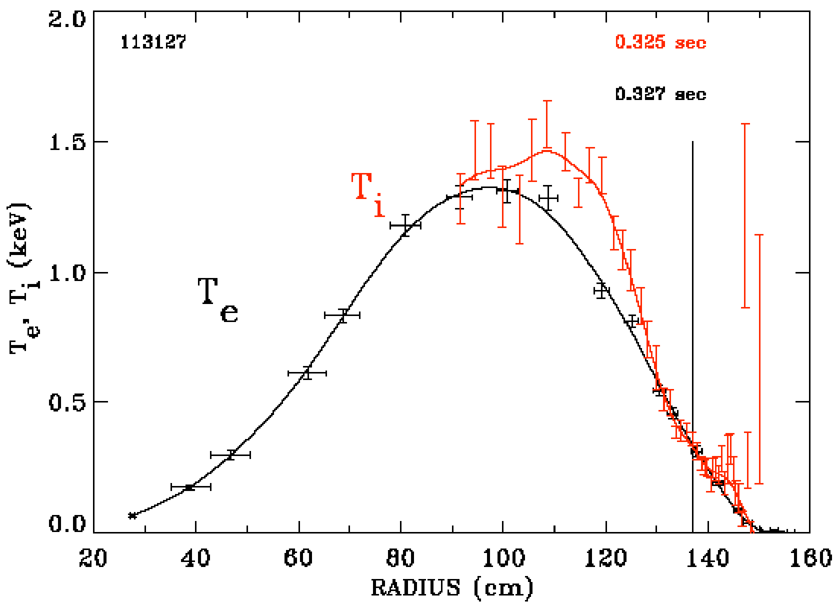


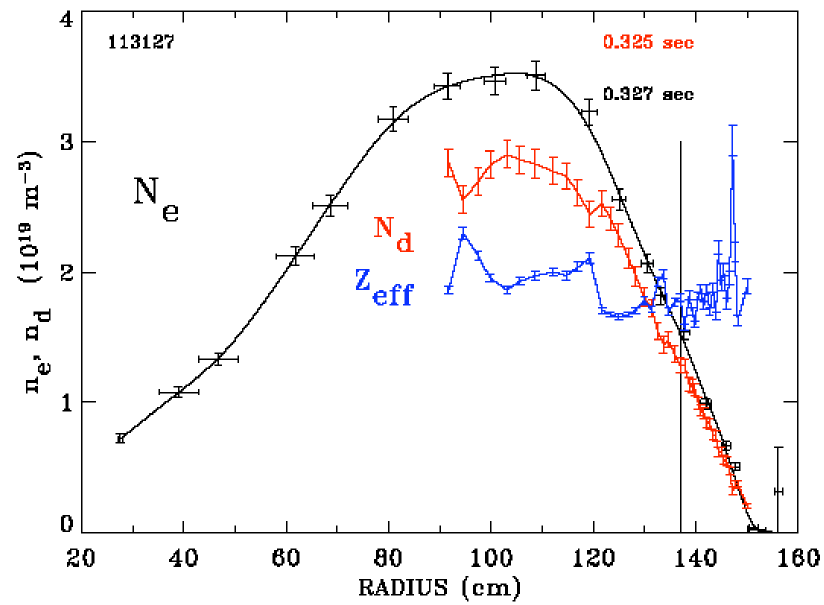
Later in ITB shot - looks 'normal' now.

Hotter than 113115, closer to marginal stability?

More v_{tor} shear than the other non-ITB cases.

Best <ñ/n> measurements





Has a relatively low v_{tor} shear.

<ñ/n> measurements at n_e = 3, 2.2, 1.1 x10^{19} /m^3.

Correlation measurement at n_e = 1.5 x10^{19} /m^3.

Important Issues for Turbulence Simulations

A 'full radius' simulation is required to include profile effects.
Parameters vary significantly in a radial domain of 50 ρ_i .
Flux tube simulation is not appropriate for low-k modes.

It is necessary to include the background ExB sheared flows,
these are expected to be a major stabilizing factor.

Kinetic electron effects enhance ITG mode turbulence,
so a non-adiabatic electron model is needed.
Need to model electron collisions, which are stabilizing.
TEM effects are significant in most tokamak plasmas,
but they are more important that usual in these simulations.

NSTX is highly shaped, with very low aspect ratio.
Need realistic geometry, not high-aspect ratio s-α model.

β~10% is low for NSTX, begin with electrostatic simulations.
Electromagnetic effects are important in higher β NSTX plasmas.

GYRO Overview

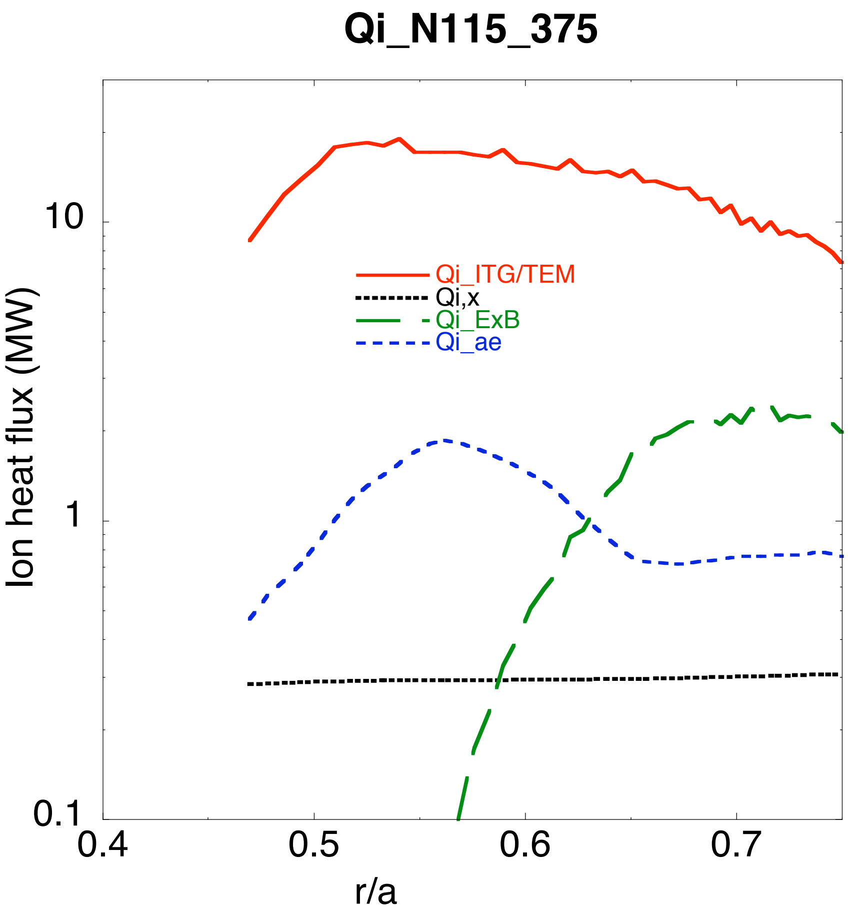
- Global gyrokinetic code GYRO contains all physics of low frequency (<< ion cyclotron) plasma turbulence assuming only that the ion gyroradius is less than magnetic field gradient length
  - Nonlinear and basic ITG with adiabatic electrons
  - Electrons (trapped and passing) electromagnetic and finite β
  - Collisions
  - Real tokamak geometry
  - Finite ρ^*
- Continuum (fluid-like) methods in 5-dimensional space $(r, \theta, n, \varepsilon, \lambda)$
- 2-modes of operation:
  - flux-tube with cyclic boundary conditions
    to be compared with Dorland 's gyrokinetic flux tube code GS2 effectively $\rho^* \to 0$
    No ExB or profile effects but otherwise identical physics and capability
  - full radius or wedge -tube with non-cyclic BC and Δn=5-10 ρ^* small but finite
- Why global full radius? Shear in the ExB velocity known to have a powerful stabilizing effect.
  But shear in the diamagnetic velocity can be just as large and cannot be treated at $\rho^* = 0$.
  Flux-tube codes at $\rho^* \to 0$ have only gyroBohm scaling and no non-local effects.

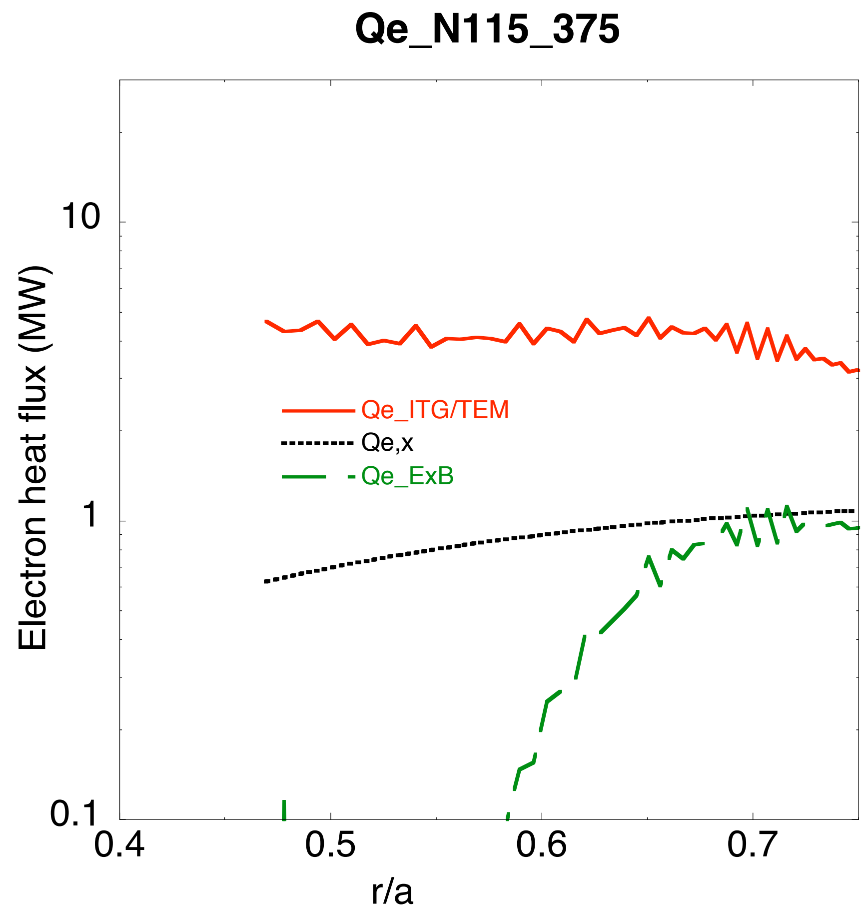
Preparation of experimental profile data

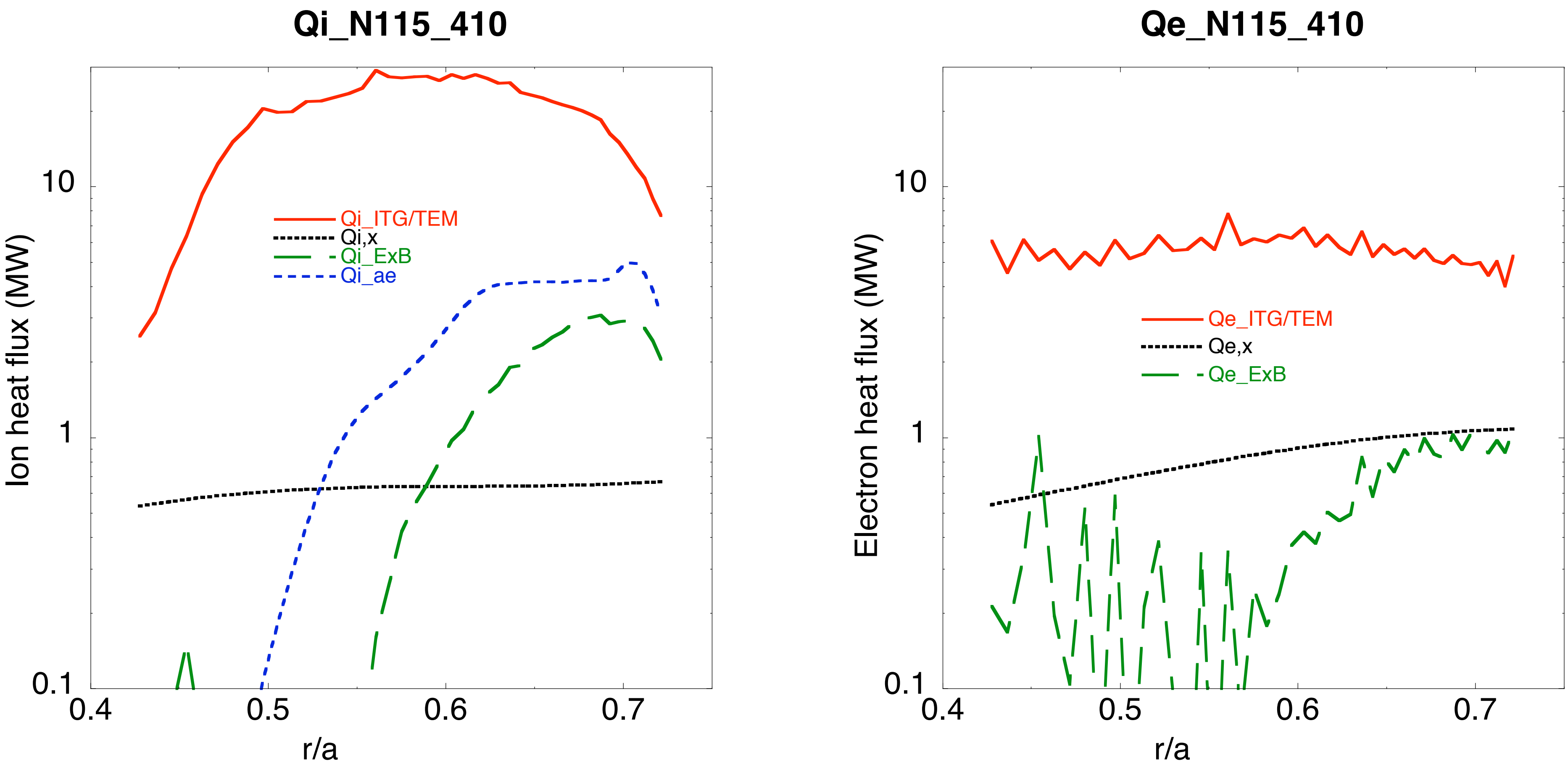
Map profile data from R to r/a with TRANSP.
Use TRANSP calculation of the magnetic equilibrium for the map.
Used "outer side only" mapping of density and temperature.
 this guarantees that n_e, T_i, T_e at same R map to same r.
 "slice and stack" generally does not map to same r.

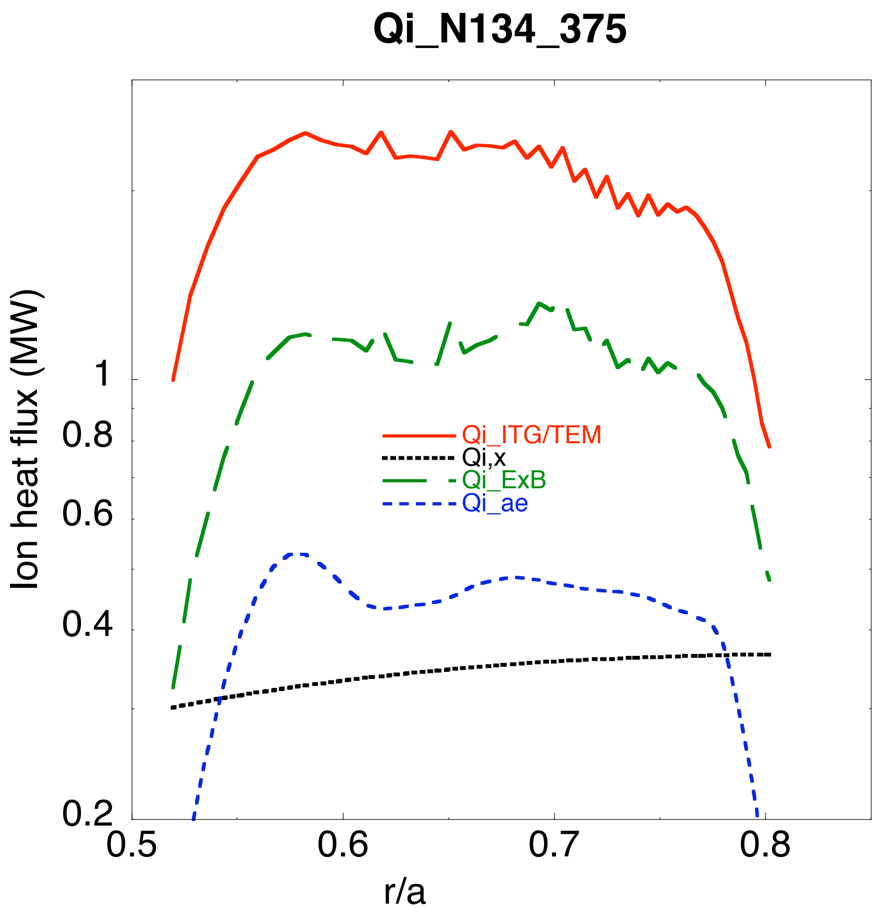
EFIT and TRANSP maps from R to r are similar for these shots.
Could use EFIT equilibria in TRANSP;
 this will be done when the MSE system is mature.
q near r/a~0.5 is uncertain without data from plasma interior.
 Repeat experiments in 2005 to obtain MSE data.

Estimate of background E_r is based on measured v_{tor} and
 NCLASS calculation of v_{pol}.

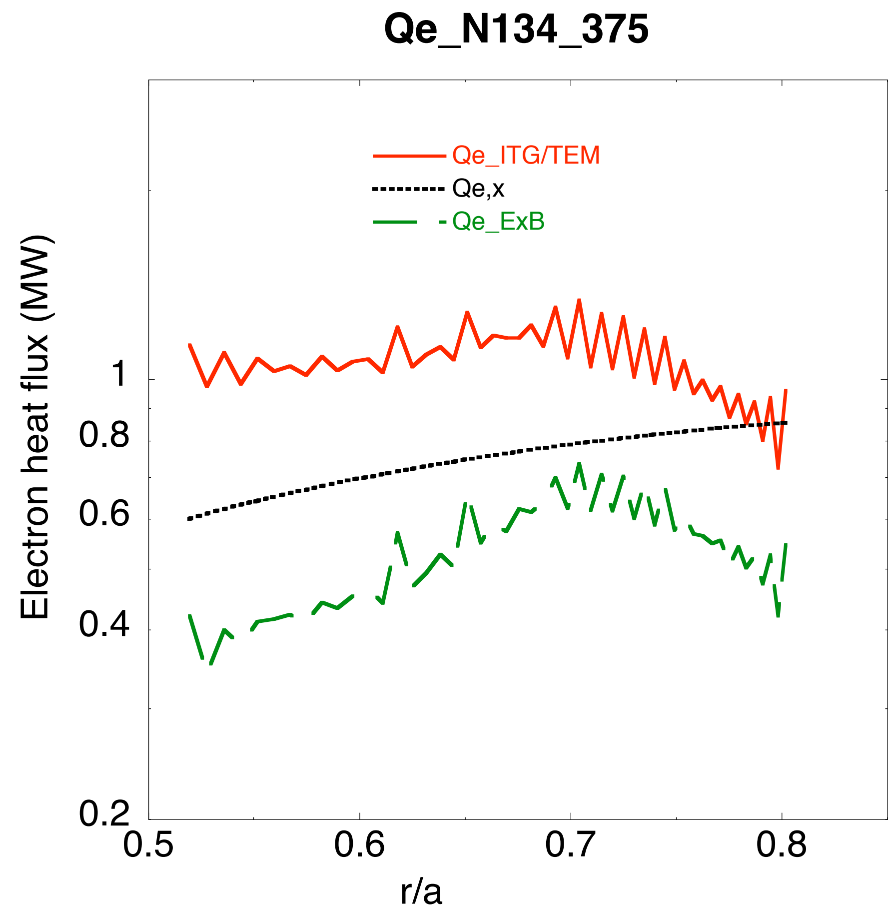

Qi_N115_375
Qi_ITG/TEM
Qi,x
Qi_ExB
Qi_ae
Ion heat flux (MW)
10
1
0.1
0.4
0.5
0.6
0.7
r/a


Qe_N115_375
Qe_ITG/TEM
Qe,x
Qe_ExB
Electron heat flux (MW)
10
1
0.1
0.4
0.5
0.6
0.7
r/a

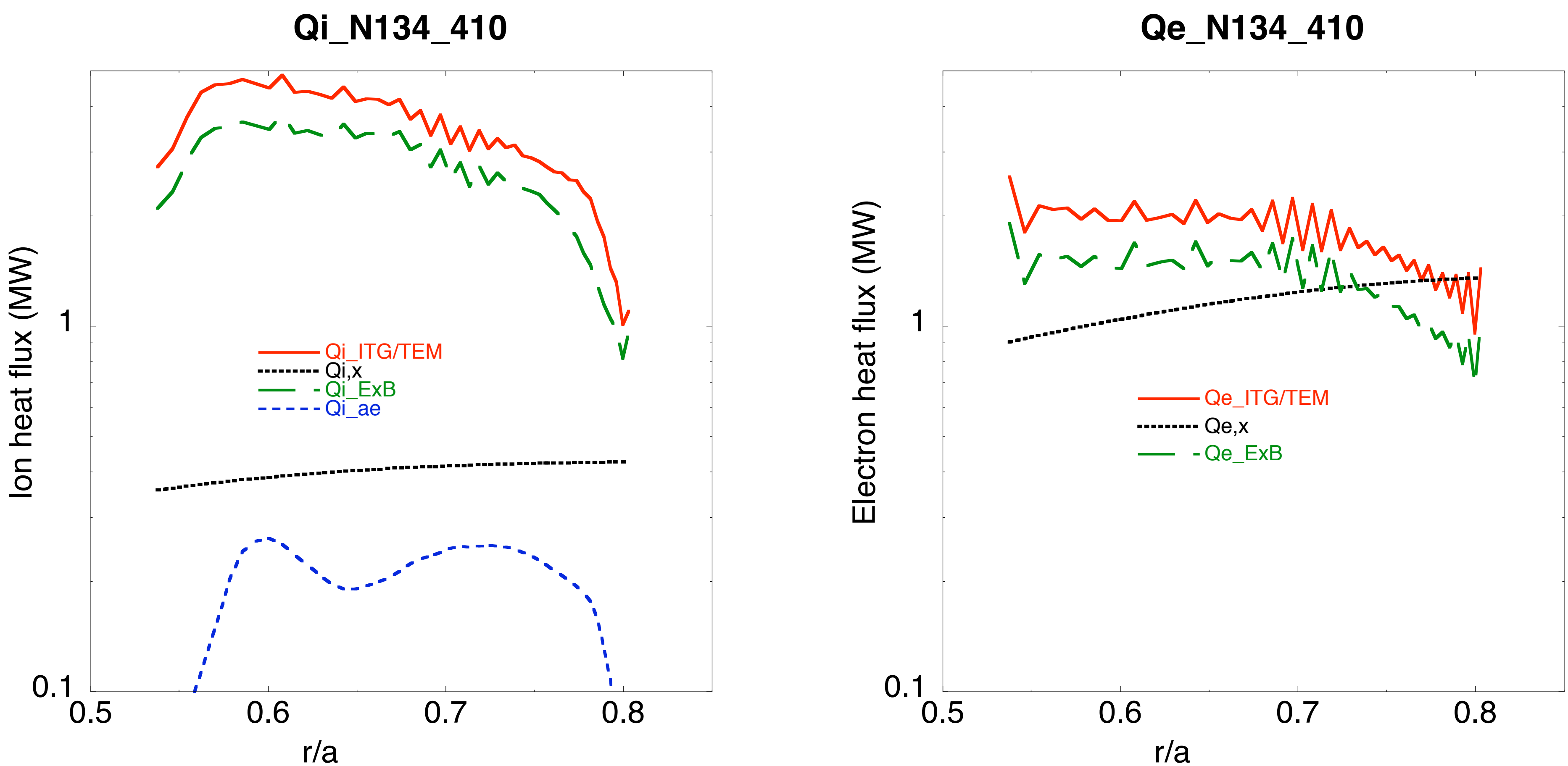

Qi_N115_410
Ion heat flux (MW)
r/a
0.1
1
10
0.4
0.5
0.6
0.7
Qi_ITG/TEM
Qi,x
Qi_ExB
Qi_ae
Qe_N115_410
Electron heat flux (MW)
r/a
0.1
1
10
0.4
0.5
0.6
0.7
Qe_ITG/TEM
Qe,x
Qe_ExB



Qi_N134_375
Ion heat flux (MW)
1
0.8
0.6
0.4
0.2
0.5
0.6
0.7
0.8
r/a
Qi_ITG/TEM
Qi,x
Qi_ExB
Qi_ae



Qe_N134_375
Electron heat flux (MW)
1
0.8
0.6
0.4
0.2
0.5
0.6
0.7
0.8
r/a
Qe_ITG/TEM
Qe,x
Qe_ExB


Qi_N134_410
Ion heat flux (MW)
1
0.1
0.5
0.6
0.7
0.8
r/a
Qi_ITG/TEM
Qi,x
Qi_ExB
Qi_ae
Qe_N134_410
Electron heat flux (MW)
1
0.1
0.5
0.6
0.7
0.8
r/a
Qe_ITG/TEM
Qe,x
Qe_ExB

Summary of Simulation Results

1) "Pure" ITG simulations (adiabatic electron response) with no ExB shear have transport fluxes near the actual power levels. However,

2) A kinetic electron treatment greatly increases the long-wavelength transport by more than an order of magnitude. This is not ETG activity, it is only TEM boosting the ITG - a well established synergy.

3) Finally, including ExB shear derived from the measured v_{tor} often *nearly* completely stabilizes the turbulence found in 2) and predicted transport fluxes are comparable the actual heating power.

4) Predicted ion heat flux is higher than the electron heat flux, but the experimental analysis reverses that ordering.

Verification: convergence testing

Varied numerical grid, produced small changes in predicted power flows:
(standard settings in green, variation in red)

Number of toroidal modes: 8 → 16

Number of trapped/passing pitch angles: 4 → 8

Number of orbit segments (error 1/N^4): 9 → 6

Number of energies in modified Gauss-Laguerre integration: 8 → 16

Validation Plan

Begin with nominal measurements of plasma parameters, then
vary them within uncertainties to:
1) estimate the uncertainty of the turbulence predictions, and
2) identify the important input parameters.

Compare predicted power fluxes with experimental transport analysis.
Compare fluctuation level and correlation length.

Look for simulations that *simultaneosly* match with
the measured power fluxes, and
measured fluctuation level, and radial correlation length.

Does a simultaneous match occur robustly, independent of which
input parameters are 'tuned' to produce a match?